Determination of the relative favourability of sites in the Arctic by topoclimatic modelling.

Clement Yuen Yau. Leung

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LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS RÉCU
DETERMINATION OF THE RELATIVE FAavourABILITY OF SITES
IN THE ARCTIC BY TOPOCLIMATIC MODELLING

by

Clement Yuen Yau Leung

A Thesis
submitted to the Faculty of Graduate Studies
through the Department of
Geography in Partial Fulfillment of the
requirements for the Degree
of Master of Arts at
The University of Windsor

Windsor, Ontario, Canada
1978
ABSTRACT

DETERMINATION OF THE RELATIVE FAVOURABILITY OF SITES IN THE ARCTIC BY TOPOCLIMATIC MODELLING

by

Clement Yuen Yau Leung

In the Arctic, energy and water budgets on rugged terrain may differ widely from those on a horizontal surface. Vegetation in this region is extremely sensitive to the local climate and may serve as an indicator of site favourability in terms of climatic stress. This study makes use of wind and global solar radiation to demonstrate the relative favourability of sites. Broughton Island (67.5 N, 64.1 W) and its adjacent Baffin coast were chosen as the test area. Seasons were defined for the area using a method based on melting-degree days. Average daily global solar radiation was computed for the spring, summer and autumn seasons based on the modified computer program developed by Garnier and Ohmura (1968). With the use of extreme wind conditions, the wind speeds at various sites on Broughton Island were calculated using empirical formulas derived from the logarithmic wind profile equation and experimental data. The SYMAP and SYMVU computer programs were employed to construct the various maps. Composite relative favourability index maps for wind and for global solar radiation were also constructed to depict the relative favourability of sites. Evidence from air photos and satellite imagery as well as field surveys support the findings. It is suggested that the method is generally applicable to coastal areas in the Arctic.
DEDICATED TO:

All the Friends of the Arctic
ACKNOWLEDGEMENTS

I would like to give my deepest and most sincere thank to my advisor, Dr. John Jacobs, who has been taking pain and patience to offer me his help and encouragement both as a teacher and as a friend. I am especially in debt to him for offering me a trip to Baffin Island in summer, 1976 to broaden my knowledge and taking wind observations in the Lake Harbour area in summer, 1977 on my behalf.

I would also like to thank Professor Ron Welch for cartographic advice and Dr. S. Tang for his assistance in the processing of the SYMAP and SYMVU/computer programs.
PREFACE

The Arctic and the Antarctic are probably the only regions left without much pollutions and contamination. At present the Arctic is still relatively unknown to most people. Many used to think of the Arctic as being uninhabitable, snow and ice covered all year round, almost lifeless and having little value for mankind. The recent exploration for resources has drastically changed the overall view of this remote region; and the development of its resources is now well underway. Studies have suggested that the Arctic has a delicately balanced environment for life, and mismanagement could result in destruction of this balance. Protection of the Arctic landscape very much depends on the results of environmental studies, and the present paper aims at such a purpose.
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CHAPTER ONE

INTRODUCTION

The term "topoclimate" as suggested by C.W. Thornthwaite (1933) has an intermediate position between macroclimate and microclimate, and is used to describe the subdivision of general climate dealing with relationships between landforms and local climates (Geiger, 1969). The most direct way of establishing topoclimate is to set up a network of observation stations on different and significant locations of a terrain. The accuracy thus very much depends on the density of the network.

As early as 1924 Shreve found that radiation differences on slopes were reflected by soil temperatures, that is, soil on the south-facing slope had temperatures higher than that on the north-facing slope. For sites in the Santa Catalina Mountains near Tucson, Arizona, he found average differences of as much as 10°C in maximum temperatures and 5°C in minimum temperatures between north and south-facing slopes.

Pioneer work in topoclimatology in a more restricted sense began with Wilhelm Schmidt (1928), who established a network of bioclimatological stations on the Lower Innze Lake, 100 km. southwest of Vienna, to assess the influence of prevailing climate on plants and animals. Maximum and minimum thermometers at three heights above and below the soil surface were installed in thirteen stations set up at elevations between 610 and 1530 meters. In 1938 A.B. Tinn analyzed the observations of twelve stations in the area of Nottingham in order to determine the influence of topography as a function of the prevailing weather situation.
From the beginning of World War II, research in topoclimatology became more refined. More stations were used and more climatic elements such as humidity, fog, frost as well as wind and temperatures were studied. Up to the early fifties, most of these studies were descriptive with few actual climatic maps. It was not until Knock (1952) that the mapping of topoclimate became important with the application of topoclimatic maps to agriculture and land planning. The first annual radiation maps were constructed by Wagner (1955) using observational data at the upper Vogtland area. Thams (1955) measured sunshine duration and constructed isohel maps (maps with lines of equal possible sunshine duration) in the Magadina plain (Italy) surrounded by high mountains. These maps were used to decide where tobacco should be planted.

Recent research in topoclimatology includes Goltsberg's study (1967) on radiation distribution on slopes and the wind regime of hilly terrain in the U.S.S.R. with the use of vast amount of data. Carnier and Ohmura (1968) developed computer programs to obtain direct and global solar radiation on slopes with high accuracy. The mountain wind systems were discussed by Flohn (1969) in great detail, and Geiger (1969) reviewed the methodology of topoclimatology and suggested directions for further research.

Studies of topoclimate in the Arctic are relatively few. Porsild (1957), a botanist working with the Arctic flora, found that the plants are extremely sensitive to the local or microclimate, which is a response to topography. The present study concentrates on such relationships with the main emphasis on solar radiation and wind which control temperatures. The adverse effect of windchill and abrasion is also considered.
CHAPTER TWO

TOPOCLIMATOLOGY AND THE ARCTIC

The main concern of this study is the way in which Arctic landscape modifies the local climate which in turn exerts influences on plants, animals and men. Landforms, described as hills, mountains and valleys, etc., can influence the local climate so that energy and water budgets on rugged terrain differ widely from those on a horizontal surface.

In terms of wind, the influence of hills and mountains can modify the airflow and hence the precipitation patterns and water balance of the region. Orographic precipitation results when moist air is forced to rise by mountain ranges lying across the path of the wind. The windward side of the mountain will usually have sufficient moisture while on the leeward side where the descent of dry, warm air occurs, a dry belt called the rain shadow may exist. In some cases, this leeward flow may cause rapid evaporation of snow or soil moisture. Through turbulent mixing, the moisture régime of an area can be affected, depending on the moisture content of the air. On the other hand, snow may be carried along by the wind from the windward slopes and accumulate leeward. This accumulated snow will then affect the water-budget of its adjacent area when melting. Crevices, hollows and surfaces normal to the wind tend to receive more precipitation. On the energy budget side, the summit and windward side of a mountain experience stronger wind, while on the leeward side the mountain itself serves as a barrier and the wind is generally reduced there. Vegetation is subject to the influence of wind by means of its destructive
mechanical action and effects on moisture distribution.

In terms of radiation, the position of a slope determines the amount of direct solar radiation — the main source of heat energy it will receive at any time. The position of a slope is in turn determined by its gradient (expressed as an angle) and aspect (expressed in terms of azimuth clockwise from true north).

At any moment, a surface will receive the maximum amount of direct solar radiation if it is aligned normal to the sun's ray. The larger the angle between the normal of the surface and the ray's path striking that surface the lesser amount of radiation the surface will receive. Therefore, at any instant, slopes with different positions will receive different amounts of direct solar radiation. Some may receive the maximum value while others may receive none at all. Since the earth rotates and the position of a slope relative to the sun changes throughout the day, the differences in daily totals received on different slopes may not be great compared with differences in the hourly totals. Nevertheless, in high latitude regions where the sun angle is always low, the effect of slope on received radiation is often important. For example, those sites receiving more radiation will have earlier snow-melt in spring and delayed snow-cover in autumn. Consequently, with the more available moisture and larger heat budget these sites can have longer growing seasons, with other factors being equal.

In the Arctic, the importance of topoclimatic can be evidenced by the fact that at some sites, particularly the south-facing slopes, heat may be just sufficient to support plant life (Geiger, 1957), hence, vegetation may serve as an indicator of site favourability. In addition, many campsites used by contemporary Inuit of the area as well as by their ancestors are found to have locally optimum climatic situations (Jacobs and Sabo, 1978). Therefore studies using
different topoclimatic parameters of these sites as compared to others might give an insight as to what degree they are more favourable in the bioclimatic sense.

As the development of the Arctic for its rich resources is undertaken more and more intensively, distance, terrain and climate are major problems to be solved especially in the mining industry. The operation of the mine is not to be interfered with by the year-round cycle of the Arctic climate. Men must be able to work in comfort in all climatic conditions. Installations must be designed to withstand the effect of low temperatures and strong winds. When energy conservation is to be considered, houses built on sheltered sites would have the advantage of lessening the amount of heat loss and thus reducing the amount of fuel necessary for heating. Knowledge of the energy budget of the area thus plays an important role in the study of natural environment as well as human activities. With its diverse topography and severity in climate, the Arctic region would be a significant place for the study of topoclimate.
CHAPTER THREE

THE MODEL

In regions of complex topography, every place is characterized by its particular location and situation, and thus by its own unique microclimate. Attempts have been made in climatology to produce cartographic pictures so as to convey the most information in the most abbreviated form. Geiger suggested two basically different ways for the approach of mapping of climate — either individual elements can be mapped, thus producing temperature and precipitation maps, fog or thunderstorm frequency maps, and so on, or an attempt can be made to arrive at a single composite form of representation (Geiger, 1973).

