ASSESSING OZONE AND FINE PARTICULATE MATTER CONCENTRATIONS AND TRENDS IN ONTARIO, CANADA, 2003 – 2012

by

Cameron Hare

A Major Research Paper

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Masters of Spatial Analysis (MSA)

Toronto, Ontario, Canada

Author's Declaration for Electronic Submission of a MRP

I hereby declare that I am the sole author of this MRP. This is a true copy of the MRP, including any required final revisions.

I authorize Ryerson University to lend this MRP by photocopying of by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

I understand that my MRP may be made electronically available to the public.

Abstract

Ambient air concentrations of ozone (O_3) and fine particulate matter ($PM_{2.5}$) in southern Ontario were analyzed in this study. Ontario is Canada's most populated province and a large area in southern Ontario shares a border with the United States of America. The 2003 Canada-U.S. Border Air Quality Strategy outlines an initiative to reduce air pollution, specifically targeting southern Ontario due to its proximity to the U.S. and its historical air pollution levels. The data were obtained from the Ontario Ministry of the Environment (MOE) website. The Air Quality Index (AQI) network consists of 40 stations across Ontario that monitor concentrations of up to six pollutants on an hourly basis. The purpose of the study was to examine ambient air quality trends from 2003 to 2012 by generating prediction surfaces using the ordinary kriging spatial interpolation technique. Average O_3 and $PM_{2.5}$ levels for each year as well as maximum pollutant concentrations for the lowest and the highest year for each contaminant were produced. Ozone is created when volatile organic compounds (VOCs) and nitrogen oxides (NO_xs) react in sunlight. Fine particulate matter is primarily released by transportation, residential and industrial processes and can cause severe cardiopulmonary damage and has been attributed to the development of diabetes. The results show that average ozone levels increased since 2003, while average fine particulate matter levels decreased. Also, the maximum concentrations per year for both contaminants decreased significantly. This indicates that ozone is a continuing problem for Ontario, but fine particulate matter has been greatly reduced and air quality has generally improved.

Acknowledgements

I would like to thank my supervisor Dr. K. Wayne Forsythe for his guidance and expertise in aiding me to complete this major research paper.

Table of Contents

Author's Declaration for Electronic Submission of a MRP ii
Abstract iii
Acknowledgements iv
Table of Contents v
List of Figures viii
List of Acronyms ix
CHAPTER 1: Introduction 1
1.1 Ozone (O_3) and Fine Particulate Matter ($PM_{2.5}$) 2
1.2 Ordinary Kriging Spatial Interpolation 3
1.3 Research Objectives 3
1.4 Major Research Paper Structure 4
CHAPTER 2: Literature Review 5
2.1 Air Pollution in Ontario 5
2.2 Trans-Boundary Air Pollution 6
2.3 Ground Level Ozone (O_3) 7
2.4 Fine Particulate Matter ($PM_{2.5}$) 8
2.5 Kriging 9
2.6 Pollutant Standards 10
CHAPTER 3: Manuscript 13
3.1 Abstract 13
3.2 Introduction 14
Ozone (O_3) 14
Fine Particulate Matter ($PM_{2.5}$) 15
Canada-Wide Standards (CWSs) and Ontario's Ambient Air Quality Criteria (AAQC) 16
Study Area 16
3.3 Data Collection 17
3.4 Methods 18
3.5 Results 20

Ozone (O_3) 20
Fine Particulate Matter ($PM_{2.5}$) 34
3.6 Discussion 48
Ozone 48
Fine Particulate Matter 49
3.7 Conclusion 52
CHAPTER 4: Recommendations and Future Research 53
REFERENCES 55

List of Tables

Table 3.5.1. Ordinary kriging average ozone statistics 22
Table 3.5.2. Ordinary kriging maximum ozone statistics 32
Table 3.5.3. Ordinary kriging average fine particulate matter statistics 37
Table 3.5.4. Ordinary kriging maximum fine particulate matter statistics 46

List of Figures

Figure 3.2.1. The ambient air quality monitoring network consists of 40 Air Quality Index (AQI) stations across the province 17
Figure 3.5.1. Maximum ozone levels 20
Figure 3.5.2. Average ozone levels 21
Figure 3.5.3. Average hours exceeding the Ontario AAQC 22
Figure 3.5.4. 2003 ordinary kriging ozone concentrations 23
Figure 3.5.5. 2004 ordinary kriging ozone concentrations 24
Figure 3.5.6. 2005 ordinary kriging ozone concentrations 25
Figure 3.5.7. 2006 ordinary kriging ozone concentrations 26
Figure 3.5.8. 2007 ordinary kriging ozone concentrations 27
Figure 3.5.9. 2008 ordinary kriging ozone concentrations 28
Figure 3.5.10. 2009 ordinary kriging ozone concentrations 29
Figure 3.5.11. 2010 ordinary kriging ozone concentrations 30
Figure 3.5.12. 2011 ordinary kriging ozone concentrations 31
Figure 3.5.13. 2012 ordinary kriging ozone concentrations 32
Figure 3.5.14. 2003 ordinary kriging maximum ozone concentrations 33
Figure 3.5.15. 2011 ordinary kriging maximum ozone concentrations 34
Figure 3.5.16. Maximum fine particulate matter levels 35
Figure 3.5.17. Average fine particulate matter levels 35
Figure 3.5.18. Average days exceeding the CWS 36
Figure 3.5.19. 2003 ordinary kriging fine particulate matter concentrations 37
Figure 3.5.20. 2004 ordinary kriging fine particulate matter concentrations 38
Figure 3.5.21. 2005 ordinary kriging fine particulate matter concentrations 39
Figure 3.5.22. 2006 ordinary kriging fine particulate matter concentrations 40
Figure 3.5.23. 2007 ordinary kriging fine particulate matter concentrations 41
Figure 3.5.24. 2008 ordinary kriging fine particulate matter concentrations 42
Figure 3.5.25. 2009 ordinary kriging fine particulate matter concentrations 43
Figure 3.5.26. 2010 ordinary kriging fine particulate matter concentrations 44
Figure 3.5.27. 2011 ordinary kriging fine particulate matter concentrations 45
Figure 3.5.28. 2012 ordinary kriging fine particulate matter concentrations 46
Figure 3.5.29. 2005 ordinary kriging maximum fine particulate matter concentrations .. 47
Figure 3.5.30. 2012 ordinary kriging maximum fine particulate matter concentrations .. 48

List of Acronyms

$\mu g/m^3$ - Micrograms per Cubic Metre

µm - Microns

AAQC - Ambient Air Quality Criteria

AQI - Air Quality Index

ASE - Average Standard Error

CCME - Canadian Council of Ministers of the Environment

CWS - Canada-Wide Standard

LOAEL - Lowest Observed Adverse Effect Level

MOE - Ontario Ministry of the Environment

NO_x - Nitrogen Oxides

NOAEL - No Observed Adverse Effects Level

O_3 - Ground-Level Ozone

PEL - Probable Effect Level

PM - Particulate Matter

$PM_{2.5}$ - Fine Particulate Matter (with a diameter of 2.5 µm or less)

ppb - parts per billion

RMSPE - Root-Mean Square Prediction Error

SRMSPE - Standardized Root-Mean Square Prediction Error

TEL - Threshold Effect Level

VOC - Volatile Organic Compound

WHO - World Health Organization

CHAPTER 1: Introduction

Air pollution is an issue of contention at all levels of government, all geographic scales, and has stakeholders in countless sectors of society. Poor air quality not only has negative effects on human health, but, as outlined by Ontario's Ambient Air Quality Criteria (AAQC), can have negative effects on odour, vegetation, soiling, visibility, or corrosion, depending on the contaminant (AAQC, 2012). Therefore, it is not a small scale issue that affects a particular group or sector, but one that spans many areas.

Ontario and more specifically southern Ontario, is dominated by major urban centres such as Toronto, London, Hamilton, and Windsor. According to 2010 estimates from the Ontario Ministry of the Environment (MOE), emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_xs) (the main precursors to ozone) were 36% and 71% respectively by transportation, and 53% and 21% respectively by industrial processes (MOE, 2013a). Considering major cities have the most automobile traffic and high levels of industrial activity, these are areas of concern for air pollution. It is slightly different for fine particulate matter, as the main emitters are residential (39%), transportation (24%) and industrial processes (30%).

Another reason southern Ontario is an area of concern for air pollution is its proximity to the United States border. According to Miller et al. (2010), over half of the air coming into Windsor, Ontario was from the United States over 48 hours, while that number climbed to over 80% when examining some 24 hour trajectories. In accordance with this reality, the Canadian Council of Ministers of the Environment (CCME) has adopted

regulations and provisions concerning trans-boundary air pollution, as well as creating goals to be met by both sides (CCME, 2012).

One of the major concerns in Ontario is the level of smog. It results from the combination of multiple contaminants and meteorological factors, and can lead to reduced visibility and adverse health effects in humans and vegetation. Smog has become such a major issue in Ontario that the MOE has developed a smog alert network, informing the province when it is bad enough to cause serious health problems (MOE, 2013c), and some areas such as Windsor have provided free public transit on days when the smog reaches dangerous levels (City of Windsor, 2003). Two of the main ingredients of smog are ground-level ozone and fine particulate matter.

1.1 Ozone (O_3) and Fine Particulate Matter ($PM_{2.5}$)

Both ozone and fine particulate matter are recognized as hazards to human health. There are of particular concern because they are the main contributors to the level of smog at any given time. Ozone is produced when VOCs and NO_xs react in sunlight, and is therefore most prominent on sunny summer days (MOE, 2013a). Ozone is not produced directly like other chemicals, and is dependent on precursors for its creation. Fine particulate matter, is produced directly, most commonly as a result of anthropogenic activity (93% is emitted by residential, transportation and industrial sectors) (MOE, 2013a). As explained previously, both pollutants react to form smog, a concern that is of high importance to the Province of Ontario.

1.2 Ordinary Kriging Spatial Interpolation

Ordinary kriging is a spatial interpolation technique that allows for the prediction of values at unsampled locations. It produces a continuous coverage surface for an area based on observations at known points. Ordinary kriging possesses an advantage over other spatial interpolation techniques in that it can be statistically validated (Gawedzki and Forsythe, 2012). Another advantage of kriging is that it does not assume a normal distribution of the data. However, if the data are normally distributed, kriging is the best unbiased predictor (Negreiros et al., 2010). The MOE AQI network measures air quality and pollutant concentrations at 40 points across the province, so the use of ordinary kriging would allow for the creation of a prediction surface that facilitates better interpretation of air quality trends.

1.3 Research Objectives

The research objectives for this paper can be divided into four sections:

1. To assess concentrations of ozone and fine particulate matter in ambient air in Ontario from 2003 to 2012.
2. To quantify the change that has occurred in that time frame.
3. To examine contaminant levels and compare them to the Canada-Wide Standard (CWS) for fine particulate matter and the AAQC for ozone for each year, and determine trends during the time period.
4. To assess the effectiveness of ordinary kriging for generating ambient pollutant concentrations.

1.4 Major Research Paper Structure

The structure of this paper is presented in a manuscript format. The first chapter provides a general introduction to the research and the objectives of the paper. Chapter 2 presents a literature review pertinent to the scope of the research project. Chapter 3 is organised as a standalone manuscript. It consists of typical journal sections including: abstract, introduction, data collection, methodology, results, discussion, and conclusion. Chapter 4 concludes the paper, briefly outlining recommendations for future research.

CHAPTER 2: Literature Review

2.1 Air Pollution in Ontario

Air pollution is a subject of concern that has been around for many years, but has increased in importance with other societal changes, the most notable of which is population growth. The drastic increase in population in past decades has seen several parallels, such as growth in population density, industry, and the number of automobiles on the road, all of which contribute to the reduction of air quality. As can be predicted, areas that have the highest population density can have the highest levels of industrial activity and the highest number of automobiles, and are consequently areas of concern for air quality and ambient pollutant levels (Kantor et al., 2010). As noted by Khan et al. (2010), the deterioration of urban air quality is causing increasing concern, and can have detrimental effects on human health.

Ontario is Canada's most populous province, and home to some of its largest cities. The Ontario Ministry of the Environment (MOE) monitors ambient air pollution by taking measurements of pollutant levels on an hourly basis at 40 stations province wide. Each station measures up to six pollutants, including ozone, fine particulate matter, nitrogen dioxide, carbon monoxide, sulphur dioxide, and total reduced sulphur compounds. As a result of its population, and concurrent level of industry and automobile use, southern Ontario has the highest levels of air pollution in Canada (Miller and Watmough, 2009). Cities have the largest impacts on air pollution and the highest levels of air pollution due to their natural concentration of humans, materials and activities (Fenger, 1999).

The particular health effects of ozone and fine particulate matter will be examined in subsequent sections, but in Toronto, general air pollution has been the cause of serious health effects. In a study by Kantor et al. (2010), province-wide emissions for Ontario were studied, as well as urban air pollution in the City of Toronto. The authors focused on Ontario and Toronto because the large population would involve a great number of individuals being affected. In addition, the study area was chosen because of increased concern due to the estimated fatalities resulting from air pollution. According to the research, approximately 1,700 deaths per year are a direct result of urban air pollution, and 5,800 deaths occur throughout the Province of Ontario (Kantor et al., 2010).

Not only is Ontario adversely impacted by air pollution in regards to human and environmental health, but in a financial aspect as well. It has been found that the impacts of fine particulate matter and ozone total approximately 9.6 billion dollars in health and environmental damages every year (Tian and Chen, 2007). The authors also found that areas of Southern Ontario exhibit the highest levels of acidic deposition, ozone, fine particulate matter and hazardous pollutants in eastern Canada.

2.2 Trans-Boundary Air Pollution

Unfortunately, despite the acts and measures in place by the Ontario Ministry of the Environment and Environment Canada to improve air quality and reduce pollutant concentrations, the source of a large percentage of air pollution is not Ontario, but the United States. Especially in south-western Ontario, trans-boundary air pollution contributes to lower air quality due to the proximity of the border. Miller et al. (2010) examined trans-boundary pollution in Windsor, Ontario. It was found that 48 hour back trajectories showed that 53 to 55 percent of air masses arriving in the city were from the

United States, while examining the 24 hour back trajectories showed that 81 to 82 percent of air originated across the border. The difference was due to air patterns, and how the source of air masses differs when comparing back trajectories spanning one day versus two days. The study was conducted for two years, 2008 and 2009, and little inter-annual variability was found (Miller et al., 2010). In another study by Galvez (2007), a model was created to examine trans-boundary air pollution in southern Ontario using 72 hour back trajectories. He found that approximately 60 percent of ozone is due to anthropogenic emission release from the United States during smog episodes. Therefore it is difficult to regulate air pollution from within Ontario as trans-boundary pollution accounts for more than half of the air pollution in the province.

2.3 Ground Level Ozone (O_3)

Ozone (O_3) has been identified as one of the pollutants of concern when dealing with air pollution, and is a major component associated with smog. Ozone is created when nitrogen oxides (NO_X) and volatile organic compounds (VOCs) interact in sunlight (Ozbay et al., 2011). Ozone is not emitted directly into the atmosphere, but relies on other meteorological factors and chemical emissions for its formation (MOE, 2013a). For example, when detailing the levels of ozone, the MOE does not show the sources of ozone itself, but the major emissions by sector of VOCs and NO_xs, as ozone is created with these two contaminants as precursors. Since ozone does not only require VOCs and NO_xs to form but sunlight and heat as well, high levels of ground-level ozone have generally been found in the summer months (MOE, 2013a). Despite cities having the highest levels of air pollution, they are generally found to have the lowest average ozone

levels. This is because when ozone reacts with NO_x, levels of which are generally highest in large cities, overall ozone levels are reduced (MOE, 2013a).

Ozone has been known as a human and environmental concern for many years, and has thus been studied extensively in the literature. Joseph et al. (2013) recognize the extensive research of the health effects of ozone, and agree that estimation of pollutant levels, though difficult due to the usual sparse distribution within air monitoring networks, is important and necessary for planning and policy making. The authors applied different spatial interpolation techniques (simple averaging, nearest neighbour, inverse distance weighting, ordinary kriging, and universal kriging) on two datasets: Houston, Texas (up to 42 air monitoring stations) and Los Angeles, California (up to 27 air monitoring stations) using the three highest maximum eight hour ozone concentrations for each area. It was found that ordinary kriging yielded superior results, along with reliable confidence intervals (Joseph et al., 2013). Hooyberghs et al. (2006) also used spatial interpolation to attempt to quantify ozone concentrations in Belgium. Comparing inverse distance weighting and ordinary kriging, the authors also found that ordinary kriging produced superior results, outperforming the other models.

2.4 Fine Particulate Matter ($PM_{2.5}$)

Fine particulate matter is of particular concern due to its ability to be inhaled deeply into the lungs (Khan et al., 2010). The naming of $PM_{2.5}$ derives from the particle size in the air; fine particulate matter has particles with a diameter of 2.5 microns (μm) or less. When inhaled, the particles can cause or aggravate serious health issues, such as cardiopulmonary and lung cancer, as well as death; Pope et al. (2002) found that an increase of 10 $\mu g/m^3$ in $PM_{2.5}$ concentrations resulted in an approximate 6% increase in

cardiopulmonary mortality and an 8% increase in lung cancer mortality. Additionally, in a study by Chen et al. (2013), based on the hypothesis that fine particulate matter can induce insulin resistance, the risk of diabetes in relation to long term exposure to fine particulate matter was examined. Based on the findings, the authors suggest that long term exposure can contribute to the development of diabetes (Chen et al., 2013). Kantor et al. (2010) also note that $PM_{2.5}$ is generally considered to be the greatest risk to human health due to its ability to enter the lungs and cause irritation and further damage.

