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# Monitoring spatial and temporal variability of air quality using satellite observation data: A case study of MODIS-observed aerosols in Southern Ontario, Canada

DongMei Chen and Jie Tian

*Department of Geography, Queen's University  
Canada*

## 1. Introduction

Aerosol refers to solid or liquid particles suspended in the air. Aerosol particles mostly originate from the earth surface and are well mixed within the atmospheric boundary layer of the atmosphere. Aerosols scatter and/or absorb solar radiation as well as emitted and reflected radiation from the earth (Ichoku *et al.*, 2004). As a consequence, aerosol particles can significantly affect radiative forcing of climate (Feczko *et al.*, 2002), and play a key role in atmospheric physics and chemistry (Figueras i Ventura and Russchenberg, 2008; Han *et al.*, 2008). Moreover, the aerosols near the ground are one of the air pollutants responsible for human health hazard. Exposure to aerosols, both short-term and long-term, may cause considerable negative health effects. Accurate mapping of those parameters and their spatial and temporal changes is important for the evaluation of the current air dispersion modeling, air pollution control regulations, and other environmental and climate change related activities (Dockery *et al.*, 1993).

A crucial step toward the understanding of the complex effects of aerosols is to study aerosol properties and distribution (Haywood and Boucher, 2000). Aerosol optical depth (AOD), a dimensionless measure of atmospheric extinction of solar radiation by aerosols, is one of the most important aerosol properties. AOD can be measured *in situ* or estimated by remote sensing. Ground-based sunphotometers can provide direct measurement of AOD. The AOD data measured by this means is very accurate with a high temporal resolution. However, the limited spatial coverage of such data largely hampers the in-depth understanding of aerosol distribution, especially for the regions with few or no sunphotometers. Remote sensing provides an alternative data resource that is prominent in studying air quality. AOD can be derived from the spectral information sensed by certain relatively new satellites such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) (Remer *et al.*, 2006; Martonchik *et al.*, 2002). Satellite remote sensing of aerosol is advantageous on several aspects, including its extensive and continuous spatial coverage and lower cost for acquisition. However, the

MODIS-derived AOD is subject to weather condition and has lower accuracy and lower temporal frequency (once a day) than the sunphotometer measurements.

A number of studies have been conducted to address the spatial and temporal variability of aerosols. Early research mainly focused on a group of cities that hold an Aerosol Robotic Network (AERONET) site (equipped with a sunphotometer). For instance, Masmoudi *et al.* (2003) found higher spatial variability of AOD and AE for the central African sites than the Mediterranean ones. The central African sites showed a lower variation with the smallest values of their measured AE due to the presence of very large dust particles. Remotely-sensed data have also been used in the analysis of aerosol loading distribution in recent years. By mapping AOD over Europe at a continental scale, Koelemeijer *et al.* (2006) clearly identified Northern Italy, Southern Poland, and the Belgium/Netherlands/Ruhr area as major aerosol source regions. Frank *et al.* (2007) used the data from MISR for an inter-annual analysis of AOD variation over the Mojave desert of southern California. The authors suggested that AOD varies significantly across the desert and therefore the AERONET site at Rogers Dry Lake (within the desert) cannot be used to represent the aerosol conditions over the entire study area. However, the relationship between aerosol distribution and land use structure/topography has not been examined in previous studies.

This chapter reviews the algorithms used to extract AOD from MODIS data and presents a case study of using MODIS AOD data to investigate the spatial-temporal distribution patterns of aerosols in southern Ontario, Canada. The relationship between land-use structure and AOD has been analyzed through a correlation analysis and discuss the impacts of topography on the aerosol distribution.

## 2. Aerosol Retrieval from MODIS data

The Moderate Resolution Imaging Spectroradiometer (MODIS) is onboard the Earth Observing System (EOS) Terra and Aqua, with daytime equator crossing times of late morning (10:30am) and early afternoon (1:30pm), respectively. It is an optical scanner that observes the Earth in 36 channels covering visible, near, and shortwave infrared from 0.4 $\mu$ m to 14.5 $\mu$ m with spatial resolution ranging from 250 m to 1 km. Since launched in 1999, the Moderate Resolution Imaging Spectroradiometer (MODIS) has provided an unprecedented opportunity to monitor aerosol (or particulate matter) status and events, and examine the role of aerosols in the earth-atmosphere system. MODIS is designed to produce a wide variety of information about the three spheres that human life depends on: geosphere, hydrosphere, and atmosphere. The MODIS science team has correspondingly developed three groups of data products (Atmosphere, Ocean, and Radiometric/Geolocation).

