DETECTING MICROCLIMATIC BIASES IN HISTORICAL TEMPERATURE RECORDS

by

KATHRYN ELIZABETH RUNNALLS

B.Sc., McMaster University, 1993
M.Sc., University of British Columbia, 1995

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

(Department of Geography)

We accept this thesis as conforming
To the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

December 2002

Department of Geography

The University of British Columbia
Vancouver, Canada

Date December 11, 2002

ABSTRACT

The quality of historical climate data is a fundamental consideration in climate change research. This thesis considers the problem of microclimatic biases in observed surface-level air temperatures, and the effect of these biases on the homogeneity of historical temperature records. An extensive literature review describes causes of potential biases in air temperature records, and demonstrates that climate station siting biases, in the form of microclimatic change in the surrounding environment, are particularly difficult to detect by conventional homogeneity analysis techniques. Such biases are therefore potentially still present in many of the records used to monitor global climate change. The microclimatic processes responsible for thermal biases in temperature records are reviewed to demonstrate the relevant physical principles. A new technique to detect microclimatic inhomogeneities in temperature records is presented. The technique is based on the construction of time series of cooling ratios derived from nocturnal cooling at neighbouring climate stations calculated from daily maximum and minimum temperatures. The 'cooling ratio' is shown to be a particularly sensitive measure of the relative microclimatic differences between neighbouring climate stations, because larger-scale climatic influences common to both stations are removed by the use of a ratio and, because the ratio is invariant in the mean with weather variables such as wind and cloud. Discontinuities in the time series of cooling ratios indicate microclimatic change in one of the temperature records. Hurst rescaling (Hurst, 1951) is applied to several time series of cooling ratios, and is shown to be helpful in identifying discontinuities in the time series. The technique is tested on several Canadian historical temperature records, and proven to effectively identify subtle microclimatic changes such as minor station relocations, vegetation growth, and encroachment of buildings and parking lots. Results of this technique are compared to those from other homogeneity assessment techniques, and the cooling ratio approach is shown to be better suited to the detection of microclimatic biases. The technique is also shown to be useful in the assessment of the homogeneity of urban temperature records. Finally, since the research highlights the significance of having detailed station metadata, recommendations are made to improve the utility of such records, along with suggestions for future research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I am grateful to the following individuals and organizations for their contributions to this work. In particular, I thank my advisor and mentor, Professor T.R. Oke, for his support, guidance, and enthusiasm for my research, which have been a great motivation. The members of my research committee, Professors T.A. Black, M. Church and I.G. McKendry, have also been supportive, providing helpful advice at many stages of my programme. Thanks are due to the staff of the UBC Geography Department, particularly Vincent Kujala, who has rescued many hard-drives and files, and Sandy Lapsky, who has taken care of many details behind the scenes. Claybrook Holsteins of New Liskeard, Ontario generously provided the field site for this research, and Erica Ellis assisted with field work. Canadian climate data used in this thesis, and access to the climate station history archives, were provided by the Meteorological Service of Canada. Anna Deptuch-Stapf of Climate Services, and Lucie Vincent of the Climate Research Branch were particularly generous with their time and expertise, and their assistance is gratefully acknowledged. The Natural Sciences and Engineering Research Council of Canada provided funding in the form of a postgraduate scholarship and funding for T.R. Oke's research. Teaching and research assistantships from the Department of Geography are also acknowledged. Finally, I am grateful for all the encouragement I have received from friends and family, and especially to Brett and Brendan for their unwavering support.

Chapter 1
INTRODUCTION

"Climate change is perhaps the most pressing and urgent environmental issue on the world's agenda." (NERC,1998).

Over the last few decades, few scientific issues have attracted as much scientific and societal interest as global climate change. Scientific publications, conference proceedings, and the number of scientists contributing to all aspects of climate change research have grown exponentially since 1970, with current annual costs of this research estimated to be 3 billion U.S. dollars (Stanhill, 2001). With the diversity of interested parties ranging from insurance companies concerned about rising costs due to an increased frequency of extreme events such as floods, droughts and hurricanes, to ecologists concerned that species of flora and fauna may face extinction in a warmer world, it is not surprising that there is strong public support for funding climate change research encompassing the full spectrum of cause and effect. Yet, a question that persistently challenges the relevancy of this research is "do we have proof that the climate is in fact changing?"

The most recent report by the Intergovernmental Panel on Climate Change (2001) claims there is now 'unequivocal' proof that Earth is getting warmer, citing evidence such as rising sea level, retreating glaciers, melting sea ice and changes to global circulation patterns (such as the increased frequency and intensity of warm-phase ENSO events). The IPCC also states that the instrumental temperature record shows "the global average surface temperature has increased by 0.6 ± 0.2 °C since the late 19th Century."

As a direct measure of a relevant climate variable, and with records extending back through the same period in which atmospheric concentrations of greenhouse gases have increased, historical air temperature records are potentially the most useful of all forms of evidence to verify the nature and magnitude of climate change. Yet, this 'proof' remains the subject of much debate. Indeed, when statements like that above -- implying that global temperature change can be determined to a certainty of two-tenths of a degree-- are paired with the IPCC (1996) statement that "the balance of evidence suggests that there is a discernible human influence on the global climate," there is an inevitable backlash from those whose economic interests are threatened by the implications of these statements.

While the process of questioning research findings is always necessary in order to advance understanding and improve research methodologies, curiously, very little of the opposing view regarding the accuracy of global temperature records makes its way into peer reviewed scientific media. Instead, much of the dissension appears in 'alternative' publications, such as Internet websites, where it can be easily dismissed as speculative or serving a particular agenda. This is an unfortunate situation, because many of the concerns of these self-described 'skeptics' may, in fact, be well founded. One need only consider the possible sources of error involved in measuring air temperatures, from observer errors and data handling, instrument errors, exposure and siting biases, to issues of spatial and temporal representativeness, in order to begin to question how it is possible to measure 'global' temperature change to a precision of 0.2°C.

This is not to say that errors are not recognized, and to a certain extent, 'corrected', before compiling global temperature data sets. There is an abundance of literature on this very subject (see Chapter 2). In fact, the compilers of large climate data bases such as the United States Historical Climatology Network (USHCN) do recognize that "no station is completely free of changes that could possibly affect its instrumental record" (Easterling et al., 1999). Rather, the problem arises when dealing with thousands of individual records (the USHCN contains over 1200 stations, the Global HCN: 7000), it is virtually impossible to identify every possible error, in every single record. Thus, it is only reasonable to be concerned that global temperature trends may have been calculated from flawed data.

One potential source of bias in historical land-surface air temperature records that is particularly difficult to detect, often overlooked, but most importantly, extremely pervasive, is the microclimatic setting of the climate station itself. The purpose of this thesis is to examine these microclimatic biases in historical temperature records. Firstly, literature is reviewed to demonstrate that such biases are both significant, and underrecognized. Secondly, the physically relevant microclimatic processes responsible for creating thermal biases are discussed, with reference to studies that have described microscale temperature variability and associated physical controls, including original observations described in Appendix 1. Thirdly, a new technique is developed that is specifically designed to detect microclimatic, or siting biases in climatological temperature records. The technique is tested on a number of records to illustrate its utility for detecting these biases in a variety of settings, including urban environments. Finally, recommendations are made for improving climate station meta-data information that proves to be crucial to the identification of siting biases, and suggestions for future research are made.

It is hoped that this work will begin the process of a more rational, scientifically based, but much needed critical discussion of the quality of global temperature records, so that necessary action can be taken to improve both our understanding of past climate change, and our ability to monitor it in the future.

Chapter 2
REPRESENTATIVENESS, HOMOGENEITY, AND THE CLIMATOLOGICAL USE OF SCREEN-LEVEL AIR TEMPERATURES: BACKGROUND AND MOTIVATION FOR THE STUDY

2.0 Introduction

The concepts of 'representativeness' and 'homogeneity' are central to the interpretation of measured climate variables. This chapter seeks to define and discuss these concepts in the context of surface air temperature measurements. Sources of inhomogeneities in historical temperature records, methods used in their detection, and current views on the quality of 'homogeneity adjusted' climate records are reviewed and used to highlight points to be investigated in the thesis research.

2.1 Representativeness

2.1.1 Definition

Although air temperatures are generally assumed to be less spatially variable than, for example, precipitation, obtaining a representative air temperature is not a simple task, particularly when the objective is to characterize global climate using data collected at a number of individual sites. Ideally, the representativeness of a potential measurement site should be assessed *before* observations are made in order to ensure that the observations adequately represent what they are intended to. Yet despite being a fundamental consideration in the proper measurement and interpretation of climate variables, representativeness is often an afterthought that occurs when the observations don't match with expectations. In some cases, this is unavoidable, such as when data collected for one purpose are analyzed for an entirely different one, or when observations from the desired location do not exist and data from the next closest site must be used. However, the greatest problem arises from the fact that 'representativeness' is an extremely difficult concept to define.

Ehinger (1993) notes that representativeness is ambiguous because it has both quantitative and qualitative aspects; and it applies to both sites and measurements. Wieringa (1997) states

> Representativity is not a universal quality like accuracy, not a fixed attribute of some (well executed) observation. Rather it depends both on the properties of the parameter... and on the application scales.

Further he notes,

> Representativity of an observation means, that its exposure, instrumentation (if any) and sampling procedure are well matched to obtain a reliable average value of the observed parameter in a pre-determined space, which we want to represent. (Wieringa, 1997).

In an attempt to promote more quantitative approaches to representativeness assessment, Nappo *et al.* (1982) define representativeness as

> The extent to which a set of measurements taken in a space-time domain reflects the actual conditions in the same or different space-time domain taken on a scale appropriate for a specific application.

Statistical techniques are sometimes used in an attempt to quantify representativeness objectively by examining the spatial variability of observations in a given network (Zemel and Lomas 1976; Nappo *et al*, 1982). Such techniques are useful to identify the optimal spacing between stations for particular purposes (e.g. frost prediction in agriculture; Zemel and Lomas 1976), however, they are not particularly useful to judge the representativeness of data being used for a purpose other than originally intended.

Ehinger (1993) also suggests use of a more quantitative concept, 'area of representativeness', which is 'the land area, expressed in square metres, within which the values measured are identical to those given by the reference instrument'. He notes that this measure will vary from one parameter to another, with the kind of weather and with the seasons, and it must take account of topographical features near the site. Ehinger fails to suggest, however, how these multiple 'areas of representativeness' can be determined. As Nappo *et al* (1982) note, 'representativeness is and will remain a value judgment.'

Pielke et al. (2000) and Pielke et al. (2002) examined the spatial representativeness of individual climate stations by comparing air temperature records from a number of sites in a relatively homogenous landscape. They found 'enormous' spatial and temporal variability, making it impossible to identify a regionally 'representative' climate station. They therefore caution against the use of single station data to infer regional climate, or the converse inference of site specific climate change predictions from coarse-scale general circulation models. Clearly, much of the current research investigating global climate change could benefit from a greater awareness of the importance of representativeness in interpreting climate data.

An illustration of the importance of ensuring that measurements are "well matched" to what "we want to represent" (Wieringa, 1997) comes from the study of Bonan, (2000). This study is an attempt to determine the regional climate changes that have occured as a result of widespread replacement of natural forests with croplands over the last century in the United States. Climate trends in predominantly forested regions (Northeast US) were compared to trends in predominantly agricultural regions (Midwest US). Stations were classified as either forest or cropland according to the predominant land cover in a 3 km x 3 km grid centred on the climate station. However, in an attempt to avoid microclimate biases, only stations that were classified as "nonvegetated," "open farmland, grasslands", or "small town less than 1000 population" within 100 m of the station were used. That is, climate stations having "forest" land cover within 100 m were expressly excluded from the study. By selecting stations in this manner, Bonan (2000) contends that the stations represent 'regional' climate, yet it is unreasonable to assume that a climate station in a small town accurately portrays either forest or cropland climate. If the potential for microclimatic biases are not addressed in these types of analyses, conclusions drawn from them may be of limited value.

2.1.2 Official guidelines for making representative measurements

Concerns about making representative temperature measurements are almost as old as the historical records themselves. The following quote appeared in the opening of *Symons's Monthly Meteorological Magazine*, October 1868:

> "...I found that scarcely any observations had been made with thermometers placed under exactly similar circumstances, and without which unity no deductions can be drawn with any claim to accuracy. Some thermometers faced the north, some the north-east, some the north-west, &c,&c. Some were from three to five feet from the ground, some ten to twenty; some were embowered, some placed in a box, some sheltered by a high house or wall, some by a low wall, or by palings, some touching a wall, and others distant from it; some were in a angle of a high building (cool as a cellar), some exposed to the sun's rays either morning or evening (Lawson, 1843)."

Symons's concern for this 'perpetuation of anarchy' was the motivation for the Strathfield Turgiss experiments, an elaborate comparison of 13 different thermometer exposures, the results of which led to the adoption of the Stevenson Screen as a standard by the Royal Meteorological Society in 1875. Other recommendations made at the same time included placement of the thermometer screen a minimum of 10 feet from any wall, and the preparations of ground plans at all stations showing the positions of the instruments and all surrounding objects (Meteorological Society, 1875). A standard measurement height of 4 feet above ground was apparently common practice by that time as well.

Shortly thereafter, the Stevenson screen became a standard in many countries around the world, and remains so to this day. (See Sparks, 1972, for a review of different exposures in use). Despite this apparent 'uniformity' of exposure, in many respects the 'perpetuation of anarchy' which concerned Symons, still persists today, and continues to pose problems in the analysis of historical temperature records.

Even the modern day WMO Guidelines for Siting of Meteorological Instruments (which are also the basis for most national meteorological service guidelines) place too much reliance on the experience and good sense of the station installers and operators in the subjective interpretation of representativeness. For example:

> For general meteorological work, the observed temperature should be representative of the free air conditions surrounding the station over as large an area as possible, at a height of between 1.25 and 2 m above ground level....The best site for the measurements is, therefore, over level ground, freely exposed to sunshine and wind and not shielded by, or close to, trees, buildings and other obstructions (WMO, 1996).

> Take [temperature] measurement under a standard shading apparatus 2 m aboveground. Ground to be covered with regularly mowed grass. Thermometer to be installed far from heat sources or water

bodies, unless these are "representative" of the region. Distance to obstacles: 4 to 10 times their height (Ehinger, 1993).

For automatic weather stations, WMO guidelines suggest "Location on ground typical of surrounding terrain. No obstruction should be closer than 4 times the height of that obstruction" (WMO, 1997). Canadian guidelines suggest that temperature measurements at a distance of 2 times the height of an obstruction are acceptable (AES, 1992).

Some of the most specific and quantitative guidelines come from the French Meteorological Service. For example, recommendations include a distance of more than 100 m from any artificial heating source or body of water, and that such surfaces should not occupy more than 10% of the area subtended by a 100 m radius, or 5% of 10-30 m radius, or any area within 10 m (Leroy, 1998; Meteo France, 1997). While such moves towards more exact specifications suggest that significant improvements in instrument siting can be expected for recently installed and future climate stations, concerns about the representativeness of historical records remain.

Despite the fact that many historical temperature records come from stations which are assumed to comply with guidelines for representative measurements, as previously discussed, representativeness can only be judged with respect to a specific purpose, or application. As Wieringa (1997) points out, WMO guidelines for representativeness were originally based on the ability to make accurate weather forecasts, and therefore, the stations are not necessarily ideally sited to give a representative record of the surrounding climate. Thus, it is essential to re-examine the representativeness of such records before attempting to interpret the data for a different purpose.

In fact, the existence of guidelines for representative measurements is a double-edged sword from the perspective of climatological analysis of historical temperature records. On the one hand, many 'official' stations do not comply absolutely with the guidelines. The guidelines describe an 'ideal' site, but often the ideals compete with practical considerations, such as costs, accessibility, and security. In other cases, initial compliance may have occurred, but changes around the station (e.g. urbanization) may have changed the representativity over time. Unfortunately, ancillary information to document aspects of the station's surroundings is often non-existent, making assessment of representativeness after the fact, an impossibility.

On the other hand, if only the records from stations proven to conform to the guidelines for representativeness were used in climatological analyses, we would then have a historical record of climate over 'flat, regularly mown grass,' but as the earth is composed of many surface types, other than 'flat, regularly mown grass', such records cannot provide a representative 'global average.' Clearly, it is desirable to obtain temperature records from all kinds of different environments, including urban areas, forests, and mountainous regions, despite the inherent difficulties in making representative measurements there.

The central focus of this thesis is the problem that arises when the representativeness of individual climate stations changes, abruptly or gradually, and then temperature records from these stations are used to describe regional or global scale climate change. Thus, a change in representativeness, is an important consideration in the assessment of climate data homogeneity, which is the subject of the following section.

2.2 Homogeneity

2.2.1 Definition

Attempts to identify temporal changes in climatological time series are limited by problems of homogeneity of the records. Conrad and Pollack (1962) define a homogeneous time series as one in which variations are caused only by weather and climate. Since it is almost impossible to assess the homogeneity of an individual time series, the concept of 'relative homogeneity' is also important.

> A climatological series is relatively homogeneous with respect to a synchronous series at another place if the differences (or ratios) of pairs of homologous averages constitute a series of random numbers that satisfies the law of errors (Conrad and Pollack, 1962).

In other words, true regional- to global-scale climatic changes should be reflected in neighbouring station records in the same way, whereas differences between stations must be due to peculiarities at one of the individual sites. In the absence of good quality information (meta-data) about a climate station's operations or changes in its surroundings, relative homogeneity assessment is often the only means of sorting out 'real' and 'artificial' components of a climate record.

The longer a station has been in operation, the more likely the possibility that it has been subject to some discontinuity, or non-climatic influence, in its observed record. For example, gradual changes in instrument calibration over time, replacement of old, or broken instruments, 'weathering' of the thermometer screen followed by repainting, and changes around a climate station site all contribute to apparent changes in the record, which could potentially augment, offset, or completely obscure 'real' changes in the climate itself. Thus the ability to detect inhomogeneities is crucial to climate studies attempting to infer climate change from instrumental records.

Mitchell (1953) presented a comprehensive framework for the classification of potential causes of secular changes in surface-temperature records. He classified potential causes of temperature change into two groups: real and apparent. The 'real' category is further classified into local effects, direct climatic effects, and other 'indirect' climatic effects. Although Mitchell's (1953) work pre-dates present-day concerns about the detection of 'Global Warming', the issues raised are still relevant to modern analyses.

Many 'non-climatic' factors causing discontinuities, or inhomogeneities, have been addressed in recent attempts to compile high quality global databases. The following discussion is not an attempt to provide a comprehensive review or critique of all of the work which has been done to identify inhomogeneities in climate records, but rather to update Mitchell's (1953) overview with more recent work on this topic. It also identifies crucial omissions in past considerations of homogeneity analyses, and these will form the basis of the present thesis. The discussion is structured to consider potential biases in temperature records at increasing scales from the measurements and instruments themselves, up to the influence of the surrounding environment. Thus, the focus of the following discussion is to clarify the nature and cause of biases in temperature observations, rather than the purely statistical manifestation of these biases in the resulting temperature records.

2.2.2 Sources of inhomogeneities in air temperature records

i) Methods of observing and data handling

Errors in observing, recording, and processing data are inevitable. Many of these errors are often caught early by quality control checks (e.g. misplaced decimals, transposed numbers). Others, such as improper rounding of decimals are unrecoverable, and can only be assigned a potential error margin. Other problems have been noted due to the conversion between Fahrenheit and Celsius scales (Guttman, 1998).

A significant methodological error to affect a majority of records, at least in the United States, was a change in the method of computing mean daily temperatures. While mean daily temperature is generally calculated as (max+min)/2, originally, it was derived from spot readings (Mitchell, 1953). Mitchell (1953) estimates this may contribute possible errors of up to 2°F in a 100 year record.

Karl *et al*, (1986) describe the 'time of observation' bias resulting from a change after 1940, when observers began recording the 24-hour max and mins in the morning, rather than at sunset. Karl *et al.* (1986) estimate this bias to be on the order of 2°C, and developed a model to estimate the possible bias at any location. At principal stations across Canada, a similar observation schedule change occurred in 1961, when the definition of the reporting day changed from the 00Z-00Z to 06Z-06Z. This change is estimated to negatively bias annually averaged minimum daily temperatures by 0.6 to 0.8°C in Eastern Canada, and by 0.2°C in Western Canada (Vincent and Gullett, 1999).

As DeGaetano (2000) reports, at volunteer climate stations, the observations schedule is determined for the convenience of the observer, and therefore biases are more difficult to identify. DeGaetano found up to 96 per cent of stations included in the monthly HCN data set have incomplete records regarding observation times. Bootsma (1976) also reported daily minimum temperature differences of 5°C or more, depending on the time of day when observations were made, which translated to differences of 1.7°C for the monthly mean minimum temperature.

Janis (2002) examined the effect of the time of observation bias on daily temperature records. Although large temperature differences did occur in a few circumstances, Janis (2002) contends that correcting daily temperature series should be avoided, since the magnitude of the bias depends on the specific observation schedule, as well as the particular weather conditions that lead to the error (e.g., a morning observation of minimum temperature could experience a positive or negative bias depending on whether a cooler day preceded a warmer day or vice versa). Janis (2002) presents a technique for identifying those situations in which the time of observation bias is most likely to occur.

ii) Instrument Biases

Mitchell (1953) estimated changes in thermometer calibration over time to contribute to an increase of slightly less than 1°F per100 years, and thermometer replacement to be on the order of ±0.3°F.

More recently, many national weather services have replaced mercury-in glass thermometers with electronically recording temperature sensors. Quayle *et al.* (1991) estimated positive biases in large-scale averages of 0.4°C for maximum temperatures, 0.3°C for minimum temperatures and 0.7°C for mean diurnal temperature range, but only 0.06°C for mean daily temperatures, caused by nearly one-half of the US National Weather Service stations replacing liquid-in-glass thermometers with thermistor-based sensors in different housing. Gall *et al*, (1992) and Kessler *et al.* (1993) subsequently reported errors at individual stations of 1 to 2°C in maximum temperatures as a result of a design error in the new housing which prevented proper aspiration rates of the sensor. Biases caused by instrument housing will also be discussed in a following section.

Guttman and Baker (1996) examined biases introduced by replacing 'conventional' measurements (HO-83 hygrothermometer) at most stations reporting hourly observations in the US with automated observing systems using model-1088 hygrothermometers. A comparison of 10 stations running both systems in parallel suggested a potential negative bias of a few tenths of a degree Fahrenheit (larger in the daytime) caused by the introduction of the automated systems. However, results also showed that this bias was minimal compared to potential biases of 'a couple of degrees' caused by siting differences, which could be either positive or negative. Siting problems are discussed in more detail in a following section.

iii) Thermometer Screen Errors

(a) **Type of screen**

The use of screens or shelters to house temperature sensors is necessary to provide protection from the elements, and to prevent direct solar radiation from falling on the sensors causing the sensor to register a temperature much higher (up to 25 K; WMO, 1996) than that of the surrounding air. However, the presence of the shield itself alters the micro-climate around the sensor. If the shield is warmed by solar radiation, it acts as an additional source of radiation to the sensor, and can also warm the air inside the screen, relative to the surrounding outside air. Such errors can be minimized if the ventilation of the screen is adequate. However, under most conditions, adequate ventilation can only be achieved by the use of artificial aspiration, which is not available at many climate observing stations. Therefore, most thermometer screens in use are capable of introducing errors into the observed air temperature.

The problem of thermometer screen design has received considerable attention dating back to the Strathfield Turgiss experiments which compared 13 different types of thermometer screens (Gaster, 1879). The motivation for modern research in this area has been partly due to the recognition that a wide variety of instrument exposures were in use before the Stevenson screen became widely adopted in the early 1900's, and therefore the continuity of the historical record is in question as a result of these changes. Furthermore, recent changes to automated systems and the high cost of Stevenson screens has led to comparisons of a variety of new screens in an attempt to avoid the introduction of further discontinuities to the record when these new systems are adopted throughout networks.

Sparks (1972) surveyed the variety of thermometer screens commonly used around the world, and summarized aspects of screen design and exposure that affect the measurement of air temperature. The following features were identified as important considerations: colour and material of the screen, exposure (e.g. location, including height above ground), non-uniformity of temperature within the screen, and thermal inertia, or 'lag' of response. The Stevenson screen was shown to have a number of defects including overheating in bright sunshine, with the resulting size of errors depending on both wind speed and direction, artificial cooling of the air when the louvres get wet, and problems with blockage of louvres and reflection from snow in colder environments. (Also see Sparks, 1970 for a summary of studies reporting errors in Stevenson Screen temperature measurements). Kiel (1996 *in* Strangeways, 1999) reported that simply painting an old screen could lower temperature measurements by 1°C.

Andersson and Mattisson (1991) investigated 7 screens (2 types of Stevenson screens, new and old, and 3 commercially available designs with different mountings) Comparisons with an aspirated Teledyne screen (reference) for a period of 1 year were made. In general, they found errors due to thermal inertia of the screens and radiation errors. Although extreme differences of 3°C were occasionally observed, average differences over months or longer periods were of the same order as the measurement accuracy. The larger, wooden screens deviated the most from the reference, with the largest errors observed in the old screen in poor condition. Above wind speeds of 1 m/s, and during cloudy periods, differences between screens tended to zero. However, during calm winds and clear skies, all screens averaged 0.5°C too high during the day, and 0.5°C too low at night compared to the reference, with extreme values of 3.0°C and -2.0°C occurring at sunset and sunrise. Andersson and Mattisson (1991) also summarize their results for characteristic weather types occurring at the location of their study in Sweden. It is important to note that such errors are not generalizable to other locations.

Chenoweth (1992) attempted to estimate biases in the US historical record caused by early unscreened 'north wall' exposures of thermometers which were common before the introduction of the 'Cotton Region Shelter' (CRS), a screen similar to the Stevenson type. Temperatures were observed several times daily for nearly 3 years. His results indicated that the CRS screens measured average annual temperatures 0.5°C warmer than the north wall exposure, mainly due to differing radiation regimes. The differences had an annual cycle, with the CRS being warmer from October to April, and cooler from May to September. Minimum temperatures averaged over the year were no different for either exposure, while maximum temperatures averaged 1.0°C higher in the CRS than the north wall.

For a shorter period, a second identical CRS was placed in the back yard near the north wall exposure. This comparison showed that proximity to the building was a more important cause of temperature differences than the exposure of the thermometers. A 'heat island' of 0.4°C was responsible for warmer temperatures observed in the summer, particularly at night, in the vicinity of a brick house compared to the open CRS. The difference was negligible in the winter.

Parker (1994) documented historical changes in thermometer screens around the world, and summarized typical seasonal and annual effects caused by these changes. Results vary with the location, and specific type of screen. The largest warm bias of 0.4°C in the mean annual temperature was identified for tropical locations due to thermometer exposure inside thatched sheds in the early days. In some locations, seasonal errors tended to cancel in the annual mean. Parker (1994) also noted significant effects on the diurnal temperature range caused by the introduction of new screens, with a tendency for the diurnal range to be reduced by the introduction of Stevenson screens in most locations, except where the change was from north wall exposure, as indicated by Chenoweth (1992).

Nicholls, *et al.* (1996) documented regional changes in Australian thermometer exposure, and indicated that the introduction of Stevenson screens in Australia probably created an artificial drop in observed temperature. However, Hughes (1995) cautions that the records used by Nicholls *et al.* (1996) also contained other discontinuities in the form of instrument deterioration and site moves, which casts doubt on their conclusions.

Nordli *et al.* (1997) reviewed the problem of thermometer screen changes in Nordic countries. They noted the following biases in monthly mean temperatures: 0.2 to 0.4°C summer warm bias caused by single louvred screens compared to double louvred; up to 0.3 °C warm bias in wall-screens compared to open locations in summer (no effect in winter), and no significant difference due to new automatic sensors compared to free-standing screens. Effects on maximum and minimum temperatures were not considered.

Lefebvre (1998) and van der Meulen (1998) describe intercomparison studies of several modern sensor shields (aspirated and unaspirated) in order to determine what effect a change to these screens would have on the continuity of climate records. The results vary from study to study, but in general, the 'cup-like' screens, such as the Vaisalla, tend to behave most like the Stevenson screen. Not surprisingly, aspirated screens perform the best, and the higher the rate of aspiration, the better, in terms of avoiding radiation errors. However, these studies indicate that discontinuities in the climate record are caused when these newer systems replace existing Stevenson screens, with biases varying from site-to-site.

In a WMO report Barnett, *et al*, (1998) conclude that modern screens represent air temperature in a more realistic way than traditional wooden Stevenson screens, but that they undoubtedly introduce discontinuities into the record. Barnett *et al.* (1998) also noted the significance of solar elevation and azimuth angle in explaining radiation errors. The largest errors were seen when the solar radiation is aligned in the same direction as the wind (i.e. the heated surface is upwind of the thermometer), and when high insolation occurs with low wind speeds. Clearly, the effect of changes in screen design on the continuity of climate records varies with the climatic regime, as well as with the peculiarities of the individual site and exposure. Thus any changes in instrumentation and shelter must be done with side-by-side comparisons of the new and the old system if the errors introduced by such changes are to be known. Barnett *et al.* (1998) also noted that despite a large number of studies attempting to quantify thermometer-screen errors, the lack of uniformity in methodology, and inadequate consideration of the effects of local climate, ground reflectivity and wind conditions prevents generalization of the results.

In general however, the foregoing results indicate that changes in screen design do introduce discontinuities into the climate records but, often, the positioning of the instrument within the screen and the relative location of the screen itself are at least as important as the screen design.

(b) **Placement of thermometer within the screen**

This problem has received considerably less attention than issues of screen design. Parry (1962) showed that even with adequate ventilation inside a wooden screen (Cotton Region Shelter), there was as much variation horizontally within the screen itself as between the inside and outside of the screen (differences of up to 0.7°C inside the screen were observed, comparable to results reported in Sparks 1972). Other studies have noted vertical differences within the screen of 0.2°C (Sparks 1972). Lin and Hubbard (1996) have also investigated temperature variations within thermometer screens.

iv) Siting biases

Although the question of biases in temperature records due to screen design has been recognized for some time, it is a problem that is somewhat manageable because changes between screen designs tend to have occurred around the same time within individual countries, and such changes are often documented. Unfortunately, the same cannot be said for biases introduced by the siting of the screens themselves. While there are, and have always been, guidelines suggesting proper siting and exposure of climate stations, the potential sitings of screens are as numerous as the number of climate stations themselves, and often, although conformity with the official guidelines is assumed, deviations from the guidelines, and exact details of the true siting characteristics are not readily known. Furthermore, this particular problem has received less research attention and is often therefore overlooked in the assessment of homogeneity of records. It often emerges as a footnote to research into other problems where it is revealed that microclimatic differences between sites are often as important as the problem under question (e.g. Guttman and Baker, 1996; Chenoweth, 1992).

This problem manifests itself in two ways in long-term climate records. The first is biases introduced when a station is physically moved (e.g. from roof-top to ground, from city to airport), and the second is the introduction of biases caused by physical characteristics of the site itself, particularly if these characteristics change over time.

(a) **Station Moves**

The longer a station has been in operation, the more likely is the possibility that the instruments have been relocated at some point in the station's history. Ideally, records of any relocations and parallel observations at the old and new sites would allow identification of the exact timing and magnitude of correction which might be needed to maintain continuity of the record. Unfortunately, the need for such information becomes evident only years later, when obvious jumps in the station record are detected.

Often, station moves will affect each station individually, depending on the relative differences between the old and new sites. However, some network wide changes have had more far reaching implications. For example, it was common practice in the United States to place temperature sensors on roof-tops rather than at ground level, but there was a gradual relocation of such roof-top stations down to the ground surface. Also in the US, a large number of urban stations were relocated to airports in the 1940s and 50s, which likely produced an apparent 'cooling' as a result. Station moves introduce abrupt jumps into the record and modern homogeneity analyses are usually able to identify this type of discontinuity.

(b) Station Surroundings

Although it is widely recognized that a station's surroundings can bias the observations made there, such influences are extremely difficult to quantify. WMO, and most national weather service guidelines for siting new stations are intended to ensure that siting biases are avoided, that is, that observations are representative of the climate of the surrounding area, not just the site itself. Problems with the guidelines with respect to representativeness for climatological purposes were noted in the preceding discussion of representativeness.

A confounding problem is that changes over time in the surrounding environment introduce biases to long-term records at stations which may have been ideally sited when first installed, but which have grown to become unrepresentative. Such biases are particularly problematic because they tend to introduce gradual changes, or trends in the record which are indistinguishable from true climatic trends, and which are difficult to detect with even modern statistical tests for homogeneity.

Problems of this nature range in scale from the growth of a single tree next to the thermometer screen, to large scale urbanization around a climate station. Although 'urban biases' in temperature records are generally considered to be more significant than 'minor' changes around a station by most who have considered the homogeneity of long term records, it is clear that seemingly insignificant changes at individual sites are capable of introducing significant biases.

Mitchell (1953) gave possible error estimates of up to 1°F/100 years in the mean annual temperature caused by 'local growth of foliage', and errors of 0.5 to 1.3°F caused by building and pavement construction. While there have been few specific studies to estimate the potential biases in long-term temperature records due to site changes other than large-scale urbanization, there is evidence to suggest that seemingly minor site changes close to the station itself are potentially just as important as larger-scale changes farther from the site.

For example, Hogg (1949) reported an average increase of 0.4°F in winter minimum temperatures after two glass houses were erected 66 feet away from the Stevenson screen. Norwine (1973) showed air temperatures around an isolated shopping complex (a large building and parking lot) were as much as 4 degrees Fahrenheit greater than the surrounding rural areas. Manley (1974) suggested that the relative warming of the long-running Radcliffe Observatory temperature record compared to other more rural sites (about 0.4°F in mean minimum temperatures), was probably due to the gradual encroachment of buildings into the area surrounding the observation site, causing a notable impediment to outgoing radiation. Manley (1974) also mentioned evidence suggesting that changes in the proportion of ploughed to grassed land at the Rothamsted agricultural site had perceptible effects on climate observations made there.

As previously noted, while investigating differences between north-wall exposures and free standing screens, Chenoweth (1992) found that microclimate differences caused by the presence of a brick house were more important than the differences between thermometer exposures. A warming of 0.4°C in minimum temperatures was observed in the screen near the house, compared to an identical screen in a nearby open field.

Guttman and Baker (1996) also noted microclimatic differences over short distances between a low-lying swampy location and another next to a runway at an airport. The differences were largest during calm, clear nights, indicating the importance of cooling differences on minimum observed temperatures. They indicated 'siting' biases on the order of several degrees, which was more significant than biases due to changes from conventional to automatic observations.

In their guidelines for classifying stations, Météo France (1997) indicates that errors of at least 1°C can be expected when measurements are within 10-30 m of an artificial heating source, (building, parking lot) or water; at least 2°C errors within 10 m of a heat source; and 5°C or more when instruments are situated directly over the source.

Concerns about the location of many temperature observation sites at airports have also been raised. Extensive tarmac, buildings and waste heat from the jet engines are all potential warming influences. Kochar and Schmidlin (1990) found temperature differences of up to 6.3°F between Akron-Canton Regional Airport and its rural surroundings, with the largest differences occurring on calm, clear summer nights. Mays (1997) also found night winter temperatures observed at Willow Run Airport, Michigan, were slightly higher than those of the rural surroundings.

Although not directly related to problems of climatological observations of air temperature, further evidence of the difficulty to obtain representative air temperatures comes from the extensive theoretical and observational studies of advection. Although not reviewed here, evidence suggests that air temperatures can be affected at significant distances downwind of different surfaces: e.g. tarmac (Rider *et al.* 1963); irrigated vegetation (de Vries, 1959); crops/roughness changes (Munro and Oke , 1975); lakes (Antonioletti *et al*, 1980; Goulter, 1990); and isolated vegetation canopies (Taha *et al*, 1991). The problem of siting biases, and the microclimatic processes relevant to screen level temperature observations are considered in more detail in Chapter 3.

v) Urbanization

The extensive literature on the 'urban heat island' phenomenon has demonstrated that air temperatures within cities are often substantially warmer than their rural surrounds. The effect is due to a number of factors, including the replacement of natural surfaces and vegetation with artificial, impermeable, and heat storing materials such as concrete, as well as changing geometry of the surface by the addition of tall buildings, and the production of waste heat from human activities. In general, the more intense the urbanization or modification of the natural environment, the greater the warmth of the city. It stands to reason, therefore, that observations of air temperatures at a climate station which is surrounded by urban growth, will reflect a gradual warming over time. Many climate stations, particularly those with the longest running records, were initially sited in cities, or have had cities grow up around them during the course of their record. In the 1940s and 1950s, particularly in North America, many urban climate stations were relocated to airports outside the city to meet the growing demand for weather observations for aviation purposes. While these moves were initially to 'cooler', non-urban surroundings, many such airports have since been surrounded by built features. The possibility of warm biases in such temperature records is now widely recognized, although there is still much uncertainty regarding the magnitude of contamination of large-scale (hemispheric or global scale) average temperatures.

At the scale of individual climate stations, potential urban biases are undeniable, and readily demonstrated by comparing synchronous temperature records from nearby non-urban stations. Depending on the desired use of the record, its representativeness can then be judged. However, the difficulty of urban biases arises in the possibility that when thousands of individual temperature records are averaged together in hemispheric or global scale studies of climate change without *a priori* knowledge of each station's exact location, the entire average could be contaminated by urban warming biases.

The detection of such a bias is particularly problematic in climate change studies, because urbanization causes a gradual warming over time, which is exactly the signal sought after as evidence that 'global warming' is occurring. Secondly, because urban effects on temperature are typically largest at night, and often insignificant by day, urbanization is likely to have a much greater effect on minimum temperatures than on mean or maximum. Many recent studies have demonstrated that historical temperature records also display a similar pattern: that is, minimum temperatures are increasing at a much faster rate than mean and maximum (e.g. Karl *et al.*, 1984; Karl *et al.*, 1991; Karl *et al.* 1993a; Easterling and Peterson, 1995a). (Karl (1984) also found that the most significant trends in minimum temperature occurred in the summer months, which is also typically the time of year when urban heat islands are largest in midlatitude cities). While the authors of these studies believe that any significant urban bias has been removed from their compiled data sets, the previous discussion included evidence that even individual buildings can create 'heat islands' which influence temperatures (Chenoweth, 1992). It is clear that the threshold that defines 'urbanization' should be lowered significantly from the standards currently used to define it. A discussion of some recent methods to remove urban biases follows.

Dronia (1967) was one of the first to suggest that urban effects distorted the record of Northern Hemisphere temperatures. However, apparent methodological problems have led to concerns about the reliability of Dronia's (1967) conclusions (Jones *et al.* 1986a). Jones *et al.* (1986a & b) claimed to have compiled the first 'homogeneous' global data base of air temperatures. Because of the lack of available station history data, and the large number of records included, they assessed relative homogeneity of mean monthly temperature records by comparing neighbouring stations. They identified urban warming in 2% of the 2666 stations, mostly from North America, which they calculated to contribute to a 0.0087 °C per year bias. However, the fact that the neighbouring stations used to identify urban trends in this study could also contain urban biases probably led to an underestimation of the potential bias.

In comparing urban-rural station pairs, Kukla *et al.* (1986) concluded that North American cities warmed at a rate of 0.12°C per decade faster than their rural neighbours. In this study, the distinction between urban and rural sites was based entirely on population. Most of the 'urban' stations were located at municipal airports, with surrounding populations of more than 100,000, whereas 'rural' stations had populations, typically less than 7,000, but in some cases, up to 40,000. Their estimate, is again an underestimate of potential urban bias because of the possibility that some of the rural stations were also influenced by urbanization.

Karl *et al.* (1988) attempted to estimate the potential urban bias in historical temperature records by developing regression equations which related temperature change to population growth. Although they found detectable warming biases in small towns (populations less than 10,000), they concluded that the net effect of urbanization in the US Historical Climate Network was small (0.06° C in the 20th century for mean annual temperatures, larger for minima) in comparison to the total observed temperature change. Their conclusion was based on the fact that 85% of the USHCN stations came from settlements with populations of less than 25,000. Since then, these regression equations based on population have often been used a method of correcting large-scale temperature averages for urban-induced inhomogeneities (Karl *et al.*, 1991; Karl *et al*, 1993a; Easterling *et al*, 1996).

Population has also been used to differentiate between 'urban' and 'rural' records in attempts to demonstrate the magnitude of urban biases in large data bases (Jones *et al*, 1990; Peterson *et al.,* 1999). In these studies, it is assumed that a data base composed of 'rural' stations is free of urban biases, and therefore represents the true 'climate' record. However, when rural stations with local populations of up to 100,000 (Jones *et al.,* 1990) are considered 'unaffected' and therefore a suitable reference with which to compare urban stations, it is not surprising that the urban-affected, and 'rural' data bases are so similar.

Peterson *et al.* (1999) compiled a separate global data base of 'rural' stations to compare with the full Global Historical Climatology Network (Peterson and Vose, 1997) data set which presumably includes some urban bias. In this case, rural and urban stations were distinguished on the basis of population ('rural' is a population less than 10 000), land use classification on Operational Navigation Charts (1:1 000 000 scale) created by the US

Department of Defense, and the intensity of surface 'night lights' observed from satellites. As both 'rural' and 'urban affected' data sets showed similar climate trends, the authors concluded the GHCN time series "is not significantly impacted by urban warming," which supported similar statements of urban biases by Jones *et al*, (1990) and Easterling *et al*, (1997). However, Hansen et al. (2001) further classified stations into three categories based on nighttime brightness: urban, periurban and unlit. They found evidence of 'urban' effects on temperature records from "small town" stations, previously thought to be unaffected by urban warming.

The use of population as a reliable indicator of the degree of urbanization around a climate station is questionable (Oke, 1997; Changnon, 1999). Gallo *et al.* (1996) found that the land use within 100 m of a station was largely responsible for the observed temperature trends, although some influence of the effect of land use up to 10,000 m away was also detected. Furthermore, Bohm (1998) showed for the city of Vienna that, although the population remained constant, re-development in areas within the city led to increased energy consumption, changes in building density and form, and reduced greenspace. Significant temperature trends of 0.6 K in 45 years were observed in Vienna, but the value varied depending on the local surroundings of the site within the city.

Changnon (1999) compared temperatures observed at a rural agricultural research site to those from the nearby University of Illinois, which experienced rapid growth between 1890 and 1950. Over the 64 year period examined, temperatures increased 0.6°C at the university site, but only 0.4°C at the rural site. Changnon (1999) points out that the heat island effect of the university is much larger than would be predicted by Karl *et al.*'s population based method. Changnon (1999) also cautions that a residual urban bias may be present in HCN data set because many of the records were observed in small towns generally assumed to be free of urban biases.

Pielke et al. (2002) compared temperature trends at several stations in Eastern Colorado, using population as an indicator of surrounding urbanization influences. However, they found significant increasing trends in minimum temperatures at one site that, despite its 'rural' population, had a very 'urban-type' exposure. These analyses confirm that population is an inappropriate measure of the potential 'urban' bias in temperature records, and imply that the immediate surroundings of the station exposure are more relevant.

Knappenberger *et al.* (1996) examined temperature records from 15 'non-urban' airports across the United States. Because they observed consistent trends of a decreasing diurnal temperature range at all stations examined, the authors contend the trends cannot be the result of urbanization, since they selected their stations to avoid 'urbanization'. However, the authors make no note of the immediate surroundings of each station, and therefore their results may be more indicative of the effects of airport growth on temperatures, rather than strictly "urbanization". Clearly, it is not reasonable to draw conclusions about the causes of climate trends unless the exact nature of the climate stations surroundings are considered. Airport climate stations are just as subject to microscale warming biases as those surrounded by large-scale urbanization.

The compilers of recent 'homogenized' data sets contend that their methods of correcting urban biases are adequate for large scale averages, but that urban biases would still be present in some local and regional scale analyses. This paradoxical position is difficult to understand. If individual records are themselves contaminated by urban biases because current methods for detecting them are inadequate, how is it possible to claim that large averages made up of such records are not biased?

The need to consider urban biases in temperature records from the perspective of the physical processes causing the biases is well illustrated by Camilloni and Barros (1997). These authors define a 'second urban bias,' in addition to the warming bias caused by urban growth, which apparently results from the negative correlation of urban-rural temperature differences and the rural temperature itself. That is, Camilloni and Barros (1997) contend that, during periods in which regional temperatures experience a warming trend, urban heat islands tend to be smaller, and therefore the urban bias in the record is smaller than during cooling periods when urban heat islands are larger. They claim that this 'second urban bias' therefore offsets the urban bias caused by urban growth during climate warming periods and augments it during cooling trends, making it more difficult to identify true climate change.

Camilloni and Barros' (1997) assertion that urban biases will somehow offset themselves as the climate warms, supports the notion that 'urban warming' is not responsible for the observed warming trends in historical temperature records. This conclusion is, however, incompatible with the basic fact that urban, or any other siting biases, are the result of the physical nature of the immediate surroundings of the measurement site itself. An unrepresentative observation is an unrepresentative observation: if a thermometer is located close to a heated building, the bias in the observed temperature will not 'disappear' if the regional climate warms. Camilloni and Barros' (1997) study, and others which attempt to describe urban biases in the absence of information about the measurement sites themselves, indicate that a demonstration of the importance of the physical processes responsible for the biases in temperature records is warranted.

2.3 Techniques for the detection of inhomogeneities in temperature records

The preceding discussion clearly shows that there are numerous potential sources of bias in long term temperature records, and that they must be carefully considered before a reliable interpretation of the records can be undertaken. Recognition of this fact has led to the development of numerous techniques for both the detection and correction of inhomogeneities in temperature records. Peterson *et al.* (1998) present a thorough review of many of these techniques being used around the world. Because the approach of the present thesis is the identification of inhomogeneities from the perspective of the physical processes causing them, rather than a purely statistical approach, the various statistical techniques of homogeneity adjustments will not be discussed in detail. Rather, homogeneity analysis will be discussed in general, with an emphasis on the strengths and inadequacies of modern approaches, in the context of the motivation for this research.

Undoubtedly the most valuable aid to the identification of inhomogeneities in climate records is the meta-data about the observations, if they exist. Station history files, inspectors reports, site maps, photos and detailed records of station moves, instrument, observer, or procedural changes can provide valuable insight into the exact timing of potential discontinuities in a station record. In the ideal case, the potential discontinuity may have been recognized ahead of time and appropriate measures may have been taken to ensure the continuity of the record. For example, if a station is moved, parallel measurements at both the old and new sites would give an indication of any differences introduced by the change in location. Unfortunately, this foresight is rare, and meta-data files are often lacking in appropriate detail, inaccurate, or non-existent, and fail to provide the necessary information to identify all potential problems in a record. Therefore, it is necessary to resort to other methods of identification of such discontinuities by examining the climate data directly.

Peterson *et al.* (1998) note that subjective judgment by experienced climatologists plays an important role at various stages of homogeneity analysis. However, it is impossible to judge the success of a subjective method which undoubtedly varies with the amount and type of experience of the individual.

The majority of modern approaches to homogeneity assessment are based on the principle of 'relative homogeneity' of Conrad and Pollack (1962), in which a candidate station's record is compared to neighboring station records, with the assumption that differences between the records are due to inhomogeneities at one of the sites. In the simplest case, such a comparison could take the form of graphing the candidate and the reference time series and visually comparing them for divergence. However, differences between stations are often more easily detected when cumulative sums of the record are plotted, or, when the differences of paired observations are plotted directly.

More common now, is the use of more sophisticated tests which can provide a statistically robust indication of significant changes in climatological time series. These methods also rely on the use of a reference time series which serves as a comparison for the candidate station. Thus, the success of such methods is entirely dependent on the choice of a reliable reference series. While some homogeneity analyses (Jones *et al.* 1986) relied on the intercomparison of several neighboring records to reveal major inhomogeneities, it has been suggested that the reliance on individual records as reference series places too much faith on the quality of individual records, and that a single composite series derived from several individual series would make a more homogeneous reference (Potter, 1981; Alexandersson, 1986; Peterson and Easterling, 1994). Keiser and Griffiths (1997) contend however, that it is uncommon to find enough suitable neighboring stations to create a composite series, and that the use of one station with high quality data as a reference is more realistic.