Yu (2010) recognizes the importance of spatial information of these pollutants for epidemiological research to further understand the health effects of fine particulate matter. The author used principal component analysis (PCA) to examine $PM_{2.5}$ trends in Taiwan, utilizing daily mean concentrations from 2006 to 2008. The findings indicated that concentrations were largely the highest in winter and the lowest in summer. Lee et al. (2012) examined $PM_{2.5}$ concentrations across the continental United States using a combination of remote sensing and a geostatistical kriging model. The authors used monthly pollutant concentration averages as their aggregations, and found that within approximately 100 metres of a monitoring station, kriging outperformed their remote sensing methods.

2.5 Kriging

Kriging is a method of spatial interpolation that generates an estimated prediction surface based on measurements at discrete points. Therefore, it is a valuable technique especially when dealing with environmental data, as they are almost always measured at discrete locations (Kumar et al., 2007) and cannot feasibly be measured continuously. This is

advantageous because kriging allows for the prediction of data values at unsampled locations (Shad et al., 2009).

Different methods of kriging have been used in the literature to assess discrete environmental data and create prediction surfaces. Forsythe et al. (2010) used ordinary kriging to interpolate zinc concentrations in Lake Ontario, and compared the prediction surfaces generated for historical and contemporary data to assess change that had occurred. Beelen et al. (2009) compared ordinary kriging, universal kriging, and regression models to predict air pollution across the European Union, and mention that both kriging techniques have been previously used to successfully model ozone and particulates at the local scale. From the results, the authors note that the kriging techniques performed substantially better when measuring PM_{10}, and ordinary kriging performed better than the regression at an urban scale. In the literature, it was found that ordinary kriging is a superior method for predicting ambient air pollution concentrations (Beelen et al., 2009; Hooyberghs et al., 2006; Joseph et al., 2013).

2.6 Pollutant Standards

In response to the increasing issue of air pollution, emissions standards have been developed in many countries and specific pollutant concentration goals have been set (Barton, 2008; WHO, 2006). However, since there is variation not simply at a global level, but at a regional and even local level, it is difficult to apply universal standards to any particular place. In 2006, the World Health Organization (WHO) published an update detailing air quality guidelines (WHO, 2006). For $PM_{2.5}$, a standard of 10 $\mu g/m^3$ was set as an annual mean, with 25 $\mu g/m^3$ as a 24 hour mean. For ozone, the standard was set at 100 $\mu g/m^3$ for an eight hour mean (WHO, 2006). In Canada, the Canadian

Council of Ministers and Environment (CCME), a joint framework involving federal, provincial, and territorial governments, are responsible for taking action on many of the modern air pollution problems being faced (Barton, 2008). In June of 2000, this group signed the Canada-wide Standards (CWSs) for two particularly dangerous pollutants: Particulate Matter (PM) and Ozone (O_3). The goal was to commit governments to significantly reduce the concentrations of these pollutants, as they have been found to be the main ingredients of smog and produce serious health effects on human populations. The CWS for PM is focused on fine particulate matter, or $PM_{2.5}$, and is expected to be 30 $\mu g/m^3$ averaged over 24 hours, while the CWS for ozone is expected to be 65 ppb averaged over eight hours (Barton, 2008).

Other standards have been developed for toxic chemicals and contaminants, and extensive research was done to obtain levels for ozone and fine particulate matter. The CCME has developed the Threshold Effect Level (TEL) and the Probable Effect Level (PEL) for many contaminants. The TEL is the level of contamination concentrations below which adverse biological effects are expected to occur rarely, while the PEL is the level of contamination concentrations above which adverse biological effects are expected to occur frequently (Gawedzki and Forsythe, 2012). Other measures that have been developed for some toxic chemicals include the No Observed Adverse Effects Level (NOAEL) and the Lowest Observed Adverse Effect Level (LOAEL). The NOAEL represents the highest level of the substance below which there are no adverse effects, while the LOAEL represents the lowest level at which there are observed adverse effects. However, there is no threshold for the health effects of ozone and particulate matter, and the above measures have not been found useful for setting standards (NEPC, 2010).

In addition to the CWSs, the Province of Ontario has another set of standards known as the Ambient Air Quality Criteria (AAQC). Developed by the MOE, the AAQC presents desirable concentrations of over 300 ambient air pollutants based on factors such as health, odour, vegetation, soiling, visibility, corrosion and others (AAQC, 2012). The AAQC, since it was developed at the provincial level, is thus a better set of guidelines to follow. The AAQC for ozone, unlike the CWS, is measured over one hour rather than eight, and is set at 80 parts per billion (ppb), rather than 65. There is no AAQC for fine particulate matter, as the MOE follows the CWS. The AAQC for ozone and the CWS for fine particulate matter were used in this study.

The AAQC for ozone and the CWS for fine particulate matter have been used in the literature, albeit not extensively. Geddes et al. (2009) conducted a study to examine nitrogen oxides, VOCs and ozone in Toronto, Ontario, Canada. The authors reference the CWSs for ozone and mention the provision of trans-boundary pollution put forward by the CCME, and how this is affecting Toronto and other areas of Ontario near the United States border. However, the MOE Air Quality Report uses these measures as benchmarks to determine the state of air quality in any particular year.

CHAPTER 3: Manuscript

USING ORDINARY KRIGING TO EXAMINE AMBIENT CONCENTRATIONS OF OZONE (O_3) AND FINE PARTICULATE MATTER ($PM_{2.5}$) IN ONTARIO, CANADA, 2003 – 2012

3.1 Abstract

Ambient concentrations of ozone (O_3) and fine particulate matter ($PM_{2.5}$) were analyzed for the period of 2003 to 2012 in Ontario, Canada. Ontario is Canada's most populous province, and consequently has the highest levels of automobile use and industrial activity, both of which play a major role in the level of air pollution. The southwestern part of Ontario is very urban, containing large population centres such as Toronto, Hamilton, London and Windsor. It has been recognized that urban areas produce the most air pollution, and will be more adversely affected by poor air quality. The data were collected by the Ontario Ministry of the Environment (MOE) Air Quality Index (AQI) monitoring network stations. Pollutant concentrations were collected on an hourly basis from 2003 to 2012. The purpose of this study was to analyze the concentration trends of each pollutant over the time period, and to use spatial interpolation techniques to generate spatial prediction surfaces for the province. Levels of ozone and fine particulate matter were then compared to the Canada-Wide Standard (CWS) for fine particulate matter and the Ambient Air Quality Criteria (AAQC) for ozone to determine trends. This could be used to facilitate environmental decision making and be corroborated with existing MOE air quality research. Ozone and fine particulate matter are the two main ingredients of smog, and both can have serious effects on human and vegetative health, odour, visibility, soiling and corrosion.

Keywords: Kriging, Ontario, Air Quality, Air Pollution, Ozone, Fine Particulate Matter

3.2 Introduction

Ontario is Canada's second largest province by area, and largest by population. It contains some of Canada's largest and most urban areas, such as Toronto, Windsor, Ottawa, and Hamilton. This also means that Ontario has the highest automobile use and some of the heaviest industrial activity in Canada. As Geddes et al. (2009) point out, vehicle registration in Ontario increased by 700,000 between 2000 and 2007). According to the Ontario Ministry of the Environment Air Quality Report 2011 (MOE, 2013a), automobile traffic is one of the main causes of air pollution; it accounts for the release of approximately 36 percent of volatile organic compounds (VOCs), 71 percent of nitrogen oxides, and 24 percent of fine particulate matter. As a result, it has been found that southern Ontario has the highest levels of air pollution in Canada (Miller and Watmough, 2009).

There are two contaminants that are especially concerning: ozone and fine particulate matter. They are the main ingredients of smog, a factor of utmost importance when considering air quality in Ontario, and both ozone and fine particulate matter have been found to cause serious health effects. Therefore to provide a detailed spatial analysis of each contaminant since 2003 would be greatly beneficial in understanding air quality trends and providing information to policy makers in Ontario.

Ozone (O_3)

Ground-level ozone is a contaminant of concern for the Province of Ontario. Naturally occurring stratospheric level ozone is beneficial to the environment, as it shields the Earth from ultraviolet radiation, but formation at ground level causes risks to human and

environmental health alike. Ozone is formed when VOCs and nitrogen oxides (NO_xs) react in direct sunlight, and is therefore most prominent on sunny summer days. Ozone has been recognized by the Ontario AAQC as a threat to human health, and desirable levels have been determined (AAQC, 2012). Tropospheric ozone, as it is also known, is a major concern for southern Ontario due to its effects on respiratory health and agricultural crops, along with its role in the formation of smog (Galvez, 2007).

Fine Particulate Matter ($PM_{2.5}$)

Fine particulate matter, the other main ingredient in the formation of smog, has a diameter of 2.5 µm or less. This classification is important, as the size of the particles relates to how dangerous the particulate matter is. Particulate matter (PM) has been studied extensively in the literature (Chen et al., 2013), and $PM_{2.5}$ is receiving more focus as the smaller particle size makes it easier for the contaminant to enter the lungs and damage health. According to Sharma and Maloo (2005), finer particulate matter has the strongest health effects. Williams (2008) also cites the World Health Organization (WHO) in concluding that there is now more reason to suggest that $PM_{2.5}$ is of greater concern than PM_{10} due to its fine fraction. Amatullah et al. (2012) studied different sizes of particulate matter and how this variability can have varying health effects on a human. They found that coarse ($PM_{2.5\text{-}10}$), fine ($PM_{0.15\text{-}2.5}$), and ultrafine ($PM_{0.2}$) particulate matter all adversely affect lung function and airway responsiveness. Also, it was found that coarse and fine particulate matter (such as present in Ontario) does most of the damage to health at the site where it is deposited in the airways (Amatullah et al., 2012).

Canada-Wide Standards (CWSs) and Ontario's Ambient Air Quality Criteria (AAQC)

Canada-Wide Standards (CWSs) were developed for many contaminants by the Canadian Council of Ministers of the Environment (CCME) in 2000 (CCME, 2013). These standards were developed to publish acceptable levels of the various contaminants, and also as goals for Canada as a whole to reach. For ozone, the CWS, expressed as an eight hour average, is 65 ppb, and for fine particulate matter, expressed as a 24 hour average, is 30 $\mu g/m^3$. However, there are also standards developed at the provincial level. The Ontario Ambient Air Quality Criteria (AAQC) details the desired levels of contaminants in ambient air in Ontario, and standards exist for over 300 contaminants. Among these is ozone, which, differing from the CWS for ozone, has an AAQC of 80 parts per billion (ppb) for one hour averages (AAQC, 2012). There is no AAQC for fine particulate matter, and Ontario uses the CWS as its standard.

Study Area

Ontario is Canada's largest province, and subsequently contains some of its largest and most industrial cities. Cities such as Toronto and Ottawa represent large populations, while others such as Windsor and Hamilton represent major industrial centres. Both of these factors are major considerations when examining air quality and pollution.

Since 2003, Ontario has experienced major population growth, along with an increase in automobile numbers and a growing industrial sector, all of which have an impact on air quality. According to the 2011 Ontario Air Quality Report, a large portion of air pollution can be attributed to automobiles and industrial activities (MOE, 2013a).

The study focuses on southern Ontario, as the Air Quality Index (AQI) station network of the MOE (see the next section) covers this area most extensively, and does not have any stations in the far northern areas of Ontario. Also, southern Ontario has a much higher population, automobile count, industrial activity and closer proximity to the United States border than the north, so it is of more concern when examining air pollution. Figure 3.2.1 shows the distribution of AQI stations throughout southern Ontario.

Figure 3.2.1. The ambient air quality monitoring network consists of 40 Air Quality Index (AQI) stations across the province

3.3 Data Collection

The data for this study were collected by the Ontario Ministry of the Environment from 2003 until 2012. Each AQI station measures hourly ambient concentrations of up to six pollutants, including ozone, fine particulate matter, nitrogen dioxide, carbon monoxide, sulphur dioxide, and total reduced sulphur compounds. Data for ozone and fine particulate matter were collected hourly at every station, from 2003 to 2012.

Since hourly data exist for every day in the 10 year period, they were aggregated before analysis based on the literature (Lee et al., 2012; Miller et al., 2010; MOE, 2013a), as

well as the CWSs for ozone and fine particulate matter. Both the WHO and the CCME recognized the same time frame for each pollutant; ozone was measured as an average over eight hours, while fine particulate matter was measured as an average over 24 hours. Also, to allow for more accurate surface predictions using ordinary kriging, the Thunder Bay AQI station was omitted from analysis. Due to the remote nature of this station, the prediction surface between it and the other AQI stations would not be accurate and the results would be skewed. Therefore, only 39 of the 40 stations were examined in this analysis, focusing on southern Ontario.

Only ozone and fine particulate matter that are measured at all of the AQI stations. The next most measured pollutant was nitrogen oxides (NO_x), which was measured at 36 of the 40 stations, while the other pollutants were measured sparsely throughout the AQI network. To include all of the pollutants would result in an incomplete and therefore inaccurate spatial analysis, so only the two pollutants with complete coverage were examined.

3.4 Methods

An ordinary kriging spatial interpolation method was used to assess air pollution in Ontario. One of the advantages of ordinary kriging over other spatial interpolation methods is the ability to statistically validate the prediction surface generated (Gawedzki and Forsythe, 2012). There are several statistics generated when the analysis is performed that can be compared to ideal numbers so the validity of the model can be judged. These statistics include the Mean Prediction Error (MPE), the Root-Mean Square Prediction Error (RMSPE), the Average Standard Error (ASE), and the Standardized Root-Mean Square Prediction Error (SRMSPE). To achieve acceptable results, the

statistics should be the following: the MPE should be as close to 0 as possible, the ASE should be as small as possible and below 20, and the SRMSPE should be as close to 1 as possible. If the SRMSPE is greater than 1, there is an underestimation of the variability of predictions; if it is less than 1, there is an overestimation of the variability (Forsythe and Marvin, 2009). Additionally, three models (Spherical, Exponential, and Gaussian) were compared based on previous ordinary kriging studies (Forsythe et al., 2010; Gawedzki and Forsythe, 2012) to determine which produced the best output statistics. These statistics and models were adhered to when choosing the best parameters for ordinary kriging.

For ozone, the maximum one hour average and the mean one hour average were applied to each station for each year. For fine particulate matter, the maximum 24 hour average and the mean 24 hour average were applied to each station for each year. These levels are both based on methods found in the literature (Hooyberghs, 2006; MOE, 2013a), as well as the CCME CWSs for fine particulate matter and the AAQC for ozone. To examine the distribution of contamination levels, the number of averages (one hour for ozone and 24 hours for fine particulate matter) that fell above and below the CWS and AAQC for each respective contaminant were examined as well. This gives good insight into how Ontario is exceeding, meeting, or falling below the CWSs for each year.

Python programming language scripts were written to parse the relevant data to apply to each station. The raw data came in a table format with hourly contaminant readings for each hour, day, station, and year. For ozone, the script pulled out the highest reading for each station year, as well as getting an average of all the values. For fine particulate

matter, the script returned the highest 24 hour average for each station from each year, as well as finding the average of all the 24 hour readings for each.

3.5 Results

Ozone (O_3)

Ozone is created from the interaction between sunlight and other chemicals such as VOCs and NO_xs. Therefore, it was anticipated that ground-level ozone levels would be the highest during the summer months as also stated in the Ontario Air Quality Report 2011 (MOE, 2013). This proved true when examining the findings, as nearly all of the maximum one hour averages were recorded between May and September.

Maximum ozone levels have been found to be fluctuating, but generally have declined since 2003. From 2003 to 2007, there are peaks and troughs, before dropping from 2008 to 2011. A slight spike was experienced in 2012. Figure 3.5.1 shows these results.

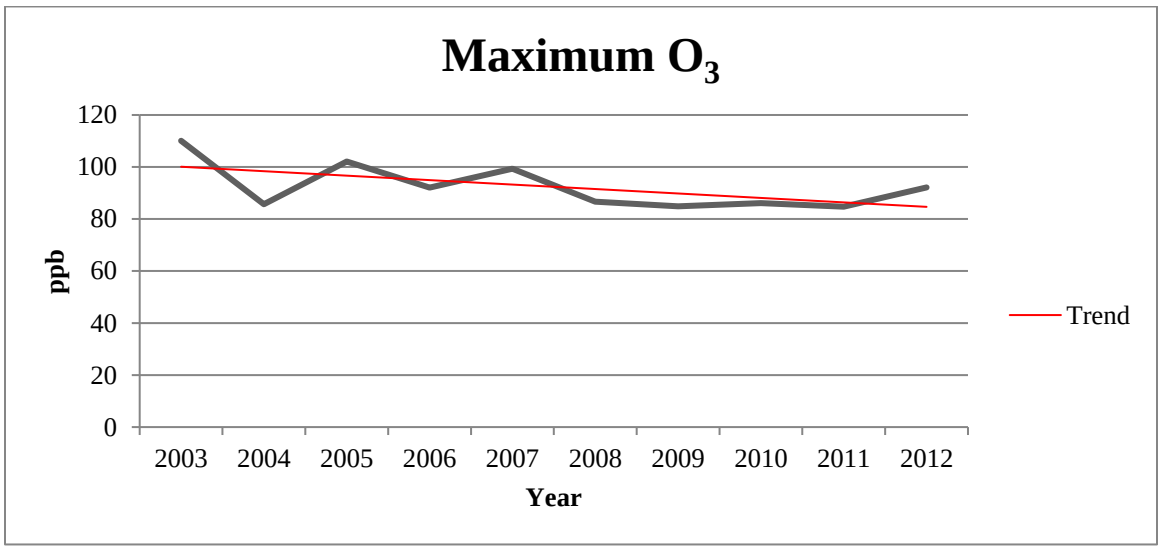

Figure 3.5.1. Maximum ozone levels trend

By contrast, the findings for the maximum ozone levels, average ozone levels for each year are steadily increasing. There are peaks and troughs throughout, but a general increasing trend can be seen. Figure 3.5.2 shows the results.

