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MICROCLIMATIC VARIABILITY WITHIN OTTAWA'S CITY CENTRE

AND ITS RELATIONSHIP TO HUMAN COMFORT

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ABSTRACT

The awareness of a unique urban climate was evident in Ancient Greek times when Hippocrates advocated orientation of houses and towns according to the prevailing climatic elements to create conditions which were healthy for human habitation. A long gap of approximately 2,000 years followed during which time sporadic interest was expressed in investigating urban climates and their effects on people.

A recognition that a city contains microclimatic cells which are created by building configuration has resulted in increased interest in the effect of microclimatic variability on human health and comfort. Urban planning projects in Kitimat, Toronto and Ottawa have attempted to incorporate climatic factors in the planning of urban areas. An underlying problem in most planning projects is the need for a common method which may provide information on unfavourable microclimates caused by inadequate building arrangements and street layouts. It is proposed that the use of human comfort indices calculated from microclimatic data, provides a rational approach to identifying problem areas by indicating the degree of discomfort experienced in given urban locations.

Empirical observations of ambient temperatures, incoming solar radiation, infrared temperatures and wind speeds were made in downtown Ottawa using a traverse method. Results show a repeatable pattern of microclimatic variability from traverse to traverse which is evidence that consistent fluctuations are caused by building configuration. Empirical data are used to predict human comfort levels to demonstrate the feasibility of using this method in urban planning. Uncomfortable areas are identified where buildings and urban features are in need of modification to improve microclimatic conditions. Wind speed and excess shading have the greatest influence on discomfort, and corrective measures in alleviating these problems are suggested.

Human comfort is emphasized as a successful method to provide a clear indication of the microclimatic conditions of a site. This method may serve as a unifying force bringing urban climatologists and urban planners into closer communication for the improvement of urban climatic conditions.

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"The Lord is the strength of my life; of whom shall I be afraid? (Psalms 27:1). Wait on the Lord: be of good courage and He shall strengthen thine heart (Psalms 27:14).

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CHAPTER 1 INTRODUCTION

1.1 Statement of Objectives

The aim of this thesis is to present human comfort indices as a method for urban planners to evaluate microclimatic variability in city centres and to determine microclimatically unfavourable areas which may be caused by building configuration. Empirical observations of microclimatic conditions were made within a section of Ottawa's downtown area to ascertain whether microclimatic variability is caused by building configuration. Microclimatic data were analyzed using human comfort indices to determine the effect of microclimatic variability on human heart rate, body cooling rate and comfort sensations. This provided an example of the feasibility of using human comfort indices as a guide in urban planning to determine "optimum" building configuration and arrangements. It is the objective of this research to demonstrate that human comfort is both a more feasible and appropriate method for evaluating downtown microclimates for urban planning than the conventional heat island approach.

1.2 Inspiration for Thesis Topic and Research

The paucity of climatic data often inhibits detailed urban climatic research and it is therefore necessary to conduct one's own empirical observations. Such was the challenge of this thesis, which was inspired

to a great extent by Garnier's (1972) human comfort study in Montreal. He used the popular methodology of the automobile traverse to collect climatic data, which were examined for the influence on pedestrian comfort and thermal strain. Garnier (1972) notes that "one aspect of urban influence which needs investigating is the effect of the city upon actual living conditions for man". The general trend in urban microclimatological studies is towards the study of dynamic aspects, without leading the results one step further to demonstrate the value of urban microclimatology. The latter can perhaps be expressed by the comfort people experience when traversing microclimatic cells within the city. An urban centre is planned and built for human use, and people are the best source of information on the city's climate. Consultation with numerous urban planners and urban climatologists revealed that the feasibility of this method is not widely recognized. This provided the impetus for examining human comfort and thermal stress in Ottawa's downtown area which is presented as a model for use in urban planning processes.

The traverse route method was employed in this thesis. However, it was conducted on foot to include the pedestrian mall and to facilitate conducting the human comfort questionnaire. It was particularly desirable to research a topic from start to finish which included collecting primary data and analyzing them, knowing that the data are original. A valuable experience in climatic methodology was gained by working with meteorological instruments in the field. Interaction with pedestrians

was extremely interesting and provided valuable input on human comfort sensation and wind conditions.

1.3 Importance of Urban Bioclimatic Research

Urban planners have become more aware of urban microclimatology in recent years because of the unfavourable microclimatic conditions such as localized wind turbulence and excess shading created by the grouping of variously shaped buildings. A sincere interest has been expressed by many planners to include climatic data in design guidelines. However, because of the difficulty in establishing criteria to determine which microclimatic conditions are unfavourable, the use of microclimatic data in urban planning has been limited. This thesis proposes that the criteria for unfavourable microclimatic conditions be set using human comfort levels, which may be predicted by mathematical formulae using microclimatological data. Human comfort criteria may thus be used to bridge the gap between urban climatologists and urban planners, since human comfort is a concept both professions can relate to.

Much of the recent urban climatic research has focused on the "urban heat island" phenomenon, which is not particularly useful to urban planning since it does not relate the results to human living conditions. The value of urban climatic research is not entirely in knowing the physics of the nocturnal urban heat island, but in understanding the climatic variability in urban climatic cells which

pedestrians experience. The scale at which urban heat island studies are conducted is too large; the city climate should be examined in finer detail, at the microclimatic level, since this is the scale of environment that pedestrians experience. In this respect the 6 or 7 meters above pedestrian surfaces should be investigated in the most detailed manner to reveal the microclimatic variability of the urban fabric.

Each house, factory, railway station, wall and pavement creates its own distinctive microclimatic envelope and these in combination produce a substantial climatic unit - the urban climate.
(Chandler, 1965)

"...A greater meaning can be gained if man as a 'physiological interface' is added to the system" (Terjung, 1970). "Credibility of any branch of science always depends on its relevance to socioeconomic systems at the time" (W.O.Haufe, Presidential Address at the 7-th International Biometeorological Congress, 1976). Awareness of climatology as an important discipline which is capable of contributing solutions to socioeconomic problems will increase if climatologists become more concerned with human issues in scientific research, and if planners are able to incorporate climatic data to design guidelines.

It is encouraging that "biometeorology continues to emerge as an increasingly important field of science in man's struggle for survival" (W.O.Haufe, President's opening remarks at the 7-th International Biometeorological Congress, 1976). In 1975 Tuller remarked that

"...a favourable trend discernible in some of the recent literature is that the findings of more studies are being applied to the interpretation of the effects of the urban environment on man". Research, particularly in The Netherlands, is revealing increasing evidence of the predominating influence of climate in the causation, triggering and development of numerous diseases, most specifically asthma, bronchitis and rheumatism. The high incidence of these illnesses in predominantly urban Western society emphasizes the need to seriously examine this relationship.

Due to the rapidly growing urban population all over the world, of which already 30% live in settlements of 5,000 or more persons and 18% in cities of more than 100,000, it is necessary to study the biometeorological aspects of our present day architectural and urban planning, which are either completely neglected or insufficiently considered by most architects, engineers and urbanists responsible for present day large scale building projects.

(Tromp, 1972)

It is important to note that a dichotomy between environmental and microclimatic issues exists in today's planning process, stemming from a poor understanding of the role of microclimatology in urban planning. Therefore, whereas "environmental" issues are considered by some town planners from the aesthetic and recreational aspects, microclimatic variability and its effect on human comfort is almost always omitted in town planning and building design. Many examples are found of towns advertized as having been planned with full awareness of the

environment, for example Columbia, Maryland (see section 2.4.2).

In most cases, no significant advances have been made over conventional planning processes in the incorporation of microclimatic input. Thus, for example, no imaginative ideas were used in open surface parking lot design, which should be a primary target in new town planning.

1.4 Abbreviations of Units

For the sake of brevity, commonly used units in this thesis are abbreviated. Less commonly used units are introduced in the body of the thesis in full with the abbreviation in brackets, after which time the abbreviated form is used. The following list is provided as a convenient reference which may be referred to during thesis reading. Units are expressed in the metric system, however, in some cases the equivalence in the English system is included in brackets.

Btu	British Thermal Units
°C	degrees Centigrade
cal	calorie
cm	centimeter
cm/sec	centimeter per second
°F	degrees Fahrenheit
hr	hour
Kcal	kilo calorie
ly/min	langley per minute
m/s	meters per second
mb	millibars
mcal	milli calorie

min	minute
mm Hg	millimeters of mercury
mph	miles per hour
sec	second

1.5 Outline of Chapter Content

Chapter 2 discusses the historical development of the awareness of the unique climate within a settled area. A brief outline is included on early attempts in history when an intuitive understanding of climatic phenomenon was used in the design of settled areas. This chapter demonstrates that prolonged periods of climatically conscious urban planning have never existed.

Since the 1900's urban climatic research gradually progressed towards the microclimatic approach, identifying building characteristics which modify the climate. Urban planners worked independently with little consultation with urban climatologists. Human comfort, which would have served as a link between these two professions, was not used. Chapter 2 includes examples of urban microclimatic research where valuable microclimatic data could have been used by urban planners if presented in a more amenable way. Examples are also included of some notable urban planning projects where an attempt was made to use climate as a factor in design guidelines. These two sections are presented to show the drift between the professions, and to emphasize the need for a method to bridge the gap between them. The use of

human comfort levels is proposed for this.

Chapter 3 discusses the microclimatic dynamics occurring within a city centre which result from building configuration. This chapter is important since the theoretical disposition of energy within a city can be used to explain and predict variability of human comfort levels. The absorption of direct beam solar radiation occurs when a building surface faces the sun. However, when this surface is shaded it experiences net cooling by longwave radiation and convection. This in turn influences the local temperature and human comfort level. Adverse wind conditions around a building are created when the height of a structure interfered with prevailing wind flow, diverting it vertically downwards. Even though an understanding of dynamics of microclimatology is not vital to the urban planner, it is vital to the climatologist in understanding reasons for variability in human comfort values. In this respect it is an eventual asset to the urban planner as well.

Chapter 4 begins with an explanation of the place of human comfort within the discipline of bioclimatology, and the significance of human comfort in the urban planning process. The significance of urban bioclimatology and human comfort is emphasized in terms of the increasing occurrence of discomfort and meteorotropic diseases in urban centres. It is suspected that inappropriate building arrangements modify the prevailing climate into unfavourable microclimates which cause human discomfort and illness. A brief recent history of bioclimatology reveals

difficulties in its being accepted as a scientific discipline in view of the declining respect for humanistic aspects in scientific research. The physiological function of human comfort is explained in terms of the thermoregulatory system, which responds to changes in climatic parameters and adjusts the body's heat balance. The occurrence of meteorotropic diseases is briefly reviewed, emphasizing the high frequency of mortality due to prolonged periods of heat waves in cities. The necessity is stated for approaching urban planning in terms of human comfort which indicates urban areas with uncomfortable microclimates and which therefore need correction.

Chapter 5 reviews the study area, research methodology, instrumentation techniques and evaluation methods. The study area is within Ottawa's central area and also coincides with City Hall's wind study area. Two sets of traverses were conducted in two different areas of the central area. Thirteen weeks of traverses were conducted within the bigger downtown study area including some 25 blocks. Twenty one measurements were recorded at twenty sites. Smaller traverses were conducted twice to examine the influences of a single downtown block on the microclimate and human comfort levels. Thirteen readings were taken at 12 sites. On some days human comfort questionnaires were distributed simultaneously with the climatic measurements to survey pedestrians' subjective opinions of the microclimates. These were compared with mathematical predictions of comfort which were calculated for each site. The mathematical evaluation of empirical data involved using

various formulae for human comfort. Heart rate predictions were also calculated based on air temperature.

In chapter 6 the analysis of empirical data is carried out to reveal the existence of microclimatic cells and to evaluate the microclimatic data in terms of human comfort levels. Variability of microclimatic data such as ambient temperature, infrared temperature, short-wave solar radiation and wind speed is examined for consistency of trends to discover whether variability is caused by building configuration. Trends in microclimatic data from one traverse to another, for both city centre and block areas, are followed and influencing factors are identified.

In chapter 6 human comfort levels are calculated for each measurement site to identify those that are unfavourable. Urban climatology researchers use extreme data and assume those to be unfavourable sites for frequent human use. This system is arbitrary and unreliable, and emphasis is placed on the feasibility of using human comfort as an appropriate way for urban planners to identify problem areas. A section on human comfort questionnaire results compares actual comfort levels experienced by pedestrians with those calculated using various formulae.

Chapter 7 summarizes the research results, dwelling mainly on human comfort values. Wind speed is found to be the most influential climatic

factor in Ottawa's downtown, creating uncomfortable microclimates in areas which would otherwise not be so. Design guidelines for downtown sites with uncomfortable microclimates are outlined, emphasizing the importance of using human comfort in determining which areas need microclimatic modification and for which reason. The use of wind barriers in the form of trees and architectural devices is suggested for various wind problems such as turbulence and wind funneling. Areas which have exceptionally comfortable microclimates should be developed into public interest spots. The use of overhangs for calm, but excessively sunny, areas is suggested to maintain an agreeable microclimate.

CHAPTER 2 HISTORICAL PERSPECTIVE OF CLIMATE AS A FACTOR IN URBAN PLANNING AND URBAN CLIMATE RESEARCH.

2.1 Historical Review of Climate in Urban Planning and Building Design

The philosophy for climatically conscious urban planning and building design dates from ancient history. Egyptian and Greek town planners and architects were, at least intuitively, aware of the existence of a modified climate around buildings. This awareness was reflected to some degree in the planning and orientation of towns proceeding in accordance with prevailing climatic conditions, particularly wind. Common sense rather than specific planning criteria were used in the planning process. Aristotle has been noted as the first town planner in history (Aldridge, 1915) since he believed that unfavourable climatic conditions and unpleasant physiologic symptoms in human beings may be alleviated by orienting buildings in accordance with prevailing climatic conditions.

The healthiest cities are those which stand upon a slope inclining to the East and so the winds which blow from the quarter of the sunrise. The next best aspect is one that is sheltered from the north wind, as cities so sheltered enjoy milder winters.

(Aristotle, Politics, Book 4)

According to M.J. Simon in "Your Solar Book", in 300 B.C. Xenophone wrote,

In houses with a south aspect, the sun's rays penetrate into the porticoes in winter, but in summer the path of the sun is right over our heads and above the roof, so that there is shade. If, then, this is the best arrangement we should build the south side loftier to get the winter sun, and the north side lower to keep out the cold winds.

Lewis Mumford (1961) notes that this is a "bit of practical wisdom that the people of the Northern Hemisphere have repeatedly lost and rediscovered over thousands of years".

Ancient Greek sensitivity to climatic modification in building clusters and towns was equalled only a few more times in history. Vitruvius is said to be the forefather of modern town planning (Lavedan, 1926) who in 300 A.D. presented ideas on town layout and building orientation using climate as the decisive factor. The need to know the natural climate on a pre-developed site was emphasized as well as climatic influences on the health of inhabitants. This mutual treatment of the two intimately associated disciplines of microclimatology and bioclimatology was not witnessed again until the mid-1900's. Vitruvius stated that the primary prerogatives in planning towns should be hygiene and human comfort, which may be achieved by the orientation of minor streets and alleys in an oblique angle to unpleasant cold winds and "infectious" hot ones (Mumford, 1961).

For when the quarters of the city are planned to meet the winds full, the rush of air and the frequent breezes from the open space of the sky will move with mightier power confined as they are in the jaws of the alleys. Wherefore the directions of the streets are to avoid the quarters of the winds so that when the winds come up against the corners of the blocks of buildings, they may be broken, driven back and dissipated.

(Vitruvius, in F. Granger trans., 1962)

The general tendency in planning of towns since Vitruvius' times was to be oblivious to the prevailing climatic conditions of the site, and to the consequences of the climate modifications after

development. A few examples are found of towns planned in order to avoid unpleasant solar or wind conditions. Such examples reflect either intuitive awareness, that is, a good common sense of the planners and developers, religious or ethnic practice, or the deliberate use of architectural or planning guidelines acquired from such works as Aristotle's or Vitruvius'. Numerous examples are briefly outlined in Aronin's book "Climate and Architecture" to which the reader is referred for details. Climatic phenomena were not considered in any consistent way in town planning because of the lack of reliable methods of data collection. Since climatic data measurement techniques were not used until 1833 urban planning was often based on the intuitive understanding of climatic phenomena occurring around buildings.

2.2 Modern Urban Climatic Research

In the early 1800's European towns experienced economic and physical expansion which produced a high level of smog. Observations of modified atmospheric characteristics included warmer town temperatures and greater cloudiness which were based on personal experiences and were lacking in objective substantiation. In 1833 Luke Howard became the first to implement quantitative urban climate investigations, in London, England. Results showed apparent temperature differences between urban meteorology stations and rural stations. An average temperature difference of 1.1°C with a maximum difference of 2.1°C was noted on a winter night (Howard, 1833 in Smith, 1974). This confirmed subjective speculations, however, unrefined measuring techniques and questionable evaluation methods suggest possible inaccuracies in results.

Alexander Ivanowich Woeikof (1842-1914), professor of Physical Geography at the University of St. Petersburg, was one of the earliest to express deep concern for the rapid expansion of urban centres.

This grouping of cities, under conditions unhealthy to body and mind, this dissociation of man and the earth is proof of a sickly state.

(Woeikof, 1901 in Thomas, 1956)

Woeikof had many supporters, and indeed the early twentieth century in Europe saw an emerging concern for the preservation of natural landscapes, with the underlying belief that urbanization and therefore man was nature's worst destroyer. Scarce rich agricultural land was being threatened by sprawling cities. Sound urban planning including climate as a factor, indeed urban planning of any sort, was not widely practiced.

In the early 1900's man rejected the earlier belief of "environmental determinism" and became an increasingly unabashed manipulator of the land. This attitude was labelled as "possibilism" believing that the natural environment provides man with several options and does not simply impose itself upon a helpless humanity (Dohrs and Sommers, 1967).

Intense urban climatic research was initiated at this time by A. Schmauss in Austria in 1914 who, on the basis of scanty reports and his own observations, theorized on the meteorological principles necessary for sound urban planning. Meteorological data in support of his arguments were available only 30 years later during which time municipal and

university weather stations recorded enough data to make it worthwhile for compilation and interpretation. Much of the impetus for this work came from the Viennese School in Austria which inspired the writing of notable urban climatologic work approached from a fundamental point of view by Louis Besson (1931), Wilhelm Schmidt (1937), Rudolph Geiger (1959) and Albert Kratzer (1937). In 1930 W.Schmidt initiated the automobile traverse procedure whereby instruments were attached to automobiles and driven through Vienna recording microclimatic variations along the measurement profile. The automobile traverse became a popular measurement technique in Europe in the 1930's and in 1936 was used in North America for the first time by Middleton and Millar (1933) who studied temperature variations in Toronto.

The active involvement by climatologists in urban climate research may have spurred European city planners to take note of the role contemporary urban form had on climate modification. Planning strategies were formulated on the best location of industries, the discriminate use of green belts and the separation of business, residential and recreational zones for proposed cities and redevelopment projects (Landsberg, 1968). Unfortunately, most of this enthusiasm remained on paper only, being interrupted by World War II.

The post World War II period instilled a different lifestyle for most Western societies. Economic development produced soaring downtown land prices, advancements in construction technology, innovative building materials and new material assembling techniques. The downtown construction boom proceeded at a faster rate than planners could plan for. Limited consideration was given to the climatic factor in town and building design,

creating a monotonous multiplicity of a standard building form regardless of variability in climate found initially on the site or created after construction. One architect expressed it thus, "...the resulting buildings have tended toward standardization of building form and fabric such that they conform to new international stereotypes" (Cole, 1977). A basic cause for the limited use of climatic data in town planning was the difficulty in bridging the gap between urban climatologists and urban planners.

2.3 Examples of Urban Microclimatologic Investigations

A progression was slowly made in the early 1900's towards the identification of urban features which cause microclimatic modification. Thus, microclimatic research proceeded mainly within the academic field and focused on identifying building characteristics such as orientation, grouping and size, which could explain the modified microclimate in the vicinity. Even though progress was made in microclimatic research and data collection methods, climatic data were still only understood among climatologists. No effort was made to translate microclimatic data into a form understandable to urban planners. The following are examples of the approach used in microclimatic research.

2.3.1 Vienna: Courtyard Study by Mahringer

Mahringer (1963) in Vienna conducted one of the first studies examining microclimatic modification induced by single structures. Temperature regimes of two courtyards measuring 15 by 8 meters in area with a 20 meter depth, and 4 by 2 meters in area with the same depth,

were measured using automatic recording instruments set on the ground. Temperatures were also recorded on the roof of the courtyard buildings and in a nearby meadow. Results showed large differences of air temperature in both courtyards from that of the surrounding air. This was attributed to the high heat capacity of the surrounding walls, reduced turbulent exchange of air mass between the inside and outside of the courtyards, and the frequent stagnation of cold air on the ground, particularly in the larger courtyard. The greatest temperature difference between the courtyards and the surrounding air mass was observed during clear sky and calm air conditions. Winter temperatures in the courtyards were markedly higher than the surrounding air which was explained by the "heating of buildings" (Mahringer, 1963).

Although radiant energy as a fundamental factor of micro-climatology was omitted, this study created a greater awareness of the existence of a microclimate around individual and small clusters of buildings.

2.3.2 Columbia, Maryland: Courtyard Study by Landsberg

A similar study in 1968 by Landsberg investigated the micro-climate of a five storey, U-shaped brick building with another building situated nearby, all of which enclosed an asphalt courtyard of 32 by 42 meters in area. Other features considered in the research were a roadway, parking spaces, a large grass lawn and a deciduous wood lot, all located in close proximity to the courtyard. The altered heat

balance of a small area was measured since "...for many reasons it is quite useful to have information available on the individual building elements that ultimately combine to form a town or city" (Landsberg, 1968).

Temperature and solar radiation were measured under clear and cloudy sky conditions from the time of the daily maximum temperature through to about two hours after sunset. During clear skies the air temperatures over the grass and in the courtyard were identical at 30.6°C . The wood lot air temperature was 0.6°C lower. The surface temperatures of the walls and parking lots were all greater than the air temperatures in naturally vegetated locations, "...a person in the courtyard exposed to the high radiative wall and ground temperatures would feel acutely uncomfortable whereas both in the open area and the wood lot either limited or no radiational heat load from terrestrial objects would be experienced" (Landsberg, 1968, p.131). The grass lawn and wood lot experienced rapid surface temperature decrease at sunset reaching a temperature close to that of the overlying air. In contrast the artificial surfaces remained 2 to 5°C warmer.

On another day a thunderstorm occurred at 1800 hours followed by a rapid cooling of the air by 4°C in 45 minutes. Immediately following the rapid draining and evaporation of water from the courtyard, its surface temperature was measured at 25°C , however, in a short time it increased by 5.5°C due to the stored heat in the materials. As a result air temperatures in the courtyard were soon 1.2°C higher than over the natural vegetation.

These observations demonstrated that even though the building complex was isolated and of a small size, an altered heat balance was created by the unique thermophysical properties of artificial surfaces.

2.3.3 Dallas & Forth Worth: Microclimatic Study by Ludwig

In search for an explanation of temperature variability in Dallas and Forth Worth, Texas, a series of automobile traverses were conducted by Ludwig (1968). Cross sections traversing the downtown area revealed that the air temperatures downtown were higher than in the north-west and south-east ends of the cross sections during the diurnal minimum temperature, whereas downtown air temperatures were lower at the time of the diurnal maximum temperatures. Closer examination showed that the warmest downtown air temperatures occurred in areas of densely packed buildings of medium height whereas areas of very tall buildings had relatively cooler air temperatures.

This refuted the theory that differences in heat capacity alone determine differences between urban and rural day time temperature patterns. This study revealed the unreliability of treating the city climate as a singular, integrated unit since despite the occurrence of an average urban heat island effect, it is not apparent at all times of the day or at all areas within the city.

