Meteorology and NO_2 variations in the Toronto-Hamilton area

Meteorological variations and their impact on NO_2 concentrations in the Toronto-Hamilton urban air-shed, Canada

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ABSTRACT

Exposure to traffic-related air pollutants has been found to be damaging to human health. Nitrogen dioxide (NO_2) levels, commonly used to indicate traffic-related pollution levels, vary significantly over small areas with higher levels found near sources such as major roads and industrial areas. The temporal and spatial variability in NO_2 levels is partly caused by fluctuations in meteorological variables, and better understanding of these meteorological influences can be used to enhance exposure assessment in health effects models.

In this study, the interaction between measured hourly NO_2 concentrations and climate variables at 11 locations in the Toronto-Hamilton Urban Airshed (THUAS) is examined. Analysis of meteorological data shows that two large urban heat islands (UHI) are present in the THUAS, centred on the downtown areas of Toronto and Hamilton. Lake breezes are found to occur frequently in the region, on up to 50% of summer days at lakeshore locations. These temperature and wind patterns influence NO_2 and pollutant distributions. NO_2 concentrations are highest in the early morning and late evening. Mean concentrations are highest in winter, although individual 1-hour NO_2 concentrations are found to be highest in summer because of higher production rates. Wind direction is the strongest control on hourly NO_2 concentration, and temperature and wind speed also have an effect. Seasonal variations in meteorology and emissions mean that the degree of spatial variability in NO_2 concentrations changes from season-to-season in the THUAS resulting in variable exposure of urban populations.

An attempt to improve an existing Land Use Regression (LUR) model, used for predicting nitrogen dioxide (NO_2) concentrations and estimating human exposure, was made by incorporating high resolution interpolated observed up- and downwind effects of wind transport on NO_2 concentrations around major roadways. Incorporation of observed wind direction effects in the LUR model slightly improved the accuracy of NO_2 concentration estimates in densely populated, high traffic, and industrial/business areas in both Toronto and Hamilton. However the short-term nature of initial NO_2 concentration

data limits the utility of the model in light of the significant seasonal variation in climate parameters in the THUAS and their influence on NO_2 transport and distribution.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Overview of urban air quality

Currently almost half the world's population lives in urban areas; in developed countries the fraction is higher at around 76 percent (PRB, 2004). This proportion is likely to increase with increasing global urbanization (United Nations Population Division, 2001; Wagner, 1999). Air pollution is a by-product of the way we live and urban air quality often suffers the most as cities contain conglomerations of emission sources including both vehicle traffic and industry. Despite improved regulation of factory and industry based emissions in recent years (Jacobson, 2002), a huge increase in the number of cars on the road during the 20th Century means that pollution, particularly traffic-related pollution, is the most significant problem concerning air quality in our cities today.

Recent studies show that both acute and chronic exposure to traffic-related air pollutants (TAP) may be associated with mortality and morbidity (Brunekreef & Holgate, 2002; Finkelstein *et al.*, 2003; Finkelstein *et al.*, 2005; Hoek *et al.*, 2002; Jerrett *et al.*, 2005a; Jacobson, 2002; Künzli *et al.*, 2000; Wark *et al.*, 1998). The length of time of exposure is important (Wark *et al.*, 1998), with cumulative exposures having a stronger effect on mortality than can be extracted from associations between day-to-day variations in air pollution and deaths (Brunekreef & Holgate, 2002).

TAP concentrations vary through space, with higher concentrations found near sources such as expressways and city centres with their higher building density, traffic volume, and industrialization (DeGaetano & Doherty, 2004; Gilbert *et al.*, 2003; Grivas *et al.*, 2004; Lewné *et al.*, 2004; Martuzevicius *et al.*, 2004; Rodes & Holland, 1981). The spatial pattern of these sources therefore, is the primary controller of the spatial distribution of pollutants, however meteorology and weather patterns also play a large role in determining how emissions are transported, diluted and dispersed across the urban environment.

Because air pollutant concentrations vary so significantly through space, and because of their important health effects, there is an increasing need to understand pollution variation at the intra-urban scale (Kanaroglou *et al.*, 2005). Developing reliable estimates of exposure for chronic studies poses many methodological challenges due to the small-area variation in TAP. The intra-urban variation and complexity of the traffic-pollution mix often necessitate the use of indicator pollutants, which can be measured through dense networks of monitors to supply spatially resolved concentration estimates.

Because of the expense associated with measuring air pollutants it seems unlikely that spatially extensive networks can be established to measure and model these contaminants. In air pollution modelling, NO_2 , a gas associated with TAP, is often chosen as a proxy for traffic pollution as it is inexpensive to measure and is a good surrogate of secondary pollutants from traffic-related combustion products (Hoek *et al.*, 2002; Kanaroglou *et al.*, 2005; Lewné *et al.*, 2004; Sarnat *et al.*, 2005; Singer *et al.*, 2004). NO_2, a secondary pollutant, is mainly formed chemically in the air by the oxidation of NO which in turn is emitted by vehicles burning fossil fuels. Minor sources of NO_2 are fossil fuel combustion and biomass burning (Jacobson, 2002). NO_2 itself is harmful to human health at levels found commonly in urban areas, triggering asthma attacks and sensitising lungs (Brunekreef & Holgate, 2002; Jacobson, 2002). NO_2 has also been related to chronic obstructive pulmonary disease and cardiopulmonary mortality, among other serious health effects (Brunekreef & Holgate, 2002; Hoek *et al.*, 2002; Jacobson, 2002; Künzli *et al.*, 2000; Wark *et al.*, 1998).

1.2 Meteorological controls on atmospheric pollutants e.g. NO_2

Meteorology is one of the major factors contributing to air pollution episodes (Seaman, 2003). Meteorology affects NO_2 distributions in many ways: atmospheric stability limits the mixing volume (Pielke & Uliasz, 1998; Seaman, 2003); mechanical and buoyant turbulence aid in dispersion; wind flow affects NO_2 transport from source to receptor (Grivas *et al.*, 2004; Jacobson, 2002; Rodes & Holland, 1981; Sturman & Zawar-Reza, 2002); and air temperature alters the rate of production of secondary pollutants and atmospheric stability (Rosenfeld, 1995).

Measurements have shown that NO_2 concentrations vary significantly diurnally due to variations in emissions (traffic rush-hours, industrial work hours), changes in atmospheric stability caused by surface heating, wind speed and wind direction, and changes in photochemical activity related to the availability of sunlight. On average, NO_2 concentrations peak in the early morning and in the late afternoon, and are lowest overnight (Collett *et al.*, 1997; Fagundez *et al.*, 2001; Gratani & Varone, 2005; Hargreaves *et al.*, 2000; Lal & Patil, 2001; Maruo *et al.*, 2003; Nagendra & Khare, 2003). Traffic volumes fluctuate throughout the day, so emission of precursor chemicals to NO_2 will also control the way NO_2 concentrations vary through time. Diurnal variations in NO_2 concentrations were also found to vary seasonally; studies in Europe, North America, and Japan have found that NO_2 concentrations are highest in winter because of higher atmospheric stability and emissions, especially from domestic heating, during the cooler months of the year (Atkins & Lee, 1995; Bell & Ashenden, 1997; Delaney & Dowding, 1998; Hargreaves *et al.*, 2000; Kirby *et al.*, 2001; Krochmal & Kalina, 1997; Lebret *et al.*, 2000; Liard *et al.*, 1999; Stevenson *et al.*, 2001).

Wind flow

Wind flow is altered in urban areas due to their built up nature; increased surface roughness due to building height increases friction and slows wind, also tall buildings may alter flow patterns and shelter or channel flow (DeGaetano & Doherty, 2004; Oke, 1987; Tumanov *et al.*, 1999). This creates an environment conducive to the build-up of pollutants. Sites which are less built-up and more open, such as many freeways or larger highways often experience lower pollutant concentrations because dispersion occurs more easily (Gratani & Varone, 2005; Stedman *et al.*, 2001). Airflow processes and energy exchange here are controlled by microscale, site-specific characteristics and processes (Arnfield, 2003).

Air pollutants are affected by wind speed in two ways. Strong winds either erode and re-suspend soil dust, raising particulate concentrations (Jacobson, 2002; McKendry, 2000), or they act to mix pollutants through a larger volume of the atmosphere, hence diluting and lowering concentrations (Martuzevicius *et al.*, 2004). Generally, particulate concentration is negatively correlated with wind speed in urban areas (DeGaetano & Doherty, 2004; Grivas *et al.*, 2004; Martuzevicius *et al.*, 2004; Mestayer *et al.*, 2003; Röösli *et al.*, 2001; Vecchi *et al.*, 2004).

Temperature

Temperatures are known to be higher in urban areas due to thermal trapping by buildings and anthropogenic release of heat (Hinkel *et al.*, 2003; Klysik & Fortuniak, 1999; Oke, 1987; Tumanov *et al.*, 1999). This phenomenon is known as the urban heat island effect and is discussed further in Chapter 4.

Higher urban ambient air temperatures are important because they affect pollutant concentrations by increasing rates of chemical reactions in the atmosphere, accelerating the formation of secondary pollutants, including NO_2. Air temperature also acts as a proxy for solar radiation levels; when air temperature is highest solar radiation is generally greatest. Therefore photochemical formation of aerosols is enhanced during high temperature periods. Higher particulate and ozone concentrations in the atmosphere also have feedback effects on air temperature; Photochemical smog reduces longwave radiation loss and re-radiates heat energy back towards the surface, especially at night (Beaney & Gough, 2002; Oke & Hannell, 1968). In this way pollutant levels are also affected by cloud cover which controls the availability of sunlight for photochemical reactions (Jacobson, 2002; Pielke & Uliasz, 1998).

Higher secondary pollutant concentrations have been found to be associated with warmer ambient temperatures in Athens, Greece and New York City (DeGaetano & Doherty, 2004; Grivas *et al.*, 2004). However, aerosol formation was found to be negatively associated with ambient temperature in Leipzig, Germany due to higher saturation of emitted gasses in cold weather and hence higher nucleation rates. This effect is confounded by reduced cold weather vertical mixing of the atmosphere caused by more stable wintertime conditions leading to higher pollutant concentrations (Wehner & Wiedensohler, 2003).

Relative Humidity

Ambient air temperatures are also related to humidity levels, confounding the effect on pollutant concentrations. The effect of humidity on particulate levels varies depending on geographic location and climate. In New York, higher humidity is associated with higher $PM_{2.5}$ concentrations, while in Cincinnati, Hong Kong and Athens, higher humidity is related to lower particulate concentrations due to hygroscopic growth of aerosols leading to deposition, precipitation, or transfer into larger, un-sampled particulate size fractions (Chan & Kwok, 2001; DeGaetano & Doherty, 2004; Grivas *et al.*, 2004; Martuzevicius *et al.*, 2004). Particulate concentrations are also reduced by precipitation, which washes particulates out of the atmosphere (Chan & Kwok, 2001; Vecchi *et al.*, 2004).

Synoptic Weather Systems

Long-range transport of secondary pollutants can occur (Chan & Kwok, 2001) in relation to particular synoptic weather types such as anticyclones - which are conducive to inversions, lighter winds and clearer skies - accelerating the formation of secondary pollutants and transporting them long distances (Grivas *et al.*, 2004). This type of event frequently occurs in Southern Ontario during summer when pollutants are transported from neighbouring U.S. states, especially from the highly industrialized and urbanized areas of the American Mid-West and Ohio Valley Regions (Beaney & Gough, 2002; Yap *et al.*, 2005). This type of long-range transport means that under certain conditions local air quality is not related to local emissions (Buchanan *et al.*, 2002).

Synoptic weather types have been found to be a strong control of particulate and NO_2 concentrations (Buchanan *et al.*, 2002; DeGaetano & Doherty, 2004; Grivas *et al.*, 2004; Keim *et al.*, 2005). Rising air in low pressure systems disperses near-surface pollution upwards, while clouds associated with regions of low pressure may also block the sun and reduce photochemical reaction rates and ozone production (Jacobson, 2002). Many high pollution episodes, such as those in New York City, Cincinnati, and

Vancouver are warm season cases with relatively weak dynamics; i.e. light winds, shallow mixing depths and no precipitation. These episodes are associated with high pressure systems, weak horizontal pressure gradients, higher air temperature and higher incoming solar radiation (DeGaetano & Doherty, 2004; Martuzevicius *et al.*, 2004; McKendry, 2000; Seaman 2000). Furthermore, high pressure systems allow for the development of local winds which may or may not enhance pollutant dispersion (Oettl *et al.*, 2001; Sturman & Zawar-Reza, 2002; Mestayer *et al.*, 2003). The highest levels of smog, ozone, and PM_{10} occur in the UK during the summer under anticyclonic conditions with S and SE flow types (Buchanan *et al.*, 2002; Jenkin *et al.*, 2002).

During summer in southern Europe the sun is intense, wind speeds are low or stagnant, there are frequent high pressure systems, high temperatures, high stability (low mixing heights), low midday relative humidity, and occasional thermally driven mesoscale circulations such as land-sea breezes, which can all lead to severe pollution events (Louka *et al.*, 2003).

Conversely, in Milan it was found that PM_1 and $PM_{2.5}$ concentrations are higher in winter than summer, with average winter concentrations being 40% and 30% higher (Vecchi *et al.*, 2004). The large seasonal difference was attributed to atmospheric stability being lower in summer than winter because of stronger surface heating and higher mixing heights. In winter low level inversions and atmospheric stagnation are frequent. Seasonal differences in emissions were also a factor, with domestic heating being an additional source in winter (Vecchi *et al.*, 2004). Particulate levels were also found to be higher in winter than summer in Basel, Switzerland; Athens, Greece; and Leipzig, Germany. Additional emissions produced by burning fuel for domestic heating, and cold starting automobile engines, combined with more stable atmospheric conditions including frequent temperature inversions are explanations for this (Grivas *et al.*, 2004; Röösli *et al.*, 2001; Wehner & Wiedensohler, 2003).

1.2.1 Urban heat island

The urban heat island (UHI) is caused by alterations made to the surface energy budget by the built environment, and by the additional heat released from human activities (Oke, 1987). The most important difference between rural and urban areas is the availability of water at the surface (Oke, 1987). In urban areas there is lower evapotranspiration due to surface impermeability and efficient drainage systems which means that net radiation (Q^*) goes preferentially to sensible heat (Q_H) and heat storage (ΔQ_S) (Grimmond, 2004; Oke, 1987; Spronken-Smith, 2002; Tumanov *et al.*, 1999). At residential sites Q_H is more important than at rural sites, taking up 40 to 60 percent of daytime Q^* (Grimmond & Oke, 2002). However, where irrigation takes place in residential areas, or if there is frequent rainfall, latent heat flux (Q_E) can be large, using 20 to 40 percent of daytime Q^* (Grimmond, 2004). The fraction of the land surface covered by vegetation and irrigation is therefore a significant control on energy partitioning between Q_H and Q_E (Grimmond, 2004; Weng & Yang, 2004). Because Q_H and Q_E are turbulent fluxes, energy partitioning has implications for turbulent mixing, and hence the dispersion of pollutants at the local scale (Avissar, 1996; Weng & Yang, 2004). Energy partitioning in urban areas may vary from season to season due to changes in the state of the atmosphere (Spronken-Smith, 2002).

Urban heat islands accelerate the formation of urban smog, with the probability of smog increasing by 6% per 1 °C increase in maximum daily temperature above 22 °C in Los Angeles (Rosenfeld *et al.*, 1995). Convergence in the local wind field caused by urban heat island circulation has implications for air pollution, reducing stability, increasing the mixing height in the surface layer, and hence enhancing turbulent dispersal of pollutants (Kossmann & Sturman, 2004).

The UHI effect is most pronounced 3-5 hours after sunset (Hinkel *et al.*, 2003; Oke, 1987; Weng & Yang, 2004). Temperature difference is eroded after sunrise as most of the solar heat goes to warming the urban fabric (Oke, 1987); this means that around midday the city is often cooler than surrounding rural areas partly because of increased shading by buildings (Klysik & Fortuniak, 1999; Weng & Yang, 2004). Consequently urban heat islands have more of an effect on daily minimum temperatures than maximums. Long-term studies of areas undergoing urban growth such as Fairbanks, Alaska; Saskatoon, Canada; and Phoenix, Arizona; showed that daily or monthly minimum temperatures increased with urbanisation at a much faster rate than maximum temperatures (Balling & Cerveny, 1987; Magee *et al.*, 1999; Ripley *et al.*, 1996).

The UHI intensity is inversely related to wind speed and cloud cover. It is the most sensitive to wind speed because turbulence and advection mix rural and urban air and break down the UHI (Hinkel *et al.*, 2003; Klysik & Fortuniak, 1999; Magee *et al.*, 1999; Morris & Simmonds, 2000; Oke, 1987; Oke & Hannell, 1968).

UHI intensity varies by season due to changes in weather and synoptic conditions. In many locations the winter heat island is larger because the release of anthropogenic heat is greater at this time of year (due to household heating requirements), reduction in urban snow (due to removal), and greater atmospheric stability in winter (due to synoptic conditions) (Hinkel *et al.*, 2003; Magee *et al.*, 1999). However, in locations where wind speeds are higher and atmospheric stability is lower in winter the UHI may be more developed in the warm months of the year. In many locations including Athens Greece, Melbourne Australia, Bucharest Romania, Birmingham England, Madrid Spain, Lodz Poland, Szeged and Debrecen Hungary, and Phoenix Arizona, UHIs are considerably larger and more frequent in summer, as clear skies and calm winds occur more often than in winter (Balling & Cerveny, 1987; Bottyán *et al.*, 2005; Klysik & Fortuniak, 1999; Morris & Simmonds, 2000; Philandras *et al.*, 1999; Tumanov *et al.*, 1999; Unger *et al.*, 2001).

1.2.2 Lake breezes

Areas located on coastlines are known to experience increased onshore breezes due to the different thermal properties of land and water. The frequency of onshore breezes is increased by the additional heat of the UHI as the contrast between land and water temperature is enhanced by the urban area. Onshore breezes may last longer or be more frequent because of the presence of a city (Martilli, 2003; Miller *et al.*, 2002; Yoshikado, 1992).

Lake and sea breezes occur frequently at coastal locations, especially during the summertime (Lyons, 1972; Simpson, 1994). The onshore breeze, which flows inland during the day, occurs because water has a larger heat capacity than land, so the land heats up much faster than water, heating the air above the land faster. This temperature difference leads to a pressure difference at low levels. At night the breeze disappears or even reverses to become a land breeze as the flow moves from the relatively cooler land to the warm water, again because of the different heat capacities of land and water. However, the daytime onshore breeze is usually much stronger than the night time land breeze (Oke, 1987; Simpson, 1994). In temperate climates onshore breezes blow on sunny days but gradient flows, particularly offshore flows, depressions and anticyclones may modify or suppress their development (Hastie *et al.*, 1999; Lennartson & Schwartz, 2002; Liu & Chan, 2002; Lyons, 1972; Lu & Turco, 1994; Masselink & Pattiaratchi, 2001; Shen, 1998; Simpson, 1994; Yimin & Lyons, 2003;).

Lake breezes were found to occur from one third of summer days in Chicago, to over 200 days per year in Perth, Australia (Lyons, 1972; Masselink & Pattiaratchi, 2001). Observations show that the lake breeze front penetrates to around 40km inland in the Great Lakes region in North America, while in sea-coast locations such as Perth and Los Angeles the sea breeze may penetrate up to 80 km inland (Masselink & Pattiaratchi, 2001; Lu & Turco, 1994).

Because of the circulatory nature of lake and sea breezes, these mesoscale systems can become closed, having significant implications for air quality, with little true air exchange taking place (Oke, 1987). This means that in coastal cities, pollutants may be re-circulated by the coastal breeze and concentrations may build up over time in inland areas (Hastie *et al.*, 1999; Jacobson, 2002; Lennartson & Schwartz, 2002; Liu & Chan, 2002; Lu & Turco, 1994; Lyons, 1972; Oke, 1987; Simpson, 1994). On the other hand, increased wind speed near the coast may also reduce pollution levels in near-shore areas (Kim *et al.*, 2001; Lu & Turco, 1994; Miller *et al.*, 2003). In Southern Ontario the arrival of the lake breeze front 32 km inland from Lake Ontario has been shown to be associated with significant rises in particulates, ozone and NO_X (Hastie *et al.*, 1999).

1.3 Simulation of temporal and spatial pattern of NO_2 concentrations

Attempts have been made to model the way pollutants are dispersed in the urban atmosphere in order to estimate levels of human exposure. However because urban populations are highly mobile, one must make assumptions about their exposures (Scoggins *et al.*, 2004). For example it is usually assumed that most of a person's time is spent at their home address. In developed countries, people spend more than 80% of their time indoors, and although indoor pollutant concentrations can differ from outdoor concentrations (Brunekreef & Holgate, 2002), outdoor air pollution concentrations are usually used to estimate exposure.

To model urban pollution, one must know the spatial distribution of sources and their temporal patterns, and one must also have an understanding of the atmospheric forces which influence emission dispersal relationships. The time scale and horizontal scale of interest for modelling determines which types of parameters are required (Moussiopoulos *et al.*, 2003). Pollution concentrations and human exposures may be predicted with such models as CALINE (Benson, 1992), health models and land-use regression.

Land use regression (LUR) is an effective and robust technique to predict air pollution concentrations such as NO_2 at a given location based on surrounding physical, land use and traffic characteristics (Jerrett *et al.*, 2005b). The LUR technique entails the use of least squares regression modelling to predict pollution surfaces based on limited pollution monitoring data and existing exogenous independent variables such as proximate land use, traffic, and physical variables. Incorporating land use variables into the interpolation algorithm leads to the detection of small-area localized variations in air pollution more effectively than standard methods of interpolation such as kriging (Briggs *et al.*, 2000; Lebret *et al.*, 2000). The main strength of the LUR technique is its reliance on short-term air pollution monitoring and ancillary data sets which makes this method relatively low cost as compared to intensive monitoring and modelling techniques.

1.4 Objectives

Few studies have made use of simultaneous meteorological and pollutant measurements at a high temporal resolution in urban areas. Knowledge of how NO_2 levels vary in space and time and are affected by regional climatic patterns will enhance understanding of human exposure over the long- and short-term in urban areas, which is increasingly linked to health effects (Hoek *et al.*, 2002; Finkelstein *et al.*, 2005). Enhanced knowledge of how meteorology influences NO_2 concentrations may contribute to understanding differences in NO_2 concentrations from other pollutants as well. The specific objectives of this research are to:

1. Investigate and characterise the spatial and temporal variability of key meteorological variables in the Toronto – Hamilton Urban Airshed (THUAS);
2. Explore the intensity and temporal characteristics of urban heat islands in the THUAS;
3. Investigate the frequency of onshore lake breezes in the region and determine their implications for air quality, in particular NO_2 concentrations, in lakeshore locations;
4. Characterise spatial and temporal variability of NO_2 concentrations in the THUAS and its fundamental meteorological controls including onshore lake breezes and urban heat islands.
5. Investigate the capabilities of LUR methodology to simulate NO_2 concentrations in the THUAS and to explore methodologies for their improvement by incorporating some meteorological variables studied under this research project.

CHAPTER 2: STUDY AREA AND METHODOLOGY

2.1 Study Area

2.1.1 Study area description

The area under study is in south-central Ontario, Canada, and includes the cities of Toronto, Burlington and Hamilton, located at the western end of Lake Ontario, and containing the Toronto-Hamilton Urban Air-Shed. The area experiences complex temporal and spatial climatic controls because of topographic variations, urban morphology, and land-water contrasts. The terrain generally slopes eastward toward the lake (76.5 m above sea level) from an elevation of 485 m a.s.l. in the far northwest of the area pictured in Figure 2.1. In the north the terrain is generally rolling and hilly, with the Oak Ridges Moraine located north of metropolitan Toronto. Further south, the Niagara Escarpment (approximately 100 m high) cuts across the landscape, dividing the city of Hamilton into two levels. The escarpment is cut through by several deep re-entrant valleys, the largest of which is Dundas valley at the south-western corner of Lake Ontario. River valleys also cut through the landscape further north, with the Credit, Humber, Don and Rouge Rivers discharging into Lake Ontario.

The Greater Toronto Area (GTA), which includes Halton county (city of Burlington), is Canada's largest metropolitan area, with a population of 5.1 million in 2001, while Hamilton has a population of 0.49 million (Statistics Canada, 2005). A 200 km stretch of shoreline reaching from Oshawa in the north to Stoney Creek, east of Hamilton City, is continuously urbanised. The GTA is one of the fastest growing conurbations in North America, increasing in population by 10% between 1996 and 2001 (Statistics Canada, 2005), much of this development is occurring in suburban areas, which increases traffic emissions. Major industrial plants are also located in the area including coal-fired power generating plants in Etobicoke, auto manufacturing units in

Oakville and Oshawa and steel-making complexes in north-eastern Hamilton.