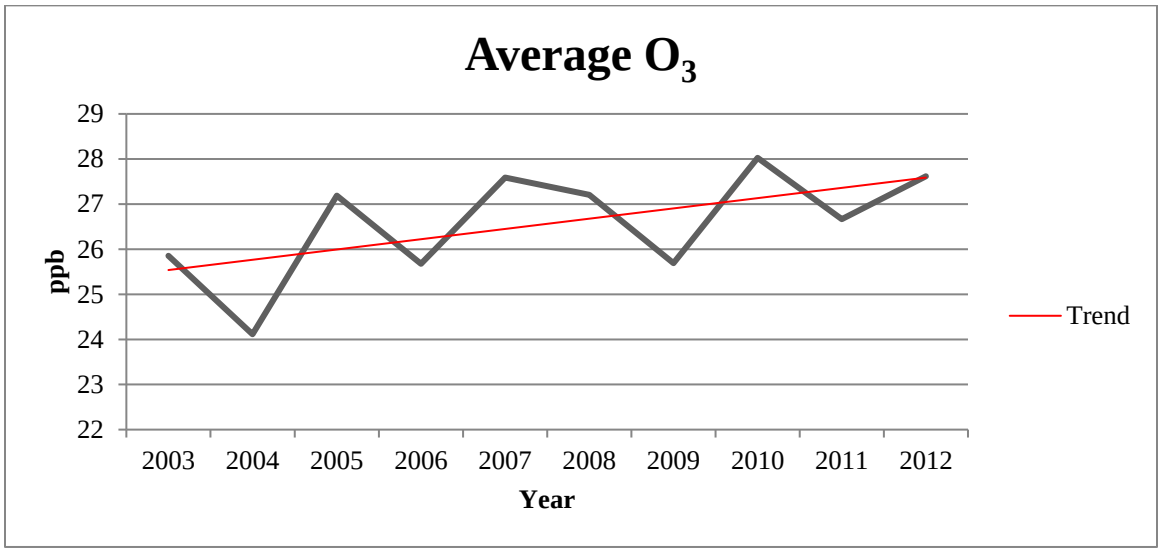

Figure 3.5.2. Average ozone levels trend

The average hours per AQI station exceeding the AAQC mirrors the maximum ozone levels. Figure 3.5.3, similar to Figure 3.5.1, shows the initial peaks and troughs before a large decline in 2008, also showing the spike in 2012. According to the MOE (2013c), 2012 appears to be an anomalous year in terms of smog alerts, as it had many more than previous years, as well as many more than 2013 (to date).

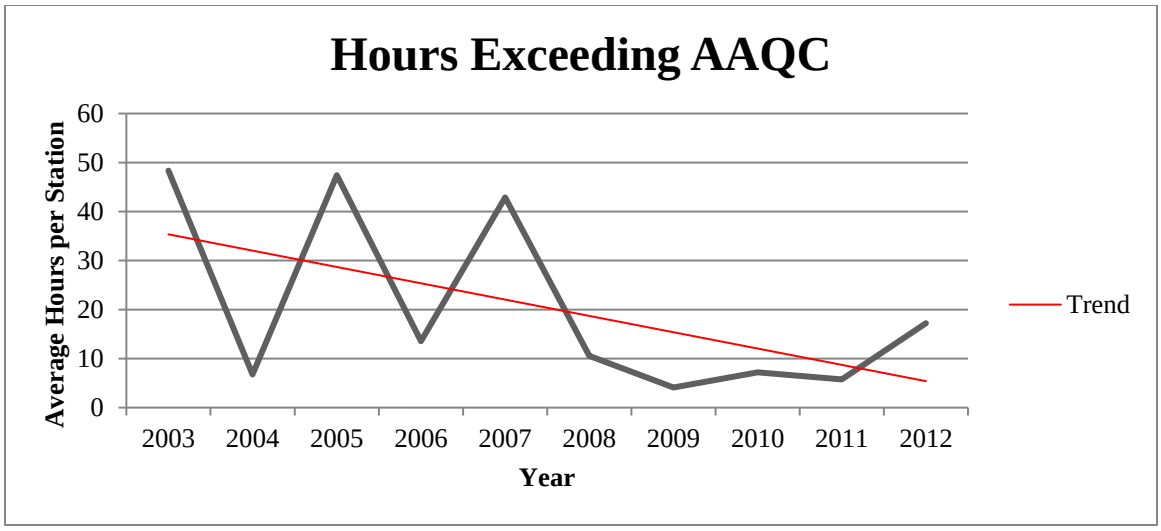

Figure 3.5.3. Average hours exceeding the Ontario AAQC

The ordinary kriging maps produced for average ozone for each year, beginning with Figure 3.5.4, were then examined. Generally, the trends shown in each map reflect the patterns shown in Figure 3.5.1. For all of the ordinary kriging prediction surfaces, the variability of predictions was slightly overestimated, as the Standardized Root-Mean-Square Prediction Error (SRMSPE) was always below 1 (Gawedzki and Forsythe, 2012). The statistics can be seen in Table 3.5.1.

Table 3.5.1. Ordinary kriging average ozone statistics

Year	Model	MPE	ASE	SRMSPE
2003	Spherical	0.010413022	3.542624196	0.99983069
2004	Spherical	-0.015705917	3.273941933	0.948989748
2005	Exponential	-0.028425011	3.183712899	0.944780088
2006	Exponential	-0.079917638	2.595975844	0.993361277
2007	Exponential	-0.067776642	2.850451305	0.973162918
2008	Exponential	0.015975435	2.82920142	0.946996013
2009	Exponential	0.029617946	2.428636948	0.956480634
2010	Exponential	0.04826623	2.793951335	0.947015023
2011	Exponential	-0.087178798	2.185501206	0.971187681
2012	Exponential	-0.035973304	2.226937451	0.970389625

Figure 3.5.4 shows ozone concentrations from 2003. One of the apparent trends is that concentrations of ozone appear to be the lowest around Toronto and Mississauga, and increase outward. All of the areas fell between 22 ppb and 30 ppb, with the highest concentrations appearing on the shores of Lake Huron and Georgian Bay. Since these represent averages for the year, no areas exceed the AAQC for ozone.

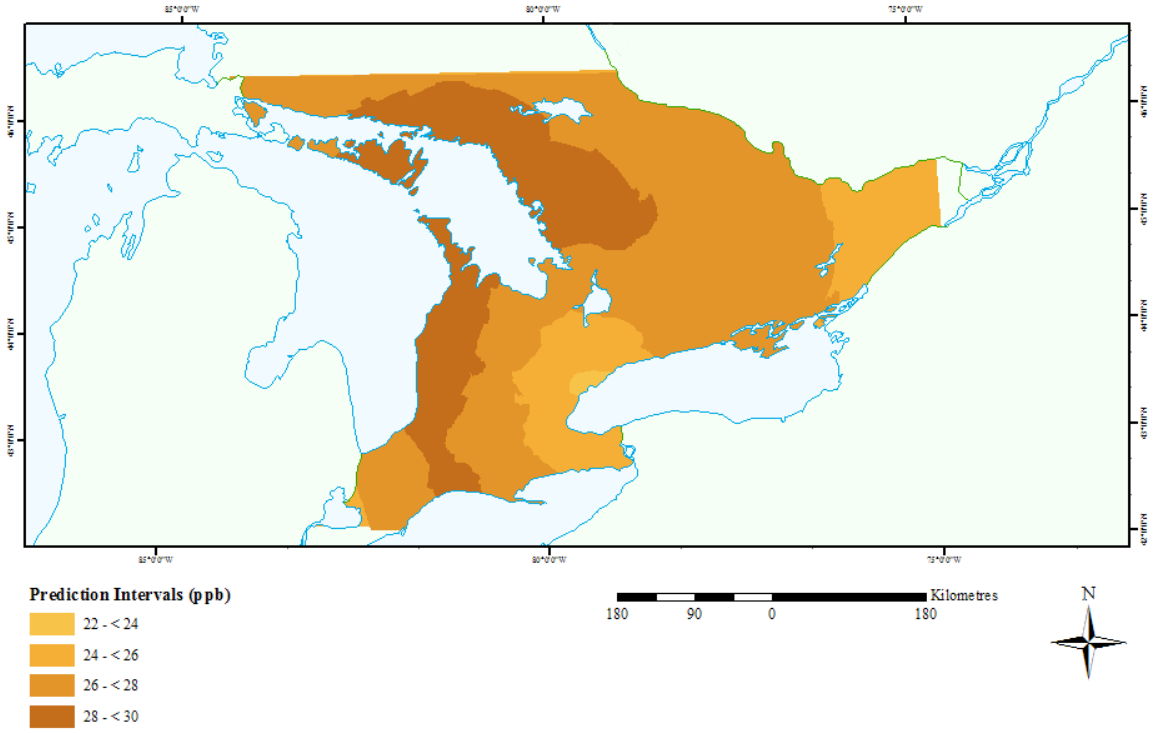

Figure 3.5.4. 2003 ordinary kriging ozone concentrations

Figure 3.5.5 shows that the results for 2004 ozone concentrations are very similar to those of 2003. When examining Figure 3.5.1, 2004 had a lower overall average than 2003. Though the increments are the same, a much larger area falls in the lowest prediction interval, and subsequently, a much smaller area falls into the highest prediction interval. The areal trends are similar to each other, with the Toronto and Golden Horseshoe area, along with Ottawa, experiencing the lowest concentrations of ground-level ozone, and the

higher concentrations appearing to the north near Georgian Bay. This can be explained by the reaction of ozone with nitrogen oxides by which ozone levels are actually reduced. Since NO_x levels are the highest in cities, ozone levels would subsequently be the lowest (MOE, 2013).

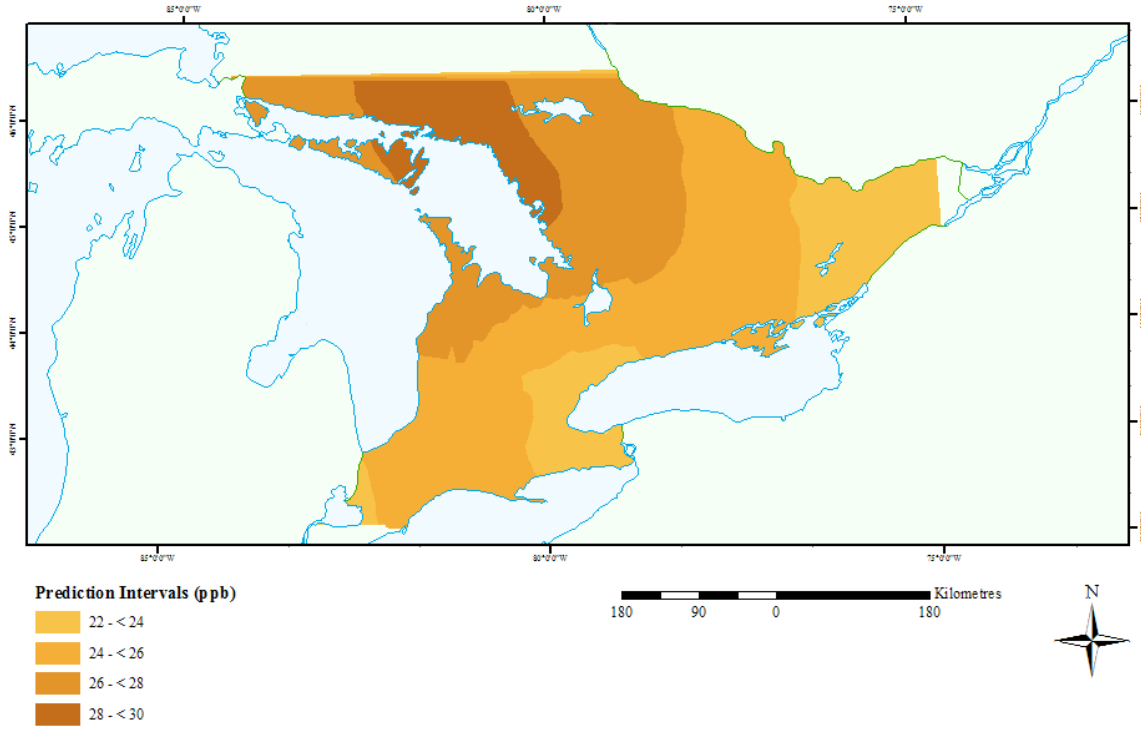

Figure 3.5.5. 2004 ordinary kriging ozone concentrations

Figure 3.5.6 again shows similar trends to the previous years. However, the pollution levels have increased, with the lowest being 24 to less than 26 ppb, and the highest being 30 to less than 32 ppb. These results are in accordance with Figure 3.5.1, which shows that average ozone levels increased in 2005 and were higher than those in 2003. Despite the difference in concentration levels, the trend is almost identical to the previous two years, showing increasing concentrations as distance increases from the larger cities such as Toronto and Ottawa. As explained for 2004, this can be attributed to the higher levels of NO_xs in large cities, resulting in the reduction of ozone concentrations.

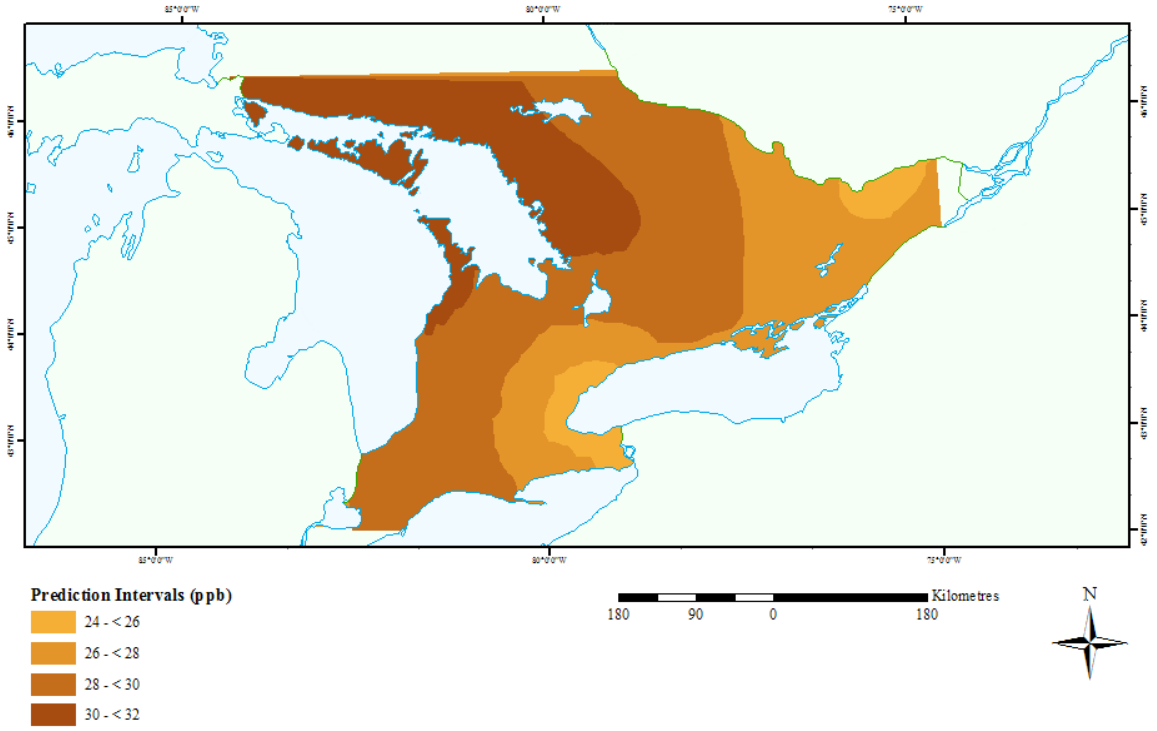

Figure 3.5.6. 2005 ordinary kriging ozone concentrations

The similarity in trends continues in 2006 as seen in Figure 3.5.7. Also, since 2005, ozone levels have gone down, and the prediction intervals have returned as they were for 2003 and 2004. It is the most similar to the 2004 ordinary kriging map, and this can be expected; according to Figure 3.5.2, both years have almost identical average ozone levels. Areas west of Toronto towards Windsor, however, now all fall below 28 ppb, whereas a length of area was predicted to have 28 ppb or higher in 2003.

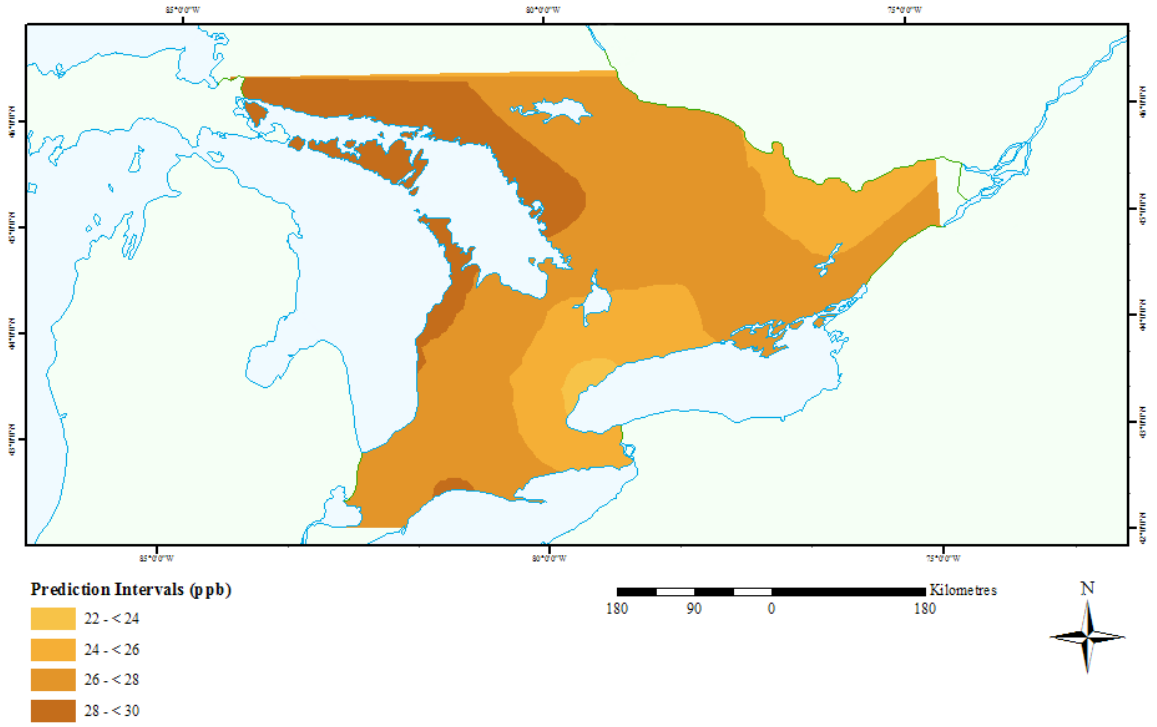

Figure 3.5.7. 2006 ordinary kriging ozone concentrations

The year 2007 shown in Figure 3.5.8 represents another increase in ozone concentrations, as can be seen in Figure 3.5.1, as well as looking at the prediction intervals, which have increased to the same levels as 2005. However, the similarity in trends for all years still exists. The area to the north near Georgian Bay no longer exhibits higher predicted concentrations, while the area around Kingston shows concentration levels greater than or equal to 30 ppb.