Another approach to the problem of inhomogeneities in the reference series is to create a first difference series, where the original time series is converted to a series of year-to-year differences (dT/dt) in an attempt to isolate the effects of potential discontinuities in only one year (Peterson and Easterling, 1994; Easterling and Peterson, 1995). Clearly this method is helpful for minimizing effects of discontinuities in the form of jumps (e.g. when a station moves, or an instrument is changed), but it cannot eliminate problems caused by trend inhomogeneities such as those resulting from gradual changes around a station. Peterson *et al.* (1998) discuss other methods aimed at minimizing or eliminating inhomogeneities in reference series.

The relative merits of individual techniques for the detection and correction of inhomogeneities in temperature records will not be discussed here. In fact, the merits of a particular approach can only be considered on a case by case basis. Peterson *et al.* (1998) outline approaches used in a number of countries, and it is clear that some techniques are better suited to particular problems depending on the amount and type of data available, as well as the resources available to perform the analysis. Peterson *et al.* (1998) also note that different techniques applied to the same data can lead to different results. Thus, there is no universally 'correct' method for dealing with inhomogeneities in climate records.

2.4 Implications for analysis of long-term temperature records

Those who use these techniques to detect and correct climate data in the compilation of large climate databases contend that the modern techniques are adequate to detect all major inhomogeneities which affect large scale climate averages. The fact that in large scale (hemispheric to global) averages, adjusted data sets are very similar to non-adjusted sets is used to support this contention (Easterling and Peterson (1995a); Peterson *et al.* 1999). In other words, any inhomogeneities undetected are insignificant when enough records are averaged together.

Nevertheless, the same researchers acknowledge that inhomogeneities at individual stations, or even in regional averages, can be significant and that, without correction, they can significantly alter the perceived climate trends. In general, the techniques used in homogeneity analysis of large data bases are inappropriate for smaller scale studies. While it might be argued that such statistical techniques are the best available solution to homogeneity problems in the absence of appropriate meta-data, or the inability to analyze detailed meta-data when thousands of stations are being considered, there are still a number of limitations inherent in previous analyses which raise concerns about the reliability of historical climate records.

While there is general consensus that the best (and presumably homogeneous) data indicate that the global mean temperature increased 0.4°-0.8°C in the twentieth century, there has been a recent shift in research focus towards examining trends in the frequency and intensity of extreme climate phenomena. The need for caution regarding the homogeneity of temperature records is perhaps even greater when 'extreme' values are interpreted.

Easterling *et al.* (1999a) note some of the problems associated with 'extreme' data including instrument changes and station moves (e.g. moving from a shaded to sunlit site could significantly increase the probability of extreme maximum daily temperatures being observed). Biases such as these may not be detected in monthly or annual mean records, but could certainly affect the frequency of days with temperatures exceeding a given threshold value. As many analyses of extreme temperatures are based on daily temperature values, or indices derived from them (Folland *et al.*, 1999; Jones *et al.*, 1999), the issue of the homogeneity of daily temperature records is paramount to the correct interpretation of such records.

Allen and DeGaetano (2000) corrected annual extreme threshold exceedences for inhomogeneities, but it is well recognized that detecting and correcting for inhomogeneities in daily records is a more difficult task. Vincent *et al.* (2002) homogenized daily maximum and minimum temperatures for Canadian stations, but inhomogeneities were first identified in annual data, and daily adjustments were interpolated from previously applied monthly adjustments. Many other studies of temperature extremes also rely on homogeneity tests of monthly data, (i.e. the methods described in Peterson *et al.*, 1998), assuming that if the monthly data pass the homogeneity test, then daily data can also be considered homogeneous. However, such assumptions may not be valid and, in fact, the opposite may be true: siting biases are probably strongest when extreme temperatures occur (e.g. calm clear nights allowing maximum cooling, or sunny days with strong radiative input).

Regardless of the underlying homogeneity (or lack thereof) of data analyzed, results of the numerous studies examining temperature extremes (e.g. Bonsal *et al.*, 2001 (Canada); Easterling *et al.*, 1999a (North and South America); Durre and Wallace, 2001, Knappenberger *et al.*, 2001, (USA); Serra *et al.*, 2001 (Spain); Horton *et al.*, 2001 (Central England and Globe); Tuomenvirta *et al.*, 2000 (Fenno-Scandia and Greenland); Salinger and Griffiths, 2001 (New Zealand)), arrive at a common result: daily minimum temperatures are increasing at a faster rate than daily maximum temperatures, and extreme 'cold' occurrences are becoming less common, while extreme hot events are either not changing, or increasing much less noticeably. (Regional and seasonal variations to this finding do occur, however.) Although most researchers dismiss inhomogeneities as the sole explanation for these trends, it is difficult to ignore the possibility that inhomogeneities, particularly those due to siting biases, may at least be contributing factors. Bonsal et al. (2001) summarize their findings as follows: "Canada is not getting hotter, but rather "less cold."" Discussions in Chapters 3 and 4 of this thesis examine the microclimatic processes relevant to siting biases, particularly their role in decreasing nocturnal cooling, demonstrating that siting biases are indeed capable of contributing to these "less cold" conditions.

The following section summarizes the considerations which form sufficient motivation for the present thesis.

2.5 Summary of points providing motivation for the present thesis

- A compilation of many records can be no more homogeneous than the individual records themselves. The fact that 'adjusted' and 'unadjusted' large databases agree (Peterson *et al.* 1999, Easterling and Peterson, 1995a) is no more an indication of the robustness of the large scale database than of the possibility that the 'adjusted' database still contains many undetected inhomogeneities.

- Although methods for detecting inhomogeneous trends in temperature series are improving (e.g. Alexandersson and Moberg 1997; Vincent 1998), non-climatic trends remain more difficult to identify than abrupt discontinuities. Gradual changes over time in a station's surroundings are likely to introduce trends in the climate record, and are therefore likely to escape detection. If a non-climatic trend is superimposed on a climatic trend of similar characteristics (such as when urban warming affects a record) it is difficult to separate the observed trend into its real climatic and 'artificial' components.

- Essentially all modern techniques are based on comparisons of test and reference stations. Although the problem of inhomogeneities in the reference series is acknowledged, it is possible that a candidate and its neighbouring stations could all be influenced by the same type of inhomogeneity (e.g. urbanization), which would not be detected by examining 'differences' between stations.

- Existing techniques are most successful at detecting inhomogeneities in smoothed time series, such as monthly, or annual averages, and any homogeneity adjustments are usually applied on the monthly, or annual series. However, few discontinuities are likely to manifest themselves uniformly throughout the year, or even over the whole day. Hence following the initial analysis of global temperatures by Jones *et al.* (1986), other studies examined maximum and minimum temperature trends (e.g. Karl *et al.* 1984, 1991, 1993a, Easterling and Peterson, 1995a). Keiser and Griffiths (1997) showed that necessary adjustments were significantly different when series of maximum and minimum monthly temperatures were analyzed compared to mean monthly temperatures. They suggested that substantial errors are introduced to a time series if these variations are not considered when homogeneity adjustments are performed.

- Potential biases introduced into a temperature record as a result of changes in the station's surroundings are generally considered insignificant in large-scale averages. However, as indicated in the preceding discussion, there is sufficient evidence to suggest that such assumptions of 'negligible' influence should be reconsidered.

- Climate station siting biases are likely to have a significant effect on extreme temperatures, and therefore studies which examine daily exceedences of thresholds or temperature indices are particularly susceptible to these kinds of influences.

- Previous considerations of biases resulting from 'station surroundings', especially urbanization, have used statistical approaches based on surrogate measures of potential biases (e.g. population, light intensity measured from satellite-borne sensors; Peterson *et al*, 1999), rather than more physically relevant measures of the characteristics of the sites themselves. Thus, a more thorough examination of station siting biases, giving consideration to the physical processes responsible for the biases, is warranted.

Therefore, the research which follows was undertaken to elucidate the nature of biases in historical air temperature records caused by the nature of the environment surrounding a climate station. This thesis seeks to demonstrate the magnitude of such biases in historical temperature records, and to indicate the potential impact of neglecting such biases in the analysis of historical temperature records.

Chapter 3
THE MICROCLIMATE OF CLIMATE STATIONS: THE PHYSICAL BASIS OF SITING BIASES IN AIR TEMPERATURE OBSERVATIONS

3.1 Introduction

In his classic text, *The Climate Near the Ground,* Rudolph Geiger, (1965) provides numerous examples of the incredible variety of microclimatic conditions that can occur over short distances as a result of variations in the near-surface physical environment. Geiger (1965) presents observations of significant air temperature differences arising from influences such as topography, soil type and treatment, proximity to water bodies, gardens, crops, orchards, vineyards, woodlands, and meadows. Yet, when it comes to assessing the homogeneity of historical air temperature records, conventional analyses all but ignore the microclimatic conditions around climate stations themselves, unless the station is situated in a major urban centre. The conventional thinking seems to be that as long as enough temperature records are averaged together, non-urban microclimatic biases will offset each other and allow the 'representative' global temperature signal to emerge. The purpose of the current chapter is to challenge this notion, by considering potential microclimatic biases in climatological records from a physical, rather than a purely statistical perspective. In particular, the microclimatic processes capable of influencing daily maximum and minimum screen-level air temperatures are considered.

The discussion which follows is intended to illustrate the kinds of thermal biases inherent to climatological temperature observations, rather than a comprehensive review. Illustrative examples of observed temperature differences or anomalies reported in published studies, along with the field observations described in Appendix 1 of this thesis are included as empirical evidence of the role of microscale influences on air temperatures. The majority of observational studies discussed here are based on simultaneous temperature differences between sites that have different site characteristics. It is assumed that these results are generally transferable to the case of temporal temperature changes at a single site whose physical characteristics change over time.

Because of the difficulty to obtain experimental control in field observations, observed between-site temperature differences are usually the result of many confounding influences. Mathematical modeling studies are useful in isolating individual influences, and therefore modeling results are included in this discussion to provide further insight into the role of surface controls.

The discussion of the physical processes is followed by a summary organized around the most common siting biases, and their probable effect on daily maximum and minimum temperatures.

3.2 A surface energy balance approach

Any given air temperature observation is the result of a variety of controls acting at many different scales. Thus, the task of separating microscale, or site-specific temperature influences from larger scale influences such as latitude, altitude, continentality, topography, and synoptic variability (air mass characteristics, cloudiness), to name a few, seems an onerous one. However, the role of site specific features can be demonstrated by considering their influences on the individual components of the surface energy balance. Thus, the discussion which follows is organized around the microclimatic processes relevant to the surface energy balance: radiation, convection, advection, evaporation, and the role of surface thermal properties.

The surface radiant energy balance can be expressed as

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \qquad (3.1)$$

where Q^* is the net radiation, K is shortwave radiation, L is longwave radiation, and down- and up- arrows indicate incoming and outgoing components, respectively.

An alternative expression for the surface radiation balance which clearly indicates the role of surface properties to the balance is

$$Q^* = (1-\alpha)K\downarrow + \varepsilon_o L\downarrow - \varepsilon_o \sigma T_o^4 \qquad (3.2)$$

where α is the surface albedo, ε_o is the surface emissivity, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and T_o is the surface temperature (K).

The simplest form of the surface energy balance is

$$Q^* = Q_H + Q_E + Q_G \qquad (3.3)$$

where Q_H is the sensible heat flux, Q_E is the evaporative heat flux, and Q_G is the ground heat flux. In certain situations, additional terms must be included in the balance to account for additional energy sources and sinks such as artificial heat sources, positive or negative storage (in the ground or within air volumes), energy used for photosynthesis, or energy used or released in melting or freezing. The role of site specific features is not obvious in this expression of the surface energy balance, but characteristics such as surface roughness and its influence on wind speed and turbulent mixing, near surface temperature and moisture gradients, surface moisture conditions, and surface thermal properties, determine the partitioning of Q^* into the different energy forms, thereby influencing the resulting microclimate and air temperature.

3.3 Radiative Processes

3.3.1 Shortwave radiant energy

The amount of shortwave radiation received at a site depends on latitude and time of year, atmospheric characteristics and weather (especially clouds), as well as the angle of the receiving surface with respect to the direction of radiation. Site specific controls on the net solar radiation relevant to climate station siting include shading effects and surface albedo characteristics. While the input of solar radiation is clearly linked to daytime temperatures, the amount of storage during the day also affects nocturnal cooling, so the receipt of shortwave radiation has an effect on both maximum and minimum daily temperatures.

(i) **Shading**

The receipt of shortwave radiation can be reduced by obstructions that fully, or partially block incoming solar radiation (e.g. walls, buildings, trees). A reduction in incoming radiation is capable of reducing both daytime, and nighttime temperatures.

Myrup *et al.* (1993) measured solar radiation and air temperature differences between four suburban sites and an unobstructed rural reference site during the summer at Davis, California. They found a strong correlation between the suburban-rural differences (both temperature and radiation) and the canopy height at the suburban site, with all sites showing maximum temperature differences compared to the control site in the morning and evening, (i.e. when shading is more significant due to the solar angle). Myrup *et al.* (1993) also concluded that the increase in turbulent mixing due to canopy height played as important a role in temperature differences as the shade effect (See section 3.5 (i)), sometimes producing positive temperature anomalies. Because the shaded sites were 'suburban' other site characteristics such as the proportion of paved surfaces, and the local urban influence would also contribute to the observed temperature differences.

Bogren *et al.* (2000) compared daytime road surface temperatures between sun-exposed and 'screened' sites in Jönköping county, Sweden. The shading was caused by vertical walls of a rock-cut that the road passed through. They found surface temperature differences of up to 13°C, depending on meteorological conditions and the solar altitude (i.e. temperature differences increased with the solar elevation). They did not report air temperature differences for the same sites.

Bogren *et al.* (2000) also studied the screening effect under different cloud conditions. The increased proportion of diffuse radiation under cloudy skies might be expected to reduce the shading potential and the resulting temperature differences. They found that for up to 3-octas of cloud cover, sun-lit and shaded surface temperature differences were approximately the same as for clear skies, and that surface temperature differences were still significant when 4-6 octas of cloud cover were present. Surface temperature differences were still detectable (approximately 2°C) under complete cloud coverage . The effect of clouds on the shading potential was most significant with greater sun elevations. It is significant to note that shading influences on surface temperatures are nearly always present, that is they are not exclusively a clear sky problem.

Bogren *et al.* (2000) also found evidence suggesting that screening of solar radiation in the daytime reduced nighttime surface temperatures because less heat was stored during the day to offset the nocturnal cooling. However, they note that variations in surface thermal properties may also have contributed to the nocturnal temperature differences. Their results indicate that because of the complex topography of their particular study area, cold air ponding is more significant to nighttime temperature differences than the influence of daytime shading.

While solid objects such as walls and buildings completely obstruct the receipt of direct shortwave radiation for certain periods of the day (depending on the geometry in relation to the sun angle), shading from vegetation is slightly more complicated because some solar radiation is transmitted, and the shading potential varies seasonally with the amount of foliage present, and between coniferous and deciduous species. Heisler (1986) measured the reduction in solar radiation received on a vertical wall due to shading by individual trees. It was noted that reductions on horizontal surfaces are expected to be slightly higher. Results varied depending on the species of tree, and with the orientation of the sun with respect to the receiving surface. Radiation reductions of up to 80 percent when the trees were in leaf, and up to 40 percent for leafless trees were reported. These results demonstrate that shading by trees is not only a summertime phenomenon, but that significant reductions in solar radiation can also occur for some species, even when the trees are leafless.

The above discussion implies that shading of a climate station site would reduce the daytime maximum air temperature, and may also slightly lower nocturnal temperatures. It should also be noted that shading of the Stevenson Screen, and the instruments within, will reduce the radiation errors of the measurement by preventing radiation absorption and subsequent warming of the instrument shelter. This effect of shading would augment the cooling (or warming) of the site itself when shade increases (or decreases).

It is possible in some cases, that an object providing shade at certain times of the day may actually reflect solar radiation towards the surface at other times, thereby partially offsetting the shading effect. (e.g. an east facing wall to the west of the site would reflect solar radiation in the morning, but block the afternoon receipt of K↓). However, the net effect of shading will be a reduction in solar radiation compared to an unobstructed site, leading to lower maximum and minimum temperatures.

(ii) Albedo

The role of the surface albedo (defined as the proportion of incident solar radiation that is reflected by the surface) in determining the microclimatic characteristics of a site is fairly straightforward: the higher the albedo, the less solar radiation absorbed, and therefore the lower the energy status of the environment. Hence, if the albedo of a site increases over time, temperatures are likely to decrease, and vice versa.

The recommended surface cover for climate station siting is short grass, having an albedo value of approximately 0.26. Albedos of other surfaces likely to be found in the vicinity of climate stations are listed in Table 3.1.

Table 3.1 Surface albedo values (Sources: Oke, 1987, Campbell and Norman, 1998)

Surface	**Albedo**
Short grass surface (0.02 m):	0.26
Grass, 1 m:	0.16
Agricultural crops :	0.18-0.25
Deciduous forest	0.10-0.20
Coniferous	0.05-0.15
Soil wet, dark:	0.05
Soil dry, dark:	0.13
Soil, wet light	0.1
Soil dry, light:	0.18
Asphalt:	0.05-0.20
Concrete:	0.10 -0.35
Brick:	0.2-0.4
Stone:	0.2-0.35
Tar and Gravel roofs:	0.08-0.18
Window glass:	0.08-0.52 (depending on zenith angle)
Snow fresh:	0.95
Snow, old:	0.4

Many of the site conditions that commonly occur around climate stations appear to reduce the overall albedo, creating a potential warming bias in the temperature record. Examples of typical surface conditions around instrument sites include muddy conditions when the site is first established, construction of asphalt, concrete, gravel or wooden walkways to the instruments; unchecked growth of grass surface; growth of shrubs and trees; encroachment by roads, parking lots, and runways and taxi-ways, and buildings. The presence of snow can significantly increase the surface albedo, but as observers repeatedly walk to the instruments, trampling and dirtying of the snow will reduce the albedo compared to a pristine 'fresh' snow surface, and likely lead to earlier melting (or a shorter snow-covered period). Also, surrounding roads and parking lots are likely to be cleared of snow, decreasing the albedo of the surrounding area.

Because of the effect of surface albedo on the overall energy status of the surface, changes to this variable are likely to affect daily maximum and minimum temperatures in the same way: that is, reduced albedo values will lead to warming of both daytime and nighttime temperatures, although the magnitude of the effect will be largest during the daytime.

Hopkins (1977) examined minimum temperature differences between similarly exposed stations in East Anglia, UK. He found that temperature differences increased linearly with distance between stations (at an average rate of 2°C per 80 km), however additional variances of 1°C resulted from albedo and soil property differences between the sites.

3.3.2 Longwave radiant energy

(i) Skyview factor

The loss of longwave radiation by the surface at night causes surface cooling. The minimum temperature that occurs at the end of the night, is therefore a function of the nocturnal radiation deficit, which in turn is strongly affected by the geometry of the site characteristics, or the skyview factor. Objects in the surface's field of view, such as buildings and trees, will reduce the net-loss of longwave radiation and therefore limit the amount of cooling compared to an unobstructed site with a skyview factor closer to 1.

A reduction in skyview factor as a result of urban structures is recognized as one of the fundamental causes of the urban heat island (the increased warmth of urban areas compared to their rural surroundings), but even small reductions in the skyview factor from a single tree or building can have detectable effects on nocturnal temperatures. Oke *et al.* (1991) used a simple 1-D energy balance model to determine the role of skyview factors in generating nocturnal surface temperature differences for calm cloudless conditions. Surface temperature differences relative to an unobstructed surface ranged from 1.1°C to 5.2°C for skyview factors of 0.8 and 0.2, respectively. It is expected that air temperature differences would follow the same pattern, but be smaller in magnitude.

Taha *et al.* (1991) reported nighttime screen-level air temperatures within an orchard in Davis, California were 1 to 2°C higher than in nearby open fields. They attributed the relative warmth to the reduced skyview factor amongst the 5 m high trees.

Any encroachment on the instrument site by buildings, walls, fences or other obstructions, as well as vegetation growth is likely to introduce a warming influence to the minimum daily temperatures observed at that site as a result of reduced nocturnal surface cooling. The daytime impact is less significant relative to solar shading, but should reduce net longwave radiation.

(ii) Surface Emissivity

The expression of the radiation balance in equation 3.2 indicates that the surface emissivity, ε_o, is also important to the surface net radiation. Because the range of surface emissivity values for most natural, and many artificial surfaces is relatively small (typically 0.90 – 0.98), emissivity changes over time would not be expected to contribute to large temperature changes. Oke *et al.* (1991) modeled the effect of emissivity variations from 0.85 to 1 on nocturnal surface temperatures, and found the effects were on the order of less than 0.5°C. Again, the impact on the air temperature would be less.

3.4 Surface thermal properties

Soil microclimates are influenced by a number of thermal properties including heat capacity, thermal conductivity, and thermal diffusivity. However, thermal admittance is the most appropriate thermal property to consider with respect to surface temperature variations. Defined as the ability of a surface to accept or release heat in response to a change in heat flux, and calculated as the square root of the product of heat capacity and thermal conductivity, thermal admittance plays a key role in the diurnal variation of temperature, and in setting the maximum and minimum values. That is, surfaces with high thermal admittances are less thermally responsive, because heat input during the day is readily accepted without a significant increase in surface temperature. At night, when the surface loses longwave radiation, a large thermal admittance allows stored heat to be released, limiting the amount of surface cooling.

Urban-rural thermal admittance differences have been shown to contribute to the nocturnal urban heat island, by affecting the surface cooling rates in both environments (e.g. Goward, 1981; Oke, 1981; Arnfield, 1990; Oke *et al*, 1991; Runnalls and Oke, 2000). Most construction materials (asphalt, concrete, etc.) have large thermal admittances, while admittances of 'natural' surfaces vary depending on soil composition, soil moisture content, pore space, vegetation cover, and snow cover. Typical values are listed in Table 3.2.

Table 3.2 Thermal admittance values for different surfaces ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$). Sources: Oke, 1981; Oke 1987.

Surface Material	**Thermal admittance Typical values/ ranges ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$)**
Sandy soil, 40% pore space	
Dry	620
Saturated	2550
Clay soil, 40% pore space	
Dry	600
Saturated	2210
Peat soil, 80% pore space	
Dry	190
Saturated	1420
Rocks	1700 –3400
Snow	
Fresh	130
Old	595
Water (20°C)	1580
Air, 10°C	
Still	5
Turbulent	390
Building Materials	
Concrete	150 -2370
Asphalt	1230 –1680
Brick	1070
Stone	2220
Glass	1110
Wood	200-540

If the surface thermal admittance around a climate station increases over time, a smaller diurnal variation in temperatures would result: that is lower daily maximum and higher daily minimum temperatures would occur. Increases in thermal admittance would occur with the addition of construction materials, compaction of the soil due to trampling, increased soil moisture, decrease in vegetation height, or vegetation removal, and trampling or compaction of snow surfaces. Decreases in thermal admittance, and subsequent increase in daily maximum/decrease in daily minimum temperatures would be expected with a decrease in soil moisture or growth of vegetation.

In the study mentioned above (section 3.3.2 (i)), Oke *et al.* (1991) modeled the effect of thermal admittance differences on surface cooling for calm clear nights. A range of thermal admittances were modeled to represent typical urban and rural surface materials. Their results showed that, following a twelve hour cooling period, the between-surface temperature differences were greater when the absolute value of thermal admittance was low. (e.g. surfaces temperatures with thermal admittances of 600 J m^{-2} $s^{-1/2}$ K^{-1} and 1000 J m^{-2} $s^{-1/2}$ K^{-1}, differed by 2.6 °C at the end of the cooling period, compared to a 0.8°C difference for thermal admittances of 1800 J m^{-2} $s^{-1/2}$ $K^{-1}$and 2200 J m^{-2} $s^{-1/2}$ K^{-1}).

In the context of climate station site influences, these results imply that small changes to the thermal admittance at a site where the thermal admittance is low (e.g. dry soils, snow), would have a greater impact on the temperatures than the same relative change in thermal admittance where the original value is higher (e.g. moist soils, bare rock). Thus, the addition of a concrete sidewalk leading up the instruments would have a larger effect on the observed temperatures at a dry site than at a moist site for two reasons: the absolute thermal admittance change would be larger at the dry site, and the low thermal admittance of the dry site is more sensitive to the change.

As mentioned, thermal admittance is a strong control on surface temperatures, and it is assumed, that under the calm, stable nocturnal conditions, the surface cooling has a strong influence on the temperature of the near surface air as well. Zdunkowski and Trask (1971) modeled surface and screen-level nocturnal cooling for four different soil types, for calm conditions. Their results showed that following 8 hours of cooling, screen-level air above a quartz sand had cooled 9°C more than air above a rocky soil, compared to a 12°C difference in surface temperatures. These results indicate that surface thermal properties at climate stations are a significant control on nocturnal cooling and therefore on minimum daily temperatures, particularly under calm conditions.

Oke *et al.* (1991) examined the combined effects of thermal admittance and surface geometry (skyview factors), and found the resulting surface temperature differences were equally sensitive to both controls.

Although the surface thermal admittance affects both warming and cooling rates of the surface, its influence is most pronounced on the nocturnal cooling phase, particularly on calm clear nights, because inversion stability concentrates effects in a shallow layer of air. Thus, it is anticipated that changes to the thermal admittance around climate stations would have the greatest effect on minimum temperatures occurring at the end of the nocturnal cooling period. Increases in thermal admittance are likely to reduce the amount of cooling, leading to increasing minimum temperatures.

3.5 Convective processes

The foregoing discussions have identified significant site controls on surface temperatures and it is assumed that screen-level air temperatures would be well correlated to the surface temperatures. While air temperature variations are largely the result of surface forcings, convective processes essentially determine how well the surface and air temperatures are linked. The relative proportioning of net radiation into sensible and latent heat forms (Q_H and Q_E), the degree of convective mixing in the air, horizontal advection of relatively warm or cool air, down-slope drainage and artificial sources of heat are all significant to screen-level air temperatures, and are also significantly influenced by site characteristics.

(i) Evaporation

If surface net radiation, Q^*, is preferentially channeled into latent (Q_E), rather than sensible heat (Q_H), less energy is available to heat the air. This partitioning is determined by the availability of moisture at the surface, but also by the air-surface moisture gradients, and the degree of convective mixing. For example, Myrup *et al.* (1993) found that increased turbulent mixing due to surface roughness elements brought relatively dry air down to the surface, and enhanced evaporative cooling of the air, compared to sites with less surface roughness, and therefore less turbulence.

The presence of vegetation also influences the evaporative flux at a site. Souch and Souch (1993) found temperature reductions of 0.7 to 1.3°C close to individual trees compared to an open site in the summer time at Bloomington, Indiana. Temperature differences were greatest in mid-afternoon, and least in early morning. While part of the observed cooling is attributable to shading effects, humidity measurements made at the same time (indicating increased vapour pressure near the trees) imply that increased transpiration by the tree was partly responsible for the lower air temperatures.

Heilman and Gesch (1991) studied potential cooling effects of turfgrass evaporation on external building temperatures in Texas, to determine if microscale evaporation exerted a noticeable cooling effect on surrounding air temperatures. They concluded that only mesoscale evaporative cooling affected screen-level air temperatures. However, McPherson *et al.* (1989) had previously demonstrated that microscale evaporative cooling was relatively more influential on air temperatures in arid environments. Again, these findings illustrate an important point: some environments are more sensitive to small microclimatic changes than others, and therefore the magnitude of a potential temperature bias caused by a particular site feature depends on the initial characteristics of the environment.

Taha *et al.* (1991) studied microclimatic effects of a small orchard (150 m across in the prevailing wind direction) in summer at Davis, California. They found significant screen-level air temperature reductions of 2°C on average (with maximum differences of 6°C) within the canopy, with cooling effects extending over 110 m downwind of the orchard (approximately 5 times the tree height). Taha *et al.* (1991) attributed the cooling effects to both shading and evaporation.

There is considerable interest in local and regional climatic effects of vegetation changes, such as deforestation, reforestation and agricultural practices. Lewis (1998) found that Western Canadian ground surface temperatures increased by 1-2 K immediately following deforestation, either by logging or forest fires. This temperature increase was attributed mainly to a reduction in evaporation and transpiration following deforestation. Air temperature differences are likely to be smaller in magnitude than surface temperature differences, as shown by Morecroft *et al.* (1998), who compared both surface and air temperatures between two types of deciduous woodlands and an open grassland location for a three year period at Oxford, UK. They reported maximum air temperature reductions of 3°C under the canopy on sunny, summer days. However, average summer temperature reductions were 0.6 to 0.9°C, and winter differences were not significant at all; similarly, nighttime temperature differences at all times of the year were not significantly different. The summer air temperature differences that did occur were strongly correlated to solar radiation, the presence and state of development of the canopy, and wind speed, indicating that the effect of vegetation on air temperatures cannot be attributed to a single factor.

Schwartz and Karl (1990) examined the regional effect of spring green-up, or leaf emergence on maximum air temperatures in the North-Eastern United States. They estimated that a cooling of 3.5°C can occur following the first appearance of leaves in the spring, and the subsequent increase in evapotranspiration. Fitzjarrald *et al.* (2000) subsequently examined turbulent flux measurements made above a deciduous forest in the North-Eastern United States. They found that sensible heat flux drops, and latent heat flux increases at the time of spring leaf emergence, leading to measurable decreases in air temperature and increases in humidity. The implications for climate station environments are that changes in vegetation (growth, removal, or changes in species composition) have the potential to alter the relative partitioning of energy into sensible and latent forms, thereby affecting the thermal and moisture characteristics of the site.

The availability of soil moisture can also influence the amount of evaporation, and therefore the near-surface air temperature. Morecroft *et al.* (1998) found that soil moisture variations were not strongly correlated to the temperature differences between a deciduous woodland and open grassland, being secondary in importance to solar irradiation, wind and leaf presence, as noted above. However, Durre *et al.* (2000) showed that antecedent soil moisture conditions at climate stations throughout the United States could explain the occurrence of many 'extreme' temperature variations, i.e. record breaking high temperatures tended to occur with extremely low soil moisture. The relationship between soil moisture and air temperatures was strongest in the southeastern United States, where local evapotranspiration is thought to be more relevant to the water balance.

In addition to natural soil moisture variations, irrigation practices are a potential source of increased evapotranspiration that may be particularly significant to climate stations located in agricultural regions where irrigation is common. The effect of evaporation on air temperature is the same, regardless of whether the soil moisture is natural in origin, or a result of irrigation, but a few studies have looked specifically at the effect of irrigation on air temperature. De Vries (1959) compared screen-level air temperatures in a dry pasture to a nearby irrigated pasture for summertime conditions in Australia. He found that the average air temperature in a two week period was 2.4°C lower over the irrigated field. De Vries (1959) also developed a mathematical model that showed the effect of irrigation on air temperatures extends a distance downwind similar to the along-wind length of the irrigated surface.

Stohlgren *et al.* (1998) used a regional climate model to explore climatic effects of changes to irrigation practices in Colorado by comparing summertime conditions for natural grasslands, dry agricultural crops, and highly irrigated crops. Model results indicated that irrigation led to temperature decreases of 0.5 to 0.9°C. Summertime air temperature trends at several climate stations in the most highly irrigated areas were also examined, and found to have experienced significant long-, and short-term cooling trends. However, it is not apparent that the individual station records used were assessed for homogeneity prior to the analysis.

Geerts (2002) demonstrated that large scale irrigation in an arid region of Australia decreased the annual range of monthly-mean temperatures by 1-2 K. The main effect was a reduction of summertime temperatures. An observed increase of summertime dewpoint temperatures indicates that increased evaporation as a result of the irrigation was likely responsible for the lower summer temperatures.

In summary, typical site specific changes around climate stations capable of affecting evaporation include changes to soil moisture status as a result of irrigation changes, or changes to ground water table, as well as changes to vegetation and replacement of natural surfaces with impermeable artificial surfaces. In general, increased moisture and/or increased vegetation should increase the amount of evaporation and lead to lower daytime maximum temperatures. Few studies have shown any significant evaporative effects on nighttime minimum temperatures.

(ii) Roughness and shelter effects

The convective transport of sensible heat towards or away from the surface affects near surface air temperatures. In general, increased roughness enhances convective transport. For typical daytime situations enhanced convection results in the removal of warm surface air and downward mixing of cooler air from aloft, thereby reducing daytime near surface air temperatures. Increased turbulent mixing can also enhance surface evaporation, leading to further cooling. As Myrup *et al.* (1993) demonstrated, surface roughness led to vigorous downward mixing of very dry ambient air, significantly increasing surface evaporation.

Under calm, clear nighttime conditions, the surface and near-surface air cool by longwave radiation emission, creating a surface based temperature inversion. Turbulent mixing transports warmer air from above down towards the surface, offsetting the radiative cooling and leading to higher minimum temperatures.

The exact positioning of the temperature measurement site with respect to the roughness elements will determine whether the site experiences enhanced convective transport as a result of increased turbulence, or reduced convective transport as a result of sheltering. For example, Gustavsson (1995) and Gustavsson *et al.* (1998) found that air temperature differences between wind-sheltered (forested) and exposed sites developed quickly after sunset, and were maintained throughout the night, with between-site temperature differences being greatest at intermediate winds speeds. Gustavsson (1995) and Gustavsson *et al.* (1998) concluded that wind shelter in the forested sites prevented the downward mixing of warmer air, and therefore lower nighttime temperatures occurred compared to the exposed sites where the development of strong surface inversions was disrupted by convective mixing. Greater cooling at the sheltered site is contrary to the expectation that cooling would be reduced because of the lower skyview factor. However, Gustavsson (1995) notes that the skyview factor is a significant control on nocturnal surface temperatures, but that air temperatures are not nearly as responsive to that control, except under very calm conditions.

The microclimate effects of windbreaks, or shelterbelts, have long been exploited for agricultural purposes. McNaughton (1988) reviewed research on the aerodynamic effects of windbreaks on the adjacent microclimate. It has been shown that a triangular 'quiet zone' exists downwind of the windbreak to a distance approximately eight times the height of the barrier. In this zone of reduced turbulence, evaporation decreases and air temperatures increase. McNaughton (1988) reports that some observations have demonstrated temperature increases of up to 2.8°C or more in the quiet zone. Downwind of the quiet zone is a zone of increased turbulence, the 'wake zone', where turbulent fluxes are enhanced, and temperatures reduced approximately the same magnitude as the quiet zone perturbations. The wake zone is more horizontally extensive, with some studies finding temperature reductions of greater than 1°C, at a downwind distance 23 times the barrier height. The dimensions of the quiet and wake zones vary with stability (i.e. the values given here are for neutral conditions, and are slightly less for unstable conditions), as well as with the porosity of the windbreak. If the windbreak is extremely porous, the quiet zone does not develop, and the most recent findings indicate that denser barriers lead to larger sheltered regions due to larger reductions in wind speed (McNaughton, 1988).

Wang and Klaassen (1995) studied the effects of an extensive rectangular network of windbreaks in Anhui Province, China. They observed a slight warming of the near-surface air during the day time as a result of decreased turbulence between the wind breaks. However, because mechanically generated turbulence is more significant at night (relative to thermally generated turbulence), the higher roughness of the windbreaks leads to increased mixing at night, and therefore reduces surface cooling.

Windbreaks, or other sheltering features are common in the vicinity of climate stations. Therefore the location of the temperature sensor within either the quiet or wake zones could introduce significant biases to the observed temperatures. Furthermore, as shelterbelts grow in height, or change in density and porosity over time, the size of the affected areas will change, further complicating the nature of the resulting bias on long-term temperature records.

In addition to the mechanical turbulent effects caused by roughness elements, differential heating of the elements can lead to thermal convection at the microscale as well. Ishida *et al.* (1996) found warm, moist rising currents of air on the sunlit side of trees, whereas cool currents descended on the shaded side. Again, depending on the specific configuration of the measurement site with respect to potential heating of surfaces, micro-thermal convection currents may bring relatively warm or cool air to the instrument area.

One final point regarding wind shelter/enhanced roughness relates to radiation errors of the instrument and screen. Adequate ventilation is required to eliminate radiation errors caused by radiative heating of the instrument and/or instrument shelter. Thus, if wind shelter increases without an accompanying increase of shade, radiation errors in the air temperature measurements may increase. For example, a building erected to the north of the instrument if the prevailing wind direction is also northerly, would reduce screen ventilation without providing any shade to offset the radiative heating.

(iii) Advection

While surface characteristics in the immediate vicinity of the observation instruments have been the focus of the discussion to this point, the influence of horizontal advection from some distance away from the instruments also has the potential to affect screen-level air temperatures when relatively warm or cool air is advected over the site. In addition, relatively dry or moist air advected to the instrument site has the potential to enhance or suppress evaporation , thereby altering the influence of evaporative cooling on the observed temperatures. Numerous theoretical treatments of local advection (e.g. Philip, 1959; Rider *et* *al.* 1963; Taylor 1969; Taylor 1970; Novak, 1990) have provided methods to calculate the downwind temperature and humidity anomalies resulting from surface inhomogeneities. The downwind vertical and horizontal effects depend on the relative changes in surface properties such as surface roughness, moisture status, and temperature differences specific to each situation. Surfaces upwind of climate stations such as roads, tarmac, runways, fields of different vegetation cover and moisture status (irrigated or unirrigated), lakes, ponds or reservoirs, all provide potential thermal biases to observed screen-level air temperatures. For example, as noted earlier, De Vries (1959) found that the effect of an irrigated surface could be detected downwind to a horizontal distance equal to the along-wind dimension of the irrigated surface.

Spronken-Smith *et al.* (2000) studied advection across an irrigated urban park in Sacramento, California. The most significant advective effect was the enhancement of evapotranspiration at the leading edge of the park, as warm dry air was advected over the moist park surface. Evapotranspiration from the park was more than 130% greater than an irrigated, rural control site, not affected by advection. This situation is similar to many typical climate stations, particularly airport stations, that are situated on grass surfaces downwind of extensive warm and dry asphalt surfaces. While increased evaporation should have a cooling effect that partially offsets the increased warmth of the advected air itself, the magnitudes of the two opposing effects are unlikely to balance. The results of Spronken-Smith *et al.* (2000) are also relevant to many 'urban' climate stations that are often located in parks or grassy areas. The representativity of such urban climate stations is therefore questionable.

While extensive urban surfaces, runways and taxiways at airports represent extreme examples of a potential warming influence at typical climate stations, observations reported in Appendix 1 of this thesis demonstrate that even seemingly minor surface variations (a gravel road, in this case) can lead to observable down-wind temperature anomalies. Figure A1.4 shows differences in 1.5 m air temperatures from identically exposed sensors above a short alfalfa crop in a clay soil for a period after sunset. A narrow gravel road passed between the two sensors, lying 15 m upwind of the second sensor. Surface temperatures indicated that the road remained warmer than the fields throughout the night. When winds were calm, there were no measurable differences between the two air temperature observations. With light southerly winds (< 2 m s^{-1}), the downwind temperatures increased by 1 °C relative to the upwind sensor, with maximum differences of 3.5 °C recorded. The fact that temperature differences occurred only when the wind direction was perpendicular to the road indicates that the road was the most likely source for the increased down wind temperatures. Source-area modeling results (Appendix 1) show that the largest temperature differences occurred when the road occupied a larger fraction of the instrument's source area.

The preceding discussion concerns surface-level inhomogeneities that are capable of producing advective effects to downwind temperatures. Three-dimensional objects such as vegetation or buildings may also provide advective heat sources, either due to different radiative and thermal properties resulting in surface temperature anomalies or, for the case of buildings, losses from interior space heating or venting of warm air from air conditioning can also heat the nearby air. These elements also increase the surface roughness, so heat losses around the building may become mixed back down to the surface as a result of increased turbulence down wind of the object.

Quintela and Viegas (1995) performed wind tunnel studies to examine convective heat losses from cubic models with differentially heated facets. Their results indicate that the amount of convection and therefore the potential downwind temperature effect varies with the atmospheric stability, as well as with the orientation of the heated facet with respect to the wind direction. Also, the position of the temperature sensor with respect to the building and the prevailing wind direction will determine the resulting effect on observed air temperatures.

Field observations of nocturnal air temperature variations in the vicinity of a rectangular metal wagon (4.3 wide by 2.8 m high) are reported in Appendix 1. The potential thermal influences were caused only by excess surface temperatures resulting from increased absorption of solar radiation during the day, and reduced cooling at night. Results indicate an envelope of warm air adjacent to the walls in a pattern consistent with the typical "horseshoe" pattern of turbulence generated by individual roughness elements (e.g. Oke, 1987). A few hours after sunset, temperature excesses of between 0.6 and 0.7 °C were observed 1.5 m downwind of the object. Temperature deficits of 0.3 °C occurred on the upwind side of the object (a distance of ½ H in front of the object, where H is the height of the object), consistent with the lifting of colder surface air ahead of the obstruction. This object represents a relatively small surface modification compared to houses, buildings, airport terminals or hangars that are often constructed in the vicinity of climate stations. The fact that a thermal effect was detectable in this case implies that constructions around climate stations are likely to exert significantly greater influences on the observed temperatures.

(iv) Cold air drainage

Gravity-induced flows of cold dense air, especially at night, can lead to significant spatial variations in temperature as a result of 'cold air pools' accumulating in low-lying areas. While these cold air flows are largely determined by the local topography, site specific controls can arise if the downslope flow is hindered by obstructions (or enhanced if obstructions are removed). Thus, vegetation growth on a sloping surface would increase the surface friction and reduce the downslope flow of surface-cooled air. Conversely, if vegetation is removed, cold air drainage would be enhanced. The effect of site controls on cold air drainage will therefore depend on whether the site was originally subject to the removal or receipt of the down-slope flows.

As noted in section 3.3.1 (i), Bogren *et al.* (2000) found that cold air drainage in the complex topography of their study area complicated their interpretation of road-surface temperature differences caused by screening influences. Söderström and Magnusson (1995) conducted mobile temperature surveys at night in southwestern Sweden to assess frost risk in an agricultural area. Although the study area was relatively flat, they found temperature variations closely followed topography, with temperature differences on the order of 2°C occurring with elevation changes of a few metres. The authors noted that the presence of obstacles such as trees and forests can significantly disrupt the down-slope flow of cold air as a result of damming, re-directing the flow around the edges, or retarding the throughflow of cold air, depending on the density and height of the vegetation.

Reference to one final study of temperature characteristics in an area of cold air drainage is included because it fittingly illustrates the inherent difficulties in attributing temperature anomalies to a particular cause. Hawke (1944) analyzed thirteen years of temperature observations from a standard climate station in Hertfordshire, UK. This particular station was noted to have the most extreme diurnal range of temperatures in the UK, including frequent summertime frosts. Although the station was considered to have 'typical exposure' for a normal climatological station, it was located on the slope of a narrow valley wall. Anomalous cold temperatures in the summer were attributed to down-slope drainage of cold air on nights with strong radiative cooling. A railway embankment at the base of the slope was thought to act as a barrier to the down-slope flow, causing the cold air to pool in the valley. Subsequently, a pedestrian tunnel was cut through the embankment which could have provided an outlet and reduced the cold air ponding, but the author could not find evidence that the opening in the embankment altered the cold air damming effect. Causes of extreme daytime temperatures were attributed to possible radiation errors of the Stevenson screen and increased reflection of solar radiation from the sloped surface near the screen (although increased shading as a result of the slope was also recognized). The nature of the soil (porous sand and gravel; i.e. low thermal admittance) was also considered to contribute to large diurnal temperature ranges.

Furthermore, Hawke (1944) observed short periods of increased temperatures on relatively calm nights, presumably the result of the down-mixing of warmer air into the cold-air 'lake' around the climate station due to mechanical turbulence generated by the surrounding hills. Thus, this particular climate station, although meeting the standard requirements for siting and exposure of instruments, was clearly subject to many of the potential thermal biases discussed in this chapter. This example clearly illustrates that interpretation of air temperature records is meaningless unless due consideration is given to the role of local influences.

3.6 Summary of typical climate station siting biases

The following table summarizes the foregoing discussion by listing common climate station characteristics, and indicating whether warming (+) or cooling (-) biases are likely to affect the daily maximum and minimum temperature records.

Table 3.3 Summary of common climate station siting biases and their effect on daily temperatures.

Physical feature changed	**Processes affected**	**Potential thermal influence**	
		T max	**Tmin**
Compaction of soil from trampling	increased albedo	-	-
	increased thermal admittance	-	+
Grass planted on bare soil	increased albedo	-	-
	decreased thermal admittance	+	-
	increased evaporation	-	-
Unchecked growth of grass or weeds	decreased albedo	+	+
	decreased thermal admittance	+	-
	increased evaporation	-	-
Change in soil moisture e.g. increased irrigation	decreased albedo	+	-
	increased thermal admittance	-	+
	increased evaporation	-	-
Addition of sidewalks, roads, Parking lots, runways	decreased albedo	+	+
	increased thermal Admittance	-	+
	decreased evaporation	+	+

Table 3.3 *continued*

Physical feature changed	**Processes affected**	**Potential thermal influence T max**	**Tmin**
	additional sources of heat (vehicle exhaust)	+	+
	higher surface temperature advective source of heat	+	+
Decreased snow cover due to clearing of roads etc., and/or earlier melting due to dirtying	decreased albedo	+	+
	increased thermal admittance	-	+
Growth of trees around site	decreased albedo	+	+
	Increased shade	-	-
	Decreased skyview Factor	0	+
	Increased roughness: (enhanced turbulence)	-	+
	(increased shelter)	+	-
	Increased evapotranspiration	-	-
Removal of trees	increased albedo	-	-
	decreased shade	+	+
	Increased skyview Factor	0	-
	Decreased turbulence	+	-
	Decreased shelter	-	+
	Decreased evaporation	+	-
Construction of buildings	Increased shade	-	-
	Decreased albedo	+	+
	Decreased skyview	0	+
	Enhanced turbulence	-	+
	Enhanced shelter	+	-
	Source of waste heat	+	+

This chapter has demonstrated the physical basis of microscale siting biases that are capable of influencing daily temperature records. Whether or not a systematic warming or cooling bias occurs in any particular temperature record depends on the exact history of the individual station, as well as on the nature of the environment in which the station is located. It is clear from the variety of potential influences, that 'non-climatic' warming or cooling trends of several degrees Celsius can potentially occur at any station—that is, such inhomogeneities are not simply an 'urban' problem. Therefore, attempts to identify suspect climate stations by such measures as surrounding population, regional land use, or remotely sensed indicators such as NDVI or night-light intensities clearly do not have the necessary resolution to identify microscale problems. In the absence of detailed knowledge of individual station histories, there is clearly a need for the development of statistical techniques specifically designed to identify biases of this type. The remainder of this thesis deals with the problem of identifying microscale inhomogeneities in historical temperature records, and presents a technique for their detection.

Chapter 4
COOLING RATIOS AS A TOOL FOR HOMOGENEITY ASSESSMENT: RATIONALE AND DEVELOPMENT OF A TECHNIQUE

4.1 Introduction:

It is clear from the discussions in Chapters 2 and 3 that the effect of microclimatic change on air temperature records is not well recognized. It is also apparent that existing homogeneity assessment techniques are not suited to the detection of these 'micro' effects for a number of reasons including the following: the magnitude of microclimatic biases may be small relative to the large variability of daily temperature values; microclimatic influences are best expressed under certain weather conditions or in specific seasons, and can therefore be obscured in monthly, seasonal, or annual averages; and, thirdly, microclimatic changes may produce temporal trends which are often difficult to distinguish from regional or global climate trends present in temperature series.