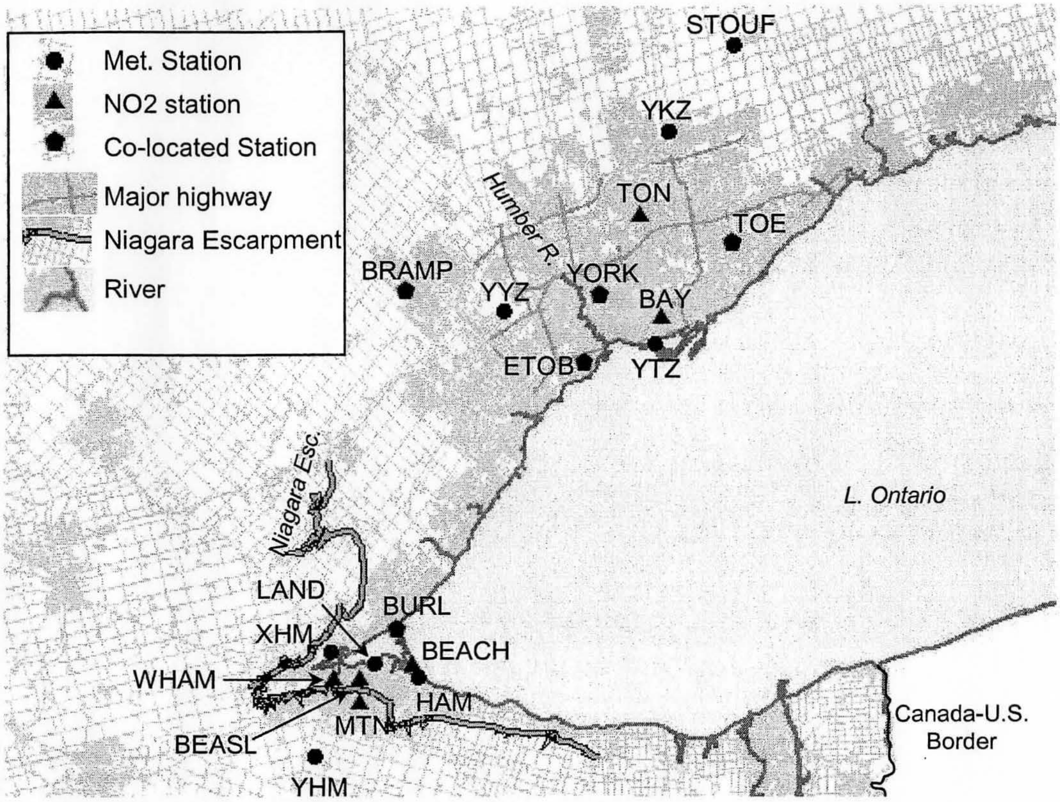


Figure 2.1: The Toronto-Hamilton Urban Air-Shed study area indicating meteorological and NO_2 sampling sites.

Heavily-used highways traverse the area, with the largest highway in Canada, the Macdonald Cartier Freeway, or 401, crossing the northern part of metropolitan Toronto and joining the lakeshore to the east of Toronto (see Figure 2.1), with some of the highest traffic volumes (up to 400,000 vehicles per day) in North America. Other major highways include the QEW-highway running along the lakeshore from Toronto to the city of Buffalo, New York, USA, and Highway-403 passing through Hamilton and Burlington.

Other major sources of pollutants in the region include coal–fired generating stations in the heavily industrialised Ohio River Valley 1,300 km to the southwest, and Nanticoke station on the north shore of Lake Erie, 53 km south of Hamilton city (Sahsuvaroglu & Jerrett, 2003).

2.1.2 Climate of the region

The climate of central southern Ontario is classed according to the Köppen classification as Dfb: humid continental with severe winters and warm summers (Ritter, 2005). Lake Ontario tends to moderate the climate with cool summers and relatively warm winters (Rouse & Burghardt, 1987). Extreme temperatures in the region range between approximately -28 °C in winter to +38 °C in the summer. Mean daily temperatures for January and July are -6.0 °C and 20.9 °C in Toronto, and -5.3 °C and 21.5 °C in Hamilton (Environment Canada, 2004). Hamilton's climate is generally warmer than that of Toronto because of its more southerly location and sheltering of many areas by the Niagara escarpment. Average annual precipitation received at Pearson International Airport (YYZ) between 1975 and 2000 is 787.63 mm and at Hamilton Airport (YHM) is 898.90 mm.

2.1.3 Air quality setting in the region

Air quality in the THUAS has become a problem for health and quality of life. Between 2000 and 2004, 64 smog advisories have been issued by Environment Canada for the region, with another 48 issued in 2005 (City of Toronto, 2006). However, average ambient NO_2 concentrations have been diminishing in the province over the last three decades, decreasing by 26% from 1975 to 2003 (Ontario Ministry of the Environment, 2004). Compared to other large cities such as Los Angeles, Hong Kong and Frankfurt, Toronto experiences a lower mean annual NO_2 concentration (20.70 ppb compared to 33.0 ppb in Los Angeles) (Ontario Ministry of the Environment, 2004). The annual US National Ambient Air Quality Standard (NAAQS) of 53 ppb and the Ontario provincial 1-hour (200 ppb) and 24-hour (100 ppb) criterion were not exceeded at any of the monitoring stations in 2002 in the THUAS (Ontario Ministry of the Environment, 2004). Although average concentrations have declined over the past three decades, the near source contribution from traffic raises the possibility that actual population exposures may be increasing. Unlike earlier periods when spatially concentrated industrial emissions or relatively homogenous NO_2 transported from the Ohio Valley predominates, the traffic contribution puts large portions of the population near the source. As a result, declining average levels may not result in lower overall population exposures and the continuing increase in traffic may pose large population health risks.

2.2 Data and Instrumentation

2.2.1 Meteorology

Wind parameters and air temperature are continuously monitored at 13 locations in the THUAS by Environment Canada and the Ontario Ministry of the Environment (MOE) (see Figure 2.1). Meteorological measurements were all made at a 10 m height using standard measurement procedures. The monitors are located in a range of environments including roadsides, highly industrialized sites, and open fields.

Air temperature and relative humidity are measured with an MSC "dewcell" (type E), consisting of a fibreglass sleeve saturated with a lithium chloride solution. The dewcell is calibrated with a mercury thermometer weekly and is accurate to 0.6 °C above freezing and 1.2 °C below freezing.

At Toronto east (TOE), Etobicoke (ETOB), Brampton (BRAMP), Burlington (BURL), Land Street (LAND), Hamilton downtown (HAM), Hamilton Botanical Gardens (XHM) and Hamilton International Airport (YHM) stations wind speed and direction are measured by a U2A anemometer, recording two-minute means. Hourly observations therefore represent measurements taken on the hour. At the remaining stations (Buttonville Airport, Toronto Island, and Pearson International Airport, abbreviated as YKZ, YTZ, and YYZ respectively) wind is measured with a 78D anemometer. This type of anemometer incorporates a microprocessor which transmits a message every five seconds containing the north-south and east-west vectors, and cup rotations. With one minute averaging this achieves a direction resolution of 1.6 degrees. From both MSC anemometer types wind direction is recorded to the nearest ten degrees. The direction is defined as that from which the wind blows. MSC wind equipment is calibrated twice yearly by technicians. Historical monthly meteorological data, including total snowfall amount and mean atmospheric pressure, were obtained from the Environment Canada website.

Continuous hourly-monitored downwelling shortwave solar radiation data is used from a site at a rural location some 74 km southwest of Hamilton (referred to as Turkey Point), close to the shore of Lake Erie. This data is measured above a pine plantation canopy at 28 m height with a four-dome net radiometer (model CRN1, Kipp and Zonen, Delft, Netherlands). Hourly atmospheric pressure measurements from the Turkey Point site are also made, using a Vaisala PTB101B barometer (model CS105, Campbell Scientific Inc., Canada). Gaps in the data were replaced with Environment Canada monthly averages.

2.2.2 NO_2

Ambient NO_2 concentrations were monitored at 7 locations in Toronto and Hamilton in 2002, 2003 and 2004. The Bay, Toronto north (TON), Beasley (BEASL) and Beach strip (BEACH) locations are not co-located with meteorological stations. Hourly NO_2 concentrations were also measured at a location in York in Toronto during 2002, and at the Resources Road (RESRD) location in west Toronto during 2003 and 2004, and at Etobicoke (ETOB) in 2002 and 2003. In Hamilton hourly NO_2 concentrations were also measured at west Hamilton (WHAM) and Hamilton mountain (MTN) locations in 2002 and 2003. Hourly NO_2 concentrations were therefore measured at 11 locations in total in 2002 and 2003, and at 8 locations in 2004 (see Figure 2.1). These measurements were made using Model TE 42C chemiluminescence NO-NO_2-NO_X analyzers (Thermo Environmental Instruments Inc., Franklin, Massachusetts, USA). This instrument works by reacting NO with O_3 to produce a luminescence with intensity proportional to the concentration. Infrared light is emitted when electronically excited NO_2 molecules decay to lower energy states according to the equation:

$$NO + O_3 \rightarrow NO_2 + O_2 + hv \quad (1)$$

where hv refers to electromagnetic radiation from sunlight. The precision of the NO_2 measurement instrumentation is assured through daily automatic zero and span checks to a known concentration of gas, through the use of a telemetry system, onsite monthly calibration of instruments against secondary transfer standards which are upheld to relevant U.S. National Institute of Standards and Technology and Pollution

Measurement Division of Environment Canada. Also, real-time statistical pattern tests are used to identify anomalies based on historical data. Accuracy estimates are not available from the MOE or MSC.

2.2.3 Gap Filling

Some of the hourly data were missing, due to instrumentation failure, maintenance and other reasons, usually for no more than four to five hours in a row; however from the middle of April to the end of May 2002 all NO_2 data is missing at eight sites due to a labour dispute. None of the data gaps were filled, as the short term gaps have little impact and are well within the margin of error (less than 2% in most cases), and the longer term gaps are too large for conventional gap-filling techniques.

2.2.4 Long-term climate

Global Daily Climatology Network (GDCN) Version 2.3 is a collection of daily climatological data using surface station observations of precipitation and temperature (National Climatic Data Center, Asheville, North Carolina, USA). Data is extensively checked to ensure erroneous values have been removed. Data was extracted using a spatial filter: from 42.88° to 44.75° latitude and -81.48° to -78.18° longitude, rendering 49 stations with daily minimum temperature values starting before or on 01/01/1975 and ending on or after 01/01/2000.

2.3 Methodology

Seasonal analysis was conducted by dividing hourly meteorological and NO_2 measurements for each year into four seasons; spring from March 15th to June 14th, summer from June 15th to September 14th, fall from September 15th to December 14th, and winter from December 15th to March 14th. Statistical calculations were carried out using Microsoft Excel and Matlab 6.5 software packages; analysis of variance (ANOVA) was performed using SPSS 11.0.

Of the 11 NO_2 monitoring stations, five are collocated with meteorological measurement stations. It was therefore necessary to pair up the remaining NO_2 stations with nearby meteorological stations so that simultaneous hourly NO_2 and meteorological measurements could be used for analysis. The pairing was done as shown in Table 2.1.

Table 2.1: Paired NO_2 monitoring locations and meteorological stations, with mean annual temperature, wind speed and NO_2 concentration for 2002.

NO_2 Station	Met. Station	Distance Apart (km)	Mean Temp. (°C)	Mean Wind speed (ms^{-1})	Mean NO_2 (ppb)
BAY	YTZ	5.32	9.4742	5.06	23.30
TOE	TOE	Co-located	11.77	1.96	21.99
TON	YKZ	10.50	8.94	3.44	21.03
ETOB	ETOB	Co-located	10.34	3.47	26.12
YORK	YYZ (temperature)	Co-located	9.55	2.03	22.82
BRAMP	BRAMP	Co-located	8.91	3.03	16.33
BEASL	LAND (wind)	2.20	-	2.76	20.94
	HAM (temperature)	7.18	11.16		
BEACH	HAM	2.15	11.16	2.86	23.16
WHAM	XHM	2.39	9.47	2.13	19.04
MTN	YHM	8.25	8.94	4.62	15.35
BURL	BURL	Co-located	10.92	2.40	17.91

Relative humidity describes how close to saturation the atmosphere is, which is dependent on air temperature. Specific humidity (kilograms of water vapour per kilogram of air ($kg\ kg^{-1}$)) is not dependent on air temperature, and it therefore a more appropriate measure of atmospheric water content. Hourly specific humidity (Q_s) and vapour pressure (*e*) were calculated for 2002 to 2004 at Pearson, Buttonville, Toronto Island, Hamilton Airport and Hamilton Botanical Gardens locations using hourly relative humidity (rh) and air temperature (T_a) measurements made at those stations, and atmospheric pressure (P) measurements made at Turkey Point according to the following equations:

$$e = 6.11 \times \frac{rh}{100} \times 10^\wedge \left(\frac{7.5 \times Ta}{237.7 + Ta} \right) \tag{2}$$

$$Qs = \frac{0.622 \times e}{P - 0.378 \times e} \tag{3}$$

where atmospheric pressure and vapour pressure are in units of hPa, and T_a is in degrees Celsius.

2.3.1 Spatial, seasonal, and inter-annual variability of meteorology

To assess whether 2002 (the year with most data availability) was a typical year in terms of climate, annual means and distributions of hourly air temperature, wind speed, wind direction and specific humidity were compared for meteorological measurement stations where data was available for all three years. ANOVA tests were also used to ascertain whether the years differed significantly from one another. The remainder of the analysis, described in the following sections and chapters, was performed only on data for the year 2002.

Seasonal variation in temperature, wind direction and speed, and specific humidity was characterised by dividing hourly meteorological measurements into four seasons for the year 2002, which were then analysed using ANOVA and descriptive statistics. Seasonal wind roses were plotted for one location each in Toronto (ETOB location) and Hamilton (HAM location) using hourly wind speed and direction measurements in WRPlot View from Lakes Environmental Software.

Seasonal variation in precipitation was assessed by using long-term data from the CDCN. Monthly precipitation totals were calculated as a percentage of mean annual precipitation using daily precipitation amounts received at Pearson and Hamilton Airports from 1969 to 2002 and displayed in a histogram.

2.3.2 Investigation of urban heat island

To establish the magnitude of urban heat islands in Toronto and Hamilton, air temperatures measured within the city are compared to simultaneous measurements in surrounding rural locations to discover how much of an effect the city has on measured air temperature. For 38 locations in central Southern Ontario a 26-year record (1975 to 2000) of daily minimum temperature and daily maximum temperature is available. To establish whether an UHI exists in the THUAS region, these stations were classified as being either rural (22 locations) or urban (16 locations) based on current surrounding land use. ANOVA tests were then carried out to establish if mean urban temperatures are statistically discernibly warmer than mean rural temperatures.

The temperature difference calculated by subtracting rural from urban temperature is known as the magnitude of the urban heat island (ΔT_{u-r}). When it is positive the city is warmer than the surrounding countryside, when it is negative the city is cooler. Although temperatures vary significantly through an urban area, just one location was selected to represent city temperature, as a very large number of sites would need to be sampled in order to properly represent the spatial variation of urban temperature, and this type of data is not available. The location chosen to represent urban temperature is that with the highest average temperatures, and represents the extreme of the urban heat island.

Diurnal

In both Toronto and Hamilton cities, temperature measurements from available stations were compared, and the sites with the warmest records were chosen as the most urban locations, and the sites farthest from that site, and least developed were chosen as the most rural locations. The hourly temperature difference (ΔT_{u-r}) between these locations is then calculated, and called the UHI magnitude.

To understand what time of day the urban heat islands of Toronto and Hamilton are most pronounced, an analysis of the diurnal pattern of the temperature difference between the rural and urban locations was undertaken. Hourly ΔT_{u-r} values were divided into 1 °C bins, and a histogram plotted to show the distribution the hourly UHI for the year. To understand how the intensity changes through the day, hourly occurrences of UHI greater than 3 °C were identified and a histogram was plotted showing how frequently UHI of this intensity occurred during each hour of the day. A similar method was followed for UHI with intensity between 2 and 3 °C, between 1 and 2 °C, between 0 and 1 °C, and also for negative ΔT_{u-r} values in 1 °C divisions.

Seasonal

To understand the seasonal variation in urban heat island strength and frequency, hourly temperature differences between the two pairs of sites were analysed by month, and histograms of varying UHI intensity plotted to show the distribution of the hourly temperature difference throughout the year.

Annual and Long-term urban heat island changes

To find out whether the urban heat island is becoming stronger or weaker over the years, one urban and one rural location were selected from the long-term climate database and the daily minimum and maximum temperatures were compared. The Downtown Toronto and Woodbridge locations were chosen as they provided an almost complete record of daily minimum and maximum temperatures for the years 1949 to 2000. Furthermore, these locations are similar in elevations (113 m and 164 m respectively) and are located at approximately the same latitude. Woodbridge is, however, further from Lake Ontario than the Downtown Toronto site. The difference between the rural and urban temperature values was then calculated for each day in the record for both maximum daily and minimum daily temperatures. This difference was then plotted as a time series graph, and a regression and determination coefficient was calculated to determine change in UHI magnitude over time.

2.3.3 Investigation of lake breeze

Diurnal variation of wind direction

To understand the occurrence and frequency of lake breezes in the THUAS, hourly wind direction measurements were analyzed from 11 locations in Toronto and Hamilton. Hourly wind direction data for each day from noon to 4:00 p.m. was compared with hourly wind direction data from midnight to 4:00 a.m. Frequency counts of wind direction during the day are compared to that during the night for each of the 16 cardinal wind directions for each meteorological station.

Identification of lake breeze days

The shoreline in the vicinity of Toronto and Burlington runs approximately northeast to southwest, while the shoreline in Hamilton runs east-west, therefore onshore breezes flow from different directions depending on which part of the coast is under consideration. Wind direction measurements were converted into polar coordinates, and days where flow reversal occurred were identified by comparing morning (7:00 a.m. to 10:00 a.m.) and afternoon (2:00 p.m. to 5:00 p.m.) average wind direction for each day of the year. On the northwest shore of Lake Ontario (between Burlington and Toronto east) onshore flow was classified as blowing from between 40° and 220° and offshore flow between 220° and 40°; on the southern shore of Lake Ontario (the shore of Hamilton city) onshore flow was classified as winds from the northern hemisphere and offshore flow from the southern hemisphere.

Effect on NO_2 concentrations

To discover the effect of the land-lake breeze circulation on air quality in Toronto and Hamilton hourly wind direction and NO_2 concentrations were plotted for consecutive days when lake breezes were thought to occur and trends in hourly NO_2 concentration and wind direction and speed compared and plotted in time series graphs.

2.3.4 Temporal variation of NO_2

Diurnal

The arithmetic mean and distribution of hourly NO_2 concentrations was calculated for each hour of the day for all 365 days of 2002. That is, the mean of 6:00 a.m. measurements for every day of the year was calculated, as was the 7: 00 a.m. mean, and so on. The hourly mean of NO_2 concentrations was also calculated in this way for each of the four seasons. In this way the average diurnal variation in NO_2 concentrations can be seen for the whole year and the seasons. These results were then plotted in time series graphs.

Seasonal

Hourly NO_2 concentrations were divided into seasons and also into months for the year 2002. Seasonal and monthly arithmetic means and distributions were then compared for different times of the year. ANOVA tests were performed on seasonal concentrations at each station to assess NO_2 seasonal variability.

2.3.5 Spatial variation of NO_2

To determine the hourly range in NO_2 concentrations in the region, the difference in NO_2 concentration recorded at the location with the highest concentration and at the location with the lowest concentration at the same hour was calculated for every hour in 2002. This difference was them plotted as a time series graph.

To assess the degree of spatial variation in hourly and 24-hour average NO_2 concentrations Coefficients of deviation (COD) were calculated. The COD is calculated between pollution concentrations measured at two locations as follows:

$$COD_{jk} = \sqrt{\frac{1}{p}\sum_{i=1}^{p}\left(\frac{x_{ij} - x_{ik}}{x_{ij} + x_{ik}}\right)^2} \qquad (4)$$

where x_{ij} and x_{ik} are 1- or 24-hour NO_2 concentrations measured at locations j and k, for time period i, and p is the number of observations compared. COD statistics are calculated between all locations in an urban area and the maximum between station COD indicates the level of heterogeneity in the region. For shorter sampling periods, such as hours or days, pollutant concentrations between sites differ more than when concentrations are averaged over longer periods (Monn, 2001). Wilson *et al.* (2005) recommends 24-hour concentrations are compared to capture diurnal patterns.

2.3.6 Meteorological control of NO_2

Wind speed impact on NO_2

Hourly wind speed and NO_2 values at the co-located and paired NO_2 and meteorological stations were divided into four seasons. Regression lines and coefficients of determination were then calculated for these hourly values with wind speed as the independent variable, to assess the relationship between NO_2 concentrations and wind speed at each location.

Wind direction impact on NO_2

To gauge the relationship between hourly wind direction and hourly NO_2 concentration, scatter plots were created with wind direction as the dependent variable using values for 2002 at each location. Scatter plots were also created for hourly values for each of the four seasons to assess seasonal variation in the wind direction relationship.

To further quantify the importance of wind direction variation at each location, NO_2 concentrations measured during hours when the wind blew from the north (between 280° and 80°), and during hours when the wind blew from the south (between 100° and 260°) were compared to ascertain whether long-range transport of NO_2 from south of the border is significant. ANOVA tests were performed to determine if there is a significant difference in NO_2 concentration for south versus north winds.

Impact of other meteorological variables on NO_2

Continuous hourly incoming solar radiation measurements from the Turkey Point site were compared to hourly NO_2 concentrations at sites in Toronto and Hamilton to determine any association between the two variables. Because the radiation monitoring site is located at such a distance from the NO_2 monitoring locations (74 km south of Hamilton City), there are likely to be differences in actual and observed incoming solar radiation levels. However, as there are no known systematic phenomena which are likely to affect shortwave radiation levels (such as increased cloudiness at the shore of Lake Erie), it is assumed that incoming solar radiation levels over the whole region are reasonably uniform.

For each of the 11 locations in Toronto and Hamilton hourly measured NO_2 concentrations were compared to incoming solar radiation levels at Turkey Point for each season in 2002. With incoming radiation as the independent variable, the relationship between the two variables was plotted for each location, along with the line of best fit and coefficient of determination. The same analysis was carried out using hourly ambient air temperature and specific humidity, where they are measured, and NO_2 concentrations measured at paired stations nearby.

2.3.7 LUR methodology to simulate NO_2 concentrations

The LUR model of spatial variation of NO_2 in Toronto and Hamilton cities was developed by creating 83 independent variables in ArcGIS (Jerrett *et al.*, 2005b). These variables were grouped into five broad categories: land use, road and traffic, population, physical geography including elevation, and meteorology (wind direction). The observed wind direction data (u and v components) were interpolated into spatial grids of 0.5 km resolution using the RBF multiquadric interpolation method to generate urban wind field datasets following the methodology of Goodin *et al.* (1980). A 17-day average u and v wind components were calculated for the 5:01 to 6:00 p.m. segment of the day, for each observation station to represent wind conditions during daily afternoon peak traffic flow when traffic emissions are highest and have the most significant impact on average NO_2 concentrations. Moreover, evening wind fields are reasonably representative of prevailing wind conditions, capturing the effect of lake breezes.

To calculate whether locations lay up or downwind of a point of emission (e.g. expressways) for a particular wind field, a continuous surface of distance from each grid point to the nearest expressway was created. The u and v components of wind were interpolated as separate scalar entities, allowing for wind direction vector calculations to be performed within the ArcGIS framework. To determine this relationship, the interaction between two vector sets is obtained by applying the dot product operation:

$$\mathbf{a} \cdot \mathbf{b} = a_1 b_1 + a_2 b_2 = |\mathbf{a}||\mathbf{b}|\cos\theta \qquad (5)$$

where a and b equal the direction vectors with components a_1 and a_2 and b_1 and b_2, which represent the direction to the nearest expressway, and wind direction with angle θ, which lies between the two. The second part of the equality in Equation 3 is an identity that provides two pieces of information: (1) the angle that accounts for the degree of relationship between the wind vector and expressway, and (2) the sign of cos θ, which shows whether a major road lies up- or downwind of any specific point of interest in study area for that particular wind field; a negative value characterises a grid cell located downwind of a major road, and positive values characterise grid cells located upwind. NO_2 concentrations were increased within a 1500 m buffer downwind of major highways

(Kanaroglou *et al.*, 2005). A sensitivity analysis was performed, and it was established that increasing NO_2 concentrations by 0.1316 ppb produced the most significant improvement in the LUR model. Because NO_2 is a rapidly forming secondary pollutant, created by oxidation of the primary pollutant NO, NO_2 concentrations have been found to be decreasing exponentially with downwind distance from major highways (Rodes & Holland, 1981; Gilbert *et al.*, 2003). There was no provision in the LUR model used in this study for exponential decrease in pollutant concentration from major highways.

CHAPTER 3: INTER-ANNUAL AND SEASONAL VARIABILITY OF METEOROLOGY

3.1 Results

3.1.1 Inter-annual Variability

Interannual variability of meteorology and NO_2 concentrations are assessed in order to establish whether the year 2002, the year under study, is a typical year.

Temperature

Analysis of hourly temperature records from the five locations where temperature measurements are available for 2002 to 2004 shows that 2002 was a warmer year. Mean annual temperatures were warmest in 2002 (see Table 3.1), because of a warmer spring and summer. 2003 was the coolest year, despite warmer summer temperatures than 2004 because of a cooler spring and fall in 2003. ANOVA testing shows that 2002 mean temperature at each station is significantly different from 2003 and 2004 means at the 95% level.

Table 3.1: Inter-annual variability in air temperature at 3 locations in Toronto, and 2 locations in Hamilton.

	Mean			Max temp recorded			Min temperature recorded		
Station	**2002**	**2003**	**2004**	**2002**	**2003**	**2004**	**2002**	**2003**	**2004**
YYZ	9.6	8.1	8.4	35.1	34.2	31.3	-16.4	-24.6	-24.2
YTZ	9.5	7.7	8.3	33.4	29.9	28.9	-15.2	-22.9	-23.4
YKZ	8.9	7.5	7.7	34.7	35.1	31.5	-17.9	-25.7	-26.7
YHM	8.9	7.5	7.8	33.4	33	30.1	-20	-24.2	-30
XHM	9.5	7.9	8.4	34.3	34.1	32	-17.5	-25.1	-23.6

Wind Speed

Analysis of inter-annual variability of wind speed from the five locations with hourly wind measurements for 2002 to 2004 (Table 3.2) shows that 2002 was a slightly windier year than 2003 and 2004 on average. Figure 3.1 shows the distribution of hourly wind speed at the five locations in Toronto and Hamilton. Wind speeds at Toronto Island (YTZ) were slightly stronger in the winter of 2002-2003, and wind speeds in Hamilton (XHM) were slightly stronger in the winter of 2003-2004 than other years, and wind speeds in all locations were slightly weaker in the summer of 2004 than the other two years. ANOVA tests show that 2002 mean wind speed at each station is differs significantly from 2003 and 2004 means at the 95% confidence level.