2.3.4 Los Angeles: City-Man System by Terjung

Microclimatic variability was substantiated by studies such as

Ludwig's, however, the methods of evaluating temperature anomalies were limited in most cases. Terjung stated in 1970 that "...no major attempts have been made to determine the energy balance climatology of cities" (Terjung, 1970). At this time in urban climatic research a necessity was felt to understand the causality and the interrelations of the energy balance. The term city-man system was used to describe the processes whereby both artificial surfaces and human beings utilize, transform and transfer energy.

The automobile traverse method was used to measure the energy balance components of the city and the human interface within a two square mile area. Direct beam solar radiation, diffuse solar radiation, albedo, terrain radiation, atmospheric counter-radiation, ground heat flux, two level dry and wet bulb temperatures and two level air velocities were recorded. The terrain temperature was derived by averaging the infrared temperatures of the four cardinal directions and of the sky in the zenith. The total environmental terrain temperature was derived from the average longwave radiation in which people exchange radiative energy with the surrounding buildings. Therefore, "...greater meaning can be gained if man as a 'physiological interface is added to the system" (Terjung, 1970). It was found that the total environmental terrain temperature was extremely low in the city centre due to the obstruction of solar radiation by tall buildings. This supported Ludwig's (1968) conjecture for the cause of low air temperatures in Dallas and Fort Worth in similar urban conditions. The net radiation revealed a high "net radiation island" in the city

centre whereas less densely built up areas with "cold" air temperatures showed the lowest values of net radiation. The surplus of net radiation in the downtown area may be explained by either lower albedo of abundant artificial surfaces, lower surface temperatures or lower terrain temperatures which would contribute to lower rates of emittance of terrestrial radiation (Terjung, 1970). The smaller range of infrared and ambient temperatures in the densely built-up area was explained by the shading of tall buildings. This method would have been more effective if it were applied exclusively in the city core, paying particular attention to building arrangements as in Landsberg's (1968) courtyard example thereby providing a more realistic conception of energy disposition and variability.

2.3.5 Victoria, British Columbia: City-Man System by Tuller

In 1975 Tuller remarked that "...a favourable trend discernible in some of the recent literature is that the findings of more studies are being applied to the interpretation of the effects of the urban environment on man". A study was conducted in Victoria, British Columbia to measure microclimatic variations due to the vertical component in the city centre and evaluate these in terms of the thermal exchange between man and his environment following Terjung's (1970) formulae.

A single block was selected and observation stations were established at the midpoints of the north, south, east and west facing

sides. Global diffuse and reflected solar radiation, radiant temperatures of the sky, horizontal surface and building surface temperatures, wet and dry bulb temperatures and wind speed were observed. Measurements began shortly after sunrise and terminated at sunset, and energy exchanges for man were calculated for each hourly period from 0800 to 1600 hours. The results of the microclimatic investigations revealed that on clear days, aspect in the city centre had the strongest influence since the greater the "open sky" seen from a pedestrian site, the greater the amount of direct solar radiation permitted to flow through. The microclimates of the four sides of the block varied considerably according to the degree of open sky view factor. Solar radiation ranged from the least amount received at the north station because of excess shading, to the most received at the south station because of shorter buildings located in the direction of incoming solar rays. The longwave radiation values were higher in the downtown stations than in the open residential areas since the vertical component contributes more area for energy processes. The average daily air temperatures generally followed the distribution of direct beam solar radiation, except in one case where the east side of the block showed higher daytime average temperatures than the west side, despite having received less insolation. This is because of the release of stored heat from the east wall when completely shaded in the afternoon. Wind flow was influenced by street orientation. It was noted that under heavy overcast, microclimatic variability was governed mainly by wind rather than solar radiation.

2.4 Examples of the Use of Climatic Data in Town Planning

Several municipalities have used climatic data in planning, but no reliable method of microclimatic evaluation is evident. The problem still exists of finding criteria to indicate whether a site contains microclimatic characteristics in need of alleviation using architectural features. The use of human comfort indices have not been used in urban planning processes; this author proposes that they would provide the best link between climatologists and planners. The use of the Beaufort Scale wind criteria has been proposed for Ottawa.

2.4.1 Kitimat, British Columbia

H.E. Landsberg in 1947 attempted to bridge the gap between climatologists and urban planners during the planning of the town of Kitimat, British Columbia. Human comfort was not used. The aim of the project was to integrate climate in the town design and demonstrate the economic feasibility in producing a climatically pleasant environment. Climatic data before development was unreliable, being derived from a third order climatic station. Minimal climatic data made it necessary to base many conclusions on inferences, analogies and general knowledge of dynamic climatology.

Analyses indicated that sunshine was not a major stress factor in the summer, however, schools were advised to be oriented to the sun to benefit in additional solar energy in the winter. West orientations were discouraged because of potential overheating during the summer (Kitimat Townsite Report, 1969). Residential areas were to be built as far to the east of the

Kitimat River as possible to avoid cold valley winds, associated snow drifting and temperature inversions. It was advised that streets should be oriented generally north-west to south-east to avoid wind funneling and snow drifting of northern winter winds and funneling of southern summer winds. A further design feature was the curvature of streets in order to dissipate wind funneling.

2.4.2. Columbia, Maryland

Columbia, Maryland, was founded in 1967 in the corridor between Washington, D.C. and Baltimore, Maryland, an area susceptible to intense air pollution. "Columbia was to be a 'planned' town with amenities and environmental quality that would offer a distinction from the stony deserts of a modern central city" (Landsberg, 1975, p.6), although it is not clear whether climate was considered as one of the environmental factors. In order to determine the extent to which this promise was fulfilled, Landsberg researched the degree of climatic modification occurring during the years of urbanization. Before commencement of town development, an extensive meteorologic survey was conducted, and as urbanization continued, meteorological monitoring continued at frequent intervals using stationary weather stations, automobile traverses and occasional low-level flights. Ambient temperature, infrared temperature, humidity and wind were recorded.

In 1968 higher temperatures in the town's core were already evident and by 1975 when the town's population approximated 20,000, nocturnal temperatures in the densely built up town centre exceeded those of the surroundings by 8°C (Landsberg, 1975). The substitution of the natural microclimates by those created by extensive artificial surfaces

and isolated high-rise structures was the cause of higher town temperatures. Individual microclimates over asphalt parking lots and surrounding single buildings were measurable as early as 1968. The high heat capacity of artificial materials and insufficient water on surfaces for evapotranspiration permitted greater incoming solar radiation storage thus increasing surface temperatures.

Valuable planning lessons should be noted from this research. Whereas Columbia was advertized as a "planned town", "as far as heat island development, wind reduction and air pollution increases are concerned, Columbia showed no significant advances over other towns of comparable size..." (Landsberg, 1975, p.49). No imaginative ideas were used in open surface parking lot design which should be the primary target in new town planning. This example indicates the dichotomy in today's planning process: whereas "environmental" issues are considered by town planners from the aesthetic and recreational aspects, micro-climatic variability is almost always omitted in town planning and building design.

2.4.3. Toronto, Ontario

Toronto's planners are seriously concerned with climate in urban redevelopment projects. The City of Toronto Planning Board undertook an intensive investigation in the 1960's in "aspects and areas of the controls, incentives and procedures in ways which will ensure more appropriate forms of change" in the urban development process (Baird et

al, 1974). This study was inspired by the people of Toronto who were concerned for the nature and extent of change in the City's Core Area, including adverse effects certain building forms may exert on the microclimate. The report "On Building Downtown" (1974) prepared by the Design Guidelines Study Group provides design guidelines which were proposed to be worked into a framework for design and construction of new developments and the renovation of old structures. The guidelines were meant to eventually lead to detailed local controls.

Guidelines are presented for sun and shade conditions for urban Toronto, the general goal of which is "to ensure that the form of new buildings creates desirable year round conditions of sun and shade" in a) designated open spaces, b) surrounding streets for pedestrians and vehicles, and c) surrounding residential buildings (Baird et al., 1974, p.30). It was recognized that building form and orientation influence the extent and duration of sunshine during different times of the year which may lead to excess solar radiation penetration in the summer unless pedestrian shelters are provided. Situations of excess shade may be created in undesirable locations such as shopping malls and outdoor cafés. The Design Guidelines Study Group suggests that buildings should allow as much winter solar radiation to reach the pedestrian levels as is feasible. However, careful urban layout and selective use of shading devices should present a choice of either sun or shading during the summer. The design guideline for wind and calm conditions states that new buildings should not "aggravate existing daily wind conditions in such ways as to either increase the wind velocity to undesirable levels

or to deflect it from places where it would be desirable" (Baird, et al. 1974). It is necessary, therefore, to provide open spaces of calm for pedestrian shopping, resting or recreation ensuring at the same time adequate breeze for dissipating automobile exhaust and pollutants into the upper atmosphere.

2.4.4 Ottawa, Ontario

The Planning Branch of the Department of Community Development in Ottawa has entered the primary stages of considering the microclimate of the downtown, albeit limited to wind problems. The intentions of the study are summarized in "Wind Study, Consideration of Wind Problems in the Downtown Core" which are:

- a) to quantify and examine the overall wind conditions in the commercial core of the Central Area,
- b) to test specific pedestrian areas,
- c) to establish criteria for the testing of private development projects.

(Chen and Hart, 1977)

The Planning Board has recognized the unattractiveness of some pedestrian areas caused by adverse wind conditions. It is proposed to compare field measurements with wind simulation tests conducted at the National Research Centre wind tunnels. Comfort levels will be determined using the Beaufort Scale wind criteria. Sites where adverse wind conditions exist are proposed to be corrected using protective means such as wind barriers. Proposed building projects found creating high wind

speeds will be modified to create more comfortable conditions.

The Inn of the Provinces Complex was one of the few projects in Ottawa which was modelled in a wind tunnel to observe wind modification. The building design that demonstrated the least amount of wind modification in the simulation test was accepted. This was a two-tower staggered design which provided adjustable features if the need for further wind improvements should arise. Since the completion of this complex, actual wind conditions correlated favourably with simulated ones and the comfort levels have been generally pleasant. The Place de Ville, Phase II with Tower 'C' which was not tested for wind modification creates severe wind turbulence as a result of its protuberance above surrounding structures.

High wind speeds in the downtown core has made it necessary for the Design Committee of City Hall to adopt a new policy whereby the pedestrian wind environment is considered in building approval. Wind simulation is proposed as a mandatory requirement for those buildings "likely to have an adverse effect on pedestrian areas or those which themselves would be affected by surrounding buildings" (Chen & Hart, 1977). The success of this project will determine whether other micro-climatic elements will be subsequently examined.

3.1 Significance of Microclimatologic Information in Urban Planning

Knowledge of microclimatic conditions caused by building arrangements are essential to urban planning in order to know the nature and extent of climate modification which people experience after new projects are constructed. The climatic factor in urban planning has generally been ignored in favour of economic, social or other factors, mainly because microclimatic data have not been translated into an understandable form, usable by urban planners who are not trained in climatology. As a result, urban climatic research, particularly of the urban heat island, has not provided adequate answers to urban planning problems. The broad area encompassed in urban heat island research necessitates deliberate "smoothing out" of the urban topography for easier comparability with rural climates. In search for an "average" urban climate, the measurement of microclimatic conditions found near clusters of buildings, in parks or in pedestrian plazas is avoided and measurements of the upper boundary layer are taken from the top of buildings. Another method is averaging climatic data collected along urban traverse routes producing a daily average value to be compared with average data obtained at airport or other peripherally located meteorologic stations.

However, the value of urban climatic research is not entirely in determining the magnitude of the urban heat island, which has been a popular preoccupation within urban climatic research. Rather, climatic variability within the urban fabric should also be an objective, since this is the climate that people experience. Once microclimatic dynamics are

understood and empirical data are available, this information should be analyzed in terms of human comfort levels to determine unfavourable microclimatic cells.

3.2 Discrepancies of Urban Heat Island Approach to Urban Climate Research

The urban heat island effect has been attributed to the higher heat capacity and thermal conductivity of urban artificial surfaces absorbing solar energy during the day and releasing it at night. Ludwig (1968) argues that thermophysical properties of materials are not entirely responsible for high urban daytime temperatures.

The heat capacity, thermal conductivity explanation leads to the expectation that the city should be cooler than the environs during the day. The absorbed heat should be conducted into the buildings and stored there without raising the temperature as much as the temperature of the soil which has poor conductivity and a relatively low heat capacity.

(Ludwig, 1968, p.82)

Many studies indicate that daytime urban temperatures are higher than rural ones. Air temperatures in London, England, are commonly 0.6°C warmer than the surrounding countryside (Chandler, 1965). Landsberg (1956) has found that in the winter air temperatures in Cleveland, Ohio, are frequently 0.6°C warmer than those recorded at the airport, whereas urban and rural temperatures, on a year-round basis, have been found to be similar.

The urban temperature measurement programme was formed to record the higher urban daytime temperatures found in Dallas and Fort Worth. An important discovery was made suggesting that air temperatures vary according to building configuration, providing evidence of microclimatic variability due to an irregular urban profile. Ludwig (1968) suggests that radiative effects rather than thermophysical properties of materials cause temperature variability, created by variable insolation absorption according to building surface exposure to solar rays. The energy balance in terms of the amount of solar energy absorbed and the amount emitted by building surfaces exposed and shaded determines temperature microclimate variability.

3.3 The "Climatologic Sheath" Concept of a Modified Climate

Climatic characteristics vary over the earth's surface due to the changeability of such surface features as topography, colour, vegetation and water bodies. Heat and moisture exchanges of different sites vary according to variations in landscape shape and roughness characteristics, orientation, exposure and aspect.

The colour, apparent density, heat capacity, moisture content and permeability of soil; characteristics of vegetation cover; the albedo and roughness of surfaces - these are all factors that influence the heat and moisture exchange and are thus important climatic factors.

(Thorntwaite, 1956, p.571)

"Seventy-five percent of the atmosphere's heat input and 100% of its moisture comes via or from the earth's surface, and surface friction accounts for the dissipation of about 40% of the atmosphere's kinetic energy" (Chandler, 1976, p. 129). Man's modification of the natural surface has produced asphalt, cement, brick and stone surfaces causing a change in the energy and water budgets and momentum of the air masses.

The preparation of a site for building involves clearing the land which modifies the natural atmospheric conditions by creating different energy, water and roughness regimes. Any structure erected on the site becomes an obstacle to wind flow and establishes different albedo, heat capacity, heat conductivity and moisture characteristics. "Climatologic sheath" (fig. 3.1) describes the modified microclimate around a single building (Ryd. 1970). The building's orientation to the sun and the prevailing wind creates different microclimatic characteristics on different sides of the building. A wall facing the sun is warmer than the opposite wall since it receives greater solar insolation. The structure is an obstruction to wind flow, and greater wind turbulence is created on the windward than on the leeward side.

The assemblage of buildings creates as many "climatologic sheaths" as there are individual buildings. A city demonstrates a multiplicity of "climatologic sheaths" and as buildings vary in size, height, material type and orientation, so do their effects on the climatic elements. The vertical aspect and dense network of urban structures no longer make it possible to distinguish the "climatologic sheaths" created by individual buildings due to the convective and advective mixing of their microclimatic air masses.

fig. 3.1 Climatologic Sheath - a modified climatic environment created around a structure.

source: Ryd, 1968, p.29.

...the lack of integration of design and planning factors have caused a climate within the city modified to the extent that it is impossible in many cases to decipher exactly which building, building feature or building cluster has incurred which climatic deviation.

(Landsberg, 1968)

Structures containing outstanding physical features such as a wide wall area exposed to the sun or the wind, dominate the air mass around them and retain their district "climatologic sheath".

3.3.1 The Energy Balance of Urban Microclimates

The vertical component of a city is responsible for climate modification. The variability in building height influences the amount of building wall exposed to the sun and prevailing wind and the amount of open sky visible at the pedestrian level - the view factor (Tuller, 1975). The resulting microclimates are created by the combination of the following factors: artificial, vertical and horizontal surfaces; the macroclimatic conditions such as the solar declination angle, the azimuth angle of the sun, temperature of the atmosphere and regional wind velocity; and the thermophysical properties of the artificial materials.

Shortwave solar radiation reaches the ground by direct transmission(Q) and diffuse rays(q). Both the urban and rural environments receive equal amounts of a direct and diffuse radiation (Q & q)

providing atmospheric conditions are equal. Short wave solar radiation and longwave counter radiation from the atmospheric impinging on an opaque surface are absorbed according to the surface properties while some is reflected. The albedo (α) of a surface determines the amount of solar radiation reflected, significantly modifying the urban energy budget. The asphalt, concrete and brick materials of a city have generally 10 to 30% lower albedo than the natural vegetation of the countryside (Friskin, 1973). Since the atmosphere and surface are warm objects they emit infrared radiation in the longwave spectrum (L) from the earth's surface at an intensity depending on its temperature. Counter radiation (L_c) is emitted from atmospheric particles towards the earth's surface. Thus, the net allwave radiation available at the earth's surface is:

$$R_n = (Q + q) (1 - \alpha) + L_c - L \quad (\text{eq. 3.1})$$

(see fig. 3.2). The artificial energy release in cities (F) resulting from automobile exhaust, heating of buildings and streets is added to the net radiation equation 3.1 when dealing with urban climates (Friskin, 1973). The net allwave radiation supplies energy for latent heat of vaporization (H), the convection heat transfer (S), and the net heat storage in the surface (G). Thus, the disposition of net energy is:

$$R = H + S + G \quad (\text{eq. 3.2})$$

Virtually all components of the urban energy budget differ from the rural energy budget. The paucity of moisture in cities due to less natural vegetation and the rapid precipitation drainage off the artificial pavements results in a smaller amount of energy expended in

fig. 3.2 Urban and rural heat budgets by day (a) and by night (b).

where: R_N - net radiation
 F - artificially generated heat within
a city
 S - convective sensible heat
 H - latent heat of vaporization
 G - heat storage in city's fabric

in the process of latent heat of vaporization. Due to the greater thermal conductivity of urban materials, the net heat storage in the surface is higher than in natural terrain and is eventually convected into the air raising the ambient temperature. The greater availability of energy in the city's atmosphere results in a greater convective sensible heat process. However, energy budget components differ according to the urban fabric; parks and vegetated sites cause greater energy expenditure during latent heat of vaporization than non vegetated areas thus lowering the atmospheric temperature. The urban fabric contains surfaces with higher thermal conductivity which absorb more solar energy, raising the atmospheric temperature above that of surrounding air when this energy is released.

3.3.2 The Influence of Building Orientation and Vertical Profile on Microclimates

Microclimatic pockets within a city are formed according to the availability of solar radiation creating varying energy budgets within a city. In the morning the sun shines from the east and given an identical atmospheric transmissivity it emits an equal amount of energy on both urban and rural surfaces. In the northern mid-latitudes the solar angle to the vertical surface is low, particularly in the winter season, shining mainly on the east, south and west sides of buildings. As the sun follows its diurnal path through the sky, buildings and streets located to the west, north-west, north, north-east and east will in turn experience some degree of shading (figs. 3.3 to 3.5). Walls and streets receive direct solar radiation when

fig. 3.3 Shading patterns at sunrise according to building surface exposure.

In the early morning the east sides of walls receive direct beam solar radiation while south and north sides receive limited amounts of diffuse and reflected radiation.

source: compiled by author

fig. 3.4 Shading patterns at noon according to building surface exposure.

Direct beam insolation at noon strikes the south side of buildings while the east side is irradiating stored energy in the longwave spectrum thus warming the surrounding air.

source: compiled by author

fig. 3.5 Shading patterns at sunset according to building surface exposure.

At sunset the west side of buildings is receiving direct beam solar radiation while the south and east sides are irradiating stored energy in the longwave spectrum thus warming the surrounding air.

source: compiled by author

building arrangements permit surfaces to be exposed to the sun during diurnal solar cycle. As direct solar radiation strikes a building on the east, south and west sides, a portion of the energy is absorbed whereas building surfaces in shade are at an energy disadvantage. In Victoria, British Columbia, a study demonstrated that shorter buildings and wider streets on the west side allowed greater penetration of radiation (Tuller, 1975). This amounted to twice more direct beam solar radiation on the west exposure than on the east exposure providing the west side with over two hours more direct beam energy than the east side.

In a flat rural topography the surface albedo determines the amount of incoming solar radiation reflected from the surface into space (fig. 3.6a). The lack of vertical intercepting features in the rural landscape allows a greater amount of direct and diffuse solar radiation to be reflected into space. The vertical component in a city modifies the net amount of energy reflected into space: for medium height and tall buildings (figs. 3.6b and 3.6c respectively) much of the insolation reflected from vertical building surfaces is intercepted by adjacent buildings or by the streets and is absorbed or rereflected. The reflected portion may be absorbed by the second building or again rereflected. Eventually, considerably more of the incident radiation in a built environment is absorbed by buildings, streets and pedestrian walkways than in the case of radiation incident on a flat surface. In the presence of tall buildings much of the absorption takes place at higher levels is much less than with shorter structures. The warmest pedestrian areas of Dallas and Fort Worth in the day time were those with densely packed buildings of medium height whereas areas of tall

fig. 3.6 The disposition of insolation on flat topography (a), in medium height building situations (b) and tall building situations (c).

source: Ludwig, 1968, p.104.

buildings recorded lower temperatures (Ludwig, 1968). Exceptions may arise when the sun's rays shine directly parallel to the street direction, however, these periods are infrequent and usually of a short duration.

The amount of diffuse beam solar radiation absorbed is determined by building orientation. The strongest diffuse beam solar energy comes from the sky closest to the sun therefore building surfaces facing this portion of the sky receive more solar energy than those facing away from the bright sky. The open sky view factor (the amount of clear sky) determines the amount of diffuse energy radiated: the greater the open sky area the greater the diffuse energy available for warming of building and street surfaces. The proportion of open sky in strategic pedestrian areas such as outdoor cafés is particularly significant on cloudy days providing supplementary energy contributing to an increase in comfort level in cool seasons.

The heat conductivity dictates the amount of energy transferred through a material. The heat capacity of materials is a product of their specific heat and density which determines their capability for heat storage. The input of energy is greater than the outflow, the surplus is stored in the material resulting in a temperature increase (the magnitude depending on the heat capacity). Solar energy is readily stored in urban materials such as asphalt, cement, stone, brick and metals. The increased amount of energy stored in the surfaces is a significant contributor in modifying the energy budget.

Some absorbed energy is radiated into the atmospheric as longwave radiation at a rate proportional to the fourth power of the absolute

temperature of the surface.

$$F = E\sigma K^4 \quad (\text{eq. 3.3})$$

where F = radiation flux per unit time and area from a black body

σ = Stefan Boltzman constant $8.132 \times 10^{-11} \text{ ly/K}^4/\text{min}$

K = absolute temperature

E = emmissivity

Good absorbers are also good emitters via the same wavelength. However, since materials absorb in the short wave and emit in the longwave, absorptivity and emissivity are often not similar (Hather, 1974).

The air is warmed by energy transfers from the surface by longwave radiation and convection of sensible heat and latent heat. A fluid heated at the bottom becomes unstable and rises convectively resulting in an active mixing layer (Friskin, 1973). The convective process continues as long as energy input at the bottom is sufficient but will be disrupted as soon as energy input wanes (Friskin, 1973). During shading direct solar radiation transmission is discontinued decreasing energy absorption in materials. Stored energy is radiated into the atmosphere in the longwave spectrum, cooling the surface and warming the air. Even though shading disrupts direct beam solar insolation, a small amount of energy continues to be supplied through diffuse, reflected and counter radiation. During these conditions surface temperatures do not rise appreciably above atmospheric temperatures once stored energy is depleted and surfaces contribute a negligible amount of longwave energy to warming the adjacent air mass.

Direct beam solar radiation warms building surfaces exposed to the sun's rays and creates pockets of higher temperature when they are shaded. Experiments in Victoria, British Columbia show that the average

daily air temperature pattern followed the distribution of direct beam solar radiation (Tuller, 1975). Higher daytime average temperatures were observed on the east side rather than on the west side of buildings despite a lower total solar radiation availability on the east side. High heat capacity of artificial surfaces allowed solar energy to be absorbed in the morning. Stored energy was gradually released during the day warming the surrounding air (Tuller, 1975).