This chapter describes the rationale and development of a new homogeneity assessment technique designed specifically to identify site-specific microclimatic effects in temperature series, through examination of ratios of night-time cooling at neighbouring climate stations. An understanding of the nature and characteristics of cooling ratios is developed through examination of several case studies. In Chapter 5, the technique is developed further, analyzing time series of cooling ratios to identify change points that may be indicative of microclimatic change. In Chapter 6, the suitability of the technique for analyzing urban temperature records is examined

4.2 Definitions

Throughout this thesis, *cooling magnitude* refers to the decrease of temperature from the daytime maximum (T_{max}) to the minimum temperature that occurs during the subsequent night or early the next morning (T_{min}), and is calculated as follows:

$$\Delta T = T_{max(j-1)} - T_{min(j)} \qquad (4.1)$$

where j is the day of the year. Historically, most climate stations have used standard maximum and minimum thermometers which are observed once or twice per day. It is acknowledged that certain limitations of standard max- and min- thermometers and/or observational procedures, may lead to occasional errors in the observed temperatures and therefore the calculated cooling magnitude. Because there is no way of determining the actual time that the observed maximum and minimum temperatures occurred, it is possible in some cases, that ($T_{max\ (j-1)} - T_{min\ (j)}$) may not represent the actual nocturnal temperature decrease. For example, sudden changes in air masses or cloud may disrupt the normal diurnal temperature pattern, causing the maximum and minimum temperatures to occur at unexpected times. Also, Bootsma (1976) demonstrated that if the daily minimum temperature is observed, and the thermometer reset, close to the time that minimum temperature occurs, there is an increased probability that the same temperature would be recorded on two consecutive days if the second day is warmer. For the purposes of this study, it is assumed that such errors are relatively rare and that, in the majority of cases, (T_{max}-T_{min}) is a reasonable estimate of nocturnal cooling.

In the literature, daily maximum-minimum temperature differences are commonly referred to as the *diurnal temperature range,* or *DTR*. However, the term *cooling* is considered to be more meaningful in the context of this thesis, because the process of nocturnal cooling is known to be influenced by the microclimatic characteristics of a site (e.g. soil moisture and associated thermal properties, sky-view factor, etc.)

Daily cooling ratios of neighbouring stations are calculated by dividing the cooling magnitude, ΔT, at a 'test' station (A) by ΔT of a nearby 'reference' station (B), and is denoted by

$$R_{A:B} = \Delta T_A \ / \ \Delta T_B \qquad (4.2)$$

Although *R* could theoretically assume a wide range of values, for neighbouring stations almost identical in every respect, *R* should equal one. If one of the stations' environments changes relative to the other, values increasingly different than one would be expected, particularly when meteorological conditions enhance spatial variations in temperatures and nocturnal cooling.

Stations may be considered neighbours if they are both subject to the same local, meso- and synoptic scale influences. Actual acceptable distances between stations will vary with the particular setting. As with all relative homogeneity assessment techniques, selecting a reliable reference station is paramount to the success of this technique. An 'ideal' reference station would be one which is known to have had a high quality observation programme, as well as experiencing no changes in its siting or exposure over the period of interest, e.g. in an open rural field. Unfortunately, it is rare to find a station that has not experienced some change in its siting or exposure. Therefore, as results in Chapter 5 will show, it is acceptable to use a reference station which has good historic meta-data which indicate the quality of the observations and a record of any changes in the surroundings of the station.

4.3 The Nature of the Cooling Ratio : characteristics and behaviour

4.3.1 Premises underlying the usefulness of cooling ratios

The usefulness of R in demonstrating microclimatic effects in temperature records is based on the following premises:

- In most cases, neighboring climate stations are subject to the same local-, meso-, regional- and synoptic-scale controls, so differences in cooling between two such stations (as expressed by $R \neq 1$) must reflect site-specific microclimate differences.
- If the microclimates of two stations do not change over time, then R will remain constant. Conversely, temporal changes of R indicate changes to the microclimatic environment of at least one of the stations.
- Microclimatic controls on nocturnal cooling are most significant during weather conditions that are conducive to cooling (namely calm, cloudless conditions).
- Microclimatic influences on air temperature differences are most evident at night when stable conditions allow surface controls to be concentrated in the surface layer.

4.3.2 Illustrative examples of the nature of cooling ratios

In order to establish whether cooling ratios are appropriate indicators of site microclimates, and particularly whether temporal changes in R can be used to identify temperature inhomogeneities as a result of microclimatic change, it is necessary to develop an understanding of the nature of R. To this end, exploratory analyses of R for several Canadian climate station pairs have been undertaken in order to understand their behaviour and characteristics, and to establish an algorithm for the technique of testing homogeneity of temperature records. Results of these analyses are described in the following sections.

4.3.3 Effect of weather on *R* variability

i) Temperature Data

The following discussion is based on cooling magnitudes calculated from temperatures observed at three climate stations near Vancouver, British Columbia: Vancouver International Airport (YVR), Steveston, and Ladner. (These records are analyzed further in Chapter 5 and site photographs are shown in Figures 5.1 and 5.2). Steveston is the reference station in both cases, because it is recognized as a good quality, long-running station that has been largely unaffected by urbanization or development over the period of its record, although there were two minor station moves (Schaefer, 1974). YVR is a principal synoptic station, with both hourly and daily records available. YVR is approximately 5 km north of Steveston, but both are located at almost equal distances from the coastline and at similar elevations (2 m and 0 m asl respectively). YVR has experienced considerable change due to the growth of the international airport and construction of runways, taxiways, hangars, terminals, and parking lots. The period of overlap for YVR and Steveston temperature records is 1937 to 1970. Ladner is approximately 12 km east-south-east of Steveston, at an elevation of 1 m asl, and has a common period of temperature observations with Steveston for 1953-1970. The Ladner station was located at a Canadian Forces Base, and it's surroundings remained essentially unchanged over the period of the record. Both Steveston and Ladner are ordinary climate stations, having daily maximum and minimum temperatures and precipitation records.

ii) The weather factor, Φ_w

Microclimatic controls on nocturnal cooling are most pronounced during calm, cloudless conditions when surface radiative losses are maximized. Therefore temperature and cooling *differences* between two sites are also greatest under such conditions, and one might reasonably expect that cooling *ratios* would also show a significant variation with weather.

The effects of cloud amount and type, along with wind speed, on the amount of nocturnal cooling can be combined into a single *weather factor*, Φ_w, as formulated by Oke (1998):

$$\Phi_w = (1-km^2)\, u^{-1/2} \qquad (4.3)$$

where k is the Bolz correction factor for cloud height (i.e. k accounts for the decrease of cloud-base temperature with increasing cloud height, and ranges from 0.16 for cirrus to 1.0 for fog, Oke, 1987), m is cloud amount in tenths, and u is wind speed in m s^{-1} . Φ_w ranges from 0 (poor cooling conditions: overcast low clouds and/or strong winds) to 1 (excellent cooling potential: clear skies and wind speeds 1 m s^{-1} or less). Note that in order to avoid unstable values of Φ_w arising from wind speeds less than 1 m s^{-1} (i.e. when $u^{1/2} < 1$, Φ_w can be very large), a lower limit of 1 m s^{-1} is set. This ensures that Φ_w will have a maximum value of 1.

This weather parameter has been shown to be related to urban-rural temperature differences (i.e. the urban heat island effect: Oke 1998, Runnalls and Oke, 2000), and dew accumulation (Richards, 2000) and is therefore potentially useful in the context of cooling ratios. Figure 4.1 shows an approximately linear relationship exists between the nocturnal

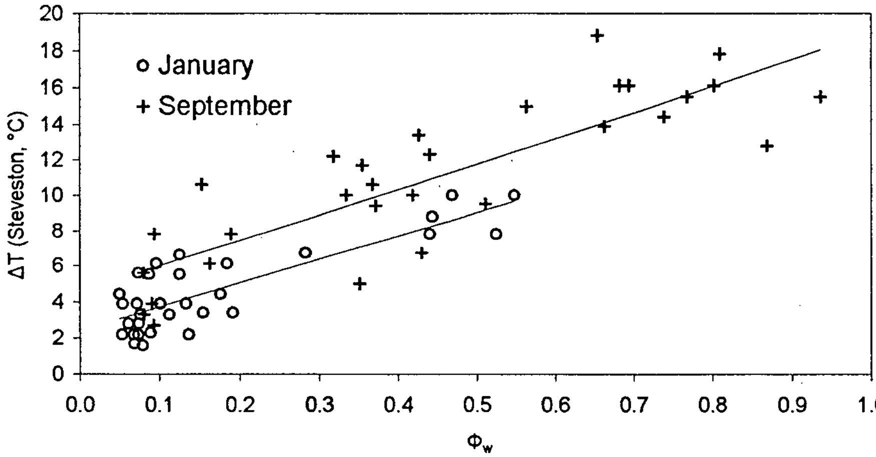


Figure 4.1 Relation between cooling magnitude at Steveston and weather (Φ_w); daily values for January and September, 1955. Φ_w ranges from 0 (strong winds, overcast low clouds) to 1 (calm, clear). (See eqn. 4.3). Regression equations for lines shown:

$\Delta T = 14.3\ \Phi_w + 4.6$, $r^2 = 0.71$ (September);

$\Delta T = 13.3\ \Phi_w + 2.4$, $r^2 = 0.70$ (January).

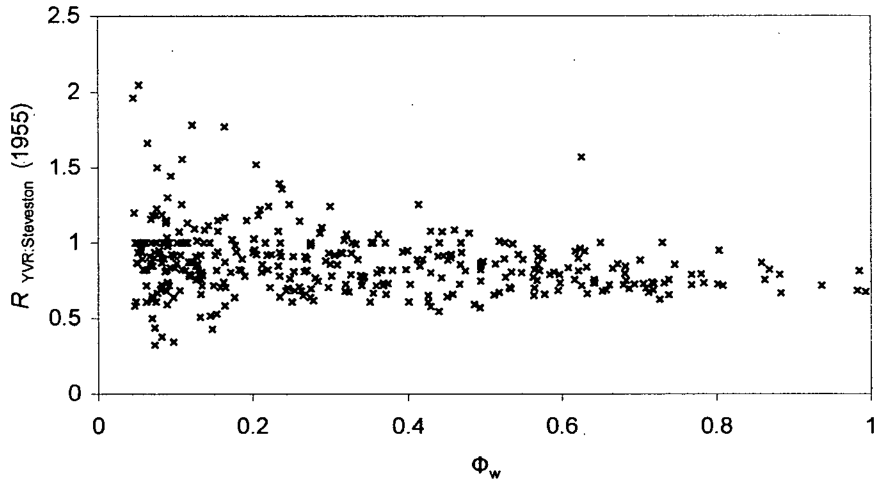
cooling magnitude at Steveston and Φ_w. Hourly cloud amount and height and wind speed data observations from the airport (YVR) were used to calculate mean Φ_w for each night.

Values for January and September are included to show the range of annual variation of cooling magnitudes. In general, a given value of Φ_w leads to greater cooling in September than January, but both show relatively greater cooling as weather conditions improve (Φ_w increases). This correlation indicates that Φ_w is an appropriate descriptor of weather conditions relevant to nocturnal cooling. Seasonal variations are explored in the subsequent section.

Figure 4.2 shows daily *R* values for an entire year (1955) as a function of Φ_w for (a) YVR : Steveston; and (b) Ladner : Steveston. 1955 was selected as illustrative because August 1955 was one of the driest on record, (2.8 mm precipitation) and this year might be expected to represent the range of possible seasonal differences, if they are significant. (Seasonality and effect of soil moisture on cooling ratios are discussed in more detail in the following sections).

The most prominent feature in Figure 4.2 is the decreased scatter with increasing Φ_w for both stations pairs. This feature may arise simply because fewer data are available at high Φ_w values. Nevertheless, it appears that stable values of the *R* emerge as Φ_w approaches 1: *R* approximately 0.75 for YVR:Steveston, and 1 for Ladner:Steveston. As a first approximation, these values appear to be approximately equal to the mean for the entire series, indicating that weather variations affect the variability, but not the central tendency of *R*.

(a)



(b)

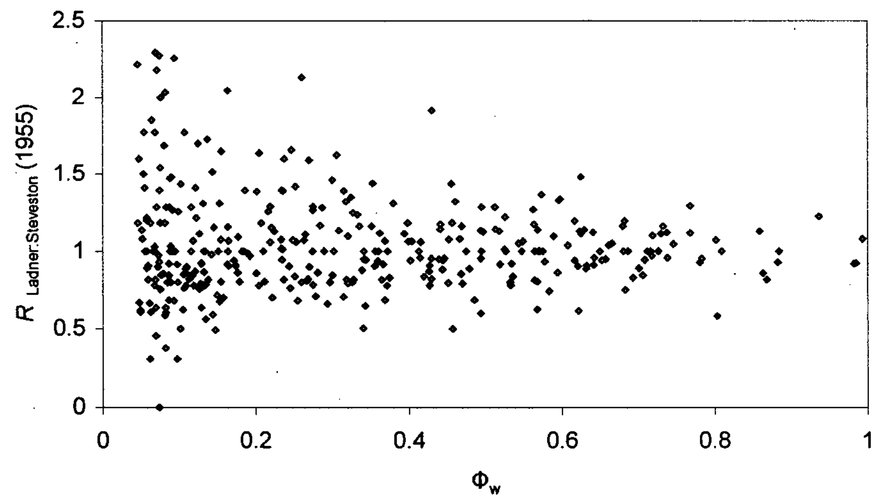


Figure 4.2 Relation between cooling ratio, R and weather, Φ_w; daily values for the year 1955. (a) YVR:Steveston; (b) Ladner: Steveston. Refer to equations 4.2 and 4.3 for calculation of R and Φ_w.

Some of the variability of R expressed in Figure 4.2 may be due to seasonal variations of the microclimatic controls on cooling at the individual sites (e.g. soil moisture, vegetation growth etc.), which are discussed in subsequent sections. Closer examination of R occurring at low Φ_w reveals that many of the R equal to unity occur when mean wind speeds are greater than 8 m s^{-1}. It is not surprising that strong winds eliminate spatial variations in temperature due to strong mixing and advection. Low Φ_w values resulting from a combination of light winds and overcast, low clouds however, still permit some expression of site control, because $R < 1$ are observed under such conditions.

Figure 4.3, a plot of $R_{\text{YVR:Steveston}}$ against the absolute cooling magnitude (ΔT) at Steveston, reveals that much of the scatter occurs when the absolute cooling magnitude itself is small (6°C or less). For example, a ratio of 1°C/ 0.5°C = 2, but is essentially meaningless because actual cooling was insignificant. Extreme outliers can also arise as a result of data errors. For example, an erroneous minimum temperature of 2.2°C instead of 12.2°C leads to a 10° error in the cooling magnitude, which can be significant in the ratio. Clearly, some form of data screening is warranted to eliminate meaningless outliers and occasions when significant cooling does not occur. The optimal method for doing so is discussed in section 4.4.

To summarize, the above results show that *relative* nocturnal cooling differences between sites are preserved under less than ideal weather conditions, even when temperature differences themselves may be quite small. Thus, it is concluded that the R for a station pair is a characteristic measure of microclimate differences, which is more easily identified under

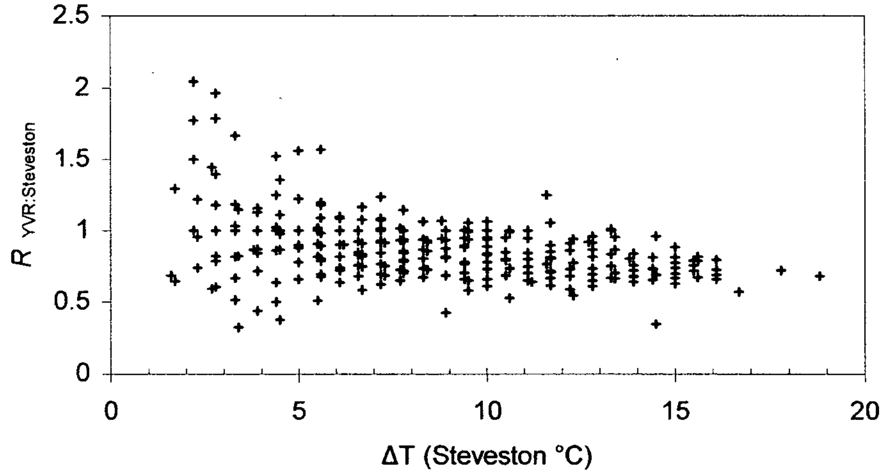


Figure 4.3 Relation between cooling ratio and nocturnal cooling magnitude at Steveston; daily values for the year 1955. Figure shows that most of the scatter in *R* occurs with small cooling magnitudes.

ideal weather conditions (when the scatter is reduced), but is also evident in the mean when conditions are less than ideal.

4.3.4 Seasonal variations of cooling ratios

The possibility that some of the scatter apparent in Figure 4.2 may be due to seasonal influences is confirmed by Figure 4.4. 1955 monthly median R (i.e. median value of daily R for each month) for nights with Φ_w >0.5 indicate that, while both series contain seasonal variations, the relationship between the two is antiphase. (*i.e.* maximum $R_{\text{Ladner:Steveston}}$ occurs with minimum $R_{\text{YVR:Steveston}}$, and *vice versa*). This feature can be explained by the seasonality of soil moisture differences between the sites. Seasonality of the $R_{\text{YVR:Steveston}}$ is consistent with typical seasonal variations in soil moisture in the area, and the associated thermal properties (Runnalls and Oke, 2000). One of the main differences between YVR and Steveston is the presence of extensive tarmac surfaces at YVR (runways, taxiways, parking lots.) Greater differentiation of microclimatic environments is expected in summer when soils are dry, since moist soils are thermally similar to tarmac. August 1955 was one of the driest on record and therefore soil moisture was low. Thus, it is not surprising to find cooling at YVR was only 73% of that at Steveston at that time. Values of $R_{\text{Ladner:Steveston}}$ close to unity imply very similar cooling regimes at both sites, consistent with their open, rural exposure, and similar soil moisture (and soil thermal properties).

The seasonality of R is likely to vary with the specific climatic regime of an area *e.g.* whether seasonal variations are mainly in soil moisture, as they are near Vancouver, or whether snow cover, vegetation, or artificial heating, *etc.* are important.

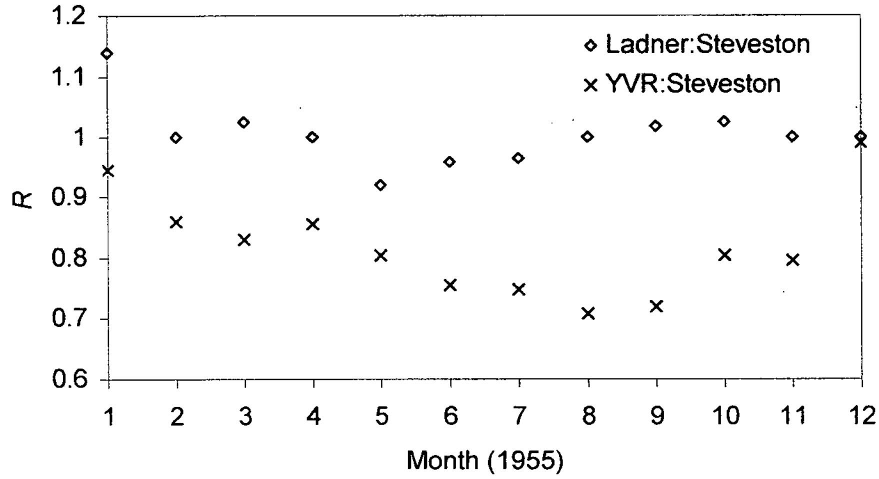


Figure 4.4 Seasonal variation of R $_{\text{Ladner:Steveston}}$ and R $_{\text{YVR:Steveston}}$. Monthly mean values for the year 1955.

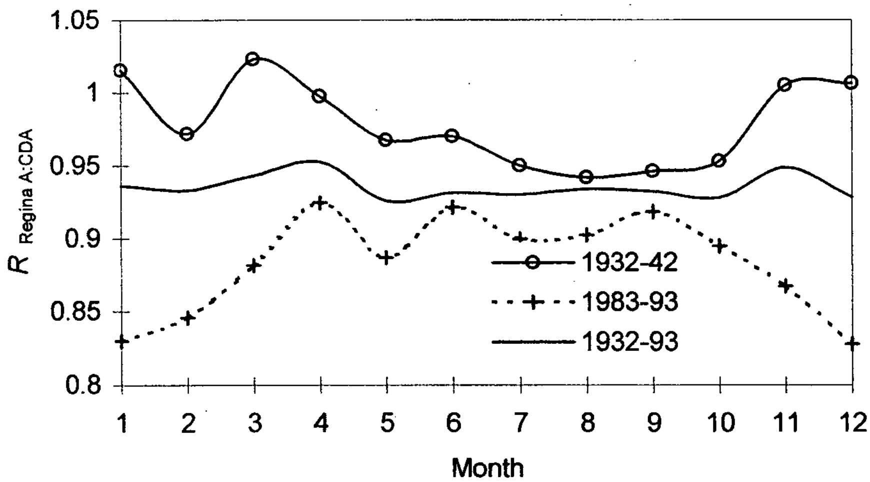


Figure 4.5 Seasonal variation of R Regina Airport: Regina CDA illustrating that seasonality of R may change over time. Data are monthly mean R for three different time periods.

It is possible that the seasonal R pattern could change over time, possibly indicating microclimatic change, or other inhomogeneities at one of the stations. Figure 4.5 shows a clear example of this possibility. In this graph, monthly median R for Regina International Airport: Regina CDA are plotted for different time periods. The seasonal pattern for the later period (1984-93) is the mirror image of the earlier period (1932-41), while the average calculated for the entire series (1932-93) displays no seasonal variation, i.e., the two patterns cancel each other. In this particular case, the change in the seasonal pattern is caused by a discontinuity in winter minimum temperatures at Regina CDA, which is apparent when examining the temperatures alone (Gullett *et al.*, 1990). The station history file does not provide any indication of the cause of this step change, and therefore no conclusions can be drawn from standard evidence as to whether it is indeed caused by a feature of the microclimatic environment, or perhaps as a result of a change in instrumentation or observation procedure. However, because the absolute value of the summer R also decreased, without a corresponding discontinuity in either the maximum or minimum temperature series, there may be more than one cause of the noted changes in R. This example is included only to demonstrate the importance of the time period selected for analysis. If the entire length of record had been used to examine seasonality in this case, one might have erroneously concluded that R for these two stations has no seasonality.

4.3.5 Role of soil moisture changes in R variability

As noted in the preceding section, seasonal variations of the $R_{YVR:Steveston}$ are probably linked to soil moisture variations and the resulting surface thermal properties. Therefore, it is also important to consider the possibility that soil moisture variations from year to year in a given season could also induce changes to R, i.e. do exceptionally wet summers lead to more winter-like R values? This question was examined by comparing $R_{\text{YVR:Steveston}}$ for the three driest Augusts (average monthly precipitation 7.8 mm) and three wettest Augusts (average monthly precipitation 77 mm). Median R for both groups were 0.81. Figure 4.6, a plot of median monthly R for both station pairs against total monthly precipitation for the period 1953-1960 shows no strong relation. Analysis of daily R values as a function of antecedent precipitation, similarly showed no relation. Therefore it appears that the range of summertime soil moisture in Vancouver does not significantly affect the estimation of the summertime R. This independence may not exist in other regions, but because most climate stations also record precipitation, the possibility of soil moisture variations causing temporal variations of R could be investigated on a site-specific basis.

4.3.6 Relationship between absolute temperature and *R*

As previously discussed, one of the difficulties in detecting inhomogeneities in temperature series arises when site-specific trends are superimposed on regional temperature trends. It therefore becomes difficult to determine how much of the observed temperature trend is due to regional warming or cooling, and how much may be a site-specific effect.

Given the relative stability of R with variations in weather, it seems likely that R values would also remain constant even if regional trends of temperature were occurring, since regional effects would be common to both stations. On the other hand, it also seems possible that microclimatic differences could be accentuated during warmer periods if differences of surface thermal properties are important to the cooling ratio. That is, during warmer periods, daytime storage might be enhanced and site specific storage differences

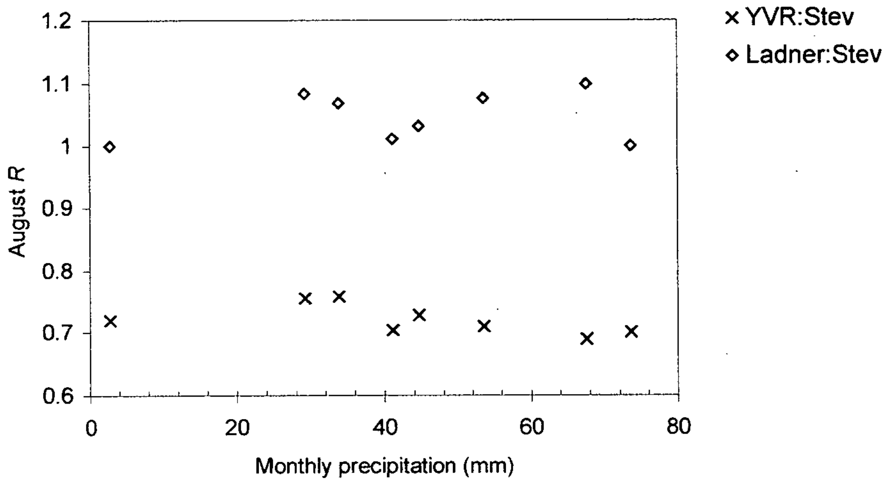


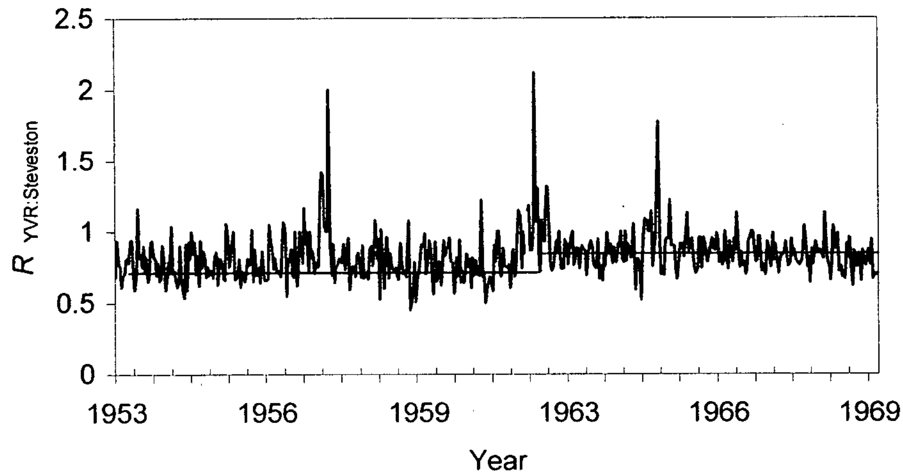
Figure 4.6 Variation of August mean R with precipitation for the period 1953 to 1960. This period was selected to show the greatest range of precipitation and soil moisture variation. The fact that R does not show a strong dependence on precipitation implies that R is likely to remain constant if regional climatic trends in precipitation occur. See also Figure 4.8.

could lead to greater nocturnal cooling differences. Therefore, the question of whether temporal trends in *R* would occur as a result of regional warming or cooling must be considered.

Zhang *et al.* (2000) reported that Southwestern British Columbia experienced a statistically significant increase in minimum daily temperatures of approximately 1°C to 1.5°C in all seasons between 1900 and 1998. Over the same period, the region also experienced a statistically significant decrease in diurnal temperature range of approximately 0.5°C to 1.0°C. (Zhang *et al.* (2000) also showed that similar, but slightly smaller, trends were evident over the period 1950 to 1998 as well, although the trends in diurnal temperature range were not statistically significant during this period). Figure 4.7b shows that the time series of monthly $R_{\text{Ladner:Steveston}}$ (1950-1970) does not exhibit any trends. The fact that the *R* remain remarkably constant during this period of regional warming, indicates that the use of a ratio eliminates the regional influence common to both series, making the *R* a useful indicator of microclimatic differences between sites.

The possibility that regional warming trends might affect *R* time series was examined further by examining the relation between median August *R* and monthly mean maximum temperatures observed at Steveston, to determine if *R* values were significantly different in warmer years than in colder years. As Figure 4.8 shows, although mean maximum temperatures range from 20°C to 24°C, *R* remains constant. Again, these results suggest that regional warming or cooling trends are unlikely to introduce temporal trends in *R* time series, thus making *R* a useful indicator of microclimatic differences.

(a)



(b)

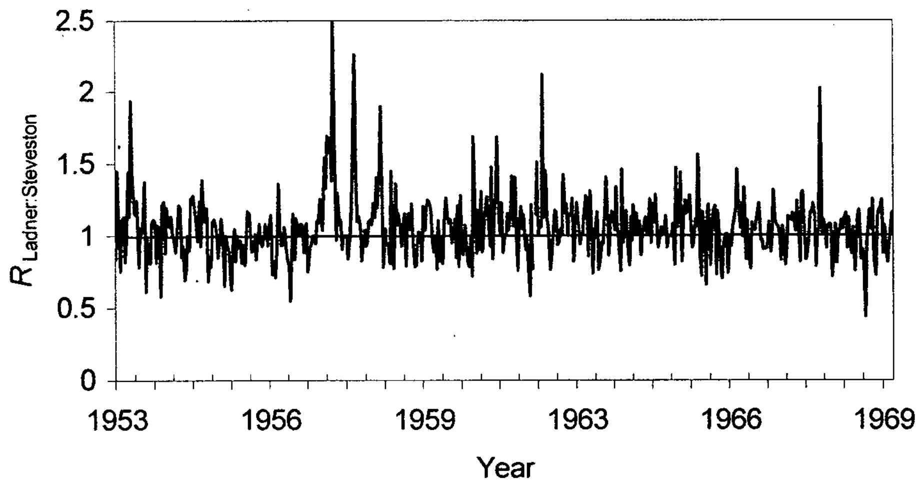


Figure 4.7 Time series of daily *R* (1953 -1970) for (a) YVR:Steveston and (b) Ladner:Steveston. A step change in the mean is evident in (a) while the long term mean in (b) remains constant. See text for explanation.

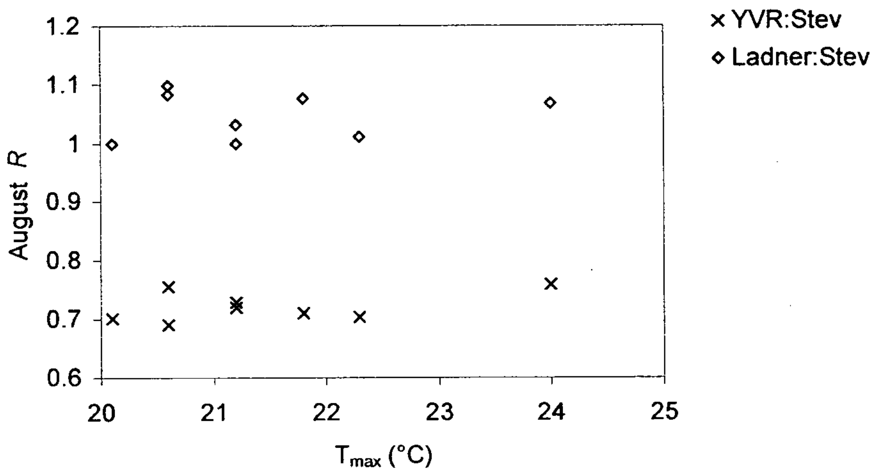


Figure 4.8 Relation between August R and August mean maximum temperatures (1953-1960) for YVR:Steveston and Ladner:Steveston. R does not show strong dependence on mean temperatures, implying that R would remain constant if regional temperature changes occurred. See also Figure 4.6.

4.4 Optimal determination of *R*

The foregoing analyses indicate that daily *R* for a climate station pair exhibits apparently random scatter that cannot be explained by weather, temperature, or soil moisture variations. Nevertheless, the central tendency of *R* appears to be constant over time, except for seasonal cycles. It is reasonable to conclude that a measure of the central tendency of *R* for a given pair of climate stations is a characteristic feature of the station pair at a given point in time that represents microclimatically controlled cooling differences between the sites. This "characteristic" remains constant over time, even with regional climate changes (i.e. trends in weather patterns, temperatures, or precipitation). Given the relative stability of *R* for a station pair, this measure seems potentially useful to identify site-specific microclimatic biases in temperature. However, given the day to day variability, it is necessary to first identify an appropriate method for calculating *R*.

As previously noted, monthly or seasonal averages can obscure microclimatic biases that may be more pronounced on certain days than on others. Therefore, it is desirable to retain the information present in daily data, yet some measure of central tendency is clearly needed because of the scatter of daily data. Figure 4.2 shows that the scatter decreases with improved weather conditions, and that the 'characteristic' *R* becomes apparent at higher values of Φ_w. In keeping with the initial premise that microclimatic effects are most pronounced under ideal weather conditions, it is desirable to calculate *R* for only these conditions. However, Figure 4.2 also shows that the central tendency of *R* does not appear to vary significantly with weather, only that scatter was greater and outliers more common at low Φ_w. It is necessary to determine, therefore, whether including this scatter biases the estimate of central tendency compared to using only *R* for ideal weather situations, and whether the extra data requirements and computations needed to calculate daily Φ_w are warranted.

Table 4.1 summarizes statistics estimated from several sub-samples of August $R_{\text{YVR:Steveston}}$ for 1953-60. This period was chosen to maximize the sample size, while at the same time ensuring that temporal trends were not present in the R series (An obvious step-change in R occurs around 1962).

Table 4.1 Comparison of statistics for subsets of August Cooling Ratios (YVR:Steveston) for the period 1953-60.

	All data	**$\Phi_w \leq 0.5$**	**$\Phi_w > 0.5$**	**50th percentile (above average cooling at Steveston)**
Maximum *R*	2	2	1.08	1.04
Minimum *R*	0.45	0.45	0.59	0.45
Mean *R*	0.79	0.82	0.74	0.74
Median *R*	0.77	0.81	0.73	0.72
Standard deviation of *R*	0.16	0.18	0.10	0.09
N	248	179	69	122
95% Confidence limits for mean, median	0.02	0.03	0.02	0.02

In addition to statistics for the entire data set (1953-60), the above table also includes three subsets of the data: poor weather conditions only ($\Phi_w \leq 0.5$); favorable weather conditions only ($\Phi_w > 0.5$); and the 50th percentile of cooling events (i.e., occasions when cooling at Steveston was large). This last subset was included to determine if it would be possible to select good cooling 'events' without the need to calculate Φ_w for each day. This alternative would make the technique more widely applicable, since many climate stations do not have nearby hourly synoptic data available with which to calculate Φ_w.

Results indicate that the scatter at low Φ_w does bias the estimate of the mean and median. R for poor weather conditions are significantly higher (95% confidence limit) than those calculated for favourable weather conditions. Inclusion of all weather conditions slightly overestimates the mean and median, relative to the $\Phi_w > 0.5$ set. There is good agreement of the means and medians estimated from the $\Phi_w > 0.5$ set, and the 50^{th} percentile cooling data. Use of the latter increased the sample size by 75%, while ensuring that nights that did not experience significant cooling were excluded. Considering the above, estimating statistical properties from 'best' cooling events in a month (the 50^{th} percentile), appears to be the optimal approach. This approach has the added considerable benefit that a reliable determination of R can be obtained without the use of detailed ancillary weather data.

Figure 4.7a and 4.7b show time series of daily August R values for 1953 to 1970, for YVR:Steveston and Ladner:Steveston. Day-to-day variability is apparent, but the mean value appears constant throughout the whole period in the Ladner:Steveston case, while a step change in the mean is evident around 1962 for YVR:Steveston. The timing of this step change corresponds to station moves at both Steveston and the Airport around this time. These series are examined in more detail in Chapter 5.

4.5 Summary of potential advantages of cooling ratios for homogeneity analysis

The above analyses suggest that cooling ratios are potentially useful to identify microclimatic biases in temperature records, offering several advantages over existing homogeneity analysis methods. In summary,

- Nocturnal cooling is a physically relevant process related to the microclimatic environment of climate stations. Cooling ratios are therefore likely to be a more physically meaningful measure of the degree of thermal modification of a climate station's surroundings than surrogate measures such as population, or satellite derived night-light intensities that are presently used to designate stations as either "rural" or "urban." (i.e. interpreted to be little or unaffected, or adversely affected, by human site disturbance).
- Cooling ratios derived from occasions when strong cooling occurs, (and therefore when microclimatic biases should be most pronounced) reduce the possibility of these subtle biases being obscured as they would be in monthly, seasonal, or annual averages.
- While temperatures themselves are inherently variable because they respond to regional or global climate trends, cooling ratios, on the other hand, appear to be remarkably stable (i.e. invariant with absolute temperature or soil moisture), making them better suited to the detection of small, site-specific trends.
- R is dimensionless, which simplifies interpretation and permits comparisons between sites.
- Cooling ratios are calculated from daily maximum and minimum temperatures, which are the basic observations made at almost every climate station so that the technique is widely applicable.

Analysis of cooling ratio time series therefore appears to be potentially useful for the identification of site specific microclimatic biases in temperature series. This possibility is explored in the following chapter, where a technique is presented to aid in the interpretation of time series of cooling ratios.

Chapter 5
ANALYSIS OF TIME SERIES OF COOLING RATIOS: APPLICATION OF HURST RESCALING

5.1 Introduction

Chapter 4 described the derivation of cooling ratio time series from climatological records of daily maximum and minimum temperatures, and demonstrated the suitability of the cooling ratio as a measure of microclimate differences between neighbouring climate stations. Change points in the time series are assumed to indicate changes to the micro-environment that influence site-specific controls on the nocturnal cooling process, and that introduce inhomogeneities into the temperature record. As discussed in Chapter 2, inhomogeneities of this type have proven difficult to detect in conventional analyses based on the temperature series alone.

The current chapter presents examples of cooling ratio time series from several pairs of Canadian climate stations, examined in conjunction with station history information. Application of the technique of Hurst Rescaling (Hurst, 1951; Outcalt *et al.*, 1997) is investigated, and found to be useful in the interpretation of the time series. These results are then compared to other homogeneity analyses of Canadian temperature records (Gullett *et al.* 1990, Gullett *et al.* 1991 and Vincent 1998) in order to illustrate the advantages of the present methods in the detection of microclimate biases in climate records.

5.2 Hurst Rescaling: background

While analyzing historical hydrological records in relation to flooding of the Nile River, Harold Edwin Hurst developed a time series transformation technique to identify long-term persistence in geophysical time series (Hurst, 1951). Since then, Hurst rescaling has been successfully used to identify distinct physical regimes within a variety of geophysical time series (e.g. precipitation: Potter 1976 and Potter 1979; river flow levels, sunspot frequency, earth-quake frequency, lake sediment varves, bedding thickness and tree ring thickness: Mandelbrot and Wallis, 1982 and Outcalt *et al.* 1997).

As outlined by Outcalt *et al.* (1997) (also see Appendix 2), Hurst rescaling entails subtracting the mean of the time series from each of the original observations. These deviations are then summed cumulatively to create a transformed time series, Q_i.. Thus for the case of time series of monthly median cooling ratios, R_i, for n months, as defined in Chapter 4 (and Appendix 2),

$$Q_i = \sum_{i=1}^{i} (R_i - \bar{R}) \qquad (5.1)$$

Then,

$$r_n = Q_{max} - Q_{min} \qquad (5.2)$$

Where r_n is defined as the *adjusted range* of the series, and Q_{max} and Q_{min} are the maximum and minimum values of Q_i, respectively. The *rescaled range* is r_n/s, where s is the standard deviation of the original time series. The rescaled range is expected to increase asymptotically with the square root of the number of observations, n. That is, $r_n/s \approx n^H$, where H, the Hurst exponent, has an expected value of 0.5. (See Appendix 2 for the calculation of H). However, it has been shown that many geophysical time series have a value of H greater than 0.5 – an occurrence termed the *Hurst phenomenon*. Elevated values of H are attributed to persistence, non-stationarity in the record mean, or pooling samples with different distribution characteristics (Outcalt *et al.* 1997).

Outcalt *et al.* (1997) also showed that if the accumulated deviations from the mean are normalized by the adjusted range of the series, $(Q_i\text{-}Q_{min})/r_n$, the normalized series can be plotted and visually inspected to identify distinct physical regimes within the series. Regime transitions are easily identified at inflection points in the normalized series. For example, a persistent period of above average conditions becomes transformed as an ascending trace, because positive differences from the mean are accumulating. A transition to below average values is marked by an inflection point, (*i.e.* a change from a positive to a negative slope) Steeper slopes result from larger deviations from the mean, and therefore small changes in the slope (*i.e.* not just changes of sign) may also signal regime transitions.

There are several advantages to this rescaling technique, the most obvious being the ease of interpretation compared to original, often highly variable time series. Also, Outcalt *et al.* (1997) point out that "*Hurst rescaling liberates investigators from using arbitrary periods or the informal method of visual decomposition.*"

Hurst rescaling is potentially useful in the analysis of time series of climate station cooling ratios (as defined in Chapter 4) as a method of identifying microclimatic regimes which could affect temperature observations. Changes to the microclimatic environment constitute changes to the physical controls on nocturnal cooling, and should therefore become evident as 'regime transitions' when the normalized transformed series is plotted.

5.3 Analysis and interpretation of rescaled cooling ratios

Hurst rescaling was applied to time series of *R* ratios from several climate station pairs to determine if this data transformation technique is useful for identifying inhomogeneities in *R* time series. In the following examples, the original time series are monthly median *R* values for the 50^{th} percentile of cooling events (i.e. only those nights which experienced above average cooling are used to calculate the median *R* value; see Chapter 4 for an explanation of the calculation of *R*). These series were then rescaled and the Hurst exponent was calculated according to the procedure outlined in Appendix 2. As the first example below illustrates, if $H = 0.5$, then inflection points on the rescaled trace are not significant; that is, the series can be considered homogeneous. If the Hurst exponent exceeds 0.5, then the rescaled trace can be inspected for trace inflections. Station history files were examined in conjunction with the trace to determine if inflection points correspond to documented physical changes to either station's micro-environment.

Although the correspondence of trace inflection points to the timing of documented site changes does not prove causality, Gullett *et al.* (1991) state that "*whenever the available historical information supports [these] mathematical changepoints with evidence of human-induced influences on the dataset, confidence is assured that the inhomogeneities are indeed unrelated to natural climate variations.*" Given the relative invariability of cooling ratios over time as outlined in the previous chapter, and the fact that the use of a ratio eliminates climatic variability common to both stations, even greater confidence can be assumed in attributing the cause of trace inflection points to documented non-climatic changes. In the case where historical records are not available to indicate the cause of the inflection point, it is still reasonable to interpret change points in the *R* series as inhomogeneities capable of biasing the record.

The station history files used in the following analyses consist of periodic reports by inspectors, photographs, site plans, maps and miscellaneous information held in the archives of the Meteorological Service of Canada in Downsview, Ontario. Station records were selected on the basis of several criteria: thoroughness of the station history file; length and completeness of temperature records; proximity to other stations in order to calculate meaningful cooling ratios; uniformity of regional characteristics to eliminate other sources of between-station differences; and the variety of site-specific features or changes at different stations which might aid illustration of the technique.

5.3.1 Example 1. Ladner : Steveston

The first example of Hurst rescaled *R* is from the station pair of Ladner and Steveston, two rural stations near Vancouver, BC. Statistics for the original and rescaled series are listed in Table 5.8. These sites were introduced in Chapter 4, and summaries of the station histories are given in Tables 5.1 and 5.2. Temperature data are available for 1953 to 1970. Site photographs are shown in Figures 5.1 and 5.2. This example illustrates the importance of calculating the Hurst exponent prior to interpreting the rescaled trace. In this case, the calculated value of *H* is 0.5, indicating the absence of mixed regimes, or essentially a random series. The apparent stationarity of the mean *R* values (Figure 5.3) supports this conclusion, yet the Hurst rescaled trace shows a number of inflection points which could have been misinterpreted as significant regime transitions if the Hurst exponent were not known.

Table 5.1 Summary of station history for Ladner, BC.

Date	**Excerpts from station history file**
24-05-1953	Excellent exposure. Open land in all directions, some shelter from a narrow windbreak to the west .
23-05-1958	A good open exposure. Screen is on a 3'3' concrete block surrounded by grass.

29-08-1963	Exposure: A heavy clay soil covered with tall wild grass which is kept trimmed short in the instrument area. A completely open area with a row of trees 30 feet to the west and a tree and two small buildings 40 feet to the north; several maximum thermometers being broken each year
19-08-1969	Maximum thermometer replaced; reading 4 degrees Fahrenheit too high
6-11-1969	Station relocated 200 feet north; no change in elevation or exposure
8-12-1969	New screen and stand
6-10-1971	Station closed

Table 5.2 Summary of station history information for Steveston, BC.

Date	**Excerpts from station history file**
1-12-1950	The instruments are located in the large back yard of the observer's property. His residence is to the south and there are a few fruit trees and small buildings to the east and west. Unobstructed to the north. The Station is located on Lulu Island in the flat lands of the delta of the Fraser River.
1959	Screen painted
13-7-1962	Observer requested to take two observations a day
11-03-1970	Station moved and downgraded to precipitation only

As the station histories imply, there is every reason to expect the individual temperature series to be homogenous, and thus the cooling ratio to remain constant over time. Both stations were well exposed in similar rural settings, with no station moves or changes to exposure throughout this period (Ladner did move a short distance, but probably too close to the end of the record to have any effect). Other than a few screen paintings, several broken maximum thermometers at Ladner, a possible change from one to two observations per day at Steveston (indicated by symbols on trace in Figure 5.3), there are no apparent sources of inhomogeneities at either site. Therefore, a stationary mean R, and a Hurst exponent of 0.5 appear to be good indicators of unchanging microclimate conditions, and homogeneity.

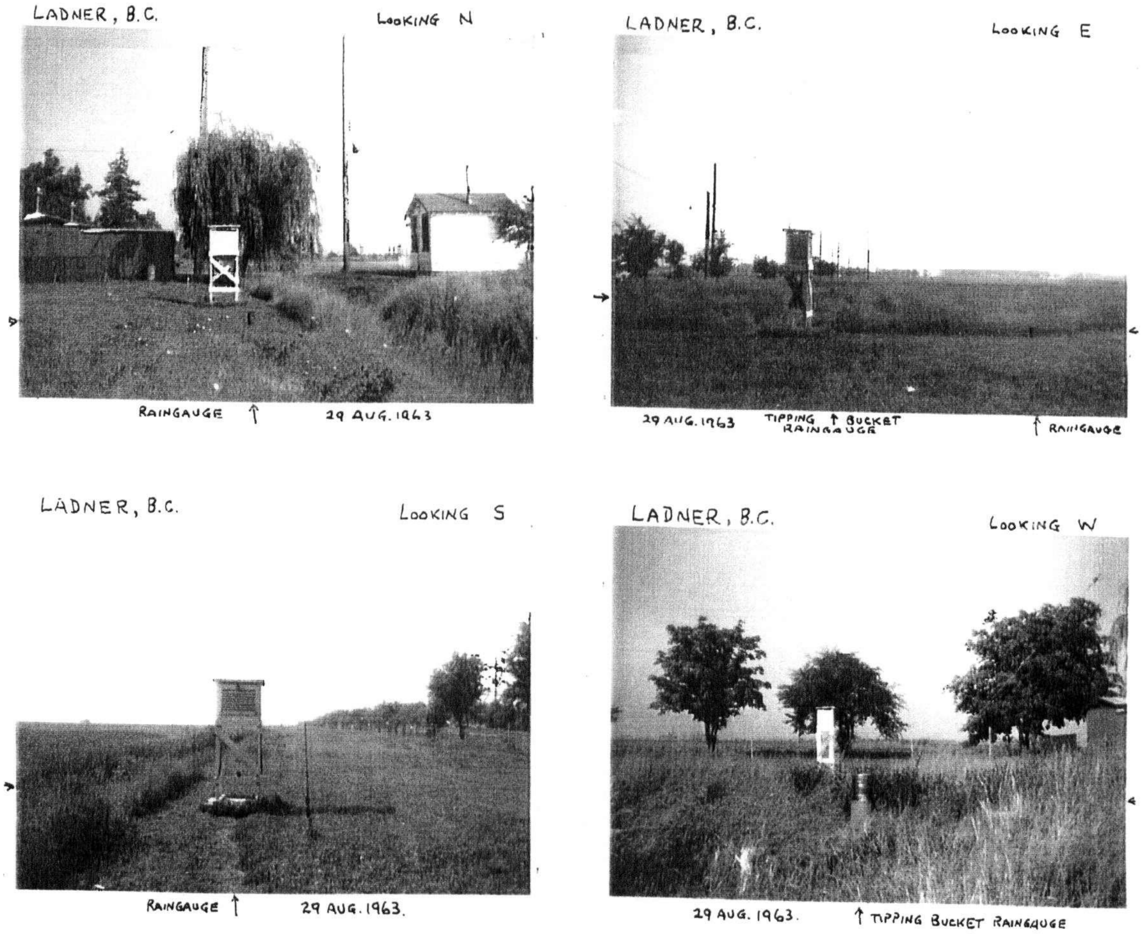


Figure 5.1 Site photographs for Ladner, B.C., August 1963.