The second type of representation is not easily achieved, since many meteorological parameters do not combine easily. When long term data are available, the mapping of individual elements can be done with ease, though manipulation of the data might become necessary.

The present study is for the purpose of depicting visually the location of relatively favourable sites when the whole area in question is affected by a certain climatic pattern. With different inputs of topoclimatic parameters, a model can be designed to determine the relative favourability or severity of a particular place as a function of its topography in relation to the chosen climatic parameters. Numerical values as well as representative indices may be generated which then can be mapped to show the microclimatic picture of the area. Ideally such an approach should be able to make use of readily obtainable topographic, climatic and remote sensing data without the need for site surveys.
CHAPTER FOUR

METHOD

The approach basically requires a topographic map with corresponding air photos covering the area in question. Large scale maps are preferred for maximum accuracy. Usually a scale of smaller than 1:250,000 would be difficult to work with since much detail will be omitted during the mapping process. Contour interval is particularly important since the smaller the interval, the more detail of terrain and slopes will be shown. Obviously the more detailed the map, the better the precision of the method. Air photos are necessary to distinguish small features often omitted on topographic maps.

Theoretically, a reference point in the study area is given a value from observed data, for example, wind data from a weather station. Subsequently a value is calculated for every location in that area according to its situation in relation to the reference point. Computer mapping is employed to give a fast and objective means to interpolate the values for each location.

I. The SYMAP Mapping Program

To present the relative favourability of sites of an area the computer program called SYMAP is employed. The program is designed to produce maps which graphically depict spatially disposed quantitative and qualitative information. When raw data are read into the computer they may be related, manipulated, weighted, and aggregated in any manner desired with the selection of various packages and options included in the program. By assigning values to the coordinate locations of data points, one to three basic types of
map, contour, conformant and proximal may be produced. Since intermediate values based on proximity to a data point are required to suit the purpose of the present study, proximal maps together with contour maps are used.

A base map is first produced to show the outline of the study area. Depending on the complexity of the local relief data points or imaginary stations are to be selected on the topographic map subjectively. Generally areas of complicated relief will have more data points while less complicated ones will have fewer. Also each data point should be representative of the terrain immediately surrounding it. The more data points a map contains, the more detail the map has, but crowding the map with too many data points would be impractical and meaningless for the purpose of computer mapping. After all the data points are chosen, their coordinates are recorded. The value of a particular climatic parameter is calculated for every data point or "station", and the computer interpolates values for all other adjacent points. The output map is in the form of aggregated symbols for the study area, and each symbol point on the map represents a value appropriating the input data of a certain climatic parameter. The input for the IBM 360 computer is cards, therefore the program will have to be punched on cards. For the present study the "User's Manual for Computer Mapping 'SYMAP', Version V" published by the Department of Geography, University of Windsor, 1974, is being used.

II. The Study Area

Broughton Island*(67.5 N, 64.1 W) and part of the eastern Baffin coast adjacent to it (Figures 1 and 2), were chosen as the test site for the model. This more or less triangular-shaped island located about 100 km. north of the Arctic Circle has a wide variety of topographic diversity, well representing the relief of the region. Across Broughton Harbour west of the island is Cumberland Peninsula of Baffin.
Figure 1. Location map of Broughton Island.
Figure 2. Broughton Island and vicinity.
Island with the Penny Ice Cap at an elevation of 2000 m. above sea level some 70 km. away.

The island measures 17.5 km. along its longitudinal axis which is oriented roughly in the true north-south direction, and is 13.5 km. across at its widest part. The island is hilly except on the west side where Broughton village is located (Figure 3). Cliffs are common features on the northwest, northeast, east and the southeast corner. At the foot of these cliffs beaches with slopes less than 10 degrees are usually found (Figure 4). The highest elevation is 600 m.a.s.l. at the southeast side of the island.

On the highest peak at the southeast side of the island is a Distant Early Warning (DEW-line) radar station which is also the official synoptic weather station Broughton Island in the Atmospheric Environment Canada (A.E.S.) register. The twenty years of record for this station provide an ample data base for the present study.

In June 1971, a climatological station was established 10 km. west of the DEW-line station near sea level at the village site by Jacobs (1973) for the Institute of Arctic and Alpine Research, University of Colorado. The station was listed as Broughton Village with the temperature record published in the Monthly Meteorological Summary of the A.E.S. In 1973, from June to December inclusive, hourly measurements were made by Jacobs of wind speed, temperature and radiation. All these data provide the basis for the present study. The hydrographic map of "Broughton Island and Approaches" (Map number 7184) published by the Canadian Hydrographic Service, Marine Science Branch of the Department of Mines and Technical Surveys (1964 edition) was used to produce the base map in the SYMAP computer program. The map scale is 1:50,000 and the area under study is represented by a size of 38 cm. x 48 cm. on the map, the contour interval being 500 ft. (152 m.). To aid in mapping the details, air photos of the area (photo number A16985-3,
Figure 3. Broughton Island — looking towards the southwest.

Figure 4. Cliffs and beaches on the northeast side of Broughton Island.
A16985-4, A16985-5, A16985-6, A16985-55) were obtained from the National Air Photo Library in Ottawa, Canada. These air photos were taken in late summer when snow cover is at a minimum, and topographic features can be identified without much difficulty.

In addition to the above information, a trip to Brroughton Island and vicinity was made by a research team headed by Jacobs and of which the author was a member in the summer months of July and August. More information on winds, slopes as well as the locations of lush vegetation and old Thule dwelling sites have become available for this model.

III. Selection of Topoclimatic Parameters

The selection of the parameters is chiefly based on the climate of slopes, since different heights, aspects and gradient could result in great diversity of local climate. For the present study, wind and global solar radiation are considered due to their central role in determining climate through the energy budget.

Wind is the most important determinant of the relative favourability of a site in terms of human comfort and plant survival. Wind chill, or convective heat loss from the body, depends on wind speed and air temperature. On a synoptic scale at any given time an air mass has more or less even temperatures, and therefore a small area in the Arctic may have approximately the same temperature everywhere at a particular height. This is not the case with wind speed since sheltered locations experience less wind and are therefore more favourable than exposed ones. In addition, winds from certain directions may be stronger, colder and more frequent than those from other directions; thus making the relative favourability of sites even more complicated but interesting to study.

Global solar radiation is the main component of the heat budget of a surface in summer. In the Arctic once a
shadow is cast on a spot, loss of surface energy is immediate partly due to insufficient heat storage, and partly due to the big contrast between surface and ambient air temperatures. When relative favourability of sites is desired, the direct solar radiation can be used since it provides relative values. For a more realistic energy budget of the area global solar radiation should be used, provided the transmissivity and the coefficient of diffused sky radiation are known.

IV. Defining the Seasons

It is necessary to compare the favourability of sites in different seasons, since one site may be climatologically more favourable than other sites in a given season but less favourable in another. Conventional seasonal names are applicable in the Arctic in some restricted sense, since their duration is irregular from year to year. Barry and Hare (1976) used the amount of snow cover found that for the middle Arctic the winter season lasts 6–8 months, spring 1 month, summer 2–3 months and autumn 1–2 months. For the present study a more definite method based on mean melting degree-days is used. In a given year, the spring season is defined as the period from the first date when the mean air temperature rises above freezing to the date after which the number of above-freezing days following is greater than that of below-freezing days preceding them. The summer season begins immediately after the last day of spring until the date when the number of below-freezing days following is greater than that of above-freezing days preceding them.

Autumn follows the last date of summer until the last date with above-freezing mean air temperature. Winter is then the period between autumn and spring.

For an area with quite a long climatological record, the four seasons can be first picked out for each year according to the above method. Daily maximum and
minimum temperatures for each station in the Arctic region can be found in the Monthly Meteorological Summary (Atmospheric Environment Service). Though the present analysis was done manually, for large numbers of stations computer analysis could be done. When the four seasons of every year are differentiated, the representative seasons are determined by taking the median of the mid-season among the years so as to eliminate the effect of extremes. The mode seems to be impractical due to the variability in seasonal length and limited record for most Arctic stations.

For Broughton Island and vicinity the seasons are selected using data from 1959 to 1975, a total of 17 years (Table 1).