3.3.3 Vapour Pressure Variability Within a City

Factors controlling the vapour pressure conditions in urban centres are a much disputed and not fully understood topic due to the uniqueness of each city climate investigated. It is generally agreed that the hydrologic cycle in a city is disrupted as precipitation reaches the surface since artificial pavements are an efficient medium in draining water rapidly into the sewer system. The drainage and evaporation of water from urban surfaces and the lack of sufficient natural vegetation to continuously supply moisture into the air through evapotranspiration theoretically suggests a decrease in absolute humidity. Even though moisture regimes in some cities comply with this theory, other cities contain higher vapour pressures than the rural environment. This may be explained by the increased moisture emittance by air conditioners and manufacturers. In a study of a courtyard arrangement it has been noted that evapotranspiration in a woodlot and over a grass lawn contributed to lower air temperatures than over dry artificial surfaces (Landsberg, 1972). This suggests the value of using parks in urban planning processes to provide localized spots of decreased air temperatures during hot summer months giving pedestrians

more comfortable environments in which to repose. Theoretically, humidity should vary according to the moisture content of materials, being higher over vegetated sites and lower over dry artificial materials. Lack of sufficient investigations of microclimatic variability of vapour pressure pose obvious problems to theoretical generalizations.

3.3.4. Variability of Wind Characteristics in Urban Centres

Wind is the climatic variable most noticed and complained about in urban centres. One major cause for the widespread awareness of wind problems is the post World War II popularity of high rise construction which has increased the frequency and occurrence of high wind speeds in the vicinity of tall buildings. The progressive loss of calm urban wind conditions for shoppers and pedestrians and indeed the increasing number of people blown over and seriously injured has inspired interest in wind investigations.

The movement of air masses in the upper atmosphere is determined by large scale weather patterns, however, air near the earth's surface flows at a slower rate because of the friction exerted by the land's topographic configuration. The modified vertical portion of air is called the boundary layer where the mean velocity increases with height and turbulence intensity decreases with height (fig. 3.7).

On the micro scale the irregular vertical component and variability in the micro-geographic texture cells of a city create small scale air circulation. Wind speed and direction modification may be reduced by thermal means of differential solar heating or mechanical means caused by building protrusion into the atmosphere.

fig. 3.7 Variation of hourly mean wind speed and idealized air turbulence conditions with height resulting in a higher boundary layer as rougher topography is encountered.

source: Penwarden and Wise, 1975, p.1;
Aynsley, Melbourne and Vickery, 1977, p.151.

The thermal-modification of air results from the solar heating of different sides of buildings creating "pockets" of warmer air when in shade. The thermophysical variability in materials among roof, plaza, street, park and parking lot surfaces also contributes to differential surface heating. As air is warmed from the bottom it rises convectively causing small intra-street circulations which may be discernible only on calm, clear days.

The more common cause of wind modification is the mechanical deflection of air. The funneling of wind along streets as it is caught between rows of tall buildings results in a modified speed and direction which poses a serious problem where the prevailing wind flow parallels the street layout.

High wind speeds around single tall buildings are caused by air deflection. As free flowing wind impinges on a wall of a protruding structure, an air pressure distribution over the surface of the windward side is created which is generally greater than the atmospheric air pressure, and is related to the local wind dynamic pressure increasing with height (Aynsley, 1977). Fig. 3.8 shows typical average air pressure distributions ascertained in wind simulation tests over the surfaces of a tall building. A pressure gradient against the wall of the building is formed decreasing upwards and downwards and horizontally around the building from a maximum pressure found usually three-quarters way up the building known as a stagnation point (Penwarden, 1975). Wind flow follows the pressure distribution from the stagnation point flowing vertically downwards towards the base of the building, and upwards over the building top. Wind diverted downwards encounters the pedestrian surface and forms a standing vortex which is characterized by high wind speeds (fig. 3.9).

fig. 3.8 Typical pressure* distribution on the windward, side and leeward walls of a model building.

* pressures are expressed as coefficients $C_p = (p - p_0) / \frac{1}{2} \rho V_H^2$

where

p = surface pressure

p_0 = static pressure in wind tunnel air stream

ρ = air density

V_H = wind speed at building height H

$\frac{1}{2} \rho V_H^2$ = dynamic pressure at roof level

source: Penwarden, 1975

fig. 3.9 Air flow around a building creating areas of high wind speeds.

source: compiled by author

Areas of suction are created close to the corners of the windward wall and on the side toward walls where the air pressure is below atmospheric (fig. 3.9). The air in the standing vortex is drawn around the corners of the windward side of the building following progressively lower air pressure gradients and flows generally parallel to the side wall forming a horseshoe wind pattern partially encircling the structure on the pedestrian level (fig. 3.9). When the distance L between a tall building and a lower one located on the windward side is increased, or in the absence of a smaller structure in the windward side, the horseshoe vortex is elongated and the wind speeds in the standing vortex are weakened. In urban centres where tall buildings are frequently located near lower structures, high vortex turbulence is a common occurrence. This wind behaviour was confirmed in wind simulation tunnels conducted at the British Research Station in England demonstrating that for conditions of average wind flow and low turbulence where L/H^* approximates unity or less the wake zone of the smaller building located upstream accentuates the standing vortex in front of the taller building (Wise, 1971). However, in turbulent boundary layer conditions the effect is reversed resulting in less turbulent conditions in the wake of the upstream building thereby decreasing vortex intensity (Wise, 1971).

Wind turbulence in the shear layers of the horseshoe vortex system is highly variable, particularly around the windward facing corners. Buildings situated side-by-side with narrow spaces between them constrict air into a smaller volume drawing it to the leeward side at a high wind speed and creating high wind turbulence. The narrower the space between adjacent buildings the greater the wind speed.

* where L = length of spacing between tall and short buildings

On the leeward side of the tall building a wake zone is present consisting of trailing vortices where wind flow is often in the opposite direction to the regional flow, frequently orbiting vertically several times before straightening out its course and proceeding downstream. The pressure distribution on the leeward side of the building is dependent on the free stream wind velocity flowing over the top of the building. The resultant effect is that the taller the building the lower are the wake pressures and the higher the wind speeds in the shear layers and wake zones. Penwarden (1975) suggests that for $R_H = h/H$ (fig. 3.9), pedestrian level wind speed at height h may exceed that of the free flowing atmosphere in the upper boundary layer at height H by a factor of $R_H = 1.2$ in the passageway of a building; whereas R_H is 0.5 in the standing vortex and 0.95 in the shear layers. Even though air circulates in a turbulent manner in the wake zone, mean wind speeds here are generally lower than in the horseshoe vortex. For $R = \text{wind speed at pedestrian height} / \text{free wind speed at pedestrian height}$ on an open site, ratios of 1.5 and 2.0 were obtained in the standing vortex and near corners respectively of buildings which are four or more times the height of surrounding structures. A ratio of 3.0 was found in passageways of buildings elevated on columns. Buildings which are less than twice the height of surrounding buildings produce an amplification of wind speed that rarely exceeds $R = 1$ (Penwarden, 1975).

CHAPTER 4 BIOCLIMATOLOGY AND HUMAN COMFORT IN URBAN CENTRES

4.1 Significance of Urban Bioclimatology and Human Comfort

Bioclimatology is defined as "a branch of ecology which studies the interrelations between chemical and physical factors of the atmospheric environment and living organisms" (Sargent and Tromp, 1964, p.1). Bioclimatic research in urban centres is a recent field of study hence its theories and methodologies are inadequately developed and not fully understood. The study of human comfort is found within the discipline of bioclimatology and is defined (by Fanger, 1970 in Plumley, 1975) as "that condition in which a person expresses satisfaction with the thermal environment". It is a subjective feeling based on the physiological and psychological functions of a human being. Human comfort is examined in terms of bioclimatology in this chapter, since the thermoregulatory system influences the thermal state of the body according to climatic conditions. Human comfort sensations result according to the thermoregulatory state, that is, it indicates whether a net heat gain or loss to the body has occurred. Human reaction to thermal change is almost instantaneous and can be dealt with by adding or taking off clothing or by moving to a more favourable microclimate. If an adverse human comfort sensation is not corrected within a reasonable time, or is encountered frequently, more serious bodily disruption may occur and effect one's well-being. Therefore, when considering human comfort levels in urban planning, it is important to keep in mind that

extreme microclimatic conditions may cause more than just discomfort, but may have more serious health implications.

4.2 Problems of Bioclimatology in Being Established as a Serious Discipline

In view of the nature of scientific thinking in the 1800's and early 1900's, climate was considered as an insignificant factor in human well-being and thus the philosophy of environmental determinism was being exchanged in favour of possibilism and probabilism. Confidence was being gained in the ability to overcome environmental stresses through technological advancements. It was believed that man's fate was in his own hands and to think that climate had any role in influencing the human organism other than imposing sensations of varying degrees of warmth and cold was absurd. Humanistic aspects of scientific investigations suffered the most during this time and in 1947 William Petersen, one of the pioneers of modern bioclimatology, acknowledged the vast disregard among medical professional of the influence of weather on human health.

Modern bioclimatology was born in the post World War II years; however, since its contents transgress beyond popular scientific thinking, it has had difficult moments in becoming established as an acceptable discipline. Among some of the problems is that for many years bioclimatologists have been borrowing from meteorologists assembled

statistics on atmospheric parameters and "then contemplating them in a sort of environmental haze" (Auliciems, 1972). There is a need for bridging the gap between meteorologists and bioclimatologists in order to become more familiar with the instrumentation techniques most appropriate in bioclimatic research and the type of data needed in physiologic investigations.

Human bioclimatologic investigations are a difficult undertaking for a number of reasons. According to S.W.Tromp, opposition in previous years has come from medical specialists who are inclined to consider the physico-chemical composition and organic structure of the human body as constant and therefore not influenced by meteorological forces (Maunder, 1970). The complexity of the human organism and the multitude of interacting meteorological parameters on the body has contributed to this confusion. A significant breakthrough occurred when it was discovered that the human body contains organs which are sensitive climate detectors, each specialized to respond to certain climatic stimuli. The term "meteorotropism" has been used to describe biologic body functions or symptoms correlated with meteorological processes. Many complex meteorotropic reactions are still poorly understood. The Biometeorological Centre in Leiden, The Netherlands, established in 1957, has been the main research centre where laboratories and climate controlled chambers are used to study symptoms appearing in blood composition and organs.

4.3 Human Comfort and the Thermoregulatory System

Meteorotropic symptoms may be consciously felt by most people; however, everyone feels various degrees of comfort and discomfort according to weather conditions. The climatic parameters most influential on human comfort are air temperature, atmospheric humidity, solar radiation and wind speed. Humans exchange heat energy with the surrounding atmosphere and surfaces; the relationship is summarized by the following equation,

$$M \pm R \pm C \pm E = Q \quad (\text{eq. 4.1})$$

where M = metabolic rate

R = radiative heat exchange

C = convective heat exchange

E = evaporative heat exchange

Q = change in the heat content of the body

(Clarke and Bach, 1971, p.41)

During the metabolic process food is used to produce energy at a rate which varies according to the physical preoccupation of the body. The amount of metabolic heat produced must be balanced by the amount of heat gained and lost via the climatic processes. The temperature of the surroundings influences the amount of radiative heat gained or lost. If the surrounding surfaces are warmer than the body surface, the body gains heat, and vice-versa. Convective heat exchange occurs

through wind movement. When the air temperature is lower than the body surface temperature, the body loses heat by convection. The mechanisms of vasodilation and vasoconstriction are involved to compensate for heat gain and heat loss respectively, returning the body to thermal neutrality.

Thermoregulation of the body is achieved by maintaining the internal core of the body close to 37°C and the outer layer of the body at about 33°C (fig. 4.1). The range of ambient temperatures most acceptable to the human body in clothed conditions is between 29°C and 31°C known as the zone of thermoneutrality. In these thermal conditions, an average person maintains heat balance through minor physiological adjustments and feels comfortable, having no desire to adjust atmospheric conditions. (However, the state of ideal comfort may vary according to the cultural background of the individual, the degree of acclimatization, the amount of clothing worn and the metabolic heart rate). Any atmospheric deviation caused by vapour pressure, wind and particularly solar radiation conditions is sensed by the temperature sensitive receptors such as nerve endings in the skin which transfer the stimulus via neurons to the reflex centre. The reflex centre consists of the hypothalamus located in the brain stem whose thermally sensitive cells initiate temperature regulation in order to maintain thermal balance. The temperature regulation centre consists of the nervous and endocrine systems which are responsible for either heat conservation or heat dissipation. The nervous mechanism involves autonomic reflexes such as

fig. 4.1 Important physical and physiological elements which control thermal balance.

source: Landsberg, 1969, p.33.

the cardiovascular system, the respiratory system and the sweating mechanism.

Heat loss from the human body is followed by reflex vasoconstriction initiated by the temperature regulating centre and the vasomotor centre of the brain stem. From the vasomotor centre neurons pass to the walls in minute arteries and veins located under the skin layer, constricting them. This inhibits further blood flow thus reducing heat loss from the blood by radiation and conduction at the skin's surface. At the same time blood pressure in the body's core rises because of increased blood content coming from the body's surface.

Continued exposure to cool temperatures over a long period of time, or a sudden decrease in temperature in a short time (both cases involving ambient temperatures below 28°C) will result in reflex shivering which produces extra metabolic heat.

At the sign of heat strain on the body, vasodilation occurs which involves the enlargement of minute arteries and veins under the skin concurrently with the lowering of blood pressure in the body's core. Heat is lost from the skin's surface by longwave radiation, convection and evaporation. A greater production of metabolic heat follows which, ironically, results in a lowering of body temperature by inducing the reflex mechanism of sweating. Sweating is initiated when the skin temperature is greater than 36°C ; water evaporates from the skin surface

resulting in body heat loss by latent heat of vaporization.

Excess sweating can result in a great loss of water and may cause health complications unless compensated immediately by drinking fluids. When excess heat income is not dissipated by thermoregular means, the body temperature increases resulting in a heat stroke or a related illness. In conditions of increasing warmth, thermally sensitive receptors in the skin detect this change sending the message to the reflex centre and to the temperature regulators. Skin at a temperature of 40°C can detect an ambient temperature difference of 9°C , however, skin at a temperature of 28°C can discriminate as little as 0.5°C air temperature change, and skin at a temperature of 40°C can discriminate 1°C ambient temperature change (Sargent and Tromp, 1964). At 45°C the skin begins to feel pain, as when sunburned (Hardy, 1972).

Atmospheric vapour pressure affects the amount of evaporation taking place from the skin. As vapour pressure increases the air becomes more saturated and does not readily accept moisture from the skin. At more than 20 mb, air temperatures over 25°C become unpleasant and a "sticky" feeling prevails. Vapour pressure determines the subjective impressions of comfort. Between 18 and 25°C moist air is distinguished quite quickly from dry air. With a drop in temperature it becomes increasingly more difficult to distinguish the amount of moisture in the air until about 50°C when skin receptors are incapable of detecting 5 % relative humidity from 30 %. Vapour pressure levels are

particularly discernible when a body sweats in warm air or during high metabolic rates.

Air movement is an important determinant of comfort sensation when the body contains excess heat. The amount of heat convection from the body is directly proportional to the square root of the speed of the wind and to the temperature gradient between the skin and the air (Sargent and Tromp, 1964). One example of this relationship is the wind chill factor which describes how wind flow at low air temperatures creates a feeling of lower ambient temperatures. The other factor is the mechanical force of wind which is detected by mechanoreceptors of the skin. In thermally neutral atmospheric conditions when no significant thermal cooling of the human organism is occurring, wind force is a nuisance because of the pressure it exerts on a person, being particularly irritating if it contains rain or dust particles. In regard to the classification of wind induced comfort levels, the clear distinction between the discomfort due to the thermal sensations of air convection and the mechanical air movement must be kept in mind. A high wind speed which would be indexed as "unpleasant" on a wind force index may actually be classified as a different sensation on a thermal wind comfort scale.

4.4 Climatic Influences on Meteorotropism

Meteorotropism is achieved by the modification of the internal

environment in and around sense organs by changing temperature, pH, osmotic pressure and concentration of electrolytes. Other organs detect changes in the external environment. A set-point or "steady-state condition" is established in the internal detectors designating normal internal conditions, and any fluctuations initiate a reaction by the detector organs (fig 4.2). The reaction is characterized by a functional deterioration of the organism resulting in a physiological and/or psychological response. The Biometeorological Research Centre in The Netherlands has identified three main groups of meteorotropic diseases. These are asthma and bronchitis, rheumatic diseases and heart diseases. A conscious awareness of climatic deviation by a human being such as discomfort due to excess solar radiation, for instance, may lead to a response through the use of clothing, shelter, heat, etc. which returns the detector's condition back to its set-point. However, meteorotropic diseases often need medical attention in order to return the body to a steady state condition.

Environmental change acts as a stimulus on an organism only if the magnitude and duration of the change are sufficient to produce a response-causing sensation of irritability (Sargent and Tromp, 1964). The response is produced as a result of an atmospheric stimulus acting directly on cells or indirectly by being transferred through the nervous system. Receptors which are either bare nerve endings or complex structures such as the eyes receive the stimulus and convert it into an electric impulse which is sent along neurons to the nervous

fig. 4.2 The physiologic regulatory response system during climatic change.

source: compiled by author

system to be received by detector organs. Detectors consist of the brain, brain stem and the spinal cord which receive these impulses in two regions; the reflex centres located in the brain stem or spinal cord which collect impulse information without necessarily organism awareness of the receipt of stimuli; and perceptual centres which create full awareness of the atmospheric change. The reflex centres cause involuntary reactions in the muscles which change their length, or in the glands which release a secretory fluid.

The duration of time necessary to arrive at a "steady-state" condition varies from an immediate adjustment achieved by the nervous system to an extended adjustment by both nerves and the endocrine system. Through the process of adaptability the extent of irritability detected by organs is decreased and a greater range of atmospheric change may be tolerated. Disease or illness results when environmental strain is too great and a return to the set-point condition may be achieved only by medical treatment.

4.5 Human Comfort, Meteorotropism and Urban Planning

It is believed that urban layout and building arrangements cause extreme microclimatic conditions which influence human comfort (Clarke and Bach, 1971). Shatluck and Hilferty (1932, 1933 in Clarke and Bach, 1971) found a higher heat-related death rate in cities than in rural areas, and the rate tended to increase with city size. Clarke and Bach's

research in St. Louis during the July 1966 heat wave shows a relationship between the average daily temperature and deaths occurring as a result of the heat. A 0.6°C increase over 32.2°C in the average daily temperature resulted in 11 heat deaths. When the average daily temperature was 35°C , 73 deaths were recorded which were attributed to heat. Such a difference of 2.8°C in the average daily temperature is approximately that between the urban and rural environments based on the afternoon and evening temperature values recorded by Clarke and Bach (1971). They suggest that since excess deaths occur only after a 24 hour period of high heat, it is not the absolute maximum temperature which causes mortality, but rather the lack of relief when the minimum temperatures remain high. Urban dwellers do not receive the intermittent cooler temperatures during a heat wave as rural dwellers do, because of the higher heat retention of urban fabrics.

A study by Mayer (1977) on bioclimatic differences based on the human heat balance (eq. 4.1) between the environments of forest, city and sea coast shows that the city is the most disadvantageous. The most striking difference was the low water vapour content of the city atmosphere.

A study conducted in the U.S. suggests that excessive heat in urban areas may be more lethal than high levels of air pollution (Ellis, 1972). Infants less than one year in age and old people are particularly vulnerable to death from acute heat illnesses since they are often incapable

of adjusting to stressful atmospheric conditions.

Another hazard is the gusty nature of wind on pedestrian plazas, which has been responsible for deaths and numerous injuries. An old woman died of a fractured skull in Portsmouth, Britain, after being swept against a tall building where wind speeds are estimated to have been 15 to 24 m/s gusting to 30 m/s. Another old woman died of head injuries in Birmingham, Britain, as a result of similar wind conditions (Penwarden, 1975).

Clarke and Bach (1971) state that "there is evidence to indicate that a large percentage of heat related deaths are of man's own design by climate modification through urbanization". Since the climatic parameters of temperature, humidity, wind speed and radiation are strongly influenced by the physical properties of the urban fabric, human comfort and physiologic conditions will also vary according to the variation in microclimate (Clarke and Bach, 1971). This forms a strong argument for the use of human comfort as an indication of the influence of urban design on human well-being. Considerations of human comfort could be incorporated into the urban planning process to alleviate or modify urban features which cause discomfort and/or irritability. For example:

Efforts by public agencies and private interest groups to revitalize the central business districts in American cities have often included large expenditures for outdoor pedestrian spaces. Many such "amenity" spaces have failed to receive more than light use. This

failure has been partly attributed to a general disregard for the physical-comfort needs of the users (Whyte, 1972 in Plumley, 1975). The need for thermal comfort is ubiquitous but seems often to be forgotten in the designs of outdoor spaces.
(Plumley, 1975)

It is predicted that by the year 2,000, about 80 % of the North American population will be concentrated in a few megalopoli covering more than tens of thousands of square miles (Clarke and Bach, 1971). The climate of these centres will differ markedly from the rural areas. "If the effects of the urban structure on climate are considered in the urban planning process, climate modification can be purposely controlled rather than allowed to inadvertently develop" (Clarke and Bach, 1971, p.52). The consideration of human comfort can be an effective method to do this.

CHAPTER 5 METHODOLOGY OF TRAVERSE DATA COLLECTION & ANALYSIS

5.1 Study Area

The sector of Ottawa's downtown chosen as the study area serves as an example of a typical downtown environment regarding vertical profile, horizontal land use characteristics and automobile and pedestrian traffic. The central area of Ottawa and the wind study area as defined by Ottawa's City Hall Department of Community Development are shown in fig. 5.1.

A busy downtown pedestrian area was desired to make bioclimatic evaluations more worthwhile and more interesting when applied to a greater number of people in a well utilized area of the city. A troublesome wind area has been identified by Ottawa City Hall (fig. 5.1) within which traverse measurements were confined to include measurements of anomalous wind velocities.

Taking into account the abovementioned points, a study area was chosen bounded by Sparks and Laurier Streets oriented approximately east-west, and Elgin and Lyon Streets oriented approximately north-south (fig. 5.3). Even though the area along Rideau Street is included in City Hall's wind study area and would have been an interesting area to traverse, it was excluded because of the extra time and volunteers necessary to adequately traverse this sector.

Source: Chen & Hart, 1977.

fig. 5.1 The Central Area of Ottawa and wind study area as defined by Ottawa's Department of Community Development.

OTTAWA - DOWNTOWN CORE

LEGEND

- ① location of measurement stations
- route of traverse

fig. 5.2 Microclimatic study area showing location of measurement stations within the boundaries of City Hall's wind study zone.

OTTAWA - DOWNTOWN CORE

SCALE

LEGEND

----- traverse route (see fig. 5.2 for location of measurement stations.

fig. 5.3 Isometric representation of buildings within the microclimatic study area.

Considering the highly variable downtown profile, a careful selection of measurement sites was necessary to incorporate a sufficient number of microclimatic pockets which would demonstrate microclimatic variability. A deliberate selection was made of certain measurement sites such as at the base of tall buildings, next to open top parking lots, near a cluster of medium height buildings and near green space which were expected to show variability in microclimatic measurements. Other measurement sites were chosen at random to provide samples of unbiasedly selected sites which would test the hypothesis of microclimatic variability. A total of twenty measurement sites was selected located on either midblocks or at intersections (fig. 5.2) which was traversed in approximately $2\frac{1}{2}$ hours (Table 5.1). A longer time period would have included a greater diurnal temperature and solar radiation range as a result of the change in solar declination which would give greater inaccuracies in data collected. Measurements were taken on the exact spot at each measurement station. Traverses were conducted regardless of the weather except when it rained or snowed.