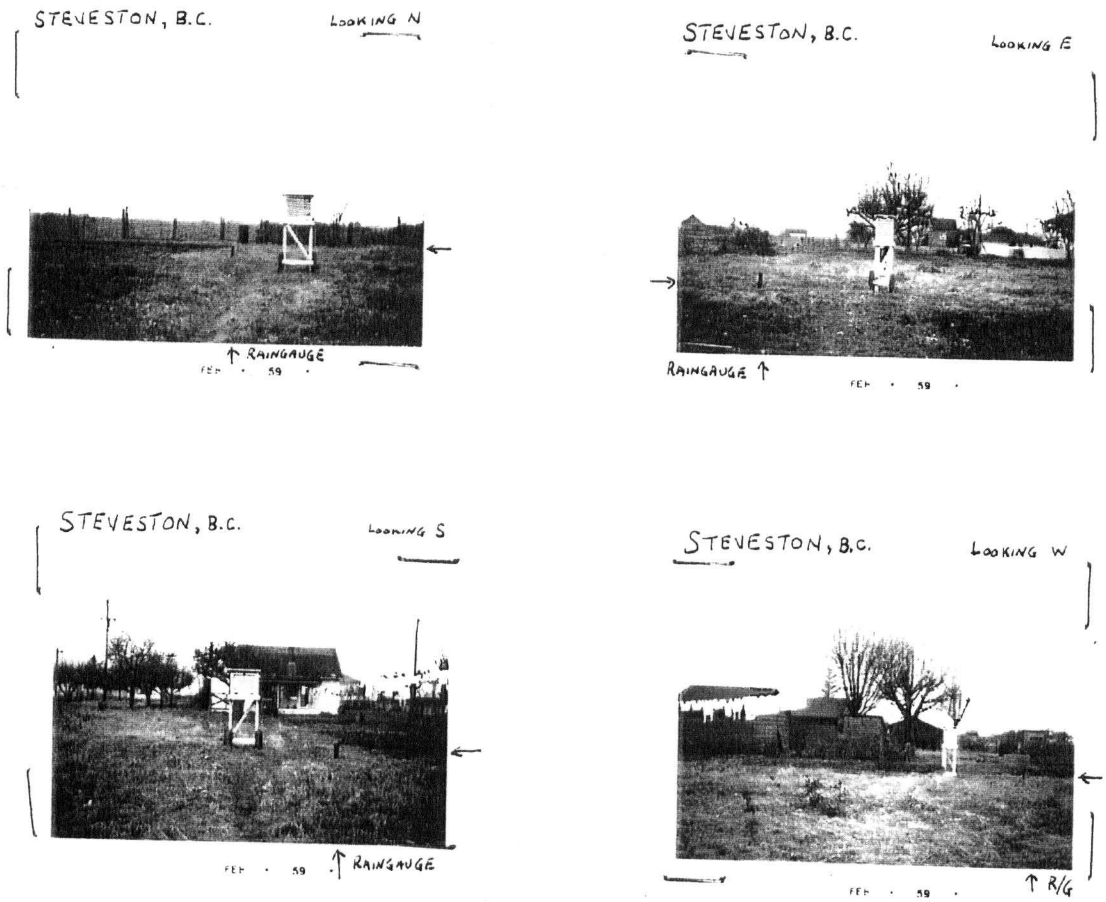


Figure 5.2 Site photographs for Steveston, B.C., February 1959.

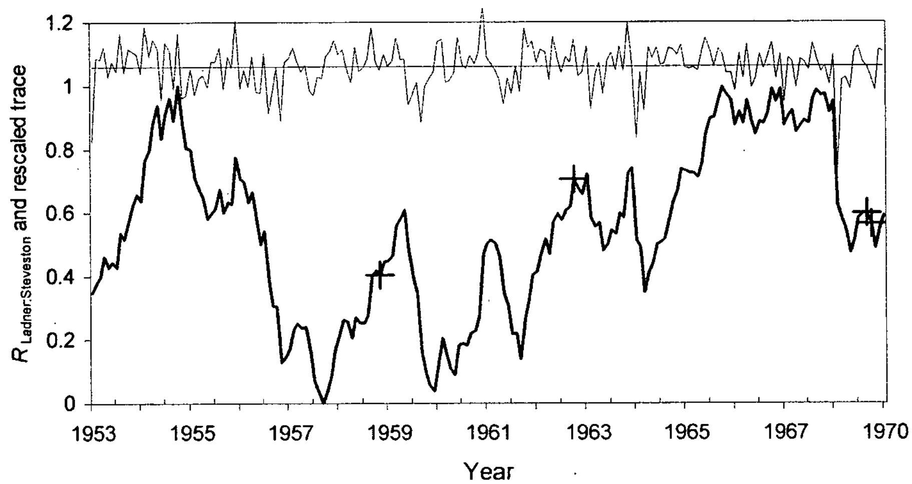


Figure 5.3 $R_{\text{Ladner : Steveston}}$, and Hurst rescaled R (bold line). $H = 0.5$
Symbols (+) denote events documented in station history files (see Tables 5.1 and 5.2).

5.3.2 Example 2: Edmonton Municipal Airport : Edmonton International Airport

Edmonton Municipal Airport and Edmonton International Airport are both first order synoptic stations near Edmonton, Alberta. The first (EMA) lies within the City of Edmonton, (3 km northwest of the city centre), and is documented to be influenced by the urban heat island effect of the city (Hage, 1972). Also, Gullett *et al.*. (1991) found the daily minimum temperature to exhibit an inhomogeneity in the form of a warming trend from 1968 to 1983, consistent with the expected influence of the urban heat island effect. Edmonton International Airport (EIA) is 26 km south-southwest of the city centre, and is generally believed to be outside of the city's thermal influence (Hage, 1972). The period of overlap for daily temperature records is 1961 to 1998. Edmonton International was not tested for inhomogeneities by Gullett *et al.*. (1991). These two stations were selected to explore the applicability of Hurst rescaling because of the extensive station history information that is available for both stations and is necessary to interpret the significance of inflection points in the rescaled time series.

The Hurst exponent calculated for the R series was 0.76, (Table 5.8) indicating the presence of mixed cooling regimes which should be apparent in the rescaled trace.

(i) Effect of seasonal variations of R

It is necessary to address the effect the seasonality of R time series (demonstrated in Chapter 4) on the interpretation of the Hurst rescaled time series. Outcalt, *et al.*, (1997) showed that seasonal cycles need not be removed before applying this technique, because they do not change the overall pattern of the rescaled trace. This also appears to be the case for rescaled R time series, as shown by the similarities of the two traces in Figure 5.4, one

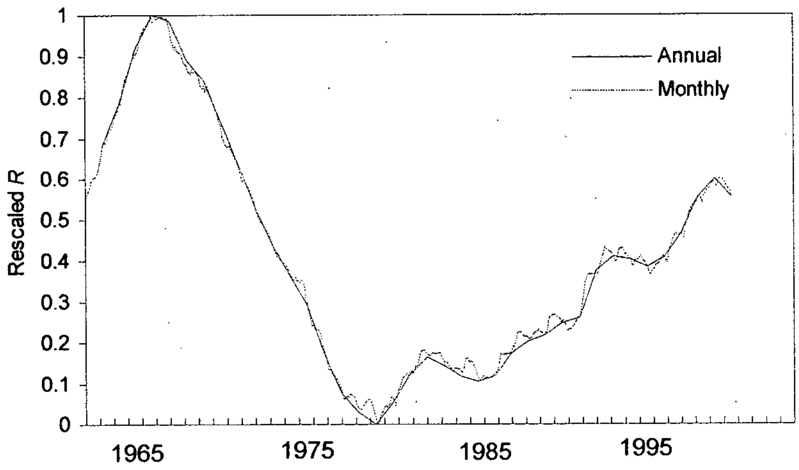


Figure 5.4 Comparison of Hurst rescaled traces using monthly and annual data for Edmonton Municipal : Edmonton International cooling ratios. $H = 0.76$ (monthly) and $H = 0.73$ (annual). Major inflection points are evident in both series.

being determined from annual mean values, the other from monthly means. Using monthly data adds only small irregularities onto the trace, but does not change the location of major inflection points. H = 0.73 for the annual series, compared to 0.76 for the monthly series (Table 5.8). Therefore, there does not appear to be any significant advantage to using either annual or monthly means. While the former may be slightly easier to interpret, the latter can be used to identify a specific month in which a regime transition occurred. Also, the sample size is reduced by a factor of 12 for the annual average, which may be problematic if the original time series is short. This problem becomes apparent in the calculation of the Hurst exponent, where values of $H < 0.5$ result from an insufficient sample size. Thus, a smaller sample size will make the significance of the rescaled trace difficult to evaluate. Throughout this chapter, time series of monthly R values are used in order to maintain a larger sample size and therefore calculate a meaningful value of the Hurst exponent.

(ii) Identification of cooling regimes in the rescaled trace

Figure 5.5 shows the R time series and the rescaled trace for Edmonton Municipal: Edmonton International for the period 1961-1991. Timing of events noted in the station history files (Table 5.3) that could possibly affect temperature observations are indicated by symbols on the trace. Changes to the immediate environment of both sites are evident in the series of site photographs shown in Figures 5.6 (Edmonton Municipal) and 5.7 (Edmonton International).

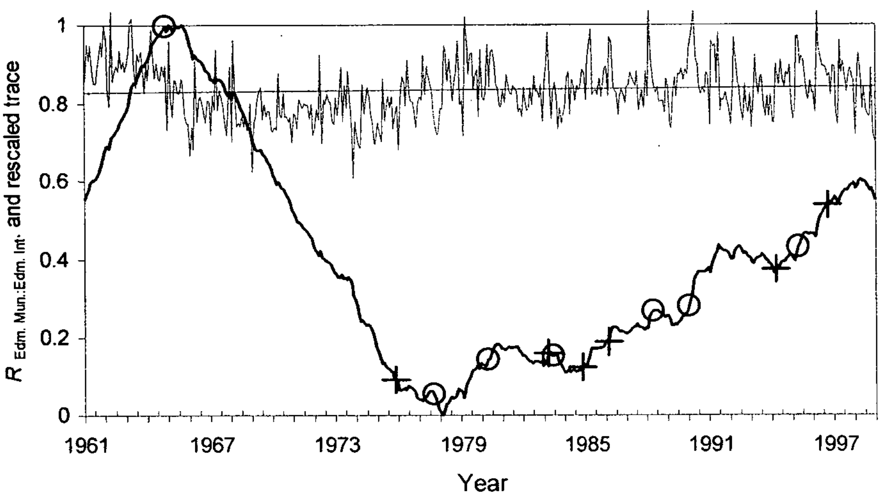


Figure 5.5 $R_{\text{Edmonton Municipal : Edmonton International}}$ and Hurst rescaled trace (bold) $H = 0.76$. Symbols denote events documented in station history files (Tables 5.3, 5.4): + Edmonton Municipal; O Edmonton International.

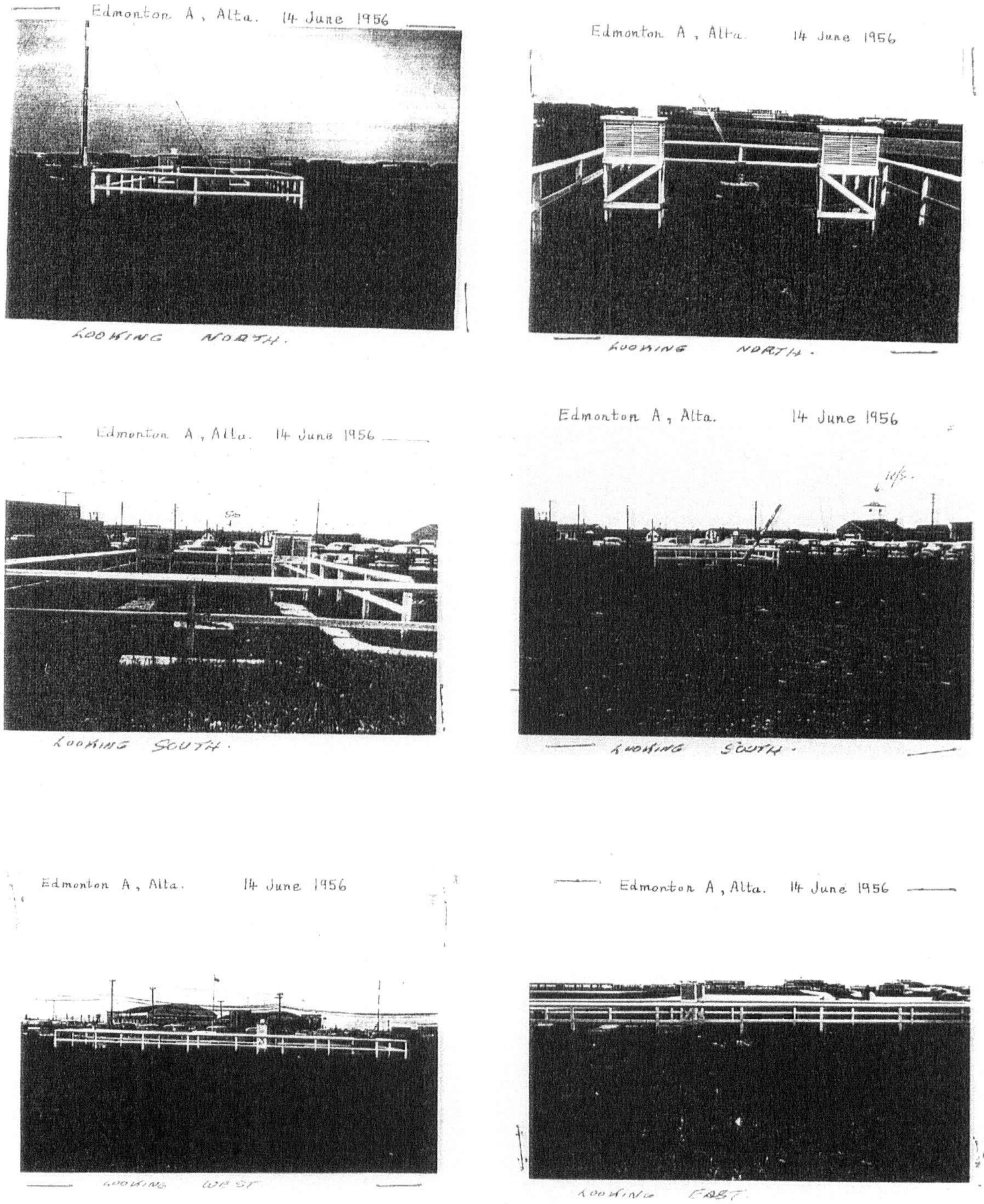


Figure 5.6 (a) Site photographs at Edmonton Municipal Airport, June 1956.

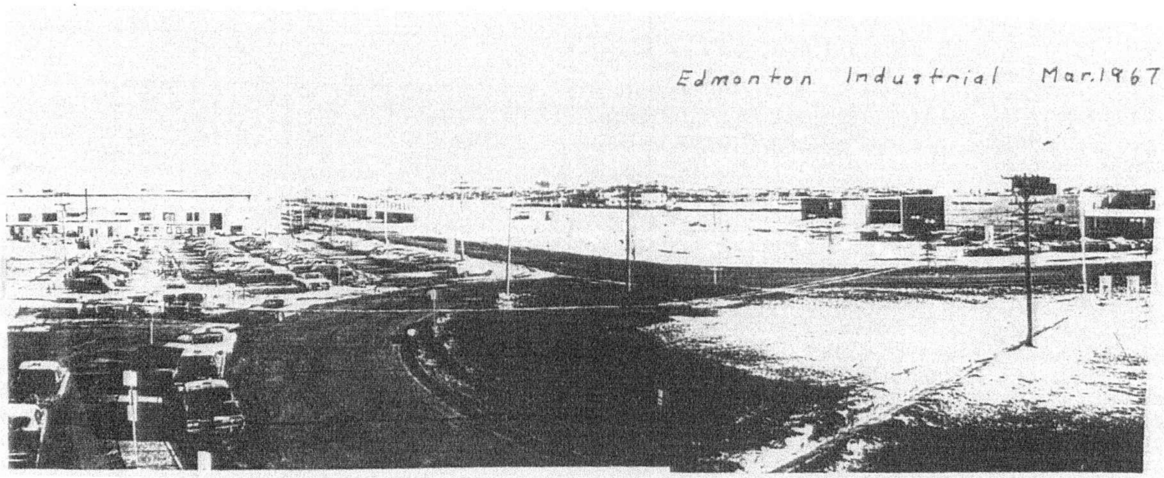
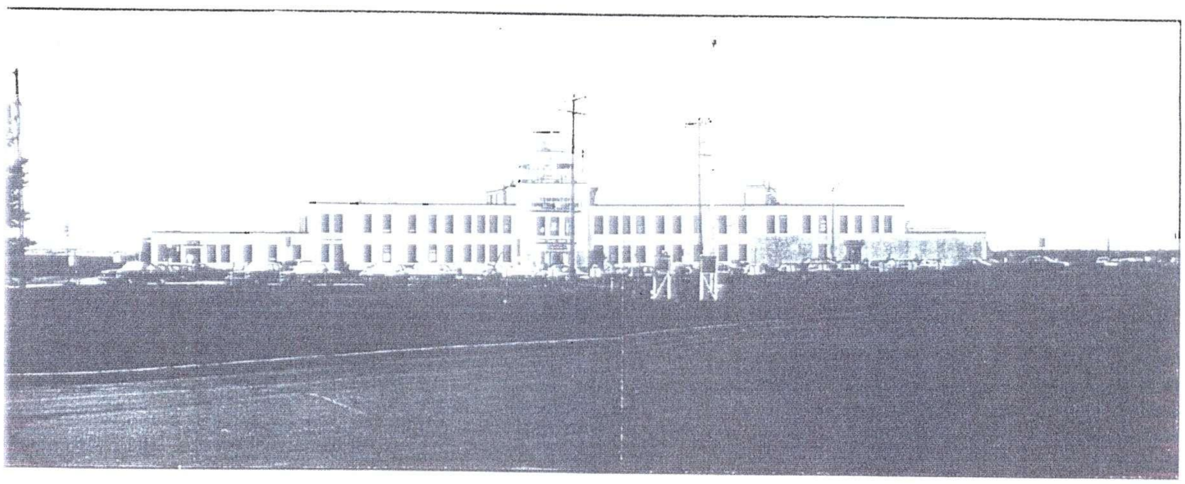


Figure 5.6 (b) Edmonton Municipal Airport instrument enclosure and surroundings, March 1967, looking south-southwest.



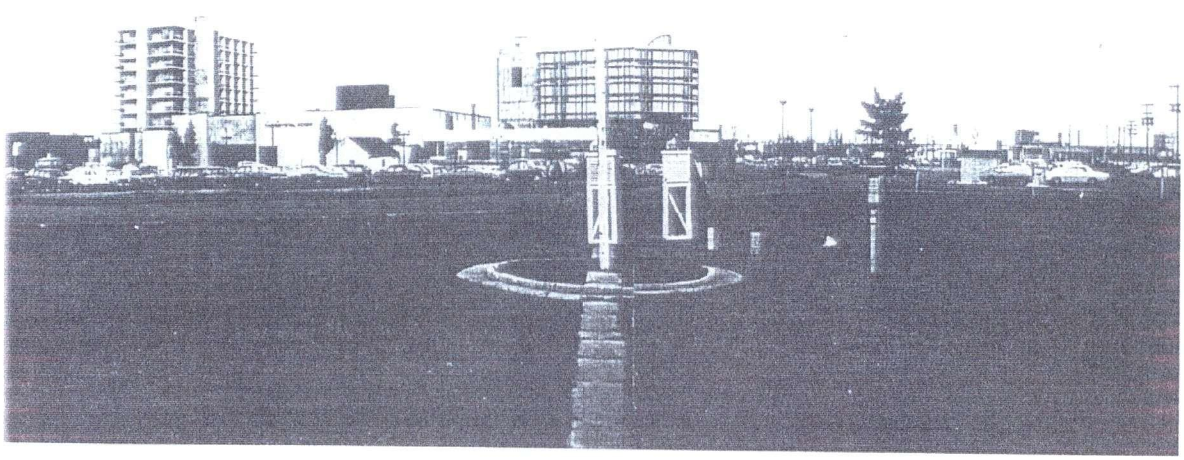


Figure 5.6 (c) Edmonton Municipal Airport instrument site, May 1973; facing north (upper photo), and south (lower photo).

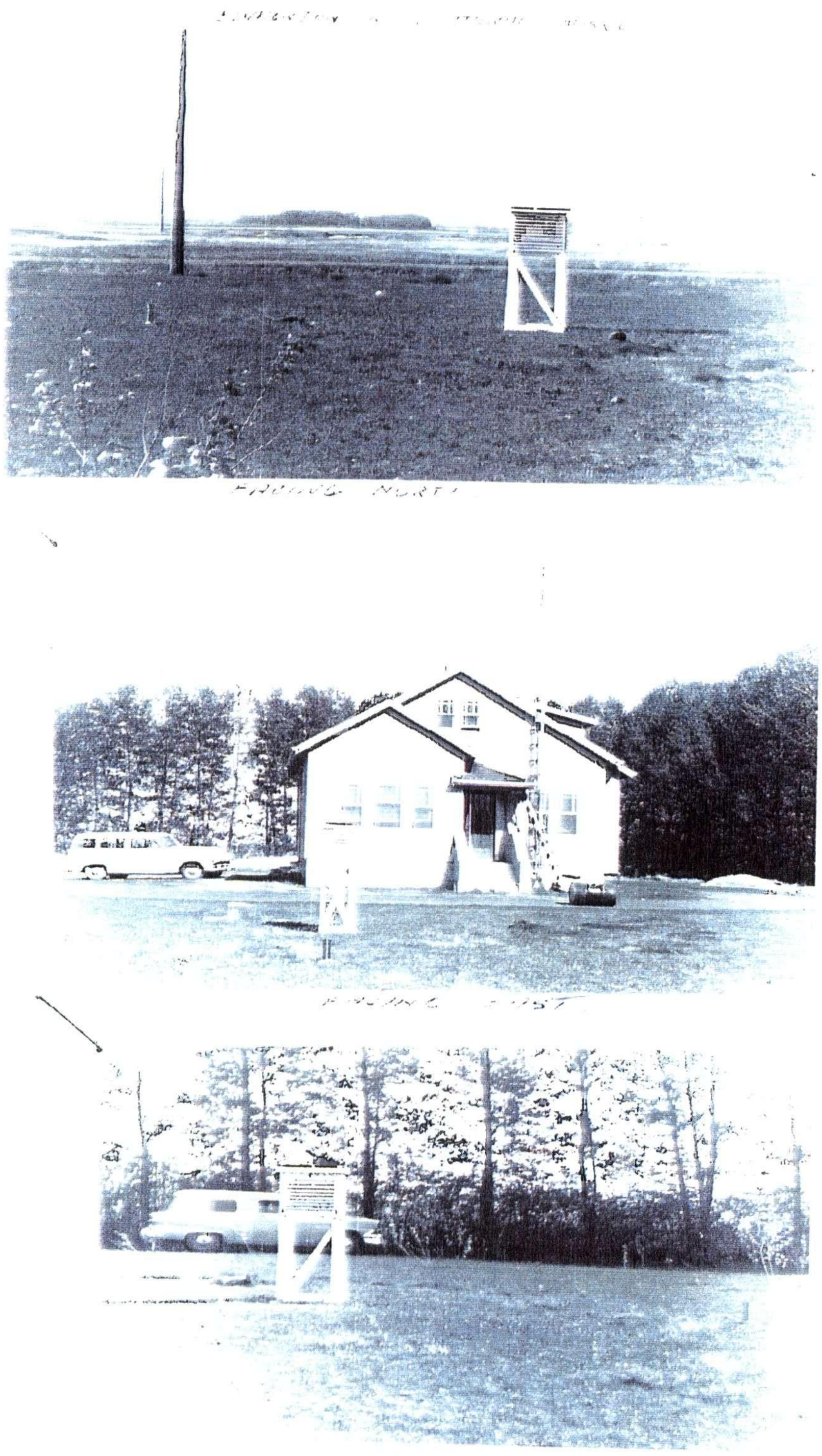


Figure 5.7 (a) Initial instrument site at Edmonton International Airport, May, 1959. Photos show views to north, east and south, top to bottom respectively.

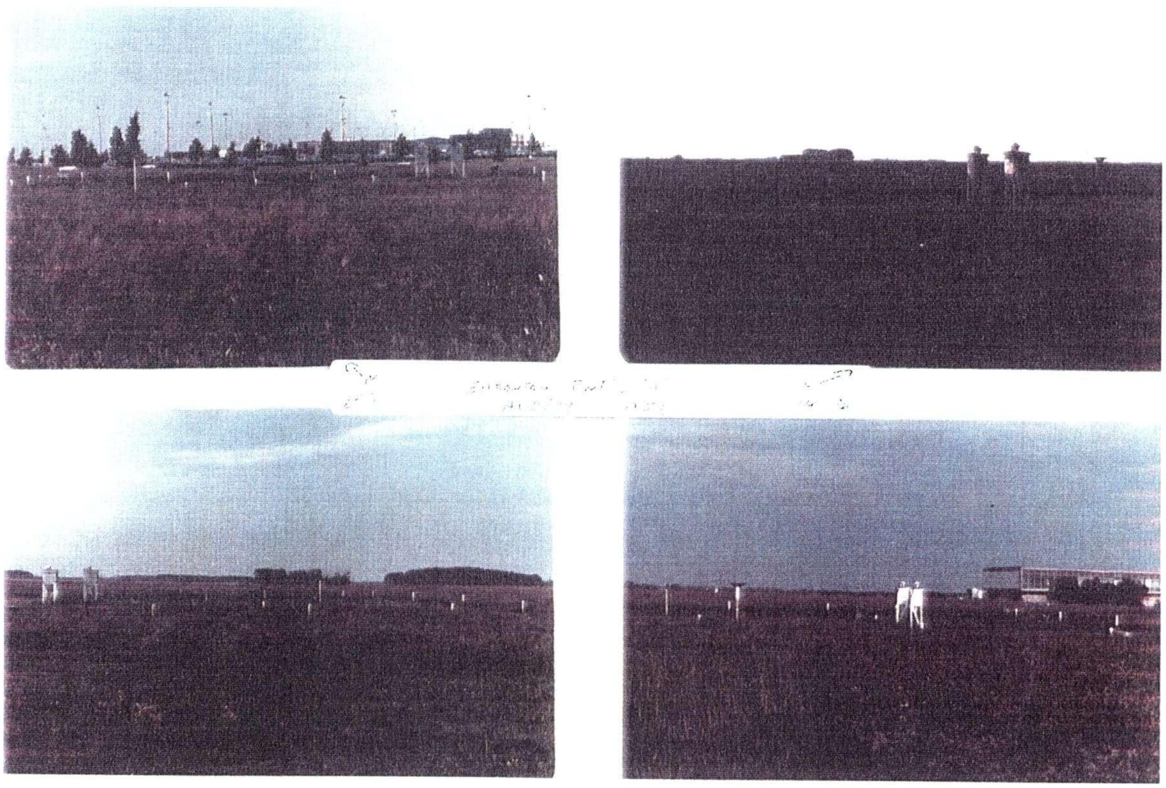


Figure 5.7 (b) Edmonton International Airport climate station, August, 1979.

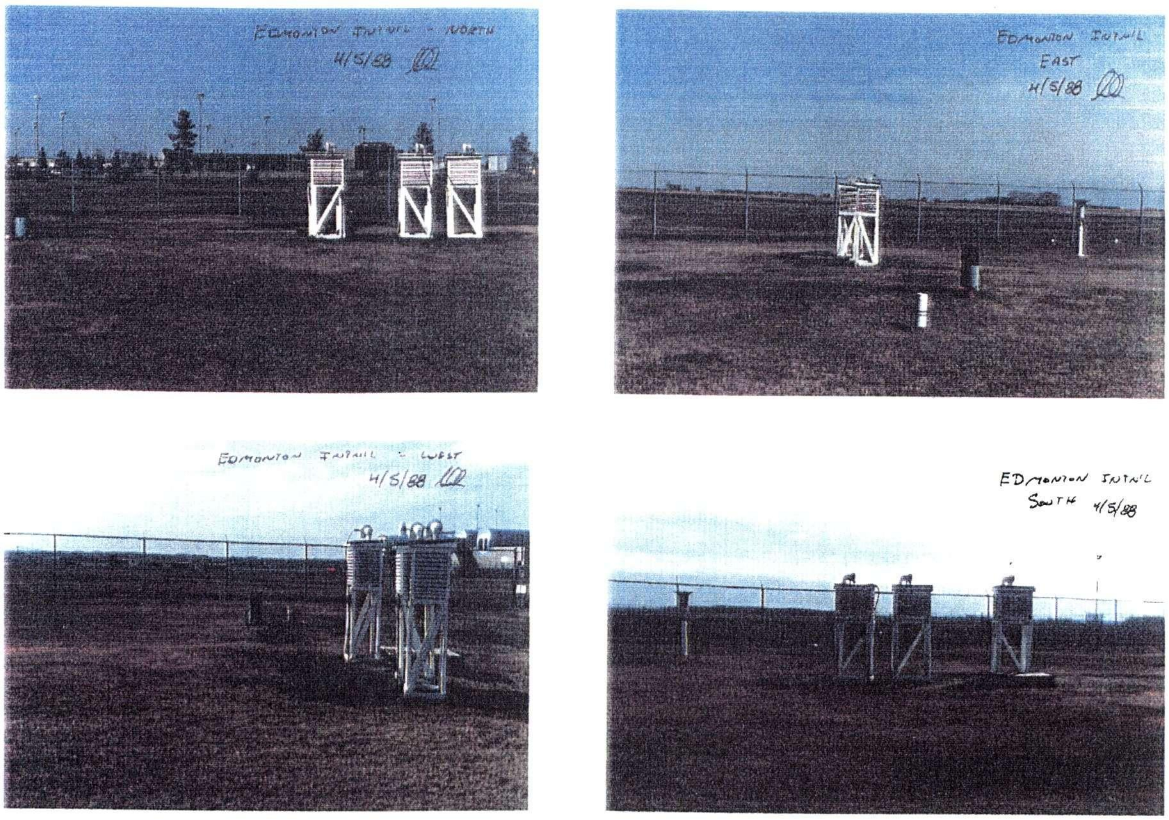


Figure 5.7 (c) Edmonton International Airport climate station, May, 1988.

Table 5.3 Summary of station history for Edmonton Municipal Airport. Comments or inferences drawn from photographs, sketches or ambiguous details are indicated in italics.

Date	**Excerpts from station history file**
30-12-1955	Suitable exposure, but close to taxi strip and parking
14-06-1956	*Photographs show large parking area immediately south of instruments*
1970	Instrument enclosure is an open circular area approximately 50 feet in diameter located approximately 100 feet southwest of Administration Building. Area is covered with grass
04-05-1973	Instrument area is immediately south of the Terminal building in an open, grassed traffic circle which has been gradually reduced in area by the widening of the roadways and the addition of new parking areas
13-11-1975	Instruments moved to a more open site: instruments are located on a level grassed area situated between the runways. The boundary of the instrument area is 300 feet north of runway 11-29 and 300 feet east of runway 03-21. All of the meteorological equipment at the station is either new or has been refurbished prior to installation in the new instrument area
16-03-1983	Several new buildings of varying heights have been constructed over the past several years
06-11-1984	Stevenson screen containing max- and min thermometers mounted on the roof of the ATB. The exposure of these instruments is compromised by the proximity of tall buildings, air conditioning and heat vents, and the gravel and tar finish on the roof
10-02-1986	Maximum and minimum thermometers were removed from service as the new R.T.D. kept track of these. *R.T.D. appears to be located at the previous original site on the ground.* All instruments meet exposure criteria.
20-03-1990	Recommendation: replace screen early summer 1990. *Not clear if screens were in fact replaced at this time.*
29-03-1994	*Station becomes automated*
28-09-1996	Three foxes are now living at the AWOS site and have been busy digging tunnel underneath the AWOS shack.

Table 5.4 Summary of station history for Edmonton International Airport. Comments or inferences drawn from photographs, sketches or ambiguous details are indicated in italics.

Date	**Excerpts from station history file**
07-05-1959	Large level yard 75 ft. West of temporary engineering office. Open exposure obstructed only by windbreak 30 ft. High to south and east. Surrounding land is fairly level and open (airport clearing) dotted with poplar bluffs except in vicinity of runways under construction.
14-11-1960	Observations officially start with opening of airport
18-11-1964	Observing site moved 1.5 miles southwest of the original site, to former Control tower located one-half mile west of the junction of runways 11-29 and 01-19. ¾ mile west of the terminal building.
12-1970	Instrument area is an open plot 200 feet south of the observing tower (since 1964). The area is grass covered
26-02-1976	All instruments have excellent exposure and no change in exposure has occurred since original installation.
30-19-1977	*Sketch shows instruments moved to south-east side of airport.*
07-08-1979	All instruments have excellent exposure. The grass in the instrument area consists of alfalfa and clover and it should be leveled and sown with a good quality of grass. A link chain is require to complete the fence. A walk is also required out to add in the instrument area because the present path becomes very muddy during inclement weather
14-04-1980	Over the winter season the area around the instrument compound was used a s a temporary parking lot. As a result the path became very muddy. The O.I.C. advised that MOT would not be using that area for parking in the future and that they would put gravel on the path. The area directly in front of the Stevenson screen becomes muddy as there is no grass growing yet. The area in the compound should be properly landscaped and seeded with grass. Platforms will have to be built in front of the Stevenson Screens. Both screens are badly in need of painting
12-06-1981	Judging by the condition of most of the outside instruments, it is evident that routine care and maintenance of this equipment is practically non-existent. *Screens have not been painted since previous report*
04-06-1982	The instrument area and vicinity was very poorly kept and untidy with paper from the construction program and the weeds permitted to grow uninhibited. OIC took swift action to have area cleaned up. Screens appear in new condition
13-06-1983	Stevenson Screens replaced as units in service had become weather-worn. New screens exposed at correct height and level Grass planted at instrument site

27-11-1984	Paint starting to flake. Re-leveled maximum and minimum thermometers; cleaned thermometer holders
10-13-1986	Screens over a grassed surface with doors facing north. Good exposure in instrument compound SE of ATB.
18-03-1987	Maintenance of the instrument area and equipment is excellent.
04-05-1988	Screens painted
22-01-1990	The ground level was noted to be rough and uneven, possibly the result of too much gopher activity and frost upheavals. Proper boardwalks (cement or otherwise) should be installed from the instrument compound entrance through to the various instruments Screens need painting Advised to replace minimum thermometer as it had definite signs of bubble formation near the top of temperature scale
12-04-1995	Screen was replaced and leveled

A few general remarks are necessary about interpreting the station history files which are rather limited in the information they provide. It is important to note that it is not always possible to determine the exact date of some of the events or changes noted. For example, inspections frequently occur a few months after a station move, so that the date of the move and the inspection are not the same. At the time of inspections recommendations are often made, such as painting the screen, or changing the observation schedule, but that does not necessarily mean the changes occur immediately after the inspection, or if they ever occur at all. Also, the inspectors' reports often refer to declining exposure over a period of a few years, so that the possible microclimatic biases occur gradually, not necessarily at one instant in time. The biggest problem by far, is that the written reports usually lack detail: often several subsequent reports indicate no changes to exposure, yet photographs clearly show that vegetation has grown, that parking lots have expanded, or that buildings have been constructed or removed. Photographs are probably the most valuable type of historical evidence to document changes to the immediate environment, but unfortunately often they are taken only once or twice during the station history. Thus, it is unrealistic to expect an exact correspondence between rescaled trace inflection points and specific dates noted in the history file, or dates inferred from the available evidence. Nevertheless, station history files remain the only source of information to attempt to explain temporal changes in the *R* series.

Despite the limitations just noted, there is excellent correspondence between major inflection points and events from the station histories (Figure 5.5). The rescaled trace exhibits significant regime transitions around 1965 (EIA moved), 1975 (EMA moved), 1978 (EIA moved November 1977), 1980 (parking around instruments at EIA ends), 1984 (EMA moved to roof), 1992 (no evidence), and 1994 (EMA automated). Smaller inflection points may be due to the seasonality of *R* values, yet some appear to be associated with minor events such as painting the screen (1988).

Identification of distinct change points in the *R* time series is complicated by the fact that both stations were affected by significant development and encroachment of the instrument sites at several different times, but both were particularly affected during the 1970s and early 1980s. Although the rescaled trace decreases over the same period, the cooling ratios alone show a definite upward trend (i.e. getting closer to a value of 1), implying that cooling regimes at the two airports were becoming more similar. This transition could result from changes at either station, but, given the nature of the development, a reasonable interpretation would be that Edmonton International was becoming more like the 'urban' Municipal airport, rather than EMA becoming more like the 'rural' EIA.

Despite the complex influences on this particular time series, through the use of Hurst rescaling it is possible to identify distinct cooling regime transitions that correspond to documented changes to the microclimate environment of the individual stations.

5.3.3 **Example 3: Woodbend:Ellerslie**

This particular station pair was investigated in order to determine the effect of vegetation growth on the homogeneity of temperature records. Ellerslie is the University of Alberta's agricultural research centre located within the city limits of Edmonton, but south of the main urban area. Although Ellerslie's temperature record unfortunately ended in 1986, it is a good 'rural' reference station that remained in the same location throughout its history (See Figure 5.8).

Woodbend is also outside of the urban centre, approximately 22 km southwest of the city (west of Ellerslie and north of Edmonton International Airport). As the photographs in Figure 5.9 show, when Woodbend was first established, the surrounding area appeared to have been recently cleared of trees. Subsequent photographs show that the surrounding trees grew back over time providing significant shelter to the instrument area. Although the sloping surrounding land is not ideal for climate station siting, Woodbend is nevertheless an excellent example of vegetation growth around the station without any other confounding changes over time (i.e. constructions, moves, observer changes etc.). It is therefore suitable for indicating possible effects of vegetation growth on the nocturnal cooling regime at the site, relative to the more open Ellerslie site. Woodbend's temperature record extends from 1973 to present, while Ellerslie's extends from 1963 to 1986, providing only a 13 year common record.

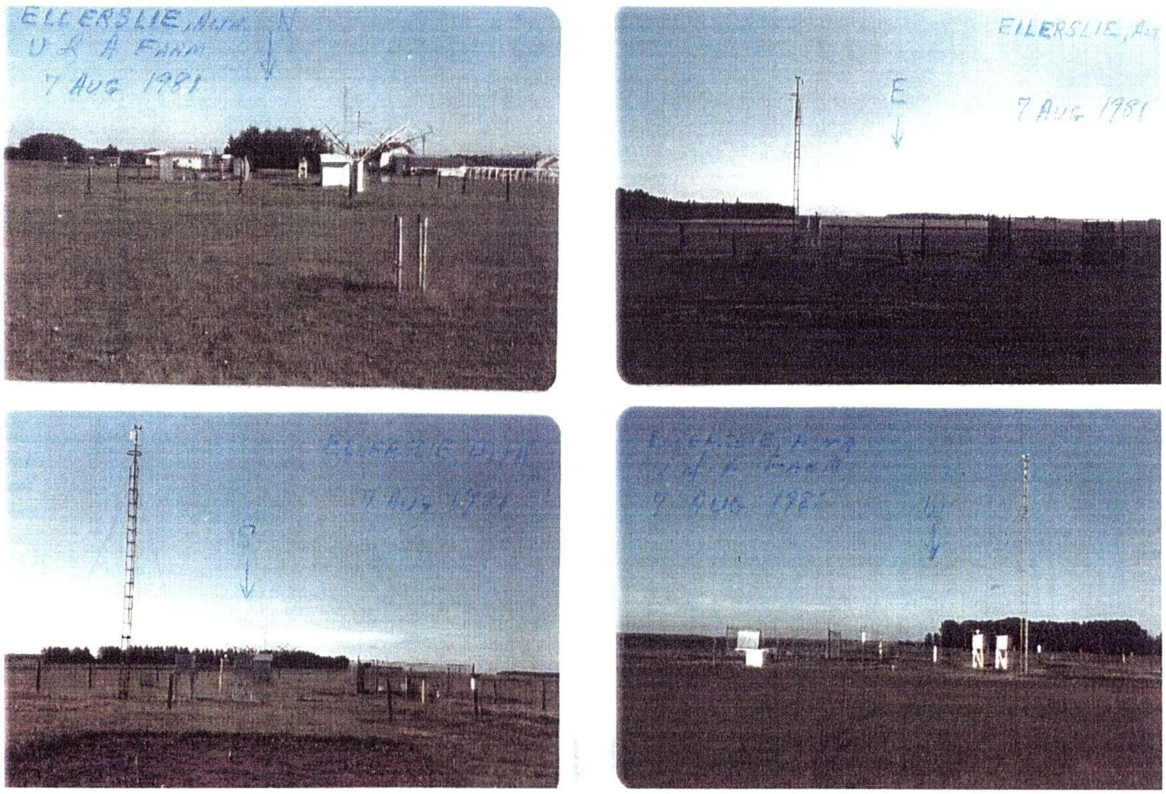


Figure 5.8 Site photographs for Ellerslie, Alberta, August 1981. Clockwise from top left, photos face north, east, west and south.

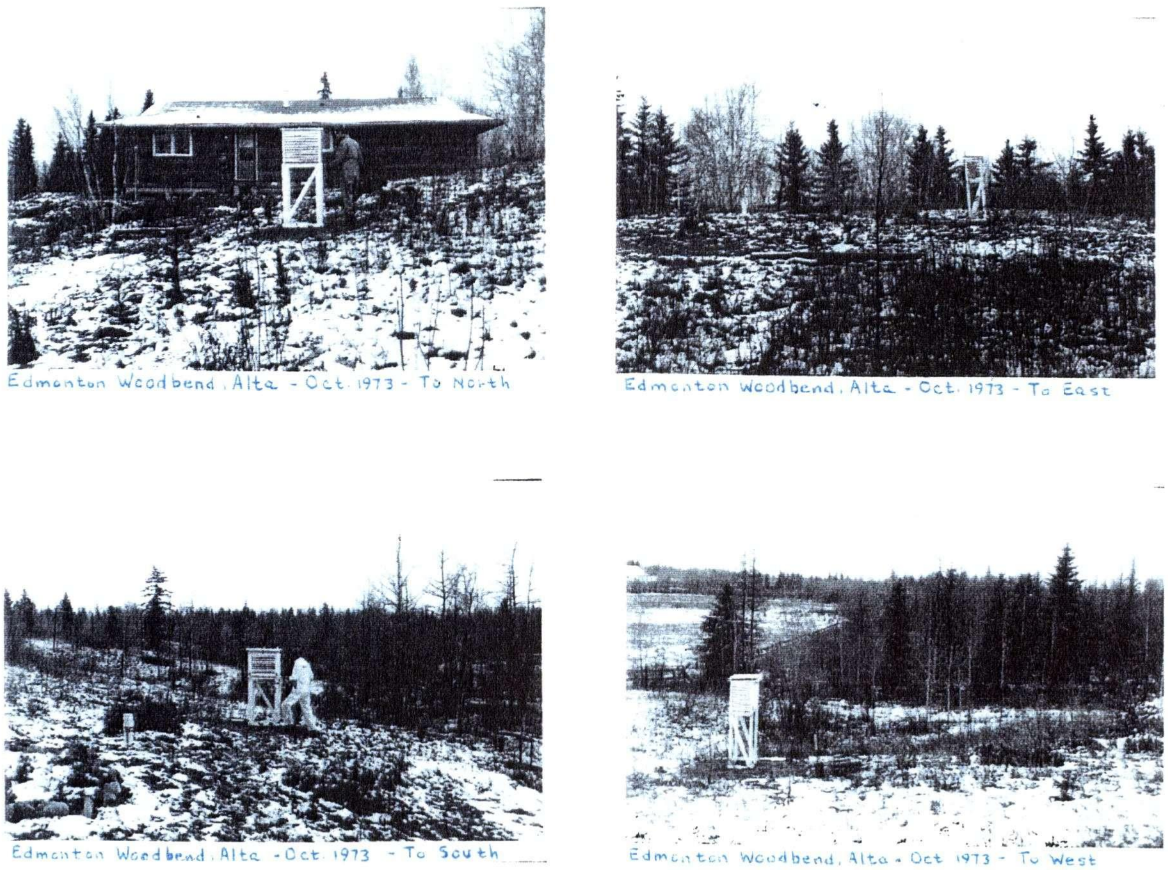


Figure 5.9 (a) Woodbend, Alberta, at time of station establishment, October 1973.

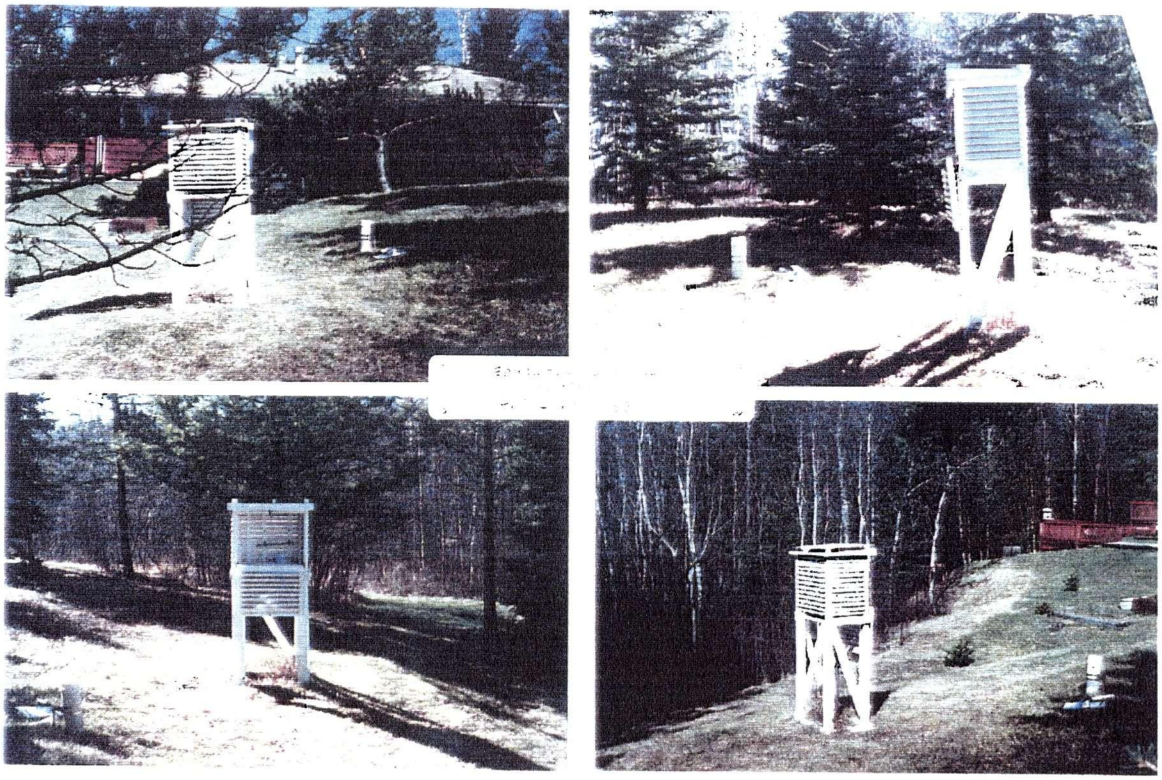


Figure 5.9 (b) Woodbend, Alberta, April 1997. Instruments remain in the same location, as 1973, but significant vegetation growth has affected the exposure.