Table 1. --The four seasons of Broughton Island

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Period</th>
<th>Median date</th>
<th>Length of season (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>May 31-Jun 22</td>
<td>Jun 11</td>
<td>23</td>
</tr>
<tr>
<td>Summer</td>
<td>Jun 23-Aug 20</td>
<td>Jul 22</td>
<td>59</td>
</tr>
<tr>
<td>Autumn</td>
<td>Aug 21-Sep 15</td>
<td>Sep 4</td>
<td>29</td>
</tr>
<tr>
<td>Winter</td>
<td>Sep 19-May 30</td>
<td>Jan 24</td>
<td>254</td>
</tr>
</tbody>
</table>

Since the data used are from the Broughton Island DEW-line station at an elevation of 600 m.a.s.l., one can expect some variations in the seasonal pattern at other locations, especially on slopes of different aspects. As a matter of fact, the difference in temperatures between the DEW-line station and the village site (10 m.a.s.l.) is generally small due to frequent inversion (Jacobs, 1974) and the above scheme can be considered as applicable to the area in general.
CHAPTER FIVE

GLOBAL SOLAR RADIATION

The global solar radiation is defined by the World Meteorological Organization as the downward direct and diffuse solar radiation as received on a horizontal surface from a solid angle of $2\pi$ (1965).

Following the usual transmission law (Haltiner and Martin, 1957), the direct solar radiation intercepted by a surface on the earth oriented perpendicular to the sun's ray is

$$I = I_0 \left(\frac{r}{R}\right) q^m$$

where $I$ is the direct solar radiation expressed in langleys per minute, $I_0$ is the solar constant, $r$ and $R$ are respectively the instantaneous and mean distances of the earth from the sun, $q$ is the mean-zenith-path transmissivity of the atmosphere, and $m$ is the optical air mass.

Since at any one time not all surfaces are perpendicular to the sun's rays, the direct solar radiation for all other surfaces can be calculated by

$$S = I \cos Z$$

where $S$ is the vertical component of direct solar radiation, and $Z$ is the zenith angle of the sun.

The zenith angle of the sun at any instant can be derived from spherical trigonometry (Humphreys, 1940) as a function of solar declination, latitude and the hour angle

$$\cos Z = \sin \phi \sin d + \cos \phi \cos d \cosh$$

where $\phi$ is the latitude of the observation point, $d$ is the declination and $h$ is the hour angle or the angle through which the earth must rotate to bring the meridian of the observation point directly under the sun.
For a sloping surface, it then follows from the cosine law of spherical trigonometry (Sellers, 1965) that
\[ S' = I \frac{\cos \theta \cos i + \sin \theta \sin i \cos(a - a')}{\cos \theta} \]
where \( S' \) is the instantaneous direct solar radiation on the sloping surface, \( i \) is the angle of the slope, \( a \) is the azimuth angle of the sun from the south, and \( a' \) is the azimuth of the normal to the vertical surface from the south.

When the coefficient of diffuse solar radiation is known, the global solar radiation received on a sloping surface then simply becomes
\[ K_g = S'(1 + D) \]
where \( K_g \) is the global solar radiation, \( D \) is the coefficient of diffuse flux.

A computer program developed by Garnier and Ohmura (1968) was modified to calculate the hourly global radiation at Broughton Island (Appendix A). The input data include declination, latitude, transmissivity, coefficient of diffuse radiation and direct solar radiation.

Transmissivity and the coefficient of diffuse radiation for each season are computed by using the radiation data already published by Jacobs (1974). The average declination is chosen for each season to compromise for the extremes. The values for extra-terrestrial radiation are conveniently selected from a table prepared by Garnier and Ohmura (1969). The optical air mass is calculated in the computer program by the formula
\[ m = \sec \theta \]
When \( \theta \) exceeds 70°, the secant approximation for \( m \) is invalid and its value given in the Smithsonian Meteorological Tables (List, 1966, p.417) is used.

The radiation values were calculated for the spring, summer and autumn seasons while those for winter were omitted due to the insignificance of solar radiation during that period (Table 2).

The print-out is in form of tables with the amount of global radiation in langleys per hour for each hour on a
TABLE 2. --Radiation data for Broughton Island (67.5°N)

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmissivity, $\varepsilon$</td>
<td>0.80</td>
<td>0.77</td>
<td>0.81</td>
</tr>
<tr>
<td>Coefficient of diffuse radiation, $D$</td>
<td>0.18</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>Extra-terrestrial radiation*</td>
<td>1.94</td>
<td>1.94</td>
<td>1.99</td>
</tr>
<tr>
<td>Declination, $d$</td>
<td>22.6</td>
<td>17.7</td>
<td>7.0</td>
</tr>
</tbody>
</table>

*Calculated by $I (\frac{H}{F})$

specific day for a surface with a given slope and azimuth.

For mapping purposes, transparent overlays were constructed to measure the gradient, azimuth and illuminated hours. The gradient-azimuth overlay can be constructed by drawing a compass rose of 360° with 10° intervals. With the topographic map of Broughton Island having a vertical interval of 500 ft. (152 m.) a slope with a gradient of $\theta$ will have a horizontal distance of $x$ meters (Figure 5).

\[ x = \frac{152}{\tan \theta} \text{ m.} \]

![Figure 5](image)

When represented on the map it is equal to

\[ x' = \frac{x}{50000} \times 100 \text{ cm.} \]  

(Table 3)

TABLE 3. --Calculation of $x'$

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$ (m.)</td>
<td>862</td>
<td>418</td>
<td>263</td>
<td>181</td>
<td>128</td>
<td>88</td>
<td>55</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>$x'$ (cm.)</td>
<td>1.7</td>
<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

For a given station on the topographic map,
the centre of the overlay (Figure 6) is first placed on the top of the hill where the station is situated. The 0-180 radial is aligned in a true north-south fashion so that the radial passing through that station indicates the azimuth of its slope. The centre of the overlay is then moved to a contour adjacent to that station. If the station is in between two contours either the higher or the lower one should be centered. If the overlay is centered on the higher contour the gradient reference line at which the lower one is touching or closest to it should be checked, and that gradient is the angle of the slope of that station. If the overlay is centralised on the lower contour then

Hill tops are assumed to be horizontal surfaces. The hourly global radiation can then be found from the tables described above.

To find whether a point or a station at a certain hour is under shadow due to blocking by its surrounding higher relief or not a second transparent overlay is
constructed. The zenith angle is worked out as before and the altitude of the sun is
\[ a = 90^\circ - Z \] (Figure 7)

For a station on a hill side or beside a hill the altitude of the sun and the height of the hill are critical for the amount of solar radiation received by it. Since the height of the obstruction (using the contour interval of 152 m.) is fixed, and the gradient and the azimuth of the station are also constant, the determinant of whether the station is illuminated or not at a certain time is the altitude of the sun, which is a function of the hour angle for a given latitude and declination.

For any altitude of the sun, if the horizontal distance between the hill top and the station is less than c (Figure 8) the station is shadowed and the radiation supposed to be received in those hours (since a is a function of h) is subtracted from the daily total.

The overlay for each season is constructed (Figures 9-11) using respectively tables 4-6.
TABLE 4. Data required to construct the overlay for shadow effect in spring at Broughton Island (d=22.3)

<table>
<thead>
<tr>
<th>Time of day (LAT)</th>
<th>Hour angle</th>
<th>Z</th>
<th>A</th>
<th>c (m.)</th>
<th>Equivalence on map (cm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>noon</td>
<td>0°</td>
<td>45°</td>
<td>45°</td>
<td>152</td>
<td>0.3</td>
</tr>
<tr>
<td>1100</td>
<td>15°</td>
<td>46°</td>
<td>44°</td>
<td>157</td>
<td>0.3</td>
</tr>
<tr>
<td>1000</td>
<td>30°</td>
<td>49°</td>
<td>41°</td>
<td>175</td>
<td>0.4</td>
</tr>
<tr>
<td>0900</td>
<td>45°</td>
<td>53°</td>
<td>37°</td>
<td>202</td>
<td>0.4</td>
</tr>
<tr>
<td>0800</td>
<td>60°</td>
<td>58°</td>
<td>32°</td>
<td>243</td>
<td>0.5</td>
</tr>
<tr>
<td>0700</td>
<td>75°</td>
<td>64°</td>
<td>26°</td>
<td>312</td>
<td>0.6</td>
</tr>
<tr>
<td>0600</td>
<td>90°</td>
<td>69°</td>
<td>21°</td>
<td>396</td>
<td>0.8</td>
</tr>
<tr>
<td>0500</td>
<td>105°</td>
<td>75°</td>
<td>15°</td>
<td>567</td>
<td>1.1</td>
</tr>
<tr>
<td>0400</td>
<td>120°</td>
<td>80°</td>
<td>10°</td>
<td>862</td>
<td>1.7</td>
</tr>
<tr>
<td>0300</td>
<td>135°</td>
<td>84°</td>
<td>6°</td>
<td>1446</td>
<td>2.9</td>
</tr>
<tr>
<td>0200</td>
<td>150°</td>
<td>87°</td>
<td>3°</td>
<td>2900</td>
<td>5.8</td>
</tr>
<tr>
<td>0100</td>
<td>165°</td>
<td>89°</td>
<td>1°</td>
<td>8708</td>
<td>17.4</td>
</tr>
</tbody>
</table>