A smaller study area on the west end of Sparks Street Mall consisting of one block was traversed on two occasions. The purpose was to measure the finer characteristics of microclimatic variability created by the two tall buildings, Holiday Inn and Tower "C" which are located on each end of the block (fig. 5.4). The traverse route consisting of 13 measurement sites was conducted from the corner of Sparks and Kent Streets, along Sparks, Lyon, Queen & Kent Streets (fig. 5.5).

TABLE 5.1

EMPIRICAL DATA: RECORDED & GRAPHED

A. CITY CENTRE TRAVERSE (20 STATIONS)

AIR TEMPERATURE		Vapor Pressure		Incoming Solar Radiation		Infrared Temperature	Wind Speed	Time Range
		Dry	Wet					
Sept. 1	X *	X	X	X	*	---	X *	12:30 - 14:40
Sept. 14	X *	X	X	X	*	X	X *	12:40 - 15:20
Sept. 22	X *	X	X	X	*	X	X *	12:35 - 15:00
Sept. 29	X *	X	X	X	*	X	X *	12:15 - 14:50
Oct. 12	X *	X	X	X	*	X	X *	12:15 - 15:00
Oct. 19	X *	X	X	X	*	X	X *	12:30 - 15:30
Oct. 27	X *	X	X	X	*	X	X *	12:18 - 14:55
Nov. 2	X *	X	X	X	*	---	X *	12:30 - 15:33
Nov. 24	X *	X	X	X	*	---	X *	12:30 - 14:53
Nov. 30	X *	X	X	X	*	---	X *	12:37 - 15:00
Dec. 14	X *	X		X	*	---	X *	12:30 - 15:37

B. SPARKS ST. - QUEEN ST. TRAVERSE (13 STATIONS)

Nov. 16	X *	X	*	X	*	X	X *	12:20 - 14:05
Dec. 1	X *	X		X	*	---	X *	12:20 - 13:36

X Measured Data

* Graphed Data

LEGEND

block traverse area

fig. 5.4 The block chosen to examine microclimatic variability on a finer scale, which is dominated by Tower C and Holiday Inn Buildings.

OTTAWA - DOWNTOWN CORE

SCALE

LEGEND

- ① location of measurement stations - city centre traverse
- * location of measurement sites during block traverse

fig. 5.5 Location of measurement stations in block traverse microclimatology study.

The time of day chosen to conduct both central area and block traverses was at the peak pedestrian activity at lunch time. The city centre traverse route was begun sometime between 12:15 and 12:40 p.m. starting at the National Arts Centre (NAC) at Elgin and Queen Streets, proceeding along Sparks, Queen, Albert, Slater and Laurier Streets (fig. 5.2). Table 5.1 lists the dates traverse routes were conducted, their duration and the kind of data collected. An account was taken of the diurnal temperature change over the time of the traverse by returning to the first measurement site, the NAC, at the end. The diurnal temperature change is shown on fig. 6.1, and climatic data were corrected according to the amount of temperature change from the time of traverse commencement to the time measurements were taken.

5.2 Instrumentation and Measurement Procedures

The traverse route was conducted on foot to include measurements on Sparks Street Mall which is closed to vehicular traffic. Meteorological instruments were portable and were easily carried in a laundry cart which was cushioned at the bottom by a blanket to resist knocks. At each measurement site four meteorological instruments were used in the following sequence. An Assmann Aspirated Psychrometer (Casella, London, England) measuring dry and wet bulb temperatures was wound up and hung on the side of the cart after checking for sufficient moisture on the wick of the wet bulb thermometer. Temperatures were recorded after completion of other measurements to ensure that the psychrometer attained maximum evaporation from the wet bulb. The Kipp solarimeter, registering incoming solar radiation intensity on a Comark Volt meter, was placed on the pavement and allowed to stabilize for a

few seconds before a reading was taken. During block traverses incoming solar radiation from the surrounding atmosphere and building surfaces was measured by pointing the solarimeter from chest height in four cardinal directions. Wind velocity was measured using a hand held cup anemometer and the maximum reading during approximately thirty seconds was recorded. Infrared temperatures of the pavement were measured using a Barnes infrared thermometer which provided a direct reading of the temperature of the surfaces in degrees Centigrade. During block traverses the infrared temperature of the "environment" was measured by pointing the infrared thermometer in four cardinal directions. Infrared temperatures were not taken on November 2, November 24, November 30, December 1 and December 14 because of difficulties in obtaining the special batteries for the thermometer and the loss of the calibrator.

It took 3 to 5 minutes per measurement site to record data, and approximately 5 minutes to arrive at the next site. Because of the curiosity of passersby it often took longer to complete measurements.

Wet, dry bulb and infrared temperatures were recorded in degrees Centigrade. Wind speed was measured in meters per second. Incoming solar radiation was measured in millivolts and converted into langleys per minute using the following calibration

$$\frac{\text{Solar radiation (millivolts)}}{17.27 \text{ (millivolts/langley/minute)}} \quad (\text{eq. 5.1})$$

5.3 Questionnaires of Human Comfort

Questionnaire surveys of human comfort were conducted on three occasions: October 12, October 19 and November 2, during which time 93, 74 and 57 people respectively were surveyed. This averaged approximately 4.7, 3.7 and 2.9 persons per measurement site respectively. While climatic measurements were being recorded following the usual traverse routine, an assistant was occupied with stopping passersby and questioning them. The reason for conducting a human comfort survey in this study was to learn how downtown pedestrians in Ottawa feel about the climatic conditions on each measurement site and whether comfort sensations varied according to climate variability. A comparison was ultimately made between the subjective interpretations of climate by pedestrians and those derived from Vinje's comfort scale.

Figure 5.6 shows the format of the questionnaire, which was structured to be understandable to the general public and could be answered in approximately half a minute. Question number one requests the person's comfort sensation on a particular site. The person was advised to reflect for a few seconds on his/her general feeling resulting from the climatic environment on the location where he/she was being questioned. Question number two was added to the questionnaire conducted on October 19 and November 2, and deals specifically with the public's attitude towards wind speed at a particular site. Question number three requests a list of clothing worn in order to subsequently judge whether an extreme or anomalous comfort sensation occurred as a result of climatic influences or the amount of clothing worn.

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CLIMATOLOGY RESEARCH

OF DOWNTOWN OTTAWA

1. Please check (✓) off how you are feeling at the present moment in the present weather conditions.

☐	1. Cold
☐	2. Uncomfortably cool
☐	3. Cool
☐	4. Comfortable
☐	5. Comfortably warm
☐	6. Uncomfortably warm
☐	7. Very uncomfortably warm
☐	8. Hot

2. Please check (✓) off how you feel about the present wind conditions.

☐	1. Extremely windy
☐	2. Uncomfortably windy
☐	3. Comfortably windy
☐	4. Not windy enough

3. Please check (✓) off what items of clothing you are presently wearing.

☐	1. Long pants
☐	2. Shorts
☐	3. T - shirt
☐	4. Long sleeved shirt or blouse
☐	5. Short sleeved shirt or blouse
☐	6. Sweater
☐	7. Light jacket (ie. blazer, etc.)
☐	8. Heavy jacket (ie. winter jacket)
☐	9. Light coat (ie. trench coat, etc.)
☐	10. Heavy coat (ie. winter coat, etc.)
☐	11. Skirt
☐	12. Dress
☐	13. Nylon stockings

THANK YOU KINDLY FOR YOUR COOPERATION

fig. 5.6 Human comfort questionnaire used during city centre traverses.

5.4 Methodology of Data Analysis

5.4.1 Organization of Empirical Data

Empirical climatic data were plotted into graph form using the Geography Department's Hewlett Packard computer. These graphs, found in Appendix 'A' for city centre traverse data and 'B' for block traverse data aid in visually appreciating the variability of climatic parameters within the study areas. Table 5.1 lists the kind of climatic data graphed, which includes essentially all data collected. An exception is made for wet bulb temperatures which were not plotted as such but were used to calculate vapour pressure.

5.4.2 Human Comfort Calculations

Table 5.2 presents a summary of the human comfort formulae used with the empirical data collected in the city centre and the block study areas. Each formula is presumably appropriate for a certain range of conditions, beyond which the results risk being inaccurate. The Fuller and Brouha Heart Rate formula is most applicable during extremely hot and humid climatic conditions which were not encountered during the study period. Heart rate calculations were done for the two warmest days, September 1 and September 14 when temperatures ranged from 20 to 24.8°C and 16.6 to 21.5°C respectively, to serve as an example of this methodology. The Hendrick Comfort formula was used to calculate comfort on September 1 since this formula is most useful for temperatures over 20°C. The Vinje

TABLE 5.2

SUMMARY OF COMFORT FORMULAE USEDCITY CENTRE TRAVERSE

Fuller & Brouha heart rate	Hendrick $T \geq 20^{\circ}\text{C}$	Vinje dry $20^{\circ}\text{C} > T < 0^{\circ}\text{C}$	Vinje wet $20^{\circ}\text{C} > T < 0^{\circ}\text{C}$	Court $T < 0^{\circ}\text{C}$
Sept.1 Sept.14	Sept.1	Sept.14 Sept.22 Sept.29 Oct. 12 Oct. 19 Oct. 27 Nov. 2 Nov. 24 Nov. 30	Sept.14 Sept.22 Sept.29 Oct. 12 Oct. 19 Oct. 27 Nov. 2	Nov.24* Nov.30* Dec.14

BLOCK TRAVERSE

Nov. 16	Nov. 16	Dec. 1*
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* stations 2, 10, 11, 12 were calculated using Vinje dry bulb formula since $T > 0^{\circ}\text{C}$

* stations were calculated using wet bulb temperatures except for Nov.30 where stations 15 and 16 were calculated using the Vinje wet bulb temperature formula since $T > 0^{\circ}\text{C}$

dry and wet bulb comfort formulae are used for data ranging between 0°C and 20°C. The Court Wind Chill formula is applicable for data below 0°C and was used for dry bulb temperatures on December 14 and wet bulb temperatures on November 24 and November 30.

5.4.2.1 Burton: Solar Radiation Expressed as Temperature Equivalence

The comfort formulae require ambient temperatures as an indication of the state of comfort. However, to provide a more accurate indication of the heat load on the human body, it was decided to combine air temperature and heating effect of solar radiation to produce an environmental temperature. The solar radiation can be expressed as an equivalent increment of temperature ΔT in degrees Centigrade using Burton's (1944) formula.

$$\Delta T = \frac{LN}{b} \quad (\text{eq. 5.2})$$

where L = solar heat load in kgcals/hr
 b = total body surface area in square meters (1.7 m^2)
 N = thermal insulation of the air in $\text{Cm}^2\text{hr/kg/cal}$.

The thermal insulation N was worked out using

$$N = \frac{0.18}{(0.61 + 0.19 \sqrt{vp/76})} \quad (\text{eq. 5.3})$$

where v = wind speed in cm/sec
 p = atmospheric pressure in cm.

(Klein, 1948). An albedo factor of 0.5 was included in equation 5.3 to compensate for the reflectivity of clothing and skin. The results of the equivalent temperature ΔT was added to air temperature in all comfort index calculations.

5.4.2.2 Fuller and Brouha: Heart Rate Index

Fuller and Brouha (1966) conducted an experiment to derive a mathematical model of the relationship between heat stress conditions and heart rate in various job environments. Heat stress was defined as "the additional load on bodily functions caused by the need to maintain a satisfactory body temperature". The primary body reaction to this load is an increase in heart rate as well as body temperature, respiration and perspiration. The conventional method of evaluating physiological discomfort - the Effective Temperature Index, is subjective, based on average responses of people. Fuller & Brouha felt that physiological measurements, in particular heart rate, should be done to confirm the subjective responses. The mathematical model is based on heart rate patterns observed during experiments of young unacclimatized males walking on a treadmill in essentially calm air conditions. The mathematical expression of this relationship is

$$HR = 0.029 MR + 0.7 (T + vp) \quad (\text{eq. 5.4})$$

where

- HR = heart rate in beats/minute
- MR = metabolic rate in British Thermal Units/hour
- T = air temperature in degrees Fahrenheit
- vp = atmospheric vapour pressure in millimeters of mercury.

Since heat stress occurs in unusually hot and humid climatic conditions, this formula risks inaccuracy or misinterpretation when used beyond this restriction. It was found that for a constant work load, the higher the air temperature the higher the heart rate and the longer the recovery rate of heart beat to the previous resting level. Normal resting levels for most healthy people may range from 70 to 90 beats/minute.

Garnier (1972) used this model to evaluate heart rate of individuals in outdoor situations in Montreal. It was applied to people walking at 4.8 kilometers/hour (3 mph) with a metabolic rate of 264,600 calories/hr (1050 BTU/hr). During these conditions a heart rate of 110 beats/minute is considered as a "safe limit" beyond which normal health may be impaired. Equation 5.4 was applied to the two warmest days, September 1 and September 14, using the same metabolic rate as did Garnier, 264,600 calories/hour. It was also assumed that on the average downtown pedestrians walk at a leisurely pace of 4.8 kilometers/hour while shopping, browsing or traversing between office and luncheon spot.

5.4.2.3 Hendrick: Human Comfort Index

The Hendrick (1959) formula was used in this study to evaluate comfort sensations on September 1 when ambient temperatures at all measurement sites were greater than 20°C. Hendrick modified the well-known temperature effectiveness index for outdoor use which provides a numerical index of comfort,

$$CI = I + \Delta I \quad (\text{eq. 5.5})$$

where CI = a numerical index of comfort
 I = effective temperature index under calm conditions

$$I = (0.5 + U^2 \times 10^{-4}) (T - 80 + 0.11U) \quad (\text{eq. 5.6})$$

where T = temperature in degrees Fahrenheit
 U = relative humidity in percent

and ΔI = is the cooling effect due to air movement,

$$\Delta I = -0.35V^{0.5}(20 + 0.5U - 0.2T) \quad (\text{eq. 5.7})$$

where T = temperature in degrees Fahrenheit
 U = relative humidity in percent
 V = wind speed in miles/hour

(Hendrick in Garnier, 1972). The numerical comfort index and equivalent sensations are presented in Table 6.11A. Since wind speed is incorporated in equation 5.7, the greater the wind speed the higher the ΔI value, therefore increasing the comfort sensation. Equation 5.6 calculates comfort according to temperature and relative humidity. As they increase the discomfort increases. In combining equations 5.6 and 5.7 the sensation according to the combined effects of temperature and wind are "balanced" providing a more accurate index of comfort than the consideration of solely one variable.

5.4.2.4. Vinje: Dry and Wet Bulb Human Comfort Index

For conditions when temperatures range between 0 and 20°C, Vinje (in Garnier, 1972) has developed two formulae which are essentially expressions of wind chill. They calculate the body cooling rate in a wind chill form. As with most body cooling rate comfort formulae, the Vinje formulae have evolved following decades of experiments simulating the physiological reactions of the human body by analogy in physical objects. The earliest experiments involved Hill's Katathermometer which would be warmed to body temperature and allowed to cool for a certain period of time, thus simulating body cooling. The temperature drop or "cooling power" is caused by combined effects of air temperature, radiation exchange and wind on the thermometer bulb. To simulate the effects of cooling rate of a sweating body in the presence of excessive humidity in the air, a wet wick was wrapped around the thermometer bulb. Vinje's formulae are essentially mathematical expressions of the cooling rate of the Katathermometer. The formula used when dealing with dry bulb temperatures in relatively dry air conditions is

$$H = 0.57 V^{0.42} (36.5 - T) \quad (\text{eq. 5.8})$$

where H = cooling power in $\text{mcal/cm}^2/\text{sec}$
 V = wind speed in meters/second
 T = dry bulb temperature in $^{\circ}\text{C}$.

During extremely humid conditions when evaporation of sweat from the skin is less easily attained, the following "wet-bulb" formula is used,

$$H^1 = (0.37 + 0.51 V^{0.63}) (36.5 - T^1) \quad (\text{eq. 5.9})$$

where H^1 = cooling power of a wet body in $\text{mcal/cm}^2/\text{sec}$
 V^1 = wind speed in meters/second
 T^1 = wet bulb temperature in $^{\circ}\text{C}$.

5.4.2.5 Court: Wind Chill Formula

For temperatures below 0°C atmospheric humidity is less significant in the process of cooling (Munn, 1970). Court (in Garnier, 1972) has developed a comfort index based on the wind chill principle which calculates the cooling power in freezing temperatures.

$$H = \frac{(10.9 V^{0.5} + 9 - V) (33 - T)}{36} \quad (\text{eq. 5.10})$$

where H = cooling power in $\text{mcal/cm}^2/\text{sec}$
 V = wind speed in meters/second
 T = air temperature in $^{\circ}\text{C}$

The comfort sensations for Court's cooling rate values can be found in Table 6.11B. Dry bulb temperatures were used for December 14 and wet bulb temperatures for November 24 and November 30. Wet bulb temperatures are less applicable in below freezing conditions with exceptions for winter joggers who work up a sweat and are liable to be chilled. Shoppers wearing heavy winter clothing inside stores during which time they become overheated and sweaty are risking a sudden cooling rate when stepping outside. This may result in a highly uncomfortable sensation which may lead to health complications.

CHAPTER 6 EMPIRICAL DATA ANALYSIS

6.1 Aim and Significance of Human Comfort Calculations

The main purpose of this chapter is to demonstrate the feasibility of using empirical climatic data in mathematical formulae to predict human comfort levels. The accuracy of the human comfort formulae are questionable, however, the aim is not to present accurate human comfort predictions, but rather demonstrate the use of human comfort levels based on microclimatic data. It is hoped that this can easily be used by urban planners to determine appropriate building arrangements for new projects, and alleviate unfavourable sites in existing areas. The advantage of simple methods is that they save time and money and do not discourage urban planners from using climatic input.

Most urban climatic data are analyzed in terms of extreme values and it is then presumed that these represent conditions unfavourable to human use. However, one can never be certain whether areas are indeed unfavourable unless human comfort is used as the guide.

6.2 Diurnal Temperature Ranges During Traverses

On September 1 the traverse route proceeded from the National Arts Centre (N.A.C.) terminating at site 20 (Laurier and Lyon Streets). From September 14 to the end of the city centre research the traverse

routes were not terminated at site 20 but a return to the N.A.C. was made where final measurements were recorded. During block traverses the route proceeded around the block returning to the first site where readings were again taken. This procedure was repeated during every traverse route to ascertain the amount of diurnal temperature change which had occurred during data collection.

Fig. 6.1 shows the diurnal temperature range which occurred during each traverse period; it was derived by calculating the difference between the temperature recorded at the beginning of the traverse and the end of the traverse at the N.A.C. During most traverse periods the ambient temperature increased; for example, on September 14 dry bulb values increased from 19.5 to 22.2 °C; on September 22 dry bulb values increased from 16.7 to 17.2 °C; on September 29 the increase was from 13.4 to 16.8 °C. The time of data collection at each site was noted on the "x" axis of fig. 6.1 and the amount of temperature increase which had occurred from traverse commencement to the time of data collection was subtracted from actual measurements. The corrected wet and dry bulb temperatures for each traverse represent readings as if recorded at the same time at all 20 measurement sites. Some days have great temperature ranges as for example, dry bulb data for November 30, September 29 and September 14, and wet bulb data for September 29, November 16 and September 14, which necessitated subtracting a higher value particularly towards the end of the traverse. Some diurnal cycles varied over a smaller range such as dry bulb data for September 22,

fig. 6.1 Diurnal temperature ranges during city centre and block traverse routes: dry and wet bulb temperatures.

November 2 and December 1, therefore the difference between the original data and the corrected data was not remarkable. No diurnal temperature range was recorded during the traverse route of December 14, therefore no corrections were necessary.

6.3 Climatic Variability in Ottawa's Downtown

This section examines the empirical data collected in the downtown area to determine the existence of microclimatic cells. The cause of these microclimatic cells is assumed to be building arrangement. This hypothesis was examined by the use of simple graphed climate data to determine whether a repeatable microclimatic pattern existed from traverse to traverse. More sophisticated methods, particularly statistical, are available. However, it is hoped that the simplicity and the effectiveness of this method may be appealing to urban climatologists and planners alike.

6.3.1 Climatic Variability Within the City Centre Traverse Area

6.3.1.1 Ambient Temperatures and Incoming Solar Radiation

Ambient temperature ranges are shown in Table 6.1. The maximum temperature range of 4.9°C was recorded on September 14 while the minimum temperature range of 1.6°C was recorded on November 24. In Appendix A temperature and incoming solar radiation variability are

TABLE 6.1

AMBIENT & INFRARED TEMPERATURE RANGES

A. CITY CENTRE TRAVERSE

DATE	AMBIENT TEMPERATURE RANGE	Nº DEGREES	INFRARED TEMPERATURE RANGE	Nº DEGREES
Sept. 1	20.0 to 24.8 °C	4.8 °C	-----	-----
Sept. 14	16.6 to 21.5	4.9	11 to 36 °C	25 °C
Sept. 22	13.2 to 17.7	4.5	10 to 28	18
Sept. 29	12.3 to 15.5	3.2	9 to 23	14
Oct. 12	16.1 to 18.0	1.9	12 to 19	7
Oct. 19	4.9 to 6.9	2.0	3 to 9	6
Oct. 27	8.2 to 10.7	2.5	5 to 20	15
Nov. 2	12.8 to 16.4	3.6	-----	-----
Nov. 24	0.5 to 2.1	1.6	-----	-----
Nov. 30	1.8 to 5.2	3.4	-----	-----
Dec. 14	-8.8 to -4.7	4.1	-----	-----

B. SPARKS ST. - QUEEN ST. TRAVERSE

Nov. 16	5.7 to 7.8	2.1	2 to 10	8
Dec. 1	-0.9 to 0.3	1.2	-----	-----

graphed on pages A-1 to A-11 for the city centre traverses. Temperature variability reveals that a pattern is repeated in a general manner for most traverses. On September 1 maximum temperatures were recorded at stations 2, 8 and 13. On September 14 the pattern of temperature variability is somewhat similar although maximum temperatures were recorded at stations 1, 3, 7 and 12. Overlapping the three charts for September 1, 14 and 22 reveals a repeatable pattern on each traverse, with three prominent temperature maxima occurring around sites 1 and 2, 7 and 8, and 12 and 13. Two sites with prominent low temperatures are sites 5, 9, and 10. Adding the chart for September 29 to the previous overlapping charts confirms this pattern and also reveals consistently high temperatures occurring at site 18.

The traverse routes of October 12 to the end show a remarkable decrease in temperature variability which generally coincides with lower absolute ambient temperatures. Referring to Table 6.1, ambient temperature ranges between maximum and minimum values on October 12, 19, and 27 were 1.9, 2.0 and 2.5 °C respectively compared to the ranges of 4.8, 4.9, 4.5 and 3.2 °C recorded on the first four traverses. Overlapping the graphs for October 12, 19 and 27 reveals that temperature trends are not repeatable from traverse to traverse, showing little resemblance to the variability recorded in the previous weeks. Some sites recorded slightly higher temperatures than would have been expected perhaps due to heat escaping from building interiors.

Temperature variability may be explained to a certain extent by incoming solar radiation which varies according to the radiation penetration permitted by building configuration, and sometimes by intermittent cloud cover. Examining temperature and solar radiation charts for each traverse reveals the similarity in radiation reception and temperature trends. This similarity implies that incoming solar radiation intensity determines to a great extent the pattern of temperature variability ranges. The solar radiation ranges are listed in Table 6.2.

As short-wave radiation is absorbed by surfaces and much is dissipated into the atmosphere via longwave radiation and convection, ambient temperatures rise. However, where solar radiation is intercepted by buildings and clouds, less energy is available to warm surrounding air thus resulting in lower temperatures. Sites 4, 5, and 6 experienced much shading because of interception of solar radiation by the Finance Building. On September 14 the solar radiation maxima at sites 1, 7 and 8, and 12 are reflected in maximum temperatures at these sites.