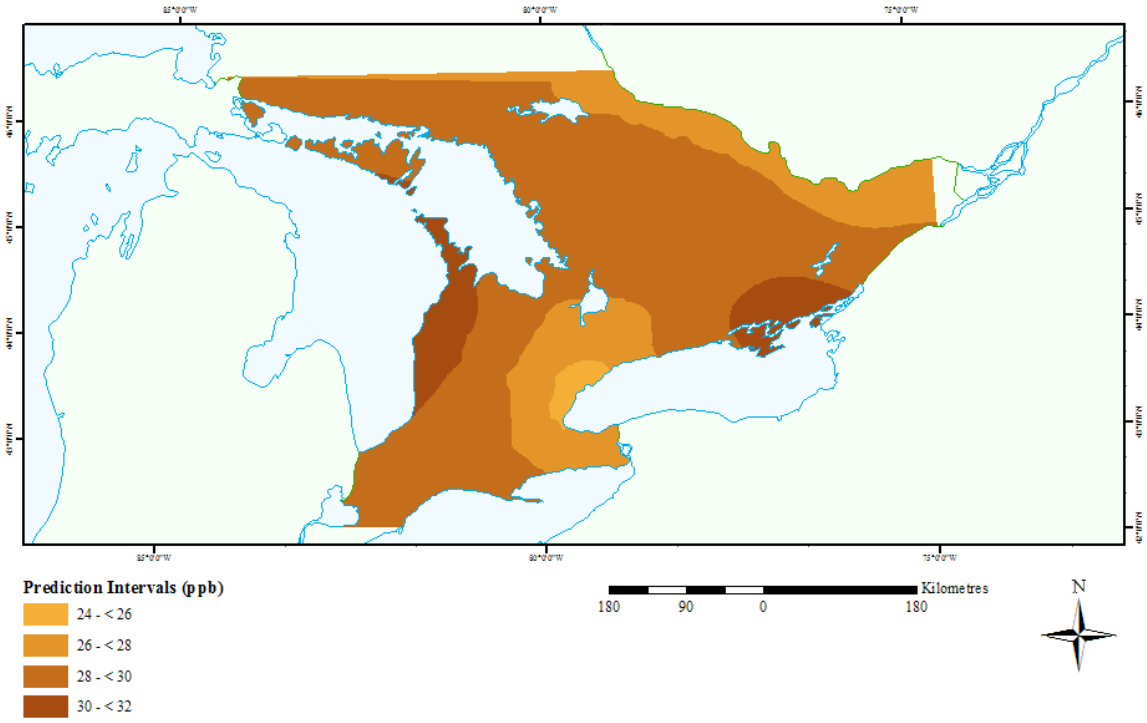

Figure 3.5.8. 2007 ordinary kriging ozone concentrations

Similar trends can be seen in 2008 in Figure 3.5.9, but the range of concentrations decreased. The lowest prediction intervals are the same as 2007, a peak year, but the highest prediction intervals are the same as the lower years. The Kingston area again shows higher ozone concentrations, and the lowest prediction area is again near Toronto and the surrounding area. More of the total area, however, falls into the second lowest prediction interval, showing improvement from the 2007 findings.

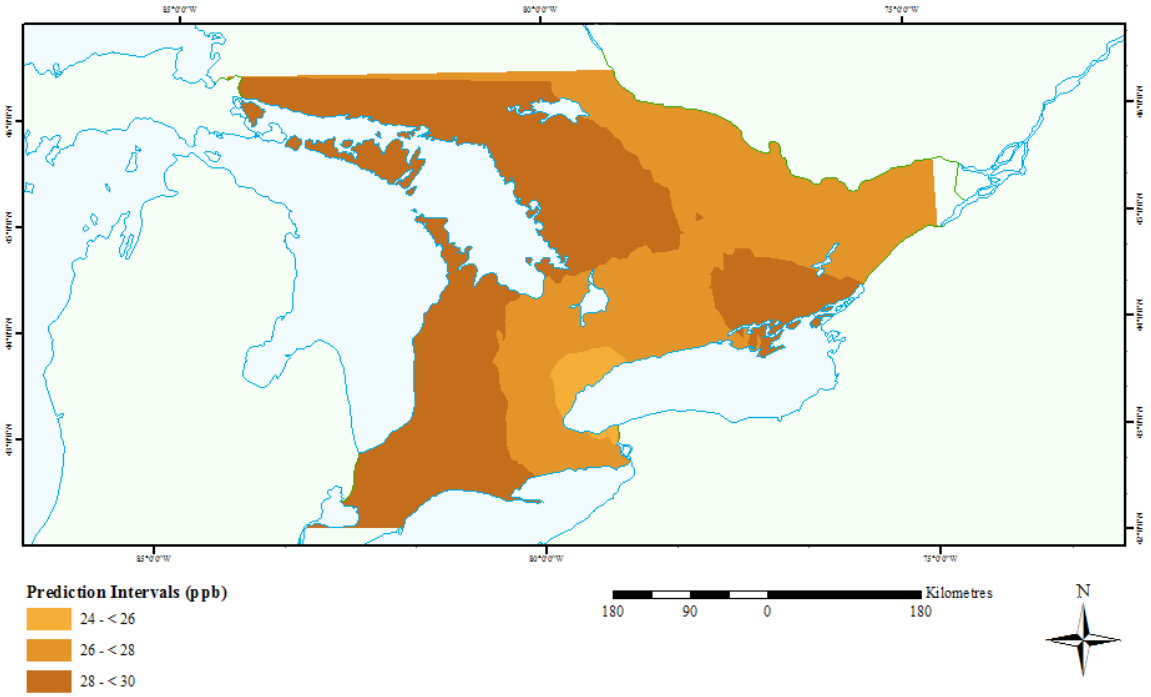

Figure 3.5.9. 2008 ordinary kriging ozone concentrations

The 2009 prediction surface in Figure 3.5.10 shows similarities to 2008 in terms of the prediction intervals, but overall shows lower concentrations. This parallels the findings in Figure 3.5.1, indicating another drop in average ozone concentrations. Though the concentration interval of 28 to less than 30 ppb is present on the map, it is only a miniscule area on the shore of Lake Huron. Again, the Toronto, Golden Horseshoe and Ottawa regions show the lowest predicted ozone concentrations, while most of the rest of the area falls in the 26 to less than 28 ppb category.

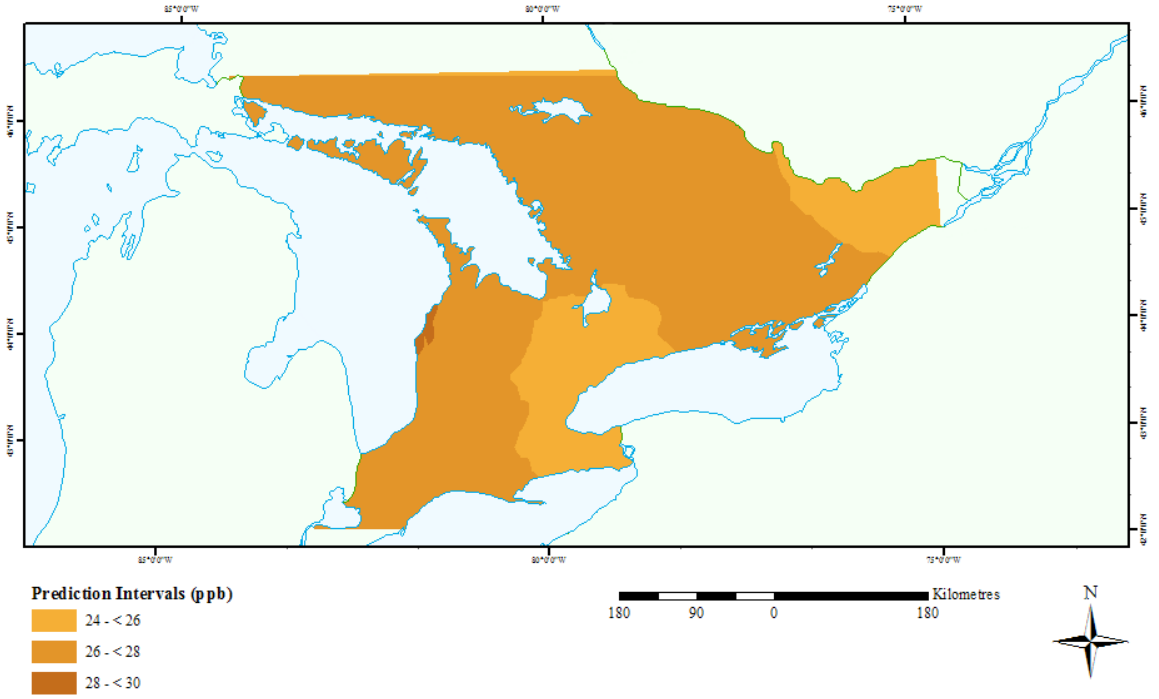

Figure 3.5.10. 2009 ordinary kriging ozone concentrations

Figure 3.5.11 shows similarities to 2009, with the exception that the ozone prediction concentrations are all higher. It also represents the year with the highest ozone concentrations for the time period. The entire area shows concentrations above 26 ppb, which had never occurred prior to 2010. There is also a large area to the west along the shore of Lake Huron that exhibits the highest concentrations of ground-level ozone.

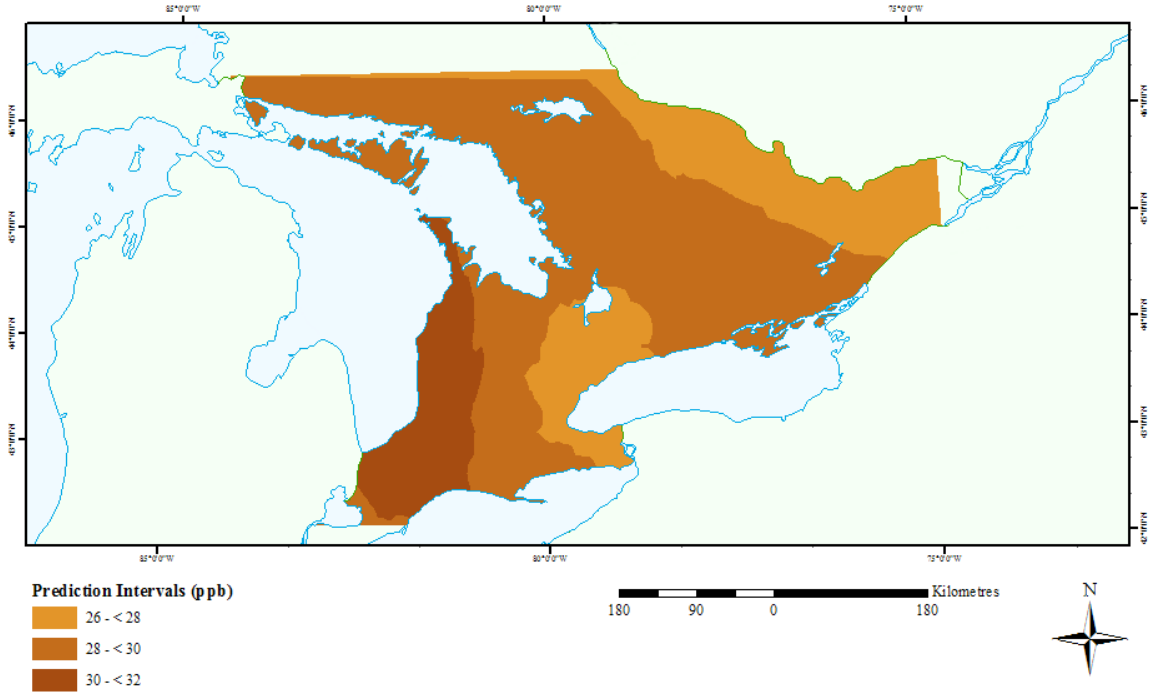

Figure 3.5.11. 2010 ordinary kriging ozone concentrations

The results for 2011 in Figure 3.5.12 show a general reduction in ozone levels across the study area. The Toronto and Ottawa regions were lower than 2010, as well as most of the surrounding area. The portion of the map that had been 30 ppb or above is now mostly below 30 ppb. The trend remains similar to all of the study years, with the big cities showing the lowest concentrations of ground-level ozone.

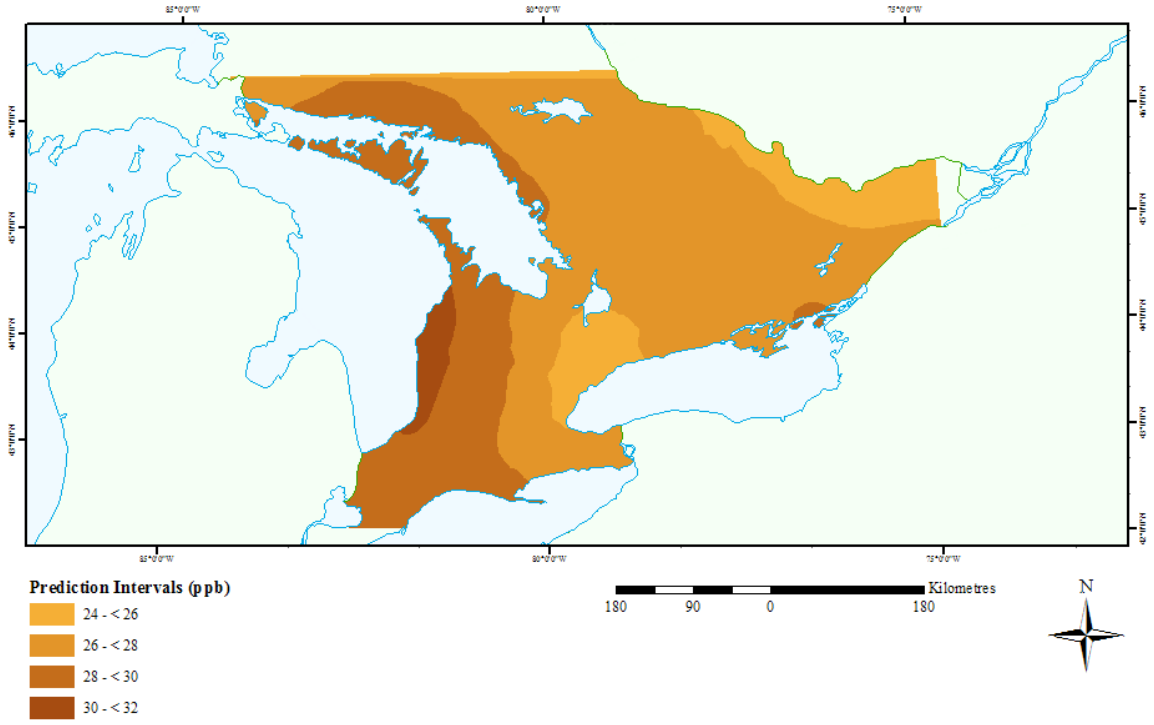

Figure 3.5.12. 2011 ordinary kriging ozone concentrations

Figure 3.5.13 shows an increase from 2011, and indeed has one of the highest ozone level averages according to Figure 3.5.2. Though similar in trend to 2011, no areas fall under 26 ppb, as in 2010. The area around Kingston again has higher predicted ozone concentrations, though the area is not as extreme as in 2010. The area that falls between 30 ppb and under 32 ppb is almost identical to that in 2010.

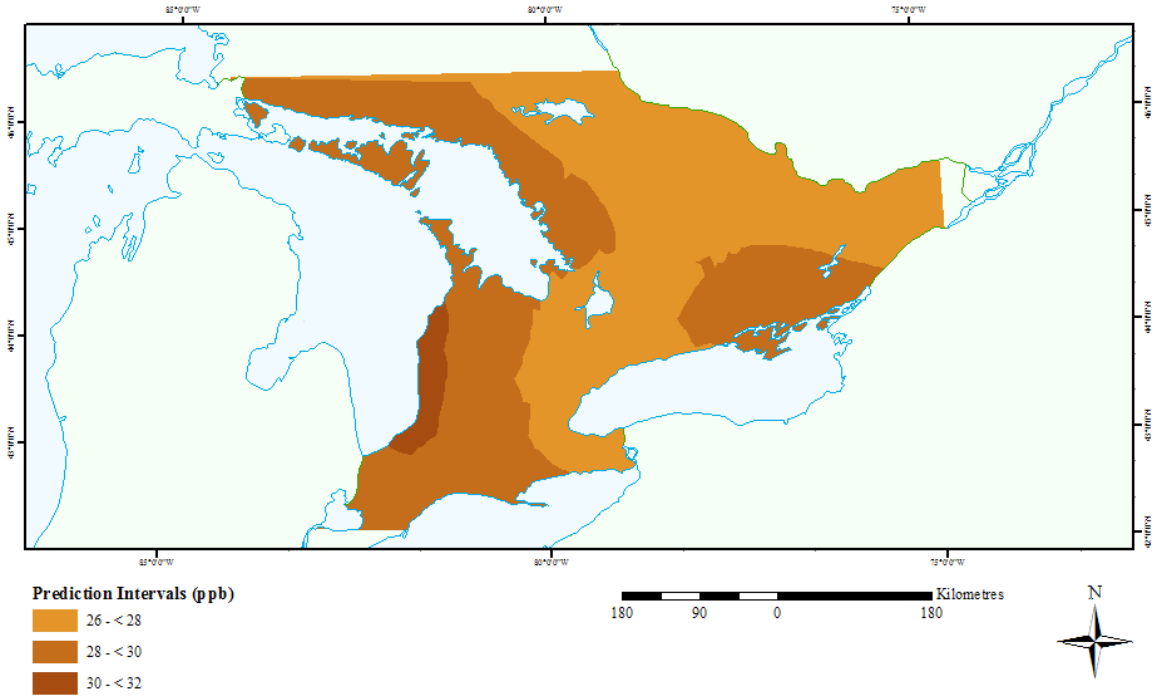

Figure 3.5.13. 2012 ordinary kriging ozone concentrations

Ordinary kriging maps were then produced for the maximum ozone readings from each station. Two maps were produced: one from the year with the highest maximum readings (2003) and one for the lowest readings (2011). Both the prediction surfaces slightly overestimated the variability of predictions with an SRMSPE below 1. The statistics can be seen in Table 3.5.2.