![Reference line](image)

**Scale -- 1:50,000**

**Figure 9. Overlay for spring shadow effect.**
### TABLE 5. — Data required to construct the overlay for shadow effect in summer at Broughton Island (d=17.7)

<table>
<thead>
<tr>
<th>Time of day (LAT)</th>
<th>Hour angle</th>
<th>$\gamma$</th>
<th>$a$ (m.)</th>
<th>$c$ (m.)</th>
<th>Equivalence on map (cm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>noon</td>
<td>0°</td>
<td>50°</td>
<td>40°</td>
<td>180</td>
<td>0.4</td>
</tr>
<tr>
<td>1100</td>
<td>15°</td>
<td>51°</td>
<td>39°</td>
<td>186</td>
<td>0.4</td>
</tr>
<tr>
<td>1000</td>
<td>30°</td>
<td>53°</td>
<td>37°</td>
<td>204</td>
<td>0.4</td>
</tr>
<tr>
<td>0900</td>
<td>45°</td>
<td>57°</td>
<td>33°</td>
<td>237</td>
<td>0.5</td>
</tr>
<tr>
<td>0800</td>
<td>60°</td>
<td>62°</td>
<td>28°</td>
<td>290</td>
<td>0.6</td>
</tr>
<tr>
<td>0700</td>
<td>75°</td>
<td>68°</td>
<td>22°</td>
<td>375</td>
<td>0.8</td>
</tr>
<tr>
<td>0600</td>
<td>90°</td>
<td>74°</td>
<td>16°</td>
<td>518</td>
<td>1.0</td>
</tr>
<tr>
<td>0500</td>
<td>105°</td>
<td>79°</td>
<td>11°</td>
<td>778</td>
<td>1.6</td>
</tr>
<tr>
<td>0400</td>
<td>120°</td>
<td>84°</td>
<td>6°</td>
<td>1524</td>
<td>3.1</td>
</tr>
<tr>
<td>0300</td>
<td>135°</td>
<td>89°</td>
<td>1°</td>
<td>6392</td>
<td>12.8</td>
</tr>
</tbody>
</table>

![Reference line](image)

**Scale — 1:50,000**

**Figure 10.** Overlay for summer shadow effect.
TABLE 6. — Data required to construct the overlay for shadow effect in autumn at Broughton Island (d=7.0°)

<table>
<thead>
<tr>
<th>Time of day (IAT)</th>
<th>Hour angle</th>
<th>Z</th>
<th>a</th>
<th>c (m.)</th>
<th>Equivalence on map (cm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>noon</td>
<td>0°</td>
<td>61°</td>
<td>29°</td>
<td>269</td>
<td>0.5</td>
</tr>
<tr>
<td>1100 1300</td>
<td>15°</td>
<td>61°</td>
<td>29°</td>
<td>279</td>
<td>0.6</td>
</tr>
<tr>
<td>1000 1400</td>
<td>30°</td>
<td>64°</td>
<td>26°</td>
<td>310</td>
<td>0.6</td>
</tr>
<tr>
<td>0900 1500</td>
<td>45°</td>
<td>68°</td>
<td>22°</td>
<td>370</td>
<td>0.7</td>
</tr>
<tr>
<td>0800 1600</td>
<td>60°</td>
<td>72°</td>
<td>18°</td>
<td>480</td>
<td>1.0</td>
</tr>
<tr>
<td>0700 1700</td>
<td>75°</td>
<td>78°</td>
<td>12°</td>
<td>707</td>
<td>1.4</td>
</tr>
<tr>
<td>0600 1800</td>
<td>90°</td>
<td>84°</td>
<td>6°</td>
<td>1351</td>
<td>2.7</td>
</tr>
<tr>
<td>0500 1900</td>
<td>105°</td>
<td>89°</td>
<td>1°</td>
<td>11280</td>
<td>22.5</td>
</tr>
</tbody>
</table>

Figure 11. Overlay for autumn shadow effect.
To determine whether a station is illuminated part of the hours of the day or not the overlay is placed with its centre at the station in question. If the station is on a contour line the next higher contour should be checked if it intersects the reference line, if so which hours are intersected. Then for those hours the radiation received will have to be subtracted from the daily total found previously (Figure 12). If the station is in between two contours either the lower one should be centered or some estimation have to be made with the use of air photos. The results would be that each imaginary station receives an actual amount of global radiation on a day representative of the average condition at the test site.

Figure 12. Example: solar radiation is blocked from 0700 to 1100 hours.

In order to map the radiation values with the SYMAP program, they are first separated into class intervals of number of langley per day and then each station is assigned a class number for input.

To determine the overall relative favourability of sites at Broughton Island a composite map using data for all three seasons were constructed. A favourability index for each station was calculated by the formula
\[ \frac{R_a}{R_m} \]

where \( I_r \) is the favourability index of global solar radiation, \( R_a \) is the sum of the average daily radiation received respectively for each of the three seasons, \( R_m \) is the sum of the maximum of the daily radiation received respectively for each of the three seasons by an optimum slope. In this case \( R_m = 2180 \) langleys (spring = 816 langleys, summer = 594 langleys, autumn = 598 langleys).

With the use of the subroutine FLEXIN in the SYMAP program, the radiation data from the three seasons already punched on cards can be manipulated.¹

Here \( I_r \) will have a value ranging from 0.0 to 1.0. The sites with the most global radiation received will have the highest favourability index while those with the least global radiation received will have the lowest favourability index.

CHAPTER SIX

THE WIND PARAMETER

The wind parameter is a difficult one to consider since winds are subject to great variations due to the diversity of local topography. When the data of a meteorological station are used they can be applied only to those nearby parts of a region with similar topography. Also, in order to get reliable averages a sufficiently long record must be available.

In general in the Arctic, the average temperatures in the lowest kilometer of the atmosphere at a particular locality show little variation with height due to frequent inversion. This effect has been found to be present at Broughton Island (Jacobs, 1973). Therefore, whether a site is relatively more favourable than another in terms of wind chill depends mainly on the degree of local reduction in wind speed.

Due to friction induced by the roughness of terrain the speed of the surface wind is less than that of the geostrophic wind. This reduction is found experimentally to be non-linear with height, and in many cases is logarithmic (McIntosh and Thom, 1972). The vertical wind shear is largest near the surface and decreases upward. Such a profile can be described by

\[ U_z = B + A \ln Z \]  \hspace{1cm} (1)

where \( A \) is a constant depending on the wind speed and the nature of the surface in question, \( B \) is the appropriate constant of integration, \( z \) is the height above the surface, and \( U_z \) is the wind speed at height \( z \).

Hence, for a given nearly geostrophic wind measured
at the summit of a hill the wind speed at lower heights can be calculated, provided the constants A and B are known.

Ideally, a mast of several hundred meters with anemometers on different heights should be erected in order to obtain the actual wind profile for a certain locality, such as a mountainous area. Since technically this is impractical for the present study, the logarithmic wind profile is assumed to fit the actual wind and the parameters A and B are found using wind speeds measured at the summit and the base.

Hourly wind data with wind measured at about 10 m.a.s.l. are available for Broughton village for 6 months from June to December, 1973 (Jacobs, 1974) and these data provide sufficient information on surface wind. The summit wind data were obtained from the DEW-line station situated on the southeast side of the island at a height of about 600 m.a.s.l. Since the two stations are more than 10 km. apart it is assumed that the village site is independent of the sheltering effect offered by the mountain upon which the DEW-line station is situated (see Figure 2 on page 10).

The wind at the DEW-line is considered to be approximately geostrophic since the station is at the highest elevation within a radius of 16 km. The average wind speeds for the stations during the same period were compared using regression analysis to determine if a relationship exists between the two winds.

The four-time daily observations of wind at the DEW-line station are serving as controls. This means when zero wind conditions are reported there, the corresponding wind data at Broughton village are ignored. This is due to the fact that oftentimes the anemometer at the latter station records some light winds which should not be taken into comparison.

The analysis shows that although there is only moderate positive correlation (+0.5) between winds at the
two sites, the result is significant (Table 7).

<table>
<thead>
<tr>
<th>Number of data pairs</th>
<th>Correlation coefficient</th>
<th>T-test value</th>
<th>Level of significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>596</td>
<td>0.5</td>
<td>13.8</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

The analysis also produced an equation of slope to yield a relationship between winds at the two stations. Unfortunately the equation failed to apply to high wind speed situation and had to be discarded. Hence the ratio of the average wind speeds for the respective stations is used to get a reduction in an average condition. Since the average wind speed for the DEW-line station is 3.5 meters per second and that for the village is 2.8 meters per second, the ratio is then

\[ \frac{2.8}{3.5} = 0.8 \]

Therefore on the average the wind speed at the village site is eight-tenths of that some 600 meters higher. The ratio seems to be justifiable with the large amount of data used.