From October 12 solar radiation intensity decreases and shows limited variability during the traverses. Comparisons of solar radiation and ambient temperatures is very difficult. On October 12 at site 7 relatively high solar radiation is accompanied by relatively low ambient temperatures and the maximum temperature occurs at site 10. The low temperatures in the first case may be caused by the short duration of solar radiation which had not permitted much warming. The higher tem-

perature at site 10 may be caused by release of stored solar energy into the atmosphere.

The vertical profile of buildings influences solar radiation reception and also air temperatures, particularly during clear skies. Three main areas in the traverse route show consistently high solar reception, sites 1, 8 and 12, and to a lesser extent site 18. Site 1 located at the N.A.C. is unsheltered from the sun, and since it faces west it receives high amounts of solar radiation during most of the day. Site 8 is located on Queen Street between Metcalfe and Elgin Streets and receives high amounts of solar radiation because the parking lot and low parking garage building on the south side of the street allow unobstructed solar penetration during most of the day. Site 18, located on the corner of Laurier and Bank Streets, is in a similar situation where low buildings on the south and south-west sides allow for solar radiation penetration.

6.3.1.2 Infrared Temperature Variability

Infrared temperatures of the pavement vary over a considerable range, for example, on September 14 from a minimum of 11°C to a maximum of 36°C. On pages A-12 to A-14 ambient and infrared temperature variability is depicted graphically, showing the extreme variability of infrared temperatures, particularly on September 14 and 22. On September 14, 22, 29 and October 12 infrared temperatures reach peak

values at sites 1, 8, 13 and 18. However, each week, as colder weather was encountered, infrared temperatures varied within a smaller range. On October 19 infrared temperature variability is only 6°C , however, on October 27 variability is somewhat higher ranging over 15°C (Table 6.1).

Infrared and ambient temperatures show a similarity in variability even though infrared maximum and minimum values are higher and lower than the ambient. The peak infrared temperatures during the first four traverses are accompanied often by low ambient temperatures. The latter case is seen most clearly on September 14 at sites 4 and 5 and on September 22 at site 5. The reverse, however, is also apparent where low infrared temperatures are accompanied by high ambient temperatures as on September 14, 22, 29 and October 12 at site 10.

The similarity in infrared and ambient temperature patterns suggests an obvious relationship between these two elements. The relationship is more clearly seen when comparing incoming solar radiation and infrared temperatures. On September 14, 22 and 29 the patterns of solar radiation and infrared temperature variability are very similar. Similar patterns are also evident on subsequent traverses, however, the limited variability in data does not accentuate patterns as clearly. As direct and diffuse solar radiation penetrates unobstructed to pedestrian level, it is absorbed by building and pavement surfaces, which consequently heat up. Thus high incoming solar radiation values on graphs A-1 to A-11 correspond closely with high infrared temperatures on graphs A-12 to A-14.

Where infrared temperatures are high for the amount of solar radiation received as on September 14 (A-12) at sites 3 and 18 suggests that stored energy in the pavement is being irradiated when direct beam solar radiation is reduced and pedestrians feel a cooler sensation.

Where air temperatures are greater than infrared surface temperatures, this implies that other artificial surfaces such as building walls may still be releasing heat into the atmosphere. Perhaps the more likely reason may be that advective air mixing may have brought warmer air from nearby microclimatic cells.

6.3.1.3 Vapour Pressure Variability

Vapour pressure variability is shown graphically in Appendix A on pages A-15 to A-24. In general, vapour pressure varies over a greater range on warmer days than on colder days (Table 6.2). On September 1 the maximum value of 11.8 mb was recorded at site 14 and the minimum value of 9.4 mb was recorded at site 13, a range of 2.4 mb. The vapour pressure range on September 14, 22 and 29 is 3.8, 5.1 and 2.7 mb respectively. Overlapping vapour pressure variability graphs for September 1, 14, 22 and 29 reveals no repeatable patterns except the slight vapour pressure increase on warm days as at site 18. Site 18 is situated on the corner of Bank and Laurier Streets where automobile exhaust or air conditioning outlets from buildings may have contributed to the higher moisture content.

TABLE 6.2

VAPOUR PRESSURE, WIND SPEED AND SOLAR RADIATION RANGES

A. CITY CENTRE TRAVERSE

date	vapour pressure range	difference mb	wind speed range	difference m/s	solar radiation range	difference ly/min
Sept. 1	9.39 to 11.90	2.51	0 to 4.9	4.9	0.06 to 1.68	1.62
Sept. 14	8.54 to 12.30	3.76	0 to 7.2	7.2	0.03 to 1.56	1.53
Sept. 22	5.46 to 10.52	5.06	0 to 7.0	7.0	0.08 to 2.03	1.95
Sept. 29	8.62 to 11.35	2.73	0 to 4.0	4.0	0.13 to 1.31	1.18
Oct. 12	11.71 to 12.39	0.68	0.5 to 13.5	13.0	0.06 to 0.75	0.69
Oct. 19	4.49 to 5.95	1.46	0 to 3.5	3.5	0.03 to 0.43	0.40
Oct. 27	4.72 to 5.47	0.75	0.5 to 6.0	5.5	0.13 to 1.33	1.20
Nov. 2	6.37 to 8.80	2.43	0 to 6.8	6.8	0.05 to 1.09	1.04
Nov. 24	3.70 to 5.20	1.50	0.3 to 7.0	6.7	0.07 to 0.27	0.20
Nov. 30	2.0 to 5.3	3.3	0 to 12.2	12.2	0.05 to 0.87	0.83
Dec. 14	-----	---	0 to 9.0	9.0	0.02 to 0.75	0.73

B. BLOCK TRAVERSE

Nov. 16	3.36 to 6.86	3.5	0 to 3.8	3.8	0.08 to 0.52	0.44
Dec. 1	2.9 to 3.4	0.5	0.7 to 5.5	4.8	0.12 to 0.31	0.19

On October 12, 19 and 27 vapour pressure varies by 0.7, 1.5 and 0.8 mb respectively. On November 30 vapour pressure is unusually high at sites 15 and 16 reaching 4.9 and 5.3 mb respectively whereas vapour pressure at the other sites ranges from 3.8 to 2.0 mb.

Warmer air parcels are expected to hold more moisture than cooler air parcels and comparing temperature and vapour pressure graphs it was expected to find a similarity in patterns. No such case is evident and vapour pressure patterns must be investigated in further detail according to land use patterns and associated microclimatic conditions. It is assumed that vegetated areas, particularly treed parks, should have higher vapour pressure due to evapotranspiration. Even though this may be evident along the Rideau Canal where vegetation is plentiful, downtown parks are not large enough to reflect this condition.

6.3.1.4 Wind Speed Variability

Wind speeds vary in an inconsistent pattern on each traverse, reflecting the fluctuating nature of this element. Each building creates unique wind conditions which are difficult to monitor unless it is researched using a dense vertical and horizontal instrumentation network. The other alternative is simulating wind speed characteristics in a wind tunnel.

Table 6.2 lists wind speed ranges for each traverse day. Most days had calm conditions on at least one site, however, wind speeds vary over a great range as is evident on the graphs on pages A-15 to A-25. The fluctuating nature of wind speed does not lend itself to comparability of trends from one traverse to another, thus no distinctive patterns of wind speed variability are evident. During data collection, on certain days wind funneling was apparent along streets oriented southwest to northeast, particularly along Sparks Street Mall (fig. 6.3). Prevailing wind flow constricted into a smaller volume of space between the two rows of buildings caused increased wind speeds. On a few occasions wind funneling occurred along streets oriented north northwest to south southeast. This was experienced as one proceeded in relative calm and as an intersecting street was approached increased wind speeds due to funneling were strikingly obvious. After crossing the intersection and continuing along the street, relatively calm air again prevailed, interrupted occasionally by vertically induced wind turbulence caused by building interception. It is evident that the high wind speeds at sites 3, 4 and 5, particularly evident on October 27, November 2, 24, 30 and December 14 are caused by wind funneling. Where air is constricted into a smaller volume of space between the Bank of Canada and Finance Buildings, wind speeds are increased.

The other anomalous wind condition was encountered at site 5 located at the base of Tower C Building. Overlapping the graphs

fig. 6.2 Vertical wind modification.

A simplified representation of the wind deflection occurring when diverted by high buildings. The direction of regional wind flow determines the side of building on which vertical deflection occurs.

source of base map: Chen & Hart, 1977.

PREVAILING SOUTHWEST - NORTHEAST
WIND FLOW

OTTAWA - DOWNTOWN CORE

PREVAILING NORTH NORTHWEST - SOUTH SOUTHEAST WIND FLOW

LEGEND

direction of wind funneling

fig. 6.3 Wind Funneling.

A simplified representation of wind funneling in conditions of north northwest to south southeast and southwest to northeast wind flow.

in Appendix A reveals that higher wind speeds at site 5 occur consistently from October 27 to December 14. The highest wind speeds encountered on site 5 during the study period was 13.5 m/s which occurred on October 12. The reason for high wind speeds is the protrusion of Tower C into the air above surrounding structures thus interrupting regional wind flow and diverting the air vertically downward toward the pedestrian level. A similar situation as shown in fig. 3.9 is created where a standing vortex on the pedestrian level results in high wind speeds. A horseshoe vortex flows on both sides of Tower C creating high wind speeds around the windward corners of the building along Lyon Street and at the entrance to the Galeries des Boutiques indoor shopping plaza

The graphs of wind speeds in Appendix A give no other indication of consistency of wind speed patterns. On a theoretical basis it may be assumed that tall buildings within the city core create similar wind turbulence as for example the new Royal Bank Building (Sparks and Metcalfe Streets), Towers A and B (Queen and Kent Streets) and L'Esplanade (Laurier and O'Connor Streets), shown in fig. 6.2.

6.3.2 Climatic Variability Within the Block Traverse Area

6.3.2.1 Ambient Temperature Variability

Graphs of ambient temperature variability are found in Appendix B

on page B-1. Block traverses were conducted late in the fall season therefore temperatures are very low. On November 16 ambient temperatures range from 5.7 to 7.8 °C, a difference of 2.1°C, and on December 1 ambient temperatures range from -0.9 to 0.3 °C (Table 6.1). Temperature variability is therefore not great, however, since only two traverses of this block were conducted, it is difficult to compare variability in search of consistent patterns. Nevertheless, ambient temperatures reveal that even around a single downtown block in less than two hours significant variability is evident which may contribute to variable physiological and comfort conditions.

On November 16 the maximum ambient temperature of 7.8°C was recorded at site 9 whereas the minimum of 5.7°C was recorded at site 8, a distance of only about 50 meters. A high exhaust content in the air is believed to be responsible for high temperatures at site 9, however, this is difficult to substantiate. A comparison of the low incoming solar radiation of 0.13 ly/min (page B-4) and the relatively high ambient temperature at site 9 seems to confirm this supposition. The infrared temperature at this site is too low to suggest that high ambient temperatures are a result of heat release from the pavement. Another possibility is that stored energy in the surfaces has warmed the air which had become stagnant.

The minimum value of 5.7°C at site 8 may be due to a prolonged shading condition which induced cooling of artificial surfaces.

During data collection it was remarked that a high wind speed occurred as a result of funneling along an open promenade located between Tower C and The Holiday Inn. This may have substituted the previously warmed air by cooler air. Relatively low wind speeds at site 9 are associated with a relatively high temperature suggesting this relationship may be true.

Ambient temperature variability on December 1 is within a small range of 1.2°C , however, sites 10, 11 and 12 recorded above freezing temperatures. These readings were taken near the Holiday Inn Hotel; site 10 was near the entrance, site 11 was on the corner of Queen and Kent Streets and site 12 was on Kent Street between Sparks Street Mall and Queen Street. The sheltered environment of these sites, particularly from high winds may be a reason for above zero temperatures, however, a high wind speed of 4.8 m/s at site 11 does not correspond with the high temperature. The most likely explanation is that stored energy released from the building surfaces and interior, escaping through doorways, contributed to high local temperatures.

6.3.2.2 Incoming Solar Radiation Variability

Solar radiation values range from 0.08 to 0.52 ly/min on November 16 and from 0.12 to 0.31 ly/min on December 1. On November 16 direct beam solar radiation occurred during the first half of the traverse after which time the sky was overcast. However, because of shading

by buildings, site 2 was the only one where high values due to direct beam radiation were recorded. It was the only spot on the Sparks Street side of the block which received direct beam radiation.

On both November 16 and December 1 low solar radiation intensity was received in front of Tower C, which obstructed solar radiation. It is possible that this site receives minimal direct beam radiation during the day even in the summer because of the height of Tower C.

On December 1 maximum solar radiation occurs at site 6 located on Lyon Street between Sparks and Queens Streets. This site is open to receiving direct beam radiation and experiences no shading from the southwest at this time of the day. This maximum value corresponds with relatively high values on November 16.

Solar radiation measurements in four cardinal directions are presented in Table 6.3. The variability of this data is shown graphically on pages B-5 and B-6. Variability of patterns are similar in all four graphs, which also correspond with the incoming solar radiation patterns recorded from the zenith (page B-4). Solar radiation recorded while facing the north direction shows a maximum value of 0.34 ly/min at site 2 which was received as diffuse and reflected energy. While facing south, direct beam solar radiation was recorded at 1.07 ly/min. Lower values were recorded when facing east (0.54 ly/min) and west (0.38 ly/min) which was received as a

TABLE 6.3

SOLAR RADIATION AND INFRARED TEMPERATURE VALUES
IN FOUR CARDINAL DIRECTIONS
BLOCK TRAVERSE

	SOLAR RADIATION ly/min				INFRARED TEMPERATURES °C			
	North	South	East	West	North	South	East	West
Nov. 16	0.05 to 0.34	0.05 to 1.07	0.04 to 0.54	0.05 to 0.38	3 to 10	2 to 8	2 to 9	2 to 7
Dec. 1	0.08 to 0.16	0.06 to 0.49	0.09 to 0.25	0.06 to 0.17	-----			

combination of direct, diffuse and reflected radiation.

It is evident therefore, that while standing on one spot a human being may experience several different sensations. The overall comfort sensation is created by the climatic conditions occurring simultaneously on all sides of an individual, and when incoming solar radiation is decreased from one direction, a decrease is also experienced in thermal comfort. On December 1 (pages B-10 to B-11) while the solarimeter faced south, site 6 received a maximum reading of 0.49 ly/min. The east and west sides received considerably less energy and the north side showed no significant energy income. Since the comfort sensation is a result of the surrounding environment, if the north facing solar radiation income was higher due to reflectivity from buildings, for example, comfort sensation would be increased.

6.3.2.3 Infrared Temperature Variability

Infrared temperatures of the pavement are shown graphically on Page B-7. These temperatures are a result of warming by incoming solar radiation, which suggests that there was considerable incoming energy at the time. Comparing this graph with incoming solar radiation (page B-4) reveals this to be true. It is presumed that sites 9 to 13 have undergone cooling by infrared radiation due to shading. Another possibility is that heat released from buildings may have caused higher ambient temperatures.

Infrared temperature variability of the "environment" in four cardinal directions is shown graphically on pages B-8 and B-9. These are dramatically different from infrared temperature patterns of the pavement, showing an inconsistency in temperature patterns measured in four cardinal directions. Even though the four infrared temperature graphs vary over a similar range (Table 6.2), values for each site vary considerably. At site 1 values of 5, 2, 2 and 7 °C for north, south, east and west facings respectively were recorded, which is a considerable range of values for a single site. Inconsistency in patterns was probably the result of variable thermophysical properties of building surfaces, which retain incoming solar radiation in varying capacities thereby releasing it at different rates.

6.3.2.4 Vapour Pressure Variability

Vapour pressure values vary over a 3.5 mb range on November 16 and over a 0.5 mb range on December 1 (Table 6.2). Two points of interest are evident on November 16 (page B-2), namely the exceptionally great decrease in vapour pressure from site 1 to 2, and the sudden rise in vapour pressure at site 10. A curious steady rise in vapour pressure during the traverse route is evident which is virtually unexplainable on the basis of traverse data. The high moisture content in the air at site 1 may be explained by the proximity of air vents near the Holiday Inn Hotel, which may have been emitting warm moisture-laden air from the indoors. At site 10, which is located at the main entrance to

the Holiday Inn, the exhaust from automobiles constantly arriving at the main doors, and the moisture-laden warm air from the interior may be one reason for the high vapour pressure.

6.3.2.5 Wind Speed Variability

On page B-3 wind speed values are found to be extremely variable, particularly on December 1. A comparison of wind speed trends on November 16 and December 1 reveals similarities in variability. On the basis of only two traverses it is extremely difficult to ascertain whether this variability occurs commonly in this area. Wind speeds range considerably in this small area, often accompanied by gustiness. On the basis of solely empirical observations it is difficult to conclude whether these wind speeds are a result of funneling or vertical diversion by single buildings. The maximum wind speed of 5.5 m/s on December 1 at site 5 was recorded at the base of Tower C, which was probably caused by vertical diversion of air down the north side of the building.

During data collection it was observed that a noticeable increase in wind speed occurred as one proceeded along Queen Street towards the open promenade located between Tower C and the Holiday Inn. The high wind speeds at this site (8) is probably a result of wind funneling from Sparks Street Mall to Queen Street. The calm conditions at sites 6 and 7 on November 16 and at site 7 on December 1 occur in a

sheltered location near Tower C, which is probably the wake zone of Tower C. The calm is suddenly interrupted by high wind speeds as one advances towards the open promenade, causing uncomfortable conditions due to wind gustiness. This situation is created either by air being constricted into a smaller volume or by vertical wind diversion along the east wall of Tower C, which is an inappropriate situation for an entranceway to shopping facilities.

Most urban climatic research ends right here. Analysis of microclimatic variability and influencing building characteristics are not sufficient or conclusive in terms of identifying the degree of discomfort unsuitable for human use. Areas with extreme climatic conditions may be presumed to be uncomfortable, however, corrective measures of urban features should be undertaken only after peoples' perception of comfort is known.

6.4 Variability of Climatic Data in Downtown Ottawa and International Airport

Table 6.4 lists dry and wet bulb temperatures derived from Ottawa's International Airport Meteorological Station, and dry and wet bulb temperatures from downtown traverses. Meteorological observations at the airport are taken every hour on the hour, therefore, downtown traverse data were calculated by averaging values closest to the hour.

TABLE 6.4

AIRPORT AND DOWNTOWN TEMPERATURES

CITY CENTRE TRAVERSE					
date	time	AIRPORT		DOWNTOWN	
		T °C dry	T °C wet	T °C dry	T °C wet
Sept 1	12:00	19.0	8.7	22.4*	14.2
	1:00	20.1	8.1	20.0	12.9
	2:00	20.9	9.9	24.8	14.3
	3:00	21.3	9.8	21.8	14.0
Sept 14	12:00	15.2	7.3	18.8*	12.7*
	1:00	17.1	7.6	19.0	13.6
	2:00	18.1	7.6	18.2*	11.7*
	3:00	19.0	6.6	18.2	11.6
Sept 22	12:00	13.5	8.6	14.9*	9.3*
	1:00	13.8	5.9	15.4*	8.6*
	2:00	13.5	4.9	17.7	9.2
	3:00	13.7	5.1	16.0*	9.8*
Sept-29	12:00	10.7	6.9	13.1*	9.9*
	1:00	13.4	8.2	13.2*	10.1*
	2:00	13.8	6.9	14.0	10.8
	3:00	14.8	6.6	13.7*	10.1*
Oct 12	12:00	15.3	10.3	16.7*	12.5*
	1:00	16.0	10.9	16.9*	12.7*
	2:00	16.4	11.3	17.7	13.1
	3:00	18.2	11.8	17.0*	12.8
Oct 19	12:00	4.4	0.6	5.4*	2.1*
	1:00	4.7	-0.2	5.1*	1.9*
	2:00	4.8	-0.2	6.5	3.4
	3:00	5.5	-0.1	6.2	2.7
Oct 27	12:00	7.6	-0.4	9.0*	4.1*
	1:00	7.6	-0.2	9.5*	4.5*
	2:00	8.4	-0.9	9.9	5.5
	3:00	8.1	-1.0	9.4*	4.4*
Nov 2	12:00	12.2	4.4	13.6*	7.9*
	1:00	13.3	4.4	13.2	7.7
	2:00	13.5	3.7	14.7	8.1
	3:00	13.5	3.6	14.8*	8.3*

CONT'D

Nov 24	12:00	-0.9	-2.7	0.8*	1.2*
	1:00	-0.9	-3.1	0.6	-1.2
	2:00	-0.8	-3.3	1.1	-1.0
	3:00	-0.9	-3.7	1.1*	0.8*
Nov 30	12:00	-0.1	-1.4	2.2*	-1.8*
	1:00	-0.2	-5.8	2.0	-1.8
	2:00	-0.9	-7.8	3.5	-0.9
	3:00	-1.7	-9.0	3.1*	-0.8*
Dec 14	12:00	-10.2	-13.3	-7.8	-----
	1:00	-9.7	-12.9	-8.7	-----
	2:00	-8.9	-12.8	-6.6	-----
	3:00	-8.2	-12.5	-6.8	-----

BLOCK TRAVERSE

Nov 16	12:00	4.3	-2.5	6.5*	2.3*
	1:00	4.8	-2.8	6.5	2.4
	2:00	5.2	-4.2	6.6*	3.7*
Dec 1	12:00	-2.8	-7.9	-0.5*	-3.7*
	1:00	-1.8	-7.8	-0.8	-3.4
	2:00	-1.2	-7.8	-0.3*	-2.9*

* Downtown traverse measurements were not always taken on the exact hour. In order to provide comparability with airport data, downtown values closest to the exact hour were averaged and presented here as estimates.

Even though most downtown dry bulb values are higher than airport data, on a few occasions downtown temperatures are considerably lower, as for example, on September 14 at 3:00 o'clock when the downtown was 0.8°C cooler than the airport, on September 29 at 3:00 o'clock when the downtown was 1.1°C cooler than the airport, and on October 12 at 3:00 o'clock when the difference was 1.2°C . This suggests that the downtown contains pockets of air which are cooler than other downtown areas and the airport. This could be due to the vertical component of the city causing shading and cooler temperatures in these spots. Supplementary climatic values for the later afternoon in the presence of increased shading and decreased solar radiation intensity may have made this supposition more plausible. On several occasions the downtown dry bulb temperatures were only slightly lower than the airport temperatures, as on September 1 at 1:00 o'clock when the difference is 0.2°C , and on November 2 at 1:00 o'clock when the difference is 0.1°C .

In most cases the downtown temperatures are significantly higher as on September 1 at 2:00 o'clock and on November 30 at 3:00 o'clock differing by 4.8°C . In other cases the downtown temperatures are more than 3°C higher than the airport, however, no consistent pattern between the downtown and airport is evident. On two traverse days, November 24 and 30, while the airport station recorded freezing temperatures downtown temperatures were all above freezing.

An interesting occurrence is the consistently higher wet bulb

temperatures in the downtown. The moisture content of city air was greater than rural air and saturation of air would occur sooner in the downtown than at the airport.

Even though a general impression of an "urban heat island" is apparent, it is clear that downtown dry bulb temperatures are not always greater than rural temperatures. This is caused by the existence of microclimatic pockets which result in variable cooling of shaded areas.

6.5 Burton: Solar Radiation Expressed as Temperature Equivalence

The temperature equivalence of incoming solar radiation was calculated for all traverse data using Burton's equation 5.2. Results of temperature equivalence for the first three traverse days September 1, 14 and 22 which contain the highest solar radiation values are shown in Tables 6.6, 6.7 and 6.8 respectively as examples of the results.