Table 3.2: Hourly wind speeds recorded in 2002 at five locations in Toronto and Hamilton.

	Mean			Max wind speed recorded			Standard deviation		
Station	**2002**	**2003**	**2004**	**2002**	**2003**	**2004**	**2002**	**2003**	**2004**
YYZ	4.74	4.45	4.48	20.56	21.11	17.50	2.78	2.83	2.75
YTZ	5.06	4.92	4.78	22.22	20.00	18.61	3.09	3.16	3.03
YKZ	3.44	3.3	3.34	16.39	14.44	12.78	2.30	2.35	2.26
YHM	4.62	4.20	4.30	19.44	20.56	16.94	2.76	2.69	2.57
XHM	2.13	2.16	2.14	10.83	13.89	9.17	1.48	1.63	1.47
Average	**4.00**	**3.81**	**3.81**	**17.89**	**18.00**	**15.00**	**2.48**	**2.53**	**2.42**

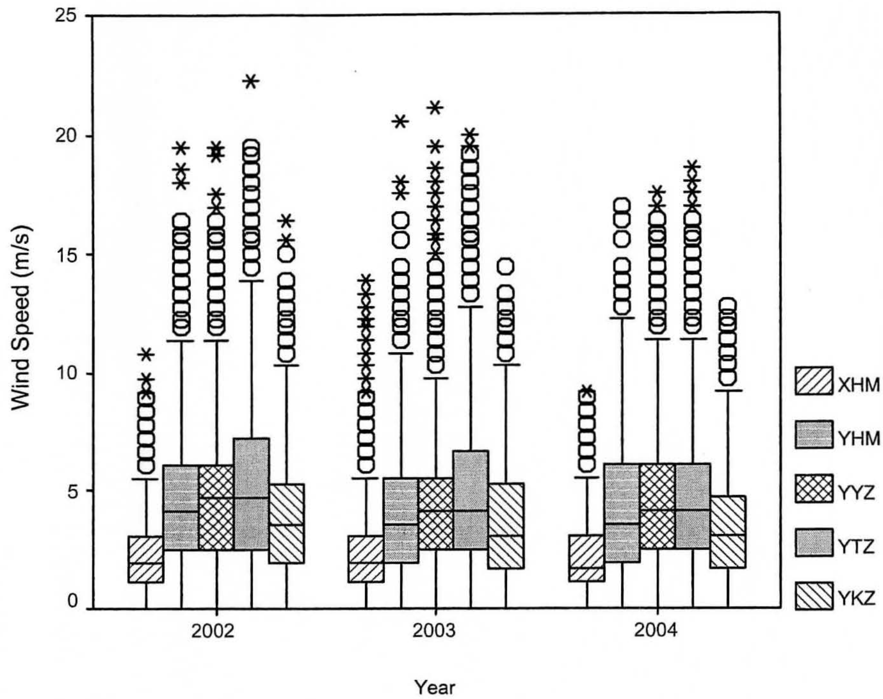


Figure 3.1: Box and whisker graph of hourly wind speed recorded at Hamilton Botanical Gardens (XHM), Hamilton Airport (YHM), Pearson Airport (YYZ), Toronto Island (YTZ), and Buttonville Airport (YKZ) for 2002-04.

Wind direction

Figure 3.2 shows 16 point wind direction frequency for 2002, 2003 and 2004 at the five locations in Toronto and Hamilton. This figure shows that in general wind direction frequencies are very similar for the three years. The largest differences between the years are as follows: At Pearson Airport (Figure 3.2 (a)) easterlies were more common in 2003 occurring 8.75% of the time compared to 5.76% of the time in 2002. At Buttonville Airport (Figure 3.2 (b)) northerlies were significantly less frequent in 2004 as compared to other years. Easterlies were also approximately 2% more common in 2003 then 2004. At Toronto Island east-northeast winds were 3-4% more common in 2003, and east winds were 3.5% less common in 2002 than the other years. North-northwest winds were also much more common in 2004 than other years. Southwest to west winds decreased by between 2 and 2.8% from 2002 to 2004.

At Hamilton Airport (Fig. 3.2 (e)) northeast and east-northeast winds were approximately 3.4% more common in 2003 than 2002, and south-southwest winds were almost 3% less common in 2003. Southwest and west-southwest winds were approximately 2.4% more frequent in 2002 than other years. At the Hamilton Botanical Gardens, northerly winds decreased by 3.2% from 2002 to 2004. East-northeast and east winds were 2.7% less common, and west-southwest winds were 3.3% more common in 2002 than other years. Standard deviation of hourly wind direction in 2002 is lower for all locations except XHM (standard deviation ranges between 106 and 107) in Hamilton, this shows that wind direction was less variable in 2002.

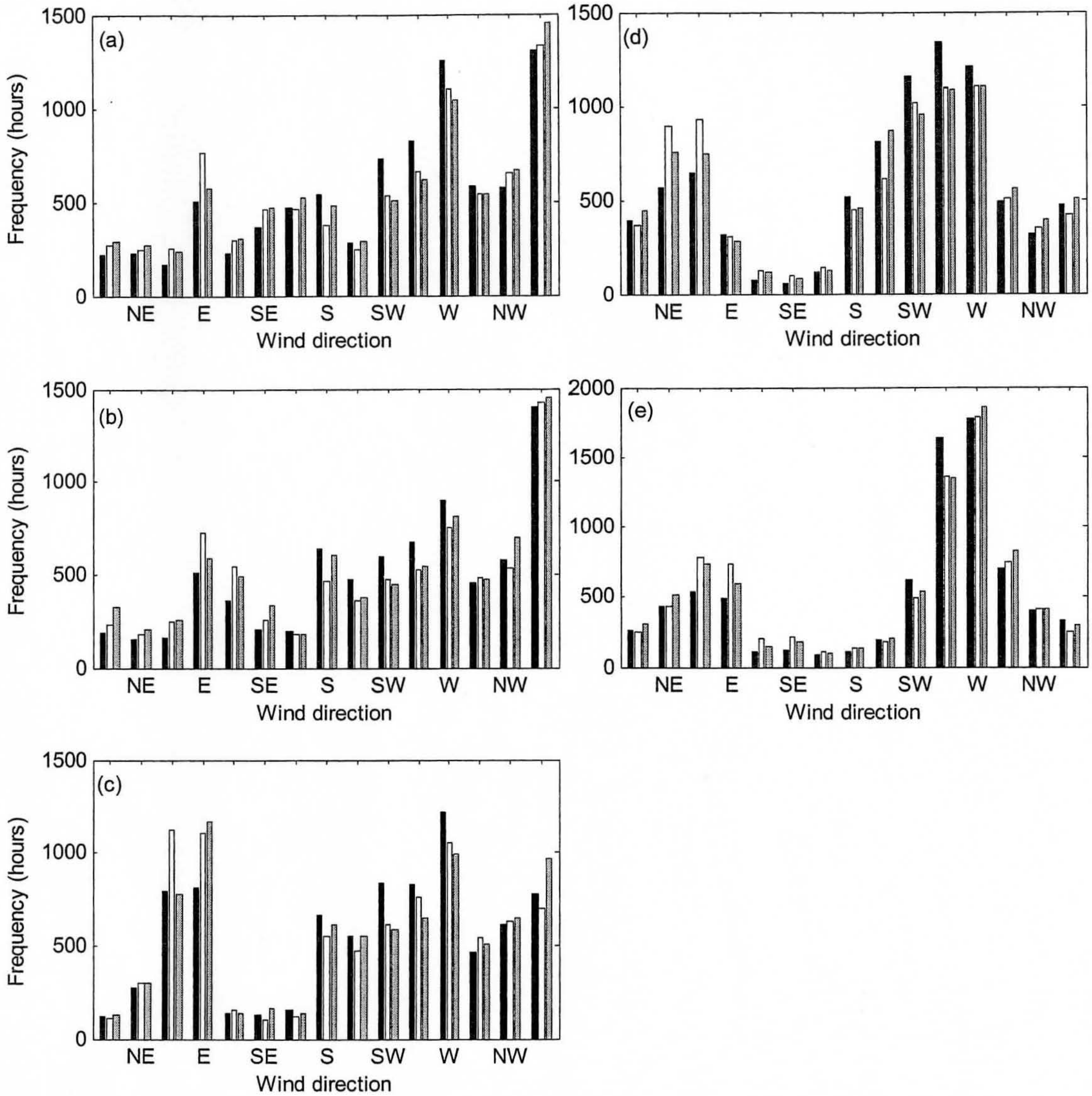


Figure 3.2: Inter-annual variability of wind direction at (a) Pearson Airport, (b) Buttonville Airport, (c) Toronto Island, (d) Hamilton Airport, and (e) Hamilton botanical Gardens for 2002 (black bars), 2003 (white bars) and 2004 (grey bars).

Specific Humidity

Inter-annual variability in specific humidity was relatively small between 2002 and 2004 at the five locations where it was measured (see Figure 3.3). However, ANOVA testing of differences in means showed that annual specific humidity in 2002 is different from that in 2003 and 2004 at the 95% confidence interval at all locations except

Buttonville. Median specific humidity is on average lower in 2002, while maximum specific humidity is higher at most locations, increasing average station specific humidity compared to other years, as can be seen in Figure 3.3.

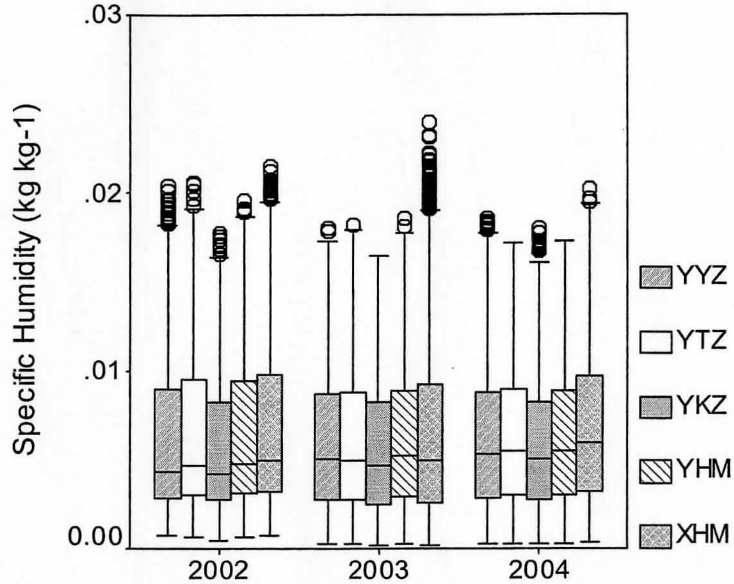


Figure 3.3: Interannual variability of hourly specific humidity distribution recorded at Pearson Airport (YYZ), Toronto Island (YTZ), Buttonville Airport (YKZ), Hamilton Airport (YHM) and Hamilton Botanical Gardens (XHM) for 2002 to 2004.

3.1.2 Seasonal Variability

Temperature

In 2002 the Downtown Hamilton location was warmest during winter, spring and summer (mean seasonal temperatures of 1.1 ˚C, 14.0 ˚C, and 24.1 ˚C respectively), while Etobicoke was warmest in fall (mean seasonal temperature of 8.8 ˚C), as shown in Figures 3.4 and 3.5. Stouffville is the coolest location during all seasons, with mean temperatures of 7.3 ˚C, 20.7 ˚C, 5.0 ˚C, and -2.4 ˚C during spring, summer, fall and winter respectively. Buttonville Airport experiences the largest range in temperature, especially during spring (ranging between -12.2 ˚C and 31.7 ˚C), summer (between 7.2 ˚C and 34.7 ˚C), and winter (between -16.5 ˚C and 17.7 ˚C). Hamilton Botanical Gardens also experiences large variations in hourly temperature during summer, with the highest hourly temperature of 34.3 ˚C and the lowest hourly temperature of 7.1 ˚C. In fall Hamilton Airport has the largest range in temperature with the maximum and minimum hourly temperatures recorded at 30.2 ˚C and -20.0 ˚C respectively. The smallest range in seasonal hourly temperature occurs at Toronto Island in all seasons except fall, when the smallest range is recorded at Hamilton Downtown (maximum and minimum hourly temperatures of 29.8 ˚C and -12.7 ˚C respectively).

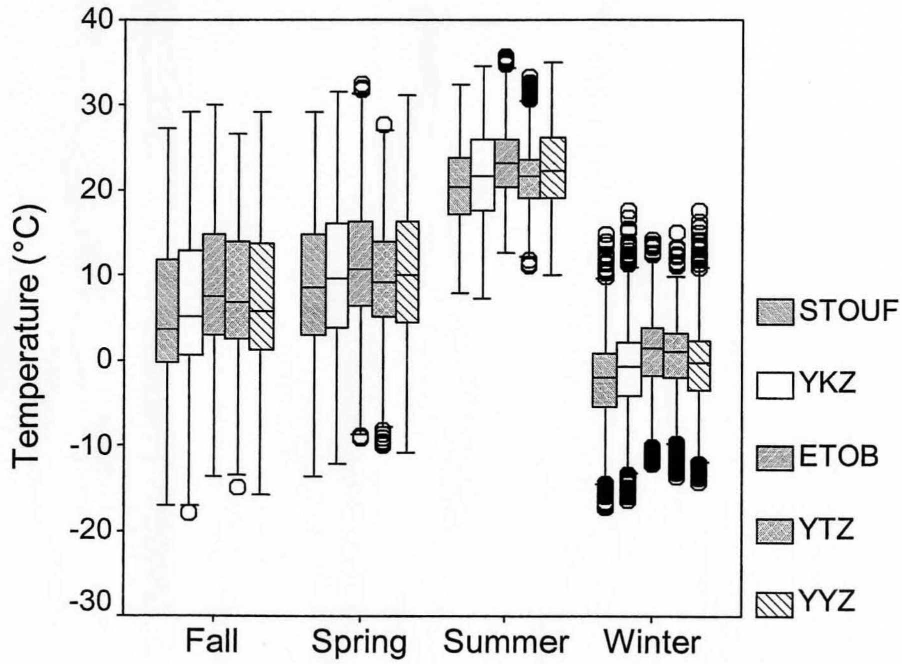


Figure 3.4: Seasonal temperature distribution at five locations in Toronto during 2002.

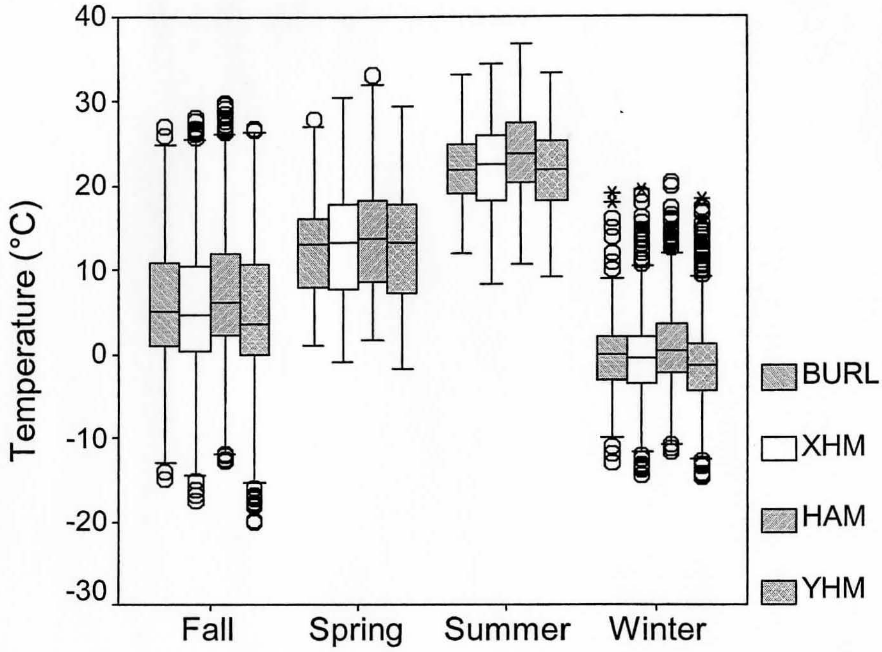
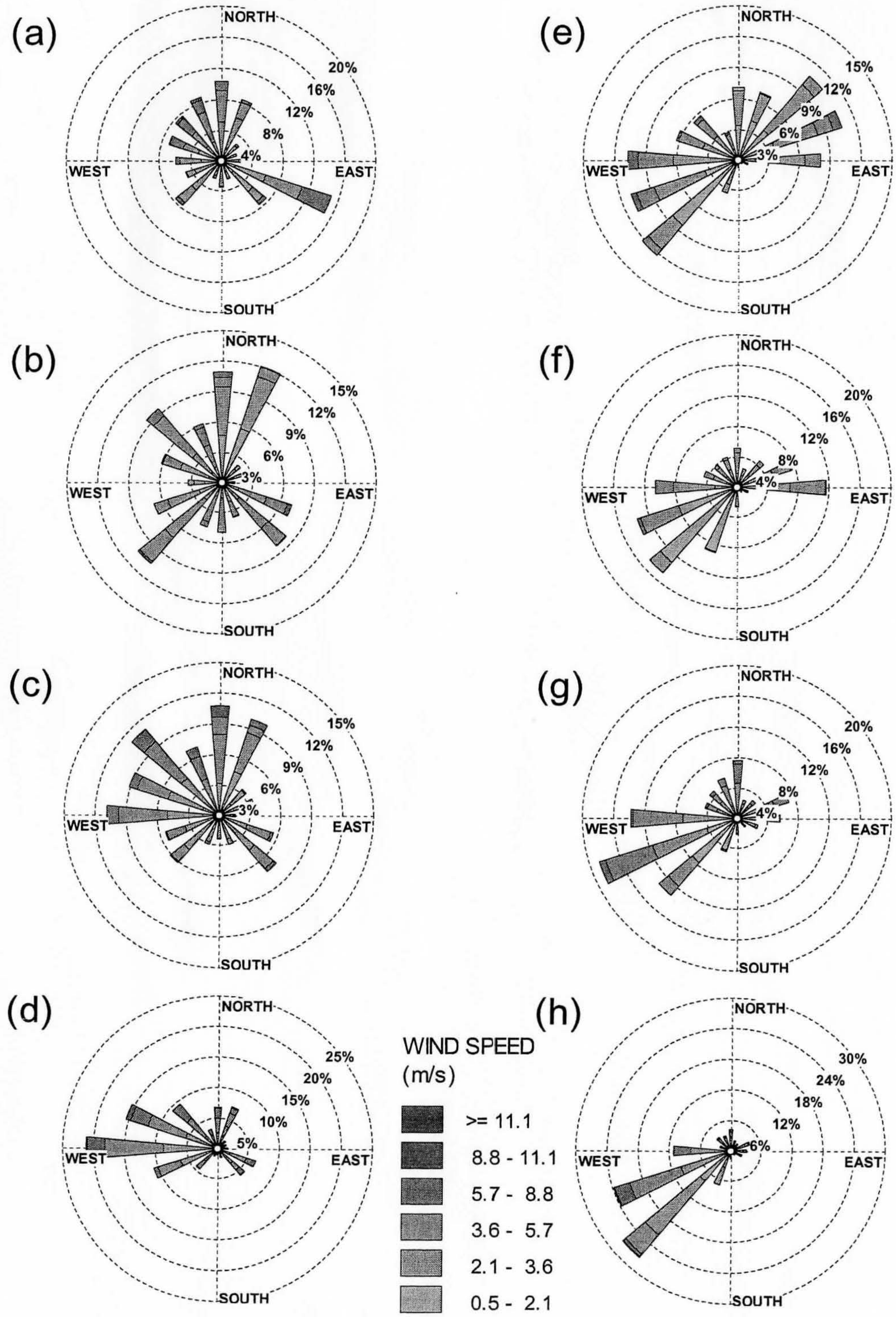


Figure 3.5: Seasonal temperature distribution at five locations in Hamilton during 2002.

Wind

In the THUAS, the prevailing wind direction is westerly, due to its location in the mid-latitudes. Lake breezes are however, common, creating onshore flow around Lakes Ontario and Erie on sunny days. Figure 3.6 shows seasonal wind roses for 2002 for the northern part of the study area (Etobicoke location, shown in Figure 3.6 (a-d)), and the southern part of the study area (Hamilton downtown) location, shown in Figure 3.6 (e-h)). North and north-west winds are less common in Hamilton because flow is diverted by the Niagara escarpment into a more south-west direction. Southeast winds are more common in Toronto (Figure 3.6 (a-d)) because this is the direction of the onshore lake breeze.


(a)
NORTH
SOUTH
WEST
EAST
4%
8%
12%
16%
20%
(b)
NORTH
SOUTH
WEST
EAST
3%
6%
9%
12%
15%
(c)
NORTH
SOUTH
WEST
EAST
3%
6%
9%
12%
15%
(d)
NORTH
SOUTH
WEST
EAST
5%
10%
15%
20%
25%
(e)
NORTH
SOUTH
WEST
EAST
3%
6%
9%
12%
15%
(f)
NORTH
SOUTH
WEST
EAST
4%
8%
12%
16%
20%
(g)
NORTH
SOUTH
WEST
EAST
4%
8%
12%
16%
20%
(h)
NORTH
SOUTH
WEST
EAST
6%
12%
18%
24%
30%
WIND SPEED (m/s)
>= 11.1
8.8 - 11.1
5.7 - 8.8
3.6 - 5.7
2.1 - 3.6
0.5 - 2.1

Previous Page - Figure 3.6: Seasonal wind roses at Etobicoke location in Toronto and Hamilton downtown location for (a) and (e) spring, (b) and (f) summer, (c) and (g) fall, and (d) and (h) winter in 2002.

During spring in Toronto (Figure 3.6 (a-d)) north-northwesterlies are most common, occurring 13.74% of the time. Easterlies are also common, occurring 9.59% of the time. In summer, north-northwest winds are more common (16.38%), and the frequency of easterly winds drops to 5.39%. In fall, west winds are most common (13.76%), followed by north-northwest and north winds. In winter, west-southwest winds are most frequent, occurring 16.70% of the time. In all seasons, north-northeast winds are least common. In Hamilton (Figure 3.6 (e-h)), westerlies are the most common wind direction and southeast winds are least common. In spring, 10.48% of winds were from the west, and east-northeast winds occurred 7.40% of the time. In summer, west winds were most frequent (11.10%), and east-northeast winds were much less frequent. In fall, west and south-southwest winds were most common (11.69% and 11% respectively), and in winter, south-southwest winds were much more common (17.75%).

Figure 3.7 shows the distribution of hourly wind speeds measured at the 13 locations in Toronto and Hamilton in 2002. Toronto east and York were the calmest locations in 2002, with mean wind speeds of 1.96 ms^{-1} and 2.03 ms^{-1} respectively. The York location also experienced the lowest range in hourly wind speeds. Toronto Island is the windiest location on average (5.06 ms^{-1}), and also experiences the strongest hourly winds (maximum hourly wind speed of 22.22 ms^{-1}) and the largest range in wind speed. The next windiest locations are the airports in Toronto and Hamilton.

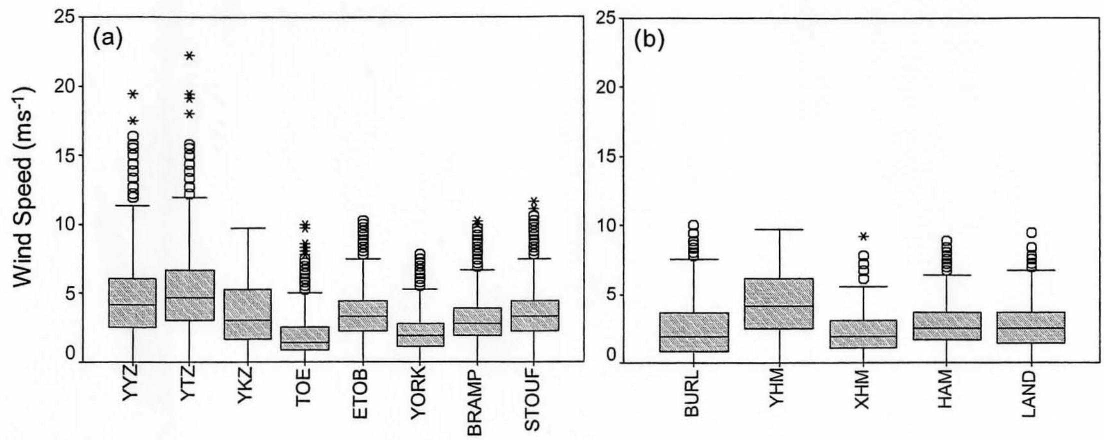


Figure 3.7: Summary of hourly wind speed measurements for 2002 at 13 locations in (a) Toronto and (b) Hamilton.

Seasonal analysis of wind speed, seen in Table 3.3, shows that Pearson Airport (YYZ) is windiest in spring and summer when the prevailing winds are from the northwest (see Figure 3.6), while Toronto Island is windiest in fall and winter when prevailing winds are from the west to southwest.

The York location has the lowest average wind speed during spring and winter, while Toronto east has the lowest mean wind speed during summer and fall; however York experiences the lowest maximum hourly wind speed during all seasons and consistently has the lowest standard deviation in hourly wind speeds (ranging between 1.0 ms^{-1} in summer to 1.3 ms^{-1} in spring and winter). Overall, wind speeds are calmest in summer and strongest in January and February.

Table 3.3: Mean and maximum hourly wind speeds, and standard deviation of hourly wind speeds (σ) for each season at 10 stations in the THUAS during 2002. Maximum values for each season are highlighted in bold.