Consider equation (1); at the Dew-line station (600 m.a.s.l.) the instantaneous wind speed is

\[ U_d = B + A \ln 600 \]

where \( U_d \) represents the wind speed at the DEW-line station, while at the village (10 m.a.s.l.)

\[ U_v = B + A \ln 10 \]

where \( U_v \) represents the wind speed at the village. Equations (2) and (3) are then combined to solve for \( A \)

\[ U_d - U_v = A (\ln 600 - \ln 10) \]

Since \( U_v = 0.8U_d \) as calculated above,

then

\[ U_d (1 - 0.8) = A (\ln 600 - \ln 10) \]

\[ A = 0.05U_d \]
When $A$ is known, the wind speed at a given height $z$ without sheltering can be calculated by the equation

$$U_d - U_z = A (\ln 600 - \ln z)$$

$$U_z = U_d (0.68 + 0.05 \ln z)$$

(4)

where $U_z$ is the wind speed at height $z$.

The above equation is applicable only to open level ground. For hilly terrain the situation is more complicated. According to the research reviewed by E.J. Plate (1971), immediately behind a shelter such as a hill is the standing eddy zone where the wind flow pattern is different from that of the undisturbed boundary layer. Backflow may occur but wind speed is reduced along the slope and some distance downwind of it. Due to the frequent inversion in the Arctic anabatic and katabatic winds are relatively unimportant (Flohne, 1969) while flows around hills or obstacles are quite frequent, as field measurements in the 1976 trip show.

A study of winds on slopes was conducted by Goltsberg (1969) in mountainous areas of Russia. From a large number of observations, he obtained ratios, etc.

Table 8 shows his results for the average ratios between wind speeds at the summit and at different parts of a hill.

**TABLE 8. —Summary of Goltsberg's wind speed ratios**

<table>
<thead>
<tr>
<th></th>
<th>Summit</th>
<th>$1 U$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward slopes</td>
<td>upper part</td>
<td>0.9 $U$</td>
</tr>
<tr>
<td></td>
<td>lower part</td>
<td>0.7 $U$</td>
</tr>
<tr>
<td>Slopes parallel to the wind</td>
<td>upper part</td>
<td>0.8 $U$</td>
</tr>
<tr>
<td></td>
<td>lower part</td>
<td>0.6 $U$</td>
</tr>
<tr>
<td>Leeward slopes</td>
<td>upper part</td>
<td>0.7 $U$</td>
</tr>
<tr>
<td></td>
<td>lower part</td>
<td>0.5 $U$</td>
</tr>
</tbody>
</table>

From Table 8 it is observed that wind reduction is at the maximum on leeward slopes and the minimum on windward slope. For lower parts of all slopes the values do include the reduction due to height (0.8 $U$ in agreement with our
observation as discussed previously). Therefore, if we assumed that Goltsberg's results apply generally in our case, the reduction due to other reasons other than height then becomes

For lower parts of slopes:

- Windward \( 0.8U - 0.7U = 0.1U \)
- Parallel to wind \( 0.6U - 0.5U = 0.2U \)
- Leeward \( 0.8U - 0.5U = 0.3U \)

The 0.1U reduction on windward slopes falls in the 'region of hill influence' where the transition to the highly retarded flow is found (Plate, 1971). This reduction seems to apply to the other two types of slopes also.

Therefore the reduction solely due to sheltering becomes

- Windward \( 0.1U - 0.1U = 0 \)
- Parallel to wind \( 0.2U - 0.1U = 0.1U \)
- Leeward \( 0.3U - 0.1U = 0.2U \)

The reductions due to 'region of hill influence' and sheltering are constant at any point along the slope of the respective hill since when they are added to the respective wind speeds at the upper part of the slope unity is obtained.

For upper parts of slopes:

- Windward \( 0.9U + 0.1U + 0.0U = 1U \)
- Parallel to wind \( 0.8U + 0.1U + 0.1U = 1U \)
- Leeward \( 0.7U + 0.1U + 0.2U = 1U \)

Therefore, for a given direction and speed of wind at the summit, the instantaneous wind experienced at a site at a height \( zz \) on a given slope can be calculated with the following equations.

For windward slopes:

\[
U_{zz} = U_d \left(0.68 + 0.05 \ln zz\right) - 0.1U_d = U_d \cdot (0.58 + 0.05 \ln zz) \tag{5}
\]

For slopes parallel to the wind:

\[
U_{zz} = U_d \left(0.68 + 0.05 \ln zz\right) - 0.2U_d
\]
\[ U_{zz} = U_d (0.68 + 0.05 \ln zz) - 0.3U_d \]
\[ = U_d (0.38 + 0.05 \ln zz) \]  

According to the shelterbelt hypothesis, sheltering on level ground decreases with increased distance downwind from the base of the slope until full strength of the wind is resumed. Calculations done by Plate (1957) show that this distance is larger than 35 h, where h is the height of the shelter. A similar result was obtained by Nageli (1941). For a very dense shelterbelt sheltering is non-linear with decreases dropping tremendously after a few multiples of shelterbelt height (Figure 13).

![Figure 13. The effect of a very dense shelterbelt. (After W. Nageli)](image)

Measurements were carried out recently by Jacobs (1977) in the vicinity of Lake Harbour, N.W.T. in order to establish an estimation of the sheltering effect in a real situation. An isolated hill on the south Baffin coast was selected for the measurement. An MRI mechanical weather station was erected on the summit at an elevation of 200 m.a.s.l. while a totalizing anemometer was located at 10 m.a.s.l. and 200 meters away from the base of the hill. As a result 58 pairs of data covering all four cardinal directions...
were obtained during the 21-day stay. Analysis of those data had produced a sheltering curve with a still sharper drop in sheltering effect (Figure 14). This seems to coincide with Nageli's finding that the denser the shelterbelt is, the sharper the drop in sheltering effect will be.

![Sheltering effect of a hill near Lake Harbour, N.W.T.](image)

Figure 14. Sheltering effect of a hill near Lake Harbour, N.W.T.

For mapping purpose it is more convenient and practical to select a point on the level ground from the slope such that the reduction becomes insignificant beyond that point. Here a linear relationship is assumed for the curve in Figure 14. The Lake Harbour data show an increase in wind speed from 0.5U to 0.8U beyond a distance out on the level from the base of the lee slope equal to the height of the hill (Figure 15). Therefore, if a linear relationship is assumed, the zone of zero sheltering would be

\[
x = \frac{(1 - 0.5)/(0.8 - 0.5)}{1h}
\]

\[
x = 1.7h
\]
Similarly, for the slope parallel to the wind the data show windspeed increases from 0.6U to 0.9U over a distance of 1h (Figure 16).

\[ x' = \frac{(1 - 0.6)/(0.9 - 0.6)}{1h} \times 1h = 1.5h \]

![Diagram](image)

Figure 16.

For the windward side the wind speed at the base of the slope is the same as that at one multiple of shelter height away, in agreement with the predicted behaviour of the shelterbelt of Plate's model (Figure 17).

![Diagram](image)

Figure 17.

In the mapping process the winds are first divided into four quadrants — northwest, northeast, southwest and southeast. For using certain wind speeds measured at the DEW-line station, the wind speeds at different heights are calculated for the respective aspect of the hills using Equations 5, 6, and 7. For wind speeds on the level ground beyond the lee slopes or slopes parallel to the wind rulers in units of multiple heights are constructed according to the following tables (Tables 9 and 10) for a map scale of 1:50,000.
TABLE 9. --Data for the construction of rulers to measure wind reduction on level ground leeward to the wind for different heights of hills (1:50,000 scale)

<table>
<thead>
<tr>
<th>Height of hill (m.)</th>
<th>1.7 multiple height (m.)</th>
<th>Equivalence on map (mm.)</th>
<th>Distance increment (mm.) away from the base of the slope for each 0.1 increase in U</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>1020</td>
<td>20.4</td>
<td>4.1</td>
</tr>
<tr>
<td>500</td>
<td>850</td>
<td>17.0</td>
<td>3.4</td>
</tr>
<tr>
<td>400</td>
<td>680</td>
<td>13.6</td>
<td>2.7</td>
</tr>
<tr>
<td>300</td>
<td>510</td>
<td>10.2</td>
<td>2.0</td>
</tr>
<tr>
<td>200</td>
<td>340</td>
<td>6.8</td>
<td>1.4</td>
</tr>
<tr>
<td>100</td>
<td>170</td>
<td>3.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

TABLE 10. --Data for the construction of rulers to measure wind reduction on level ground parallel to the wind for different heights of hills (1:50,000 scale)