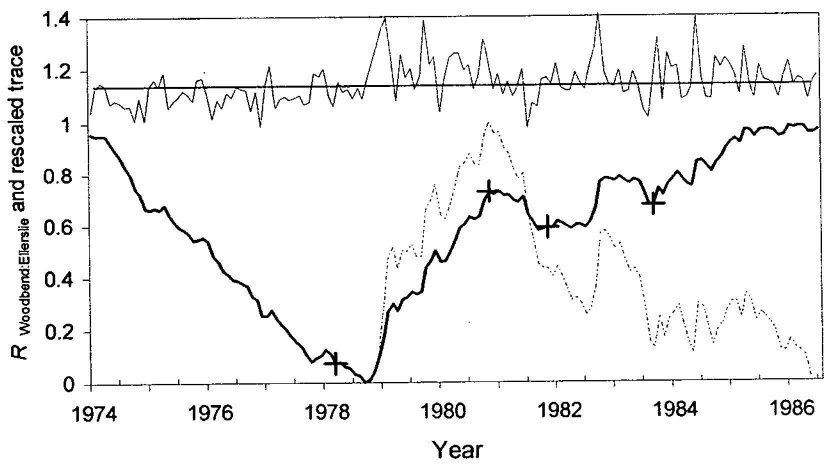


Figure 5.10 $R_{\text{Woodbend : Ellerslie}}$ (upper trace), and Hurst rescaled traces for the periods 1973-1986 (solid) and 1979 - 1986 (dashed). + denotes events documented in Woodbend's station history file (Table 5.5). H = 0.69 for the period 1973-86 , H = 0.34 for 1979-86.

Figure 5.10 shows the original R series for Woodbend:Ellerslie, as well as the rescaled trace, and the rescaled trace determined for the period 1979-1986. A step change in the original R trace is apparent around 1979, and is clearly supported by the change in slope of the rescaled trace. For this reason, a second Hurst rescaling analysis was performed on the series for the period after 1979 to determine if the large step change might obscure smaller inflection points in the trace. Comparison of the two rescaled traces indicates that while they are quite different in form, trace inflections occur at the same time in both series implying that the 1979 step change does not prevent the identification of smaller inflection points. Furthermore, the Hurst exponent was calculated for both series, with $H = 0.69$ for the longer record, and $H = 0.34$ for the shorter record (Table 5.8), implying that the shorter record is less reliable because of its smaller sample size.

The step change in 1979 is attributed to the Woodbend series (rather than to Ellerslie), because a similar step change occurs in the R series for Woodbend: Edmonton International (not shown). Examination of the station file (Table 5.5) indicates that late in 1978 the observation schedule at Woodbend changed from twice daily to only once per day. Such changes in observation schedules have been documented to have detectable effects in the minimum temperature series (See Chapter 2). Interestingly, the 1978 inspector's report for Woodbend still notes "no changes" to the surrounding environment, whereas every report after that (starting in 1981) notes increased tree height. Therefore, perhaps at least part of the 1979 change in the R series may be attributable to noticeable vegetation growth.

Upon examining the period following the step change in 1979, a small negative trend in the original R series is identifiable; Woodbend's cooling decreased 7 per cent relative to the more open Ellerslie site over the 8 year period. Such a trend is consistent with the reduced radiative cooling expected as the sky-view factor decreases with increased vegetation growth. However, vegetation growth could have other effects on the cooling regime as well, such as preventing cold air drainage away from the site and insulating the soil surface as the canopy layer deepened. As discussed in Chapter 3, vegetation growth could also influence the daytime maximum temperature in several ways: cooling of the ground from the increased shade and increased evapotranspiration, and/or warming by reducing natural ventilation of the Stevenson screen. Thus, while Hurst rescaling appears useful to identify physical cooling regime changes, the task of determining the exact physical mechanism responsible for the change is much more complex.

Despite the small Hurst exponent for the 1979-86 rescaled *R* series, implying that the sample is too small to allow reliable interpretation of inflection points, most of the inflection points do occur with documented changes in the history file, (Table 5.5) such as the replacement of the screen in 1981, and the planting of additional trees near the instruments in 1983.

Table 5.5 Summary of station history for Woodbend, Alberta. Comments or inferences drawn from photographs, sketches or ambiguous details are indicated in italics.

Date	Excerpts from station history file
25-10-1973	Gentle rolling, wooded countryside. House 45'x24'x13' 55 ft north. Trees to 20' high 100' south and west. Trees to 20' high 55' east. Good exposure.
01-04-1978	Reduce program from twice daily to the 0800 am report, only.
04-03-1981	Increased height of trees and bush. Trees to 8 m in height 30 m south and west. Trees to 8 m high 17 m east. Reconditioned screen installed. Small separation of approximately 0.3°C removed from minimum thermometer.
15-03-1982	Trees to 8.2 m in height. Rain-gauge will have to be relocated within the next several years due to increasing height of nearby trees 0.5 – 1

	metre in height at present
01-02-1984	*Site plan sketch shows rain gauge has been relocated due to planting of trees (heights of 0.3 to 1.5 m—possibly same small trees noted in 1982)* Changed minimum thermometer
15-02-1983	Some increase in height of trees & bush
28-05-1987	Washed screen.

5.3.4 Example 4: Regina A: Midale

Cooling ratios for the station pair Regina Airport and Midale, Saskatchewan were of interest for two reasons: first, the flat, uniform regional topography minimizes potential sources of between-station differences, ensuring that differences between climate stations are likely due to site-specific influences; and secondly, maximum and minimum temperature series from both stations had been analyzed by Gullett *et al.* (1990) and Gullett *et al.* (1991) and determined to be homogeneous despite station history information at Regina Airport indicating significant encroachment by buildings and runways (Figure 5.11). In fact, inspector reports throughout the 1980s repeatedly made reference to the "heat island problem" at the airport site. Thus comparisons between Gullett *et al.*'s (1990) technique and the Hurst rescaling technique might help to establish whether the latter offered any particular advantages in the detection of site-specific inhomogeneities.

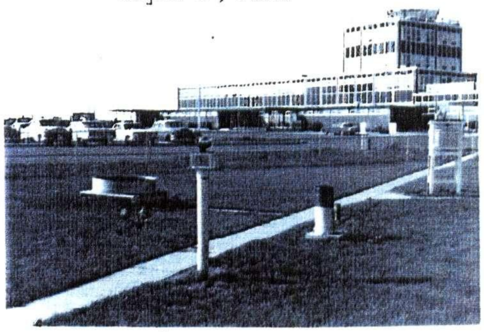
Midale is a long running climate station located approximately 120 km southeast of Regina. Despite a few small moves, its surroundings remained distinctly 'rural' throughout its history, although for a brief period it was located in a very sheltered garden. (Figure 5.12).

It is helpful to examine the *R* series and the rescaled trace together (Figures 5. 13a) in order to interpret the changes identified. Because of a major inflection point in 1961, rescaling analysis was also performed on the period 1963-1991 (Figure 5.13b) to make smaller regime transitions easier to identify. Statistics for both time series are given in Table 5.8. The cause of the significant change in 1961 is probably related to the construction of the new ATB and parking lot in 1960, and a relocation of the instruments around the same time. Interestingly, Gullett *et al.* (1990) also note a "statistically significant" inhomogeneity in the Regina minimum temperature series at approximately the same time, but determined it to be "climatologically insignificant", and therefore the entire temperature series was labeled "homogeneous". This issue is discussed in more detail in section 5.5.

The *R* series (Figure 5.13a) exhibits an increasing trend between approximately 1950 and the mid 1960s, followed by a decreasing trend in the annual mean of approximately 8% to 1984. The decrease is consistent with increased development occurring at Regina A over the same time period. Instruments were moved to a more open site in the fall of 1983, and a minor inflection point in the rescaled trace is evident at about the same time. Another significant change in the rescaled trace occurs in 1988 (Figure 5.13b), but again the cause of this change is difficult to identify. Significant development was occurring at Regina A around this time, so it is possible that not all of the changes were documented in the station history files

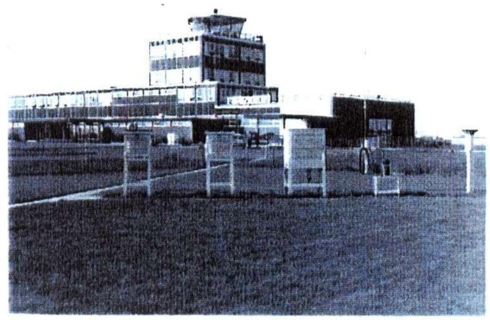
Other inflection points in the rescaled trace correspond to the station move from the City of Regina to the Airport in 1932, and substantial construction (runways and buildings) in the late 1930s. A slight change in slope of the rescaled trace occurs following the relocation of the Midale station in 1964. Two other relocations of the Midale station in the 1950s do not appear to affect the rescaled trace, nor do other noted events such as screens being painted. Inflection points around 1927, 1931, and 1980 can not be explained by the evidence in the history files.

Regina A, Sask.



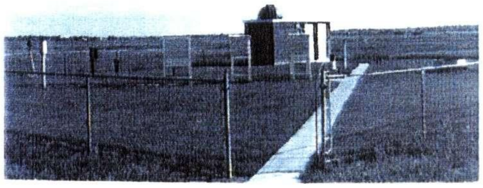
June 1964 FROM NORTH

Regina A, Sask.



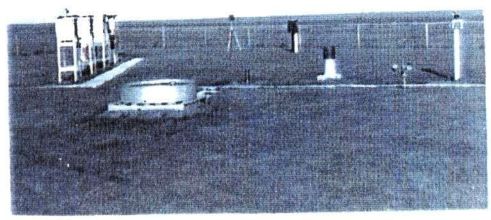
June 1964 FROM NORTH

Regina A, Sask.



From south

Regina A, Sask.



From east

Figure 5.11 (a) Regina A. climate station site, June, 1964.

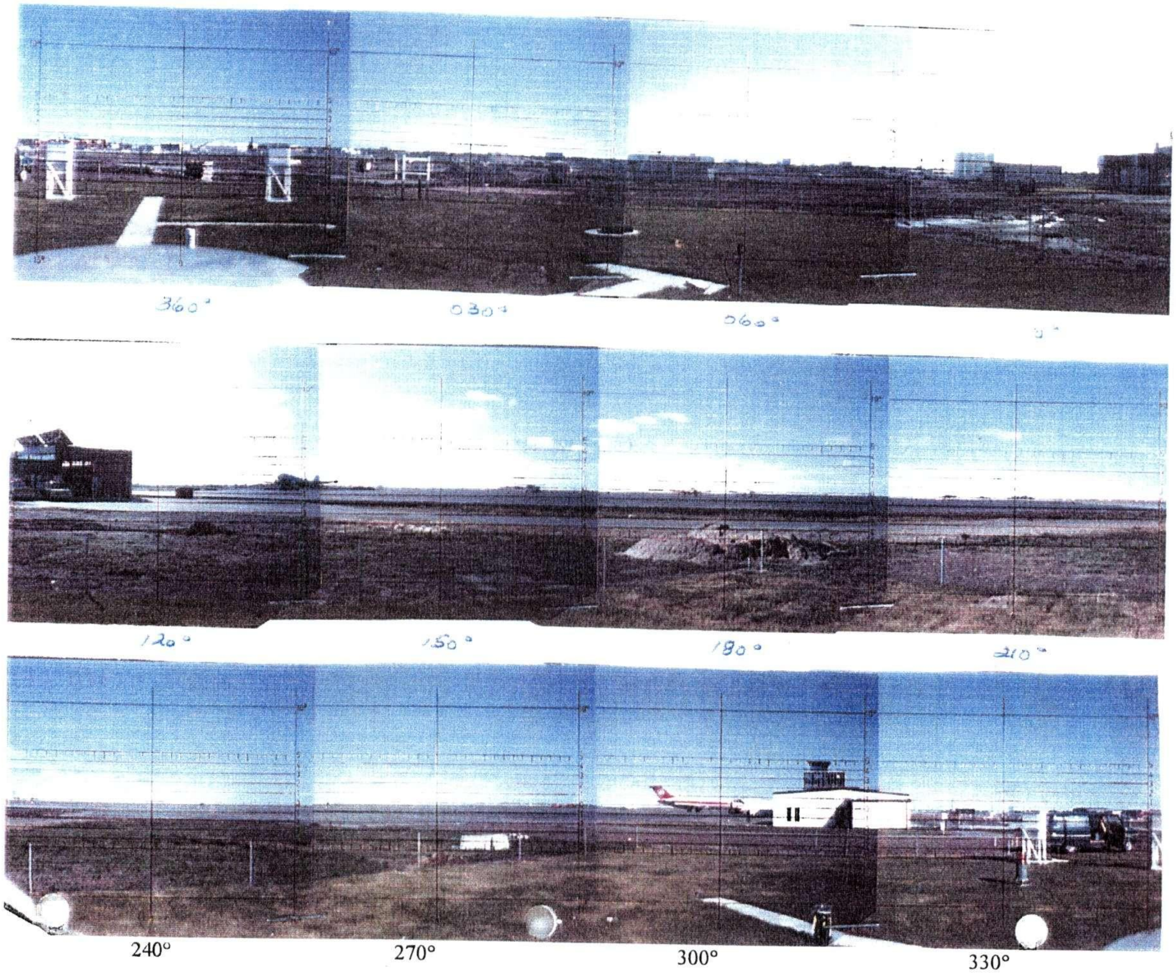
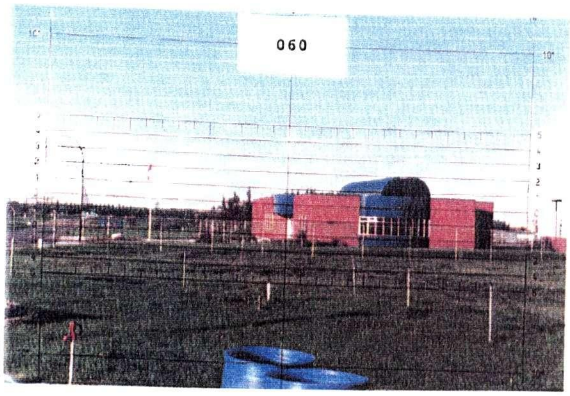
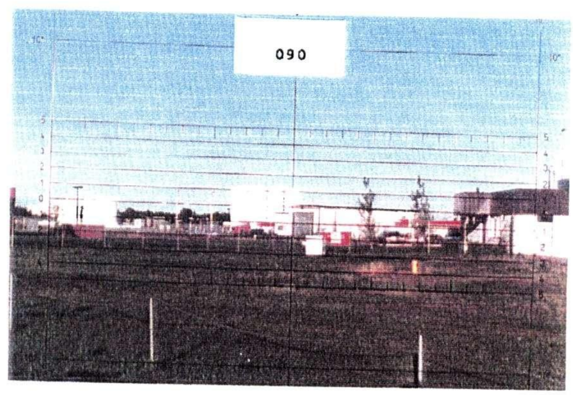


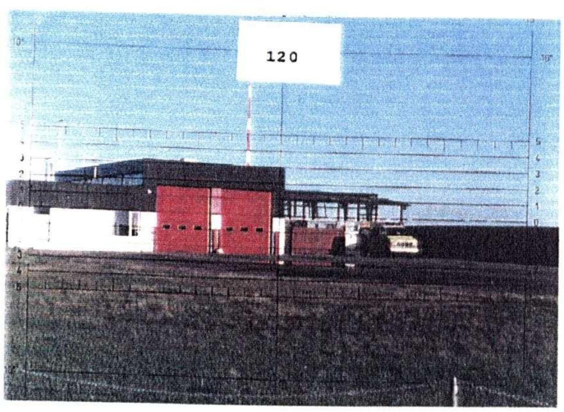
Figure 5.11 (b) Regina A. climate station surroundings, August, 1983.

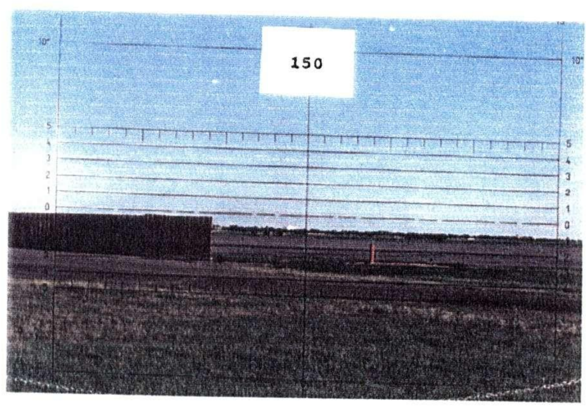

360

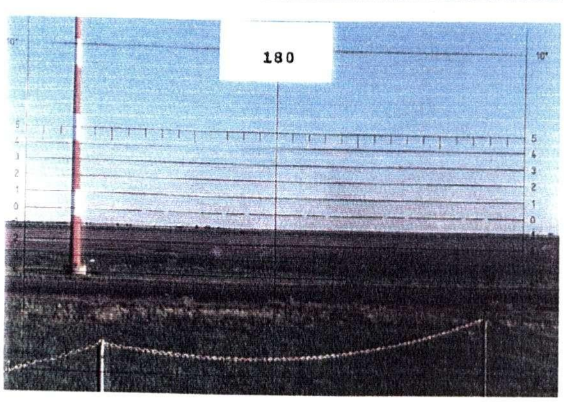

030


060


090


120


150


180


210

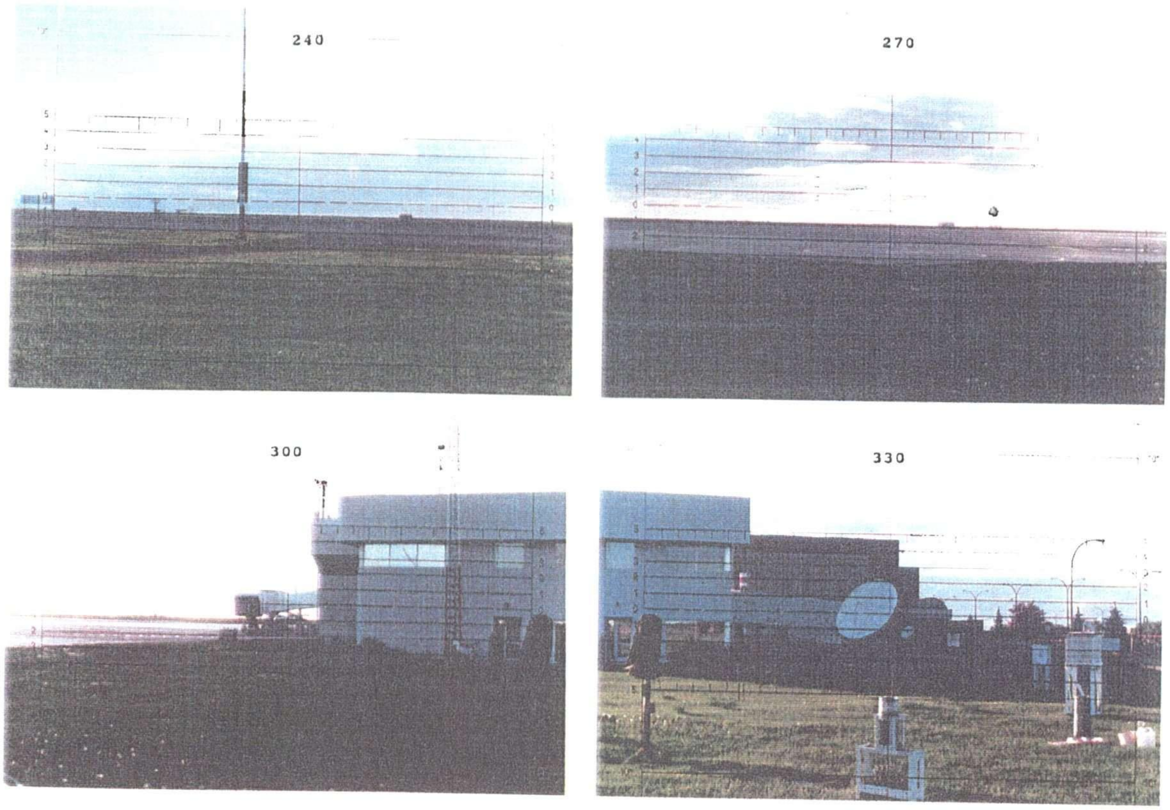


Figure 5.11 (c) Regina A., 1993.

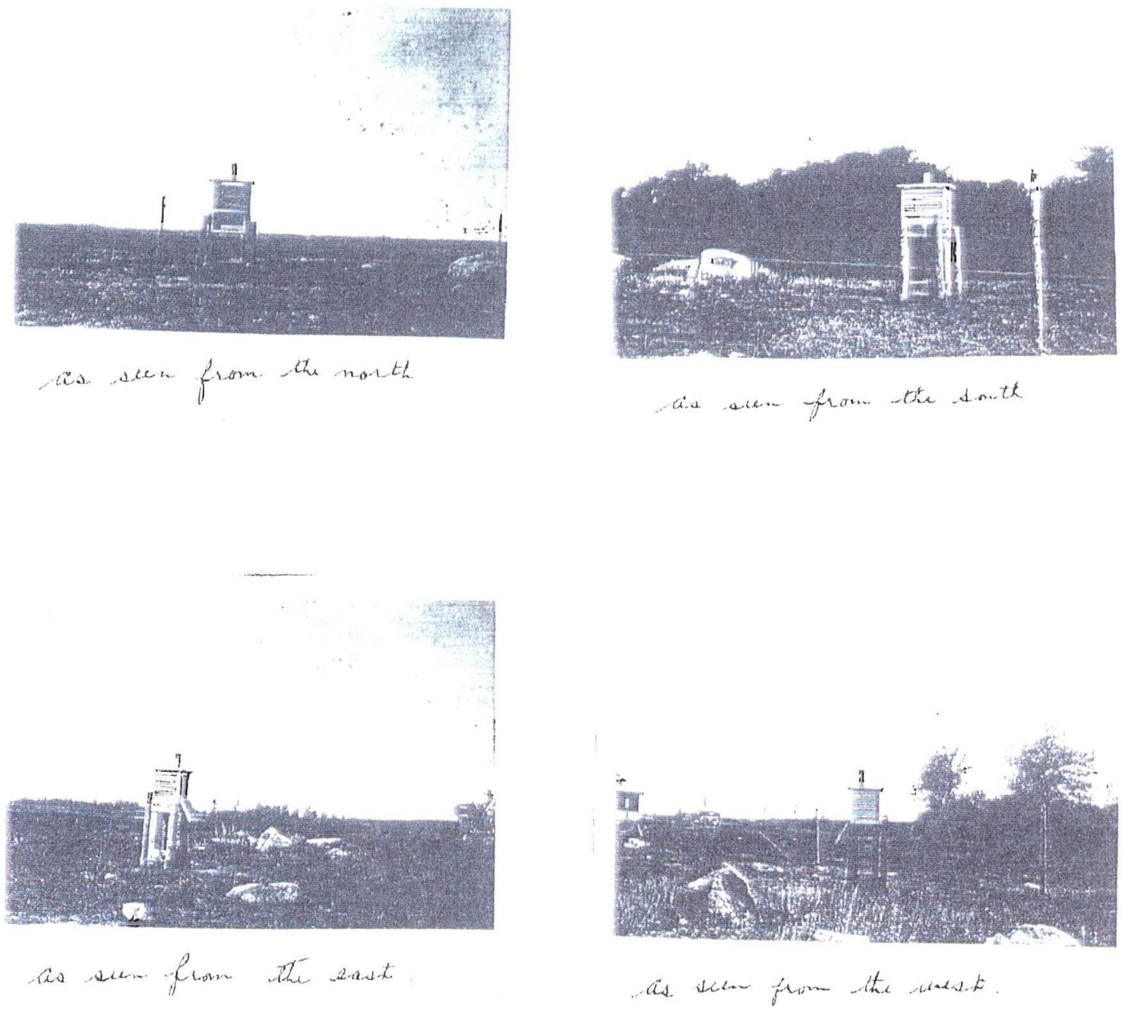
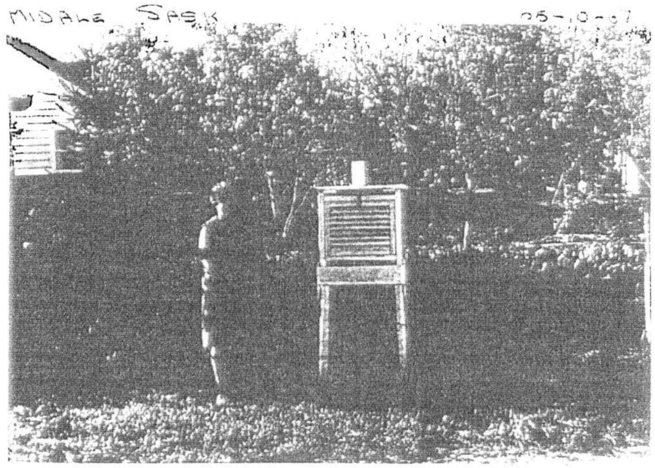


Figure 5.12a. Midale climate station site, circa 1934.



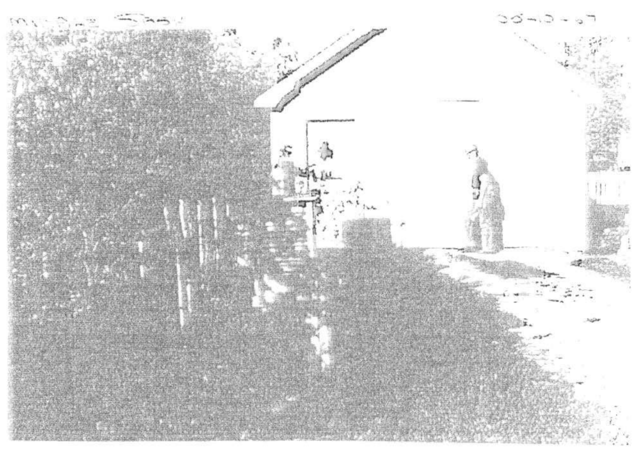


Figure 5.12b. Midale station location from 1964-1967.

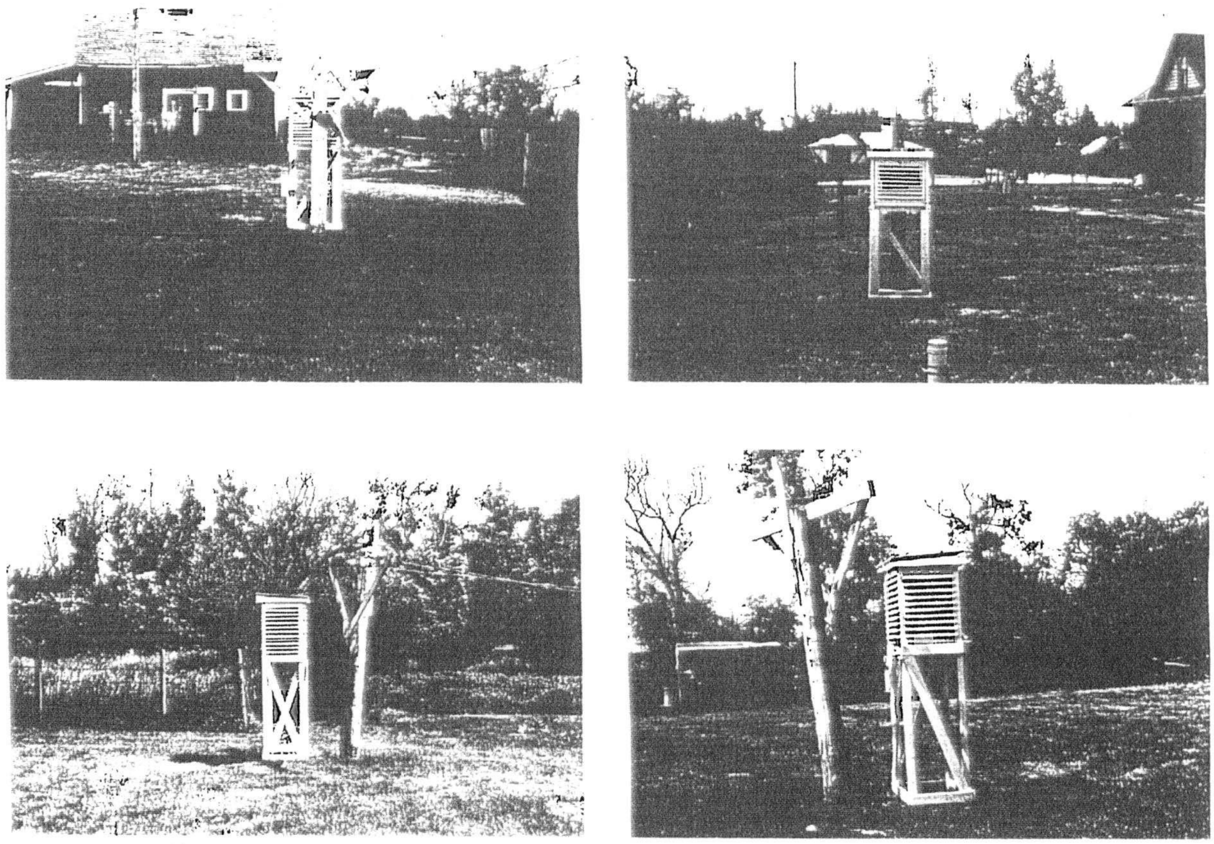


Figure 5.12c. Midale,1986. The station remained in this location from 1967 to 1991.

Table 5.6 Summary of station history for Regina A (including airport development). Italics denote editorial comments derived from photographs, sketches, or ambiguous details.

Date	Excerpts from station history files
8-9-1932	*Station moves from city centre to Regina Airport*
1938	Runway 07-25 built; runway 12-30 reconstructed
1939	Admin building and control tower built
1940	3 new hangars built; more lighting added
03-05-1943	Screen being moved shortly *(not clear if or when move actually happens)*
Fall-1948	Screen painted
11-1952	Runway 07-25 completed
10-1954	Screen painted
30-05-1956	*Sketch shows screen is now 120 feet south-east of administration building. Possibly as result of the move referred to in 1943.*
1960	NEW airport terminal building completed 60 m south west of instruments—large parking lot appears to have been added at same time to south east of instruments
10-1962	Screen painted
23-11-1962	*IR notes no grass beneath the screen—but "will be" which seems to imply a station move, or at least significant ground cover changes. Grass is beneath the screen in previous (1957) and subsequent (1963) IR reports.* *Also notes length of cable for psychrometer motor is 600', whereas previous IR indicated 220': again indicating screen has moved farther from the main weather office.*
10-1963	Screen painted
1964	*Photos show area right below screen is bare soil—possibly trenched to provide cable*
15-09-1966	Screen painted
06-1967	1000' extension to runway 12-30
03-11-1977	Screens leveled; stands reset in the ground to correct the approximately 10° tilt caused by the soil shifting toward an area that had been trenched and loosely back filled, some years previous
16-12-1982	Instruments are exposed on a grassed, fence protected area to the North of the Airport Terminal Building (approx. 60 m). Exposure that was fair originally has been steadily declining in the past three years. Airflow from the South is 'Poor' due to the obstruction of the A.T.B., all other quadrants, with the exception of the Northwest are only fair, due to the addition of buildings and vehicle parking lots. Stevenson Screen needs paint. *Photos show trailer and garage/hangar to W and NW that were not apparent in previous photos.*
14-09-1983	*Station moved*: Instruments are located on a newly constructed grassed

	area, position approximately 115 m southeast of the existing Airport Terminal Building. Site is located on the "Air" side of the security fence, with the immediate perimeter marked with a post and chain fence. Exposure is excellent in all directions except some sheltering to the northwest by the terminal building. Area to the NE is being developed for paved vehicle parking. Area to the SE contains an aviation fuel depot and fire hall. Area to the SW is paved aircraft taxi and parking space. New stands and screens installed, and given additional coat of paint.
22-03-1984	The exposure of the instrument area can be expected to be reduced once the terminal building and weather services building is completed. The observing horizon will also be reduced. The vast expanses of surrounding pavement will continue the heat island problem as before.
28-02-1985	*Same site description as 1983.* The instrument area is occasionally subjected to "propwash" from taxiing aircraft, unwanted snow from airport snow removal vehicles, and the vast expanses of dark pavement might have an adverse effect on temperature values.
11-02-1988	Immediately to the south of the instrument area is a blacktopped access road for the firehall. To the southwest is paved aircraft parking, and apron, while to the north and northeast, it will remain open, as it comprises airport roadways, and vehicle parking areas. *"Propwash" problem is noted again.*
1989	*Subsequent photos indicate some time after September 1989 a new brick building was constructed to the northeast of the instrument area*

Table 5.7 Summary of station history for Midale, Saskatchewan.

Date	Excerpts from station history files
1932	Screen painted
1934	*Sketch shows 20' high bush 45' to the north, northwest; land slopes downward to south 6'/200'.*
14-05-1951	*Screen in poor condition—will be painted*
08-01-1952	Station moved 0.5 miles north
03-1955	*Station moved to nearby CPR station*
1956	Screen painted
17-08-1960	Screen in small lot 75 feet south of railway station -no adjacent obstructions. The surrounding countryside is flat and bare of trees. *Has probably been in this location since 1955.*
01-06-1964	*Station relocated 0.5 or 5 miles northeast but observer remained the same since 1955.*
05-10-1967	*Photos show poor exposure: instruments close to trees and house/shed.*

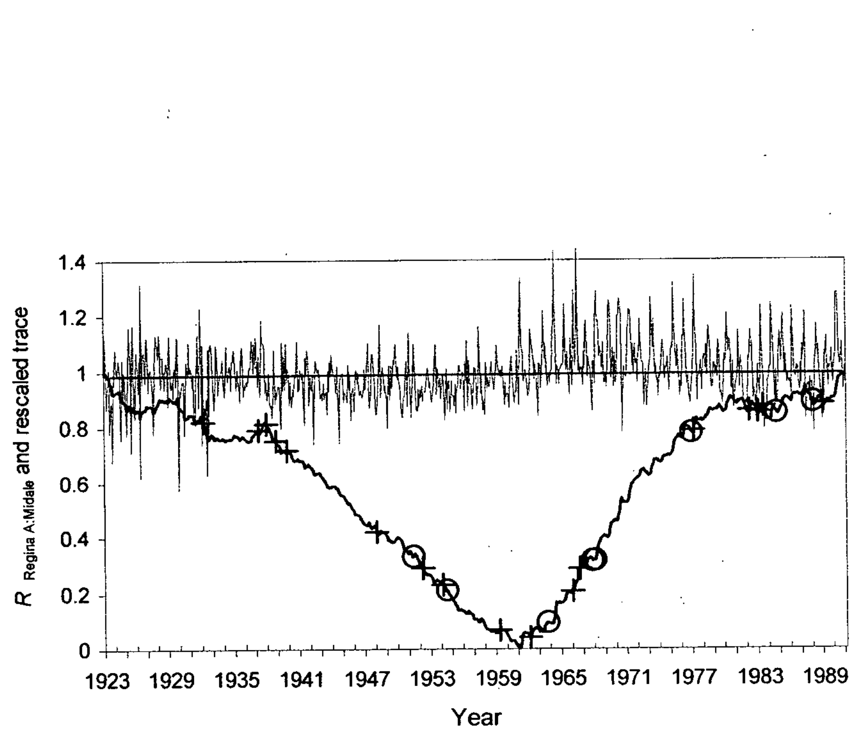
01-07-1968	*Station relocation to 0.5 miles northeast of railway station, but officially installed/inspected 04-10-1968. Exposure is better (less sheltered), but photos still show buildings, trees, and car parked near the screen.*
03-08-1977	*Photos show no changes in exposure since 1968*; Immediate exposure: Good, in open, well exposed farmyard on northern edge of town. Surrounding: slightly rolling, open farmland. Screen painted September 12, 1977
20-10-1981	*Photos show same exposure*
08-06-1985	Screen painted
24-07-1986	*Photos show still no changes to exposure*
10-1988	Screen painted
03-11-1991	Station closed

5.4 The use of composite reference series

As the preceding analyses have shown, temperature records from stations that appear homogeneous may still exhibit discontinuities due to subtle site changes or instrument changes, etc. Thus, when cooling ratio time series are constructed using a single reference station, it is difficult to determine whether discontinuities in the series are due to the test, or the reference station. If sufficient station history information is not available, as is often the case, it may be impossible to determine the source of the discontinuity. This problem has been overcome in other homogeneity analyses by using composite reference series constructed from a number of surrounding records (e.g. Gullett *et al.*, 1991; Peterson and Easterling, 1994). By combining records from several stations, it is assumed that inhomogeneities in the individual stations will be 'smoothed' out, thereby reducing the reliance on any individual station and its station history information. A similar approach might also be useful in the construction of cooling ratio time series.

Figure 5.14 shows the cooling ratio time series, and rescaled series for Regina A. and a composite reference series constructed from averaging cooling magnitudes at four nearby

(a)



(b)

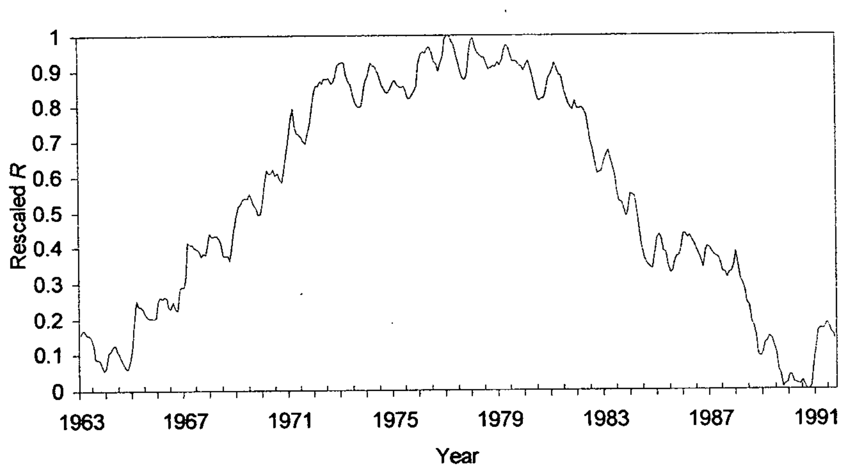


Figure 5.13 (a) $R_{\text{Regina A:Midale,}}$ and Hurst rescaled R (bold). $H = 0.73$. Symbols denote events documented in station history files (Tables 5.6 and 5.7). + Regina A; O Midale.

(b) Hurst rescaled cooling ratios for the period 1963-1991. $H = 0.64$. Note that the form of the rescaled trace is different than in (a) because the means of the two periods are different.

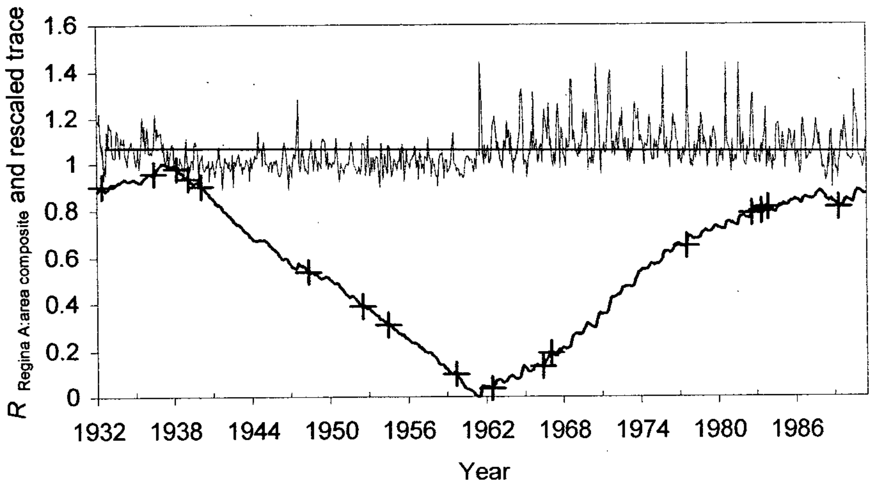


Figure 5.14 R $_{\text{Regina A:area composite}}$, and Hurst rescaled trace (bold). H = 0.77. + denotes Regina A station history events (Table 5.6).

stations (Midale, Lumsden, Muenster and Regina CDA). Statistics are given in Table 5.8. These stations were selected to obtain the longest possible record for analysis (1932-1991). The form of the rescaled series is very similar to that for Regina A:Midale (Figure 5.13), with major inflection points in 1939 and 1961, and some smaller slope changes in 1948 and 1989 that correspond to documented changes in the station history changes. The 1961 discontinuity in the cooling ratio series is more obvious than in Figure 5.13, with an apparent step change in the mean, as well as increased variability occurring around that time.

The similarity between the results using single and composite reference series indicates that the latter is a useful approach when a single suitable homogenous reference station is not available. However, particularly when subtle siting biases are the focus of investigation, the use of a single reference station with good meta-data is preferable. The availability of data, meta-data and availability of suitable reference stations will therefore determine which approach should be used in any particular analysis.

Table 5.8 Summary of statistics for time series of R, and Hurst rescaled values.

Time series	n	*mean*	s	Q_{max}	Q_{min}	r_n	H
Ladner:Steveston	193	1.06	0.07	0.40	-0.57	0.97	0.50
Edmonton Mun. A: Intl. A.							
Monthly:	456	0.83	0.07	3.38	-4.13	7.51	0.76
Annual:	38	0.83	0.04	0.27	-0.34	0.61	0.73
Woodbend:Ellerslie							
1973-86	153	1.15	0.08	0.08	-2.48	2.55	0.69
1979-86	92	1.17	0.26	1.14	-0.04	1.19	0.34
Regina A:Midale							
1923-91:	818	0.99	0.10	0.23	-13.29	13.51	0.73
1963-91:	346	1.03	0.11	3.94	-0.64	4.57	0.64
Regina A: area composite	714	1.06	0.09	1.83	-12.02	13.8	0.77

5.5 Comparison between Hurst rescaling results and other homogeneity analysis techniques

5.5.1 Double Mass Analysis and Parallel CUSUMS

As Peterson *et al.* (1999) have described, there are several techniques commonly used for detecting inhomogeneities in climate records. Theoretically, many of these techniques could be applied to time series of cooling magnitudes, or cooling ratios, as an alternative to Hurst rescaling. Two techniques that might potentially yield similar results to Hurst rescaling are double mass analysis (e.g. Kohler, 1949) and the technique of parallel cumulative sums (Rhoades and Salinger, 1993). Double mass analysis involves plotting the cumulative sum of a given variable (e.g. minimum temperature, cooling magnitude, or their respective deviations from the mean of the series) at a candidate station against that of a neighbouring station. Changes of slope of this line indicate a potential inhomogeneity in one of the records. In the present context, if cooling magnitudes are analyzed, then the slope of the double mass plot represents a 'cumulative cooling ratio' for the station pair, and a change of slope should indicate a change in cooling, or a potential discontinuity, in one of the records.

Double mass analysis was applied to the monthly cooling magnitudes at Regina A and Midale. The results, as shown in Figure 5.15a, indicate some minor changes in slope of the mass curve. Comparison of the double mass plot with Hurst rescaling of the same records (Figure 5.13) shows that Hurst rescaling is much better suited to the detection of subtle discontinuities in the cooling record. The reason for the differing results probably lies in the magnitudes of the discontinuities relative to the original values. That is, when a cooling ratio time series is constructed, the values analyzed are close to unity, whereas in this case, the cumulative sum of monthly cooling magnitudes over a seventy year period exceeded 13,000. Thus, small changes to the *cooling ratio* are more obvious than are changes to the slope of the *cumulative cooling magnitudes* mass curves. This problem may be avoided if shorter time periods are chosen for analysis. However, this method would first require subjectively choosing the time periods to be analyzed and repeating the computations several times.

Double mass analysis of the cumulative deviations of cooling magnitude from the mean of the series might also make the discontinuities slightly easier to identify. However, it appears that the rescaling of these deviations to values between 0 and 1 is the key to making the discontinuities stand out. Another advantage of Hurst rescaling is the fact that the time scale is retained in the plot, making it easier to identify the date of a discontinuity. Also, the original cooling ratio time series and the Hurst rescaled trace can be plotted on the same scale, which helps to identify discontinuities.

As Peterson *et al.* (1999) indicate, one of the limitations of double mass analysis, is that, if a discontinuity is indicated by a change of slope, it is not possible to determine which of the two records is responsible for the discontinuity. To overcome this problem, Rhoades and Salinger (1993) developed a technique called parallel CUSUMS, in which cumulative deviations from the long-term mean values are plotted from several neighbouring stations. Change points common to all of the series likely reflect regional climate changes, whereas inflection points that occur in only one of the series is likely a discontinuity unique to that particular record.

Figure 5.15b shows the results of a parallel CUSUMS for Regina A and Midale. Ideally, several neighbouring series would be plotted together so that the discontinuity can be attributed to the correct record. Only two records are shown here for illustrative purposes.

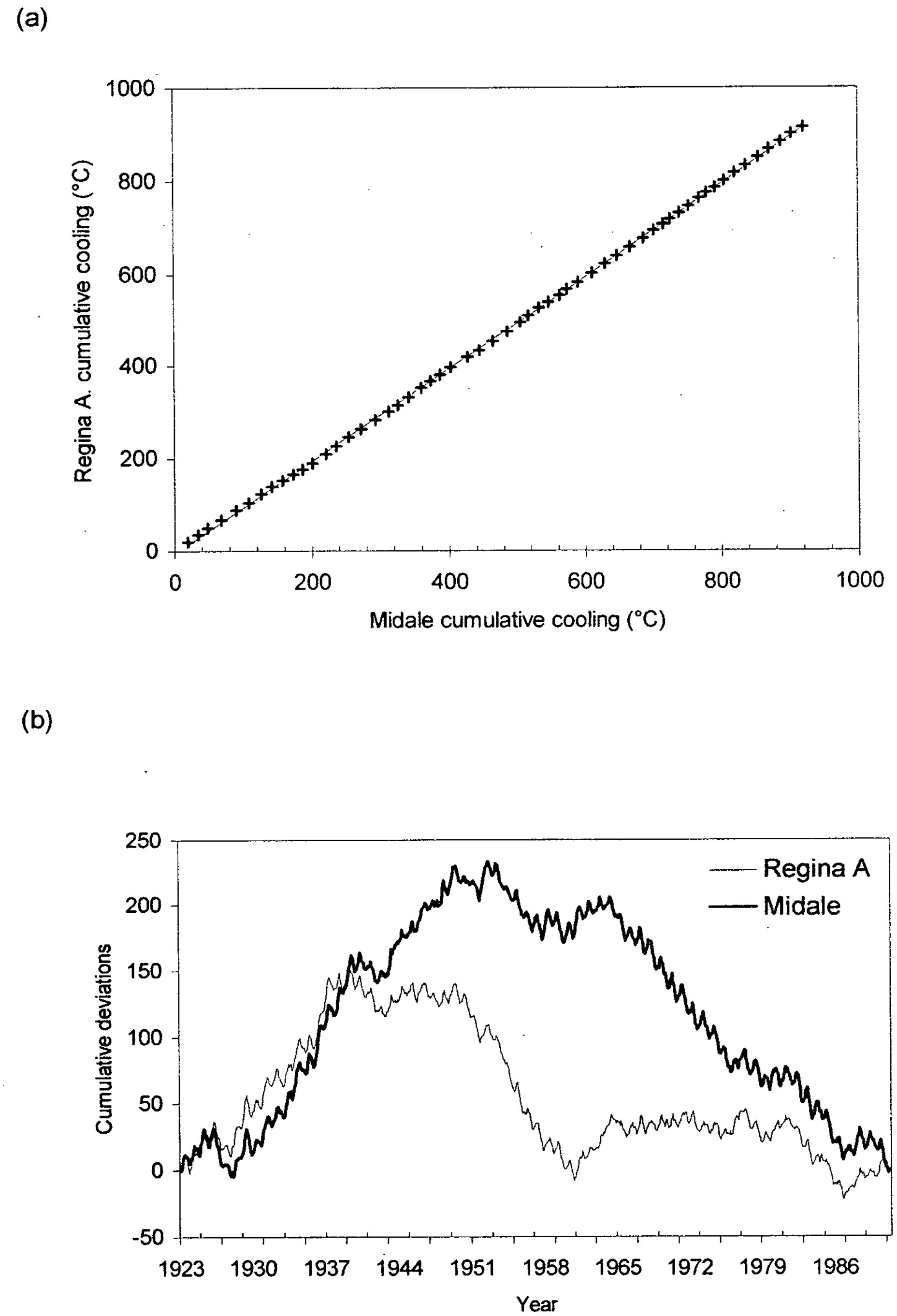


Figure 5.15 Alternative techniques for homogeneity assessment of time series. applied to Regina A. (a) Double mass analysis (cumulative monthly median cooling) (b) Parallel CUSUMS (cumulative deviations from mean).