Calculations of thermal insulation were done by first employing equation 5.3 which incorporates the two variables of wind speed and atmospheric pressure. Wind speed varies with measurement site (Table 6.5). Hourly values of atmospheric pressure were collected at Ottawa's International Airport Meteorology Station and applied to downtown situations. It is assumed that the atmospheric pressure difference between the airport and the downtown is negligible due to the short distance. Hourly atmospheric pressure during the traverse duration did

TABLE 6.5

THERMAL INSULATION OF THE AIR

measurement site	SEPT. 1		SEPT. 14		SEPT. 22	
	mean air pressure 75.6cm	thermal insulation*	mean air pressure 75.6cm	thermal insulation*	mean air pressure 76.0 cm	thermal insulation*
	wind speed cm/sec		wind speed cm/sec		wind speed cm/sec	
1	0	0.295	75	0.079	250	0.049
2	200	0.054	200	0.054	310	0.045
3	250	0.049	200	0.054	380	0.041
4	300	0.046	0	0.295	700	0.031
5	250	0.049	150	0.061	400	0.040
6	0	0.295	300	0.046	100	0.070
7	150	0.061	130	0.064	50	0.092
8	50	0.092	0	0.295	300	0.046
9	230	0.051	200	0.054	0	0.295
10	200	0.054	75	0.079	200	0.054
11	220	0.052	400	0.040	150	0.061
12	350	0.043	200	0.054	150	0.061
13	350	0.043	620	0.033	130	0.064
14	0	0.295	0	0.295	300	0.046
15	100	0.071	0	0.295	50	0.092
16	350	0.043	620	0.033	300	0.046
17	150	0.061	720	0.031	0	0.295
18	50	0.092	400	0.040	0	0.295
19	490	0.037	300	0.046	0	0.295
20	250	0.049	200	0.054	100	0.070

* in $\text{Cm}^2\text{hr/kg/cal}$

TABLE 6.6

SEPTEMBER 1: TEMPERATURE EQUIVALENTS OF SOLAR RADIATION

measurement sites	wind speed cm/sec	solar radiation ly/min	temperature equivalence °C
1	0	1.62	8.4
2	200	1.65	1.5
3	250	1.53	1.3
4	300	0.14	0.1
5	250	0.14	0.1
6	0	0.13	0.6
7	150	1.68	1.8
8	50	1.65	2.7
9	230	0.06	0.1
10	200	1.51	1.4
11	220	1.62	1.5
12	350	1.62	1.2
13	350	1.59	1.2
14	0	1.53	8.0
15	100	0.09	0.1
16	350	1.62	1.2
17	150	0.09	0.1
18	50	1.62	2.6
19	490	1.62	1.1
20	250	1.65	1.4

TABLE 6.7SEPTEMBER 14: TEMPERATURE EQUIVALENTS OF SOLAR RADIATION

measurement sites	wind speed cm/sec	solar radiation ly/min	temperature equivalence °C
1	75	1.53	2.1
2	200	1.51	1.4
3	200	1.48	1.4
4	0	0.08	0.1
5	150	0.08	0.1
6	300	0.08	0.1
7	130	1.56	1.8
8	0	1.48	7.7
9	200	0.10	0.1
10	75	0.22	0.3
11	400	0.03	0.0
12	200	0.77	0.7
13	620	0.61	0.4
14	0	0.38	2.0
15	0	0.31	1.6
16	620	0.30	0.2
17	720	0.30	0.2
18	400	0.30	0.2
19	300	0.30	0.2
20	200	0.30	0.3

TABLE 6.8SEPTEMBER 22: TEMPERATURE EQUIVALENTS OF SOLAR RADIATION

measurement sites	wind speed cm/sec	solar radiation ly/min	temperature equivalence °C
1	250	1.77	1.5
2	310	0.21	0.2
3	380	0.39	0.3
4	700	0.23	0.1
5	400	0.14	0.1
6	100	0.23	0.3
7	50	1.74	2.8
8	300	1.80	1.5
9	0	0.08	0.4
10	200	0.17	0.2
11	150	0.32	0.3
12	150	2.03	2.2
13	130	0.36	0.4
14	300	1.44	1.2
15	50	0.11	0.2
16	300	0.13	0.1
17	0	0.26	1.4
18	0	1.68	8.7
19	0	0.36	1.9
20	100	0.54	0.7

not vary significantly and the average value over the three hour period was used in the thermal insulation calculations (Table 6.5). For example, the atmospheric pressure for September 1 varies from 75.53 to 75.66 cm Hg during traverse time, and the average of 75.6 cm was used in the thermal insulation equation. The highest atmospheric pressure values were found on November 16 which were averaged to 76.4 cm, and the lowest values were found on November 24 which were averaged to 74.3 cm.

Atmospheric pressure has limited effect on thermal insulation as compared with wind speed. Assuming wind speed constant at 200 cm/sec, an atmospheric pressure of 75.6 cm (as on September 1) results in thermal insulation of $0.054 \text{ Cm}^2\text{hr/kg/cal}$. An increase in atmospheric pressure to 80 cm in the same wind speed results in a thermal insulation of $0.053 \text{ Cm}^2\text{hr/kg/cal}$. This very high value of 80 cm is unlikely to occur but is used here to demonstrate the negligible influence on thermal insulation.

The other variable used in the thermal insulation equation, wind speed, was derived from the downtown traverses and varied significantly enough during the traverse to influence the thermal insulation results. Table 6.5 lists wind speed for September 1 varying from calm conditions (0 cm/sec) to a maximum of 490 cm/sec (at site 19). This variability is reflected in the thermal insulation results, where calm wind results in a high thermal insulation of $0.295 \text{ Cm}^2\text{hr/kg/cal}$ and a 490 cm/sec

wind results in a lower thermal insulation of $0.037 \text{ Cm}^2\text{hr/kg/cal}$. On September 14 the maximum wind speed of 720 cm/sec (site 16) results in a thermal insulation value of $0.031 \text{ Cm}^2\text{hr/kg/cal}$. The higher the wind speed in constant solar radiation conditions, the lower the thermal insulation capacity of the air.

The temperature equivalence values in Tables 6.6, 6.7 and 6.8 are influenced primarily by the thermal insulation results which are in turn influenced by wind speed values. The higher the wind speed the lower the temperature equivalence of incoming solar radiation. In Table 6.6 for September 1, calm wind conditions at sites 1 and 14 along with a high solar radiation value result in a high temperature equivalence of radiation of 8.4°C and 8.0°C respectively. This increase in heat load significantly alters thermal comfort sensations. Even though site 6 has calm wind conditions, the low solar radiation value of 0.13 ly/min measured in a shady spot calculates to a low temperature equivalence value of 0.6°C .

Table 6.7 for September 14 shows a similar situation. Where wind speed is zero and incoming solar radiation is high as for site 8, the temperature equivalence value is high which is 7.7°C . In diffuse solar radiation conditions as at site 14 (0.38 ly/min) and site 15 (0.31 ly/min), the temperature equivalence of solar radiation is lower at 2.0 and 1.6°C respectively. In shady conditions where solar radiation is even lower, for example, at site 6 (0.08 ly/min), the temperature equivalence

is very low which is 0.1°C . However, calm wind conditions at site 4 presents a potential condition for high temperature equivalence, but the low solar radiation value of 0.08 ly/min calculated to a very low temperature equivalence of 0.1°C .

Table 6.8 shows that the one high value of temperature equivalence of 8.7°C at site 18 occurs in a condition where there is no wind and a high solar radiation of 1.68 ly/min .

These first three traverses received higher solar radiation than all subsequent traverses resulting in relatively high temperature equivalence values. Solar radiation intensity in the later autumn season was low, consequently producing low temperature equivalence values which were accentuated in shady locations. This has particular importance in terms of human comfort, since higher solar radiation results in higher temperature equivalence thereby increasing comfort sensation. Locations which do not permit solar radiation penetration in the autumn have cooler microclimates and may be used less frequently than locations open to radiation penetration.

6.6 Fuller and Brouha: Heart Rate Index

The Fuller and Brouha Heart Rate Index (eq. 5.4) was calculated for September 1 and 14 to present an example of this methodology. Tables 6.9 and 6.10 list predicted heart rate values for September 1 and 14 respectively for two climatic conditions, excluding temperature

TABLE 6.9

SEPTEMBER 1: FULLER AND BROUHA HEART RATE VALUES

measurement sites	heart rate* no radiation load	temperature equivalence °C	heart rate*including radiation load	% increase heart rate
1	88.0	8.4	93.9	6.3
2	87.7	1.5	88.8	1.2
3	85.7	1.3	86.7	1.2
4	84.2	0.1	84.3	0.1
5	83.5	0.1	83.5	0.0
6	85.9	0.6	86.3	0.5
7	84.9	1.8	86.2	1.5
8	87.2	2.7	89.1	2.1
9	83.7	0.1	83.8	0.1
10	84.9	1.4	85.9	1.2
11	87.0	1.5	88.0	1.1
12	87.5	1.2	88.3	0.9
13	89.0	1.2	89.8	0.9
14	88.5	8.0	94.1	6.0
15	84.9	0.1	84.9	0.0
16	85.3	1.2	86.2	1.0
17	84.9	0.1	84.9	0.0
18	86.4	2.6	88.2	2.0
19	85.5	1.1	86.3	0.9
20	86.3	1.4	87.3	1.2

* in beats per minute

TABLE 6.10

SEPTEMBER 14: FULLER AND BROUHA HEART RATE VALUES

measurement site	heart rate* no radiation load	temperature equivalence ^{OC}	heart rate* including radiation load	% increase heart rate
1	82.9	2.1	84.4	1.4
2	81.6	1.4	82.5	1.1
3	83.2	1.4	84.2	1.2
4	80.4	0.1	80.5	0.1
5	78.8	0.1	78.9	0.1
6	79.3	0.1	79.3	0.0
7	85.2	1.8	86.5	1.5
8	83.1	7.7	88.5	6.1
9	80.6	0.1	80.7	0.1
10	81.0	0.3	81.2	0.2
11	80.3	0.0	80.3	0.0
12	81.3	0.7	81.8	0.6
13	81.1	0.4	81.4	0.4
14	81.0	2.0	82.4	1.7
15	80.9	1.6	82.0	1.3
16	79.3	0.2	79.5	0.3
17	80.0	0.2	80.2	0.2
18	81.1	0.2	81.3	0.2
19	79.5	0.2	79.6	0.1
20	80.8	0.3	81.0	1.0

* in beats per minute

equivalence due to radiation load (second column) and including temperature equivalence of solar radiation (fourth column). The Fuller and Brouha formula is most applicable in extremely hot and humid weather conditions. Even though these conditions were not experienced during the study period, a significant increase in heart rate was indicated when the results were recalculated using the temperature equivalence of solar radiation. Calculated heart rates, excluding radiation load, varied from a maximum of 89 beats/minute at site 13 to a minimum of 83 beats/minute at site 5. This is within the range of normal heart beat for most healthy people, which is between 70 and 90 beats/minute.

The formula requires two variables, ambient temperature and vapour pressure. The vapour pressure does not vary significantly enough during the traverse time to influence the heart rate results. On September 1 vapour pressure values range from a maximum of 8.9 mm Hg to a minimum of 7.0 mm Hg. On September 14 vapour pressure values range from a maximum of 9.2 mm Hg to a minimum of 6.4 mm Hg. If temperature is assumed constant at 70°F and body metabolism constant at 264,000 cal/hr, vapour pressure of 6.4 mm Hg results in a heart rate of 84 beats/minute. Vapour pressure increase to 9.2 mm Hg only increases heart rate to 86 beats/minute.

Increase in ambient temperature and temperature equivalence of solar radiation is more influential in accelerating heart rate (fig. 6.4).

fig.6.4 Heart rate variability with ambient temperatures on September 1 and September 14.

* includes temperature equivalence of solar radiation.

In Tables 6.9 and 6.10 the heart rate values where radiation was incorporated into calculations are higher, particularly where temperature equivalence of solar radiation is high, as on September 1 (Table 6.9) at sites 1, 14 and, to a lesser extent, 8 and 18. According to these calculations, high temperature equivalence of solar radiation may contribute to heat stress conditions causing strain on the heart which may be manifested in meteorotropic symptoms. At site 1 the high temperature equivalence of 8.4°C caused a 6.3 % increase in heart rate to 94 beats /minute. At site 14, 8.0°C temperature equivalence of solar radiation increased heart rate by 6.0 % to 94 beats/minute. The high solar radiation is responsible for heart rates surpassing the safe limit of 90 beats/minute and may present health problems particularly for those suffering from heart ailments. Both these sites are located in open areas unobstructed by vertical interception and which receive considerably more solar radiation. Areas which receive constantly high amounts of solar radiation, creating excess stress on the heart, should have shelters erected for pedestrian protection. This would be most useful during the summer.

The other sites containing high heart rates are clearly seen on fig. 6.4. On September 1, sites 2, 8, 11, 12, 13 and 18 have heart rates between 88 and 90 beats/minute. It is conceivable that in the summer these heart rates would surpass 90 beats/minute. Sites such as these should be provided with solar shelters.

On September 14 ambient temperatures and temperature equivalence of solar radiation are lower which is reflected in the lower heart rates. The highest heart rate is at site 8 where the increase in temperature equivalence of solar radiation by 8.8°C increased the heart rate from 83 to 88 beats/minute. The heart rate pattern during the traverse follows basically the pattern of September 1 therefore indicating the microclimatic repetition of temperatures.

6.7 Hendrick: Human Comfort Index

The Hendrick human comfort formula (eq. 5.5) is designed to be used when ambient temperatures exceed 20°C . For this reason the sensations in Table 6.11A range from "uncomfortably cool" to "extremely uncomfortable", which are experienced in very warm weather. The sensations change as temperature is increased bringing greater comfort during cooler temperatures (around 25°C) or as temperatures increase over 30°C , resulting in uncomfortable sensations. During the latter condition increased wind speed brings cooling power which lowers the sensation to more comfortable levels. When temperature conditions creating a comfortable sensation are accompanied by increased wind speeds, discomfort resulting in a "cool" or even "uncomfortably cool" sensation is followed due to the cooling power of the air.

Ambient temperatures on September 1 are not exceedingly high, in fact at site 5 a value of 20.0°C was recorded which is the lowest

TABLE 6.11 A

HENDRICK COMFORT INDEX

NUMERICAL COMFORT INDEX $CI = I + \Delta I$	SENSATION
less than -5	uncomfortably cool
-1 to -5	cool
0	comfortable
1 to 5	comfortably warm
6 to 10	uncomfortably warm
11 to 15	very uncomfortable
more than 15	extremely uncomfortable

TABLE 6.11 B

VINJE AND COURT FORMULAE COOLING RATES

COOLING RATE $\text{mcal/cm}^2/\text{sec}$	SENSATION
less than 5	hot
5 to 10	pleasant or mild
11 to 15	cool
16 to 21	very cool
22 to 27	cold
28 to 33	very cold
34 to 39	biting cold
more than 40	exposed skin freezes

source: Garnier, 1972, p.277, Landsberg, 1972, p.14.

permissible value used in the Hendrick Index. The highest value of 24.8°C was recorded at site 13. When the temperature equivalence of solar radiation is included with ambient temperature, a significant increase in comfort sensation is evident.

The effective temperature formula (eq. 5.6) incorporates two variables: ambient temperature and relative humidity. The relative humidity on September 1 ranges between the maximum value of 47 % at site 6 and the minimum value of 30 % at site 13. However, the variability in relative humidity does not influence significantly the results of the effective temperature index. For example, assuming a stable air temperature of 21.1°C (70°F), at 30 % relative humidity the effective temperature index I is -4.999; at 47 % relative humidity the effective temperature index I is -4.974. In contrast, temperature variability influences the resulting effective temperature index I . For example, assuming a stable relative humidity of 30 %, at an ambient temperature of 20°C (68°F) the effective temperature index is -5.984; at an ambient temperature of 30°C (86°F) the effective temperature index increases to 3.017.

The cooling effect due to air movement ΔI was added to the effective temperature index I . Three variables are used: ambient temperature, relative humidity and wind speed of which wind speed is the most important. In conditions where temperatures approximate 20°C , the greater the wind speed the greater its cooling power which

results in an increase in discomfort. In Table 6.12 it is clear that the calm air conditions at sites 1 and 14 increase the comfort sensation from "cool" to "comfortably warm". Higher wind speeds at other sites lower the comfort index to a numerical index which is not accurately represented on the comfort scale except by "uncomfortably cool" which applies to any values which are less than -5.

The "environmental" temperature is increased when temperature equivalence of the radiation load is added to ambient temperature. The temperature equivalence of solar radiation (which is responsible for creating more comfortable conditions) is listed in Table 6.12. At site 1 an 8.4°C temperature increase augments the comfort level from "cool" to "comfortably warm". The same increase in comfort level occurs at site 14 where temperature equivalence of radiation load equals to 8.0°C. Other increases in comfort sensation occur at sites 8 and 18 where temperature equivalents of 2.7 and 2.6 °C respectively create a "cool" sensation rather than the "uncomfortably cool" which would have been felt if the incoming solar radiation value was lower.

The amount of sunshine, particularly in the autumn, is crucial for increasing human comfort levels. The warmest sensations on September 1 were experienced at sites 1 and 14 where there was no wind and temperatures were high. These two sites might be suitable for the location of outdoor cafés or sitting areas. The openness of a café which experiences unobstructed solar radiation and calm air conditions, would be economically

TABLE 6.12

SEPTEMBER 1: HENDRICK HUMAN COMFORT INDEX
CITY CENTRE TRAVERSE

measurement sites	temperature °C	wind speed m/s	comfort sensation		radiation load °C	increased comfort due to radiation load	
			CI	comfort sensation		CI	comfort sensation
1	23.3	0	-3.0	cool	8.4	+1.2	comfortably warm
2	23.8	2	-7.4	uncomfortably cool	1.5	-6.4	uncomfortably cool
3	21.9	2.5	-9.1	uncomfortably cool	1.3	-8.2	uncomfortably cool
4	20.7	3	-11.2	uncomfortably cool	0.1	-11.1	uncomfortably cool
5	20.0	2.5	-11.5	uncomfortably cool	0.1	-11.4	uncomfortably cool
6	21.3	0	-4.8	cool	0.6	-4.5	cool
7	22.0	1.5	-8.8	uncomfortably cool	1.8	-7.6	uncomfortably cool
8	23.0	0.5	-5.3	uncomfortably cool	2.7	-3.8	cool
9	20.4	2.3	-10.8	uncomfortably cool	0.1	-10.7	uncomfortably cool
10	21.0	2	-9.7	uncomfortably cool	1.4	-8.8	uncomfortably cool
11	22.7	2.2	-7.9	uncomfortably cool	1.5	-6.9	uncomfortably cool
12	23.2	3.5	-8.4	uncomfortably cool	1.2	-7.6	uncomfortably cool
13	24.8	3.5	-6.4	uncomfortably cool	1.2	-5.6	uncomfortably cool
14	23.4	0	-3.0	cool	8.0	+1.1	comfortably warm
15	21.3	1	-8.1	uncomfortably cool	0.1	-8.1	uncomfortably cool
16	21.5	3.5	-10.6	uncomfortably cool	1.2	-9.7	uncomfortably cool
17	21.3	1.5	-8.8	uncomfortably cool	0.1	-8.7	uncomfortably cool
18	22.0	0.5	-6.4	uncomfortably cool	2.6	-4.9	cool
19	21.1	4.9	-12.2	uncomfortably cool	1.1	-11.4	uncomfortably cool
20	22.1	2.5	-8.9	uncomfortably cool	1.4	-8.0	uncomfortably cool

beneficial for the owner and pleasant for the patron. The Hendrick human comfort index indicates that most other sites could be uncomfortably cool and therefore unsuitable for such indoor facilities. A café located in the shade of tall buildings (as on the west end of Sparks Street Mall) would not have as many clients simply because people do not enjoy sitting outdoors in a cool environment, particularly in the shade. Where solar radiation is plentiful, but high wind speeds cause lower human comfort levels (as for example at sites 3, 12 and 13), wind barriers in the form of trees or architectural devices may be effective in decreasing wind movement, thereby increasing the comfort of the site. An outdoor restaurant located at site 3 experiences plenty of sunshine because the Bank and Sparks Street intersection permits unobstructed solar radiation. However, wind movement creates a cool microclimate as well as mechanical interference by lifting objects off the tables.

During the summer the cafés or sitting areas receiving unobstructed solar radiation may be hot and extremely uncomfortable. Overhangs over the seating area, or deciduous trees in portable containers, would alleviate potential heat stress while creating an aesthetically pleasing environment.

6.8 Vinje: Dry and Wet Bulb Comfort Index

The Vinje dry and wet bulb formulae (eq. 5.8 and eq. 5.9) were used

to calculate comfort sensations for most of the traverse routes (Table 5.2). The formulae utilize wind speed in m/s and dry bulb temperatures in $^{\circ}\text{C}$ and indicate the amount of cooling of the human body in $\text{mcal}/\text{cm}^2/\text{sec}$ occurring in a given atmospheric condition. These formulae are applicable where ambient temperatures range between 0 and 20°C . The comfort level is found by comparing the cooling rate to the comfort level (Table 6.11B). The temperature equivalence of solar radiation was added to ambient temperatures in all calculations and provides a more realistic approximation of human comfort conditions. Low solar radiation values in the later autumn contributed negligible temperature equivalence values.

Within the applicable temperature range minimum cooling of the human body may induce a comfort sensation of "hot" (with less than $5 \text{ mcal}/\text{cm}^2/\text{sec}$ cooling) or with a high wind speed in cold temperatures a great deal of cooling may result in a condition where "exposed skin freezes" (more than $40 \text{ mcal}/\text{cm}^2/\text{sec}$). The cooling rate of the human body is dependent essentially on wind speed; in stable air temperatures the higher the wind speed the greater the cooling rate. For example, assuming that air temperature is stable at 20°C , a 2 m/s wind speed results in a cooling rate of $12.58 \text{ mcal}/\text{cm}^2/\text{sec}$. An 8 m/s wind speed results in increased cooling of $22.52 \text{ mcal}/\text{cm}^2/\text{sec}$. Referring to Table 6.11B this increases the comfort sensation from "cool" to "cold". However, a slight breeze of 0.75 m/s when the temperature is 20°C results in a "pleasant" or mild sensation due to the lower cooling power

of the wind speed. This implies that high wind speeds, particularly when encountered unexpectedly as when going around a corner, cause discomfort. In the autumn, the lower the wind speed the more comfortable the site. Some wind movement is beneficial, to disperse pollutants and, in the summer, add to the comfort sensation in very warm temperatures.

When an absolutely calm wind condition is recorded, equation 5.6 is calculated to be zero, regardless of the air temperature, which corresponds with a "hot" sensation in Table 6.11B. However, since the Vinje index is designed to calculate the cooling power of wind, windless conditions are not accurately represented. Therefore, for all cases during traverse data analysis where zero wind speed is encountered, no comfort sensation is listed. This demonstrates the disadvantage of using mathematical formulae to predict human comfort. However, since some inaccuracy is encountered, it is advisable to use more than one formula to incorporate the influence of several climatic parameters on human comfort.

During the autumn season extreme microclimatic conditions are commonly encountered within a short time period during the day and within a small area of the downtown, as a result of variable shading patterns. Comfort sensations may thus vary considerably from one block to the next. In the autumn it is advantageous to receive as much solar radiation as the location permits, to increase comfort sensation when cooler temperatures prevail. This results in greater pedestrian

activity and therefore stimulates the economy of shops and services. Conversely, low solar radiation and high wind speeds, which may be occurring at a nearby shaded location or on the north side of the building, create a cooler microclimate which results in an "uncomfortable" or "cool" sensation. This may cause less pedestrian traffic.

6.8.1 City Centre Traverse

Tables 6.13 to 6.21 list Vinje dry and wet bulb cooling rates and corresponding comfort sensations for the city centre traverses. Wind speeds recorded at the measurement sites are included for purposes of determining the influential factor of wind speed on the cooling rate. The dry bulb temperature at site 7 is greater than 20°C, therefore the Hendrick comfort index was used resulting in an "uncomfortably cool" sensation. This result is not directly comparable with the rest of the Vinje sensations since it was not derived from a cooling rate calculation.