<table>
<thead>
<tr>
<th>Height of hill (m.)</th>
<th>1.3 multiple height (m.)</th>
<th>Equivalence on map (mm.)</th>
<th>Distance increment (mm.) away from the base of the slope for each 0.1 increase in U</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>780</td>
<td>15.6</td>
<td>3.9</td>
</tr>
<tr>
<td>500</td>
<td>650</td>
<td>13.0</td>
<td>3.3</td>
</tr>
<tr>
<td>400</td>
<td>520</td>
<td>10.4</td>
<td>2.6</td>
</tr>
<tr>
<td>300</td>
<td>390</td>
<td>7.8</td>
<td>2.0</td>
</tr>
<tr>
<td>200</td>
<td>260</td>
<td>5.2</td>
<td>1.3</td>
</tr>
<tr>
<td>100</td>
<td>130</td>
<td>2.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Thus the relative wind speed at a site of known elevation on a slope can be obtained by simply picking the value from the appropriate table. For a site on level ground the appropriate ruler (Figure 18) is aligned along the hilltop-station axis on the map in such a way that the end of the ruler marked the most reduction (0.5 for leeward and 0.6 for parallel) is touching the base of the slope. Since the ruler is marked every 0.1U from 0.5U or 0.6U to 1U the mark where the site is situated is the reduction ratio. When the wind speed at the summit is multiplied by this ratio the actual wind speed at the site in question can be determined.
Leeward to the wind

<table>
<thead>
<tr>
<th>Ht. of hill (m.)</th>
<th>600</th>
<th>500</th>
<th>400</th>
<th>300</th>
<th>200</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>2.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Parallel to the wind

<table>
<thead>
<tr>
<th>Ht. of hill (m.)</th>
<th>600</th>
<th>500</th>
<th>400</th>
<th>300</th>
<th>200</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>2.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>2.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>2.9</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 18. Rulers to measure wind reduction on level ground.

It is not particularly useful to map low wind speeds since the reduction is insignificant and differences between sites throughout the area will be minimal. For the study area, winds with speed-range according to the Beaufort Scale were grouped for the different seasons (Table 11) in such a way that in a given season the highest wind speed-range occurs at least once a year on the average from a quadrant that wind would be representative of that quadrant. Without exception the strongest wind are found from the northwest for all seasons and the strength is of the gale force (with a mean speed of 19 meters per second) in winter time (represented by the mid-winter period from January 9 to February, when the lowest temperatures are also attained). Since mid-winter has comparatively the strongest winds for other quadrants the mapping of the actual values was done with reference to this period (Tables 12 and 13). As a result winds from the four quadrants produced four corresponding wind speed maps by the SYMAP program.

With the use of the Broughton Island data, wind speed reduction ratios were calculated by the formula
TABLE 11. --Highest observed wind speeds for Broughton Island by quadrant (1964-76).*

<table>
<thead>
<tr>
<th>Term according to Beaufort Scale</th>
<th>Mean wind speed in m/sec</th>
<th>Winter</th>
<th>Summer</th>
<th>Spring</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NE</td>
<td>SE</td>
<td>SW</td>
<td>NW</td>
</tr>
<tr>
<td>Light Breeze</td>
<td>2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Gentle Breeze</td>
<td>5</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Moderate Breeze</td>
<td>7</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Fresh Breeze</td>
<td>10</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Strong Breeze</td>
<td>13</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Near Gale</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gale</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Based on the average of at least one observation per year.
TABLE 12. —Reduction of wind speed according to height and sheltering for observed extreme winds at Broughton Island (wind speeds in meters per second)

<table>
<thead>
<tr>
<th>Ht (m)</th>
<th>Windward</th>
<th>Parallel wind</th>
<th>Leeward</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>19.0</td>
<td>19.0</td>
<td>19.0</td>
</tr>
<tr>
<td>580</td>
<td>17.1</td>
<td>15.2</td>
<td>13.3</td>
</tr>
<tr>
<td>550</td>
<td>17.0</td>
<td>15.1</td>
<td>13.2</td>
</tr>
<tr>
<td>530</td>
<td>17.0</td>
<td>15.1</td>
<td>13.2</td>
</tr>
<tr>
<td>520</td>
<td>17.0</td>
<td>15.0</td>
<td>13.2</td>
</tr>
<tr>
<td>490</td>
<td>16.9</td>
<td>14.9</td>
<td>13.1</td>
</tr>
<tr>
<td>460</td>
<td>16.9</td>
<td>14.9</td>
<td>13.0</td>
</tr>
<tr>
<td>430</td>
<td>16.8</td>
<td>14.8</td>
<td>12.9</td>
</tr>
<tr>
<td>400</td>
<td>16.7</td>
<td>14.8</td>
<td>12.9</td>
</tr>
<tr>
<td>380</td>
<td>16.7</td>
<td>14.7</td>
<td>12.9</td>
</tr>
<tr>
<td>370</td>
<td>16.6</td>
<td>14.7</td>
<td>12.8</td>
</tr>
<tr>
<td>340</td>
<td>16.5</td>
<td>14.5</td>
<td>12.8</td>
</tr>
<tr>
<td>300</td>
<td>16.4</td>
<td>14.4</td>
<td>12.6</td>
</tr>
<tr>
<td>270</td>
<td>16.3</td>
<td>14.3</td>
<td>12.5</td>
</tr>
<tr>
<td>260</td>
<td>16.3</td>
<td>14.3</td>
<td>12.5</td>
</tr>
<tr>
<td>240</td>
<td>16.2</td>
<td>14.3</td>
<td>12.4</td>
</tr>
<tr>
<td>230</td>
<td>16.2</td>
<td>14.3</td>
<td>12.4</td>
</tr>
<tr>
<td>210</td>
<td>16.1</td>
<td>14.2</td>
<td>12.3</td>
</tr>
<tr>
<td>180</td>
<td>16.0</td>
<td>14.1</td>
<td>12.2</td>
</tr>
<tr>
<td>150</td>
<td>15.8</td>
<td>13.9</td>
<td>12.0</td>
</tr>
<tr>
<td>120</td>
<td>15.6</td>
<td>13.7</td>
<td>11.8</td>
</tr>
<tr>
<td>90</td>
<td>15.3</td>
<td>13.4</td>
<td>11.5</td>
</tr>
<tr>
<td>80</td>
<td>15.2</td>
<td>13.3</td>
<td>11.4</td>
</tr>
<tr>
<td>60</td>
<td>14.9</td>
<td>13.0</td>
<td>11.1</td>
</tr>
<tr>
<td>50</td>
<td>14.7</td>
<td>12.8</td>
<td>10.9</td>
</tr>
<tr>
<td>30</td>
<td>14.3</td>
<td>12.4</td>
<td>10.5</td>
</tr>
<tr>
<td>10</td>
<td>13.2</td>
<td>11.3</td>
<td>9.4</td>
</tr>
</tbody>
</table>

Windward, Parallel wind, and Leeward columns represent wind speeds in meters per second.
TABLE 13. --Reduction of wind speed according to height for observed extreme winds at Broughton Island (wind speeds in meters per second)

<table>
<thead>
<tr>
<th>Height (m.)</th>
<th>Effect of height only</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>19.0 10.0 7.0 5.0</td>
</tr>
<tr>
<td>580</td>
<td>19.0 10.0 7.0 5.0</td>
</tr>
<tr>
<td>550</td>
<td>18.9 10.0 7.0 5.0</td>
</tr>
<tr>
<td>530</td>
<td>18.9  9.9 7.0 5.0</td>
</tr>
<tr>
<td>520</td>
<td>18.9  9.9 7.0 5.0</td>
</tr>
<tr>
<td>490</td>
<td>18.8  9.9 6.9 5.0</td>
</tr>
<tr>
<td>460</td>
<td>18.8  9.9 6.9 4.9</td>
</tr>
<tr>
<td>430</td>
<td>18.7  9.8 6.9 4.9</td>
</tr>
<tr>
<td>400</td>
<td>18.6  9.8 6.9 4.9</td>
</tr>
<tr>
<td>380</td>
<td>18.6  9.8 6.8 4.9</td>
</tr>
<tr>
<td>370</td>
<td>18.5  9.8 6.8 4.9</td>
</tr>
<tr>
<td>340</td>
<td>18.5  9.7 6.8 4.9</td>
</tr>
<tr>
<td>300</td>
<td>18.3  9.7 6.8 4.8</td>
</tr>
<tr>
<td>270</td>
<td>18.2  9.6 6.7 4.8</td>
</tr>
<tr>
<td>260</td>
<td>18.2  9.6 6.7 4.8</td>
</tr>
<tr>
<td>240</td>
<td>18.1  9.5 6.7 4.8</td>
</tr>
<tr>
<td>230</td>
<td>18.1  9.5 6.7 4.8</td>
</tr>
<tr>
<td>210</td>
<td>18.0  9.5 6.6 4.7</td>
</tr>
<tr>
<td>180</td>
<td>17.9  9.4 6.6 4.7</td>
</tr>
<tr>
<td>150</td>
<td>17.7  9.3 6.5 4.7</td>
</tr>
<tr>
<td>120</td>
<td>17.5  9.2 6.4 4.6</td>
</tr>
<tr>
<td>90</td>
<td>17.2  9.1 6.3 4.5</td>
</tr>
<tr>
<td>80</td>
<td>17.1  9.0 6.3 4.5</td>
</tr>
<tr>
<td>60</td>
<td>16.8  8.9 6.2 4.4</td>
</tr>
<tr>
<td>50</td>
<td>16.6  8.8 6.1 4.4</td>
</tr>
<tr>
<td>30</td>
<td>16.2  8.5 6.0 4.3</td>
</tr>
<tr>
<td>10</td>
<td>15.1  8.0 5.6 4.0</td>
</tr>
</tbody>
</table>
\[ R = 1 - \frac{U_{zz}}{U_d} \]

where \( R \) is the wind speed reduction ratio.