Although several change points are evident in the series, determining which ones are common to both series, and which are unique, is not straightforward. This task is even more difficult when multiple series are examined together. Clearly, Hurst rescaling therefore has the advantage that only one trace needs to be examined, (although as indicated earlier, plotting the original cooling ratio series with the rescaled trace is optimal), and inflection points are easily identified.

Thus, alternatives to Hurst rescaling should not be ruled out as possible tools in the analysis of cooling ratio time series. Ultimately, the choice of which technique to use depends on the preference and experience of the individuals conducting the analysis.

5.5.2 Multiple linear regression technique of Gullett *et al.* (1991)

Gullett *et al.* (1991) present results for individual Canadian climate stations tested for homogeneity using a multi-phase regression technique. This technique was then extended by Vincent (1998) and used in the selection of stations to be included in the Canadian Historical Temperature database (CHTD) (Vincent and Gullett, 1999). According to Vincent and Gullett (1999) the CHTD contains the most reliable monthly temperature data in Canada and is intended for climate change analyses. It is therefore useful to compare the results of the rescaled cooling ratio analyses to those of Gullett *et al.*, (1991) to determine if it is possible to improve the homogeneity of the CHTD records.

Gullett *et al.* (1991) reported that both the maximum and minimum monthly temperature series for Midale, Saskatchewan were homogeneous for the period 1923 to 1988. (1988 was the latest year tested for all records). Also, the minimum temperature series for Regina A was found to be homogeneous from 1904-1988, while the maximum temperature series was found to contain step changes in 1913 and 1932, but was otherwise 'homogeneous'. Regina

A was consequently one of the 210 stations included in the CHTD (Vincent and Gullett, 1999). (Midale was not included in the CHTD, because it closed in 1991).

It is important to note that in the earlier analysis, Gullett *et al.* (1990) reported finding a number of inhomogeneities at the 95% significance level in the Regina A time series, particularly one in the minimum temperature series between 1961 and 1963. However, Gullett *et al.* (1990) conclude that "the step changes identified... were small and although statistically significant at the 95% level, were in fact, climatologically insignificant", and therefore Regina A's minimum temperature record was deemed to be "homogeneous". This conclusion was supported at least in part, by the fact that no evidence in the station history file could be found to indicate a possible cause for these inhomogeneities (Gullett *et al.* 1990).

Results of the Hurst rescaled cooling ratio series for Regina A: Midale call into question Gullett *et al.*'s (1990) conclusion of 'climatological insignificance'. That is, if regime transitions are apparent in the rescaled *R* series, then it is not reasonable to assume that the temperature series is homogeneous. Furthermore, closer scrutiny of the station history files can often reveal or, at least, imply potential reasons for some of the inhomogeneities (or cooling regime transitions). For example, the step change in minimum temperature at Regina A which was deemed to be insignificant by Gullett *et al.* 1990, appears as a significant regime transition in the rescaled trace (occurring in November 1961). Although there were no station inspections at either Regina A or Midale in 1961, a report in November 1962 (Table 5.7) has the following curious entry: in response to the questions on the IR form asking "Is there grass beneath the screen?", the 1962 Regina A report has the following entry "no— will be", implying that there was some recent disturbance to the instrument site, since there was grass in the previous report (1957). The possibility of a small instrument relocation is also suggested by the fact that the same IR report notes the length of the psychrometer motor cable to be 600 feet, whereas the previous report stated the cable was 220 feet long. While it is entirely possible that the cable was simply replaced, it also seems plausible that the screens may have been moved perhaps within the same enclosure, but nevertheless necessitating a longer cable. If there was in fact a small move, it is not possible to determine the precise date. The change may also be related to the construction of a new terminal building in 1960.

1961 was also the year in which a nation-wide change in observing times occurred at principal stations. Daily maximum and minimum temperature observations changed from the 00Z-00Z climatological day to the 06Z-06Z day. Biases introduced by this change are discussed by Bootsma (1976). Vincent and Gullett (1999) found that biases resulting from this change were not large enough to affect mean monthly temperatures for provinces west of Manitoba (because of the timing of the observation schedule in relation to the occurrence of the minimum temperature). However, it is interesting that 1961 appeared to be the most significant cooling regime transition evident in the rescaled time series, implying that the observation schedule change may have been more significant to the homogeneity of the temperature series than analysis of monthly temperature series reveals.

While the 1932 step change documented by Gullett *et al.* (1991) is also evident in the rescaled trace and apparently caused by the station moving from the City of Regina to the Airport site, a number of other regime transitions, either not identified, or not considered significant by Gullett *et al.* (1991), are evident in the rescaled time series and/or the original *R* series. In particular, a trace inflection around 1939 corresponds to the beginning of significant development at the airport, including expanded runways, new buildings and a control tower. The most significant problem noted in the history files is "the heat island problem" due to vast expanses of surrounding pavement, and gradual encroachment of the site. Although Gullett *et al.* (1991) found no evidence of this warming problem in the temperature series, the decreasing trend in the *R* series between 1964 and 1984 is entirely consistent with the expected thermal influence of extensive paved surfaces around the site. The decreasing trend ends when the Regina A instruments are moved in late 1983, a change which again, was not identified (or not considered significant) in the analysis of Gullett *et al.* (1991).

Gullett *et al.* (1991) also analyzed the Edmonton Municipal Airport record (but not the International Airport) and found a trend in the maximum temperature series between 1938 and 1983, while the minimum was found to contain step changes in 1942 and 1969. As the analysis in section 5.3.2 showed, many significant regime transitions are apparently caused by station relocations (1975, 1984, 1986) and the station automation in 1994. Thus the use of rescaled series of cooling ratios appears to be much better suited to the identification of the more subtle effects that may not be apparent in average temperature data, but which are nevertheless affecting cooling regimes at individual sites.

Finally, although Woodbend Alberta was not tested by Gullett *et al.* (1991), analysis in Section 5.3 clearly showed that the growth of vegetation around the site is likely to be responsible for the observed sustained increased slope of the rescaled *R* series, and the slight decrease of the *R* itself following the late 1970's. Gullett *et al.* 1991 concluded after examining many station records that "contrary to popular expectation...extensive growth of surrounding vegetation..." generally has had little or no effect on the resulting data series.

Thus, analysis of cooling ratio time series, along with the technique of Hurst rescaling appears to be better suited to the identification of subtle site changes that may not be obvious in monthly averages, but nevertheless are contributing to biases in the temperature data.

5.6 Summary of findings

The preceding results clearly show that analysis of cooling ratio time series, and in particular, Hurst Rescaling of cooling ratios, is a valuable approach to the detection of subtle, site specific biases in temperature observations. This approach constitutes a significant improvement to conventional techniques of homogeneity which have been unsuccessful in identifying such biases in temperature records.

Calculation of the Hurst exponent can indicate whether significant changes to cooling regimes have occurred, and if so, then examination of both the Hurst rescaled trace and the cooling ratio time series in conjunction with station history information can often help to determine the cause and timing of the inhomogeneities.

The above examples have shown that gradual changes in the immediate environment over time, such as vegetation growth, (and, presumably, the more abrupt changes due to its removal), or development and encroachment (paths, roads, fences, buildings) of the instrument site typically lead to trends in the cooling ratio series, whereas distinct regime transitions are caused by seemingly-minor instrument relocations (such as from one side of the airport to another, or even within the same instrument enclosure). This contradicts the finding of Gullett *et al.* (1991) that only substantial station moves, involving significant changes in elevation and/or exposure are detectable in temperature data. However, it is not surprising that small station moves, even when the elevation, or apparent exposure does not change, are capable of introducing inhomogeneities into the record, as there are usually many confounding changes occurring at the same time. For example, screens are typically re-painted, cleaned, or replaced, new instruments are provided, and observers are reinstructed about their practices. Furthermore, it is common for the new instrument site to be without grass for a few years, and there are many indications of muddy conditions around the instruments until grass is planted and properly maintained. These factors, combined with subtle changes in the immediate surroundings (such as moving away from a parking lot or building), appear to be a significant cause of inhomogeneities in the temperature records. As isolated occurrences, activities such as painting, cleaning, or relevelling screens or instruments do not frequently cause significant changes to cooling regimes.

These results also reiterate the importance of maintaining detailed station history files that could help to identify the causes of the discontinuities identified by this technique. The results also imply that it is necessary to re-examine previous homogeneity analyses and the large data bases of supposedly 'homogeneous' temperature data developed from them.

In the next chapter, this technique is applied to urban temperature records to investigate its usefulness in analyzing the more complex problem of urban biases in historical temperature records.

Chapter 6
APPLICATION OF COOLING RATIO ANALYSIS FOR HOMOGENEITY TESTING OF URBAN TEMPERATURE RECORDS

6.1 Introduction:

The analyses presented in Chapter 5 demonstrated that minor site disturbances around climate station environments are capable of introducing biases to long-term temperature records, and that time series of cooling ratios are useful for identifying these biases. The examples given in Chapter 5 represent relatively simple environments in which, for the most part, changes to the surrounding environment could be identified from the station history file.

In the present chapter, the analysis is extended to consider the case of climate stations subject to more extreme site modification in the form of large-scale urbanization. It is useful to determine if the cooling ratio approach can offer additional insights into the detection of urbanization influences on temperature records, beyond those warming trends identified by conventional homogeneity techniques. Also, it is important to determine whether relatively minor site changes, such as those examined in Chapter 5, are still identifiable when they are superimposed on the larger-scale influence of urbanization. To this end, daily temperature records from Toronto, Montreal and Vancouver are examined. Also, reference is made to the Edmonton Municipal Airport record that was previously analyzed in Chapter 5. Although some interpretation is limited by insufficient station history information, a recurrent weakness of climate records, some generalizations about the utility of cooling ratios for the examination of urban records are possible.

6.2 Toronto (Bloor Street)

Regular daily temperature observations began at King's College, now the University of Toronto, in September, 1840. Although the instruments were moved short distances around the campus, particularly in the 1970's and 1980's, the station was well maintained and the data are of high quality. Toronto Bloor Street is also an excellent site to examine potential urbanization effects on temperatures. In 1840, the campus was on the edge of a town of approximately 15,000 people, but today it is near the centre of the largest metropolitan area in Canada, with a population of more than 4.5 million. Urban induced warming trends have been identified in the temperature record (e.g. Thomas, 1971), however the homogeneity analysis of Gullett *et al.* (1991) of Toronto's monthly and annual temperatures yielded 'unclear' results. Therefore it is useful to determine how the cooling ratio technique presented in chapters 4 and 5 performs in homogeneity analysis of these urban temperature records.

Unfortunately, there are few suitable reference stations available for the same period as the Toronto record. Woodstock, Ontario was considered as a rural reference for Toronto because its record extends over the same period as Toronto's, but closer examination of the Woodstock station history reveals it to have been poorly exposed, initially amongst a stand of trees, then later adjacent to a brick wall, and so it was considered an unsuitable reference station for the purposes at hand. Therefore, two separate cooling ratio time series have been calculated; one using Guelph Ontario Agricultural College for the period 1899 to 1973, and another, Woodbridge, Ontario, for the period 1948-2001. Station history summaries for all three stations are given in Tables 6.1-6.3.

Table 6.1 Summary of station history for Toronto (Bloor Street), Ontario. Italics denote comments or inferences drawn from photos, sketches, or other indirect evidence.

Date	**Notes from station history file**
1839	Located on Bathurst Street
26-03-1907 *or* 1908	Temporarily moved to 719 Spadina Ave.; *conflicting reports as to correct year of move*
10-09-1909	Relocated to Bloor Street
1967/68	*Photos indicate poor exposure; concrete sidewalk constructed across instrument compound; date uncertain*
1969	Change in observation schedule
19-07-1972	Relocated to King's college Road approximately 100 feet from previous site; new location 12 feet from road, 52 feet east of 40' high building (Sir Sanford Fleming Bldg.), 60 feet north of 20' high building, 75' west of 60' high building; iron fence surrounds instrument site
11-02-1977	*Sir Sanford Fleming Building burns down, 6" of water from fire fighting on ground around instruments*
17-03-1977	Plywood fence erected around instruments for repairs to SSF building; *Screen vandalized around same time, then later replaced*
05-1978	Relocation to Queen's Park and Hoskin Ave; site is more open, 0.5 Ha grassed area with a few mature trees around perimeter, 27.5 m south of Law Department building
10-1978	Wooden box attached to screen to hold data recorder
18-06-1985	Instruments vandalized; new screen and max and min thermometers
28-05-1987	Relocation 150 m northwest of previous site; exposure worse than before: 10 m east of 3 story stone building, large trees nearby
03-07-1990	Screen painted

Table 6.2 Summary of station history for Guelph, Ontario. Italics denote comments or inferences drawn from photos, sketches, or other indirect evidence.

Date	**Notes from station history**
1932	*IR notes 'excellent' location, but non-standard, poorly ventilated screen; recommends replacing screen*
1948	Screen painted; black tarpaper on roof of screen
March 1950	*Moved to 'poor' location, shaded by buildings and trees; indicates screen to moved to better location "this spring"*
1958	*Site sketch shows better location; date of move is uncertain*
1961	Screen painted
1962	Exposure is very open, surrounded by agricultural test plots
1973	Closed

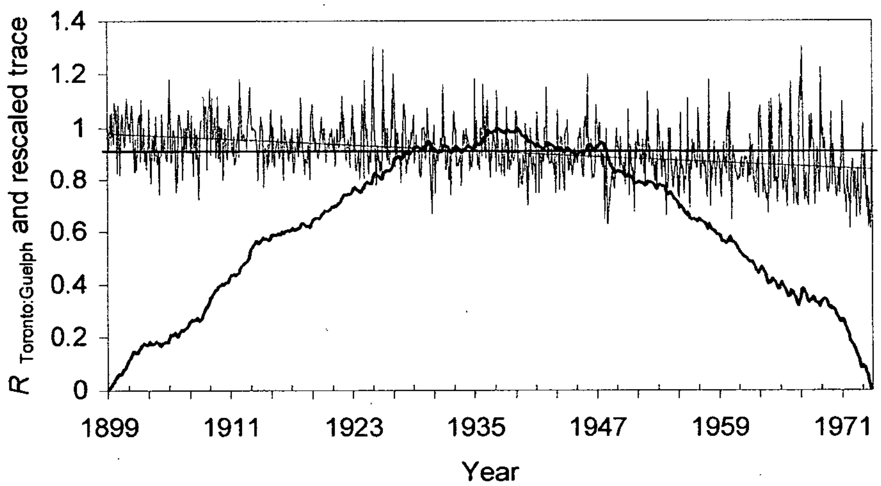
Table 6.3 Summary of Woodbridge Ontario Station History. Italics denote comments or inferences drawn from photos, sketches, or other indirect evidence.

Date	Excerpt from station history file
March 4, 1950	*Sketch shows screen is 60' south of (20 m high) house, 80' east of road* open land, high grass and low shrubs to south; immediately north of house are mature trees backing onto steep ravine of Humber River Valley
1956	Screen painted
12 August, 1975	Screen "shaky", recommended replacement
18 May 1977	Instruments moved approximately 80' northeast of original position; now 15' east of house on grass surface, stand of trees to east of site
21 December, 1993	Moved 600 m southeast of original site*; new yard, but still back on to same ravine.* 21 m east of house, 10 m south of 2.5 m cedar hedge

Figure 6.1 shows cooling ratios and the corresponding Hurst rescaled trace for Toronto:Guelph. The Hurst Exponent, H, is 0.75 for this series (Table 6.6), indicating that mixed cooling regimes are present in the series. In contrast to any of the time series examined in Chapter 5, the Toronto:Guelph cooling ratio series displays a strong downward trend, with a decrease of approximately 18 percent over the entire 74 year period. As a result of this trend, the Hurst rescaled trace shows the major inflection point in the middle of the series. This is the point when deviations from the long-term mean of the series become negative. Thus caution must be exercised in interpreting Hurst rescaled traces when significant temporal trends are present, as the major inflection point may occur in the middle, rather than the end of a regime.

The downward trend apparent in the cooling ratio series is consistent with results of studies that have shown nocturnal cooling rates are significantly reduced in urban areas compared to rural areas (e.g. Oke and Maxwell, 1975; Hage, 1972; Runnalls and Oke, 2000). Therefore urban development leads to decreased cooling over time. The cooling ratio

(a)



(b)

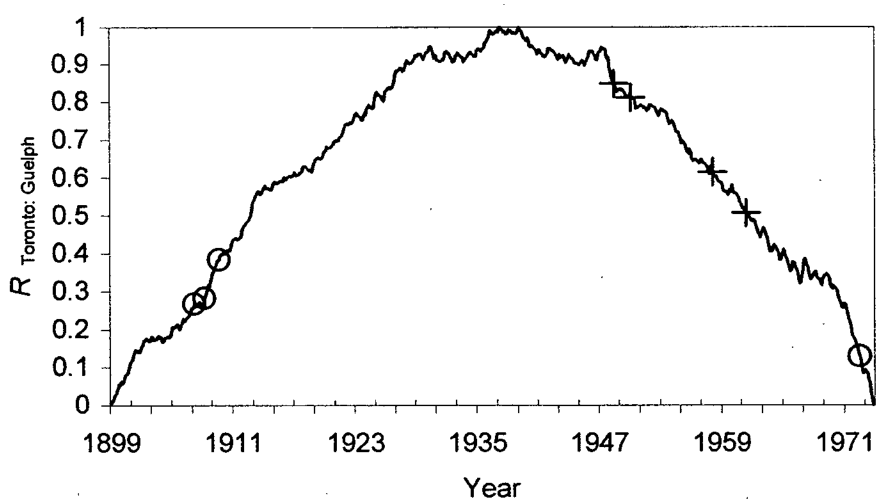


Figure 6.1 (a) Cooling ratio time series for Toronto (Bloor Street): Guelph, linear trend line and mean; Hurst rescaled series (lower trace.)
(b) Rescaled cooling ratio as in (a), but dates of site changes have been indicated with symbols: Toronto: O, Guelph +. $H = 0.75$.

technique may provide insight to the question of whether the strong urban trend masks the smaller scale potential biases of the immediate site characteristics.

Closer examination of the Hurst rescaled trace (Figure 6.1) reveals small inflection points superimposed on the larger trend, some of which correspond to events from the station history indicated by symbols on the trace. However, regime transitions are not as obvious as they were for some of the previous analyses in Chapter 5.

Because of the consistent linear trend in the Toronto:Guelph cooling ratio series, it is possible to remove the trend and calculate a new Hurst rescaled trace. After removing the trend, the Hurst exponent was determined to be 0.68, slightly less than the original series (0.75, Table 6.6). This value still indicates the presence of distinct regimes in the series. The effect of removing the trend from the original cooling ratio series is shown in Figure 6.2. In this case, the effect of the temporary re-location of the Toronto site between 1907 (or 1908) and 1909 shows up as a definite regime transition, as does the move of the Guelph station in 1950. Other change points are also evident, but no causes from the station history files can be found. It is possible that thermometers may have been replaced, and screens replaced or painted, or other physical changes to the sites may have occurred that were not documented in the history files. Guelph is an agricultural research station, so there may have been changes to the surrounding crops, surface treatments or irrigation practices that are not documented, but which could have contributed to cooling regime changes.

Comparison of Figures 6.1 and 6.2 implies that a strong urban influence can make it more difficult to detect more minor site changes by this technique. Removing the trend in the cooling ratio series may be an option, but simple linear trends are unlikely to occur in all cases, (see sections 6.3, 6.4), making it more difficult to remove the urban influence.

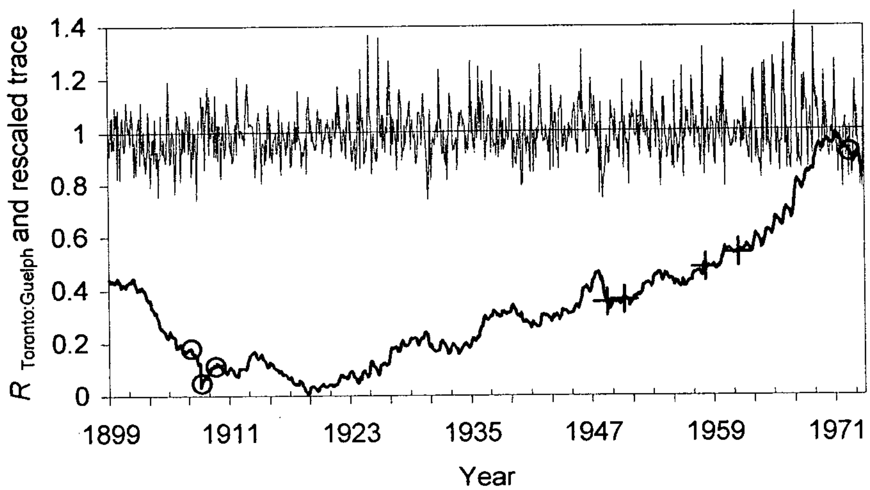


Figure 6.2 Toronto:Guelph cooling ratio time series and Hurst rescaled trace, after removal of linear trend in the cooling ratio time series. $H = 0.68$ Symbols are as per Figure 6.1.

Removing the trend in this case was done for illustrative purposes, but it is not recommended as a general rule.

The more recent portion of Toronto's temperature record has been investigated using Woodbridge as a reference series. Woodbridge is a volunteer station that has been observing since 1948. The station was recognized as a good quality station which had only one observer and remained in the same location until 1993 (except for a small instrument move within the yard in 1977). Woodbridge is a small town northwest of Toronto, and the observation site is located in a residential area that is adjacent to a wooded ravine. Although the town itself has experienced significant urban development over the years of observation, the ravine has prevented the observation site itself from being encroached upon by development.

Figure 6.3 shows cooling ratios and the Hurst rescaled trace for Toronto:Woodbridge. Significant events from the stations' histories are indicated by symbols on the rescaled trace. Unlike the Toronto:Guelph series, a consistent downward trend of cooling ratios is not apparent, yet the Hurst exponent of 0.73 indicates the series contains inhomogeneities (Table 6.6). There appears to be a downward trend at the beginning of the series (until about 1960), followed by a decade of slightly increased values, then a sharp decline in the early 1970s. The Toronto instruments were relocated on the campus three times during this period: 1972, 1978, and 1987. The first move occurs shortly after the main inflection point of the rescaled trace, however, it does coincide with a changepoint in the cooling ratio series itself. As with the Toronto:Guelph analysis, the timing of the major inflection point of the rescaled trace may represent the midpoint of a trend, and not necessarily a regime transition.

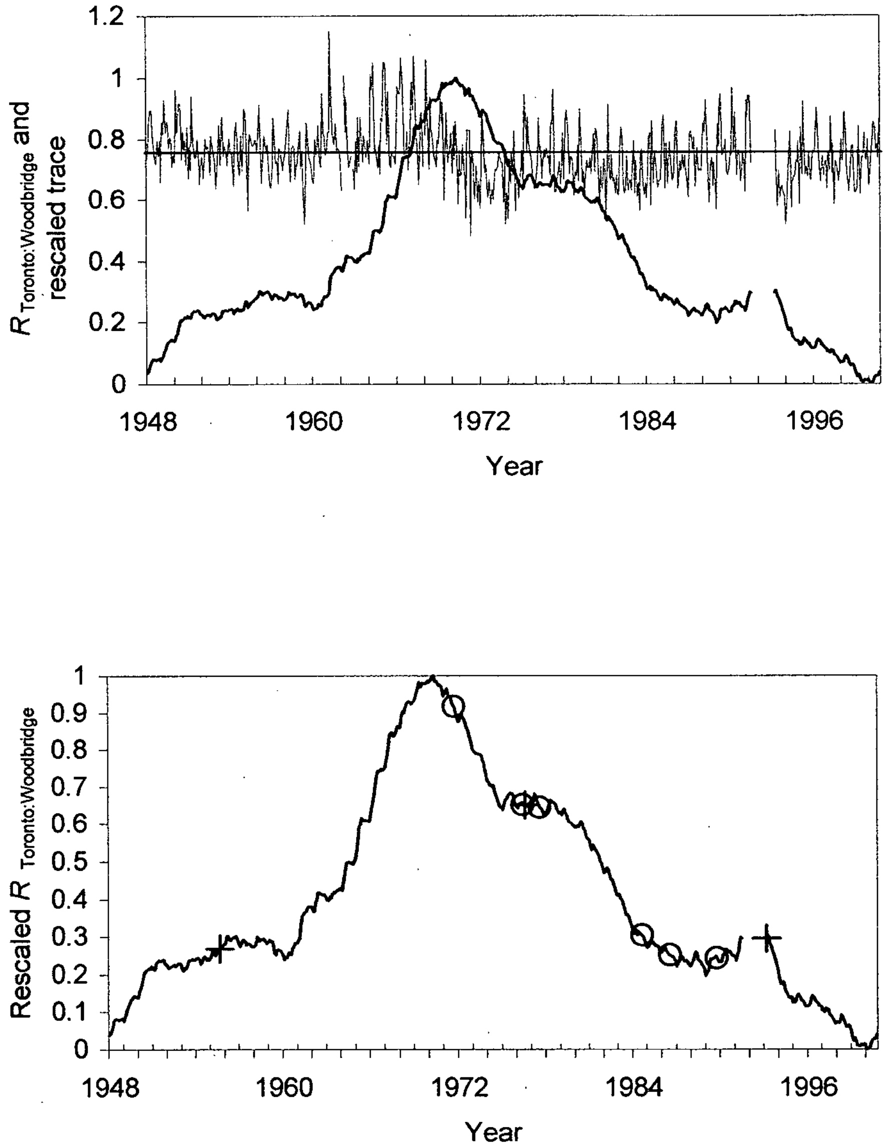


Figure 6.3 (a) Cooling ratio time series for Toronto:Woodbridge and Hurst rescaled trace. $H = 0.73$.

(b) Hurst rescaled trace as in (a), events documented in station history files indicated with symbols. Toronto: O, Woodbridge +.

A definite regime transition is apparent in the late 1970s that corresponds to small moves at both sites. Another distinct regime transition occurs in 1985, corresponding to the replacement of the screen and thermometers at Toronto, following vandalism to the instruments. The Toronto station moved again in 1987, and the screen was repainted in 1990, at which time there is slight trace inflection. The 1993 move of the Woodbridge station also occurs with an inflection of the rescaled trace. Although the move was only 600 m from the original site, the screen was placed closer to the ravine and the trees, and there was a new observer.

The Toronto analysis therefore shows that, despite substantial urbanization that might be expected to dominate the cooling regime at that site, the effects of minor relocations and instrument replacements could still be identified in the cooling ratio series. These results imply that the immediate site characteristics are just as relevant to the homogeneity of urban temperature records as are the details of population growth for the entire urban area

6.3 Montreal (McGill)

Daily temperature observations began on the campus of McGill University in 1871, providing another long running urban record. Montreal grew from a population of 217,000 in 1891, to just over 1 million today; the surrounding metropolitan area currently has a population of nearly 3.5 million. Oke (1973) documented a maximum nocturnal urban heat island of 12°C for the city, and Oke and Maxwell (1975) demonstrated a significant reduction in nocturnal cooling rates in Montreal compared to its rural surroundings. Thus, the temperature record from the McGill station is likely to contain a significant urban bias. Gullett *et al.* (1991) tested the homogeneity of this particular record, and found step changes in maximum temperature in 1914 and 1955, and step changes in the minimum temperature record in 1914 and 1948, but the causes of these discontinuities could not be identified.

Analysis of the McGill record is limited by the lack of suitable reference stations for the same period, and the McGill record itself does not appear to be of as high quality as the Toronto station, having had fewer inspections, and having used non-standard equipment at times. For example, from 1963 to 1988, maximum and minimum temperatures were taken from thermograph traces, rather than standard maximum and minimum thermometers, because the Stevenson Screen was considered esthetically unacceptable for location on the Campus. There was one documented relocation to a different area on campus on December 1, 1961. Urban development near the campus itself has been significant, and many station inspection reports in the later years note that visibility from the site is limited by the surrounding hi-rise buildings. Unfortunately there are few photos in the station history file to document temporal changes to the surrounding environment.

St. Hubert Airport, a Canadian Forces base approximately 12 km east of the city centre was selected as a reference series for McGill, as its temperature record extends from 1928 to present, with a period of missing data in the 1940s. Although the town of St. Hubert itself has a documented urban heat island effect (Oke, 1973), the airport was, at least initially, in a more 'rural' area. Recent photos show the instrument site to be well exposed in an unobstructed, flat grassed area. Unfortunately, the station history file began in 1981, so nothing about its history for the first 50 years can be determined. Although a detailed interpretation of the McGill:St. Hubert A. records is therefore somewhat limited, the cooling ratio time series is nevertheless valuable.

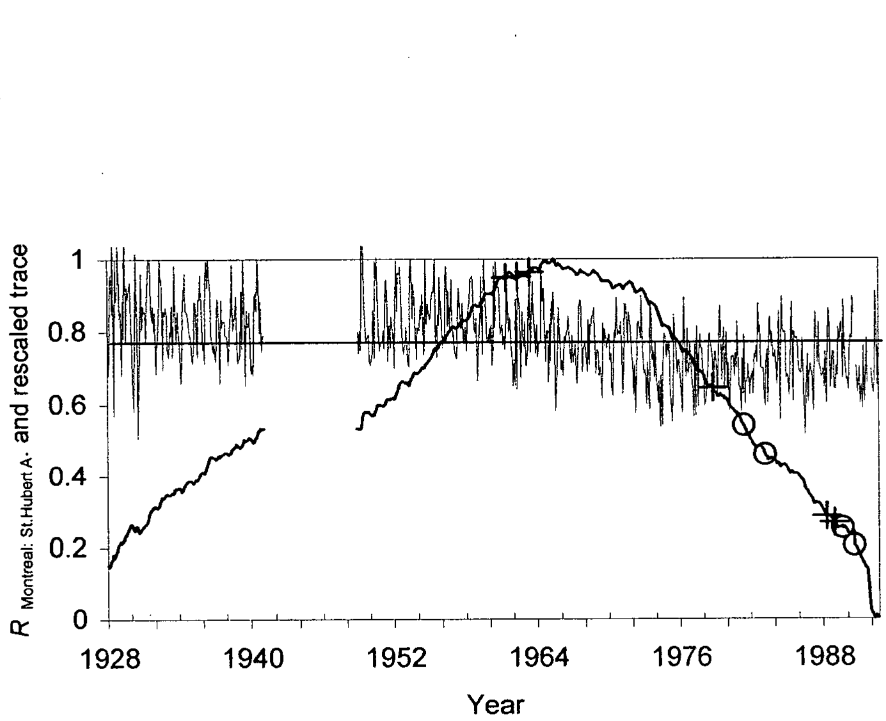


Figure 6.4 Cooling ratio time series for Montreal (McGill) :St. Hubert A. and Hurst rescaled trace. $H = 0.81$. Station history events denoted by + and O, respectively.

As Figure 6.4 shows, like the Toronto:Guelph example, cooling ratios for McGill:St. Hubert Airport show a distinct decrease over the length of the record, as expected for an urban record. Unlike Toronto:Guelph, however, the decrease is not a linear trend, but a period of very strong decreasing cooling ratios occured between 1955 and 1975, followed by a period when the mean cooling ratio remained stationary. Interestingly, the period of decreasing cooling ratios corresponds to a period of major urban growth and construction in the city. Development stopped abruptly in the 1970s as a result of the political instability at that time. This 'slow-down' appears to be reflected in the urban cooling, as the decreasing trend ends at the same time.

The Hurst exponent for this series is 0.81 (Table 6.6), and the Hurst rescaled trace of the cooling ratio series shows a similar form to that of Toronto:Guelph with the major inflection point located in the middle of the series that is not necessarily indicative of a regime transition. Thus, again it is helpful to examine both the cooling ratios and the Hurst rescaled trace together in order to correctly identify regime transitions.

A few minor slope changes on the rescaled trace are evident, one corresponding to the McGill relocation in 1961; one in 1973 without any supporting evidence; 1987, perhaps caused by a return to the use of Stevenson Screens at McGill; and another around 1989 when instruments and screen were again replaced following vandalism. There is some evidence in the history file that instruments at St. Hubert A. were moved in 1982, and a slight slope change in the rescaled trace is apparent at that time.

Thus, the Hurst rescaled cooling ratio series is remarkably similar to that of Toronto:Guelph, indicating a significant decrease in cooling conditions over time at the McGill station, consistent with the expectations of urbanization (the heat island effect). Also, as with the Toronto analysis, the strong urban influence does not prevent identification of biases caused by relatively minor site changes like small relocations and instrument replacements.

Table 6.4 Station history summary for Montreal (McGill).

Date	Comment from station history file
1933	Notes unsatisfactory exposure; too sheltered for visibility observations
01-12-1961	Station relocated to Physics building
01-12-1962	Observation schedule changed
12-1963	No Stevenson screen; maximum and minimum temperatures taken from recording charts
11-1964	Trees 60-70 feet high in a circle of about 30 feet around exposure
August 1976	Letter promises annual station inspection, as there has not been one since 1964
09-05-1979	Observer changed
16-11-1988	New screen and thermometers following vandalism in October 1988
07-1989	Automated temperature sensors installed following theft of previous instruments

Table 6.5 Summary of station history for St. Hubert A.

Date	Comment from station history
January 1982	New screen and thermometer; may have moved to a new site
October 1983	Screen replaced
01-03-1990	'remote' temperature sensor installed
17-12-1990	Some instruments moved
15-03-1991	Screen may have been replaced

6.4 Vancouver

Vancouver, British Columbia, Canada's third-largest metropolitan area, provides an interesting comparison to Toronto and Montreal. Unfortunately, a comparable long-term record for downtown Vancouver does not exist. Daily temperatures were observed from the Port Meteorological Office for the period 1898 to 1948, but the programme was discontinued shortly after a measurement site was established at Vancouver International Airport in the late 1930s. Nevertheless, these 50 years encompass the period of most rapid urbanization in the downtown area, as the central city population grew from 19,000 in 1891 to 344,000 in 1951. Oke *et al.* (1992) estimate that an urban heat island of 9°C was probably established by the 1930s based on the urban structure and population at that time.

Figure 6.5 shows Vancouver PMO: Steveston cooling ratios and the Hurst rescaled trace. Steveston is a suitable reference site for Vancouver, and was previously described in Chapters 4 and 5. Despite the rapid urban development occurring at this time in Vancouver, the cooling ratio time series does not display the expected consistent decrease that was evident in the Toronto and Montreal records. Cooling ratios decrease significantly between 1902 and 1915; there is an overall increase between 1915 and 1930, followed by a decrease again to the end of the record. There is a marked decrease in cooling ratio variability after 1934, for which there is no evidence in either history file.

The Hurst rescaled trace of the cooling ratio series is also markedly different than those of Toronto and Montreal. It is characterized by more obvious inflection points, that are more closely paired to regime transitions evident in the cooling ratio series itself. The Hurst exponent is estimated to be 0.70 (Table 6.6), indicating that the change points in the rescaled trace are significant. Oke *et al.*(1992) indicate that the PMO instruments were relocated several times during this period, around the harbour and within the city centre. These relocations could account for the lack of characteristic 'urban trends' in the cooling ratio series, particularly if the harbour locations were very close to the water, and farther from the buildings and streets of the urban location. It is not unreasonable to expect differences

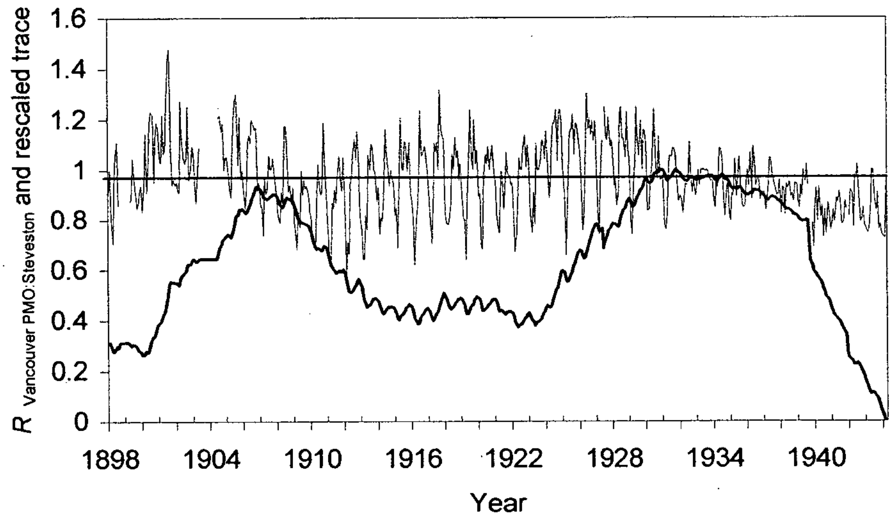


Figure 6.5 Vancouver PMO: Steveston cooling ratio (upper) and rescaled trace (lower). $H = 0.70$.

between Vancouver and the other cities, given Vancouver's complex coastal location and topographic influences.

Oke and Maxwell (1975) found that nocturnal cooling rates in Vancouver were 0.3° per hour greater than those in Montreal, that is, Montreal experienced a slightly greater urban influence. The differences between the cities were attributed to differences in size, industrial characteristics, vegetation, and proximity to water bodies.

6.5 Edmonton

The Edmonton Municipal Airport was analyzed in Chapter 5, but makes an interesting comparison with the other urban records because of its location near the centre of the city of Edmonton. Hage (1972) found that Municipal Airport temperatures exceeded those at Edmonton International Airport by 5 to 7°C when intense urban heat islands occurred, indicating that the Municipal Airport temperatures are indeed influenced by the urban setting. Yet, analysis in Chapter 5 (Figure 5.5) did not reveal any of the persistent trends that were so evident for Montreal and Toronto. Small changes to the surroundings of the instruments at Edmonton, such as parking lots, buildings, and small moves around the airport were clearly evident in the Hurst rescaled trace, indicating that these kinds of changes are more significant to homogeneity of the record than are the effects of urban development in its surroundings.

Although the population of metropolitan Edmonton grew from 401,000 in 1965 to 917,500 in 1998, it is quite probable that physical changes to the environment in the vicinity of the Municipal Airport as a result of urban development would have been complete long before 1961, the beginning of the cooling ratio record. Therefore, the lack of trends in the cooling ratio series during this period is not surprising: a similar pattern emerged in the later part of Toronto's record as well. To summarize the significance of the Edmonton record, then, it seems reasonable to suggest that despite being an "urban airport", as far as the climate station itself is concerned, the immediate surroundings are more 'airport' than 'urban' in nature, and consequently, minor site changes in the immediate vicinity of the instruments are far more significant to the homogeneity of the temperature record than the fact that the population of the surrounding city more than doubled.

Table 6.6. Summary of statistics for time series of cooling ratios and Hurst rescaled series, for urban records.

Time series	n	R	s	Q_{max}	Q_{min}	r_n	H
Toronto:Guelph	898	0.91	0.11	17.08	-0.004	17.08	0.75
Trend removed	898	1.00	0.10	5.98	-4.78	10.71	0.68
Toronto:Woodbridge	611	0.75	0.10	10.29	-0.42	10.71	0.73
McGill:St.Hubert A.	678	0.78	0.10	17.73	-3.18	20.91	0.81
Vancouver:Steveston	532	0.97	0.14	8.14	-3.73	11.88	0.70

6.6 Summary

The analyses of urban temperature records presented in this chapter indicate that the cooling ratio technique presented in Chapters 4 and 5 is not only useful in assessing the homogeneity of urban temperature records, but it is particularly well suited to detecting small siting biases that would otherwise be obscured by the effects of urbanization. Although the presence of significant temporal trends commonly seen in urban records may complicate the interpretation of the Hurst rescaled series, examining the time series of cooling ratios in combination with the Hurst rescaled trace can aid identification of significant change points in the thermal regime of the site.

The results of the cooling ratio analysis of these urban records differ from those of Gullett *et al.* 1991). In particular, the cooling ratio approach appears to offer the advantage of being able to identify siting biases in addition to the stronger urban warming trends. For example, Gullett *et al.* (1991) described their results for Toronto as 'unclear', whereas the analysis in this chapter showed a strong trend of decreased cooling, upon which smaller discontinuities related to minor station relocations, or other site characteristics, were superimposed. Gullett *et al.* (1991) found step changes in the earlier part of Montreal's record, whereas this analysis showed a period of significant decreased cooling that corresponds to a period of major urban development in the city. Finally, while Gullett *et al.* (1991) found trends in maximum temperature, and two step changes in the early part of the Edmonton Municipal Airport record, this analysis did not identify significant trends in cooling, but was very successful at identifying discontinuities that correspond to documented site changes. Therefore, the technique developed in this thesis appears to be well suited to identifying both siting and urban biases in temperature records.

Hansen *et al.*(2001) outline the most recent research attempts to create homogeneous temperature data bases for use in global climate change studies. Their suggested 'improvements' over previous techniques involve classifying climate stations as rural, periurban or urban, based on satellite derived night-light intensities. Stations identified as 'rural' by the lack of night lights are used to correct urban temperature records by a "two-legged" linear adjustment scheme, aimed at minimizing the differences between the urban and rural trends. Stations outside of the United States are corrected in similar way, but the classification of urban and non-urban stations is done using population data.

The nature of inhomogeneities demonstrated in this chapter indicate that biases in urban temperature records are not necessarily linear, nor are they clearly related to population or other surrogate measures of present city size. The adjustment of temperature records by removing linear trends where none exist is likely to introduce, not remove, inhomogeneities. Clearly, local effects on temperatures are too important to be ignored. The proper adjustment of urban records can only be done in consideration of the unique history of each station: the inhomogeneities in many urban temperature records may be distinctly non-urban in origin and character, while many 'rural' stations may be subject to urban-like biases in their immediate surroundings which cannot possibly be identified from population or night-light intensity. Because both urbanization and minor site characteristics alter the nocturnal cooling process, identification of temperature record inhomogeneities from the perspective of this physically relevant process seems to be the first step towards establishing meaningful homogeneity correction procedures.

Chapter 7
SUMMARY AND CONCLUSIONS

7.1 Summary of findings

Two of the objectives of this thesis were to determine if microclimatic biases constitute a significant potential source of error in long term temperature records, and to develop an understanding of this problem by examining the physical microclimatic processes that could affect climatological observations of air temperatures. An extensive review of the literature has demonstrated that there is evidence suggesting microclimatic biases are potentially significant sources of error in temperature records, but they are often overlooked by conventional homogeneity analysis techniques.

A theoretical discussion of the microclimatic processes responsible for thermal biases at climate stations provided further insight into the physical nature of how siting characteristics affect air temperature measurements. Furthermore, this discussion revealed that the wealth of knowledge in the fields of micrometeorology, as well as applied fields (e.g. agriculture, road climatology) could be exploited to provide additional insights to the problem of evaluating air temperature biases. Advection, turbulent transport of latent and sensible heat, aerodynamic roughness effects, and radiative transfer are all relevant to microscale temperature variability.

A technique to detect microclimatic biases in temperature records was developed, and shown to be successful in identifying discontinuities due to changes in climate station environments, including minor relocations and instrument exposure problems such as vegetation growth or encroachment by development. The technique is based on the construction and analysis of time series of climate station cooling ratios. Cooling ratios are particularly well suited to this purpose because nocturnal cooling is a physically relevant process that is strongly influenced by surface conditions. Time series of monthly cooling ratios are constructed from occasions with significant nocturnal cooling. Surface controls on cooling are best expressed when radiative cooling is strong, so selecting the best cooling events eliminates the need to stratify by weather conditions, thus simplifying the application of the technique considerably.

Between-station cooling ratios are much less variable than daily temperatures, making it easier to detect discontinuities in the series. The use of ratios of cooling at neighbouring stations allows regional temperature trends common to both stations to be eliminated, thus making the ratio a good indicator of microclimatic conditions only. This feature overcomes one of the major limitations of conventional homogeneity analysis, which is that it is difficult to detect microclimatic trends when they are superimposed on regional temperature trends.

The application of Hurst rescaling is valuable in the analysis of the time series of cooling ratios. Calculation of the Hurst exponent indicates whether change points in the cooling ratio time series are significant discontinuities, or merely random variations. Graphical analysis of the Hurst rescaled time series of cooling ratios allows the approximate date of a discontinuity to be identified. Results of several case studies showed that the majority of inflection points in the rescaled time series of cooling ratios corresponded to documented events in the stations' histories, such as small moves, construction in the vicinity of the instruments, vegetation growth, and surface conditions in the instrument area (e.g. mud or grass). Such events were not detected in previous homogeneity analyses, and are typically considered to be insignificant to the homogeneity of temperature records. However, the results presented here indicate that it is necessary to re-evaluate previous homogeneity analyses.

The cooling ratio analysis is also useful in examining the homogeneity of urban temperature records. Strong trends of decreased urban cooling relative to the non-urban reference station are apparent in both the Toronto (Bloor Street) and Montreal (McGill) records. However, examination of both the cooling ratios, and the Hurst rescaled series together is helpful in the identification of smaller inhomogeneities that relate to documented site changes, such as small station moves. These results indicate that the strong urban effect does not mask the smaller site influences. The implications of this finding are significant to previous studies that have 'corrected' urban temperature records by assuming the urban bias grows linearly with the size of the city as measured indirectly by population, or satellite derived night-light intensity. The results of this study illustrate that proper correction of urban climate records can only occur if consideration is given to microscale site characteristics, and individual histories at each station. Linear corrections applied to records where the biases do not always cause artificial linear trends only serves to introduce additional inhomogeneities into the temperature records.

The value of the cooling ratio technique for homogeneity analysis can be summarized as follows:

- It is physically, rather than statistically based; by selecting data for occasions when microclimatic site-specific controls on nocturnal cooling are best expressed, the technique is thus particularly well suited to identifying microclimatic biases.

- The use of ratios constructed from 'neighbouring' climate stations, eliminates regional trends common to both records, that could otherwise obscure microclimatic trends.
- The technique successfully identifies site-specific, microclimatic biases that are rarely detected by conventional homogeneity techniques.
- The technique focuses on microclimatic controls without requiring ancillary weather data such as cloud and wind. Thus, it can be applied to most climate records.
- Data requirements are minimal, and the technique is not computationally intensive.
- This technique is applicable to the analysis of urban temperature records. It permits identification of site-specific biases in addition to larger, urban warming trends, thus it offers new insights into the possibility of correcting urban temperature records.

The main limitation of this technique is that a temperature record can only be tested if a suitable neighbouring reference station exists. Thus, remote stations that may be hundreds of kilometres apart cannot be analyzed by this technique. Even if a suitable neighbouring station can be found, sufficient station history information is required in order to correctly interpret the apparent discontinuities. Unfortunately, station history information is rarely complete, and sometimes missing entirely; a problem mentioned as a limitation in almost every homogeneity analysis. To overcome this limitation, if more than one possible reference station exists, multiple station pairings can be analyzed to identify the record containing the discontinuity. Also, as shown in Chapter 5, the creation of composite reference series from a number of surrounding stations may be a solution to reduce the reliance on any single reference station.

7.2 Implications for the climatological use of historical air temperature records

Although the research in this dissertation focused on specific Canadian historical temperature records, the findings have broader implications. In particular, the results cast doubt on the meaningfulness of climate change analyses that rely on historical air temperature records from standard near-surface stations. Of the 15 station records examined, only one pair of stations (Ladner:Steveston) was free of microclimatic biases. Whilst these stations were not chosen on a random basis many of the records that contained microclimatic biases had previously passed homogeneity assessments. This clearly demonstrates that so-called "homogeneous" temperature data bases used in the assessment of regional, national, hemispheric and global temperature trends still harbour residual biases.

The question of assigning an exact magnitude to the net effect of these microclimatic biases in large-scale compilations will require a more thorough representative sampling and assessment of the database in question. This is beyond the scope of this dissertation and the resources available to a single researcher. Nevertheless, the Canadian examples can probably be viewed as close to a "best case scenario." Despite a well-funded meteorological service, and minimal space constraints for climate stations relative to many other regions in the world, encroachment upon instrument sites in the form of vegetation growth and/or development (roads, runways, parking lots, and buildings) was a common feature of the Canadian records examined. There can be little doubt that the great preponderance of climate stations experience a tendency to become increasingly more, not less, developed over time.