	Spring			Summer			Fall			Winter		
Station	**Mean**	**Max. Hourly**	**σ**	**Mean**	**Max. Hourly**	**σ**	**Mean**	**Max. Hourly**	**σ**	**Mean**	**Max. Hourly**	**σ**
YYZ	**4.9**	**19.4**	2.9	**4.0**	**15.0**	**2.3**	4.6	**20.6**	2.6	5.5	19.4	3.0
YTZ	**4.9**	17.5	**3.1**	3.6	12.2	2.1	**5.0**	18.1	**2.9**	**6.8**	**22.2**	**3.4**
YKZ	3.7	12.8	2.3	2.7	10.3	2.1	3.1	15.6	2.2	4.2	16.4	2.4
XHM	2.4	8.9	1.5	1.6	6.1	1.0	2.0	7.8	1.3	2.6	10.8	1.7
HAM	2.7	8.6	1.4	2.1	6.1	1.2	3.0	8.6	1.6	3.5	10.8	1.8
TOE	2.2	10.0	1.6	1.5	7.2	1.0	1.7	8.1	1.2	2.5	10.0	1.7
ETOB	3.6	10.3	1.8	2.8	6.9	1.3	3.3	8.6	1.5	4.1	11.1	1.8
YORK	2.1	7.8	1.3	1.7	5.3	1.0	1.9	6.1	1.1	2.4	8.3	1.3
BRAMP	3.2	10.6	1.6	2.5	6.4	1.2	2.9	7.5	1.5	3.6	11.9	1.8
STOUF	3.8	10.3	1.8	2.9	7.8	1.4	3.3	10.6	1.6	4.2	13.1	1.9

Humidity

Hourly specific humidity measurements are calculated for five locations in the THUAS during 2002. Figure 3.8 shows seasonal analysis of this information. Specific humidity is highest during the summer and lowest in the winter. Standard deviation of hourly humidity measurements is highest during the fall. Mean seasonal specific humidity is highest at Hamilton Botanical Gardens during all seasons, followed by Toronto Island and Hamilton Airport.

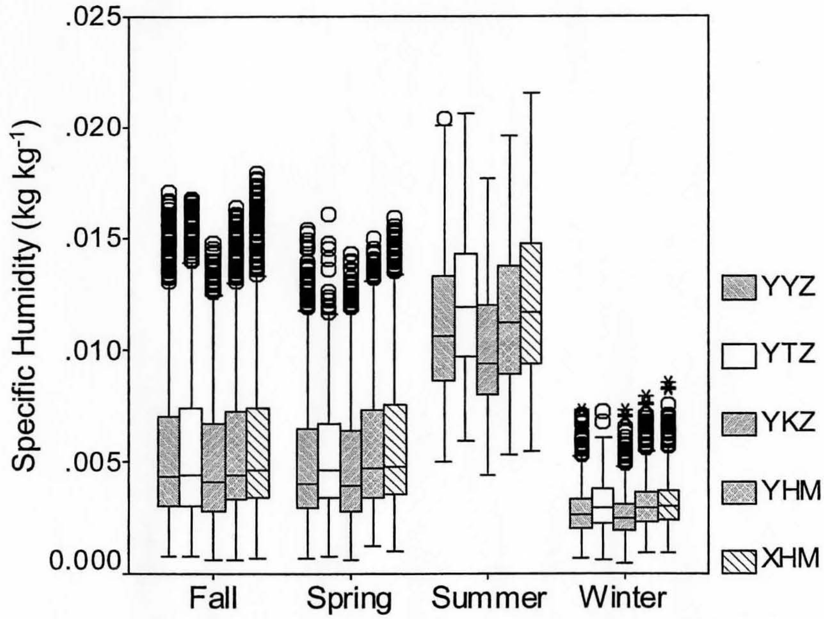


Figure 3.8: Mean seasonal specific humidity (kg kg^{-1}) at five stations in the THUAS in 2002.

Precipitation

More rain falls in the warm months of the year than the cold months. Figure 3.9 shows the seasonality of precipitation during the period from 1969 to 2000 at Pearson and Hamilton Airports. In Toronto (Figure 3.9 (a)) most rain (10.15%) falls in August, and least precipitation falls in February (5.25%). In Hamilton (Figure 3.9 (b)), precipitation is slightly more evenly distributed throughout the year. Most rain falls in July (9.65%), and least precipitation again occurs in February. Precipitation in March is significantly higher in the 32-year average for Hamilton than in Toronto (8.13% compared to 7.11% respectively).

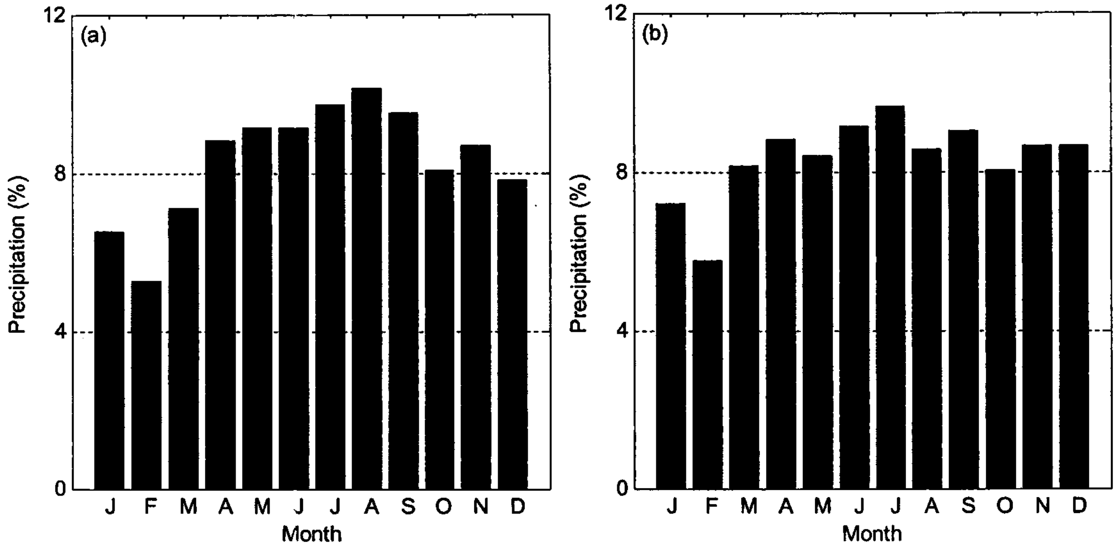


Figure 3.9: Average annual distribution of precipitation at (a) Pearson Airport and (b) Hamilton Airport for 1969 to 2000.

3.2 Discussion

3.2.1 Inter-annual variabiltiy

Despite analysis of variance testing showing that there are significant differences in mean annual temperature, wind speed and specific humidity, between 2002 and the following two years, the differences are small. The largest data sets are available for the year 2002, so analysis and results in the following chapters are based only on 2002 measurements, but that we can assume that the conclusions drawn from these analyses will be applicable to the longer term.

3.2.2 Seasonal variability

Temperature

Locations closer to Lake Ontario are warmer, especially during spring because of the relatively warm lake, and also because of the location of areas of higher urbanisation near the lake. Locations such at Stouffville and Buttonville Airport, which are least moderated by the lake, experience the largest variations in hourly and seasonal temperature. In late fall, lake waters overturn, so the lake is not as effective at moderating temperature at the island location, while the built-up centre of Hamilton is more effective at reducing daily temperature ranges.

Wind

Seasonal variation in wind speed and direction is caused by changes in synoptic patterns and the position of the jet stream. The most built-up locations experience the slowest wind speeds on average because of increased friction with urban surfaces. The Toronto Island location is windiest because of the relatively lower friction of the lake surface, and its unsheltered position on Toronto Island on Lake Ontario.

Areas northwest of Pearson Airport in Toronto are the least built up, while there are many tall buildings and dense development west, south, east and north of the airport, hence summer north-westerly winds are the least hindered by friction and are strongest at Pearson Airport. Winter winds arriving at Toronto Island from the south west first pass over Lake Ontario, where friction is lower and they may pick up speed, also, because of synoptic patterns, winter winds are generally stronger than other times of the year in all locations.

Humidity

Humidity is higher in Hamilton as it is located on the Niagara peninsula between Lakes Ontario and Erie. Likewise, specific humidity is high at Toronto Island due to proximity to open water sources. Humidity is likely to be lower in urbanized areas due to there being more impermeable surfaces and storm water drains, so that surface water is removed quickly and is not available for evaporation.

Specific humidity levels are highest during the summer when lake waters are warmest and higher temperatures increase evaporation from the Great Lakes. Hourly humidity measurements vary the most during the fall, reflecting the fact that some days in this season can be very summer-like and humid, due to the proximity of the Great Lakes, and other days in fall may be more similar to winter conditions with cooler conditions suppressing evaporation and leading to drier air.

CHAPTER 4: URBAN HEAT ISLAND

4.1 Results

4.1.1 Long-term data

For the 38 locations in central Southern Ontario with a 26-year record (1975 to 2000) of daily minimum temperature and daily maximum temperature, box plots of the 26-year mean daily maximum and daily minimum temperatures are shown in Figure 4.1. ANOVA testing shows that both daily maximum and daily minimum temperatures are significantly warmer at urban locations, compared to rural locations at the 95% confidence level. The temperature difference is larger for daily maximum temperatures, with urban stations having an average of 12.4 °C while the rural location average is 11.5 °C. For minimum daily temperature, the urban location average is 3.0 °C and the rural location average is 2.2 °C. Again, the rural locations were more southerly on average, further from Lake Ontario, and at higher (47.64 m) average elevations, so part of the difference in temperature can be attributed to these factors.

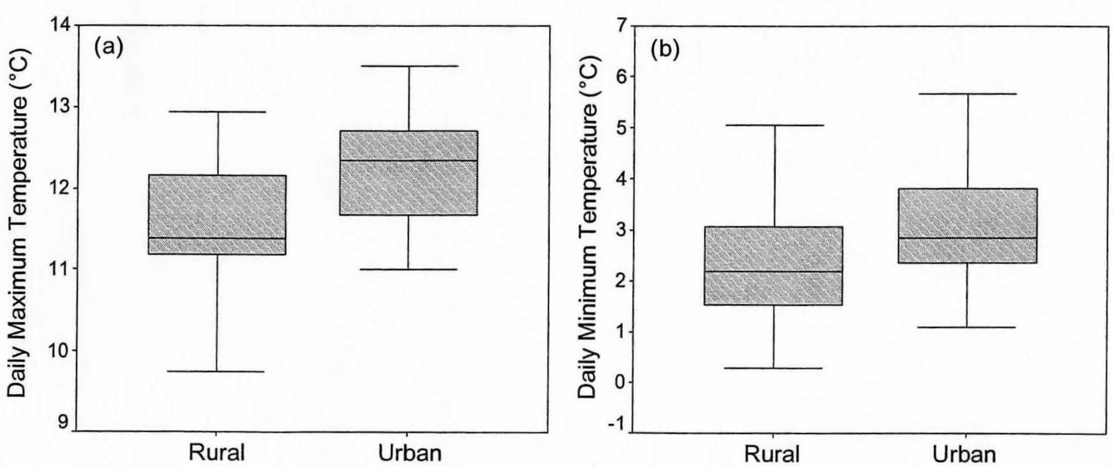


Figure 4.1: 26-year mean daily (a) maximum and (b) minimum temperature at rural (n = 22) and urban (n = 16) locations.

The 52-year daily minimum and maximum temperature record from Downtown Toronto and Woodbridge locations were used to calculate the UHI change over time for Toronto city. Time series analysis of ΔT_{u-r} shows that the average difference in daily minimum temperatures between Woodbridge and Toronto is 3.36 °C, and that this magnitude does not follow an increasing or decreasing trend over the 52-year record (see Figure 4.2). Daily maximum temperature at Toronto is on average 0.67 °C warmer than that at Woodbridge, again following no positive or negative trend with time.

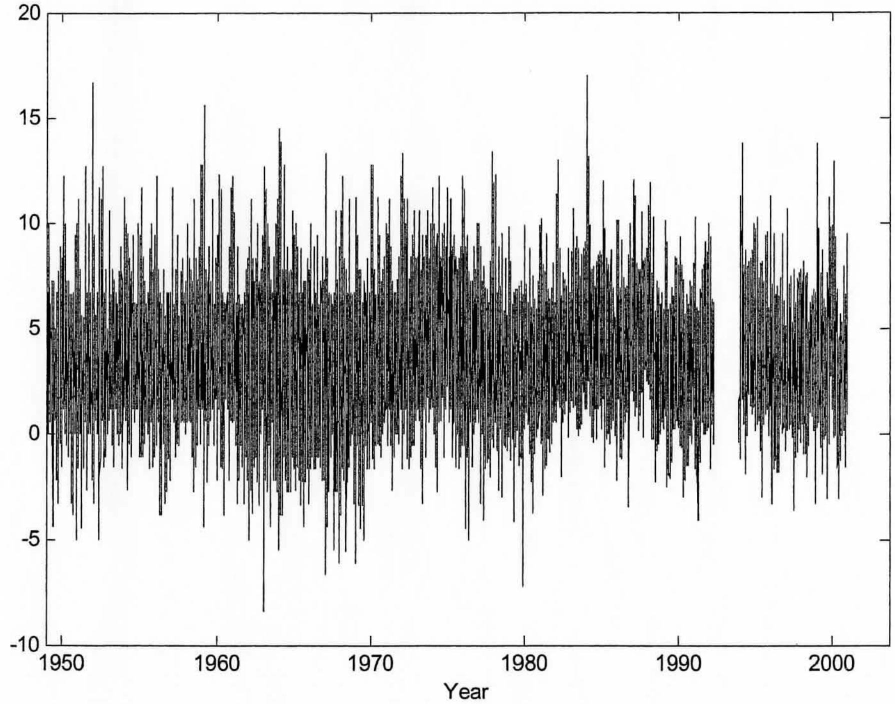


Figure: 4.2: Time series of daily minimum temperature difference between Downtown Toronto and Woodbridge locations, 1949 to 2000. Daily temperature data was not available between May 1992 and December 1994.

4.1.2 Diurnal

In Toronto, the locations selected were Etobicoke, a highly urbanized location southwest of downtown Toronto and on the lake shore, and Brampton, a semi-rural location on the north-western edge of the Greater Toronto Area. In Hamilton the two locations selected were Hamilton Airport, in a rural area south of the city, and Hamilton downtown, located at Woodward Avenue south of Burlington Street. Figure 4.3 shows that hourly temperature differences at the two pairs of stations ranged between -7 °C and +5 °C, with a difference of between 2 °C and 3 °C being most common at the Toronto pair (44.55 %), and a difference of between 1 °C and 2 °C being most common at the Hamilton pair (29.14 %). UHI intensities of up to 5 °C are relatively common in both cities, with an intensity of 4 to 5 °C occurring during 11.59 % of hours in Hamilton, and 2.92 % of hours in Toronto. Brampton (the Toronto rural location) was warmer than Etobicoke for 6.88 % of hours and Hamilton Airport was warmer than the downtown for only 3.63 % of hours.

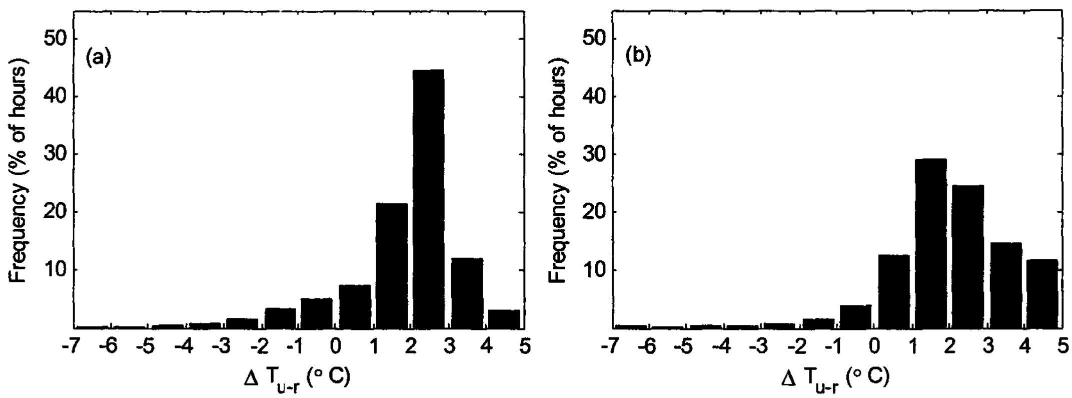


Figure 4.3: Frequency and intensity of temperature difference between (a) Etobicoke and Brampton, and (b) Hamilton Airport and Downtown calculated for all hours in 2002.

Figure 4.4 shows the diurnal frequency of positive hourly temperature differences (urban *heat* island), where hourly temperature measured at Etobicoke is warmer than hourly temperature measured at Brampton, and Figure 4.5 shows the diurnal frequency of negative hourly temperature differences (urban *cooling* island). It can be seen that the largest urban heat islands in Toronto (Figure 4.4 (a) & (b)) are most common at night, especially between 2:00 and 4:00 a.m., while ΔT_{u-r} greater than 3 °C is very uncommon during the day. Smaller positive urban heat islands (Figures 4.4 (c) & (d)) and negative urban heat islands (Figure 4.5) are more common in the daytime than at night. Negative ΔT_{u-r} are very uncommon during the night time hours in Toronto.

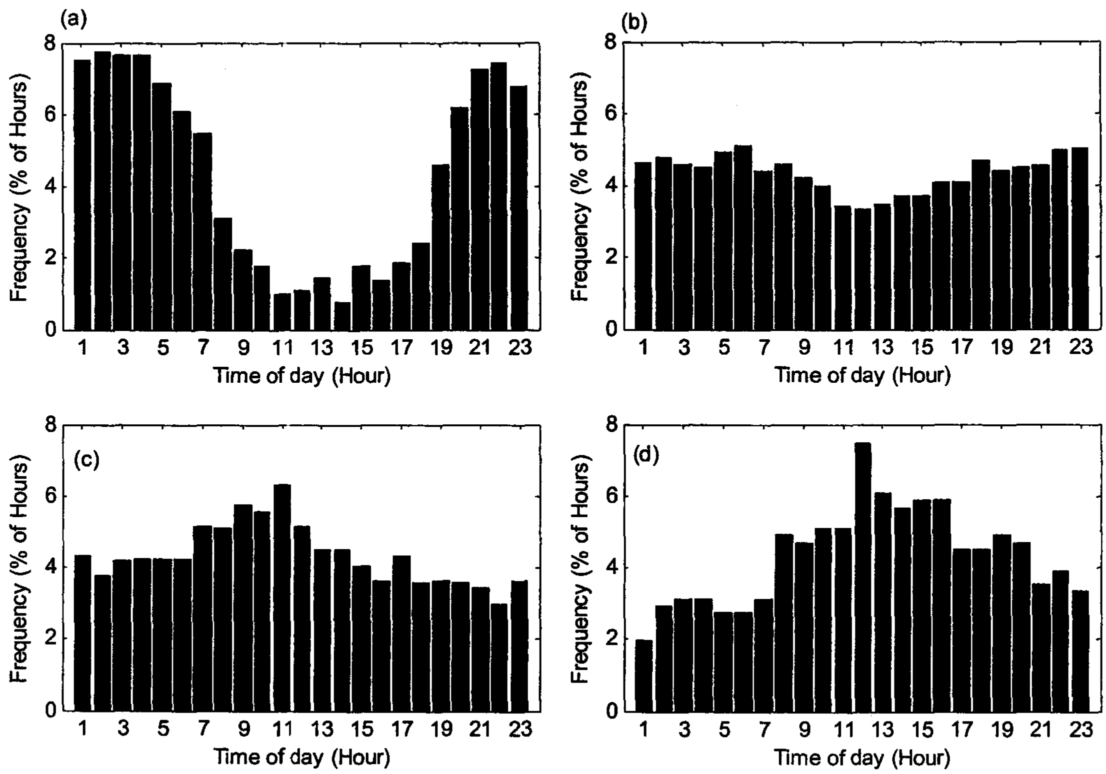


Figure 4.4: Diurnal frequency of ΔT_{u-r} with intensity (a) greater than 3°C, (b) between 2 and 3°C, (c) between 1 and 2°C, and (d) between 0 and 1°C in Toronto for all hours in 2002 (urban *heat* island).

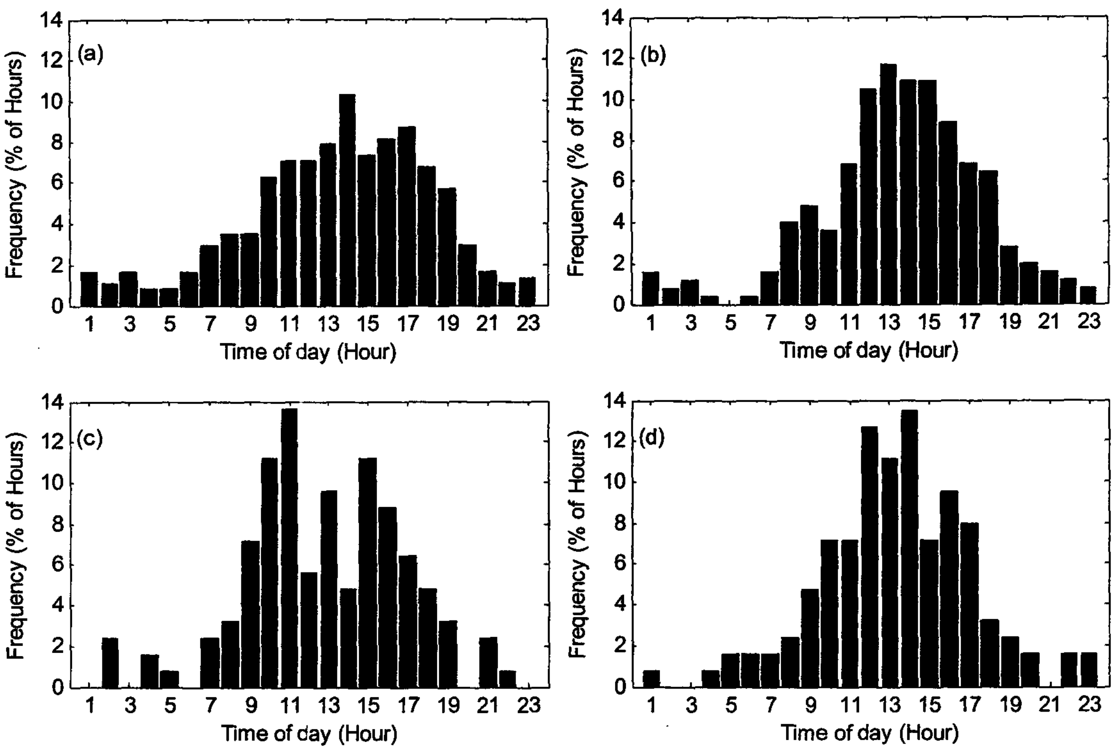


Figure 4.5: Diurnal frequency of $\Delta T_{u\text{-}r}$ with intensity (a) between 0 °C and -1 °C, (b) between -1 °C and -2 °C, (c) between -2 °C and -3 °C, and (d) less than -3°C for Toronto in 2002 (urban *cooling* island).

The diurnal frequency of positive hourly temperature differences in Hamilton City shows a different pattern to that in Toronto. Figure 4.6 shows the diurnal frequency of positive hourly temperature differences between Hamilton Airport and Hamilton downtown (urban *heat* island), and Figure 4.7 shows the diurnal pattern of the negative differences. In Hamilton the largest positive urban heat islands (Figure 4.6 (a)) are more common in the day time, especially between 5:00 a.m. to 3:00 p.m. The more moderate positive UHIs (Figure 4.6 (b), (c) & (d)), however, are more common at night. Negative hourly temperature differences (Figure 4.7), where ambient hourly air temperature at Hamilton Airport is warmer than in downtown Hamilton are more common in the afternoon hours, especially between midday and 7:00 p.m. The largest negative temperature differences (Figure 4.7 (d)) are much less common overnight and in the early hours of the morning, as in Toronto.

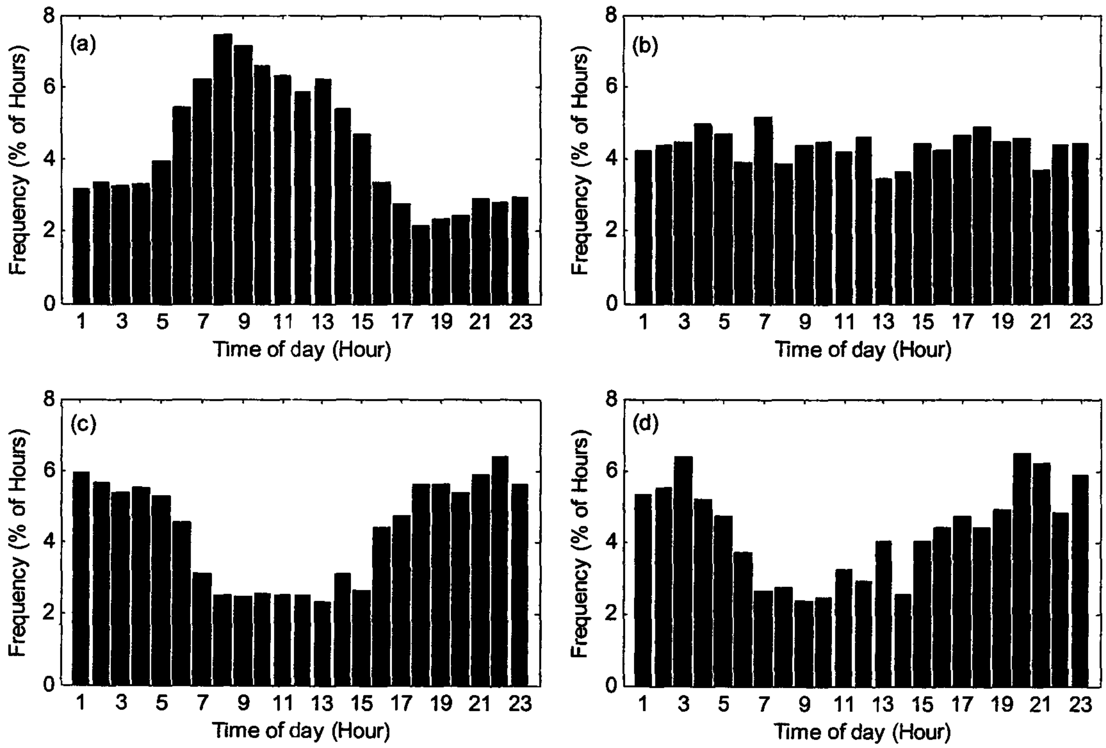


Figure 4.6: Diurnal frequency of ΔT_{u-r} with intensity (a) greater than 3°C, (b) between 2 and 3°C, (c) between 1 and 2°C, and (d) between 0 and 1°C in Hamilton for all hours in 2002 (urban *heat* island).