Table 3.5.2. Ordinary kriging maximum ozone statistics

Year	Model	MPE	ASE	SRMSPE
2003	Spherical	0.25476527	11.70531671	0.982511633
2011	Spherical	0.137377466	7.108358458	0.973711537

Maximum ozone levels in 2003, shown in Figure 3.5.14, all exceeded the AAQC for ozone. Every part of the interpolation surface has concentrations of at least 95 ppb, with areas around Kingston and Windsor reaching between 115 and 120 ppb.

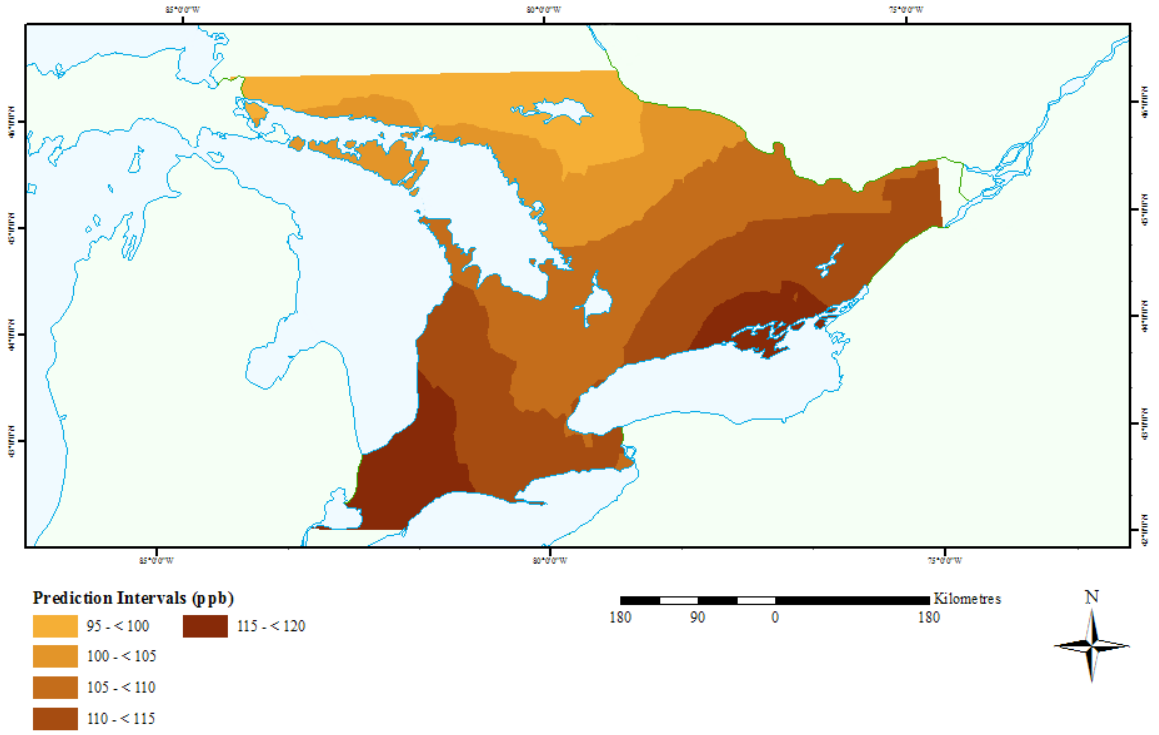

Figure 3.5.14. 2003 ordinary kriging maximum ozone concentrations

Figure 3.5.15 shows a drastic reduction in maximum ozone levels. Nearly the whole area has concentrations below the lowest area in 2003. Only a small area falls above 100 ppb, an area which had concentrations over 110 ppb in 2003. The AAQC of 80 ppb was represented as an isoline on the map to show the separation. Maximum ozone levels were so high in 2003 that the isoline could not be plotted on the map. The 2011 map (Figure 3.5.15) shows that a vast area in the north falls below the AAQC even during the hour in which ozone levels are the highest. According to the MOE (2013a), the reduction in ozone levels from 2003 to 2011 can be attributed to the progressive reduction in NO_x emissions in Canada and the United States, which also reduces the influence of transboundary pollution.

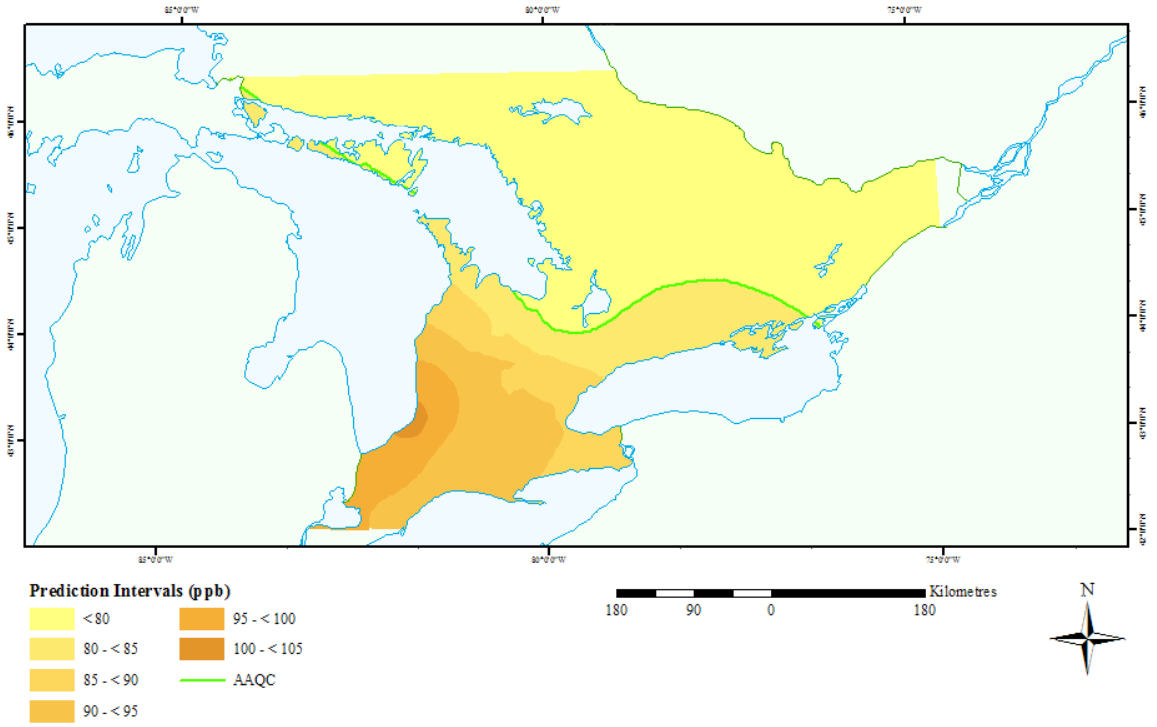

Figure 3.5.15. 2011 ordinary kriging maximum ozone concentrations

Fine Particulate Matter ($PM_{2.5}$)

Fine particulate matter, unlike ground-level ozone, does not rely on other chemicals or meteorological conditions for its creation, and so does not have a season or time of year in which it is particularly serious. Therefore, dates for which there is the maximum $PM_{2.5}$ reading are distributed throughout the year, and are not focused in the summer months.

All of the fine particulate matter findings are promising in the context of air quality in Ontario. Maximum $PM_{2.5}$, while fluctuating from 2003 to 2007, has experienced a steady decline since then, and has fallen to under 25 $\mu g/m^3$, which is not only a large decrease from the approximately 42.5 $\mu g/m^3$ it was in 2003, but also falls below the CWS. The results can be seen in Figure 3.5.16.

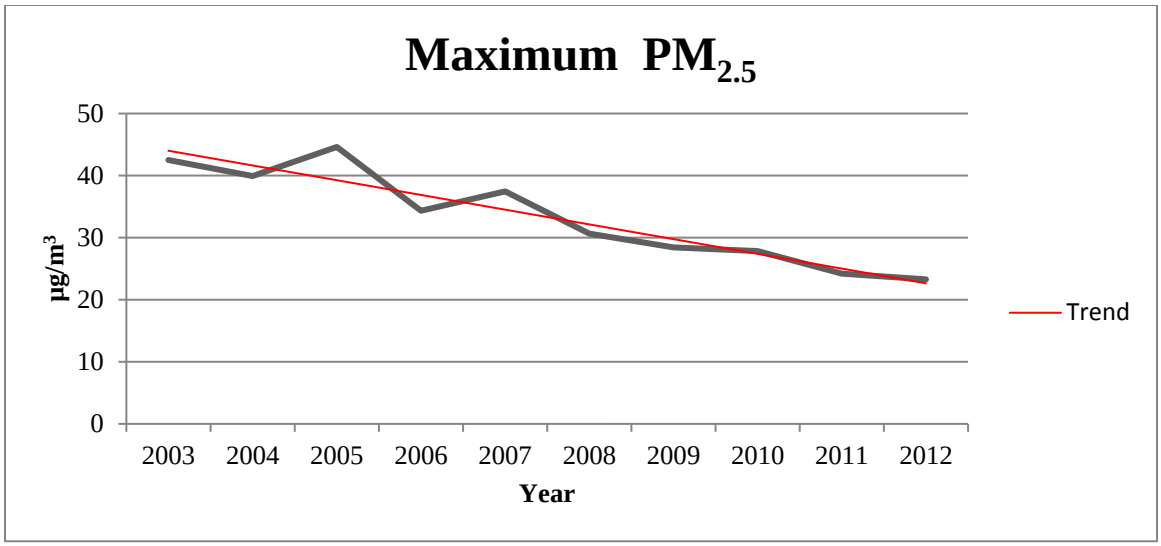

Figure 3.5.16. Maximum fine particulate matter levels trend

A similar trend can be seen when looking at average fine particulate matter. Fluctuations from 2003 to 2007 can be seen, but since then it has dropped to its lowest point in 2009, and from then has leveled off at approximately 5 µg/m^3, lower than the 7 µg/m^3 average in 2003. The results can be seen in Figure 3.5.17.

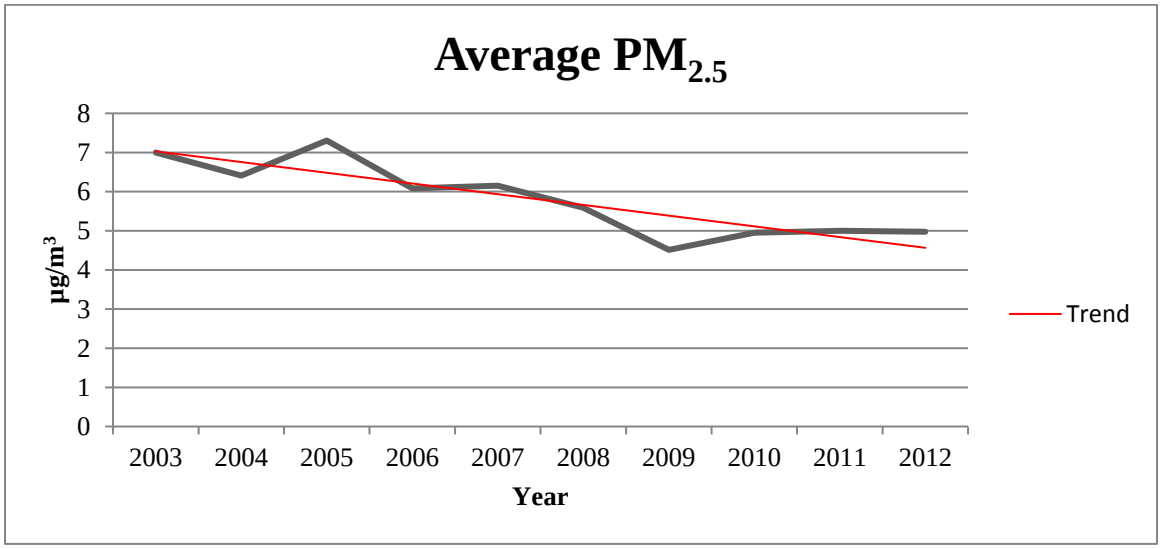

Figure 3.5.17. Average fine particulate matter levels trend

Perhaps the most encouraging statistic is that of the average number of 24 hour periods in which the CWS was exceeded. Similar to the other figures, fluctuations can be seen from 2003 to 2007, with the average number of days per station exceeding the CWS reaching almost 10 in 2005. Since 2007, however, this number has dropped drastically, culminating in close to 0 days in 2012 that exceeded the CWS per AQI station. The results can be seen in Figure 3.5.18.

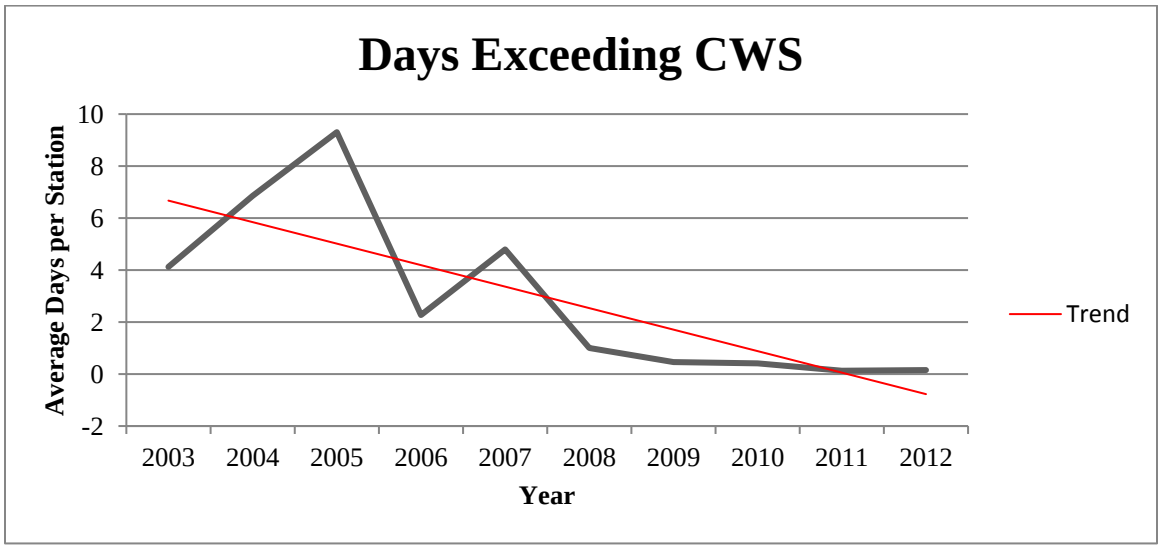

Figure 3.5.18. Average days exceeding the CWS

The ordinary kriging maps for average fine particulate matter levels for each year were then examined. For the most part, the prediction surfaces slightly underestimated the variability of predictions for most of the years examined, but slightly overestimated the variability of predictions for 2003, 2004, and 2009. The statistics can be seen in Table 3.5.3.

Table 3.5.3. Ordinary kriging average fine particulate matter statistics

Year	Model	MPE	ASE	SRMSPE
2003	Exponential	0.008555585	1.313369575	0.929714455
2004	Spherical	0.070017801	1.228212032	0.995646593
2005	Spherical	0.095736946	1.110966834	1.049512054
2006	Gaussian	0.022354019	0.930343775	1.003293787
2007	Spherical	0.055951884	0.961749278	1.014364628
2008	Spherical	0.053981896	0.914757062	1.02941605
2009	Spherical	0.031358227	0.918704231	0.974947744
2010	Spherical	0.029973126	0.953317665	1.044477564
2011	Spherical	0.056066514	0.929530686	1.003947428
2012	Spherical	0.029819743	0.967414484	1.033578291

The 2003 $PM_{2.5}$ kriging prediction map in Figure 3.5.19 shows general north to south decreasing concentrations, with the exception of the Sault Ste. Marie station, the most north-westerly. The area east to west from the Golden Horseshoe to the Windsor area has the highest concentrations, and pockets above 8 µg/m^3 are evident near Hamilton and Windsor.