In this study, these changes often led to observable reductions in nocturnal cooling, as expected from the nature of the physical processes involved. The implications for the homogeneity of other historical temperature records are evident: at least part of the warming trend indicated by the instrumental record of the last century may be due to minor development and encroachment problems around many of the world's climate stations, not just the more obvious effects of urban development that have been recognized.

The work here highlights just how sensitive temperature records are to seemingly minor changes in the nature of the immediate site. It also shows how invaluable it is to have a meticulously recorded and archived meta-data file regarding site properties, and the measurement and observation methods employed. By extension it also implies that the current use of remote and coarse methods of classifying stations, such as those involving the population of the adjacent census district or the brightness of night lights in the area seen from a satellite, are likely to be wholly unsuited to the task. The core of this work demonstrates a method to detect the effects of site change on air temperature records and it has been applied to sites in what is one of the world's better networks of climate stations. The outcome is a clear indication that biases exist. At present it has not been exploited to see if a means of 'correcting' records subject to bias can be developed.

It would be unreasonable to assume that these demonstrated uncertainties in historical temperature records can be taken as evidence that global climate change is not occurring and the results of this work should not be so interpreted. Again, the important point that emerges from this research is that further investigation is necessary to determine if indeed these biases affect the reliability of the instrumental temperature record with respect to providing an accurate representation of global temperature change. Unless the problem of microclimatic biases in historical records can be adequately addressed, further efforts to refine the estimate of the magnitude of global temperature change from instrumental records may not be particularly valuable. Thus, understanding global climate change by examining other forms of geophysical evidence and the relevant biophysical processes involved emerges as a more relevant focus for climate change research.

7.3 Recommendations for climate station meta-data requirements

Although the lack of quality meta-data information for climate stations has been mentioned as a limiting factor in almost every study of climate data homogeneity, it seems to be necessary to emphasize again how indispensable such information is in assessing potential siting biases in climate records. This study has shown that minor site changes introduce discontinuities into temperature records and, therefore, the more information that can be obtained regarding the nature and timing of these events, the easier the identification of these biases. While nothing can be done to improve the situation for past records, the following recommendations are put forth as necessary elements that should be included in order to improve meta-data records for the future. It is acknowledged that financial and human resource limitations make frequent 'official' station inspection reports impractical. Therefore, most of the suggestions listed below could be carried out by the observers themselves, reducing the need for regular official inspector site visits.

- Firstly, the easiest to obtain, and by far the most valuable sources of information are site photographs. Even if no other information is available for the station history, photographs can provide valuable information about the station surroundings.

Photographs should be taken from the same location, preferably in each summer and winter. (A lack of foliage in fall and winter photographs can create a misleading impression of the extent of shelter around the instruments). Regular photographs can easily document changes to the surroundings, and help to determine the timing of changes that might not otherwise be noted in the written reports.

- Fish-eye lens photographs taken at the surface would also indicate the amount of shelter, and the extent to which nocturnal radiative cooling might be affected. It is recognized that it may not be practical for these photographs to be taken as frequently as regular photographs but, if included as part of the regular inspector's report, particularly for stations influenced by vegetation growth or ongoing encroachment by buildings, they would provide essential information about changes.
- An alternative to fish-eye photos that could also be used to document instrument surrounds, is the rainguage exposure device developed by the UK Meteorological Office (pers. comm. Hatton, 1998). This device is a hemispherical mirror with angular elevations etched on the mirrored surface. When placed on the rainguage and photographed, this device shows obstructions on the horizon.
- Aerial photographs could also be beneficial in documenting surrounding land use changes such as agriculture, deforestation, urbanization, and problems of encroachment. If a series of aerial photographs exists for the station of interest, they could be particularly useful when little or no station history information has been recorded.
- Detailed sketches of the instrument locations showing distances from roads, parking lots, buildings, as well as heights of surrounding obstructions can be as valuable as photographs with respect to reconstructing the station's history.

- Detailed information about all aspects of station moves is required. Photographs should be taken at the old and new sites. The exact date of when the move actually happens must be recorded. This point seems elementary, but for the stations examined in this study, the exact date of the move was often impossible to determine, particularly if the move was small (e.g. one part of the airport to another; front yard to back etc.). Frequently station inspectors might recommend that the instruments be moved, but it was usually impossible to determine when, or if, the recommendations were instituted.
- Also, regardless of how big or small an instrument move is, full documentation of all changes that take place at the time is necessary; e.g. if the screen was replaced or painted, new thermometers installed, or if there was a different surface cover at the new site.
- Similarly, the exact date when instruments are replaced and screens painted should be recorded.
- All relevant physical characteristics of the surroundings should be documented when the station is established, and again if it moves; e.g.
    - Topography, such as whether the station is located on a slope or in a valley bottom,
    - The type of soil, along with moisture characteristics or drainage; i.e. does the site get muddy in the spring? If the instruments are in a yard or garden, is there irrigation, if so, how often?
    - If the site is an agricultural region, the types of crops grown, irrigation/drainage practices, and timing of harvesting and ploughing should be recorded.

- Similarly, details of any other activities or land use in the vicinity could be relevant e.g. if near a parking lot, is it heavily used, 24 hours a day, only in certain times of the year?

- Finally, given the importance of climate station history information, priority should be given to making these meta-data available to users in a convenient form. Ideally, searchable databases that would allow researchers to easily search for information such as instrument changes or relocations, would greatly simplify the current time-consuming task of searching through paper files, or even digitized images of paper files.

Wieringa (2002) presents a template for meta-data requirements that, if adopted as part of the WMO official Guidelines, would provide the minimum necessary station exposure information to significantly improve the meta-data relevant to wind, temperature and other variables. Thus, if the above suggestions could be incorporated into Wieringa's (2002) template, the ability to identify and assess the quality of observed surface level climate data could be greatly improved.

The results presented in this thesis have shown that it is no longer reasonable to assume any change is too small to affect the homogeneity of the climate record. Seemingly minor changes to climate instruments and their surroundings can have a detectable influence on the nocturnal cooling regime, and therefore the continuity of the temperature records. Therefore, when it comes to maintaining station history information, it is not possible to have too much information.

7.4 Recommendations for future research

This thesis has demonstrated that microclimatic features are a potential source of bias in historical temperature records, and a technique for detecting these biases has been presented. Because questions of data quality and representativeness are of crucial importance to much of climate change research, there are many possible applications and extensions of this work, that are summarized below.

- The cooling ratio technique could be used to re-evaluate the homogeneity of records in large temperature databases such as the USHCN, GHCN and the CHTD. Depending on available resources, either a complete reassessment, or a random sampling of records within these data bases would provide an indication of the possible number of records likely to be affected by these biases, as well as the potential magnitude of the residual bias.
- In addition, a random sampling of station history meta-data to document whether there is a preponderance of certain kinds of changes would be useful; e.g. is it more common for vegetation to grow than to be removed? Do station moves usually involve transfer to more open sites, or to more sheltered sites? Again, such an analysis would help to establish whether systematic biases tend to occur, or if, as is often assumed, biases typically offset each other. Examination of a greater number of records may lead to generalizations about the nature of the microclimatic biases that occur in certain environments. *e.g.* are there typical cooling regime changes associated with climate stations at airports, in agricultural areas or in small residential areas?

- As noted in Chapter 6, there appears to be an important role for this technique in re-assessing the homogeneity of urban temperature records. The ability of this technique to identify siting biases superimposed on more significant urban warming trends could lead to improved correction techniques, which currently assume urban records contain linear warming trends only.
- The technique itself may be adaptable so that it could become a correction scheme for temperature records. More research needs to be done on this subject to determine if a 'cooling ratio' based technique has any advantages over conventional homogeneity correction methods.
- One possible application of a cooling ratio based scheme is in analyses of climate extremes. Extreme daily temperatures are the most likely to be affected by the kinds of microclimatic biases considered in this thesis. Presently, these studies rely on homogeneity testing of monthly or seasonally averaged temperatures, in which subtle microclimatic biases are difficult to detect. Because the cooling ratio approach is based on data when cooling is maximized, it is well matched to analyses of extreme minimum temperatures.
- In some situations, 'warming ratios' may be a more appropriate measure of microclimatic biases that are likely to affect daily maximum temperatures, such as thermal advection from 'hot spots' (e.g. parking lots or airport runways), or changes to the amount of shade by nearby obstacles. Thus, it might be instructive to determine if the use of warming ratio time series offers any additional advantages to the technique presented here.

- The technique presented herein could be valuable for local-scale climate studies, where site-specific influences undetected by conventional homogeneity techniques could significantly bias individual records. Again, the minimal data requirements and simplicity of computations allow the cooling ratio homogeneity assessment technique to be easily applied.
- The approach presented in this thesis may be adaptable for detecting inhomogeneities in other climate records also subject to station siting biases. (*e.g.* precipitation, humidity, wind speed, or solar radiation.)
- Finally, the cooling ratio itself, which characterizes between-site microclimatic differences but, unlike temperature differences, is invariant in the mean with weather conditions, may present a useful approach in a number of applied fields where between-site temperature differences are of concern, such as urban heat island studies, agriculture, including frost or dew prediction, road climatology, and bioclimatology.

In conclusion, a more general objective of this work was to demonstrate the need for greater awareness of inhomogeneities in historical climate records. By demonstrating the existence of a potential problem, advocating a more physically-based understanding of the processes involved, as well as presenting a technique for detecting these biases, an important step has been taken towards improving our ability to both interpret historical climate change, and to accurately monitor it in the future.

BIBLIOGRAPHY

Alexandersson, H., 1986: A homogeneity test applied to precipitation data. *Journal of Climatology*, **6**, 661-675.

Alexandersson, H., and A. Moberg, 1997: Homogenization of Swedish temperature data Part I: Homogeneity test for linear trends. *International Journal of Climatology*, **17,** 25-34.

Allen, R.J. and A.T. DeGaetano, 2000: A method to adjust long-term temperature extreme series for nonclimatic inhomgeneities. *Journal of Climate*, **13**, 3680-3695.

Anderson, T., and I. Mattisson., 1991: A field test of thermometer screens. Swedish Meteorological and Hydrological Institute, Report No. RMK 62, 41 pp.

Antonioletti., R., A. Baille, and B. Itier, 1982: Influence du'ne nappe d'eau sur le microclimat environnant i. Etude in situ d'un etang naturel. *Journal de Recherches Atmopsheriques*, **16,** 337-351.

Arnfield, A.J., 1990: Canyon geometry, the urban fabric and nocturnal cooling. *Physical Geography*, **11**, 220-239.

Ashie, Y., T. Asaeda, V.T. Ca, and T. Yoshimura, 1998: Wind tunnel test of air flow and temperature field around a rectangular building**.** Proc. 2nd Japanese-German Meeting, Report of Research Center for Urban Safety and Secuity, Kobe University, Special Report No. 1, 230-234.

Atmospheric Environment Service, 1992: Guidelines for Co-operative Climatological Autostations, Version 2.0. Atmospheric Environment Serivce of Canada, Downsview, Ontario. 84 pp.

Barnett, A., H.D.G. and D.W. Jones, 1998: Instruments and Observing Methods, Report No. 66: Recent changes in Thermometer Screen Design and their Impact. WMO/TD No. 871.

Bogren, J., T. Gustavsson and U. Postgard, 2000: Local temperature differences in relation to weather parameters. *International Journal of Climatology*, **20,** 151-170.

Bohm, R., 1998: Urban bias in temperature time series—a case study for the city of Vienna, Austria. *Climatic Change*, **38**, 113-128.

Bonan, G.B. 2000: Observational evidence for reduction of daily maximum temperature by croplands in the Midwest United States. *Journal of Climate*, **14,** 2430-2442.

Bonsal, B.R., X. Zhang, L.A. Vincent and W.D. Hogg, 2001: Characteristics of daily and extreme temperatures over Canada. *Journal of Climate,* **14,** 1959-1976.

Bootsma, A., 1976: A note on minimum temperature and the climatological day at first order stations. *Atmosphere*, **14,** 53-55.

Camilloni, I., and V. Barros, 1997: On the urban heat island effect dependence on temperature trends. *Climatic Change*, **37**, 665-681.

Campbell, G.S., J. M. Norman 1998: *An Introduction to Environmental Biophysics.* 2nd ed. Springer-Verlag New York Inc., New York. 286 pp.

Changnon, S.A., 1999: A rare long record of deep soil temperatures defines temporal temperature changes and an urban heat island. *Climatic Change*, **42**, 531-538.

Chenoweth, M., 1992: A possible discontinuity in the U.S. historical temperature record. *Journal of Climate*, **5,** 1172-1179.

Conrad, V., and L.W. Pollack, 1962: *Methods in Climatology* 2nd Edition. Harvard U.P., Cambridge, Mass.

DeGaetano, A.T. 2000: A serially complete simulated observation time metadata file for U.S. Daily Historical Climatology Network stations. *Bulletin of the American Meteorological Society*, **81**, 49-67.

De Vries, D.A., 1959: The influence of irrigation on the energy balance and the climate near the ground. *Journal of Meteorology*, **16,** 256-270.

Dronia, H., 1967: Der städteeinfluss auf den welweiten temperaturtrend. (On urban influences on worldwide temperature trends.) *Meteorologische Abhandlung,* Berlin, **74**, 68 pp.

Durre, I. J.M. Wallace and D.P. Lettenmaier, 2000: Dependence of Extreme daily maximum temperatures on antecedent soil moisture in the contiguous United States during summer. *Journal of Climate*, **13**, 2641-2651.

Durre, I, J.M. Wallace, 2001: The warm season dip in diurnal temperature range over the Eastern United States. *Journal of Climate*, **14,** 354-360.

Durre, I, and J.M. Wallace, 2001: Factors influencing the cold-season diurnal temperature range in the United States. *Journal of Climate*, **14**, 3263-3278.

Easterling, D.R., and T.C. Peterson, 1995a: The effect of artificial discontinuities on recent trends in minimum and maximum temperatures. *Atmospheric Research*, **37**, 19-26.

Easterling, D.R., and T.C. Peterson, 1995b: A new method for detecting undocumented discontinuities in climatological time series. *International Journal of Climatology,* **15,** 369-377.

Easterling, D.R., T.C. Peterson, and T.R. Karl, 1996: On the development and use of homogenized climate datasets. *Journal of Climate*, **9,** 1429-1434.

Easterling, D.R., B. Horton, P.D. Jones, T.C. Peterson, T.R. Karl, D.E. Parker, M.J. Salinger, V. Razuvayev, N. Plummer, P. Jamason, and C.K. Folland, 1997: Maximum and minimum temperature trends for the globe. *Science*, **277**, 364-367.

Easterling, D.R., H.F. Diaz, A.V. Douglas, W.D. Hogg, K.E. Kundel, J.C. Rogers, and J.F. Wilkinson, 1999: Long-term observations for monitoring extremes in the Americas. *Climatic Change,* **42**, 285-308.

Easterling, D.R., T.R. Karl, J.H. Lawrimore and S.A. Del Greco, 1999: United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data for 1871-1997. ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 84 pp.

Ehinger, 1993: Instruments and Observing Methods, Report No. 55: Siting and Exposure of Meteorolgical Intruments. WMO/TD No. 589

Fitzjarrald, D.R., O.C. Acevedo and K.E. Moore, 2001: Climatic consequences of leaf presence in the eastern United States. *Journal of Climate*, **14**, 598-614.

Folland, C.K., C. Miller, D. Bader, M. Crowe, P. Jones, N. Plummer, M. Richman, D.E. Parker, J. Rogers, and P. Scholefield, 1999: Workshop on indices and indicators for climate extremes, Asheville, NC., USA, 3-6 June 1997, Breakout group C: Temperature indices for climate extremes. *Climatic Change,* **42**: 31-43.

Gall, R., K. Young, R. Schotland, and J. Schmitz, 1992: The recent maximum temperature anomalies in Tucson: Are they real or an instrumental problem? *Journal of Climate*, **5,** 657-665.

Gallo, K.P., D.R. Easterling, and t.C. Peterson, 1996: The influence of land use/land cover on climatological values of the diurnal temperature range. *Journal of Climate*, **9,** 2941-2944.

Gaster, F., 1879: Report on experiments made at Strathfield Turgiss in 1869 with stands or screens of various patterns, devised and employed for the exposing of thermometers in order to determine the temperature of the air., Meteorological Office Report for the year ending 1879, 13-39.

Geerts. B., 2002: On the effects of irrigation and urbanisation on the annual range of monthly-mean temperatures. *Theoretical and Applied Climatology*, **72**, 157-163.

Geiger, R. 1965: *The Climate Near the Ground.* Harvard University Press, Cambridge, Ma. 611 pp.

Goulter, S., 1990: An estimation of temperature changes near Lake Pukaki, South Canterbury, since the enlargement of the lake. *New Zealand Journal of Geology and Geophysics,* **33**, 41-47.

Goward, S.N., 1981: Thermal behaviour of urban landscapes and the urban heat island. *Physical Geography*, **2,** 19-33.

Gullett, D.W., L. Vincent, and P.J.F. Sajecki, 1990: Testing for homogeneity in temperature time series at Canadian climate stations. Report No. 90-4, Atmospheric Environment Service, Downsview. 43 pp.

Gullett, D.W., L. Vincent, and L.H. Malone, 1991: Homogeneity testing of monthly temperature series, Report No. 91-10, Atmospheric Environment Service, Downsview.46 pp.

Gustavsson, T. 1995: A study of air and road-surface temperature variations during clear windy nights. *International Journal of Climatology*, **15,** 919-932.

Gustavsson, T. M. Karlsson, J. Bogren, and S. Lindqvist, 1998: Development of temperature patterns during clear nights. *Journal of Applied Meteorology*, **37**, 559-571.

Guttman, N.B., 1998: Sources and effects of inhomogeneity in long-term metropolitan temperature records, American Meteorological Society 2nd Urban Environment Symposium, Albuquerque, NM, November 2-6, 1998.

Guttman, N.B., and B.C. Baker, 1996: Exploratory analysis of the difference between temperature observations recorded by ASOS and conventional methods. *Bulletin American Meteorolgical Society*, **77,** 2865-2873.

Hage, K.D., 1972: Nocturnal Temperatures in Edmonton, Alberta. *Journal of Applied Meteorology*, **11,** 123-129.

Hansen, J. R. Ruedy, M. Sata, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson and T. Karl. 2001. A closer look at Unites States and global surface temperature change. *Journal of Geophysical Research*, **106,** D20. 23, 947-23,963.

Hatton, D. 1998: Meteorological Office, Wokingham, UK, June, 1998. Personal Communication.

Hawke, E.L., 1944: Thermal characteristics of a Hertfordshire frost-hollow. *Quarterly Journal of the Royal Meteorological Society*, **70**, 23-48.

Heilman, J.L. and R.W. Gesch 1991: Effects of turfgrass evaporation on external temperatures of buildings. *Theoretical and Applied Climatology,* **43**, 185-194.

Heisler, G.M., 1986: Effects of Individual trees on the solar radiation climate of small buildings. *Urban Ecology*, **9**, 337-359.

Hogg, W.H., 1949: Effect of heated glasshouses on minimum temperatures in a nearby screen. *The Meteorological Magazine*, **78,** 335-336.

Hopkins, J.S. 1977: Spatial variability of daily temperature and sunshine over uniform terrain. *Meteorological Magazine*, **106,** 278-292.

Horton, E.B., C.K. Folland, and D.E. Parker, 2001: The changing incidence of extremes in worldwide and Central England Temperatures to the end of the Twentieth Century. *Climatic Change*, **50**, 267-295.

Hosker, R.P. Jr., 1986: Flow around isolated structures and building clusters: a review. ASHRAE Transactions 1985, **91**.

Hughes, W.S., 1995: Comment on D.E. Parker, 'Effects of changing exposure of thermometers at land stations'. *International Journal of Climatology*, **15,** 231-234.

Hurst, H.E. 1951: Long-term storage capacity of reservoirs. *Transactions of the American Society of Civil Engineers*, **116**, 770-808.

IPCC, 2001: *Climate Change 2001: The Scientific Basis.* Cambridge University Press, Cambridge. 881 pp.

IPCC, 1996: *Climate Change 1995. The Science of Climate Change*, Cambridge University Press, Cambridge, 572 pp.

Ishida, H. N. Aratani, and Y. Honma. 1996: Study on the outdoor micro-climate near a building and trees in summer (Poster Contribution) *in* International Conference on Urban Climatology June 10-14 1996, Essen, Germany, 203-204.

Janis, M.J. 2002: Observation-time-dependent biases and departures for daily minimum and maximum air temperatures. *Journal of Applied Meteorology*, **41**, 588-603.

Jones, P.D., P.Y. Groisman, M. Coughlan, N. Plummer, W.C. Wang , and T.R. Karl, 1990: Assessment of urbanization effects in time series of surface air temperature over land. *Nature*, **347,** 169-172.

Jones, P.D., S.C.G. Raper, and T.M.L. Wigley, 1986b: Southern Hemisphere surface air temperature variations: 1851-1984. *Journal of Climate and Applied Meteorology*, **25,** 1213-1230.

Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F.Diaz, P.M. Kelly, and T.M.L. Wigley, 1986a: Northern Hemisphere surface air temperature variations: 1851-1984. *Journal of Climate and Applied Meteorology*, **25**, 161-179.

Jones, P.D., E.B. Horton, C.K. Folland, M. Hulme, D.E. Parker and T.A. Basnett, 1999: The use of indices to identify changes in climatic extremes. *Climatic Change*, **42,** 131-149.

Karl, T.R., C.N.H. Williams, P.J. Young, and W.M. Wendland, 1986: A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temepratures for the United States. *Journal of Climate and Applied Meteorology*, **25,** 145-159.

Karl, T.R., G. Kukla, and J. Gavin, 1984: Decreasing diurnal temperature range in the Unites States and Canada from 1941 through 1980. *Journal of Climate and Applied Meteorology*, **23,** 1489-1504.

Karl, T.R., G. Kukla, N.V. Razuvayev, M.J. Changer, R.G. Quayle, R.R. Heim, D.R. Easterling, and C.B. Fu, 1991: Global Warming: Evidence for asummetric diurnal temperature change. *Geophysical Research Letters*, **18,** 2253-2256.

Karl, T.R., H.F. Diaz, and G. Kukla 1988: Urbanization: Its detection and effect in the United States climate record. *Journal of Climate*, **1,** 1099-1123.

Karl, T.R., P.D. Jones, R.W. Knight, G. Kukla, N. Plummer, V. Razuvayev, K.P. Gallo, J. Lindseay, R.J. Charlson, and T.C. Peterson, 1993a: A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. *Bulletin of the American Meteorological Society*, **74**, 1007-1022.

Karl, T.R., R.G. Quayle, and P.Y. Groisman, 1993b: Detecting climate variations and change: new challenges for observing and data management systems. *Journal of Climate*, **6,** 1481-1494.

Keil, M., 1996: *Temperature measurements in a Stevenson screen.* University of Reading, Department of Meteorology Report.

Keiser, D.R., and J.F. Griffiths, 1997: Problems associated with homogeneity testing in climate variation studies: a case study of temperature in the Northern Great Plains, USA. *International Journal of Climatology*, **17,** 497-510.

Kessler, R.W., L.F. Bosart, and R.S. Gaza, 1993: Recent maximum temperature anomalies at Albany, New York: fact or fiction? *Bulletin of the American Meteorological Society*, **74**, 215-226.

Knappenberger, P.C., P. J. Michaels, R.E. Davis, 2001: Nature of observed temperature changes across the United States during the 20th century. *Climate Research,* **17**, 45-53.

Knappenberger, P.C., P.J. Michaels, P.D. Schwartzman, 1996: Observed changes in the diurnal temperature and dewpoint cycles across the United States. *Geophysical Research Letters*, **23**, 2637-2640.

Kochar, N., and T. Schmidlin, 1990: Heat island of the Akron-Canton Regional Airport, Ohio, *Geographical Bulletin*, 45-55.

Kohler, M.A., 1949: Double-mass analysis for testing the consistency of records and for making adjustments, *Bulletin of the American Meteorological Society*, **30**, 188-189.

Kukla, G., J. Gavin and T.R. Karl, 1986: Urban warming. *Journal of Climate and Applied Meteorology*, **25,** 1265-1270.

Lefebvre, G., 1998: Comparison of meteorological screens for temperature measurement, *in* Instruments and Observing Methods, WMO Report No. 70, WMO/TD No. 877 pp 315-336, WMO.

Leroy, M. 1998: Meteorolgoical measurement representativity, nearby obstacles influence, *in* Instruments and Observing Methods, WMO Report No. 70, WMO/TD no. 877, pp51-54, WMO.

Lewis, T. 1998: The effect of deforestation on ground surface temperatures. *Global and Planetary Change,* **18**, 1-13.

Lin, X., and K.G. Hubbard, 1996: Microclimate inside temperature radiation shields. HPCC Report 96-2. University of Nebraska, Lincoln.

Mandelbrot, B.B. and J.R. Wallis, 1969: Some long-run properties of geophysical records. *Water Resources Research*, **5**, 321-340.

Manley, G., 1974: Central England tempratures: Monthly means 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society*, **100,** 389-405.

Mays, R., 1997: The Urban Heat Island Effect at Willow Run Airport. M.S. Thesis, Eastern Michigan University, Ypsilanti, Michigan.

McNaughton, K.G., 1988: 1. Effects of windbreaks on turbulent transport and microclimate. *Agriculture, Ecosystems and Environment* **22/23**, 17-39.

McPherson, E.G., J.R. Simpson, M. Livingston, 1989: Effects of three landscape treatments on residential energy and water use in Tucson, Arizona. *Energy and Buildings,* **13,** 127-138.

Météo-France, 1997: Test methods for comparing the performance of radiation shields and definitions of important characteristics, ISO/TC 146 SC5 Meteorology WG3, 1997 14 pp.

Meteorological Society, 1875: Report of the Council, Annual General Meeting, 1875. *Quarterly Journal of the Meteorological Society,* **2,** 310-317.

Mitchell, J.M. Jr., 1953: On the causes of instrumentally observed secular temperature trends. *Journal of Meteorology,* **10,** 244-261.

Morecroft, M.D., M.E. Taylor, and H.R. Oliver, 1998: Air and soil microclimates of deciduous woodland compared to an open site. *Agricultural and Forest Meteorology,* **90,** 141-156.

Munro, D.S., and T.R. Oke, 1975: Aerodynamic boundary-layer adjustment over a crop in neutral stability. *Boundary-Layer Meteorology,* **9,** 53-61.

Myrup, L.O., C,E, McGinn, and R.G. Flocchini, 1993: An analysis of microclimatic variation in a suburban envrironment. *Atmospheric Environment,* **27B**, 129-156.

Nappo, D.J., J. Caneill, R.W. Furman, F.A. Gifford, J.C. Kaimal, M.L. Kramer, T.J. Lockhart, M.M. Pendergast, R.A. Pielke, D.Randerson, J.H. Shreffler, and J.C. Wyngaard, 1982: The workshop on the representativeness of meteorolgical observations, June 1982, Boulder, Colo. *Bulletin of the American Meteorological Society,* **63,** 761-767.

NERC, 1998: *Climate Change—Scientific Certainties and Uncertainties,* National Environmental Research Council, Swindon.

Nicholls, N., R. Tapp, K. Burrows and D. Richards, 1996: Historical thermometer exposures in Australia. *International Journal of Climatology,* **16,** 705-710.

Nordli, P.O., H. Alexandersson, P.Frich, E.J. Forland, R. Heino, T. Jonsson, H. Tuomenvirta, and O.E. Tveito, 1997: The effect of radiation screens on nordic time series of mean temperature. *International Journal of Climatology,* **17,** 1667-1681.

Norwine, J. 1973: Heat Island properties of an enclosed multi-level suburban shopping center. *Bulletin of the American Meteorological Society,* **54,** 637-641.

Novak, M.D., 1990: An approximate analytical theory to predict the diurnal effects of local advection. *Agricultural and Forest Meteorology,* **51,** 159-176.

Oke., T.R.,1973: City size and the urban heat island. *Atmospheric Environment,* **7,** 769-779.

Oke, T.R., 1981: Canjoyn geometry and the nocturnal urban heat island: Comparison of scale model and field observations. *Journal of Climatology,* **1,** 237-254.

Oke, T.R. 1987: *Boundary Layer Climates,* 2nd ed. Methuen: London. 435 pp.

Oke, T.R., 1997: Urban Climates and global environmental change. *in Applied Climatology: Principles and Practice,* Thompson, R.D. and A. Perry, eds., Routledge, London, 273-287.

Oke, T.R., 1998: An algorithmic scheme to estimate hourly heat island magnitude, *in* Preprints, American Meteorological Society 2nd Urban Environment Symposium, Albuquerque, NM, November 2-6, 1998, 80-83.

Oke, T.R., G.T. Johnson, D.G. Steyn, and I.D. Watson, 1991: Simulation of surface urban heat islands under "ideal" conditions at night, Part 2: Diagnosis of causation. *Boundary-Layer Meteorology,* **56,** 339-358.

Oke, T.R., and G.B. Maxwell, 1975: Urban heat island dynamics in Montreal and Vancouver, *Atmospheric Environment*, **9**, 191-200.

Oke, T.R., M. North, and O. Slaymaker, 1992: Primordial to prim: A century of environmental change, in *Vancouver and its Region*, G. Wynne and T.R. Oke, eds. UBC Press, Vancouver. 146-170.

Outcalt, S., K.M. Hinkel, E.Meyer, A.J. Brazel, 1997: Application of Hurst rescaling to geophysical serial data. *Geographical Analysis*, **29,** 72-87.

Parker, D.E., 1994: Effects of changing exposure of thermometers at land stations. *International Journal of Climatology*, **14,** 1-31.

Parry, H.D., 1962: The problem of atmospheric temperature measurement, *in* Temperature: Its Measurement and Control in Science and Industry, C.M. Herzfeld, ed. Pp 805-810, Reinhold Publishing Corporation, New York.

Peterson, T.C., and D.R. Easterling, 1994: Creation of homogeneous composite climatological reference series. *International Journal of Climatology*, **14,** 671-679.

Peterson, T.C., and R.S. Vose, 1997: An overview of the Global Historical Climatology Network temperature database. *Bulletin of the American Meteorlogical Society*, **78,** 1-13.

Peterson, T.C., K.P. Gallo, J. Lawrimore, T.W. Owen, A Huang, and D.A. McKittrick, 1999: Global rural temperature trends. *Geophysical Research Letters*, **26,** 329-332.

Peterson, T.C., D.R. Easterling, T.R. Karl, P. Groisman, N. Plummer, N. Nicholls, S. Torok, I. Auer, R. Boehm, D. Gullett, L. Vincent, R. Heino, H. Tuomenvirta, O. Mestre, T. Szentimrey, J. Salinger, E. J. Forland, I. Hanssen-Bauer, H. Alexandersson, P. Jones, D. Parker, 1998: Homogeneity adjustments of *in situ* atmospheric climate data: a review. *International Journal of Climatology*, **18,** 1493-1517.

Philip, J.R., 1959: The theory of local advection: I. *Journal of Meteorology*, **16**, 535-547.

Pielke, R. A., Sr., T. Stohlgren, W. Paron, N. Doesken, J. Money, L. Schell, and K. Redmond, 2000: Spatial representativenss of temperature measurements from a single site. *Bulletin of the American Meteorological Society*, **81**, 826-830.

Pielke, R. A., T. Stohlgren, L. Schell, W. Parton, N. Doesken, K. Redmond, J. Money, T. McKee and T.G.F. Kittel, 2002: Problems in evaluating regional and local trends in temperature: an example from Eastern Colorado, USA. *International Journal of Climatology,* **22**, 421-434.

Potter, K.W., 1976: Evidence for nonstationarity as a physical explanation of the Hurst Phenomenon. *Water Resources Research*, **12**, 1047-1052.

Potter, K.W., 1979: Annual precipitation in the Northeast United States: Long memory, short memory, or no memory? *Water Resources Research*, **15**, 340-346

Potter, K.W., 1981: Illustration of a new test for detecting a shift in mean in precipitation series. *Monthly Weather Review*, **109,** 2040-2045.

Quayle, R.G., D.R. Easterling, T.R. Karl, and P.Y. Hughes, 1991: Effects of recent thermometer changes in the cooperative station network. *Bulletin of the American Meteorological Society*, **72**, 1718-1723.

Quintela, D.A., and D.X. Viegas, 1995: Convective heat losses from buildings, *in Wind Climate in Cities*, J.E. Cermak *et al.* (eds.), 503-522.

Richards, K., 2000: Observation and Modelling of Urban Dew, Ph.D Thesis, University of British Columbia, Geography, 322 pp.

Rider, N.E., J.R. Philip, and E.F. Bradley, 1963: The horizontal transport of heat and moisture—a micrometeorological study. *Quarterly Journal of the Royal Meteorological Society*, **89,** 507-531.

Rhoades, D.A., and M.J. Salinger, 1993: Adjustment of temperature and rainfall records for site changes., *International Journal of Climatology*, **13**, 899-913.

Runnalls, K.E., and T.R. Oke, 2000: Dynamics and controls of the near-surface heat island of Vancouver, British Columbia. *Physical Geography*, **21**, 283-304.

Salinger, M.J. and G.M. Griffiths, 2001: Trends in New Zealand daily temperature and rainfall extremes. *International Journal of Climatology*, **21,** 1437-1452.

Schaefer, D.G., 1974: Climatic fluctuations in the Fraser River Delta, Steveston, British Columbia, 1896-1974. Report to the Atmospheric Environment Service, Vancouver. 18pp.

Schwartz, M.D., and T.R. Karl, 1990: Spring phenology: nature's experiment to detect the effect of "green-up" on surface maximum temperatures. *Monthly Weather Review*, **118**, 883-890.

Schmid, H.P., 1994: Source areas for scalars and scalar fluxes. *Boundary-Layer Meteorology*, **67**, 293-318.

Schmid, H.P., 1997: Experimental design for flux measurements: matching scales of observations and fluxes. *Agricultural and Forest Meteorology,* **87**, 179-200.

Schmid, H.P. and T.R. Oke, 1990: A model to estimate the source area contributing to turbulent exchange in the surface layer over patchy terrain. *Quarterly Journal of the Royal Meteorological Society*, **116**, 965-988.

Serra, C., A. Burgueno, and X. Lana, 2001: Analysis of maximum and minimum daily temperatures recorded at Fabra Observatory (Barcelona, NE Spain) in the period 1917-1998. *International Journal of Climatology*, **21**, 603-616.

Söderström, M. And B. Magnusson, 1995: Assessment of local agroclimatological condition—a methodology. *Agricultural and Forest Meteorology,* **72**, 243-260.

Souch, C.A. and C. Souch 1993: The effect of trees on summertime below canopy urban climates: a case study Bloomington, Indiana. *Journal of Arboriculture*, **19(5)** 303-311.

Sparks, W.R., 1972: The effect of thermometer screen design on the observed temperature, WMO Geneva. No. 315.

Spronken-Smith, R.A. T.R. Oke, and W.P. Lowry, 2000: Advection and the surface energy balance across an irrigated urban park. *International Journal of Climatology*, **20**, 1033-1047.

Stanhill, G., 2001: The growth of climate change science: a scientometric study. *Climatic Change*, **48,** 515-524.

Stohlgren, T.J., T.N.Chase, R.A. Pielke Sr., T.G.F. Kittels and J.S. Baron, 1998: Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. *Global Change Biology*, **4**, 495-504.

Strangeways, I. 1999: Back to basics: The 'met. enclosure': Part 4—Temperature. *Weather*, **54,** 262-269.

Symons, G.J., 1868: Thermometer stands and shade temperatur. *Symons's Monthly Meteorological Magazine,* **3** (October), 137-138, 155-157.

Taha, H., H. Akbari, and A. Rosenfeld, 1991: Heat island and oasis effects of vegetative canopies: micro-meteorological field-measurements. *Theoretical and Applied Climatology*, **44**, 123-138.

Taylor, P.A., 1969: A model of airflow above changes in surface heat flux, temperature and roughness for neutral and unstable conditions. *Boundary-Layer Meteorology*, **1**, 18-39.
Taylor, P.A., 1970: Airflow above changes in surface heat flux, temperature and roughness; an extension to include the stable case. *Boundary-Layer Meteorology* **1**, 474-497.
Thomas, M.K., 1971: A survey of the urban effect on the climates of Canadian cities. Climate Division, Atmospheric Environment Service, CDS No. 11-71, Downsview.
Tjemkes, S.A. and J. Reiff 1989: A paramerization scheme for the minimum surface temperature of a saturated vegetated clay soil. *Journal of Applied Meteorology*, **28,** 1244-1248.
Tuomenvirta, H., H. Alexandersson, A. Drebs, P. Frich, P.O. Nordli, 2000: Trends in Nordic and Arctic temperature extremes and ranges. *Journal of Climate*, **13,** 977-990.
van der Meulen, J.P., 1998: A thermometer screen intercomparison, *in* Instruments and Observing Methods, WMO Report No. 70, pp 319-336, World Meteorological Organization, Geneva.
Vincent, L.A., 1998: A technique for the identification of inhomogeneities in Candian temperature series. *Journal of Climate*, **11,** 1094-1104.
Vincent, L. And D.W. Gullett, 1999: Canadian historical and homogeneous temperature datasets for climate change analyses. *International Journal of Climatology*, **19,** 1375-1388.
Vincent, L.A. X. Zhang, B.R. Bonsal, W.D. Hogg, 2002: Homogenization of daily temperatures over Canada. *Journal of Climate* **15**, 1322-1334.
Wang, H, W, Klaassen, 1995: The surface layer above a landscape with a rectangular windbreak pattern. *Agricultural and Forest Meteorology,* **72**, 195-211.
Wieringa, J., 1997: Climatological use of station network data, in E.U. COST Seminar on data Spatial Distribution in Meteorology and Climatology, pp. 1-11, Volterra, Italy.
Wieringa, J. 2001: Davenport roughness classification, and other metadata necessary for station data quality. 5th European Conference on Applications of Meteorology (ECAM), Budapest, 24-28 September 2001.
Wieringa, J. 2002: Station exposure metadata needed for judging and improving quality of observations of wind, temperature and other parameters. WMO-TECO-2002 Conference, Bratislava, September 2002. Paper P2(2).

WMO, 1996: Gutide to meteorological instruments and methods of observation, 6th ed. WMO-No. 8, Geneva.
WMO, 1997: Instruments and Observing Methods: Guidance on Automatic Weather systems and their implementation. WMO Geneva, 78 pp.
Zdunkowski, W.G. and D.C. Trask, 1971: Application of a radiative-conductive model to the simulation of nocturnal temperature changes over different soil types. *Journal of Applied Meteorology*, **10,** 937-948.
Zemel, A., and J. Lomas, 1976: An objective method for assessing representativeness of a station network measuring minimum temperature near the ground. *Boundary-Layer Meteorology*, **10,** 3-14.
Zhang, X., L.A. Vincent, W.D. Hogg and A. Niitsoo, 2000: Temperature and preciptiation trends in Canada during the 20th Century. *Atmosphere-Ocean 38(3)* 395-429.

Appendix 1
OBSERVATIONS OF MICROSCALE SPATIAL VARIABILITY OF SCREEN-LEVEL AIR TEMPERATURES: THERMAL INFLUENCES OF SURFACE FEATURES

A1.1 Introduction

Standard climate stations rarely conform to the WMO siting and exposure guidelines absolutely. Even the most "rural" stations are often near roads, parking lots, vegetation or buildings; features that could potentially affect the surrounding air temperature measurements. Although such influences are usually overlooked or considered minor, there is little observational evidence to support such assumptions. This Appendix describes results of an observational study of the spatial variability of screen-level air temperatures near a road and a simulated building, to determine what, if any, effect these features have on air temperatures observed in their vicinity.

A1.2 Field site, instrumentation and methods

The observation site was a farm in the Temiskaming district of northeastern Ontario (47° 37' 20.4" N, 79° 48' 45.3" W; altitude 238 m asl). The main measurement site was a flat, well-exposed field of short alfalfa growing in clay soil, approximately 200 m west of a windbreak of mature spruce trees. A crop of canola grew 500 m south of the instrument area, and a mixed-species forest lies 1.5 km to the south. During the period of the measurements, the canola crop was harvested, and in its freshly mowed state it presented minimal roughness differences from the alfalfa field where the measurements took place.

A narrow gravel road (7 m wide) running east-west separated the field from another alfalfa crop to the north of the road. With predominantly southerly winds at night, this arrangement provided an ideal site to observe any thermal influences of the road on nocturnal temperatures. The road was separated from the fields by shallow ditches on both sides (approximately 0.5 m deep), but which did not contain any water at the time of the observations, and which had vegetation growing in them to a similar height as the crops. On the up wind side of the road, a narrow strip of canola (recently mowed) and a wire fence, about 10 m from the road, separated the road from the alfalfa field. Figure A1.1a, shows the road and field where measurements were made, while A1.1b shows the simulated building, discussed in Section A1.5.

Background meteorological variables monitored during the observation period included wind speed and direction at 2 m height (R.M. Young wind sentry), air temperature and relative humidity (Vaisala temperature-relative humidity probe at 1.5 m), net all-wave radiation (Swissteco net pyrradiometer), incoming longwave radiation (Eppley pyrgeometer), incoming solar radiation (Kipp and Zonen pyranometer) and ground surface temperature (Everest infra-red thermometer; 60° field of view). CSI 21x electronic data loggers recorded all observations. These variables were sampled every 30 seconds and 5 minute averages were recorded. In addition, spot measurements of building surface, ground, and road temperatures were made with a hand-held Minolta infrared thermometer.

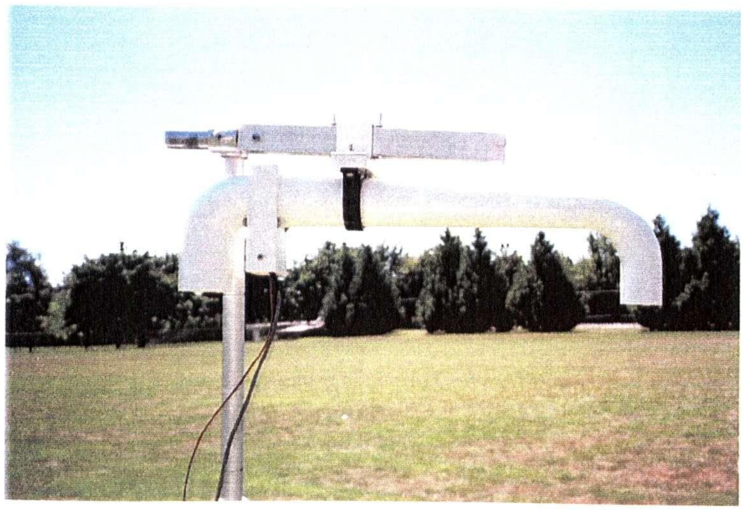
The air temperature sensors used were four identical aspirated thermocouples (CSI model ASPTC) mounted at 1.5 m above the ground, (Figure A1.2a). The thermocouples were chromel-constantan, 0.008 cm in diameter, and aspirated at 5.5 m s^{-1} as given by the manufacturer's specifications. The sensors were sampled at a rate of 10 Hz, and one minute averages were recorded on CSI 21x data loggers. The ASPTC were placed in different configurations around the simulated building and the road during the observation period.

(a)

(b)

Figure A1.1 Location of field observations (a) looking up-wind (south) of the gravel road, (b) the simulated building.

(a)



(b)

Figure A1.2 (a) CSI ASPTC model aspirated thermocouple, and (b) mobile assembly used for temperature transects.

One ASPTC was mounted on a wheel base (Figure A1.2b) so that it could be easily moved around in order to sample temperatures at many locations in a relatively short period of time. The procedure for making the transects was to move the sensor, leave it in one position for two minutes, then move it again. One complete transect around the building took approximately one hour, while a transect across the road and down-wind of it took approximately 30 minutes. Such transects were taken near sunset, a few hours after sunset, and at sunrise.

Vertical air temperature profiles were also observed, using 30 awg copper-constantan thermocouples located at 1, 5, 10, 50, 100 and 150 cm above the ground. These vertical thermocouple arrays were co-located with the ASPTC, including the mobile one, to provide profiles at various locations around the features of interest.

A1.2.1 Intercomparison of temperature sensors

Controlled laboratory comparisons of the four ASPTCs used in this study showed that there were no measurable between-sensor differences when all sensors were connected to the same data logger. However, sensor placement in the field required that each ASPTC be connected to a separate data logger, thereby introducing another source of variability to the observations. Side-by-side comparisons of the instrumentation as configured for the field measurements were made over a period of several days, and under a range of meteorological conditions. While daytime temperatures differed by as much as 0.8°C for one-minute averages, night-time temperature differences (the focus of this study) were smaller and less variable, averaging between 0.06 and 0.2°C. The observations discussed in the remainder of this Appendix involve temperature differences between the mobile sensor and two other

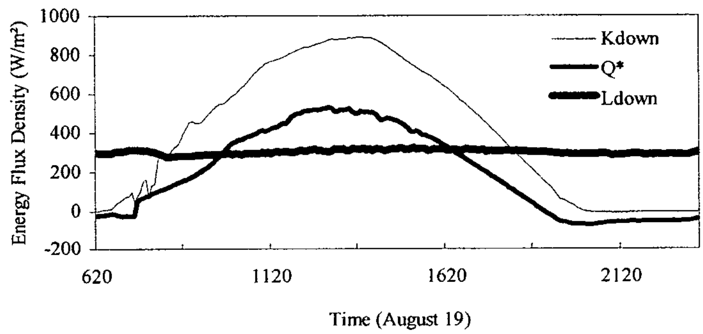
ASPTC. The mobile ASPTC measured consistently higher than both of the other sensors. For the case of the road observations (Section A1.3), the mean difference between sensors was 0.1°C, with a standard deviation of 0.09°C. Because the instrumental differences were an order of magnitude smaller than the observed temperature differences during the measurement period, corrections were not applied in this case. However, for the case of the measurements around the simulated building, (Section A1.5), a correction of 0.1°C was applied to the observed temperature differences to account for the consistently higher readings of the mobile ASPTC.

A1.3 Effect of a gravel road on surrounding air temperatures

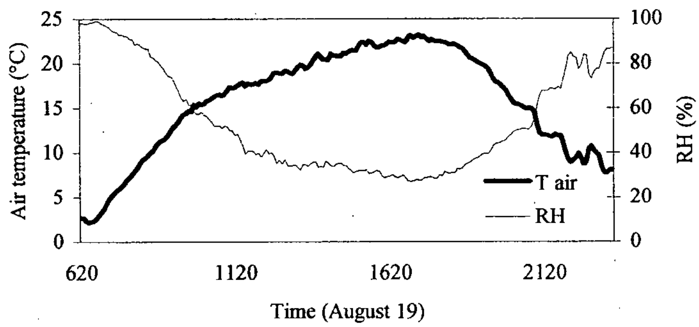
Temperature measurements near the road were made August 19-20, 1998. Meteorological conditions prior to the measurements are shown in Figure A1.3. The preceding day was characterized by clear skies with strong solar radiation (maximum 891 W m^{-2}), and light southerly winds (<3 m s^{-1}). Air temperatures reached a maximum value of 23.2 °C, and upwind surface temperatures reached 36.5 °C. Surface temperatures of the road and the downwind field were observed to be 35 °C at 1420 h, but unfortunately, surface temperatures at the time of the maximum were not captured.

The main thermal effect of the road occurs at night; the road cools more slowly than the adjacent fields (Figure A1.4(a)). The road surface temperature dropped to a minimum of 11.5 °C, whereas the downwind field surface temperature was 3.8 °C. This difference indicates that the road was a potential source of warm air to the downwind site, albeit covering only a small area.