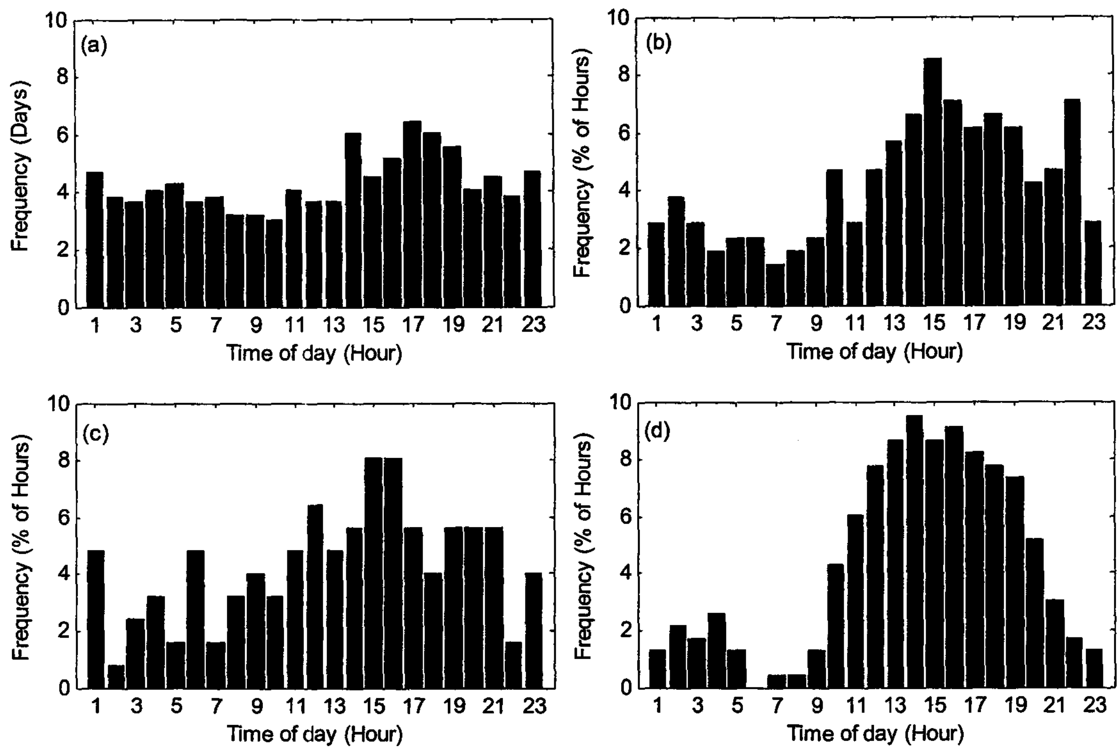


Figure 4.7: Diurnal frequency of ΔT_{u-r} with intensity (a) between 0 ˚C and -1 ˚C, (b) between -1 ˚C and -2 ˚C, (c) between -2 ˚C and -3 ˚C, and (d) less than -3˚C for Hamilton in 2002 (urban *cooling* island).

4.1.3 Seasonal

The seasonal frequency of positive and negative ΔT_{u-r} between Brampton and Etobicoke in Toronto are shown in Figures 4.8 and 4.9 respectively. It can be seen in these figures that for all of April and most of July a large number of hours of temperature measurements were missing. The strongest urban heat islands (Figure 4.8 (a)) occur mainly in late winter and late summer to fall. ΔT_{u-r} where Etobicoke is 2 to 3 ˚C warmer than Brampton (Figure 4.8 (b)) occurs more evenly through the year, with a slightly lower frequency during the warmer months. Less intense heat islands (Figure 4.8 (c) & (d)) are slightly more common in the summer than the winter. Negative ΔT_{u-r} in Toronto (Figure 4.9) occurs most frequently during the winter months of the year.

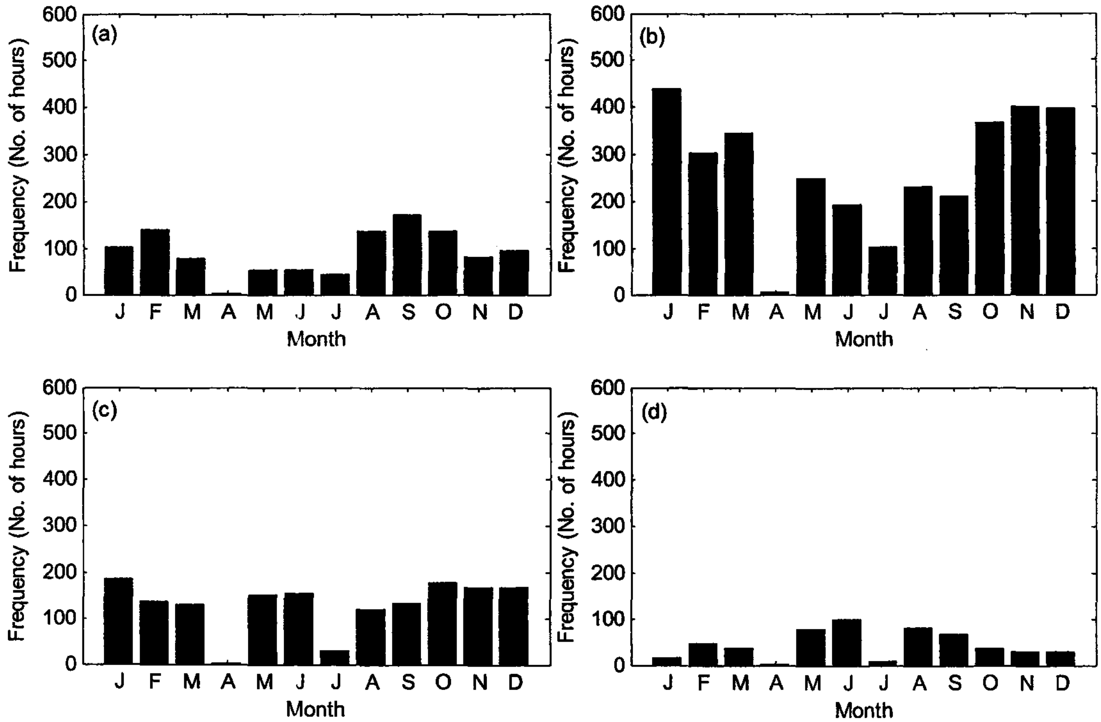


Figure 4.8: Seasonal pattern of hourly temperature difference between Brampton (rural) and Etobicoke (urban) of (a) greater than 3 ˚C, (b) 2 to 3 ˚C, (c) 1 to 2 ˚C, and (d) 0 to 1 ˚C in 2002.

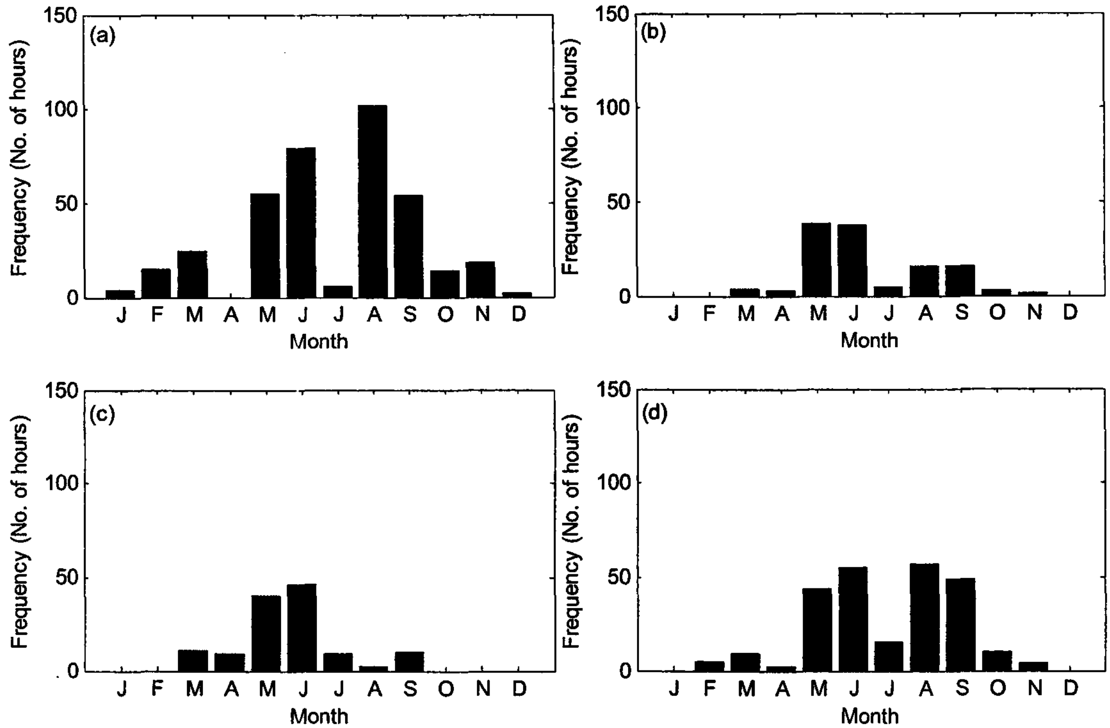


Figure 4.9: Seasonal pattern of hourly temperature differences between Brampton and Etobicoke of (a) 0 to -1 ˚C, (b) -1 to -2 ˚C, (c) -2 to -3 ˚C, and (d) less than -3 ˚C in 2002.

The seasonal frequency of positive and negative $\Delta T_{u\text{-}r}$ between Hamilton Airport and Downtown Hamilton are shown in Figure 4.10 and 4.11. Only a small number of hours of temperature differences were missing from this record, mostly in November. The largest positive $\Delta T_{u\text{-}r}$ differences (Figure 4.10 (a)) are most common in January and April, and are also common in June and July. $\Delta T_{u\text{-}r}$ where the airport is 2 to 3 ˚C warmer than downtown (Figure 4.9 (b)) are more evenly distributed throughout the year. Less intense heat islands (Figure 4.10 (c) & (d)) are more common in winter and late summer to fall. Negative $\Delta T_{u\text{-}r}$ differences (Figure 4.11) again occur most often in spring and the warmer months of the year.

The UHI in Toronto is therefore more common and more intense in the cooler months of the year, while Hamilton's UHI does not change as much with the seasons, though it is slightly more frequent and intense during the winter and spring months.

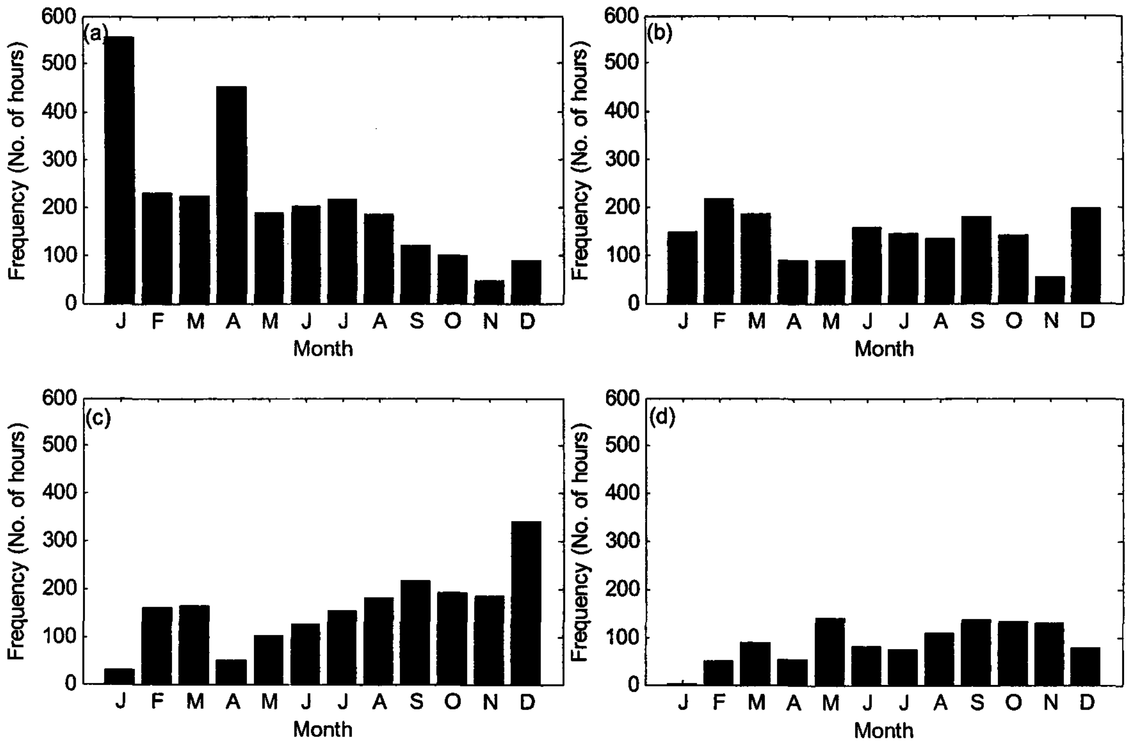


Figure 4.10: Seasonal pattern of hourly temperature difference between Hamilton airport (rural) and Hamilton downtown (urban) of (a) greater than 3 ˚C, (b) 2 to 3 ˚C, (c) 1 to 2 ˚C, and (d) 0 to 1 ˚C in 2002.

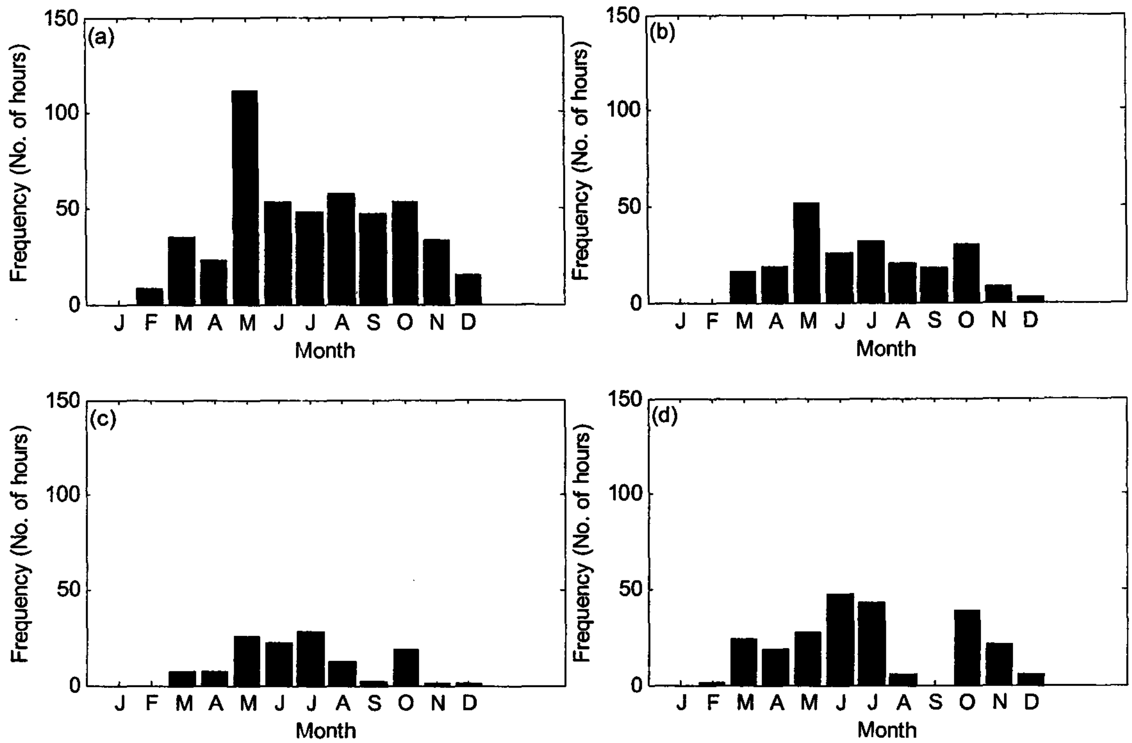


Figure 4.11: Seasonal pattern of hourly temperature differences between Hamilton airport and Hamilton downtown of (a) 0 to -1 °C, (b) -1 to -2 °C, (c) -2 to -3 °C, and (d) less than -3 °C in 2002.

4.2 Discussion

The magnitude and sign of the UHI change through space and time in response to changes in solar radiation receipt, energy partitioning, mixing by wind, and land surface albedo (Oke, 1987).

Long-term

The long-term daily minimum and maximum temperature record show that the difference in temperature between Woodbridge and Downtown Toronto has not changed significantly over the last 52 years. This indicates that the urban heat island in Toronto, in particular downtown, is not becoming stronger over time, at least in relation to the temperature at Woodbridge. As it is known that the population of Toronto has grown as well as its spatial extent over this time period, it can be assumed that Toronto's UHI is becoming larger spatially, as increasing regulation of industry, and property taxation has lead to the relocation of businesses, industry and population away from the city centre. This may mean that the Woodbridge site has in fact experienced urbanisation as well, becoming more suburban than rural, meaning that relative changes in $\Delta T_{u\text{-}r}$ over time are concealed.

2002 hourly temperature differences

Comparison of hourly temperature measurements at the two pairs of urban and rural locations in Toronto and Hamilton show that the urban locations in the THUAS are significantly warmer than rural locations most of the time, indicating that an UHI exists and is likely to enhance lake breeze formation, which has implications for pollutant transport and dispersion.

Part of this difference in temperature between rural and urban sites can be attributed to differences in elevation, and differences in proximity to Lake Ontario. The station in Brampton is located at 232 m a.s.l., while Etobicoke is at 97 m elevation, a 135 m difference, and the Hamilton Airport is located above the escarpment at 237 m a.s.l., and the downtown is at 77 m a.s.l., a difference in elevation of 160 m. This elevation difference is likely to account for both rural locations being approximately 1 °C cooler than corresponding urban locations, due to the environmental lapse rate (6 °C cooling per 1000 m). The urban locations are also much closer to the lake, which has a moderating effect on temperature, meaning the nearby sites are likely to be relatively cooler in summer and warmer in winter than sites at greater distances from the lake.

Diurnal differences

The largest differences in temperature are found at night, with the downtown centres being up to 5 °C warmer than surrounding rural areas. Negative temperature differences, when rural sites are warmer than urban sites, (Figures 4.5 and 4.7) are most common in the middle of the day when incoming solar radiation is maximum, meaning that shading by buildings and the higher albedo of urban surfaces leads to a relatively lower urban temperature (Klysik & Fortuniak, 1999; Oke, 1987; Weng & Yang, 2004). However, at the Hamilton pair of locations, large positive temperature differences are found in the morning to middle of the day as well This is due to large anthropogenic sources of heat (steel mills) near the downtown Hamilton site which act to increase daytime temperatures, and due to the sheltering effect of the Niagara escarpment which reduces wind speeds and mixing in low-lying areas of the city. Urban heat islands, and especially urban cooling islands, are not as frequently as strong in Hamilton as in Toronto. This is because Hamilton city is smaller in spatial extent, has less built-up area, and hence the climate is more influenced by surrounding land-uses, especially at night.

This diurnal pattern in the UHI has consequences for lake breeze occurrence; because the Hamilton UHI is more intense during the day when lake breezes are known to occur, lake breeze frequency may be enhanced at lakeshore locations.

Seasonal differences

Seasonal analysis of UHI frequency shows that the UHIs in both Toronto and Hamilton are most developed in the cooler months of the year (Figures 4.8 and 4.10) because of the release of anthropogenic heat from domestic heating (Hinkel *et al.*, 2003), a reduction in turbulent mixing caused by surface heating (Oke, 1987; Oke & Hannell, 1968), and increased atmospheric stability because of the cold surface temperatures (Magee *et al.*, 1999). This seasonal variation is not as pronounced at the Hamilton UHI because of the relatively large amounts of anthropogenic heat released at all times of the year from the steel mills. We can therefore conclude that the largest UHIs occur in the cooler months of the year, and at night, except in proximity to large sources of anthropogenic heat which may make urban areas warmer than surrounding areas at all times of the day.

The largest positive urban heat islands in Hamilton (Figure 4.10 (a)) occur most frequently in the months of January and April. These are the two months in this year with the highest snowfall amounts; 45.2 cm and 44.6 cm for the months of January and April respectively. This can be compared to snowfall amounts in February and March, and November and December of 33.4 cm, 19.2 cm, 9.0 cm and 14.8 cm. Snow lying on the ground increases the surrounding countryside's albedo, reducing air temperatures, while snow removal in the city reduces albedo allowing urban temperatures to become significantly warmer. Snowfall amounts were distributed more evenly through the winter in Toronto in 2002, so its effect on UHI intensity is not as noticeable.

The midsummer UHI in Hamilton is also reasonably well developed. This can be related to anthropogenic release of heat from air conditioning, which is not as easily dispersed in Hamilton as in Toronto due to the city's sheltered location at the base of the Niagara Escarpment.

Negative heat islands, where the rural site is warmer than the urban site (Figures 4.9 and 4.11) occur most frequently in the warmer months of the year in both cities, in part this is because of increased shading by urban buildings and urban trees (cities may have more trees than surrounding areas), especially in the middle of the day in summer (Klysik & Fortuniak, 1999), and because of the urban locations' proximity to the lake. During the warmer months of the year the lake is relatively cooler than the land because of its higher heat capacity, and so nearby locations are influenced and cooled by lake temperatures more than the more distant rural locations.

It can therefore be concluded that the UHI in Toronto is more common and intense in the cooler months of the year, while Hamilton's UHI does not change as much with the seasons, but is slightly more frequent and intense during winter and spring. The presence of these well developed urban heat islands in close proximity to the coastline is likely to enhance the frequency and intensity of onshore flow (lake breezes) due to their further enhancing temperature differences between land and water (Martilli, 2003; Miller *et al.*, 2002; Yoshikado, 1992). This effect is caused by the additional heat of the UHI and can have serious implications for pollutant dispersal in the city (Hastie *et al.*, 1999; Jacobson, 2002; Kim *et al.*, 2001; Lennartson & Schwartz, 2002; Liu & Chan, 2002; Lu & Turco, 1994; Lyons, 1972; Miller *et al.*, 2003; Oke, 1987; Simpson, 1994), as will be discussed further in the following chapter.

CHAPTER 5: LAKE BREEZES

5.1 Results

5.1.1 Diurnal variation in wind direction

Hourly wind direction measurements for each day from noon to 4:00 p.m. are compared with hourly wind direction data from midnight to 4 a.m. in Figure 5.1. At locations on the northwest shore of Lake Ontario (Figure 5.1 (a-e)), onshore (SW to SE) winds blow much more frequently in the day than during the night. At locations on the southern coast of Lake Ontario (Figure 5.1 (f-h)), onshore (NE and E) winds are also more common during the day than night. There is some evidence that a land breeze flows in Hamilton at night; Figure 5.1 (g) & (h) shows SW and WSW winds are more frequent at night than during the day at Hamilton downtown and Hamilton Airport locations. At Hamilton Botanical Gardens the land breeze is more westerly because of the orientation of the valley (Dundas) it is located in, and channelling of flow by the escarpment. Northerlies occur 0.96% of the time during the day and 17.81% of the time during the night at Hamilton Botanical Gardens.

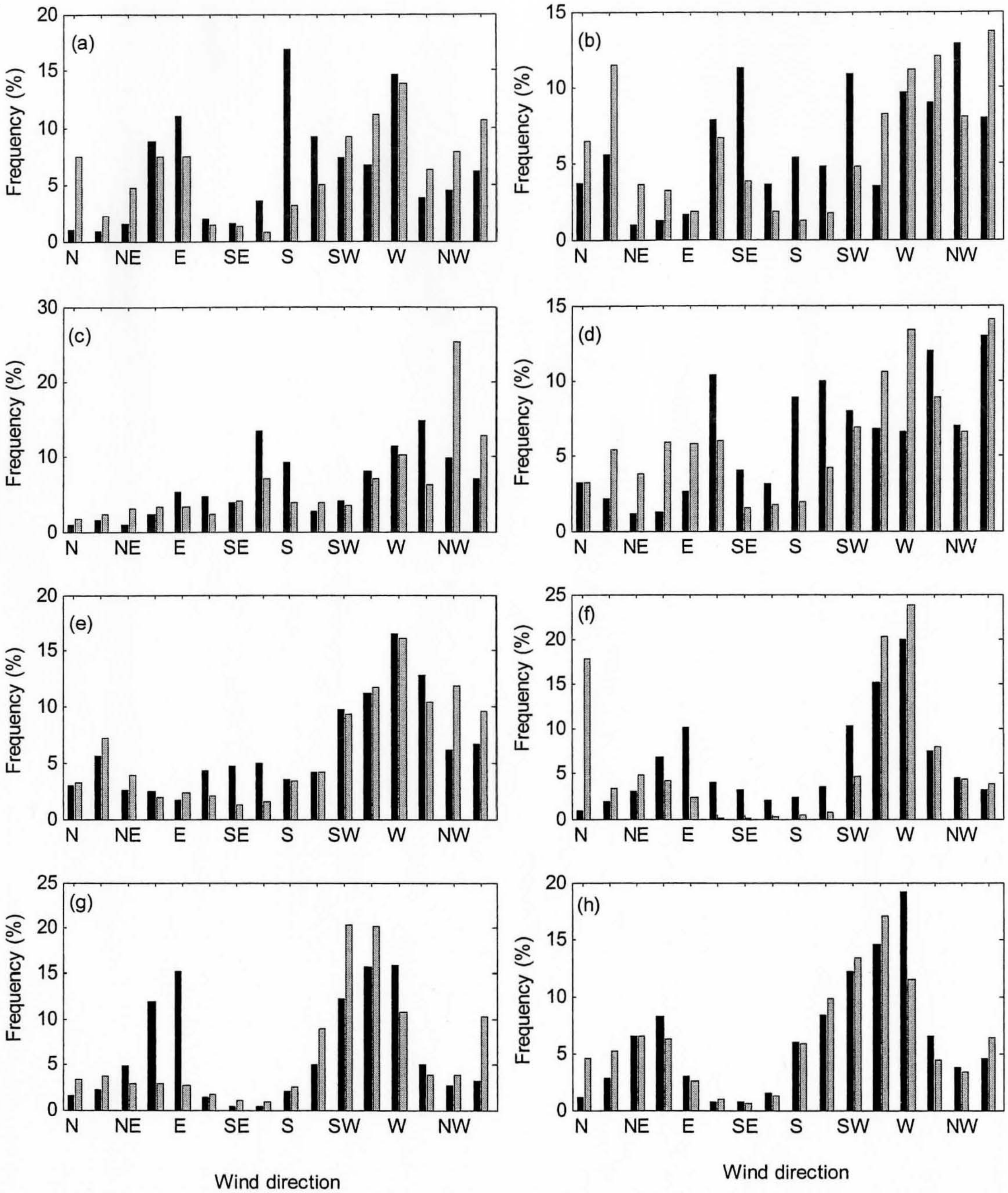


Figure 5.1: Wind direction frequency for day (black bars) and night (grey bars) at (a) Toronto Island (77 m from the lake), (b) Etobicoke (97 m) from the lake, (c) York (117 m from the lake), (d) Toronto East (173 m), (e) Brampton (232 m), (f) Hamilton Botanical Gardens (102 m), (g) Hamilton downtown (77 m), and (h) Hamilton Airport (238 m) in 2002.