The reduction ratios were worked out according to Table 14 and four maps each representing one of the four quadrants were produced. These maps, besides showing the relative favourability of sites at a glance, have the advantage of being general in that actual wind speed at a particular site can be calculated for any instantaneous wind.

**TABLE 14. —Wind speed reduction ratio according to height and sheltering for Broughton Island**

<table>
<thead>
<tr>
<th>Reduction ratio</th>
<th>Windward</th>
<th>Parallel wind</th>
<th>Leeward</th>
<th>Effect of height only</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>10-30 m.</td>
<td>-</td>
</tr>
<tr>
<td>0.4</td>
<td>-</td>
<td>10-30 m.</td>
<td>50-240 m.</td>
<td>-</td>
</tr>
<tr>
<td>0.3</td>
<td>10-30 m.</td>
<td>50-240 m.</td>
<td>260-580 m.</td>
<td>-</td>
</tr>
<tr>
<td>0.2</td>
<td>50-210 m.</td>
<td>260-580 m.</td>
<td>-</td>
<td>10 m.</td>
</tr>
<tr>
<td>0.1</td>
<td>230-580 m.</td>
<td>-</td>
<td>-</td>
<td>30-240 m.</td>
</tr>
<tr>
<td>0.0</td>
<td>summit</td>
<td>summit</td>
<td>summit</td>
<td>250 m. to summit</td>
</tr>
</tbody>
</table>

In order to determine the overall relative favourability of sites at Broughton Island a composite map was constructed incorporating data for all four quadrants. In accordance with findings described previously, the wind speed in the winter season was again chosen for this purpose.

A favourability index for each station was calculated by the formula

\[ I_w = 1 - \frac{S_a}{S_m} \]

where \( I_w \) is the favourability index; \( S_a \) is the sum of the actual wind speeds experienced from the four quadrants, \( S_m \) is the sum of the maximum wind speeds at the DEW-line station from the four quadrants, in this case.
\[ S_m = 19 + 10 + 7 + 5 \]
\[ = 41 \]

Again the subroutine FLEXIN in the SYMAP program was used to manipulate the wind speed data from the four quadrants already punched on cards.

Since \( S_a \) can have a maximum value equal to \( S_m \) and a minimum value half of that of \( S_m \), \( I_w \) will have a value ranging from 0.0 to 0.5. The sites with the highest combined wind speed will have the lowest favourability index values while those with the lowest combined wind speed will have the highest favourability index values.
CHAPTER SEVEN

THE RELATIVE FAVOURABILITY MAPS

The relative favourability of sites at Broughton Island is demonstrated by thirteen maps produced by the SYMAP program. The wind parameter is illustrated by nine maps — four for the calculated wind speed, four for the wind speed reduction ratios, and one showing the composite wind favourability index. The radiation parameter is illustrated by four maps — three showing respectively the spring, summer and autumn average daily global solar radiation and one showing the composite radiation favourability index. A relief map of Broughton Island was constructed for comparison (Figure 19).

All calculated windspeed maps as described in Chapter Six use a class interval of 1 meter per second, since in practical situations fractions are meaningless. The darkest tone with overprinting represents the highest wind speeds while the lightest tone with dots represents the lowest wind speeds for each map. Figure 20 shows wind speeds at the various locations when the DEW-line station is recording a 19 meters per second wind from the northwest quadrant. Apparently the sites with the highest wind speeds are the hilltops, plateaus, and the windward slopes close to the summit. Sites with the lowest wind speeds (9-10 meters per second) are found along the south shores of both the island and the adjacent Baffin coast. The village site in this case is experiencing quite a strong wind with a speed of 16-17 meters per second due to its openness to the wind.

Figure 21 shows a wind of 10 meters per second from the northeast attained at the DEW-line station. The sites
Figure 19. Broughton Island — relief.

Only 500-ft. (150 m.) intervals are drawn.
Figure 20. Wind speed map of Broughton Island — northwest wind at 19.0 meters per second at the summit.
Figure 21. Wind speed map of Broughton Island — northeast wind at 10.0 meters per second at the summit.
having the lowest wind speeds (5-6 meters per second) again are found along the south shore of the island and continuing around its southwest corner until sheltering is no longer provided for by the hill. The elevated beaches on the northwest side of the island are also protected by the cliffs rising east of them. The village site and the surrounding plain apparently are outside the influence of the lee slope and are registering a wind of 8-9 meters per second. On the Baffin coast sporadic shelters are provided by small hills and deep valleys. Needless to say, the unprotected plateau experiences wind speeds similar to those at the DEW-line station.

As for a wind speed of 7 meters per second from the southeast blowing over the DEW-line station (Figure 22), those areas with the lowest wind speeds (3-4 meters per second) are found almost exclusively on the entire west coast of the island. Conversely, all hilltops and plateaus show the least sheltering with a wind speed of 6-7 meters per second.

The weakest mean wind is from the southwest at 5 meters per second, shown by Figure 23. Since only three class-intervals (2 meters per second to 5 meters per second) were used, the differentiation in terms of site favourability is the least of all four maps. Areas with relatively high wind speeds are expanded due to the above reason but are still confined to areas of high elevations and plateaus. The sheltered areas (with wind speed of 2-3 meters per second) are found on the beaches on the east coast of the island and on those parts of the Baffin coast protected by hills.

A more applied form is to construct wind speed reduction ratio maps so that for a given windspeed and wind direction at the DEW-line station (Figures 24, 25, 26 and 27), the wind speeds at all locations can be calculated by multiplying the reduction ratio at the point in question on the appropriate map with the wind speed.
Figure 22. Wind speed map of Broughton Island — southeast wind at 7.0 meters per second at the summit.
Figure 23. Wind speed map of Broughton Island — southwest wind at 5.0 meters per second at the summit.
Figure 24. Wind speed reduction ratio at the various locations on Broughton Island — northwest wind.
Figure 25. Wind speed reduction ratio at the various locations on Broughton Island — northeast wind.
Figure 26. Wind speed reduction ratio at the various locations on Broughton Island — southeast wind.
Figure 27. Wind speed reduction ratio at the various locations on Broughton Island - southwest wind.
The calculated wind speed maps only depict relatively favourable sites with respect to a particular wind direction, and the wind-speed reduction ratio maps are comparable only when a constant wind speed is assumed for all quadrants. To locate overall relatively favourable sites, the composite favourability index map (Figure 28) was constructed by the method described in Chapter six. The index values ranged from 0.0 to 0.5 and were divided into five classes. Sites having index values of less than 0.1 are the least favourable while those with values more than 0.4 are the most favourable. On the map, the hilltops and the plateau obviously show the same unfavourability explained by the previous maps. A vast area, consisting particularly of the central part of the island, the village site and a major portion on the southern part of the Baffin coast, are intermediately favourable. The comparatively more favourable sites are found along a narrow strip of coast on the island's south and sporadically on the low-lying protected beaches for other areas. The results strongly reflect the weighting of the northwest wind.

On the airphotos (as mentioned previously) and the Landsat-1 satellite imagery taken in summer but in different years snow banks are found on the south-facing slopes especially those along the south coast of Broughton Island (Figure 29). This seems to suggest the strong northeast-northwest winds blowing snow over to the lee side are weakened at these locations, thus depositing a larger amount of snow which is still unmelted in mid-summer.

The global radiation maps are more comparable, since consistent interval classes were used throughout. With an average solar declination of +22.6° the spring map (Figure 30) represents the highest energy Broughton Island receives for all seasons. Though the south-facing slopes found mostly on the south coast receive the highest radiation of slightly over 800 langleys per day, most areas,
Figure 28. Composite relative favourability index map of Broughton Island — wind parameter.
Figure 29. Snowbank on a south-facing slope.
Figure 30. Average daily global solar radiation over Broughton Island — spring. (Declination=+22.6°)
particularly those with gentle slopes or horizontal surfaces like the village site, have radiation in the 700 to 800 langleys per day range. North-facing slopes receive relatively less radiation since the sun is at its lowest position at midnight (local apparent time) and at noon reception is blocked by the local skyline. Those sites receiving the lowest radiation are confined to crevices where only a glimpse of the sun is seen during the whole length of the day. Both the summer and autumn global solar radiation maps (Figures 31 and 32) show more or less the same pattern with a gradually decreasing amount of radiation for each station due to the lowering sun angle. The maximum global radiation received on a 20°–30° south-facing slope averages about 700 and 600 langleys per day respectively for summer and autumn. Next to the crevices, a north-facing slope of more than 30° gradient receives the least amount of less than 260 and 50 langleys per day, respectively for summer and autumn.