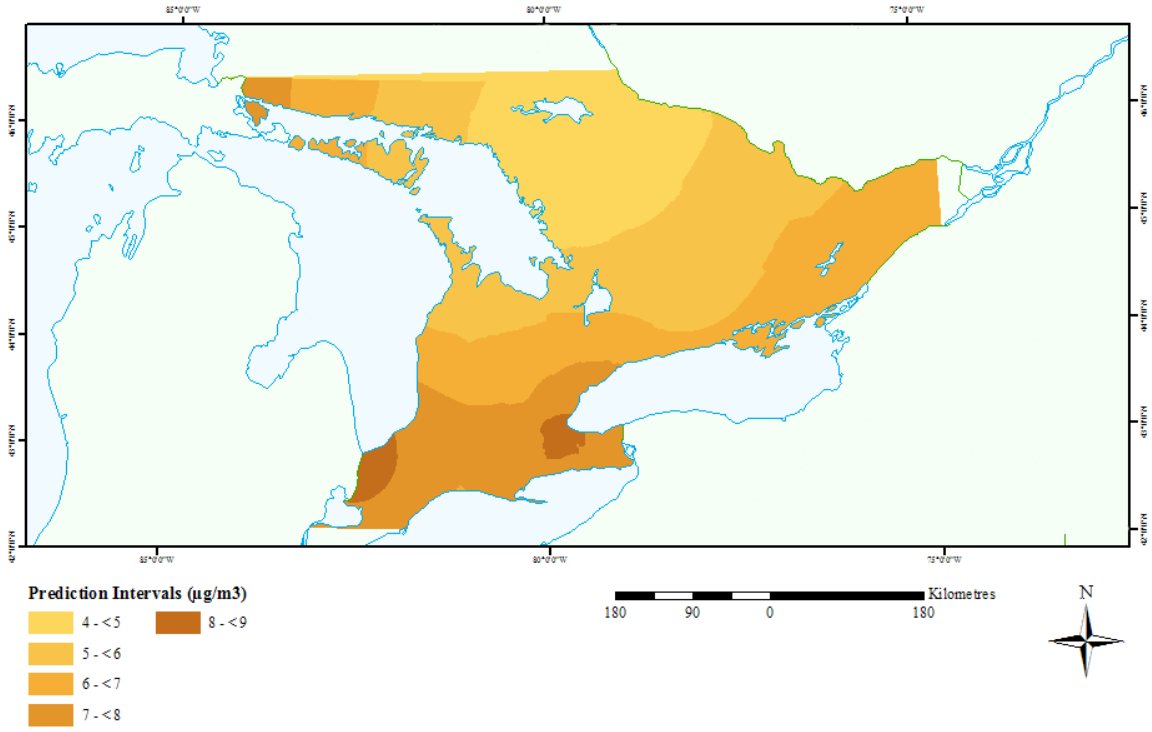

Figure 3.5.19. 2003 ordinary kriging fine particulate matter concentrations

Figure 3.5.20 shows a similar trend to 2003, but with a reduction in predicted $PM_{2.5}$ concentrations in many areas. As seen in Figure 3.5.17, average levels did drop slightly from 2003 to 2004, and the map reflects that drop. Most of the northern part of the prediction surface now falls under 4 µg/m^3, a level at which no area was in 2003. Similar pockets exist around Hamilton and Windsor, though around Hamilton it fell to under 8 µg/m^3, while the area around Windsor remained the same.

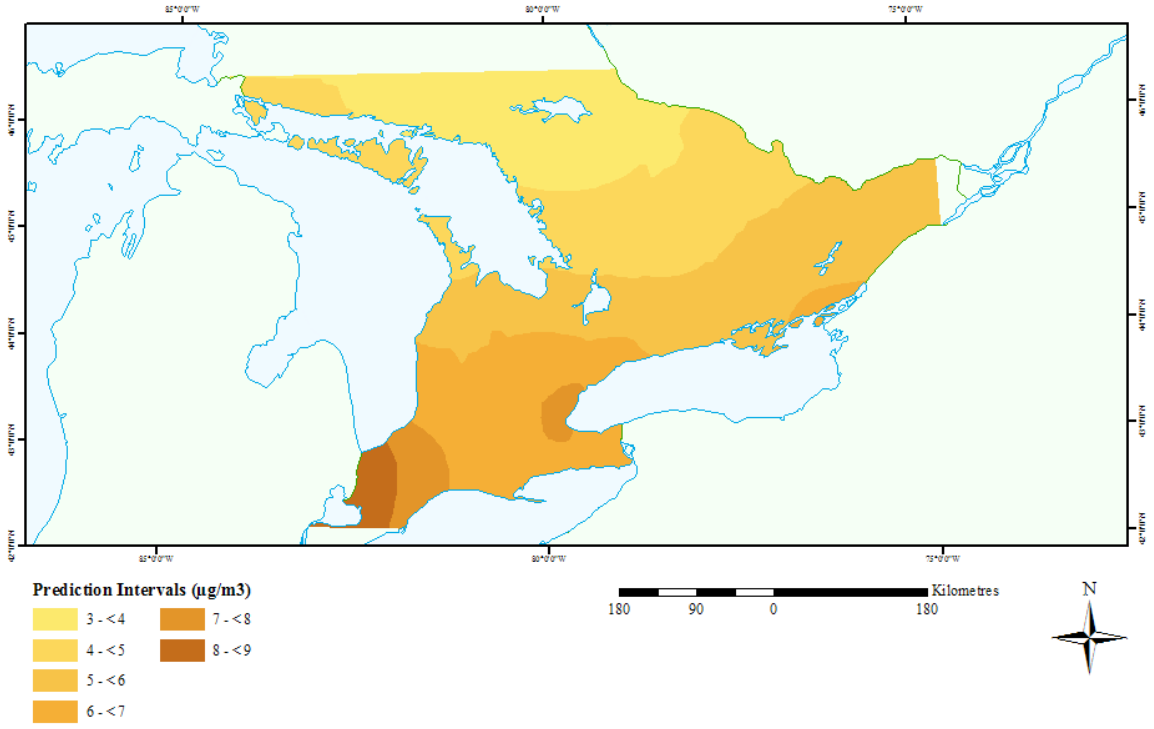

Figure 3.5.20. 2004 ordinary kriging fine particulate matter concentrations

Figure 3.5.21 represents the year with the highest average $PM_{2.5}$ concentrations, and Figure 3.5.17 reflects that statistic. While sharing the similar north-south trend as the other years, all of the areas fall above 4 µg/m^3, as in 2003. Hamilton and the surrounding area are also similar to 2003, but the concentrations in the Windsor area have increased. A large portion of the area is now above 9 µg/m^3, and a small area exceeds 10 µg/m^3.

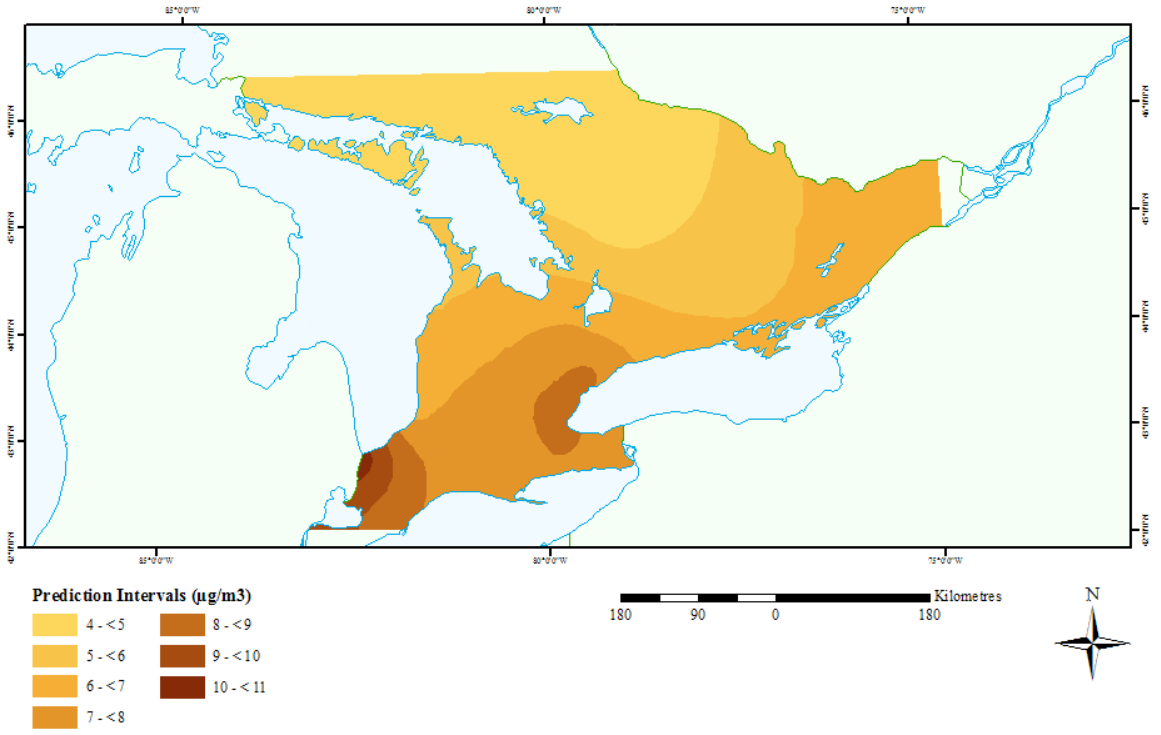

Figure 3.5.21. 2005 ordinary kriging fine particulate matter concentrations

A drastic reduction in fine particulate matter levels across the province can be seen when examining Figure 3.5.22 as compared to Figure 3.5.21. The northern part of the prediction surface is similar, falling between 4 and under 5 µg/m^3, but it is the southern part, especially near Windsor and the United States border that shows much lower concentrations. No part of that area now falls above 8 µg/m^3, whereas in 2005 there was a small area that fell above 10 µg/m^3. As well, a region around Hamilton that had concentrations between 8 and 9 µg/m^3 has fallen to between 6 and 7 µg/m^3. The lowest average fine particulate matter concentrations since 2003 were observed in 2006. According to the MOE Air Quality in Ontario 2006 Report, this year had the lowest recorded $PM_{2.5}$ statistics since it was included in the Smog Alert Program in 2002 (MOE, 2007).

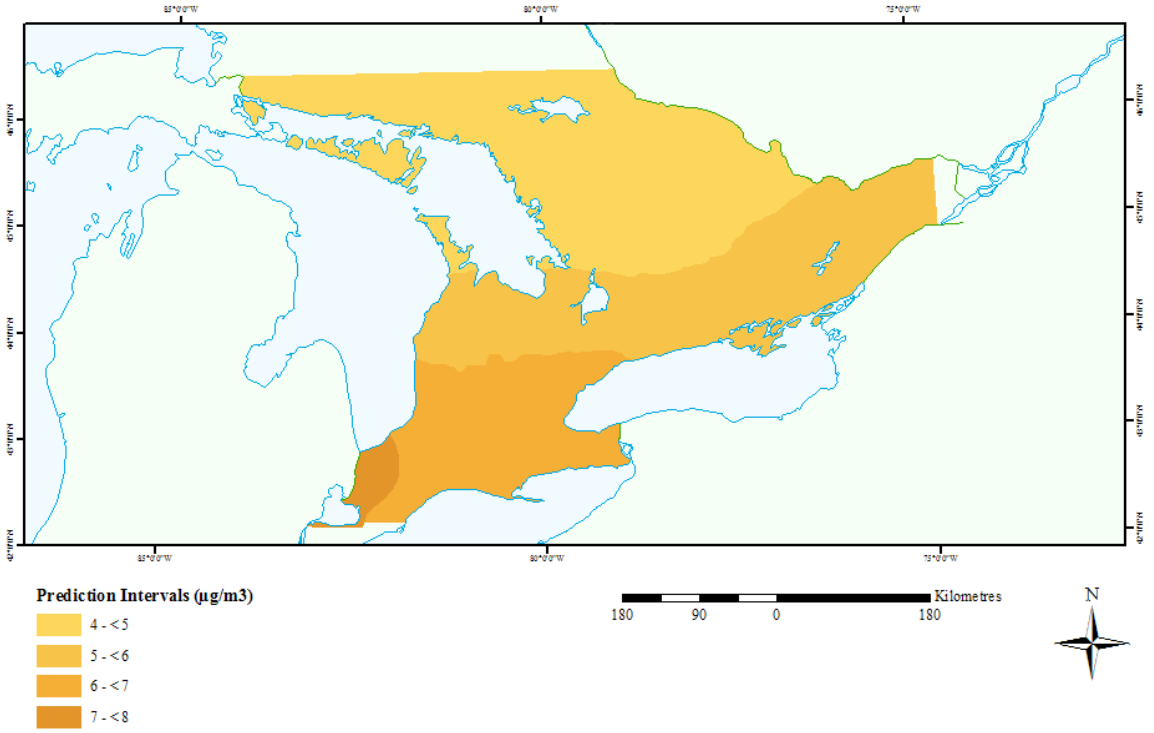

Figure 3.5.22. 2006 ordinary kriging fine particulate matter concentrations

Figure 3.5.23 shows similar trends to 2006, but extends in both directions. For example, the northern part of the study area now shows concentrations between 3 and 4 µg/m^3, where it had been between 4 and 5 µg/m^3 previously. Conversely, around the Windsor area, average concentrations rose to between 8 and 9 µg/m^3 where they had been between 7 and 8 µg/m^3 in 2006, and the Niagara Falls area also experienced an increase.

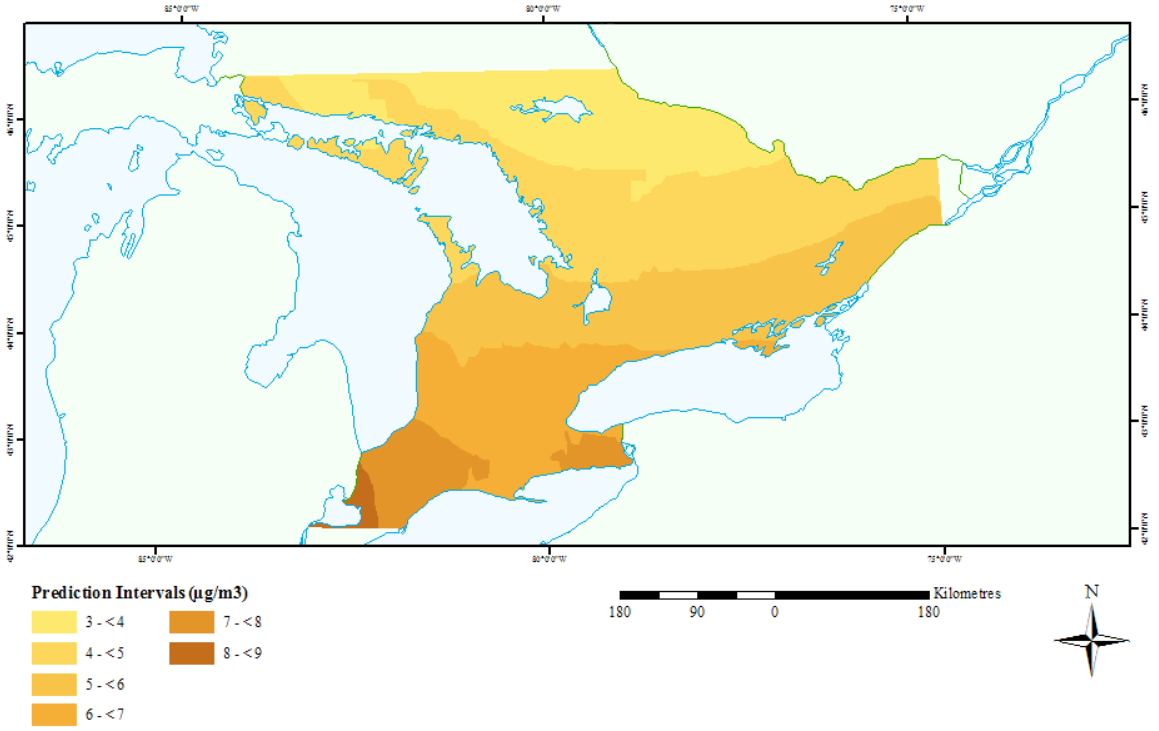

Figure 3.5.23. 2007 ordinary kriging fine particulate matter concentrations

Figure 3.5.24 shows a similar trend to 2007, but has a larger area in the north that falls in the lowest prediction interval category. However, a smaller area falls into the highest two prediction intervals, which is the area surrounding Windsor.

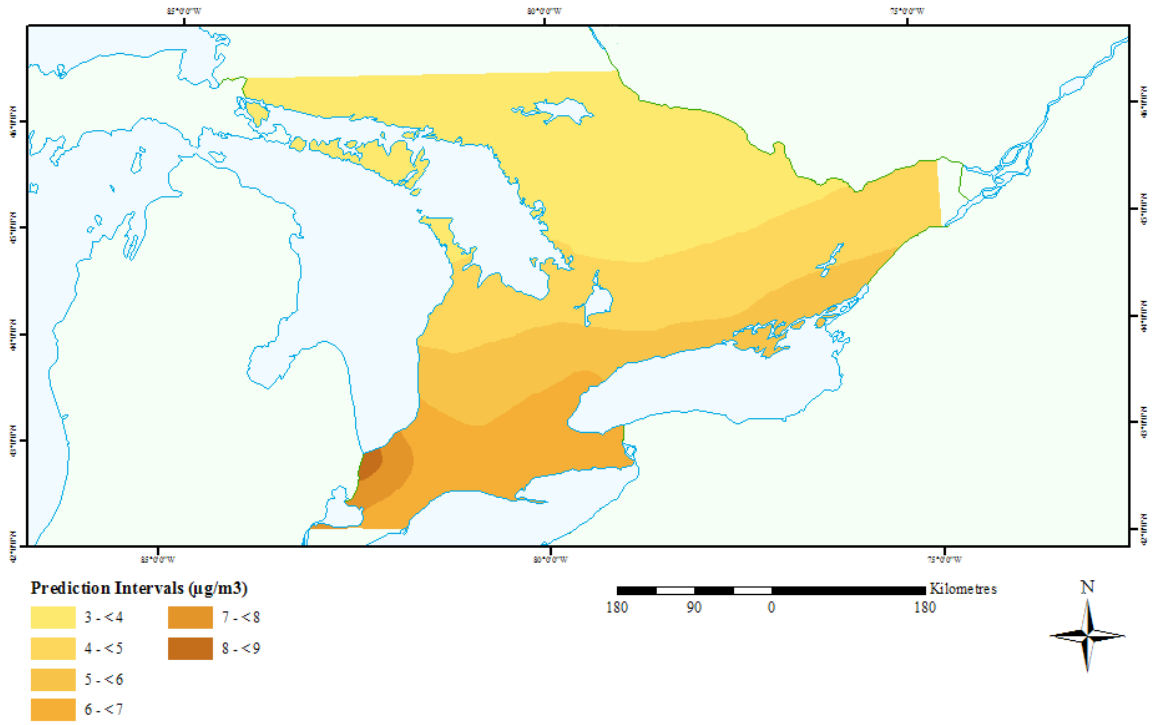

Figure 3.5.24. 2008 ordinary kriging fine particulate matter concentrations

Similar trends can again be seen in Figure 3.5.25, but an overall reduction of predicted fine particulate matter levels is evident. In the north, there is a large area where predicted $PM_{2.5}$ levels fall below 3 µg/m^3, the first time an area has been in that category in the study period. At the higher end, the area around Windsor encompassing the highest two prediction intervals is identical, but now falls between 6 and 8 µg/m^3, rather than 7 and 9 µg/m^3 in 2008. It can also be seen that 2009 is the year with the lowest average fine particulate matter levels in the time period studied.