5.1.2 Identification of lake breeze days

Days where flow reversal occurred were identified as having average offshore flow in the morning and average onshore flow in the afternoon. Table 5.1 shows the frequency of occurrence of lake breezes at sites on the northwest shore of Lake Ontario (first nine locations), and on the southern shore (last four locations). Lake breezes were found to occur least frequently at sites farthest from Lake Ontario, where the lake breeze does not penetrate inland as frequently, and in the most built up areas such as Etobicoke, York and Downtown Hamilton. Lake breezes were also found to be much more common on the northwest shore of Lake Ontario (Toronto city), occurring on average on 16.19% of days, as compared to 11.37% of days of the year in Hamilton.

Seasonal analysis of lake breeze frequency is also shown in Table 5.1. Lake breezes are most common in summer, occurring on 22.8% of days on average on the north-western shore, and 14.8% of days on the southern shore. Lake breezes are next most frequent on average in fall, and least common in winter (8.72% and 6.45% of days in winter on the north and south shore respectively).

Table 5.1: Frequency of lake breezes recorded at various locations in the THUAS in 2002.

Location	Distance to L. Ontario (m)	Number of days with flow reversal: Spring	Summer	Fall	Winter	2002 Total
YTZ	0	23	28	22	16	89
BURL	0	11	15	17	4	47
ETOB	2,408	8	20	16	4	48
YORK	2,607	7	23	17	9	56
TOE	5,011	16	26	20	10	72
YYZ	10,963	21	28	20	8	77
YKZ	18,469	18	26	19	12	75
BRAMP	19,649	6	12	15	5	38
STOUF	20,990	9	9	7	5	30
HAM	400	8	14	12	7	41
LAND	721	6	17	14	6	43
XHM	800	14	14	11	6	45
YHM	11,887	11	9	12	5	37

5.1.3 Impact on NO_2 concentrations

To understand the effect of the land-lake breeze circulation on air quality in the THUAS over periods of a few days, hourly NO_2 concentrations and wind direction measurements are plotted in Figure 5.2 for August 7th to 10th 2002 (DOY 219 to 222), days when flow reversal occurred. Hourly wind speed measurements during this time are also plotted in Figure 5.3 for a location in Toronto and in Hamilton for the same time period.

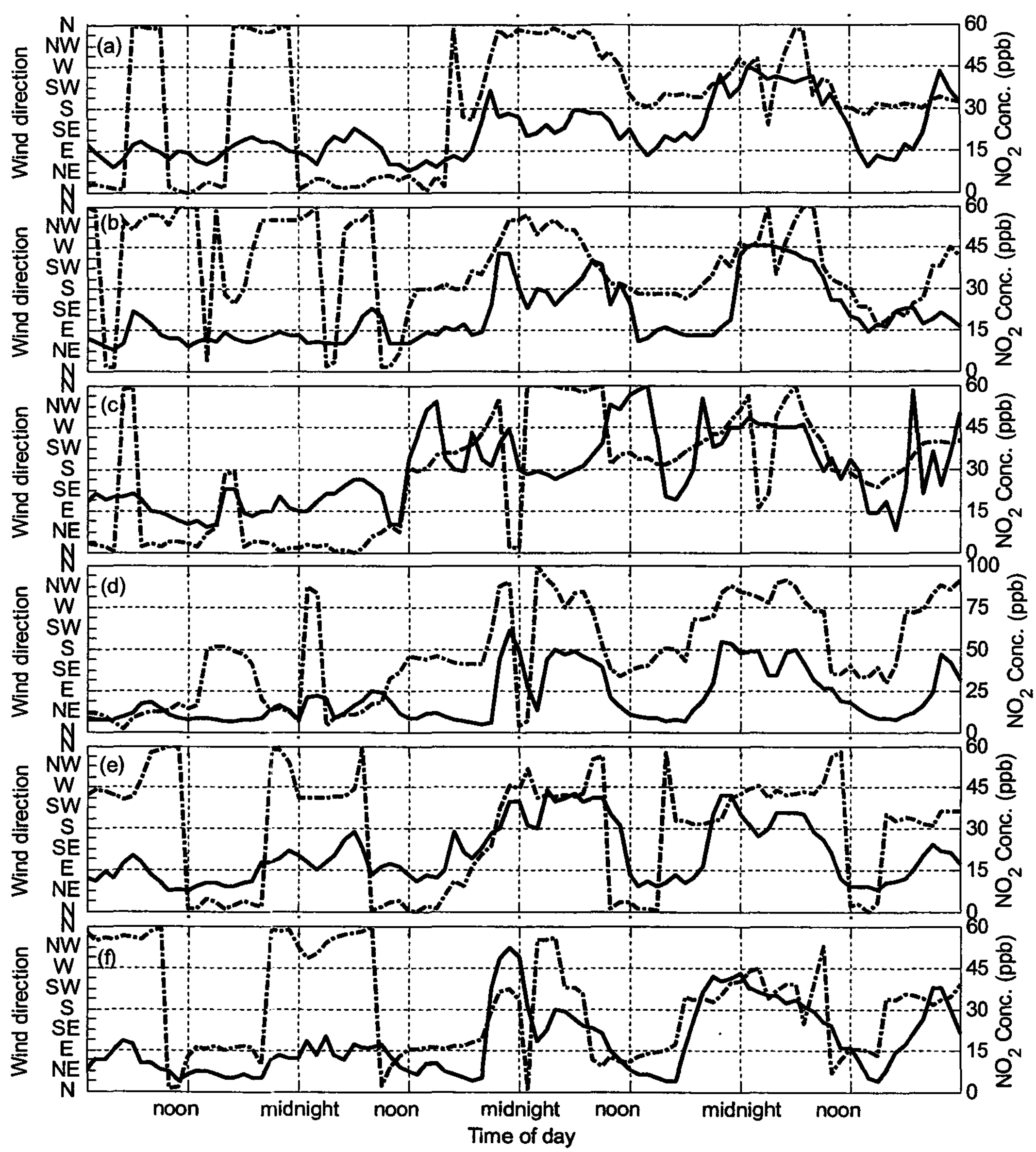


Figure 5.2: Time series of hourly wind direction (dashed line) and NO_2 concentrations (solid line) at (a) Toronto East, (b) Bay/Toronto Island, (c) Etobicoke, (d) Burlington, (e) Beasley/Land and (f) Beach/Hamilton downtown locations for the period August 7th to 10th, 2002.

On the first day and into the morning of the second day no diurnal pattern in NO_2 concentration is evident, general wind direction is from the north and NO_2 concentrations are lower. Wind speeds at this time are relatively high in Toronto, and higher overnight compared to the following nights in Hamilton. No lake breeze occurs at all on the first day at Toronto East (Figure 5.2 (a)). On the last three days the lake breeze wind pattern is much clearer, and NO_2 concentrations are relatively high, especially at the three most northerly locations (Figure 5.2 (a-c)). At the three more southerly locations (Figure 5.2 (d-f)) NO_2 concentrations are high overnight, but during the middle of the day are not significantly higher than on the first day.

At most locations the arrival of the lake breeze is associated with a short term spike in NO_2 concentration (see peak at noon on day three at the Toronto East location, Figure 5.2 (a)), but after this NO_2 concentration generally decreases as the afternoon progresses, especially at the Beach location on days two to four.

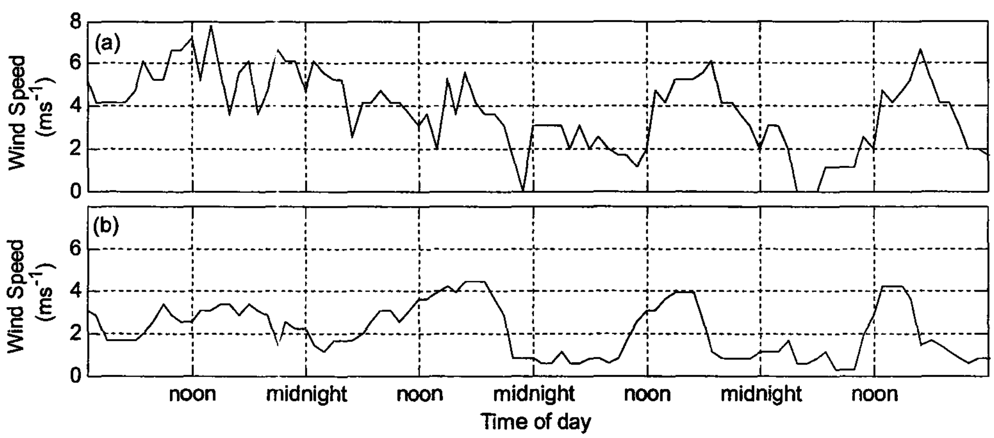


Figure 5.3: Time series of hourly wind speed at (a) Toronto (YYZ), and (b) Hamilton (HAM), for the period August 7th to 10th, 2002.

5.2 Discussion

Lake breeze frequency

Lake breezes therefore, can be said to occur frequently in the region, especially during the warmer months of the year. Lake breezes are most common in locations close to the lakeshore, but in built-up areas buildings act to break-up and slow the onshore flow.

The high frequency of northerlies occurring during the night at Hamilton Botanical Gardens (Figure 5.1 (f)), is possibly caused by density driven flows from areas of higher elevation to the north of West Hamilton. However higher frequency of nocturnal northerlies is also recorded at the other two Hamilton sites (Figure 5.1 (g) & (h), neither of which could be affected by density driven flows from the north. During calm conditions wind direction is set as equal to zero degrees, so the higher frequency of northerly wind direction measurements at night may in fact signify a higher frequency of calm conditions, which has important implications for air quality, reducing nocturnal mixing and dispersion of pollutants.

Lake breezes are most common in summer, occurring on 22.8% of days on average on the north-western shore, and 14.8% of days on the southern shore. Lake breezes were found to be slightly more frequent in Chicago, another Laurentian Great Lake city, where Lyons (1972) found lake breezes to occur on one third of summer days. It is well known that formation of a lake breeze requires reasonably clear skies, and weak gradient winds, which allow for the build-up of a temperature difference between lake and land (Masselink & Pattiaratchi, 2001; Simpson, 1994). These conditions are more common in summer and fall in the THUAS; hence lake breezes are more common during these seasons. In winter wind speeds are much higher, increasing the temperature difference required between lake and land for the development of a lake breeze (Simpson, 1994).

Effect of urban heat island

The presence of large urban areas on the shoreline of Lake Ontario is likely to enhance lake breeze frequency by increasing land-lake temperature contrasts (Martilli, 2003; Miller *et al.*, 2002; Yoshikado, 1992). Table 5.1 provides evidence for this enhancement; the difference in frequency of lake breezes experienced on the north-western shore and southern shore of Lake Ontario can be attributed to the difference in the size and extent of the urban heat islands of the two areas. On the north-western shore there is a larger population, more development, a larger area of land covered by city and larger and more heavily used roadways and buildings, as compared to that of the southern shore. The more intensively urbanised north shore therefore, has a larger UHI, which increases the temperature difference between the land and the water, especially in summer. Hamilton city on the other hand, is smaller, less sprawling and has a UHI which covers a smaller area. In addition, the presence of the escarpment running perpendicular to the direction of onshore flow may contribute to slowing and reducing lake breeze frequency. The fact that lake breezes occur less often at Burlington than Toronto Island, despite both stations being located on the same shoreline can be attributed to the presence of a less well developed UHI around the Burlington site, but also to Burlington's lake head location. Moreover, the Brampton and Buttonville stations are similar distances from the lakeshore, however almost twice as many lake breezes are recorded at the Buttonville site. This may be attributed to the denser development and larger UHI around Buttonville enhancing lake breeze formation, as well as different topography and urban morphology.

Impact on NO_2 concentrations

Although NO_2 concentrations are on average higher during the last two days depicted, this can be attributed to the fact that during the preceding days a stronger northerly wind was blowing, which is associated with lower NO_2 concentrations because there are fewer upwind sources of pollutants (see Section 6.1.3). Meteorological conditions during the latter three days analysed indicate that gradient flow was lighter and from the south west, allowing for the development of the lake breeze and long-range advection of polluted air masses from higher emission regions to the southwest. Higher average NO_2 concentrations during lake breeze days can therefore be contributed to long-range transport rather than recirculation and build-up due to the lake breeze. Furthermore, there is no evidence that NO_2 concentrations accumulate over time with consecutive lake breeze days, as peak daily NO_2 concentrations actually decrease during the course of the four days of consecutive lake breezes in August 2002 (Figure 5.2). A short-term study by Hastie *et al.* (1999) found that the arrival of the lake breeze front was associated with a significant short-term rise in particulates, O_3 and NO_x at a location 32 km inland from the Lake Ontario shore. Figure 5.2 shows that a short-term spike in NO_2 concentration coincides with the early afternoon change in wind direction (arrival of the lake breeze front); however this influx of initially polluted air is followed by relatively cleaner air from over the lake, as NO_2 concentration declines through the afternoon. There is no evidence for the occurrence of well developed nocturnal land breezes on either the north-western shore or the southern Hamilton shore, which would be required for the recirculation and build-up of pollutants in the lake breeze system, hence NO_2 concentrations do not increase over the course of consecutive lake breeze days. The well developed nocturnal heat islands in both Toronto and Hamilton reduce or eliminate the temperature difference between the lake and land surface at night, reducing the likelihood of a land breeze developing.

Therefore, the lake breeze acts to protect lakeshore locations to some extent from full exposure to pollutants advected from the southwest on summer days with light gradient flow. However at inland sites, locations are now exposed to pollutants from windward emission sources in the path of the lake breeze.

CHAPTER 6: NO_2 CONCENTRATIONS

6.1 Results

6.1.1 Spatial variability

In the THUAS 1-hour concentrations of NO_2 at the 11 sites range between 0 and 141 ppb. Mean concentrations for the year at each site are between 15.35 ppb and 26.12 ppb. Hourly NO_2 concentrations are negatively skewed, meaning there are few very high concentrations (see Figure 6.1). In Toronto mean annual NO_2 concentrations are generally lower to the east and west of the city and highest around downtown and the western lakeshore (Bay and Etobicoke locations) and to the northwest of the downtown (York location). On average NO_2 concentrations for the year in Hamilton are lower than in Toronto, with a mean at the five Hamilton locations of 19.28 ppb compared to a mean of 21.93 ppb at the six Toronto locations. The Etobicoke location recorded the highest mean NO_2 concentration (26.12 ppb in 2002), yet the York location recorded the maximum hourly NO_2 concentration of 141 ppb in late November of that year; the mean for the year at York was 22.82 ppb. In Hamilton the Beach location experiences the highest mean annual NO_2 concentration (23.16 ppb for the year). In 2002 the highest individual 1-hour NO_2 concentration recorded in Hamilton is 84 ppb at the west Hamilton location. The lowest mean annual NO_2 concentration in the THUAS is recorded at the mountain location (mean of 15.35 ppb in 2002), which is located in the upper city in a predominantly residential and open area.

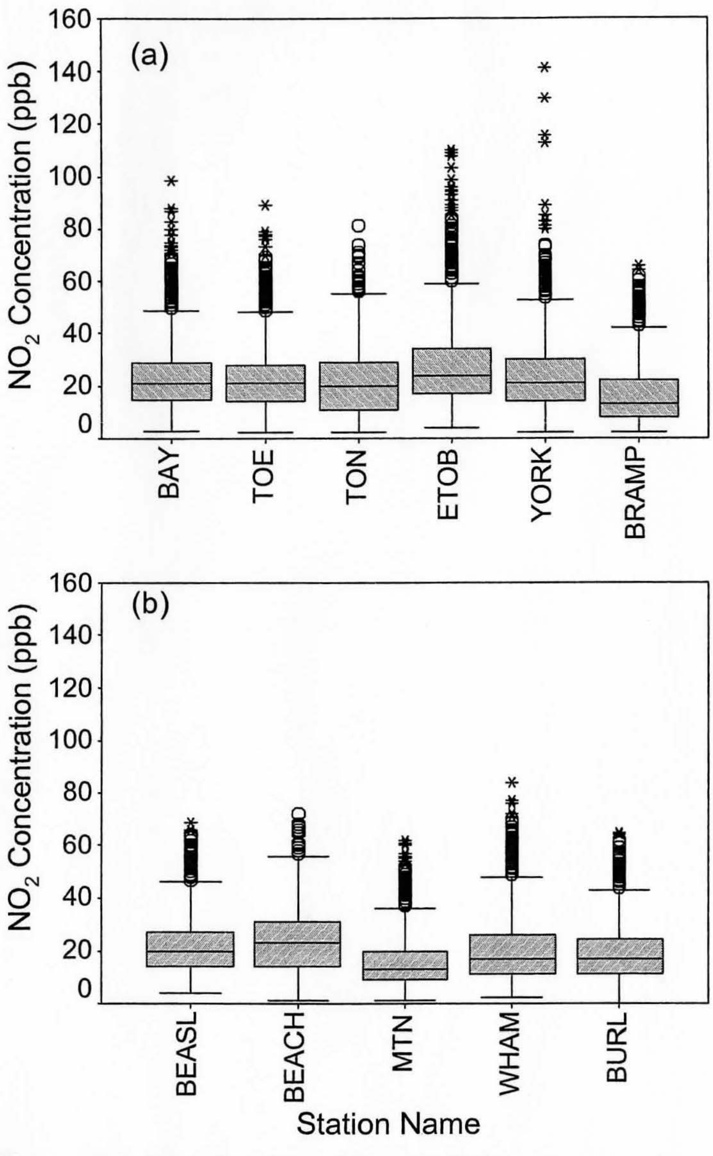


Figure 6.1: Distribution of hourly NO_2 concentrations at (a) Toronto stations and (b) Hamilton stations in 2002.

The difference in NO_2 concentrations recorded between the locations with the highest and lowest concentration during each hour of the year is depicted as a time series graph in Figure 6.2. The difference in hourly NO_2 concentrations between the 11 locations ranges between 3 and 101 ppb. It can be seen in Figure 6.2 that the largest ranges in NO_2 concentrations occur in summer, and are smallest in winter and early spring. The average difference between warmest and coolest of the 11 locations at each hour for the whole year is 22.97 ppb, with average seasonal differences being 21.25, 29.18, 21.59, and 19.79 ppb for spring, summer, fall and winter respectively. There is a period in early winter when the difference in NO_2 concentrations reaches 100 ppb at 10 a.m. on the 11th of December, and declines back to 35 ppb by 12 noon of the same day. At this time it was recorded that at the York location in west Toronto NO_2 concentration was the highest in the region at 141 ppb, and the Etobicoke location to the south closer to the lakeshore recorded 89 ppb, while the lowest concentration of 41 ppb was recorded at the Beach in Hamilton.

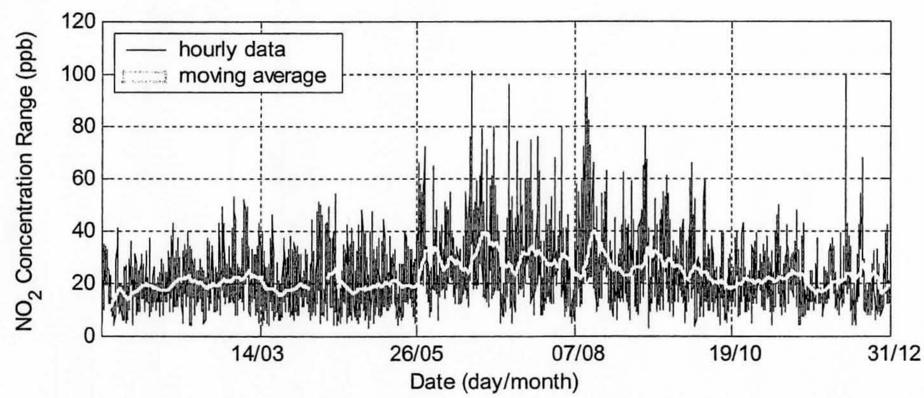


Figure 6.2: Difference in highest and lowest hourly recorded NO_2 concentration from 11 locations in Toronto and Hamilton in 2002. Black line is hourly difference; white line is 8-day moving average of the difference.

In order to be able to produce valid chronic exposure estimates for NO_2, it must be known if the spatial pattern of NO_2 holds true for all seasons. To determine the degree of spatial variability of pollutants, several methods can be employed; the absolute concentration differences between sites, correlation or regression between sites, the coefficient of variation, which is especially useful for time series studies, or the coefficient of divergence (COD), which is useful for spatial studies of air pollution health effects. The COD statistic ranges between zero and one, with a COD of zero meaning that NO_2 concentrations are identical at the two sites and NO_2 levels are homogeneous, while a COD value approaching one indicates maximum heterogeneity in NO_2 concentrations (Wilson *et al.*, 2005).

When average 24-hour NO_2 concentrations are divided into four seasons for the year 2002, the maximum COD of 24-hour average NO_2 concentrations measured at six locations in Toronto is highest in summer (COD = 0.43) and lowest in winter and fall (see Table 6.1). Similarly, maximum COD for the five Hamilton measurement sites is highest in summer (COD = 0.39) and lowest in winter (COD = 0.30).

Wilson *et al.* (2005) suggest that a coefficient of divergence between two locations of 0.20 or less should be classified as homogeneous when studying particulate distributions in urban areas. According to this criterion NO_2 distribution in the THUAS is heterogeneous, as maximum COD statistics for all seasons are greater than 0.20.

COD statistics based on different times of the day show that the geographic pattern of NO_2 throughout the day is reasonably consistent. The day is divided into morning rush-hour (6:00 a.m. to 10:00 a.m.), midday (11:00 a.m. to 4:00 p.m.), evening rush-hour (5:00 p.m. to 9:00 p.m.), and overnight (10:00 p.m. to 5:00 a.m.) periods. The lowest degree of heterogeneity was found during the morning rush-hour in both cities (0.31 and 0.36 in Toronto and Hamilton respectively). That is, during the morning rush-hour NO_2 concentrations vary the least through space in the THUAS. In Toronto maximum COD values for the midday, evening rush-hour, and overnight period were 0.43, 0.38, and 0.39 respectively. In Hamilton they were 0.44, 0.44, and 0.39.

Table 6.1: Maximum COD values for different seasons, and times of the day calculated between stations in Toronto and Hamilton cities for 2002.