(a)



(b)



(c)

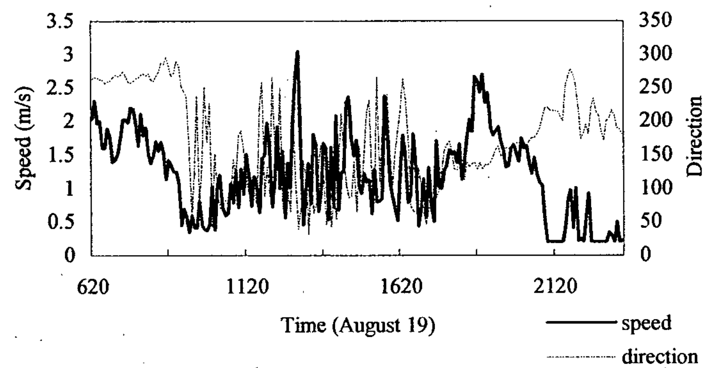
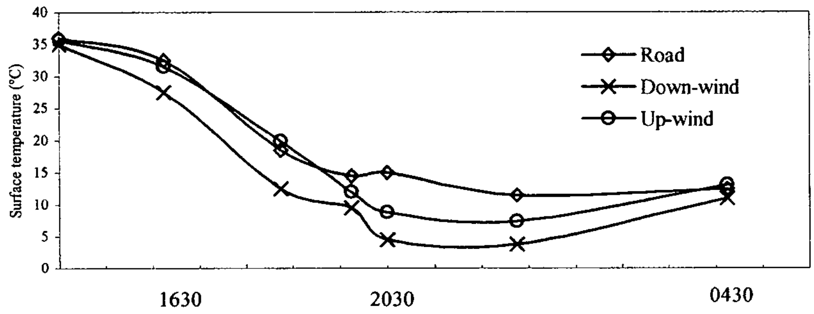


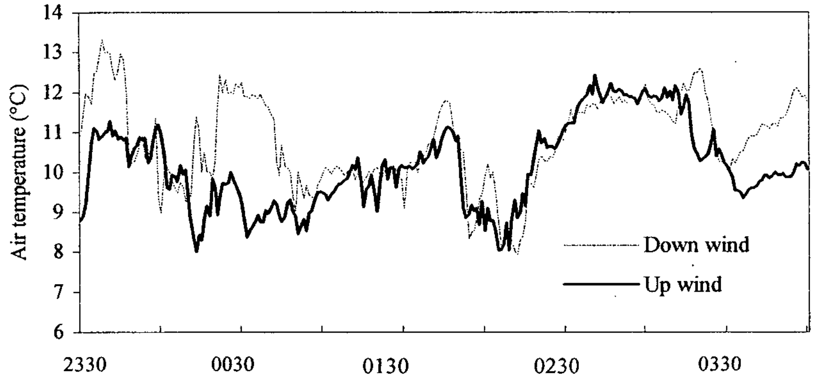
Figure A1.3. Meteorological conditions preceding road observations. August 19, 1998. (a) Incident short-and longwave and net all-wave radiation. (b) Air temperature and relative humidity. (c) Wind speed and direction.

(a)



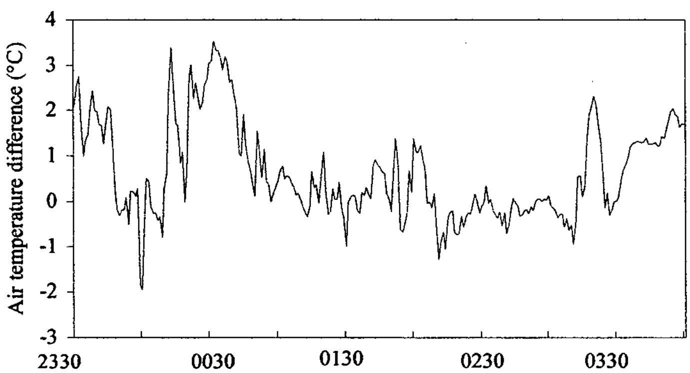
Time (August 19-20)

(b)



Time (August 19-20)

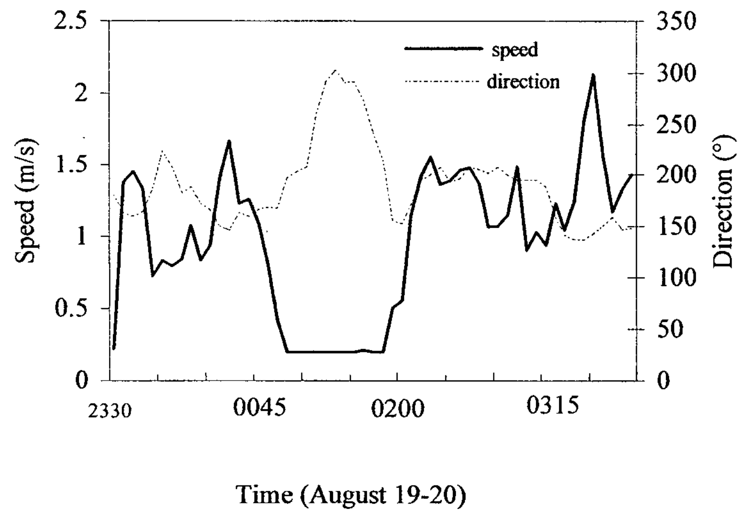
(c)



Time (August 19-20)

Figure A1.4 (a) Surface temperatures, (b) air temperatures, and (c) air temperature differences between the road and up- and down-wind fields. August 19-20, 1998.

(a)



(b)

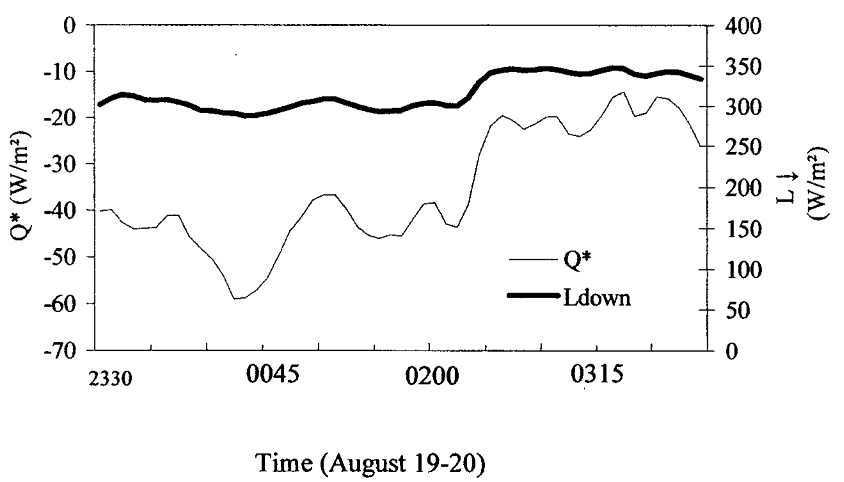


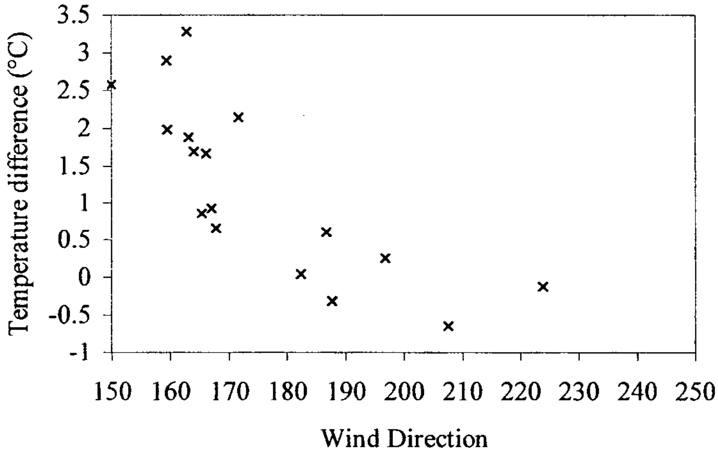
Figure A1.5 Meteorological conditions during night of road measurements August 19-20, 1998. (a) Wind speed and direction. (b) Incident long-wave, and net all-wave radiation.

Incoming longwave and net radiation following 2330 h are shown in Figure A1.5b. Skies remained clear until approximately 0230 h, then cloud developed caused both Q^* and L$\downarrow$ to increase sharply by approximately 40 W m^{-2}. Although temperature transects were made across the road and down wind of it at sunset and sunrise, the most interesting results were obtained when the mobile sensor was stationary 15 m downwind of the road between the transects (i.e. after sunset). 1 minute average air temperatures up- and downwind of the site during this time are shown in Figure A1.4b, and the temperature difference in A1.4c. Of interest are the two sustained periods when the downwind temperature exceeded that upwind by more than 1 °C. The first period begins at 2330h and was 12 minutes in duration, while the second lasted approximately 40 minutes, starting shortly after 00h. For a period of 6 minutes, the difference exceeded 2.9 °C, with a maximum difference of 3.5 °C. After 100 h, the differences were much less, often insignificant.

When viewed in conjunction with the wind speed and direction data for the same period (Figure A1.6), it is clear that the largest temperature differences occurred with light winds of less than 2 m s^{-1}, and when winds were southerly (i.e. blowing over the road to the downwind sensor). When the speed decreased to calm (anemometer stall speed) the temperature difference essentially disappeared. Thus, during the calm period (100 h to 150 h), air temperatures were largely governed by the immediately underlying surface, which for both up- and downwind sensors was short alfalfa in clay soil. With light southerly winds air over the relatively warm road surface was advected to the downwind sensor, resulting in a large, positive temperature difference.

Unfortunately the ideal meteorological conditions did not persist throughout the night in order to observe the effect of the road on the minimum air temperature after a full night of

(a)



(b)

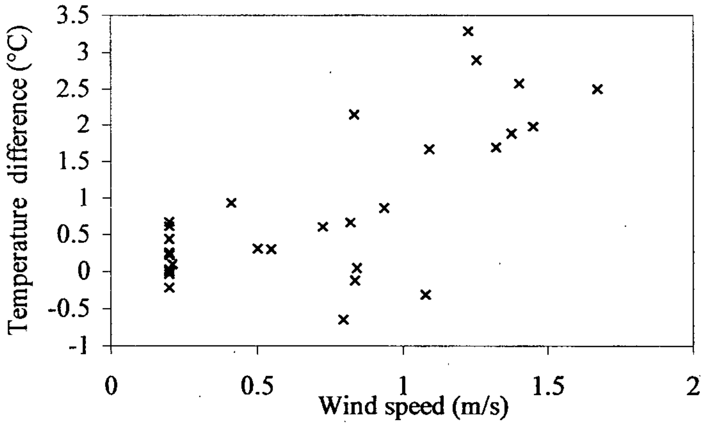


Figure A1.6. Relation between down-wind/up-wind air temperature difference and (a) wind direction and (b) wind speed. Data are 5 minute averages for the period 2330 - 0100 h, August 19-20.

strong cooling. At 0230 h wind speeds increased slightly, clouds formed, and temperature differences were eliminated. Both surface and air temperatures increased in response to the cloud cover. By 0400 h, the field surface temperature had increased to the same as the road, thus eliminating any potential thermal source differences.

A1.4 Source Area Model (SAM) results

In order to determine if the road was within the source- area for the down-wind sensor, the numerical source-area model, or SAM (Schmid and Oke, 1990; Schmid, 1993, 1997) was run for the period in which these temperature anomalies were observed. The model requires inputs of sensor height, roughness length, and atmospheric stability (Obukhov length), and calculates the source area, or "portion of the upstream surface containing the effective sources and sinks contributing to the turbulent exchange processes at a given point in the surface layer" (Schmid and Oke, 1990) using a reverse plume diffusion approach. Output consists of calculated upwind and lateral dimensions of regions of the surface contributing to different proportions of the total flux or scalar concentration as observed at the sensor's position.

A roughness length of 1.5 cm for the alfalfa crop was assumed (i.e. $Zo = 1/10\ h$, where h is the height of the roughness elements: Oke, 1987). Estimates of stability in the form of Richardson's number (Ri) were obtained from

$$Ri = g/\overline{T}\ \overline{(dT/dz)}\ \overline{(du/dz)}^{-2}$$

using temperature and wind observations described in Section A1.2.

The relationship

$$z/L = Ri/(1\text{-}5Ri)$$

was then used to calculate the Obukhov length, *L*.

Results for three different stability conditions are shown in Figure A1.7. These three situations were chosen to illustrate both the range of stability conditions, and the range of observed air temperature differences. Although these values of Ri are approaching those for stable conditions (i.e. >0.25), and therefore there is the possibility that non-turbulent processes are present, the results indicate that the road was at times potentially influencing the down-wind temperature observation.

When Ri was small (least stable) the downwind-upwind temperature difference was at its maximum of approximately 3°C. SAM results indicate that at this time, the road crossed both the 90% and 50% source areas. When Ri was 0.1, the source area shifted slightly upwind, so that the road crossed only the 90% source area. The upwind-downwind air temperature difference at the time was 0.8°C. During the most stable conditions (Ri=0.16) the road just barely intersected the 90% isopleth, and therefore did not affect the downwind temperature observation (i.e. upwind-downwind temperature difference of 0 °C)

Thus, model results indicate that the road was within the source area contributing to the downwind temperature observations, and the observations indicate that temperature differences between 1 and 3°C persisted for close to 1 hour. Had the meteorological conditions remained favourable for continued cooling throughout the night, it is likely that the thermal influence of the road would have persisted as well.

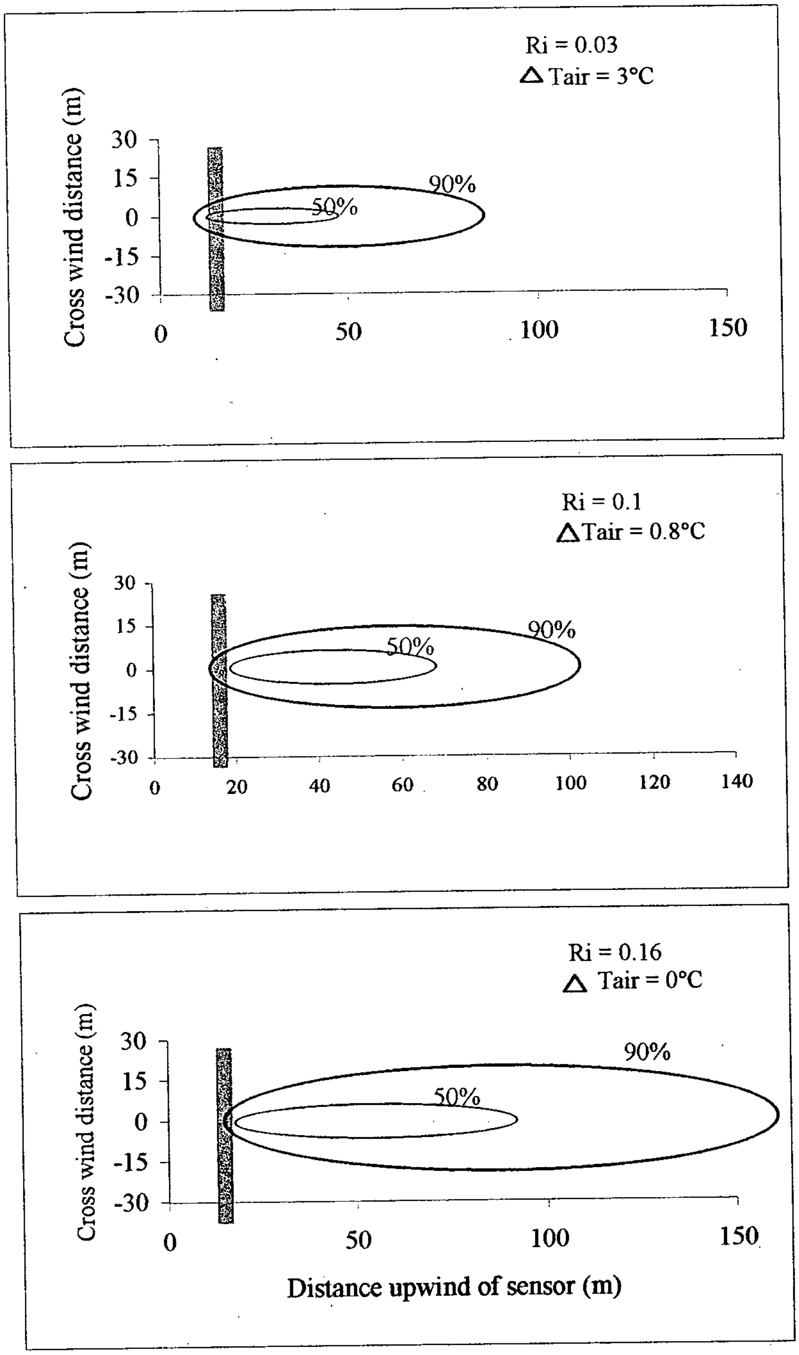


Figure A1.7 90% and 50% scaler concentration source areas for temperature sensor 1.5 m above the ground. Conditions for three stabilities are given: Ri= 0.03, 0.1, 0.16. Position of road is indicated by shading.

This greater than 3°C increase in downwind air temperature is larger than what would be commonly expected for such an apparently minor surface feature. The road is only 7 m wide and surrounded by considerable expanses of vegetation-covered fields; indeed if a climate station had been located there, its siting would have been considered "ideal" in most respects. In light of these findings, not only does the potential exist for substantially greater influences on air temperatures observed at climate stations in the vicinity of large parking lots and airport runways for example, but even the small concrete or gravel walkways often constructed to provide a pathway up to Stevenson screens are capable of introducing significant warmth to the air temperatures observed nearby if the wind is aligned appropriately.

A1.5 Effect of a small building on surrounding air temperatures

In contrast to the road which is essentially a one-dimensional case, the influence of a building on the surrounding air temperature is substantially more complex because of the three-dimensional geometry. Not only does the building have more surface area, as well as different thermal properties compared to the surrounding ground, it is also a roughness element that disrupts the air flow that would normally be present over expanses of open flat fields. Therefore, as well as providing an additional source of heat, the turbulence generated by the rough object under stable nocturnal conditions could result in the down-mixing of warmer air aloft, and therefore increase the air temperature observed at screen level.

In order to determine the potential influence on the surrounding air temperature, a small building was simulated by placing a grain-filled steel harvest wagon of dimensions 4.3 m x 2.4 m x 2.8 m high in an open field of short alfalfa (Figure A1.1(b)). By using a wagon instead of a real building, the structure could be moved to any location and isolated from other features such as trees, roads, or buildings. Also, the block-like shape of the structure was simpler and more symmetric than most buildings.

The long axis of the wagon was oriented northwest to southeast. Sheets of galvanized steel were secured at the base of the wagon to prevent airflow underneath. Instrumentation consisted of three identical aspirated fine-wire thermocouples (CSI ASPTC model) mounted 1.5 m above the surface. Two sensors were placed southwest of the wagon, one 1.5m from the base of the southwest wall (approximately ½ *H*, where *H* is the height of the object), and one at 3 m, or approximately 1 *H*. The predominant wind direction at night was southwesterly, and so these instruments were usually upwind of the wagon. The third sensor was the mobile one, described previously.

Measurements were made on two consecutive nights, August 12-13 and 13-14, 1998. Meteorological conditions for that period (including daytime) are shown in Figure A1.8. Measurements began in late afternoon of August 12 and therefore did not capture all of the antecedent daytime conditions; however, strong solar radiation, clear skies and light winds prevailed during the day. Surface temperatures observed using a Minolta IR thermometer at 1600 h. showed that the southwest-facing wall of the wagon was 48°C, while the surrounding ground was at 32°C. Maximum air temperatures reached approximately 23°C. During the night of the 12^{th}-13^{th} , winds were very light (less than 1.5 m s^{-1}, with frequent calm periods). The wind direction was consistently south-westerly. Skies remained cloudless throughout the night, and therefore Q^* was strongly negative. Conditions were ideal to promote cooling, and surface and air temperatures dropped to around 5°C at the time of the minimum on August 13th.

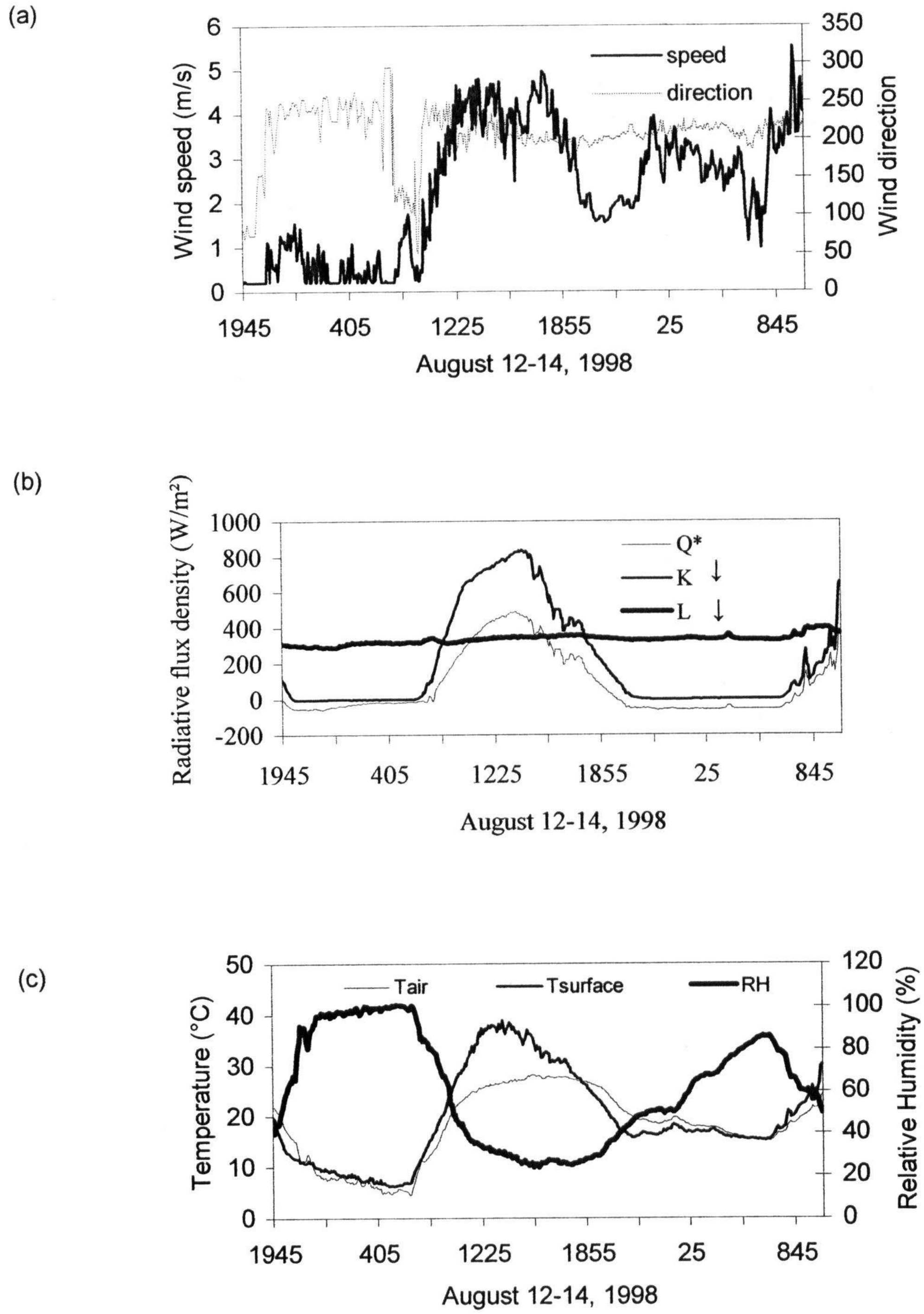


Figure A1.8. Meteorological conditions during the 'building' observation period. (a) Wind speed and direction. (b) Incident short- and longwave, and net all-wave radiation. (c) Air and surface temperatures and relative humidity.

The second day started out sunny and clear. Air temperatures reached approximately 25°C, and ground surface temperatures rose to 38°C. Wind speed increased to over 3 m s^{-1} in mid afternoon, and the solar radiation curve indicates slight cloudiness throughout the afternoon. On the second night, except for a lull to 2 m s^{-1} around sunset, winds were south-south-westerly, with speeds between 3 and 4 m s^{-1}. Much less cooling occurred, with minimum air temperatures remaining about 10°C warmer than the previous night.

Temperature transects using the mobile thermometer were undertaken at sunset, a few hours after sunset, and sunrise. Surface temperatures for all surfaces of the building and the ground were measured at the completion of each transect using the Minolta IR thermometer.

A1.5.1 Wall and ground surface temperatures

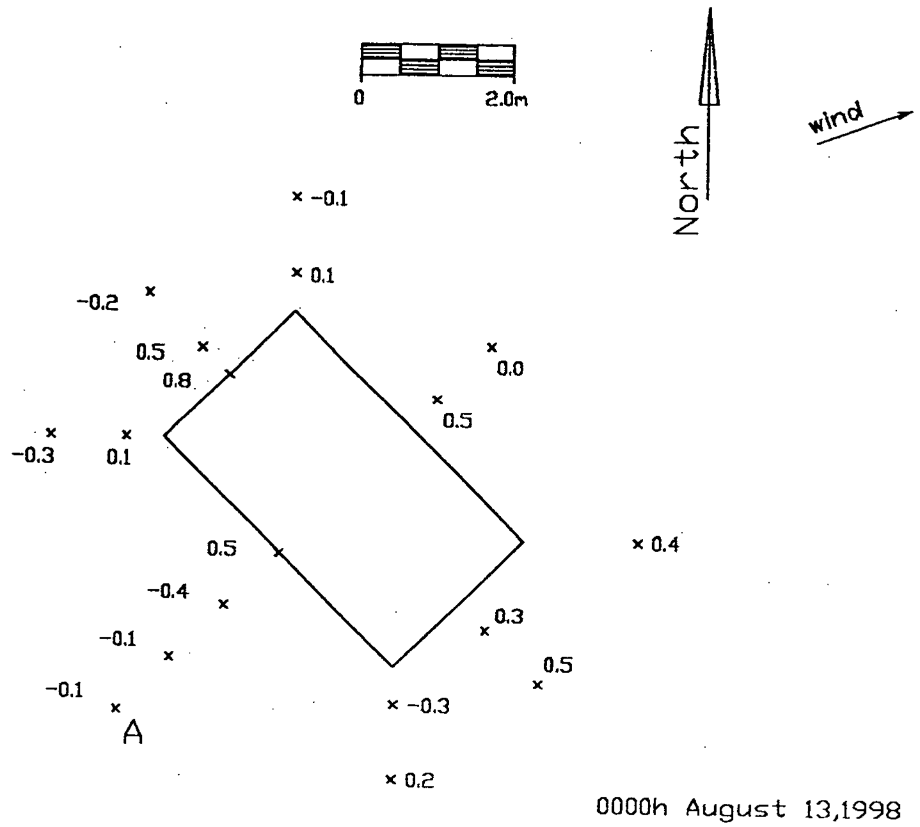
The potential thermal influences of the building can be described by examining the rate of change of the surface temperatures of the various facets of the building and the ground surrounding it, compared to cooling of the open ground surface away from the building. On the first day, maximum surface temperature on the south-west facing wall exceeded 48°C. Throughout the observation period, the exposed ground surface remained cooler than the wall surface. The greatest difference between the ground and south-west wall occurred shortly before sunset, when the ground was 25.8°C cooler. As cooling continued throughout the night, the wall temperatures were similar to each other, but the ground surface remained 3 to 4 °C cooler than the walls. Ground temperatures next to the building approached those of the walls, and therefore also remained 3 to 4 °C higher than the open ground. By 0100h, the walls were approximately the same temperature as the reference 1.5 m air temperature.

On the second night, temperature differences near sunset were substantially less than on the preceding day, with a difference of approximately 8°C between the south-west facing wall and the exposed ground (c.f. >25°C on the first night). Higher wind speeds on the second day were likely responsible for preventing the same degree of spatial variability in temperatures from developing as they did during the first night. Cooling following sunset was also significantly less than the first night, but by sunrise, the open ground was 3°C cooler than the walls, comparable to the first night. Walls equilibrated with the air temperatures around sunset, except for the northwest facing wall which remained slightly warmer until just before sunrise. Thus, particularly around sunset, significant surface temperature differences existed, providing a possible source of heat to influence air temperatures in the vicinity of the building.

A1.5.2 Air temperatures

Figure A1.9 shows temperature excesses observed by the mobile temperature sensor compared to the sensor located 3 m (approximately 1*H*) upwind of the building, for the post-sunset runs. Although temperature transects were made at sunset, winds were virtually calm throughout the run. As a result, the thermal influence of the relatively warm wagon was not advected downwind and therefore spatial temperature differences were not observed, and results are not shown.

Observations around midnight (approximately 2.5 hours after sunset) indicate the presence of a relatively warm envelope of air surrounding the wagon (Figure A1.9a). The warmest areas were immediately adjacent to individual walls, with a differences of up to a)



b)

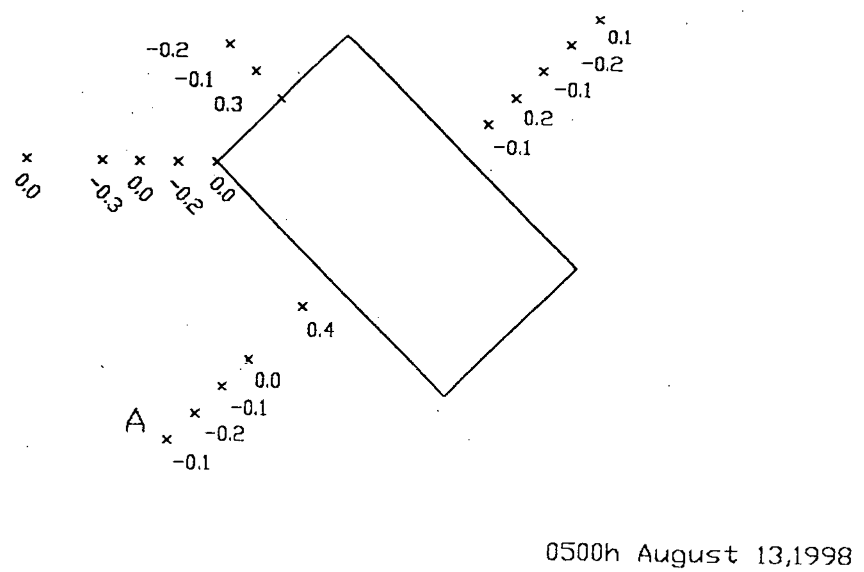
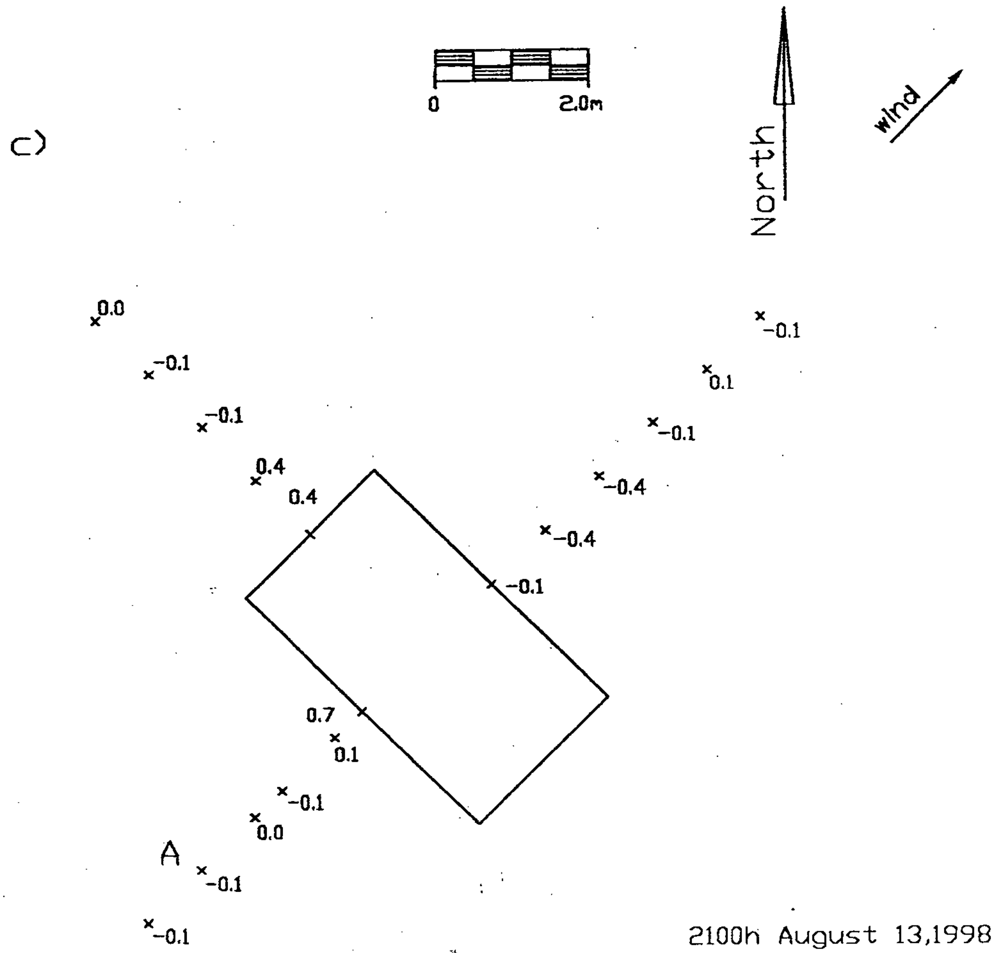


Figure A1.9 Plan view of air temperature variability around a rectangular obstacle. Temperature differences are relative to up-wind sensor located at position A.
a) 0000h August 13; b) 0500h, August 13; c) 2100h August 13; d) 0500h August 14.



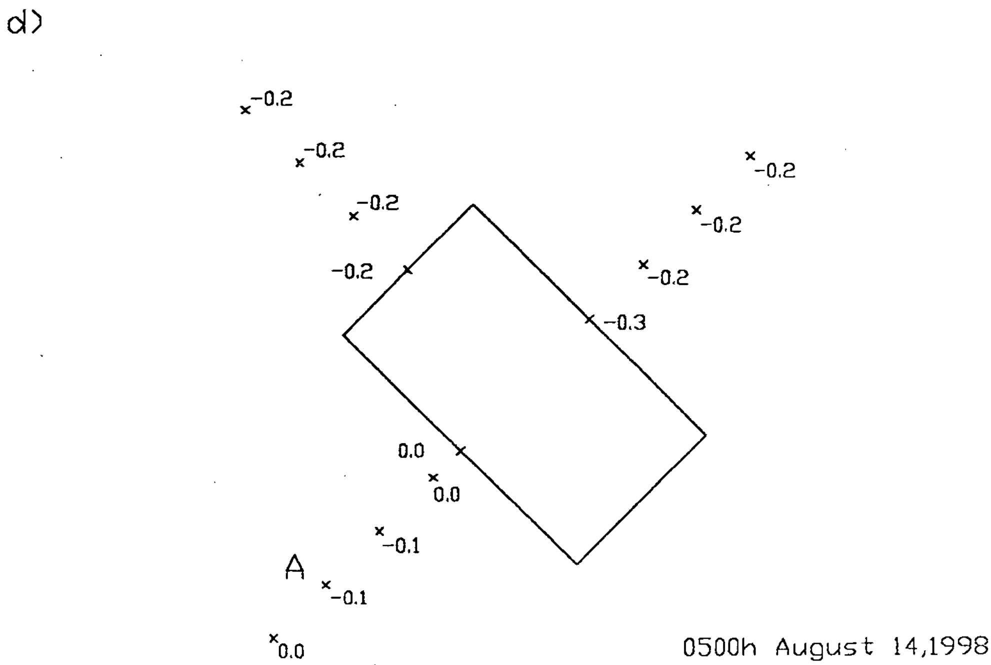


Figure A1.9, continued.

0.8°C occurring next to the north-west wall, and 0.5°C next to the southwest wall. 0.5 m out from the wall, differences of 0.2 to 0.5°C were observed. 1.5 m out from the walls, no effect was observed near the northwest wall, but to the south and east, differences were still significant (0.1°C to 0.6°C).

Air temperature differences were smaller at sunrise than they were at midnight (Figure A1.9b). At 0.5 m away from the walls, air temperatures were up to 0.3°C warmer than upwind of the wagon. At 1.5 m from the wall, temperature differences were negative or negligible except east of the building, where warm spots were observed at 1 and 3 m away from the wall.

On the second night at sunset temperatures adjacent to the southwest and northwest walls were respectively 0.7 and 0.4°C warmer than the upwind reference temperature (Figure A1.9c). At 0.5 m from the walls, the differences were 0.1 and 0.4°C. Downwind of the building, temperatures were slightly less than the upwind reference temperature.

By sunrise, the relative warmth next to the southwest wall had been eliminated, while small negative differences were observed downwind of the northwest and northeast walls. The higher wind speeds on this night presumably increased the homogenization of air temperatures relative to the first night.

A1.5.3 Discussion

Much of the research concerning air flow around buildings has been concerned with the turbulent properties around the buildings with respect to wind loading, pedestrian comfort and pollutant dispersion. As a result, the nature of flow around isolated buildings characterized by the displacement, cavity, and wake zones, upwind and lateral vortices, flow separation and re-attachment is fairly well documented (*e.g.* Hosker, 1986).

Most research on heat losses of buildings has been concerned with the rate of heat loss from the building with implications for energy use within the building itself (*e.g.* Quintela and Viegas, 1995). Few studies have been concerned with the downwind effects on air temperature that the excess heat would cause. One exception is the study by Ashie *et al.* (1998), who measured temperature variations around a rectangular block in a wind tunnel under different atmospheric stabilities. They found warm spots downwind of the block in unstable conditions, whereas cool spots were found down-wind under stable conditions.

Conditions in the field were significantly different from Ashie *et al.*'s (1998) more controlled wind-tunnel measurements, accounting for the differences between the findings. In Ashie et al's (1998) tests, the "building" was the same temperature as the surrounding horizontal surface. The situation in the field is much more complex, with each of the facets of the building at different temperatures, as well as spatial variability of ground surface temperature in the vicinity of the building.

The results of the present study can be explained qualitatively in the context of the flow patterns introduced by the building to the stable upwind air (Figure A1.10). In the vertical, upward displacement begins to occur up to a distance of $3H$ upwind of the obstruction. For stable conditions, this results in cooler surface air being lifted vertically. This potentially explains the observation (not shown) that the sensor at $\frac{1}{2}H$ upwind of the building persistently recorded temperatures more than 1°C below the sensor $1H$ upwind, during the first night (differences were less than 0.4°C on the second night). On the downwind side of the obstruction, air is recirculated in the wake of the building, bringing

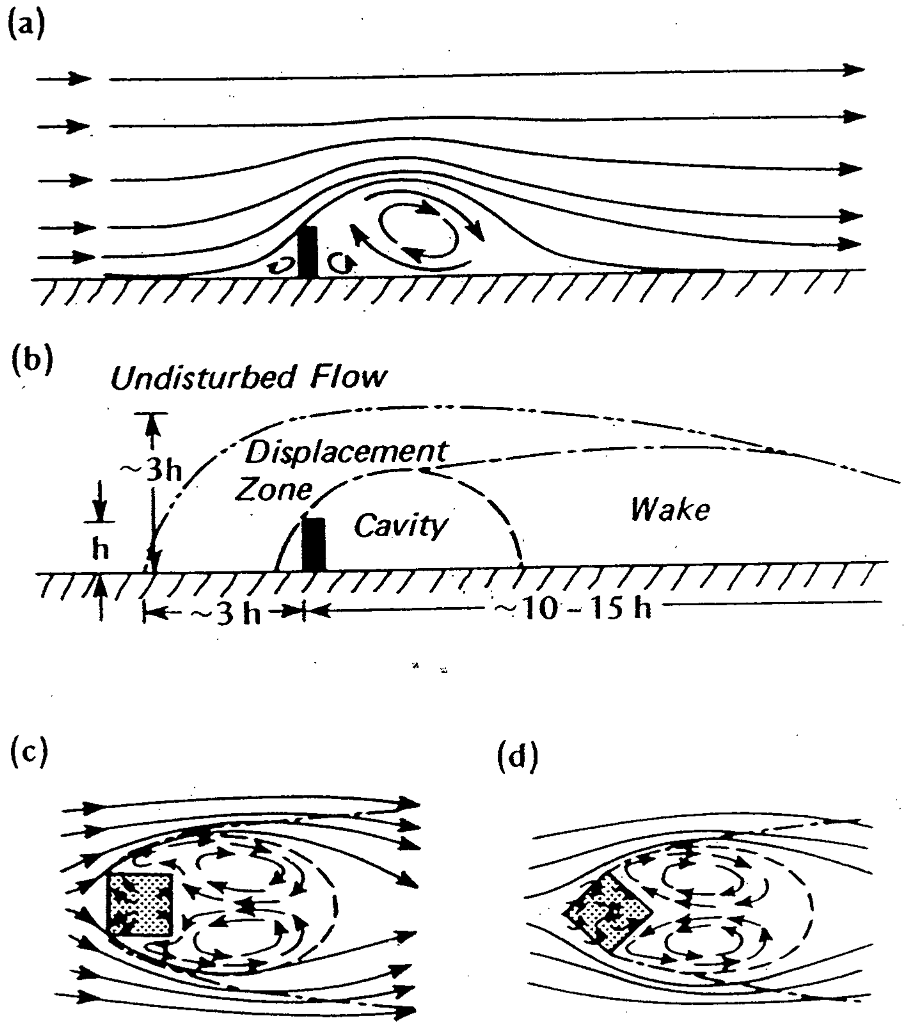


Figure A1.10 Generalized stream lines and flow patterns around a solid barrier. a) and b) vertical cross section for barrier placed normal to flow; c) plan view for building normal to the flow, and d) plan view for orientation diagonally to the flow. (After Oke, 1987.)

relatively warm air down to surface level, and at the same time incorporating into the mix the warm air that is rising vertically from the roof and walls.

Figure A1.10c shows a plan view of the typical lateral and downwind zones affected by a building. Recirculation behind and to the sides of the building helps to mix the warm air adjacent to windward walls into the cavity zone. This pattern explains the positive temperature anomalies observed 1.5 m away from the walls parallel to the wind direction, and the relatively warm areas near the centre of the downwind wall of the building. With slight variations in wind direction and speed, the theoretical patterns shown in Figure A1.10 would be constantly shifting and changing. Nevertheless, the observations indicate a similar "horse-shoe" pattern of thermal influence extending laterally and downwind of the building.

A1.6 Summary

Observations of screen-level air temperatures near a gravel road and a small building indicate that even seemingly minor surface features such as these can exert significant thermal influences on the surrounding air temperatures, particularly during stable night-time conditions. A 7 m wide gravel road was found to increase downwind temperatures by as much as 3.5°C for short periods of time, and more than 2°C for a 30 minute period. If meteorological conditions had remained favourable, it is possible that the downwind thermal anomalies would have persisted throughout the night.

Significant temperature anomalies were also observed in the vicinity of a small building. Greater than 0.5°C increases in temperature were observed within a zone of approximately ½ the height of the building during light winds and stable nocturnal conditions, but even during more neutral conditions with stronger winds and greater mixing, measurable warm and cool spots were observed up to 2 *H* downwind of the building.

Implications of these findings are significant to the siting of climate stations and to the interpretation of air temperatures recorded there. If even seemingly minor surface features are capable of influencing nearby air temperatures, then the potential for excessively warm temperatures in the vicinity of larger buildings, parking lots, or airport runways must therefore be much greater than conventionally assumed. Clear skies and light winds occurring in this study were close to ideal for the development of spatial variability in air temperatures, and consequently, the observed temperature anomalies were probably close to the maximum possible for such features. In the context of typical climate station records, the net bias introduced into monthly or longer-term average temperatures would depend on the frequency of occurrence of these particular meteorological conditions, and is therefore site specific.

Appendix 2
ALGORITHM FOR CALCULATING COOLING RATIOS AND HURST RESCALING FOR HOMOGENEITY ANALYSIS OF TEMPERATURE RECORDS

The following outline describes the steps necessary for the application of the technique developed in the body of the dissertation for homogeneity analysis of temperature records. The algorithm is general: that is, only the calculation steps are presented, not specific computer programming code. The procedure is not computationally intensive and can be easily applied using standard spreadsheet software, although a customized computer program may be desirable, particularly if many temperature records are being analyzed.

Application of the algorithm presupposes that station pairs have been selected as suggested in Chapter 4, i.e. both stations are subject to the same synoptic and topographic controls and differ only in their microclimatic setting, records are reasonably long to permit changes over time, and that the station chosen as a reference has sufficient station history information available to assure the record is of high quality and possible inhomogeneities could be identified from the history information.

A. Creation of a cooling ratio time series:

i) Calculation of daily cooling:

A time series of daily cooling (ΔT_j) at each station is calculated from the daily maximum and minimum temperatures (T_{max} and T_{min}):

$$\Delta T_j = T_{max\,(j-1)} - T_{min\,(j)}, \qquad \text{(A2.1)}$$

where j refers to the day of the year.

ii) Selection of the >50th percentile of cooling events in each month:

Cooling magnitudes from step i) that are greater than the median monthly cooling at each station are retained for further analysis. The reason for this selection, as outlined in Chapter 4, is to ensure that only occasions when sufficient cooling occurred to permit site specific controls to have an influence on the cooling process, are retained for analysis.

iii) Determination of daily cooling ratios (R_j):

Using the >50th percentile data,

$$R_j = \Delta T_{j\,(test\ station)} / \Delta T_{j\,(reference\ station)} \qquad \text{(A2.2)}$$

iv) Monthly median cooling ratio (R_i):

Monthly median values are computed from the data in step iii above, resulting in a time series of monthly median cooling ratios that can be analyzed for trends or change points, or subjected to further analysis.

B. Hurst rescaling of time series of R_i (modified from Outcalt *et al.*, 1997):

i) The mean of the series is subtracted from each of the n values of the original series.

ii) Deviations from the mean are accumulated to create a transformed series, Q_i.

$$Q_i = \sum_{i=1}^{i} (R_i - \bar{R}) \qquad \text{(A2.3)}$$

iii) The adjusted range,

$$r_n = Q_{max} - Q_{min} \qquad \text{(A2.4)}$$

where Q_{max} and Q_{min} are the maximum and minimum values of Q_i, respectively.

iv) The Hurst exponent, H, is approximated by the method given by Outcalt *et al.* (1997), that is

$$H = log\ [r_n/s]/log\ n, \qquad \text{(A2.5)}$$

where s is the standard deviation of the original record .

v) The value of H determines whether further analysis is necessary:

- If the value of H is approximately 0.5, then variations in the series of R are random, and not indicative of regime transitions.

- If H is greater than 0.5, this is the *Hurst phenomenon*, indicating that the series likely contains distinct regimes of different distributional characteristics. In the present context, values of H greater than 0.5 indicate that the microclimatic controls on nocturnal cooling at one of the stations have changed during the record. That is, elevated values of H indicate the presence of site specific inhomogeneities in the temperature record. Further graphical analysis can identify the timing of these cooling regime transitions.

- If the value of H is less than 0.5, this indicates the sample size, n, is too small to permit conclusions about the significance of any of the change points: that is, the record is not long enough.

vi) If the Hurst phenomenon is present, graphing the rescaled time series can lead to the identification of the timing of regime transitions. The transformed series, Q_i, is normalized by the adjusted range as follows:

$$Q_i' = (Q_i - Q_{min}) / r_n \qquad \text{(A2.6)}$$

Q_i' is therefore a series of normalized, accumulated deviations from the mean. Normalization limits the values of Q_i' to values between 0 and 1, and greatly simplifies the interpretation of the variability of the original series. When Q_i' is plotted, inflection points and changes in the slope can be interpreted as follows:

- An ascending trace indicates a period of 'above average' conditions. The larger the deviations from the mean, the steeper the slope.
- A descending trace indicates persistence of below average conditions.
- Changes to the slope and/or changes to the sign of the slope indicate regime transitions.

A more meaningful interpretation can be achieved if the rescaled trace is plotted on the same graph as the original cooling ratio series. Regime transitions apparent in the rescaled trace can then be compared to determine if the regime change occurred with an increase or decrease in cooling ratios, a change in variability, the beginning or end of a trend etc.

As noted in Chapter 6, when the original series contains persistent trends, an inflection in the rescaled traces occurs in the middle of the trend, rather than at either end. Therefore, the importance of examining both the original and the rescaled trace is clear.

vii) The timing of regime transitions can then be compared with station histories for both records in an attempt to identify the cause. If there is insufficient history information, the analysis may be repeated with a third station as a reference series for both records used in the first analysis, provided a suitable third candidate station exists. By creating two new cooling ratio series and the associated Hurst rescaled series, it is then possible to identify which station in the pairing contained the inhomogeneity identified in the analysis.