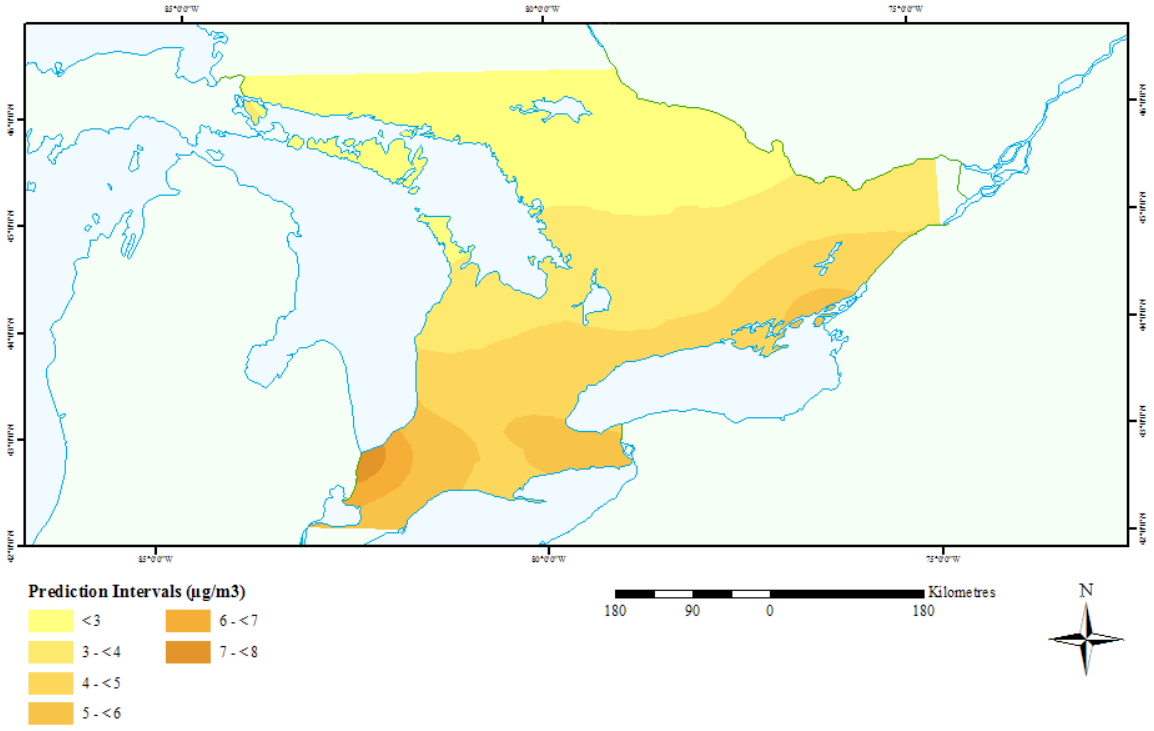

Figure 3.5.25. 2009 ordinary kriging fine particulate matter concentrations

Though 2009 was found to have the lowest $PM_{2.5}$ concentrations for the whole year averaged over all of the AQI stations, Figure 3.5.26 shows the lowest prediction levels across the province. Compared to Figure 3.5.25, a similar area falls below 3 µg/m^3, but no areas exceed 7 µg/m^3 for the first time in the study period.

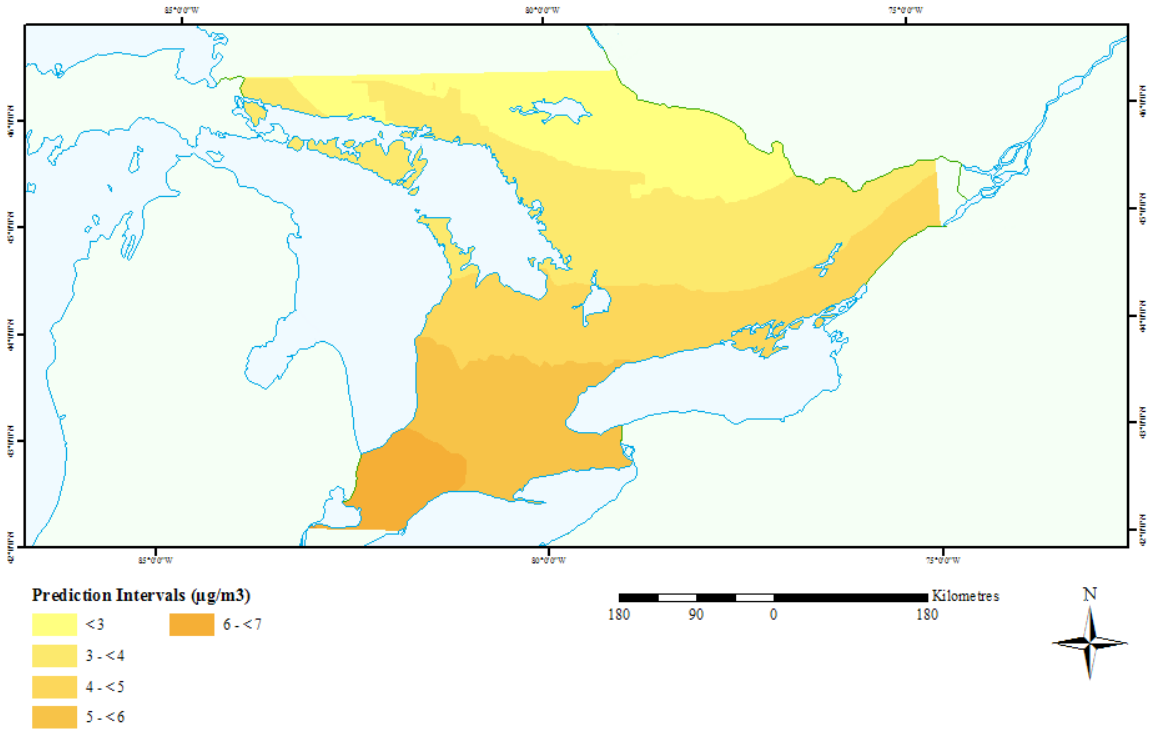

Figure 3.5.26. 2010 ordinary kriging fine particulate matter concentrations

Figure 3.5.27 shows a slight increase in fine particulate matter from 2011. A small area near Windsor once again exceeds 7 µg/m^3, and there is a smaller area in the north that falls below 3 µg/m^3. Overall the trends are very similar to 2010 and there is no drastic change in predicted $PM_{2.5}$ levels.

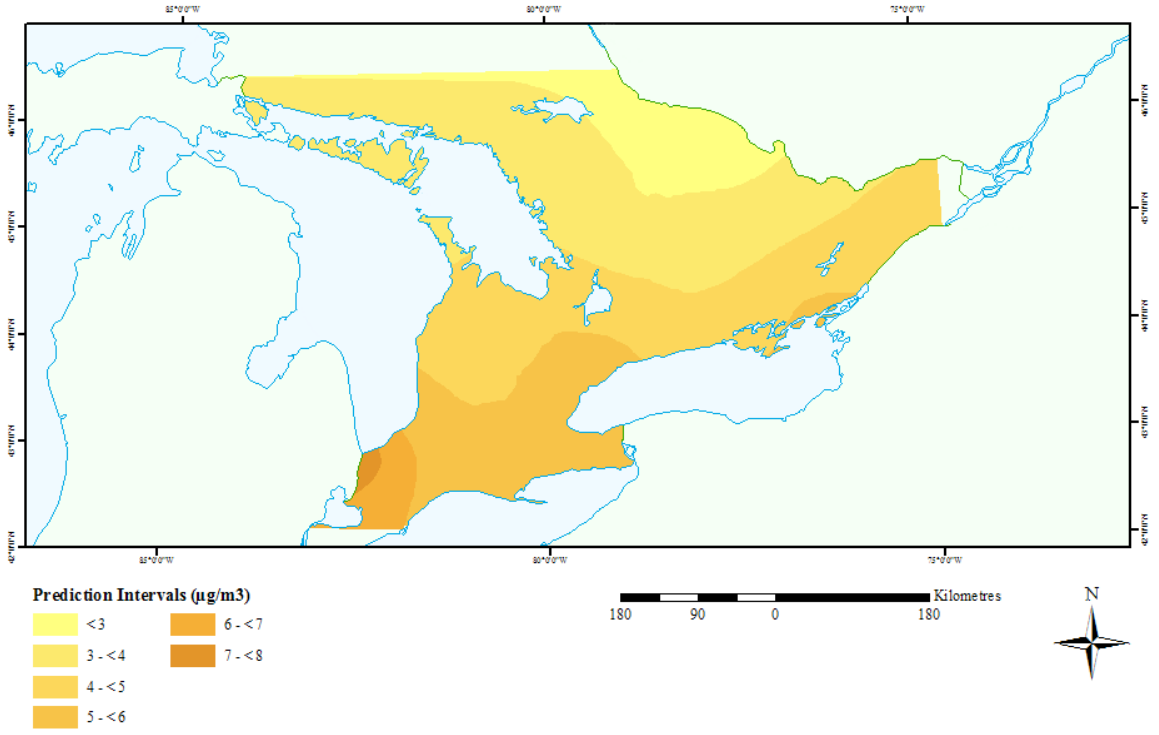

Figure 3.5.27. 2011 ordinary kriging fine particulate matter concentrations

Figure 3.5.28 represents a reduction in predicted fine particulate matter levels since 2011 and reveals one of the lowest concentration prediction surfaces overall. Though the area in the northern part of the kriging surface below 3 µg/m^3 is smaller than the previous year, the area in the south exceeding 6 µg/m^3 is also the smallest in the study period.

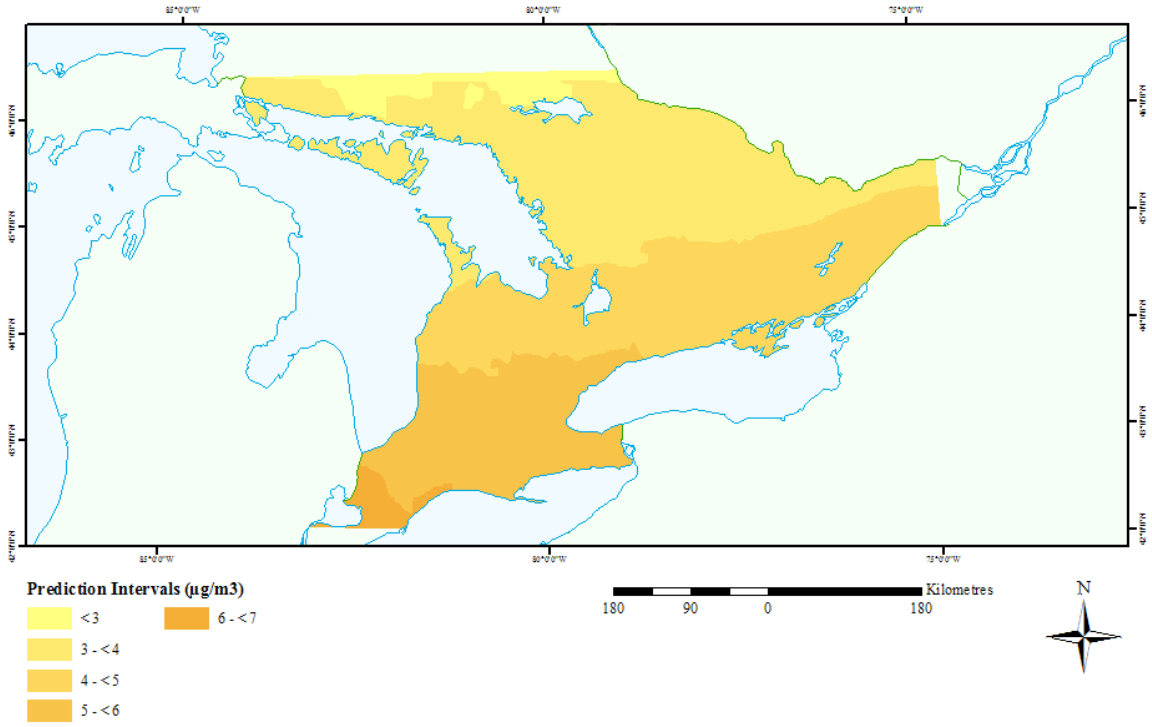

Figure 3.5.28. 2012 ordinary kriging fine particulate matter concentrations

The maximum fine particulate matter readings were also examined using ordinary kriging for two years: 2005, the year with the highest maximum levels, and 2012, the year with the lowest. Both prediction surfaces slightly underestimated the variability of predictions, with the SRMSPE being above 1. The statistics can be seen in Table 3.5.4.

Table 3.5.4. Ordinary kriging maximum fine particulate matter statistics

Year	Model	MPE	ASE	SRMSPE
2005	Exponential	-0.047755425	4.2781557	1.083965352
2012	Spherical	0.014626286	4.317073273	1.078006144

Figure 3.5.29 shows high concentrations across the province. Only a small area falls between 40 and 42 µg/m^3, and, similar to the 2003 maximum ozone map in which no area fell below the AAQC, no area falls below the CWS.

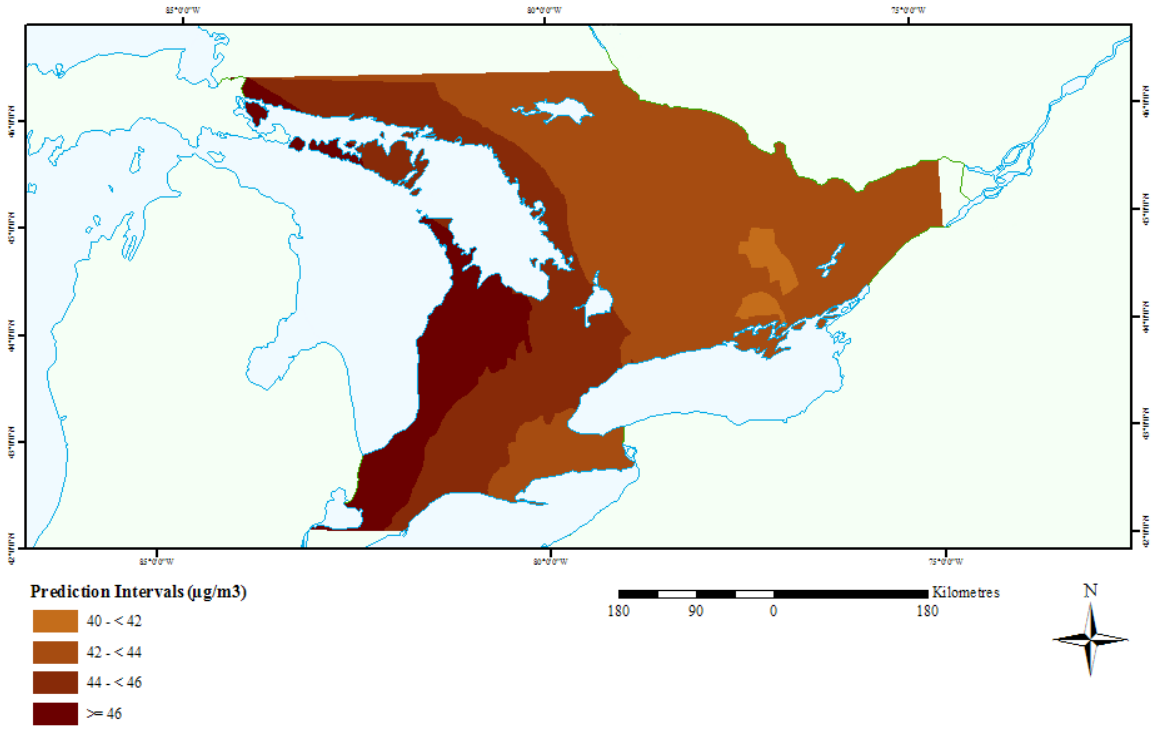

Figure 3.5.29. 2005 ordinary kriging maximum fine particulate matter concentrations

Figure 3.5.30 portrays the extreme reduction in maximum fine particulate matter levels since 2005. The entire prediction surface has concentration levels below the CWS, so it could not be displayed on the map as it was for ozone. This means that even for the 24 hour periods in which $PM_{2.5}$ levels were the highest for the entire year, the CWS of 30 $\mu g/m^3$ was not predicted to be exceeded. Based on Figure 3.5.16, as well as findings from the MOE (2013a), maximum (and average) $PM_{2.5}$ concentrations have been steadily declining since 2003 and have been reduced by approximately 30 percent (MOE, 2013a).