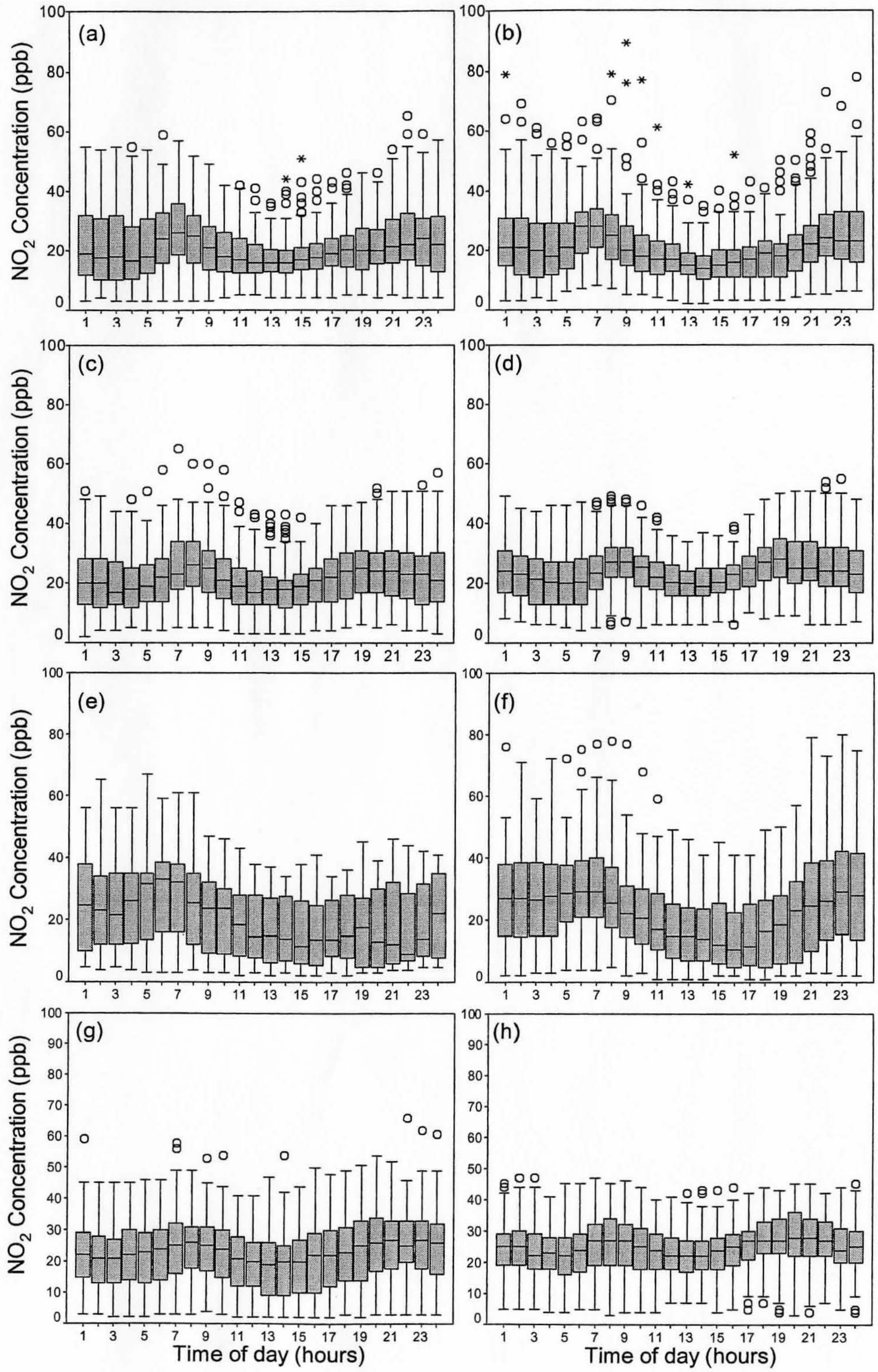
	Season			
City	**Spring**	**Summer**	**Fall**	**Winter**
Toronto	0.34	0.43	0.28	0.25
Hamilton	0.38	0.39	0.34	0.30
	Time of day			
	Morning	**Midday**	**Evening**	**Overnight**
Toronto	0.31	0.43	0.38	0.39
Hamilton	0.36	0.44	0.44	0.39

Furthermore, the relative order ranked COD statistics for each monitoring location pair follows very similar patterns for each of the four periods of the day in each city, meaning that the relative difference in NO_2 concentrations stays the same through the day. We can therefore conclude that the geographical pattern of NO_2 concentrations in the THUAS is consistent throughout the day.

6.1.2 Temporal variation of NO_2

Diurnal variations

Figure 6.3 shows NO_2 concentrations measured for each hour of the day for the four seasons in 2002 for Toronto East and Beach locations. At these and all other locations, NO_2 concentrations are on average highest in the morning and lowest at noon. NO_2 concentrations peak between 6:00 and 8:00 a.m., fall to the lowest concentration of the day between 1:00 and 4:00 p.m., and then rise to a more sustained high concentration, which peaks sometime between 4:00 p.m. and 1:00 a.m. Overnight between 1:00 and 5:00 a.m. NO_2 concentrations decline. The diurnal pattern is similar at both locations shown, however at the Beach location (Figure 6.3 (e-h)), NO_2 concentrations are more variable (taller bars), especially in spring and summer. The highest individual 1-hour NO_2 concentrations are found to occur during the morning peaks in summer and fall.


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
NO2 Concentration (ppb)
Time of day (hours)
0
20
40
60
80
100
1 3 5 7 9 11 13 15 17 19 21 23

Previous page - Figure 6.3: NO_2 concentration distribution for each hour of the day at Toronto East during (a) spring, (b) summer, (c) fall, (d) winter and at Beach location during (e) spring, (f) summer, (g) fall and (h) winter in 2002.

The seasonal differences in the diurnal pattern of NO_2 concentration (Figure 6.3) are small and mainly related to the timing of peak concentrations. For example the evening peak in winter comes much earlier than in summer because the night falls earlier. In winter the diurnal signal is shorter and clearer, and there is less variation in concentration. The afternoon nadir in average concentration is highest in winter and lowest in summer; at the Toronto East location in summer the nadir in the mean hourly NO_2 concentration occurs at 2:00 p.m. at 14.44 ppb, in spring the nadir occurs at 1:00 p.m. and the average concentration is 16.96 ppb, in fall the nadir occurs at 2:00 p.m. with an average concentration of 17.89 ppb, and in winter the nadir is at 1:00 p.m. with a concentration of 19.81 ppb (see Figure 6.3 (a-d)).

In Hamilton there are more variations from the typical diurnal pattern in NO_2 concentration. At the Beasley location in spring and summer there is an additional peak in hourly-averaged NO_2 concentration at 3:00 to 5:00 pm, as shown in Figure 6.4. It is a minor local peak, increasing by 1 to 2 ppb.

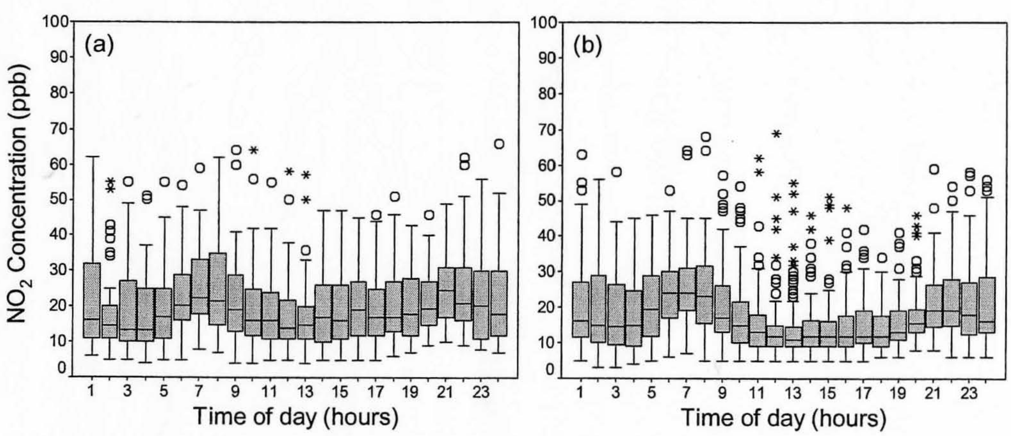


Figure 6.4: Diurnal variation in NO_2 concentration distribution at Beasley location in Hamilton for (a) spring and (b) summer in 2002.

Seasonal

Table 6.2 shows the 2002 seasonal averages, and maximum and minimum 1-hour NO_2 concentrations at the 11 locations in the THUAS. Mean seasonal NO_2 concentrations are generally lowest in summer or spring and highest in fall and winter, although at each location the maximum 1-hour NO_2 concentration is most often recorded in summer. The minimum 1-hour NO_2 concentration of 0 to 3 ppb at each location is also most often recorded in summer. The Etobicoke location experiences the largest variation in mean NO_2 concentrations between the seasons, with the mean NO_2 concentration in summer being 30.16 ppb and the mean concentration in spring being 21.61 ppb; a difference of 8.55 ppb.

Table 6.2: Seasonal means (M.), medians (Med.), and maximum and minimum recorded hourly NO_2 concentrations at 11 locations in Toronto and Hamilton in 2002.

Location	Average Seasonal Concentration (ppb)								Max. Seasonal Concentration (ppb)				Min. Seasonal Concentration (ppb)			
	Spring		Summer		Fall		Winter		Sp.	Su.	F.	W.	Sp.	Su.	F.	W.
	M.	Med.	M.	Med.	M.	Med.	M.	Med.								
BEASL	21	18	19	15	22	20	23	21	66	69	61	60	4	3	4	6
BEACH	20	19	23	22	23	24	25	25	67	80	66	50	2	1	2	3
MTN	18	15	14	11	16	13	16	14	62	65	56	57	1	1	2	3
WHAM	18	14	18	14	20	18	19	16	66	71	63	84	2	1	3	3
BURL	16	14	18	15	20	19	18	17	52	65	58	44	2	0	2	2
BAY	23	20	21	18	23	22	25	24	73	99	57	63	5	3	4	6
TOE	21	19	21	19	22	21	24	23	69	89	65	55	3	2	2	4
TON	21	18	19	16	21	20	23	22	70	81	70	55	3	2	3	3
ETOB	22	19	30	28	26	24	24	23	76	110	89	61	4	5	4	5
YORK	26	23	20	18	22	20	25	24	73	89	141	59	5	2	4	6
BRAMP	17	12	13	10	17	14	18	15	61	64	66	55	3	2	3	3

Figure 6.5 shows a five-day moving average of hourly NO_2 concentrations measured at three of the most urbanized locations in the THUAS: Beasley, Toronto East and Etobicoke. The figure shows that NO_2 concentration is reasonably consistent throughout the year, experiencing large fluctuations on relatively short time scales. Five-day average NO_2 concentration at Etobicoke peaks in July to August, at which time of the year there is the most variation between locations.

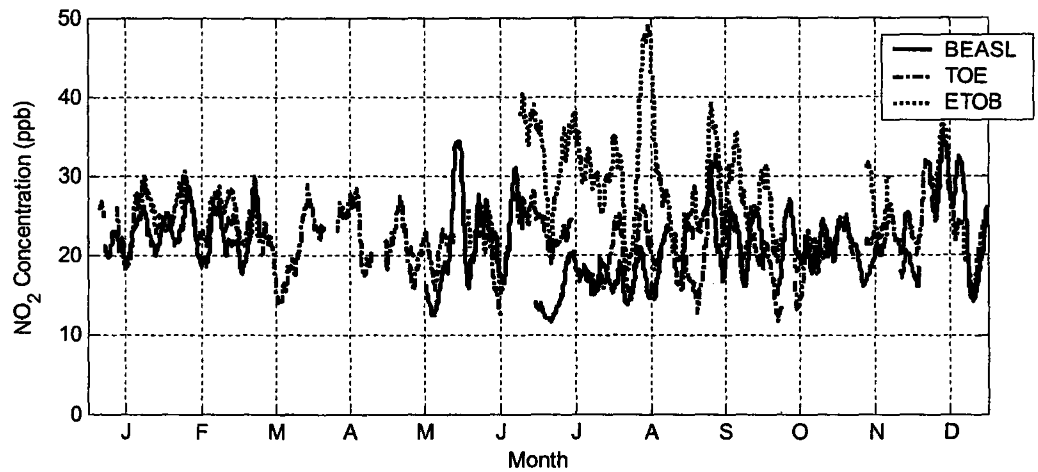


Figure 6.5: Five-day moving average of hourly NO_2 concentrations measured at Beasley, Toronto East and Etobicoke in 2002.

Figure 6.6 shows more clearly that during the warmest months of the year the mean average hourly NO_2 concentrations are lowest, while individual 1-hour NO_2 concentrations reach their highest levels. Figure 6.6 (a) shows that at Toronto East the mean NO_2 concentration in fall and winter is slightly higher, but that in spring and summer the highest individual hourly NO_2 concentrations are recorded. The lowest hourly NO_2 concentrations recorded during winter are higher than the other seasons, indicating that NO_2 levels are constantly elevated during the winter season. The inter-quartile range of hourly NO_2 concentrations is relatively uniform during all months of the year at Toronto East, but at the Beach location (Figure 6.6 (b)) the inter-quartile range in summer is much larger than in winter, indicating that there is much more variation in recorded hourly concentrations during the warm months.

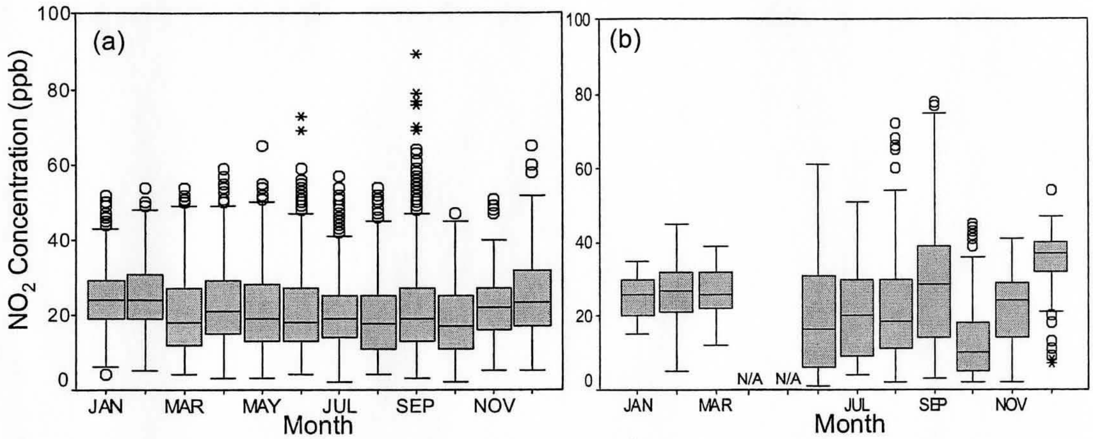


Figure 6.6: Monthly distribution of hourly NO_2 concentration measurements at (a) Toronto East and (b) Beach locations in 2002. Hourly data is not available for April and May at Beach location.

6.1.3 Meteorological Control on NO_2 concentrations

Wind

Analysis of the relationship between wind speed and NO_2 concentration shows that lower hourly NO_2 concentrations are associated with higher wind speeds; with wind speed accounting for 25% of the variation in NO_2 concentrations on average at all stations in the THUAS. This relationship is strongest in winter, with wind speed explaining 32% of the variance in hourly NO_2 concentrations, and weakest in fall and summer when hourly wind speed explains 24% of the variance in NO_2 concentrations. Figure 6.7 demonstrates the relationship between NO_2 concentration and wind speed at the Toronto East location during spring, summer, fall and winter. The relationship is clearly weakest in summer.

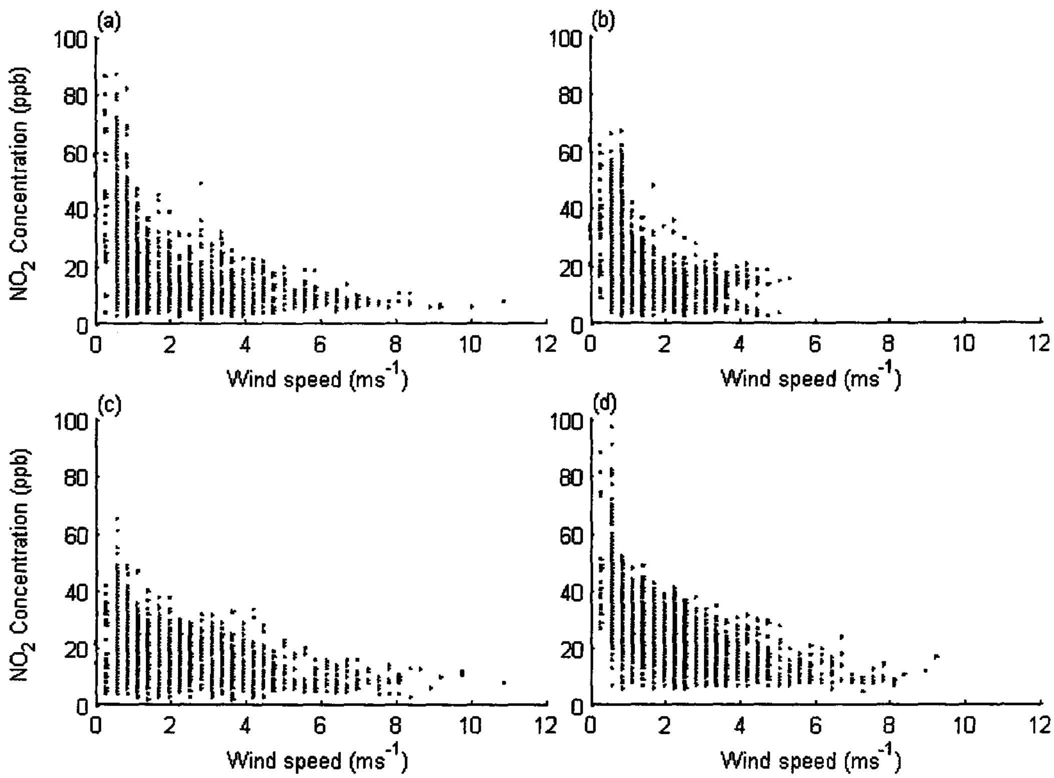


Figure 6.7: Relationship between wind speed and NO_2 concentration at Toronto East location during (a) spring, (b) summer, (c) fall and (d) winter in 2003.

Hourly wind direction and hourly NO_2 concentration for 2002 were compared at each location pair. Figure 6.8 shows that at each location there are wind directions for which hourly NO_2 concentrations are significantly higher. For most locations south to southwest winds are associated with higher maximum and minimum NO_2 concentrations. At the Brampton location (Figure 6.8 (c)), easterly to southerly winds are also associated with higher NO_2 concentrations. The Toronto East, Bay and Etobicoke locations (Figure 6.8 (a), (d) & (e)) experience higher NO_2 concentrations during northeast and east winds. At York high hourly concentrations of NO_2 are found when the wind is blowing from the northwest. On the southern lake shore, the Beasley and Beach (Figure 6.8 (g) & (h)) locations experience higher NO_2 concentrations (especially at the Beach location with higher minimum concentrations for southwest) when the wind is blowing from the southwest to west, and a few hours of higher NO_2 concentrations occur with northeast to east winds (onshore lake breeze direction).

At most locations southerly winds are associated with significantly higher NO_2 concentrations than for northerly winds. For example at the Brampton location the mean concentration for north winds is 13.29 ppb and for south winds is 20.70 ppb in 2002, a significant difference at the 95% confidence level. However the influence of southerly and northerly winds depends on surrounding land use, for example at the Toronto East location there is virtually no difference in means (21.75 ppb and 21.50 ppb for north and south winds respectively).

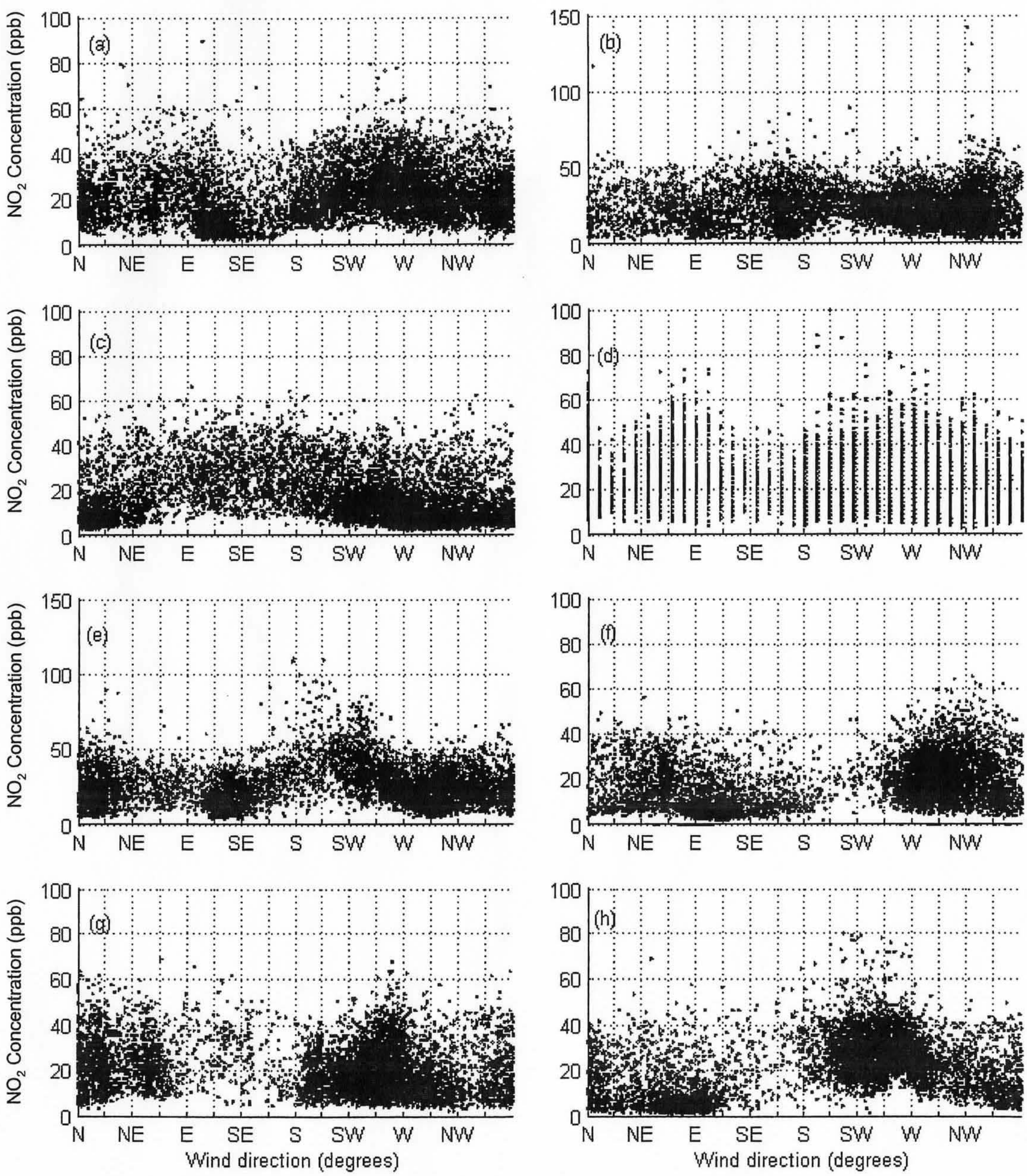


Figure 6.8: Hourly NO_2 concentration and wind direction at (a) Toronto East, (b) York, (c) Brampton, (d) Bay/Toronto Island, (e) Etobicoke, (f) Burlington, (g) Beasley/Land and (h) Beach/Hamilton downtown locations in 2002.

Air temperature and incoming solar radiation

Temperatures in the study region are warmest in Toronto East and downtown Hamilton, followed by other urbanised locations along the lakeshore. Hourly temperatures are coolest at the least urbanised locations, at higher elevations and furthest away from the lake. Urban locations closest to the lakeshore experience the smallest range in annual temperatures due to moderation by the lake. The lake introduces a time lag in warming and cooling with spring lake waters being cooler than the land and late summer lake waters being warmest. Warmer air temperatures are also associated with sunny days. Analysis of hourly NO_2 concentrations, and temperature and incoming solar radiation measurements shows that both temperature and incoming solar radiation are negatively associated with hourly ambient NO_2 concentrations. Hourly temperature is compared to NO_2 measured at co-located and paired stations. Hourly incoming solar radiation is measured at a rural location located some 74 km southwest of Hamilton at Turkey Point, and compared to hourly NO_2 concentrations measured in the THUAS. The strongest relationship between temperature and NO_2 concentration was found during spring. At many locations the relationship is not significant at all ($R^2<0.04$), especially in fall and winter. Highest incoming solar radiation levels and temperatures are found at midday, when NO_2 concentrations are lowest.

The strength of the relationship between NO_2 concentration and incoming solar radiation differed widely between locations, as can be seen in Table 6.3; at York in the summer of 2002 incoming solar radiation explained 20% of the variation in hourly NO_2 concentration there, while at Etobicoke incoming solar radiation had no discernable relationship with NO_2 concentration during all seasons apart from spring ($R^2 = 0.04$). There is no discernable relationship at all between hourly NO_2 concentrations and incoming solar radiation levels during winter.

Table 6.3: Strength of relationship (determination coefficient) between hourly incoming solar radiation at Turkey Point and hourly NO_2 concentration measured at locations in the THUAS for four seasons in 2002.

Location	Spring	Summer	Fall	Winter
BEASL	-	0.07	0.04	-
BEACH	-	0.11	-	-
MTN	0.08	0.12	-	-
WHAM	0.04	0.09	0.05	-
BURL	0.04	0.11	0.05	-
BAY	0.06	0.06	0.04	-
TOE	0.05	0.09	-	-
TON	0.06	0.08	0.04	-
ETOB	0.04	-	-	-
YORK	0.16	0.20	0.08	-
BRAMP	0.06	0.10	0.04	-

Specific humidity

Hourly specific humidity calculated at Buttonville, Pearson, Toronto Island, Hamilton Botanical Gardens, and Hamilton Airport was compared to hourly NO_2 concentrations measured at nearby locations (see Table 2.1 for location pairings). No statistically discernable relationship was found between the two variables; however the data does suggest that there may be a very weak positive relationship between specific humidity and NO_2 concentration at some times and locations. This relationship is strongest in the warm months of the year, especially at the west Hamilton and mountain sites where specific humidity explains 10% of the variation of NO_2 concentration in summer and spring respectively.

6.1.4 Simulation of spatial patterns of NO_2 concentrations using LUR model

Variables which were found to be significantly related to NO_2 concentrations predicted by the land use regression model are summarized in Table 6.3. These variables and the distances within which they have an effect are different in the Toronto and Hamilton models. Each variable took the expected sign, with traffic density within a 500 m buffer in Toronto, and a 300 m buffer in Hamilton resulting in higher NO_2

concentrations. Negatively associated variables were 500 m proximity to open space in Hamilton, and distance to lake, and longitude.

Table 6.4: Summary table of all significant variables in Toronto and Hamilton LURs, and the distance within which they have an effect.

Variables	Toronto	Hamilton
Roads	Highways 200 m Major roads 50 m	Highways 50 m -
Land use categories	Industry 750 m - -	Industry 200 m Open 500 m Downtown industrial core 1000 m
Population density	Dwelling density 2000 m	-
Geographic location	- longitude	Distance to lake -
Traffic	Traffic density 500 m	Traffic density 300 m
Wind	Downwind of all highways 1500 m	Downwind of 403-Highway

The inclusion of wind fields into the LUR model improved the accuracy of NO_2 predictions for health exposure studies. The incorporation of wind fields raised R^2 values for the Toronto prediction surface from 0.65 to 0.69, and from 0.75 to 0.76 for the Hamilton NO_2 surface, the prediction surfaces are shown in Figure 6.9. Modelled NO_2 surfaces displayed higher pollutant concentrations downwind of major expressways in both Toronto and Hamilton, as would be expected based on source-receptor relations.