It is evident from Tables 6.13 to 6.21 that there is a considerable variability in cooling rates and comfort sensations on each traverse day suggesting that indeed microclimatic variability influences comfort sensations. This relationship is particularly evident between wind speed and cooling rate. On September 14 (Table 6.13) sensations vary from a minimum cooling rate of 7.5 mcal/cm²/sec at site 1 resulting in a "pleasant" sensation, to a maximum cooling rate of 25.5 at site 17 resulting in a "cold" sensation. The Hendrick human comfort index

TABLE 6.13
SEPTEMBER 14, 1978: VINJE DRY & WET BULB COMFORT INDEX
CITY CENTRE TRAVERSE

measurement site	wind speed	DRY BULB		WET BULB	
		cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	0.75	7.5	pleasant, mild	17.3	very cool
2	2	13.0	cool	26.0	cold
3	2	12.3	cool	24.9	cold
4	0	----	----	----	----
5	1.5	13.4	cool	25.9	cold
6	3	17.2	very cool	35.6	biting cold
7	1.3	*	uncomfortably cool*	20.8	very cool
8	0	----	----	----	----
9	2	14.0	cool	28.8	very cold
10	0.75	8.9	pleasant, mild	19.4	very cool
11	4	19.0	very cool	39.8	biting cold
12	2	13.0	cool	27.9	very cold
13	6.2	21.6	cold	48.1	exposed skin freezes
14	0	----	----	----	----
15	0	----	----	----	----
16	6.2	23.9	cold	48.9	exposed skin freezes
17	7.2	25.5	cold	52.0	exposed skin freezes
18	4	18.9	very cool	37.9	biting cold
19	3	17.2	very cool	34.7	biting cold
20	2	13.7	cool	28.5	very cold

* Hendrick scale since $T > 20^{\circ}\text{C}$, $CI = -8.02$

revealed a warm comfort sensation at site 1 as well indicating that this site (N.A.C.) may have a favourable microclimate which can possibly be developed into a pleasant sitting area or outdoor café. During the summer overhangs could be used to protect clients and passersby from excessive solar radiation. A comparison of cooling rates with wind speeds reveals the influential nature of wind on comfort. Low wind speeds of 0.75 m/s at site 1 and site 10 result in "pleasant" sensations at both locations. As wind speeds increase, cooling rates increase producing less comfortable sensations. In order to ensure that wind movement at site 1 does not disrupt the warm comfort sensations, wind barriers in the form of coniferous trees or architectural devices may be used to block prevailing wind flow. In the summer these may be removed to allow cooling by wind movement.

The wet bulb formula calculates cooling rates from a sweating body, a condition which may occur frequently in warm and particularly humid weather. Cooling rate is greater from a wet skin due to evaporation than from a dry skin, which explains the higher cooling rate values for wet bulb than dry bulb temperatures (Tables 6.13 to 6.21). In Table 6.13 cooling rates range from a minimum of $17.3 \text{ mcal/cm}^2/\text{sec}$ at site 1 which results in a "very cool" sensation, to a maximum of $52 \text{ mcal/cm}^2/\text{sec}$ at site 17 which suggests that exposed skin would freeze. This situation is extreme and would never occur when wet bulb temperatures range between 10.8 and 13.6 °C. This shortcoming of the wet bulb formula manifests itself in all wet bulb conditions where high wind

speeds result in redundantly extreme sensations. On September 14 wind speeds over 6.2 m/s correspond with the "exposed skin freezes" index. On September 22 wet bulb temperatures range between 7.8 and 11.8 °C, and wind speeds over 3.8 m/s result in the sensation of "exposed skin freezes". This situation is repeated on September 29 at site 12 where wind speed was recorded as 4 m/s and wet bulb temperature as 10°C.

In slightly lower wind speeds the sensation of "biting cold" was calculated for wet bulb temperatures. This condition was encountered on September 14 at sites 6, 11, 18 and 19 where wind speeds of 3, 4, 4 and 3 m/s respectively were measured. This sensation is also extreme and unlikely to be experienced in temperatures between 10.8 and 13.6 °C. The other sensations are more believable, which range from "very cool" to "very cold", however, since the other sensations are suspiciously low, it is presumed that the same is true with these sensations. A greater emphasis is placed on the dry bulb values since the wet bulb cooling rates appear to be unreliable.

On September 22 (Table 6.14) a "pleasant" sensation was calculated for dry bulb temperatures at sites 7, 13 and 15 as a result of low wind speeds of 0.5, 1.3 and 0.5 m/s respectively, coupled with relatively high ambient temperatures of 15.8, 18.0 and 15.7 °C respectively. At site 16 a relatively high temperature of 16.3°C was recorded which would potentially create pleasant conditions. A wind speed of 3 m/s resulted in a cooler sensation. This suggests that these sites

TABLE 6.14
SEPTEMBER 22, 1978: VINJE DRY & WET BULB COMFORT INDEX
CITY CENTRE TRAVERSE

measurement site	wind speed	DRY BULB		WET BULB	
		cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	2.5	15.3	cool	31.3	very cold
2	3.1	18.9	very cool	37.8	biting cold
3	3.8	21.1	very cool	41.5	exposed skin freezes
4	7.0	28.7	very cold	57.1	exposed skin freezes
5	4.0	23.7	cold	45.5	exposed skin freezes
6	1.0	12.1	cool	24.1	cold
7	0.5	7.7	pleasant, mild	17.6	very cool
8	3.0	17.2	very cool	36.7	biting cold
9	0	----	----	----	----
10	2.0	16.5	very cool	33.0	very cold
11	1.5	14.0	cool	28.6	very cold
12	1.5	12.4	cool	26.3	cold
13	1.3	9.4	pleasant, mild	26.1	cold
14	3.0	17.9	very cool	38.2	biting cold
15	0.5	8.9	pleasant, mild	19.2	very cool
16	3.0	18.2	very cool	36.8	biting cold
17	0	----	----	----	----
18	0	----	----	----	----
19	0	----	----	----	----
20	1.0	11.4	cool	22.8	cold

would be found enjoyable by most people as long as wind speed is minimal. If detailed microclimatic and human comfort investigations were carried out they would reveal these sites to be consistently more comfortable than most others, and it might be worthwhile to develop them into a café, sitting area or recreation area. If these developments are found unnecessary or uneconomical, urban planners should prevent the construction of tall buildings in the vicinity which create wind turbulence thus decreasing the comfort level. It is possible that comfortable conditions in these areas result in greater economic activity due to higher pedestrian traffic.

On September 29 (Table 6.15) cooling rates are not significantly lower than on September 22 even though dry bulb temperatures are on the average a few degrees lower. This condition is a result of lower wind speeds on September 29 which cause a lower cooling rate to take place. The most comfortable sensation of "pleasant" was calculated at site 10 where the cooling rate is $9.5 \text{ mcal/cm}^2/\text{sec}$. The dry bulb temperature of 13.6°C is actually lower than most temperatures, however, the low wind speed of 0.5 m/s suggests that this site is a pleasant one to be in. Site 10 is located near an outdoor parking lot with no tall buildings in close proximity. Low wind speed may have been a result of the lack of tall buildings which would create wind turbulence. Even though the lack of high wind speeds in the autumn and winter results in comfortable conditions for pedestrians, it is conceivable that in the summer this site is uncomfortably warm because of the high absorption of solar

TABLE 6.15
SEPTEMBER 29, 1978: VINJE DRY & WET BULB COMFORT INDEX
CITY CENTRE TRAVERSE

measurement site	wind speed	DRY BULB		WET BULB	
		cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	1.0	12.3	cool	21.9	cold
2	2.5	19.5	very cool	33.7	biting cold
3	3.2	20.2	very cool	36.2	biting cold
4	2.2	18.9	very cool	32.1	very cold
5	1.8	17.4	very cool	29.6	very cold
6	0	----	----	----	----
7	1.0	12.7	cool	22.4	cold
8	0	----	----	----	----
9	1.0	13.0	cool	23.1	cold
10	0.5	9.5	pleasant, mild	18.3	very cool
11	1.5	15.2	cool	26.5	cold
12	4.0	23.1	cold	41.4	exposed skin freezes
13	1.5	14.8	cool	26.0	cold
14	1.5	15.0	cool	26.1	cold
15	1.5	15.1	cool	26.2	cold
16	0	----	----	----	----
17	0	----	----	----	----
18	2.0	15.6	very cool	28.2	very cold
19	2.0	17.5	very cool	30.8	very cold
20	1.0	12.5	cool	22.6	cold

radiation by the black top parking lot. Parking lots create a problem in terms of seasonally unfavourable microclimates which is difficult to solve unless the approach to parking lot design is changed. A possible alternative is the construction of underground parking lots using the top as a park, café, restaurant, etc. Perhaps a less expensive alternative is a low rise, multistorey parking house with a treed front area and a roof used in the same way as in an underground construction. If this is not economical or feasible, certainly an inexpensive solution is planting deciduous trees and grass along the pedestrian walkway to provide at least a thin strip of comfort. Small strips of grass and trees between rows of cars may add greater comfort for people using the parking lot. Vegetation contributes significantly as wind barriers, solar radiation interceptors as well as pollution removers and noise reducers.

On October 12 (Table 6.16) dry bulb temperatures are higher than on September 29, however, high wind speeds ranging from 0.5 to 13.5 m/s caused higher cooling rates to occur. The unusually high wind speed of 13.5 at site 5 on Sparks Streer Mall resulted in a high cooling rate of $33.8 \text{ mcal/cm}^2/\text{sec}$ corresponding to the "biting cold" sensation. This comfort sensation did not occur since temperatures were not low enough to result in extreme thermal discomfort. This reflects again the main disadvantage of using mathematical formulae. During data collection extreme discomfort was experienced as a result of the wind force which made walking difficult. Blowing sand entering the eyes and the mouth

TABLE 6.16
OCTOBER 12, 1978: VINJE DRY & WET BULB COMFORT INDEX
CITY CENTRE TRAVERSE

measurement site	DRY BULB		WET BULB	
	cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	2.0	cool	27.4	cold
2	7.8	cold	54.0	exposed skin freezes
3	2.5	very cool	30.0	very cold
4	3.5	very cool	35.7	biting cold
5	13.5	biting cold	71.7	exposed skin freezes
6	11.0	very cold	63.8	exposed skin freezes
7	5.0	very cool	41.0	exposed skin freezes
8	2.0	cool	26.8	cold
9	4.8	very cool	40.9	exposed skin freezes
10	1.4	cool	22.8	cold
11	9.0	very cold	57.5	exposed skin freezes
12	4.0	very cool	37.6	biting cold
13	4.5	very cool	39.9	biting cold
14	1.3	cool	22.6	cold
15	0.5	pleasant, mild	16.3	very cool
16	5.0	cold	41.9	exposed skin freezes
17	6.0	cold	45.9	exposed skin freezes
18	9.5	very cold	58.2	exposed skin freezes
19	5.0	cold	42.4	exposed skin freezes
20	3.5	very cool	35.1	biting cold

caused particular displeasure.

The west end of Sparks Street Mall shows repeated discomfort due to high wind speeds as on November 2, 24 and 30; the highest being recorded on October 12. This area is consistently uncomfortable and should be redesigned using overhangs over the walkway to interrupt vertical wind movement. Since this mall receives minimal amount of solar radiation due to the closely spaced tall buildings, it may be feasible to enclose it creating an indoor walkway. Supplementary lighting may be added while skylight roofs may be installed to allow natural light to enter as well. An aesthetically pleasing environment may be created with plants, exhibitions, sitting areas, etc. while protecting the people from excess wind movement.

On October 12 a "pleasant" sensation at site 15 is caused by a low wind speed of 0.5 m/s and a relatively high temperature of 18.4°C. This comfort sensation was also recorded on September 22 which emphasizes the potential use of this site for public interest such as a park.

On October 19 (Table 6.17) dry bulb temperatures range from 4.9 to 6.9 °C, lower than on October 12, however, a greater frequency of discomfort is not apparent because wind speeds are significantly lower. On October 27 a significant variability in cooling rate occurs, particularly at the first 10 sites; this results in rapid variation in comfort sensations as one traverses these microclimatic cells.

TABLE 6.17
OCTOBER 19, 1978: VINJE DRY & WET BULB COMFORT INDEX
CITY CENTRE TRAVERSE

measurement site	wind speed	DRY BULB		WET BULB	
		cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	0	----	----	----	----
2	1.2	19.1	very cool	32.3	biting cold
3	1.0	17.2	very cool	29.9	very cold
4	0	----	----	----	----
5	0.3	10.8	cool	20.9	very cool
6	0	----	----	----	----
7	0	----	----	----	----
8	1.0	16.8	very cool	29.2	very cold
9	1.2	18.3	very cool	31.6	very cold
10	2.0	23.1	cold	39.2	biting cold
11	0	----	----	----	----
12	2.5	25.2	cold	42.8	exposed skin freezes
13	1.5	19.7	very cool	34.0	biting cold
14	2.0	22.9	cold	39.3	biting cold
15	1.0	16.9	very cool	29.9	very cold
16	0.3	10.2	pleasant, mild	20.5	very cool
17	0.5	13.3	cool	24.3	cold
18	0	----	----	----	----
19	0.5	13.1	cool	23.9	cold
20	3.5	29.8	very cold	51.5	exposed skin freezes

TABLE 6.18
OCTOBER 27, 1978: VINJE DRY & WET BULB COMFORT INDEX
CITY CENTRE TRAVERSE

measurement site	DRY BULB		WET BULB	
	cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	2.0	very cool	35.9	biting cold
2	0.5	cool	22.5	cold
3	2.5	cold	41.7	exposed skin freezes
4	6.0	biting cold	63.5	exposed skin freezes
5	5.5	very cold	59.6	exposed skin freezes
6	2.3	cold	39.8	biting cold
7	2.2	very cool	37.1	biting cold
8	3.8	cold	49.4	exposed skin freezes
9	4.0	very cold	51.9	exposed skin freezes
10	1.8	very cool	35.6	biting cold
11	1.0	cool	28.1	very cold
12	3.0	cold	44.2	exposed skin freezes
13	3.0	cold	43.3	exposed skin freezes
14	3.5	cold	47.3	exposed skin freezes
15	3.0	cold	43.5	exposed skin freezes
16	0.5	cool	21.7	cold
17	1.0	cool	28.4	very cold
18	0.5	cool	22.1	cold
19	3.0	cold	45.0	exposed skin freezes
20	0.5	cool	22.2	cold

TABLE 6.19
NOVEMBER 2, 1978: VINJE DRY & WET BULB COMFORT INDEX
CITY CENTRE TRAVERSE

measurement site	DRY BULB		WET BULB	
	cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	3.2	very cool	39.1	biting cold
2	1.0	cool	25.3	cold
3	1.5	very cool	29.4	very cold
4	5.8	very cool	55.1	exposed skin freezes
5	5.2	cold	50.9	exposed skin freezes
6	2.0	very cool	34.6	biting cold
7	1.0	cool	23.3	cold
8	1.0	cool	22.7	cold
9	2.5	very cool	36.3	biting cold
10	2.2	very cool	34.1	biting cold
11	6.8	very cold	58.8	exposed skin freezes
12	1.6	cool	29.1	very cold
13	1.1	cool	25.1	cold
14	0	----	----	----
15	2.8	very cool	36.5	biting cold
16	0.1	hot	13.2	cool
17	0.9	cool	22.7	cold
18	0.5	pleasant, mild	19.2	very cool
19	3.0	very cool	39.3	biting cold
20	0.8	cool	22.8	cold

On November 24 (Table 6.20) at sites 12 and 14 (on Slater Street) high cooling rates result in a "biting cold" sensation; this suggests wind funneling along Slater Street. Wind barriers installed at the west end would prevent this funneling.

The main influencing factor according to Vinje's dry bulb human comfort levels is wind speed. High wind speeds in Ottawa's downtown may be a result of vertical wind down buildings, or wind funneling along streets running parallel to the prevailing wind. High wind speeds are particularly stressful in the fall and winter when human comfort levels would otherwise be tolerable without the wind. Where high wind speeds are a problem, for example the west end of Sparks Street Mall and Slater Street, it is expected that shops and services might suffer from decreased business. In these situations indoor shopping malls profit considerably more than outdoor shops. To create more comfortable microclimates, the use of overhangs, trees and architectural devices is suggested to alleviate vertical wind flow and wind funneling. In the summer uncomfortable sensations due to high wind speeds are less noticeable, although the mechanical disturbance of wind may be irritating. The use of wind barriers is also advised in these situations.

6.8.2 Block Traverse

Table 6.22 lists Vinje dry and wet bulb cooling rates and comfort sensations for the November 16 single block traverse. Significant

TABLE 6.20
 NOVEMBER 24, 1978: VINJE DRY & COURT COMFORT INDICES
 CITY CENTRE TRAVERSE

measurement site	VINJE: DRY BULB		COURT: WET BULB	
	cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	32.3	very cold	23.4	cold
2	28.2	very cold	21.8	cold
3	45.9	exposed skin freezes	29.2	very cold
4	44.0	exposed skin freezes	28.4	very cold
5	37.3	biting cold	25.9	cold
6	32.3	very cold	23.4	cold
7	18.4	very cool	16.9	very cool
8	20.2	very cool	17.9	very cool
9	11.8	cool	13.5	cool
10	12.1	cool	13.9	cool
11	26.9	cold	21.0	very cool
12	38.1	biting cold	25.8	cold
13	19.9	very cool	17.6	very cool
14	36.0	biting cold	25.2	cold
15	19.8	very cool	17.6	very cool
16	19.9	very cool	17.6	very cool
17	26.8	cold	21.0	very cool
18	31.7	very cold	23.2	cold
19	32.4	very cold	23.3	cold
20	26.6	cold	20.6	very cool

TABLE 6.21
NOVEMBER 30, 1978: VINJE DRY & COURT COMFORT INDICES
CITY CENTRE TRAVERSE

measurement site	VINJE: DRY BULB		COURT: WET BULB	
	cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	35.9	biting cold	26.1	cold
2	43.3	exposed skin freezes	29.7	very cold
3	51.0	exposed skin freezes	32.1	very cold
4	49.5	exposed skin freezes	31.6	very cold
5	54.6	exposed skin freezes	33.1	very cold
6	44.4	exposed skin freezes	30.1	very cold
7	----	----	----	----
8	----	----	----	----
9	43.4	exposed skin freezes	29.1	very cold
10	43.1	exposed skin freezes	29.3	very cold
11	31.8	very cold	24.4	cold
12	24.8	cold	20.7	very cool
13	16.1	very cool	16.4	very cool
14	30.7	very cold	24.0	cold
15	31.5	very cold	52.5*	exposed skin freezes
16	28.1	very cold	45.5*	exposed skin freezes
17	34.0	biting cold	25.5	cold
18	22.4	cold	20.0	very cool
19	42.6	exposed skin freezes	29.6	very cold
20	38.2	biting cold	27.7	very cold

* Vinje wet bulb index was used since temperatures are above 0°C.

TABLE 6.22
NOVEMBER 16, 1978: VINJE DRY & WET BULB COMFORT INDEX

BLOCK TRAVERSE

measurement site	wind speed	DRY BULB		WET BULB	
		cooling rate mcal/cm ² /sec	comfort sensation including radiation load	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	3.2	28.0	very cold	46.7	exposed skin freezes
2	2.5	24.0	cold	44.0	exposed skin freezes
3	0	----	----	----	----
4	3.8	29.8	very cold	53.1	exposed skin freezes
5	2.0	22.7	cold	39.5	biting cold
6	0.5	12.6	cool	23.6	cold
7	0.5	12.4	cool	23.2	cold
8	3.0	27.8	very cold	47.1	exposed skin freezes
9	1.0	16.3	very cool	28.5	very cold
10	3.5	28.5	very cold	47.5	exposed skin freezes
11	1.3	18.7	very cool	32.0	very cold
12	0.8	15.3	cool	26.6	cold
13	0.3	10.4	pleasant, mild	19.8	very cool

variability in cooling rates is evident, as a result of variable micro-climatic conditions. Block traverses were conducted to demonstrate the occurrence of several microclimates within a single block area. The west end of Sparks Street Mall was chosen since this was known to have unfavourable conditions. In the downtown, it is the vertical component of buildings which, to a large extent, influences the micro-climatic conditions at pedestrian level. Urban planners should take note that where buildings are more densely arranged, and particularly where high rise structures are in close proximity to lower buildings, more detailed microclimatic investigations are advisable. Human comfort levels will vary considerably in the presence of high wind speeds and variable shading. On November 16, cooling rates vary from 10.4 to 29.8 mcal/cm²/sec. Within this range comfort sensations include "pleasant", "cool", "very cool", "cold" and "very cold", all within a single block area.

It is evident again that cooling rates are influenced primarily by wind speeds. With lower wind speeds comfort sensations are increased and vice-versa. At sites 1 and 4 (Sparks Street Mall) where comfort sensations are "very cold", wind speeds are 3.2 and 3.8 m/s respectively. The same is true at sites 8 and 10. It would be necessary to conduct further block traverses, particularly in other seasons, to substantiate whether these sites are consistently windy. Steps could then be taken to design appropriate wind barriers. It is again suggested that the best solution to uncomfortable conditions is to

enclose the mall, converting it into an indoor walkway. It is particularly important to ensure comfortable microclimates within this area since several entrances to government offices and shopping plazas are located here.

6.9 Court Wind Chill Index

6.9.1 City Centre Traverse

For temperatures below 0°C , the Court Wind Chill formula (eq. 5.10) was used to calculate body cooling rate. The comfort sensations corresponding with the degree of cooling are the same as for Vinje cooling rates, found in Table 6.11B.

It may be questioned why it is necessary to investigate human comfort levels in below zero temperatures, since any site will most probably be found uncomfortable in these conditions. However, high wind speeds can cause a great variation in relative comfort sensations due to the wind chill factor. Buildings which cause wind turbulence or wind funneling creating high wind speeds, increase discomfort in the winter. On December 14, for example, high wind speeds of 7,7 and 9 m/s at sites 3, 4 and 5 (Sparks Street Mall) are responsible for the high cooling rates resulting in a "biting cold" sensation.

TABLE 6.23

DECEMBER 14, 1978: COURT WIND CHILL INDEX - DRY BULB

CITY CENTRE TRAVERSE

measurement site	wind speed	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	3.0	27.1	cold
2	2.0	26.0	cold
3	7.0	35.0	biting cold
4	7.0	35.7	biting cold
5	9.0	38.0	biting cold
6	1.5	21.8	cold
7	1.5	22.9	cold
8	0	----	----
9	0.3	15.6	very cool
10	3.0	27.3	cold
11	3.0	26.7	cold
12	2.5	25.1	cold
13	0.5	17.6	very cool
14	2.0	24.2	cold
15	0.5	17.4	very cool
16	0	----	----
17	0.5	17.9	very cool
18	2.0	24.7	cold
19	2.5	26.8	cold
20	0	----	----

6.9.2 Block Traverse

On December 1 dry bulb temperatures were just below 0°C except at sites 10, 11 and 12 where temperatures of 0.1, 0.2 and 0.3 °C were recorded respectively. The Vinje dry bulb formula was used to determine comfort at these sites; however, they are not directly comparable with the Court results. The highest Court cooling rates occur at sites 1, 4, 5, 6, 8 and 9 resulting in a "cold" sensation. The high wind speeds of 4 and 5.5 m/s on Sparks Street near Tower C and the wind funneling between Tower C and the Holiday Inn at sites 8 and 9 are mainly responsible for the high cooling rates. It is interesting to note that this wind funneling occurs at the entrance to The Promenade indoor shopping plaza, a phenomenon which was evident in previous traverses. This condition is definitely disagreeable since it may discourage people from using the shopping facilities. High wind speeds at site 9 were at the entrance to the Holiday Inn Hotel, an inappropriate area to experience discomfort.