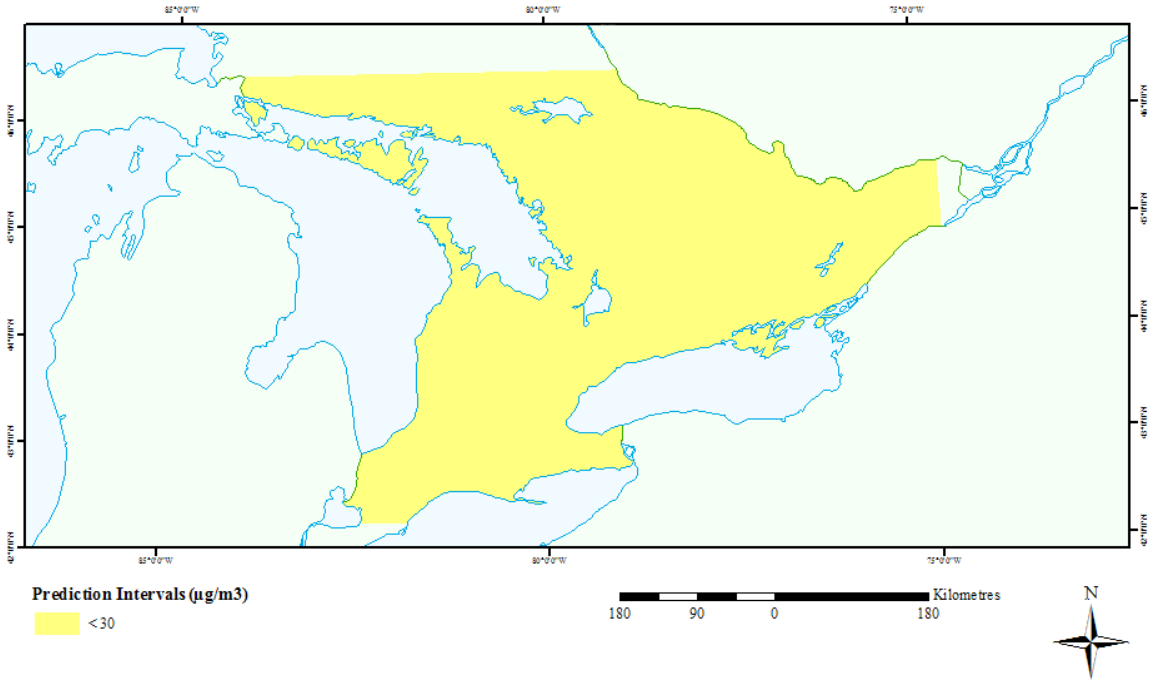

Figure 3.5.30. 2012 ordinary kriging maximum fine particulate matter concentrations

3.6 Discussion

Ozone

The results show that, though average ozone levels are fluctuating, they are gradually increasing. The year with the lowest average ozone levels and with the lowest predicted surface was 2004, while 2010 was the highest, with 2012 being one of the highest as well. Conversely, the days with a maximum 1 hour ozone reading above the AAQC are generally declining, as well as the maximum average ozone levels. This trend has been identified in the literature; Williams (2008) notes that although peak concentrations have been declining rapidly, average levels have begun to increase, especially in urban areas.

One noticeable trend when examining the ozone concentrations was that the lowest predicted concentrations were around large cities, and the concentrations would increase

with distance from these cities. When considering air pollution, this seems counterintuitive, as it would be expected that major cities would generate the most air pollution from their larger industrial and automobile presence. This is especially true when considering that industry and automobile use together account for 89% and 92% of VOC and NO_x emissions respectively, two of the main precursors to ozone. However, it has been noted in the Ontario Air Quality Report 2011that ozone concentrations are generally lower in urban areas (MOE, 2013a). This is because ozone concentrations are reduced when a reaction occurs with NO_x. This explains the trend in the ordinary kriging maps, where Toronto and the surrounding area were almost consistently predicted to have the lowest concentrations of ozone.

Fine Particulate Matter

Fine particulate matter levels decreased steadily across Ontario from 2003 to 2012. The years with the highest averages and prediction surfaces were 2003 and 2005, while 2010 and 2012 appeared to have the lowest prediction surfaces province-wide. As well, average maximum fine particulate matter and 24 hour periods that exceeded the CWS have also greatly declined since 2003.

In contrast to the findings for ozone, fine particulate matter levels were shown to be the highest in major population centres and industrial cities. For example, the Windsor area almost always had the highest predicted concentrations, and the Golden Horseshoe area near Hamilton was also a hot spot, particularly from 2003 to 2005 (Figures 3.5.19, 3.5.20, and 3.5.21). These results show that higher $PM_{2.5}$ concentrations are correlated with high levels of industrial and anthropogenic activity.

One of the reasons for the decline in pollutant concentrations is a result of government regulations and programs, one of which is Ontario's Drive Clean program. Drive Clean is an initiative created by the MOE to reduce vehicle emissions. Vehicle emissions create over 18 percent of pollution in Ontario that can lead to the creation of smog, and Drive Clean aims to mitigate those emissions. The program reduces emissions by an annual average of 36 percent (MOE, 2013b). This is likely a major factor when looking at the reduction of fine particulate matter levels across Ontario, since approximately a quarter of all $PM_{2.5}$ emissions come from automobiles. The program was implemented to reduce emissions by focusing on proper vehicle maintenance and identifying emissions problems. Drive Clean acts to improve vehicle fuel consumption and lessen pollutant release (MOE, 2013b).

The notion of trans-boundary pollution is one of the main things to take into consideration when examining air pollution in southern Ontario. Both the CCME and governments in Canada and the United States have agreements concerning trans-boundary air pollution to mitigate the effects and to lower emissions that could harm both sides. Therefore, despite government efforts such as Drive Clean, much of the cleanliness of Ontario's air is dependent on other sources. This was likely the cause of the air quality trends experienced, especially when examining fine particulate matter. There was a general north-south trend of increasing concentrations, likely due to the proximity of the southern part of Ontario to the United States. As mentioned previously, in additional findings by Galvez (2007), approximately 60 percent of ozone during smog episodes was due to anthropogenic emission release from the nearby United States.

The distribution of points may also have had an effect on the outcomes of some of the prediction surfaces. This was mainly an issue for the Sault Ste. Marie station, as it was fairly remote and distant from the rest of the stations. Therefore, if it had an anomalous year, its value would have a strong influence on the surrounding area without an AQI station. The Thunder Bay AQI station was omitted from analysis for this specific reason, so while the omission of Sault Ste. Marie would result in a less complete analysis, it may have provided more accurate results for the rest of the area. For example, in Figure 3.5.19, 2003 average $PM_{2.5}$ concentrations, the Sault Ste. Marie station has a high concentration. Since the closest AQI station to the east is still quite far, the prediction surface is heavily based on that reading. The result is relatively high predicted values for the surrounding area, which may not be an accurate representation of realistic concentrations. With this in mind, the point density among the 39 stations that were analyzed could have affected the results. Areas in which there was a high density of points, such as the Greater Toronto Area, would have produced more accurate results, as the distance in between the stations is smaller and therefore the predicted readings in between will be closer to observed measures. In areas where the points are far apart, the prediction surface can become less accurate since the observed values it relies on are far away.

For both pollutants, a spike in ambient concentrations was experienced. There is little literature or information as to why this occurred (the MOE Air Quality Report for 2012 will be released in 2014) but it does coincide with the number of smog alerts. In 2011, there were only 5 smog advisories lasting a total of 9 days. Comparing this to 2012, there were 12 smog advisories lasting a total of 30 days (MOE, 2013c). The increase in both

particles led to a large increase in the number of smog episodes across Ontario. In terms of the cause of this increase, it appears that 2012 is an anomalous year; according to 2013 smog statistics up to August 22, 2013, only 1 smog advisory has occurred lasting for a total of 2 days (MOE, 2013c).

3.7 Conclusion

This analysis provided a spatial investigation of air quality trends in Ontario since 2003. Ozone and fine particulate matter were targeted, as both are proven detriments to human and environmental health, and are the two main ingredients of smog. The findings can be used for environmental organizations and political planning as well, and can corroborate current air quality reports published in Ontario. The annual air quality report released by the MOE, for example, only includes readings from 19 of the 40 AQI stations, and does not include a strong spatial aspect, so a kriging prediction surface can benefit the statistical analysis of air pollution in Ontario.

It was found that from 2003 to 2012, average ozone concentrations generally increased, while average fine particulate matter concentrations generally decreased. However, maximum levels for each year of each contaminant decreased from 2003 to 2012. The average amount of times the AAQC for ozone and the CWS for fine particulate matter was exceeded has also greatly declined since 2003, indicating promising results for air quality in Ontario.

CHAPTER 4: Recommendations and Future Research

One of the caveats of this research project is the notion of trans-boundary air pollution. As explained in Chapter 2, most of the air pollution in Ontario is not generated in Ontario, but comes from other sources across the United States border. Thus, while this analysis shows the trends of air quality in Ontario in recent years, it does not account for sources of pollution. Therefore, it would be prudent to conduct a further study on pathways of air to track where the pollution is coming from and attempt to quantify how much is created in Ontario and how much is from foreign sources.

Another area to be explored for air quality in Ontario is the effect that elevation has on contaminant readings. Each AQI station has a different height of air intake in metres, as well as the elevation above sea level in metres. For example, the elevation above sea level ranges from 55 metres at the Cornwall station to 330 metres at the Guelph station. The height of air intake also ranges from 3 metres at several stations to 15 metres at the Chatham station (MOE, 2013a). Therefore, it would be pertinent to examine whether or not the elevation at which the samples are taken has an effect on the observations.

Other ambient air pollutants could be examined as well to provide a more complete analysis on the state of air quality. Ozone and fine particulate matter were chosen for this study since they were measured at each of the 40 AQI stations, which resulted in a more complete spatial analysis. However, certain stations across the AQI network also measure nitrogen dioxide, carbon monoxide, sulphur dioxide, and total reduced sulphur compounds. Fenger (1999) suggests that sulphur dioxide, nitrogen oxides and carbon monoxide fall under the category of major pollutants. Therefore, a future study could

examine the concentrations of the additional four contaminants to determine their trends since 2003 for a more complete air quality analysis.

Additionally, different kriging methods could be examined to determine their effectiveness in modeling ambient air pollutant concentrations. For example, Guo et al. (2007) used fuzzy membership grade kriging to predict PM_{10} levels in California. Similarly Shad et al. (2009) used fuzzy genetic linear membership kriging to examine PM_{10} levels in Tehran. Other methods have been used in the literature as well, such as universal kriging and inverse distance weighting (Beelen et al., 2009; Hooyberghs et al., 2006; Joseph et al., 2013). Therefore, the same study could be conducted using a different kriging or spatial interpolation method, and the results could be compared to determine the best predictor.

While decreasing maximum ozone levels initially looks promising for air quality in Ontario, it can also mean in increase in NO_x, another harmful greenhouse gas. Since its reaction with ozone reduces overall ozone concentrations, this could mean an increase in NO_x concentrations, which is arguably a more dangerous pollutant. Therefore, research should be done into the prominence of NO_x in Ontario, as well as its relationship to ozone levels at each measurement.

An additional area to be explored is pollutant concentrations in the United States. Transboundary pollution has been explained in one context, but pollution also enters the United States from Canada. Therefore, it would be useful to perform kriging in areas surrounding Ontario in the United States to compare pollutant concentrations and their relation to transboundary pollution.

REFERENCES

Amatullah, H., M. L. North, U. S. Akhtar, N. Rastogi, B. Urch, F. S. Silverman, C. Chow, G. J. Evans, and J. A. Scott. 2012. Comparative cardiopulmonary effects of size-fractioned airborne particulate matter. *Inhalation Toxicology*, 24(3), 161-171.

Barton, J. 2008. Canada-Wide Standards and Innovative Transboundary Air Quality Initiatives. *Journal of Toxicology and Environmental Health, Part A*, 71, 74-80.

Beelen, R., G. Hoek, E. Pebesma, D. Vienneau, K. de Hoogh, and D. J. Briggs. 2009. Mapping of background air pollution at a fine spatial scale across the European Union. *Science of the Total Environment*, 407(6), 1852-1867.

Canadian Council of Ministers of the Environment (CCME). 2013. 2010 Progress Report on the Canada-Wide Standards for Particulate Matter and Ozone.

Chen, H., R. T. Burnett, J. C. Kwong, P. J. Villeneuve, M. S. Goldberg, R. D. Brook, A. van Donkelaar, M. Jerrett, R. V. Martin, J. R. Brook, and R. Copes. 2013. Risk of Incident Diabetes in Relation to Long-term Exposure to Fine Particulate Matter in Ontario, Canada. *Environmental Health Perspectives*, 121(7), 804-810.

City of Windsor. 2003. *Free Transit on Smog Days (Archive)*. Retrieved July 16, 2013, from: http://www.citywindsor.ca/residents/transitwindsor/Rider-Programs/green-initiatives/Pages/Transit-on-Smog-Days-Archive.aspx

Fenger, J. 1999. Urban air quality. *Atmospheric Environment*, 33, 4877-4900.

Forsythe, K. W., and C. H. Marvin. 2009. Assessing historical versus contemporary mercury and lead contamination in Lake Huron sediments. *Aquatic Ecosystem Health & Management*, 12(1), 101-109.

Forsythe, K. W., K. Paudel, and C. H. Marvin. 2010. Geospatial Analysis of Zinc Contamination in Lake Ontario Sediments. *Journal of Environmental* Informatics, 16(1), 1-10.

Galvez, O. 2007. Synoptic-scale transport of ozone into Southern Ontario. *Atmospheric Environment*, 41(38), 8579-8595.

Gawedzki, A. and K. W. Forsythe. 2012. Assessing Anthracene and Arsenic Contamination within Buffalo River Sediments. *International Journal of Ecology*, 2012, 1-9.

Geddes, J. A., J. G. Murphy, and D. K. Wang. 2009. Long term changes in nitrogen oxides and volatile organic compounds in Toronto and the challenges facing local ozone control. *Atmospheric Environment*, 43, 3407-3715.

Guo, D., R. Guo, and C. Thiart. 2007. Predicting air pollution using fuzzy membership grade Kriging. *Computers, Environment and Urban Systems*, 31, 33-51.

Hooyberghs, J., C. Mensink, G. Dumont, and F. Fierens. 2006. Spatial interpolation of ambient ozone concentrations from sparse monitoring points in Belgium. *Journal of Environmental Monitoring*, 8, 1129-1135.

Kantor, I., M. W. Fowler, A. Hajimiragha, and A. Elkamel. 2010. Air quality and environmental impacts of alternative vehicle technologies in Ontario, Canada. *International Journal of Hydrogen Energy*, 35, 5145-5153.

Khan, F., Y. Shirasuna, K. Hirano, and S. Masunaga. 2010. Characterization of $PM_{2.5}$, $PM_{2.5\text{-}10}$ and $PM_{>10}$ in ambient air, Yokohama, Japan. *Atmospheric Research*, 96(1), 159-172.

Kumar, A., S. Maroju, and A. Bhat. 2007. Application of ArcGIS Geostatistical Analyst for Interpolating Environmental Data from Observations. *Environmental Progress*, 26(3), 220-225.

Lee, S., M. L. Serre, A. van Donkelaar, R. V. Martin, R. T. Burnett, and M. Jerrett. 2012. Comparison of Geostatistical Interpolation and Remote Sensing Techniques for Estimating Long-Term Exposure to Ambient $PM_{2.5}$ Concentrations across the Continental United States. *Environmental Health Perspectives*, 120(12), 1727-1732.

Miller, D. E., and S. A. Watmough. 2009. Air pollution, climate, soil acidity, and indicators of forest health in Ontario's sugar maple forests. *Canadian Journal of Forest Research*, 39, 2065-2079.

Miller, L., S. Farhana, and X. Xu. 2010. Trans-boundary air pollution in Windsor, Ontario (Canada). *Procedia Environmental Sciences*, 2, 585-594.

National Environment Protection Council. 2010. Review of the National Environment Protection (Ambient Air Quality) Measure: Discussion Paper, Air Quality Standards.

Negreiros, J., M. Painho, F. Aguilar, and M. Aguilar. 2010. Geographical Information Systems Principles of Ordinary Kriging Interpolator. *Journal of Applied Sciences*, 10(11), 852-867.

Ontario Ministry of the Environment (MOE). 2007. Air Quality in Ontario 2006 Report.

Ontario Ministry of the Environment (MOE). 2013a. Air Quality in Ontario Report for 2011.

Ontario Ministry of the Environment (MOE). 2013b. *Drive Clean*. Retrieved July 22, 2013, from: http://www.ene.gov.on.ca/environment/en/category/drive_clean/

Ontario Ministry of the Environment (MOE). 2013c. *Smog Advisory Statistics.* Retrieved August 8, 2013, from: http://www.airqualityontario.com/press/smog_advisories.php

Ozbay, B., G. A. Keskin, S. C. Dogruparmak, and S. Ayberk. 2011. Multivariate methods for ground-level ozone modeling. *Atmospheric Research*, 102(1-2), 57-65.

Pope III, C.A., R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, and G. D. Thurston. 2002. Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *Journal of the American Medical Association*, 287(9), 1132-1141.

Shad, R., M. S. Mesgari, A. Abkar, and A. Shad. 2009. Predicting air pollution using fuzzy genetic linear membership kriging in GIS. *Computers, Environment and Urban Systems*, 33, 472-481.

Sharma, M., and S. Maloo. 2005. Assessment of ambient air PM_{10} and $PM_{2.5}$ and characterization of PM_{10} in the city of Kanpur, India. *Atmospheric Environment*, 39(33), 6015-6026.

Standards Development Branch, Ontario Ministry of the Environment. 2012. Ontario's Ambient Air Quality Criteria (AAQC).

Tian, J., and D. M. Chen. 2007. Evaluating Satellite-Based Measurements for Mapping Air Quality in Ontario, Canada. *Journal of Environmental Informatics*, 10(1), 30-36.

Williams, M. L. 2008. Air Quality Risk Management. *Journal of Toxicology and Environmental Health, Part A*, 71, 9-12.

Wong, D. W., L. Yuan, S. A. Perlin. 2004. Comparison of spatial interpolation methods for the estimation of air quality data. *Journal of Exposure Analysis and Environmental Epidemiology*, 14, 404-415.

World Health Organization. 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide; Global update 2005; Summary of risk assessment.

Yu, T. 2010. Chararcterization of ambient $PM_{2.5}$ concentrations. *Atmospheric Environment*, 44(24), 2902-2912.