In Toronto high predicted concentrations of NO_2 (up to 93.6 ppb) are shown around the expressways (Figure 6.9 (b)), especially on the downwind side, for example north of the highway-401 and east of the Don Valley Parkway in the north of the city. Large areas of high NO_2 concentrations are also found in the downtown area, and north east of the major highways in Etobicoke (in the west of the city), as would be expected due to high traffic volumes and the direction of the average winds at this time of the day. Figure 6.10 shows predicted NO_2 concentrations at the intersection of the Don Valley Parkway and highway-401 in more detail. It can be seen that to the north and east of the highways and intersection NO_2 concentrations are higher, due to the prevailing south-westerly wind. A similar pattern can be seen in Hamilton around highway-403 located south west of the city (Figure 6.9 (d)), where higher NO_2 concentrations are predicted north of the highway.

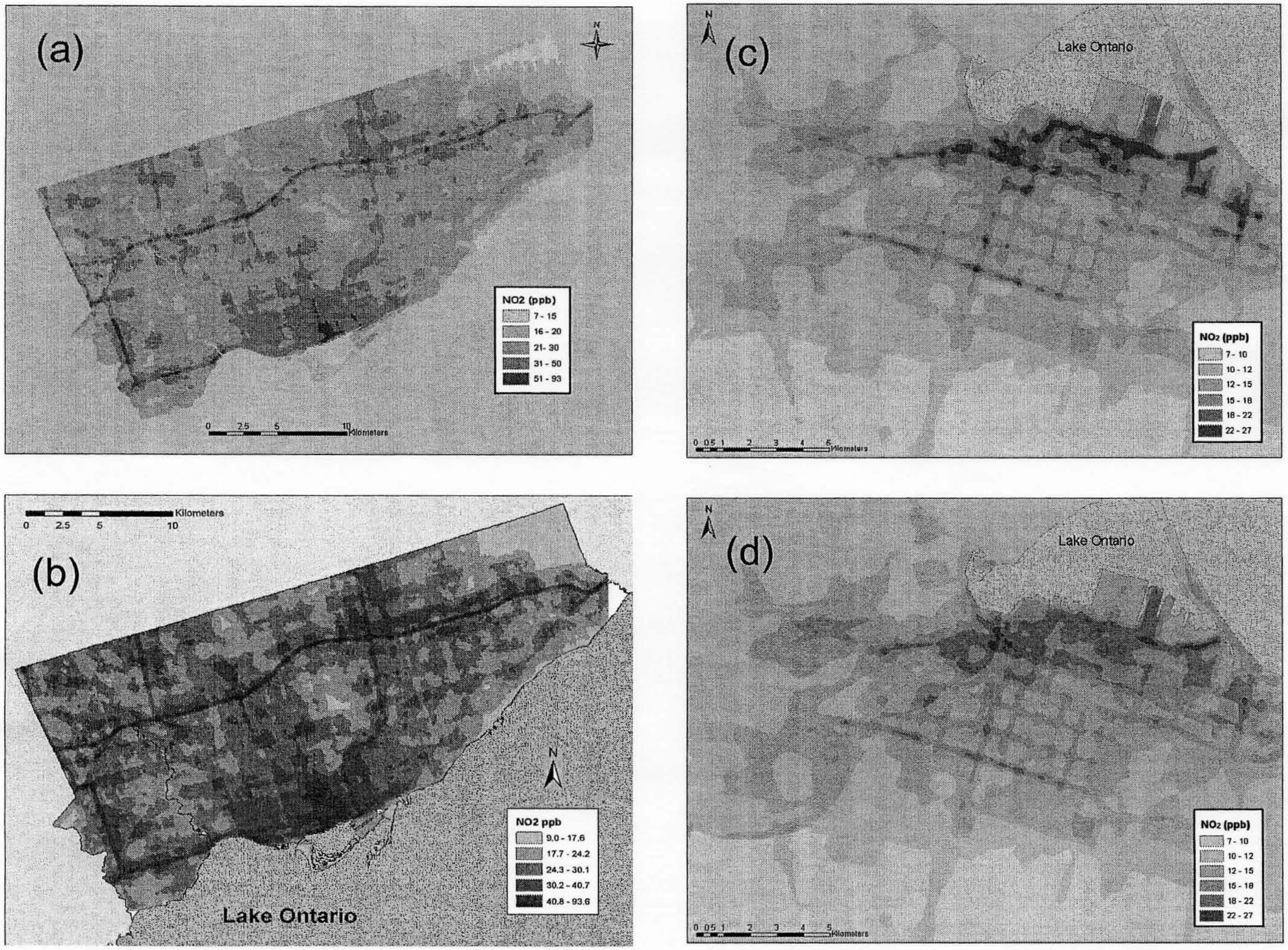


Figure 6.9: Average afternoon rush hour NO_2 concentrations estimated by LUR model without wind direction effects (top panels), and with wind direction effects (bottom panels) for (a) and (b) Toronto, and (c) and (d) Hamilton.

NO_2 concentrations were predicted to be lower in Hamilton than in Toronto, with the maximum value being 27 ppb (Figure 6.9 (d)). The highest values are found in the downtown area and along major arterial routes, and there are noticeably higher pollutant concentrations in the areas located between the escarpment and the lake shore (especially in the west of the city).

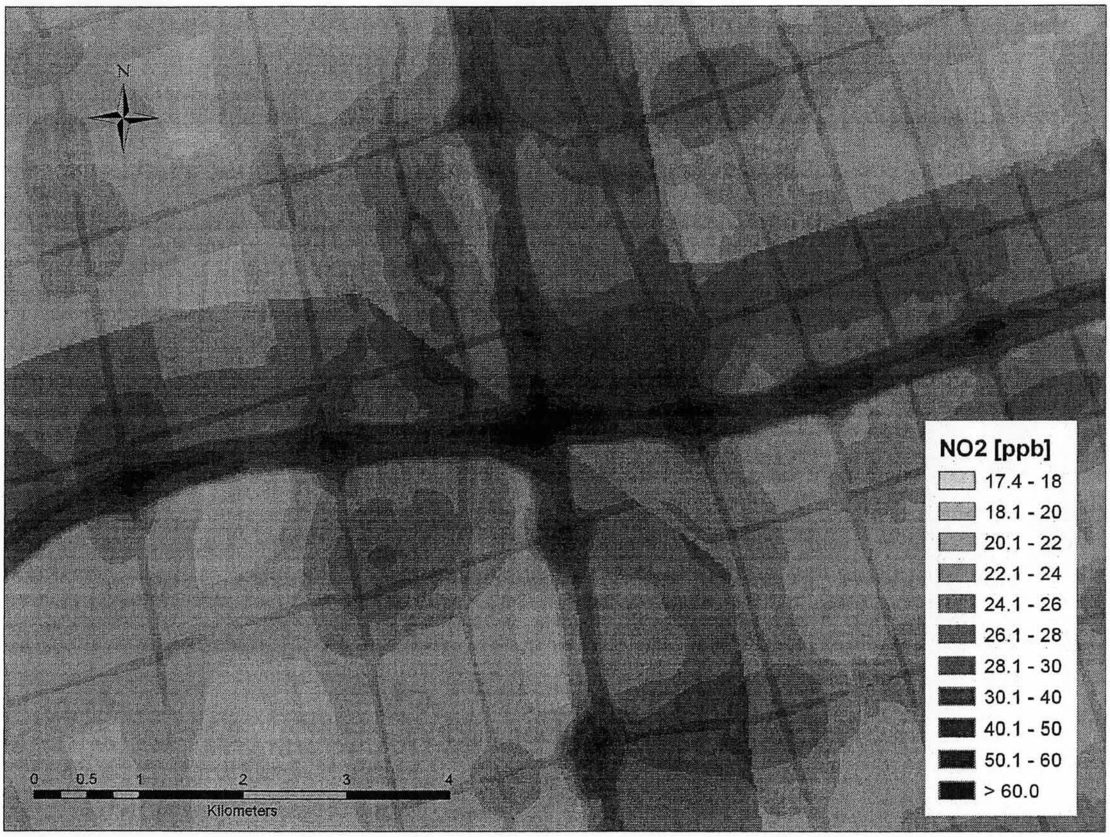


Figure 6.10: Predicted NO_2 concentrations estimated by LUR model with wind direction effects at the intersection of the Don Valley Parkway and highway-401 in northern Toronto.

6.2 Discussion

6.2.1 Spatial variability of NO_2 concentrations

NO_2 concentrations are lower in Hamilton than in Toronto on average because Hamilton is a smaller city (with a population of approximately 500,000), with less traffic, the major source of NO_2 (Burton & Shepherd, 1997; Jacobson, 2002).

The two sites where the highest levels of NO_2 are measured are Etobicoke and York. These two sites are both located in proximity to sources of pollutants; there is a coal-fired power plant located near the lakeshore in Etobicoke, which released 4933.9 x10^3 kg of NO_2 in 2002 (NPRI database, 2005), and several industrial sources nearby to the York location. Similarly, the highest NO_2 concentrations in Hamilton are measured at the Beach location, which is located in east Hamilton, in the lower city and in close proximity to large sources of emissions such as the steel mills, highways, and industrial and business areas. The site in West Hamilton where the highest 1-hour NO_2 concentration was measured in 2002 is also located close to highway-403, which experiences heavy traffic volumes and is situated at a confined location at the bottom of the Dundas Valley.

The largest differences in hourly NO_2 concentration between sites occurred during summer, and the smallest differences occurred in winter. The largest 1-hour difference in 2002 however, occurred at 10:00 a.m. on December 11. At this hour NO_2 concentration was highest at the York location, and lowest at the Beach location in Hamilton. This spike in the difference of recorded NO_2 concentration between stations may have been caused by there being different emission patterns in the two cities at this time, or by changes in the weather conditions which affected one city and not the other such as atmospheric inversion conditions in one location and not in the other.

In order to be able to produce valid chronic exposure estimates for NO_2, it must be known if the spatial pattern of NO_2 holds true for all seasons. The COD is a measure of relative pollution concentration uniformity through space, and has been applied to particulate concentrations in urban areas (Wilson *et al.*, 2005). In agreement with the previous finding, maximum COD is highest in both cities in summer, and lowest in winter. Seasonal changes in intra-urban heterogeneity are related to seasonal changes in meteorology; in summer wind speeds in the region are lower, meaning that less mixing takes place in the lower boundary layer, and more local-area variation in NO_2 concentrations occurs. Furthermore emission patterns and photochemical activity also vary with the seasons.

According to the criterion of Wilson *et al.* (2005), NO_2 distribution in the THUAS is heterogeneous, yet seasonal COD varies significantly. Maximum COD is 0.18 higher in summer than winter in Toronto, so it can be concluded that the geographical pattern of NO_2 concentration and exposure is significantly different in summer and winter; therefore estimates based on measurements taken at one time of the year are not sufficient to predict long-term exposure. In Hamilton the range in maximum COD between summer and winter is small, meaning that estimates based on one time of year alone are more likely to be accurate.

Maximum COD calculated for various times of the day indicate that during the morning rush-hour NO_2 concentrations vary the least through space in the THUAS, however, the differences in maximum COD for each time of the day are small, as are the ranked order of station concentrations, so we can therefore conclude that the geographical pattern of NO_2 concentrations in the THUAS is consistent throughout the day.

6.2.2 Temporal variability of NO_2 concentrations

The morning peak in NO_2 concentration occurs when atmospheric stability is highest, and emitted NO_2 is being distributed through a small mixing volume of atmosphere. Moreover, rush-hour occurs during this period and emissions are highest. NO_2 concentrations are lowest from 1:00 to 4:00 p.m. due to atmospheric instability and turbulent mixing caused by strongest incoming solar radiation. The evening peak in concentrations is caused in part by the evening rush-hour (which is spread over a longer period of time than the morning rush-hour) and by higher atmospheric stability at this time of day. Overnight NO_2 concentrations decline because of dwindling emissions (traffic) during this time, and because there is no sunlight so O_3 is not formed and there is less O_3 available to react with emitted NO to form NO_2. The lack of sunlight overnight also means that NO_2 is no longer broken down into NO and atomic oxygen, and consequently NO_2 concentrations decline slowly through deposition (Jacobson, 2002).

The timing of the diurnal peaks in concentration changes with the seasons, due to changes in timing of incoming solar radiation. In Hamilton the additional afternoon peak in hourly-averaged NO_2 concentration at the Beach location may be caused by local increases in emissions (traffic in the afternoon rush-hour), or by local circulations such as a lake breeze, which transport emissions from the highway inland to the measurement site.

6.2.3 Meteorological Control

Spatial and temporal variations in NO_2 concentration can be related to changes in meteorological variables, in particular wind and temperature. One of the key factors affecting atmospheric NO_2 concentrations is wind speed, which creates mechanical turbulence, and aids in the dispersion and mixing of pollutants through the atmosphere (Jacobson, 2002; Pielke & Uliasz, 1998). Lower NO_2 concentrations are found to be associated with higher wind speeds, especially in winter when cool surface temperatures enhance stability and suppress dispersion and mixing in the lower atmosphere. Therefore open locations which have higher wind speeds are less likely to experience pollution problems while confined locations, especially those containing sources, such as highways located at valley bottoms or in urban canyons, are likely to experience pollution accumulation.

In summer it is likely that other factors that influence secondary pollutant production have a more dominant effect than wind speed, such as surface heating by the sun leading to decreased atmospheric stability and enhanced buoyant turbulent mixing and dispersion of pollutants away from the surface. In winter wind speeds are on average higher and so have a greater ability to disperse pollutants. Wind speeds are also higher during the daytime than overnight, contributing to the diurnal pattern in NO_2 concentrations observed.

Wind direction affects NO_2 concentrations by transporting pollutants from source to receptor. For most locations south to southwest winds are associated with higher NO_2 concentrations. This is mainly thought to be due to long-range transport of pollutants from areas south of the THUAS such as industrial areas in south-western Ontario, and the Ohio Valley. The unique variation of NO_2 with wind direction at each location however, is dependent on proximate sources of NO_2 surrounding the measurement locations.

The degree of influence of southerly and northerly winds also depends on surrounding land use, for example at the Toronto East location there is virtually no difference in means for north and south winds because this site is at a very urbanised and built-up location, with the large highway-401 located 2.92 km northwest of the monitoring location, reducing the north-south contrast. This highlights the difference between long-range and proximate sources of NO_2. In most cases, and in the short-term, proximate sources have more of an influence on NO_2 concentrations; however in the longer term long-range transport from southern sources have a significant effect on daily NO_2 concentrations.

Similar results were found in the UK, where weather-type variation explained a significant portion of concentration variation, indicating that long-range transport may mean that under certain conditions local air quality is not related to local emissions (Buchanan *et al.*, 2002).

Higher concentrations recorded during easterly and southerly winds are caused by the fact that Brampton is located on the north-western edge of the THUAS. This means that winds blowing from the south to east arrive from the urban areas, where traffic volumes are higher, and so have higher NO_2 concentrations. At Toronto East, Bay and Etobicoke, higher concentrations during northeast and east winds are related to the location of denser and more heavily trafficked urban areas to the north and east. NO_2 concentrations are higher at York because of nearby industry and highways, high concentrations during northwest winds are attributed to highway-401, Canada's busiest highway, which is located 3.32 km to the north-northwest. Higher NO_2 concentrations at York when winds are from the south and southeast are associated with traffic emissions from Eglinton Avenue. Higher NO_2 concentrations recorded at Beach and Beasley locations in Hamilton occur because these sites are located northeast of the central city where traffic and industrial emissions are higher. At these locations northeast to east winds are also associated with higher concentrations because of the steel refineries which are located 3.20 km northeast of Beasley station, and the QEW highway which is located 1.3 km northeast of the Beach station.

NO_2 concentrations are found to be negatively associated with temperature and incoming solar radiation, with the lowest NO_2 concentrations being found in the middle of the day, when solar radiation and temperature are generally highest. This is partly because atmospheric stability is lowest due to surface heating and higher wind speeds at this time of day. Also, NO_2 is broken down in the presence of sunlight to form NO and atomic oxygen, which then reacts with molecular oxygen (O_2) to produce O_3 according to the photostationary-state equations (Jacobson, 2002). NO_2 is produced by the reaction of emitted NO (mainly from traffic) and O_3 in the atmosphere. Therefore, increased levels of solar radiation are likely to have the effect of destroying more NO_2 in the atmosphere and creating more O_3. Clearly other factors have a relatively stronger influence on NO_2 concentrations, such as the higher rate of vehicle use and emissions during the daytime when air temperatures are relatively warmer. Also, other sources of pollutants such as industry operate more during the daytime than night.

There is a wide variation in the strength of the relationship between incoming solar radiation and NO_2 concentration at different measurement sites, which can mainly be attributed to surrounding land use. At Etobicoke the relationship is very weak or nonexistent, which may in part be explained by the fact that the Etobicoke location is less than one kilometre from a very busy highway (the QEW), where it is likely that there is sufficient NO being emitted from passing traffic so that concomitant increases in rates of scavenging and destruction of NO_2 by ambient O_3 do not reduce daytime levels significantly, as NO is in surplus.

There is no discernable relationship between NO_2 concentration and incoming solar radiation levels at any location in winter because low temperatures at this time of the year mean that surface heating and turbulence caused by solar radiation is minimal, so does not cause dispersion of the pollutant. Furthermore, daylight hours are shorter in the winter, reducing the amount of NO_2 destroyed in the production of O_3.

The relationship between specific humidity and NO_2 concentration is very weak, indicating that humidity has little control on NO_2 production or dispersion. As specific humidity is generally highest in this region when temperatures are high, specific humidity may in fact be a proxy for temperature, which accelerates the formation of NO_2. The positive association between hourly specific humidity and NO_2 concentration may also be because higher specific humidity is found when the atmosphere is more stable and dispersion of pollutants is limited, or because humidity increases when the winds blow from a southerly direction because sources of NO_2 are located south of the study area. Furthermore, higher specific humidity has been found to be associated with higher NO_2 concentrations because the rate at which the gas is formed is enhanced by the presence of humidity (Seaman, 2000). The relationship is strongest in summer because humidity is highest in summer.

Seasonal synoptic control

During the winter mean NO_2 concentrations are highest, however in summer the highest 1-hour NO_2 concentrations are recorded. This is because of changes in seasonal and synoptic weather patterns which change the meteorological controls on NO_2 dispersion. In winter wind speeds are on average higher, aiding in dispersion of pollutants, however higher emissions in winter, and higher atmospheric stability during periods of calm winds, mean that dispersion is on average lower and mean concentrations are higher. In summer anticyclones are more frequent, bringing clearer skies and lighter winds. This, combined with long-range transport of secondary pollutants from south-westerly directions mean that peak NO_2 concentrations can reach very high levels. However because incoming solar radiation and temperatures are higher, the lower atmosphere is less stable due to surface heating, and NO_2 is destroyed by sunlight in the production of O_3, so summer NO_2 concentrations are on average lower than in winter.

6.2.4 NO_2 exposure estimation

The inclusion of wind fields into the LUR model makes a small improvement in the prediction ability of the surface, increasing R^2 values for modelled surfaces by 0.04 and 0.01 in Toronto and Hamilton respectively. The inclusion of an extra variable in the model obviously increases the degrees of freedom of the calculation of the R^2 statistic, so in effect the true improvement may not in fact be significant at all. However, wind significantly influences the horizontal transport and distribution of pollutants as well as vertical mixing and dispersion (DeGaetano & Doherty, 2004; Seaman, 2000), so it is vital to consider wind flow when predicting intra-urban variations on NO_2 concentrations, especially in cities such as Hamilton where wind flow is significantly affected by local topography.

Higher predicted NO_2 concentrations on the lower level of Hamilton can be attributed to topographically reduced wind speeds resulting in less mixing and dispersion of pollutants, and to higher traffic volumes in this part of the city. The proximity of Lake Ontario also effects local wind flow and pollutant concentrations, an effect which is captured by the Land Use Regression Model; NO_2 concentrations are not as high as may be expected along the Queen Elizabeth Way (the bridge located in the upper right of Figure 6.9 (d)) because the wind direction at this time of day lake breezes mean that cleaner air is advected onshore from over the lake.

Modelled NO_2 surfaces displayed higher pollutant concentrations downwind of major expressways in both Toronto and Hamilton. This means that residents living downwind of major highways and intersections experience a chronic exposure condition, while those living upwind are somewhat 'protected' by the prevailing wind and exposed to lower average pollutant concentrations.

The impact of wind fields on NO_2 and other air pollutant concentrations in urban areas needs to be taken into account in health studies as the location of study subjects in relation to likely exposure fields throughout the day will change as the subject moves about, and as exposure fields move and evolve throughout the day. Improved understanding of the relationship between local wind fields and air pollution concentrations may help in the formulation of strategies to mitigate its effect on human health. Diurnal variations in wind flow are therefore also important as the population moves about through the day and their exposure changes.

The uniformity of NO_2 concentrations measured at various locations in both Hamilton and Toronto was determined by calculating the coefficient of determination during each season. This analysis confirms that NO_2 concentrations are indeed heterogeneous in the THUAS, and hence exposure estimates need to be made using techniques which can predict local scale variation of NO_2. However the current Land Use Regression model used in this research was developed by Jerrett *et al.* (2005b) using NO_2 data collected during a 17-day period, representing conditions during only one season of the year. The COD statistic indicates that the degree of heterogeneity of NO_2 concentrations within the cities, in Toronto especially, varies significantly by season, as wind, temperature, synoptic patterns, lake breeze frequency, and urban heat island patterns vary significantly by season. For the LUR model to produce more accurate exposure estimates it would be necessary to incorporate more data, and to perhaps develop regressions for each season, or for the warm and the cool halves of the year, in the Land Use model.

CHAPTER 7: CONCLUSIONS AND IMPLICATIONS

7.1 Conclusions and suggestions for future work

This research examines interactions between meteorology and traffic-based pollution in a large Canadian population centre (THUAS). These mechanisms and associations can be used to further our understanding of traffic-related health effects by better quantifying what parts of the population are exposed to the pollution. These interactions can be used to improve existing land-use based NO_2 prediction models by incorporating meteorological controls on NO_2 distributions for health effect studies.

Meteorology

This analysis indicates that an urban heat island effect with two nodes centred on Toronto and Hamilton city centres is present, with the UHI being strongest during the cooler months of the year, especially at night. This UHI has implications for human health, exacerbating summer extreme temperatures, and affecting rates of chemical reactions, production of photochemical smog, and enhancement of lake breeze strength and frequencies.

Lake breezes

Analysis of hourly wind measurements showed that lake breezes occur frequently in the afternoon in the region, and occur on almost 50% of summer days at lakeshore locations. The arrival of the lake breeze increases NO_2 concentrations at many locations for up to two hours. The lake breeze does not increase NO_2 concentrations over the longer term through the re-circulation of pollutants, as has been found to occur at some coastal city locations. Instead, as the afternoon progresses and the lake breeze continues to flow inland, NO_2 concentrations are shown to decrease as the pollutants are flushed from the system. Cumulative exposure to harmful pollutants has a stronger effect on mortality than can be extracted from associations between day-to-day variations in air pollution and deaths (Brunekreef & Holgate, 2002); the lake breeze in the THUAS therefore, effectively shelters coastal populations from the full extent of NO_2 exposure they would otherwise experience. This has implications for urban planning; if the city continues to expand inland, the population living there will be exposed to NO_2 (and probably many other co-pollutants that vary with NO_2) for longer durations.

NO_2 variability

Hourly NO_2 concentration measurements from a relatively dense network of monitoring sites are related to hourly meteorological measurements in the THUAS. NO_2 concentrations show marked diurnal and seasonal cycles, with maximum concentrations during the winter, and morning and evening hours. Minimum NO_2 concentrations are found around midday and in summer. However it is in summer and fall that the highest 1-hour NO_2 concentrations are found, reaching up to 141 ppb at the most urbanised location. This implies that the peaks are likely related to a blend of anthropogenic and meteorological influences, with higher emissions and higher atmospheric stability contributing to the diurnal peaks, and higher temperatures contributing to summer short-term peaks.

NO_2 distribution is strongly influenced by wind direction and speed and proximate sources, with wind direction controlling pollutant transport from source to receptor. Analysis of NO_2 concentration variation by wind direction shows that areas downwind of major highways, urban centres and industry are exposed to higher pollutant concentrations. Long-range transport of NO_2 also plays a significant role in temporal variability of NO_2, especially from sources south-west of the THUAS. Seasonal variability of average wind direction therefore means that population exposure varies by season also. Such information could be used to predict pollution concentrations and exposures with such models as CALINE, health models and land-use regression.

As meteorology and NO_2 concentrations follow seasonal patterns, so too does the degree of spatial variability of NO_2 concentrations. The spatial pattern of NO_2 variation is not consistent over seasons. In Toronto NO_2 concentrations are much more homogeneous in winter than summer. This means that exposure models reflecting local-scale variability need to account for this seasonal variation. The geographic pattern of NO_2 variation in Hamilton is reasonably consistent over seasons. The geographic pattern of 1-hour NO_2 variation at different times of the day is also found to be consistent in the THUAS.

Suggestions for future research

This study has investigated how a prominent marker for traffic pollution varies in relation to meteorological influences. Through a detailed analysis of the NO_2-meteorology relationship, key information that can be used in exposure assessments in the study area and other places has been generated. Wind direction is the strongest control on hourly NO_2 concentration, while temperature and wind speed also have an effect. Seasonal patterns display significant spatial heterogeneity, suggesting that health effects assessments need to be based on seasonal pollutant measurements. Future research using NO_2 or related gases as a proxy for traffic-related pollution will have to assess the influence of meteorology carefully to ensure health effects assessments have minimal error in the exposure assignment.

The current Land Use Regression model developed by Jerrett *et al.* (2005b) was slightly improved by the incorporation of wind direction influences on NO_2 distributions, it could be further improved by incorporating NO_2 concentration measurements from different times of the year to reflect the impact of seasonal changes in wind, temperature, synoptic conditions, urban heat island magnitude, and lake breeze frequency on local scale NO_2 variations.

CHAPTER 8: REFERENCES

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