6.10 Human Comfort Questionnaire Results

The intention of performing the human comfort questionnaires was to compare pedestrian perception of microclimate with the mathematical predictions of Vinje and Court. The questionnaire surveys were a laborious task and provided variable results since it was not known how long a person had been outside, what the metabolic rate was, what was the

TABLE 6.24

DECEMBER 1, 1978: COURT WIND CHILL INDEX - DRY BULB
BLOCK TRAVERSE

measurement site	wind speed	cooling rate mcal/cm ² /sec	comfort sensation including radiation load
1	1.5	19.2	very cool
2	1.0	20.2*	very cool
3	2.0	20.7	very cool
4	4.0	25.1	cold
5	5.5	26.9	cold
6	3.5	23.9	cold
7	0.7	16.2	very cool
8	4.9	26.5	cold
9	3.9	25.0	cold
10	2.8	31.9*	very cold
11	4.8	39.9*	exposed skin freezes
12	3.0	32.6*	very cold
13	3.2	23.3	cold

* Vinje formula was used for these stations since ambient temperatures and temperature equivalents of radiation load sum to be greater than 0°C.

degree of acclimatization, and what influence cultural background had. During urban planning processes it may be necessary to conduct questionnaire surveys despite the labour and cost, since it is valuable to know peoples' reactions to local atmospheric conditions.

The human comfort questionnaire responses for October 12, 19 and November 2 are listed in Tables 6.25, 6.26 and 6.27 respectively. The wind speed, ambient temperatures and vapour pressure for each measurement site are listed in each table to indicate the microclimatic conditions prevalent at the time of questionnaire response.

On October 12 (Table 6.25) the high wind speed of 13.5 m/s at site 5 did not seem to influence the thermal comfort of pedestrians, since most felt "comfortable". At site 6 a slightly lower wind speed of 11 m/s generated one response of feeling "cold" and two responses of a "cool" sensation. It is not certain whether the air movement actually influenced thermal cooling, or whether the mechanical hindrance of wind caused people to think that they should be feeling cooler sensations. The sample size for each site is very small, however, it is evident that in the same climatic conditions, a range of opinions on comfort sensation were surveyed which sometimes includes three different sensations per site. This may be caused by the factors mentioned above. At almost every measurement site the majority of people chose "comfortable" as how they felt in immediate climatic surroundings.

TABLE 6.25

HUMAN COMFORT QUESTIONNAIRE RESULTS

OCTOBER 12, 1978

SITE	W. S. ¹	T °C ²	V. P. ³	COMFORT LEVELS ⁴					
				1	2	3	4	5	6
1	2.0	16.8	12.1						
2	7.8	16.2	11.7		1 ⁵		2		
3	2.5	17.2	12.0			1	4	1	
4	3.5	16.8	11.9			3	12		
5	13.5	16.9	11.8			1	6		
6	11.0	17.0	12.0	1		2	3		
7	5.0	17.8	12.0		2	2	4		
8	2.0	17.8	12.2				1	2	
9	4.8	17.8	12.1				3	1	
10	1.4	18.8	12.4				2		1
11	9.0	17.5	12.0			1	3	2	
12	4.0	18.0	11.9			1	4		
13	4.5	18.2	12.0			1	3		
14	1.3	19.0	11.9			1	5		
15	0.5	18.4	12.4				1	1	
16	5.0	18.4	12.0			1	5	1	
17	6.0	18.7	12.0				1		
18	9.5	18.9	12.0				6		
19	5.0	18.3	11.9				1		
20	3.5	18.6	12.1						

1. Wind speed meters per second
2. Actual temperatures recorded at each site and not corrected for diurnal change
3. Vapour pressure in millibars
4. Comfort levels
 1. Cold
 2. Uncomfortably cool
 3. Cool
 4. Comfortable
 5. Comfortably warm
 6. Uncomfortably warm
 7. Very uncomfortably warm
 8. Hot
5. Number of responses

A comparison of Ottawa's subjective responses with the Vinje mathematically simulated responses for October 12 (Table 6.28) reveals a discrepancy. In general, the Vinje calculations suggest cooler sensations than were actually experienced by pedestrians. For example, at site 5 most pedestrians considered the microclimate to be "comfortable" whereas Vinje's predicted cooling rate suggests that the sensation should be "biting cold". The Vinje cooling rates are obviously too extreme for the temperature conditions of that day. At site 8 most pedestrians felt "comfortably warm" whereas the Vinje calculation infers that a "cool" sensation should be felt.

In Table 6.26 human comfort results and comments on wind condition on October 19 are listed. Wind speeds are lower than on October 12. A "cold" sensation was felt by some people at sites 2, 6, 9, 11 and 17 and "uncomfortably cool" sensations were felt at sites 3 and 4 on Sparks Street Mall. Higher wind speeds did not seem to influence enough people questioned to draw conclusions on the relationship between wind speed and comfort sensation. It is ironic that even though calm conditions prevailed at several sites, two people at these sites experienced "cold" sensations. This may have been caused by insufficient solar radiation intensity.

Table 6.29 compares Vinje's mathematical predictions and pedestrian subjective responses. Since wind speed on this day is lower than on October 12, the Vinje comfort sensations approximated subjective

TABLE 6.28
COMPARISONS OF VINJE'S AND OTTAWA'S HUMAN COMFORT
SENSATIONS, OCTOBER 12, 1978

site	Vinje comfort sensations	Ottawa's comfort sensations
1	cool	-----
2	cold	uncomfortably cool 1 comfortable 2
3	very cool	cool 1 comfortable 4 comfortably warm 1
4	very cool	cool 3 comfortable 12
5	biting cold	cool 1 comfortable 6
6	very cold	cold 1 cool 2 comfortable 3
7	very cool	uncomfortably cool 2 cool 2 comfortable 4
8	cool	comfortable 1 comfortably warm 2
9	very cool	comfortable 3 comfortably warm 1
10	cold	comfortable 2 uncomfortably warm 1
11	very cold	cool 1 comfortable 3 comfortably warm 2
12	very cool	cool 1 comfortable 4
13	very cool	cool 1 comfortable 3
14	cool	cool 1 comfortable 5
15	pleasant	comfortable 1 comfortably warm 1
16	cold	cool 1 comfortable 5 comfortably warm 1
17	cold	comfortable 1
18	very cold	comfortable 6
19	cold	comfortable 1
20	very cool	-----

TABLE 6.26

HUMAN COMFORT QUESTIONNAIRE RESULTS

OCTOBER 19, 1978

SITE	W. S. ¹	T ²	V. P. ³			COMFORT LEVELS ⁴						WIND CONDITIONS ⁵			
			1	2	3	1	2	3	4	5	6	1	2	3	4
1	0	5.6	5.1												
2	1.2	5.2	4.9	1				3	3 ⁶					2 ⁶	1
3	1.0	6.2	4.6		1			2					1	3	
4	0	5.6	5.0		1									3	1
5	0.3	5.2	5.0					1						1	1
6	0	6.3	5.0	1				4	5					6	
7	0	6.2	4.8					2	2					5	
8	1.0	7.2	5.0					3	1			1		3	
9	1.2	7.3	4.9	1				2	3			1		2	
10	2.0	6.8	5.1					2	5					6	
11	0	7.5	6.0	1				1	3				2	5	
12	2.5	7.2	5.1					1	3					4	
13	1.5	8.2	5.0					2	2					2	
14	2.0	7.6	5.0											4	
15	1.0	8.2	4.5											3	
16	0.3	7.7	4.9						3					3	
17	0.5	6.5	4.6	2				1	1				1	3	1
18	0	7.8	5.1					2	1					2	
19	0.5	7.0	4.8					1	1					2	
20	3.5	7.2	4.8											2	

1. Wind speed in meters per second
2. Actual temperatures recorded at each site and not corrected for diurnal change
3. Vapour pressure in millibars
4. Comfort levels see table 6.25
5. Wind conditions
 1. Extremely windy
 2. Uncomfortably windy
 3. Comfortably windy
 4. Not windy enough
6. Number of responses

responses more closely, although some discrepancy still exists.

On October 19 most people felt that it was comfortably windy at most sites, however, wind speeds are reasonable, ranging between 0 and 3.5 m/s. At sites 8 and 9 there were two opinions that wind conditions were "extremely windy", an unreasonable opinion since wind speeds were 1 and 1.2 m/s respectively. A number of people felt it was "uncomfortably windy"; however, several responses that it was "not windy enough" were given at sites 1, 3, 4 and 18 where wind speeds were 0, 1, 0 and 0 m/s respectively. This reflects the difficulties of dealing with personal responses on comfort, and the need for a large sample. It may be said that the occurrence of high wind speeds is more serious than the occurrence of low or no wind, particularly in the fall and winter seasons. Not everybody can be satisfied. The problem faced by urban planners is to decide what microclimatic conditions are comfortable for the majority of pedestrians. This could be achieved by conducting questionnaire surveys for a large sample. Those buildings and services which are most frequently used should be considered first, whereas uncomfortable conditions in areas of little public interest or use are not a priority.

Table 6.27 lists comfort sensations and comments on wind conditions for November 2 during which time temperatures were anomalously high for the autumn season and wind speeds were moderate. Most people questioned felt "comfortable" in these conditions; however, several individuals felt "cool" and "comfortably warm" and one person felt

TABLE 6.27

HUMAN COMFORT QUESTIONNAIRE RESULTS

NOVEMBER 2, 1978

SITE	W. S. 1	T 2	V. P. 3	COMFORT LEVELS 4						WIND CONDITIONS 5			
				2	3	4	5	6		2	3	4	
1	3.2	14.8	6.6			16	2					16	2
2	1.0	13.2	6.7			3						3	
3	1.5	12.8	7.4			3				1		2	
4	5.8	13.1	6.8		2	1						3	
5	5.2	13.5	7.6		1	2				2		1	
6	2.2	13.1	6.4		1	2						4	
7	1.0	14.7	7.4			2	1			1		2	
8	1.0	16.3	7.1			3						3	
9	2.5	14.3	6.4			3						3	
10	2.2	14.2	6.7			3				1		3	
11	6.8	14.5	6.5			3						4	
12	1.6	14.5	7.0			2						2	
13	1.1	15.2	7.0			3	1					4	
14	0	14.6	7.1		1	2	1					4	
15	2.8	14.6	7.7			3				1		3	
16	0.1	14.9	7.6		1	2						3	
17	0.9	14.4	8.8			3						3	
18	0.5	14.9	6.9			4						4	
19	3.0	14.0	6.5									1	
20	0.8	14.5	6.6					1					

1. Wind speed in meters per second
2. Actual temperatures recorded at each site and not corrected for diurnal change
3. Vapour pressure in millibars
4. Comfort levels see table 6.25
5. Wind conditions see table 6.26
6. Number of responses

"uncomfortably warm". It is interesting to note that whereas temperatures and average wind speeds on November 2 are lower than on October 12, more people felt "comfortable" on November 2 than on October 12. This is probably the result of the sudden temperature increase on this day which followed seasonally cooler temperatures. Since people were beginning to acclimatize to cooler weather, a sudden temperature increase resulted in a favourable response which seems to have been somewhat exaggerated.

A comparison of Vinje's mathematical predictions and subjective responses for November 2 (Table 6.30) reveals that a certain comparability in sensations is apparent. As usual, however, the Vinje formula implies more discomfort than was actually indicated by pedestrians at most sites.

The results of the extremely small sample of people questioned do not lend themselves reliably to suggestions for corrective measures at uncomfortable sites. A general trend in responses shows most people object to high wind speeds, particularly on the west end of Sparks Street Mall and around the Place de Ville office complex (the latter was not researched in this study). Many people found opening doors to buildings difficult in the presence of high wind speeds. Many felt something should be done about the construction of tall buildings which were in many cases thought to be aesthetically disturbing as well as climatically incompatible with surrounding structures. This particular comment was directed to the construction of the Royal Bank extension

TABLE 6.29

COMPARISONS OF VINJE'S AND OTTAWA'S HUMAN COMFORT

SENSATIONS, OCTOBER 19, 1978

site	Vinje comfort sensations	Ottawa's comfort sensations	
1	-----	comfortable	3
2	very cool	cold cool	1 3
3	very cool	uncomfortably cool cool	1 2
4	----	uncomfortably cool comfortable	1 1
5	cool	cool comfortable	1 5
6	----	cold cool	1 4
7	----	cool comfortable	2 2
8	very cool	cool comfortable	3 1
9	very cool	cold cool comfortable	1 2 3
10	cold	cool comfortable	2 5
11	----	cold cool comfortable	1 1 3
12	cold	cool comfortable	1 3
13	very cool	cool comfortable	2 2
14	cold	comfortable	2
15	very cool	comfortable	3
16	pleasant	comfortable	3
17	cool	cold cool comfortable	2 1 1
18	----	cool comfortable	2 1
19	cool	cool comfortable	1 1
20	very cold	----	

TABLE 6.30

COMPARISONS OF VINJE'S AND OTTAWA'S HUMAN COMFORT
SENSATIONS, NOVEMBER 2, 1978

site	Vinje comfort sensations	Ottawa's comfort sensations	
1	very cool	comfortable	1
		comfortably warm	2
2	cool	comfortable	3
3	very cool	comfortable	3
4	very cool	cool	2
		comfortable	1
5	cold	cool	1
		comfortable	2
6	very cool	cool	1
		comfortable	2
7	cool	comfortable	2
		comfortably warm	1
8	cool	comfortable	3
9	very cool	comfortable	3
10	very cool	comfortable	3
11	very cold	comfortable	3
12	cool	comfortable	2
13	cool	comfortable	3
		comfortably warm	1
14	----	cool	1
		comfortable	2
		comfortably warm	1
15	very cool	comfortable	3
16	hot	cool	1
		comfortable	2
17	cool	comfortable	3
18	pleasant	comfortable	4
19	very cool	uncomfortably warm	1
20	cool	----	

which was partially completed at this time. It had already been criticised for shading the east end of Sparks Street Mall.

Although peoples' comments were instructive, not enough responses were collected to suggest structural modifications. It is advised that peoples' views of urban microclimates should be included in urban planning processes along with mathematical models to evaluate comfort conditions.

CHAPTER 7 CONCLUSIONS

The intention of this thesis was to introduce human comfort as an alternative method to determine unfavourable microclimatic conditions in urban areas. It is felt that this objective was accomplished in the demonstration of using empirical microclimatic data in human comfort formulae. A relationship was clearly shown between microclimatic variability and human comfort variability. An emphasis was placed in this research on using human comfort as a more logical guide in outlining urban planning guidelines to alleviate unfavourable microclimates. This is a strikingly different planning proposal from most conventional ones which do not use human comfort models, or microclimatic information of any sort. With increasing awareness of the influence of climate on human physiology, the use of human comfort seems to be a rational tool for use in planning processes.

A review of the historical development of the role of climatology in urban planning reveals a sporadic use of climatic information, even though the interest in the climate of towns has a long history. Recent efforts to use climatic data are encouraging; however, examples cited in the thesis lack a unifying method which could be easily used in any urban planning situation. The most common method is simply examining empirical data in the search for extreme conditions, which are then assumed to be unfavourable for frequent human use. Even though extreme climatic values are most often found unfavourable, this arbitrary

method has been criticized for producing inconsistent results. The gap between urban planners and climatologists has grown even wider with increasing debate on the most effective method.

In this thesis human comfort calculations were done to demonstrate the variability of human comfort levels with microclimatic data, and to emphasize the value of using this method to locate unfavourable areas within the downtown. The absolute human comfort results are not necessarily accurate. Rather, human comfort as a method was found to be effective in determining uncomfortable sites. Corrective measures were suggested according to the comfort level of the sites. The use of this method would link urban climatologists and planners, since microclimatic data may be evaluated in terms of human comfort values either by climatologists or urban planners and easily understood by both.

An example of how urban planners may use human comfort information was provided, with an evaluation of influencing microclimatic factors. All human comfort indices reveal a correlation between wind speed and human comfort. In temperatures below 20°C, an increase in wind speed causes a decrease in comfort levels. Areas which are susceptible to high wind speeds, such as the west end of Sparks Street Mall, experience a higher degree of discomfort. An added problem is excess shading due to the height of the buildings. Tall buildings cause problems of wind turbulence and shading, and create uncomfortable microclimates

as well as aesthetically unpleasant environments. Unless building arrangements are such that they reduce wind turbulence, the building of tall structures should be limited to areas away from shops and services, or should be disallowed altogether. High wind speeds in existing problem areas may be controlled by the use of wind barriers, such as trees or architectural devices, and would be especially important in the autumn season when comfort may be increased in calm air conditions bringing more people outdoors. It was found that the addition of temperature equivalence of solar radiation increases comfort; therefore, sunny sites are to be preserved during the autumn to attract pedestrians. Calm air and high solar radiation at the N.A.C site contribute to high comfort levels. This site has the potential of being developed into an outdoor attraction during the autumn, such as a café or sitting area. In the summer the same microclimatic conditions would cause excess heat load; however overhangs and trees would be an effective method to overcome this.

Asphalt top parking lots are found to have extremely comfortable microclimates in the autumn. Even though this is favourable in a cool season, it is assumed that in the summer these areas have extremely uncomfortable microclimates due to the high absorption of solar radiation. Parking lots are a particular urban problem which should be improved in design to provide more comfortable conditions. The use of vegetation along pedestrian walkways is one way to improve the microclimate.

The cool temperatures and bright sunshine in the autumn season provide an opportunity for pedestrians to spend time outdoors shopping, browsing or enjoying the warmth. Areas such as the west end of Sparks Street Mall are not only windy but also shady most of the day and do not provide pedestrians with a comfortable environment. It is conceivable that shops and services along this mall do not prosper as well as if they were in a more comfortable microclimate. Benches provided along this mall are rarely used. Areas located in direct sunshine and calm air are comfortable and pleasant and may be popular as well as profitable. Areas which are sunny but windy may acquire a more comfortable microclimate by the use of wind barriers.

In the winter, high wind speeds increase discomfort in temperature conditions which are already uncomfortable. Wind funneling should be corrected by the use of coniferous trees or wind barriers located at the end of the street where funneling originates. Wind turbulence should be alleviated by the use of overhangs which would dissipate vertical downwash of wind while protecting pedestrians. This would also make the opening of doors to the building easier.

It is believed that the use of human comfort in urban planning will lead to a greater awareness of urban climatic problems and hopefully more comfortable urban environments. Guidelines for uncomfortable sites given in this thesis are examples of how the approach to human comfort analysis could proceed. Every site requires different corrective

measures and should therefore be examined individually. The method of incorporating design guidelines according to the human comfort and microclimatic conditions of the site "...suggests both potential humanness of urban climate and uniqueness of each city's climate - pointing the way for urban planners and designers to include climate in their work in a way they seldom approach doing today" (Lowry, 1972).

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APPENDIX A

CLIMATIC DATA VARIABILITY

CITY CENTRE TRAVERSE

TEMPERATURES IN CENTRAL OTTAWA

SEPTEMBER 1, 1978

LYCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

SEPTEMBER 1, 1978

TEMPERATURES IN CENTRAL OTTAWA

SEPTEMBER 14, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

SEPTEMBER 14 1978

TEMPERATURES IN CENTRAL OTTAWA

SEPTEMBER 22, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

SEPTEMBER 22, 1978

TEMPERATURES IN CENTRAL OTTAWA

SEPTEMBER 29, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

SEPTEMBER 29 1978

TEMPERATURES IN CENTRAL OTTAWA

OCTOBER 12, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

OCTOBER 12 1978

TEMPERATURES IN CENTRAL OTTAWA

OCTOBER 19, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

OCTOBER 19 1978

TEMPERATURES IN CENTRAL OTTAWA

OCTOBER 27, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

OCTOBER 27 1978

TEMPERATURES IN CENTRAL OTTAWA

NOVEMBER 2, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

NOVEMBER 2 1978

TEMPERATURES IN CENTRAL OTTAWA

NOVEMBER 24, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

NOVEMBER 24 1978

TEMPERATURES IN CENTRAL OTTAWA

NOVEMBER 30, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

NOVEMBER 30 1978

TEMPERATURES IN CENTRAL OTTAWA

DECEMBER 14, 1978

INCOMING SOLAR RADIATION CITY CENTRE TRAVERSE

DECEMBER 14 1978

WIND SPEEDS CITY CENTRE TRAVERSE

SEPTEMBER 1, 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

SEPTEMBER 1, 1978

WIND SPEEDS CITY CENTRE TRAVERSE

SEPTEMBER 14, 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

SEPTEMBER 14 1978

WIND SPEEDS CITY CENTRE TRAVERSE

SEPTEMBER 22, 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

SEPTEMBER 22 1978

WIND SPEEDS CITY CENTRE TRAVERSE

SEPTEMBER 29 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

SEPTEMBER 29 1978

WIND SPEEDS CITY CENTRE TRAVERSE

OCTOBER 12 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

OCTOBER 12 1978

WIND SPEEDS CITY CENTRE TRAVERSE

OCTOBER 19 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

OCTOBER 19 1978

WIND SPEEDS CITY CENTRE TRAVERSE

OCTOBER 27 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

OCTOBER 27 1978

WIND SPEEDS CITY CENTRE TRAVERSE

NOVEMBER 2, 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

NOVEMBER 2 1978

WIND SPEEDS CITY CENTRE TRAVERSE

NOVEMBER 24 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

NOVEMBER 24 1978

WIND SPEEDS CITY CENTRE TRAVERSE

NOVEMBER 30 1978

VAPOUR PRESSURE CITY CENTRE TRAVERSE

NOVEMBER 30 1978

APPENDIX B

CLIMATIC DATA VARIABILITY

BLOCK TRAVERSE

AMBIENT TEMPERATURES BLOCK TRAVERSE

NOVEMBER 16 1978

AMBIENT TEMPERATURES BLOCK TRAVERSE

DECEMBER 1 1978

VAPOUR PRESSURE BLOCK TRAVERSE

NOVEMBER 16 1978

VAPOUR PRESSURE BLOCK TRAVERSE

DECEMBER 1 1978

WIND SPEEDS BLOCK TRAVERSE

NOVEMBER 16 1978

WIND SPEEDS BLOCK TRAVERSE

DECEMBER 1 1978

INCOMING SOLAR RADIATION - SKY
BLOCK TRAVERSE
NOVEMBER 16 1978

INCOMING SOLAR RADIATION - SKY
BLOCK TRAVERSE
DECEMBER 1 1978

INCOMING SOLAR RADIATION - NORTH FACING

BLOCK TRAVERSE

NOVEMBER 16 1978

INCOMING SOLAR RADIATION - SOUTH FACING

BLOCK TRAVERSE

NOVEMBER 16 1978

INCOMING SOLAR RADIATION - EAST FACING
BLOCK TRAVERSE
NOVEMBER 16 1978

INCOMING SOLAR RADIATION - WEST FACING
BLOCK TRAVERSE
NOVEMBER 16 1978

AMBIENT & INFRARED TEMPERATURES - BLOCK TRAVERSE
NOVEMBER 16 1978

INFRARED TEMPERATURES - PAVEMENT
BLOCK TRAVERSE
NOVEMBER 16 1978

INFRARED TEMPERATURES - NORTH FACING

BLOCK TRAVERSE
NOVEMBER 16 1978

INFRARED TEMPERATURES - SOUTH FACING

BLOCK TRAVERSE
NOVEMBER 16 1978

INFRARED TEMPERATURES - EAST FACING

BLOCK TRAVERSE

NOVEMBER 16 1978

INFRARED TEMPERATURES - WEST FACING

BLOCK TRAVERSE

NOVEMBER 16 1978

INCOMING SOLAR RADIATION - NORTH FACING

BLOCK TRAVERSE

DECEMBER 1 1978

INCOMING SOLAR RADIATION - SOUTH FACING

BLOCK TRAVERSE

DECEMBER 1 1978

INCOMING SOLAR RADIATION - EAST FACING
BLOCK TRAVERSE
DECEMBER 1 1978

INCOMING SOLAR RADIATION - WEST FACING
BLOCK TRAVERSE
DECEMBER 1 1978