The favourability index map (Figure 33) for global solar radiation with the method described in Chapter five is quite representative of the overall picture, since it makes use of accumulated values. With ten interval index classes, intermediate sites can be differentiated more readily. The south-facing slopes found mostly on the south coast of Broughton Island and on other hills definitely receive the greatest amount of global radiation. Horizontal and relatively flat areas being second to the south-facing ones while the east- and west-facing slopes are intermediate. North-facing slopes, which receive the least amount of energy, and crevices, which receive an even smaller amount, occupy a relatively small land surface of the study area.

Lushness of vegetations usually gives a great deal of information on the heat budget of the area since surface heat energy is critical to plant life. Field observation during the 1976 summer trip to Broughton Island had shown
Figure 31. Average daily global solar radiation over Broughton Island — summer. (Declination=+17.7°)
Figure 32. Average daily global solar radiation over Broughton Island — autumn. (Declination=+7.0°)
Figure 33. Composite relative favourability index map of Broughton Island — global solar radiation parameter.
that lush areas were found almost exclusively on south-facing slopes. The two major areas examined were the west end of the south coast of Broughton Island and the central part of the south side of Kikitalakjuak Island about 25 km south of Broughton Island. On more-stable slopes of less than 10° gradient, meadows were often found. The Landsat-1 satellite imagery further confirms this finding. The imagery taken in spring (# 1674-15152, June 17, 1974) shows that vegetation had begun to emerge on most south-facing slopes on terrain along the Baffin coast together with its adjacent islands, but the north-facing slopes were still snow-covered. The summer imagery (# 1714-15255, July 7, 1974 and # 1749-15185, August 11, 1974) indicates most of the snow-cover was gone except for some snowbanks left in sheltered areas on south-facing slopes. Lushness of vegetation immediately below these snowbanks was very prominent. This is probably due to the availability of meltwater as well as the interception of more solar radiation. Great contrasts can be seen when the north and south-facing slopes running along the whole length on the south side of Kikitalakjuak Island are compared.

In summary, for Broughton Island, the relatively most favourable sites are found along the south shore. These areas are protected from the northerly winds and global solar radiation is received at a maximum. The combination of wind and radiation qualitatively can well explain the sharp contrast of relative favourability in terms of plant habitat. On a north-facing slope wind stress and erosion are strongest, and soil particles, once formed, are easily blown away and deposited at the base of hills or sometimes in small crevices. Much snow is also removed in this manner and deposited on the lee slopes by the northerly winds. The water budget during the growing season is therefore different between windward and lee slopes. The greater amount of heat energy is evidenced by plant species in
abundance. In addition, the more intense surface heating produces a greater range of diurnal surface temperatures. Given this temperature regime and the supply of water from snowbanks, frost action, chemical weathering and thus soil formation are accelerated. Except for the localized snowbanks, adjacent areas become snow-free. With this continuous supply of water, greater amount of heat energy, richer soil, and protection from the strong northeasterly winds, the south-facing side of a hill having terraces or stable slopes is doubtlessly more favourable than its north-facing counterpart. Slopes of the east and west aspects are intermediate between the two.

Since maps produced by the SYMAP program use rounded intervals, the absolute values of spatially continuous data cannot be illustrated. As a complement of SYMAP for the purpose of generating three-dimensional displays of data its companion program called SYMVU was used.

The SYMVU program, besides having the feature of presenting a new way to perceive all kinds of quantitative data (in this case wind and global radiation in addition to relief) on a continuous surface, also accomplishes the task of differentiating absolute values within a class produced by the SYMAP program. In this way extreme values with their approximate locations can be detected readily, provided the viewing angle is appropriate. Thus, the SYMVU program suggests an additional way to map topoclimatic. The wind favourability index map and global solar radiation favourability index map (Figures 34 and 35) are used here for demonstration, along with the relief map of Broughton Island (Figure 36).
Figure 34. Composite wind favourability index map of Broughshon Island (constructed with SYAVU).
Figure 35. Composite global solar radiation favourability index map of Broughton Island (constructed with SYAVU).
CHAPTER EIGHT

CONCLUSION

The model uses the two parameters, wind speed and global solar radiation, to demonstrate how topography modifies the local climate, and how some places are relatively more favourable than others in terms of climatological stress. On the basis of long-term wind records for Broughton Island, the model shows that places sheltered from the northwest wind, i.e., usually in the low-lying, southwest- to south-facing areas, are the most favourable. The opposite is true for summits and exposed or windward slopes. In terms of radiation, the south-facing slope again is the most favourable location, receiving the maximum amount of energy during the noon hours with the highest sun angle. The north-facing slope is generally the least favourable in this respect exceeded only by ravines and crevices.

Qualitatively, the results are in agreement with both field observations and evidence from satellite imagery. Thus, the present method for determining the relative favourability of sites seems to be applicable to coastal areas and adjacent small islands in the Arctic. For large mountain ranges like those on the Baffin mainland, the radiation parameter would need to be modified with consideration given to orographic influences on cloud cover. The wind parameter is also more complicated, since katabatic winds become important in areas of very great relief. The diurnal difference in winds, which ties in closely with solar radiation, is significant; therefore, studies concerning the linking of radiation with wind through the
diurnal temperature regime need to be explored more fully if the method described here is to be extended to such areas.

As mentioned before, the method possesses the advantage of depicting the relative favourability of sites without the need for field surveys. It is particularly applicable in the Arctic, where wind and radiation are critical factors determining site favourability in a natural sense.

The radiation parameter can be readily applied by using direct solar radiation if the coefficient of diffuse sky radiation is not available. Therefore, only the latitude of the study area, the solar declination, and the solar constant at that time of the year need to be known. The transmissivity for the Arctic atmosphere is in the 0.7 to 0.8 range for clear sky conditions.

For other regions in the Arctic where the height of the reference station is different from that of the Broughton DEW-line station, the wind speeds of the various sites can be calculated with equations (4), (5), (6) and (7) described in Chapter six. As a matter of fact, calculation shows that the wind speed at a height of 1000 meters is only 2.5 percent, an insignificant amount, stronger than that at 500 meters according to the logarithmic wind profile. Examination of the relief maps of the Arctic reveals that heights of greater than 1000 meters are rarely found in the coastal areas. Therefore, the wind reduction ratio table of Broughton (p.39) is applicable to other areas.

A shortcoming of the wind model is that not all regions have similar topography. It therefore represents a general approximation of wind reduction without regard for the microclimate of small features. In addition, in places where there are no meteorological stations, wind speeds and directions must be estimated from synoptic charts. Therefore, a study of the synoptic wind in relation to surface winds is
suggested for further improvement of the method.

When the actual wind speeds are established for a study area, the data can be manipulated for other purposes as desired. An example given here is to calculate windchill in relation to human comfort, a method developed by Beal (1974). The model simulates a wind speed of 19 meters per second from the northwest with a temperature of -20°C, quite typical of a winter wind storm at Broughton Island. The resulting map produced using the SYMAP program is shown in Figure 37, and the statements of the subroutine FLEXIN used in manipulating the data are shown in Appendix B.

In conclusion, the method presented here gives a reasonable representation of relative topoclimatic variability in an Arctic region. Further field studies, particularly wind and temperature measurements, would undoubtedly permit a refinement of the semi-empirical relationships used here. Because of the ever-changing atmosphere and the vast, dissimilar areas that are involved, a high degree of accuracy cannot be established easily. Nevertheless, the method does achieve the purpose of indicating in-a quantitative way the degree to which some sites in the Arctic are more favourable than others, and hopefully it will find application in studies of plants, animals, and human settlement in Arctic regions.
Figure 37. Windchill map of Broughton Island using H.T. Beal's model.
Appendix A. Computer program for calculating hourly global solar radiation on slopes.
SUBROUTINE FLEXIN(I, FORM, T, FIRST)

LOGICAL FIRST

READ(5,600)

600 FORMAT(15X, F15.0)

A = 20.0

VWSTR = 3.0 + 0.05 * R(V, A + 5.0) / (R(V, A + 5.0) + 16) + 0.92 * R(V, A + 5.0) / 1(R(V, A + 5.0) + 0.72)

HEAT = 12.5 + 0.1 * (37 - A) + 0.03 / R(V, 30.0, A) + 0.05 / (R(V, A + 5.0, A) + 10) + C * 0.7 + 0.14 / (33 - A) + 0.25 * (33 - A) / (R(V, A + 5.0, A) + 0.72) - 120 + 6

T = HEAT

RETURN

END

FUNCTION R(V, TS, A)

IF(V < 0.1) P = 1

P = 0.0488 * (TS + 273) / 10000 * (A + 273) * 2 / 10000 * ((TS + 273) / 100) * (A + 273) / 100) * (3.79 + V * (0.7 + 2.0) * ((TS - A) * 2 * (1 + 3 * A))

R = 1.6 / P

RETURN

END

Appendix B. The Subroutine FLEXIN in the SYMAP program to calculate windchill values according to H.T. Beal's model.
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