The MODIS Atmosphere products are provided in data level 2 (5-minute swath granules) and data level 3 (global grid maps) according to the Distributed Active Archive Center (DAAC) data level scheme. In particular, the MODIS atmosphere product (level 2) provides retrieved Aerosol Optical Depth (AOD), representing columnar aerosol loading of the atmosphere, at a typical spatial resolution of 10 km. Two separate algorithms are applied for the retrieval of aerosols over land (Kaufman *et al.*, 1997a) and ocean (Tanre *et al.*, 1997). Over land, the retrieval is made at two wavelengths independently: 0.47  $\mu$ m and 0.66  $\mu$ m with the

aid of additional information from the 2.12  $\mu\text{m}$  channel. The strategy for retrieving AOD over land from MODIS is introduced by Kaufman *et al.* (1997a). The satellite-measured reflectance  $\rho_{\lambda}^*$  at a particular wavelength can be approximated by:

$$\rho_{\lambda}^*(\theta_o, \theta, \phi) = \rho_{\lambda}^{\alpha}(\theta_o, \theta, \phi) + \frac{F_{\lambda}(\theta_o)T_{\lambda}(\theta)\rho_{\lambda}^s(\theta_o, \theta, \phi)}{1-S_{\lambda}\rho_{\lambda}^s(\theta_o, \theta, \phi)} \tag{1}$$

where  $\rho_{\lambda}^{\alpha}$  is the atmospheric path reflectance.  $F_{\lambda}$  represents the normalized downward flux for zero surface reflectance.  $S_{\lambda}$  is the atmospheric backscattering ratio.  $\rho_{\lambda}^s$  is the angular spectral surface reflectance.  $\theta_o, \theta$ , and  $\phi$  denote solar zenith angle, satellite zenith angle, and solar/satellite relative azimuth angle, respectively. Each term on the right hand side of Equation (1), except for the surface reflectance, is a function of the aerosol type and loading (AOD).

The reflectance sensed by the satellite sensor is separated into the surface reflectance and atmospheric path reflectance. Dark objects (e.g. vegetated and dark soil surfaces) are selected for AOD retrieval for their relatively low reflectance (at the visible bands). The older versions of the retrieval algorithm over land (e.g. C004-L) assume that aerosol is transparent in the 2.12  $\mu\text{m}$  channel. The empirical relationships (correlation) between the surface reflectance at 0.47  $\mu\text{m}$ /0.66  $\mu\text{m}$  and 2.12  $\mu\text{m}$  wavelengths have been recognized by Kaufman *et al.* (1997b). The physical reason for the correlation was found to be the combination of absorption of visible light by chlorophyll and infrared radiation by liquid water in healthy vegetation (Kaufman *et al.*, 2002). Therefore, the surface reflectance at 0.47  $\mu\text{m}$  and 0.66  $\mu\text{m}$  can be estimated based on the satellite-measured reflectance at 2.12  $\mu\text{m}$ . In contrast, the surface reflectance in the most recent version of the algorithm over land (C005-L) is not only a function of the surface reflectance at 2.12  $\mu\text{m}$ , but also a function of the scattering angle and the “greenness” (a parameter like the well-known Normalized Difference Vegetation Index) of the surface in the mid-Infrared spectrum (Levy *et al.*, 2007). Moreover, the C005-L algorithm also assumes that the 2.12  $\mu\text{m}$  channel contains information about coarse mode aerosol as well as the surface reflectance. Assuming that a small set of aerosol types and loadings can describe the range of global aerosol, the MODIS aerosol retrieval algorithm relies on a lookup table (LUT) procedure (instead of real-time calculation). Radiative transfer calculations are pre-computed for a set of aerosol and surface parameters. The satellite measured radiance and the estimated surface reflectance are used as input into the LUT to retrieve AOD at 0.47  $\mu\text{m}$  and 0.66  $\mu\text{m}$ . The strategy of the algorithm is to examine the LUT to determine the conditions that can best mimic the MODIS-observed spectral reflectance, and retrieve the associated aerosol properties including AOD. The AOD at 0.55  $\mu\text{m}$  can then be obtained by interpolating the values at 0.47  $\mu\text{m}$  and 0.66  $\mu\text{m}$  using the Ångström exponential (AE) coefficient, which is given by

$$\alpha = -\frac{\log\frac{\tau_1}{\tau_2}}{\log\frac{\lambda_1}{\lambda_2}} \tag{2}$$

where  $\tau_1$  and  $\tau_2$  represent the AOD values at the wavelengths of  $\lambda_1$  and  $\lambda_2$  , respectively.

The global validation of the MODIS AOD collection 5 products shows a MODIS/ AERONET regression line of  $y=1.01x+0.03$ ,  $r=0.9$  (Levy *et al.*, 2007). It should be noted that surface reflectivity has impact on accuracy of MODIS-derived AOD as the relationships between

visible reflectance and mid-infrared are used in the MODIS aerosol retrieval algorithm to derive AOD over land. For very dark surfaces, the surface reflectance in the red channel may be overestimated, resulting in an underestimate in the derived AOD. Moreover, the highest latitude of the study area is below 47°N so that the solar elevation is high enough to allow retrieval of AOD by the algorithm, even in the mid-winter period.

### 3. Study Area

The study area of this research is Southern Ontario, the key agricultural and industrial area of Canada and home to nearly 12 million people based on 2006 demographics (Statistics Canada, 2007). Extending over southern Ontario is mainly the physiographic region of the Great Lakes-St Lawrence Lowerlands (Bone, 2005). Figure 1 shows the location of the study area. A continental climate affects this temperate mid-latitude region. The climate is highly modified by the influence of the Great Lakes: the addition of moisture from them increases precipitation amounts. The spatial and temporal distributions of both anthropogenic and natural aerosols are of particular concern due to their consequences on local climate and impacts on the local residents' health. The latest studies indicate that areas of southern Ontario often experience the highest levels of PM<sub>2.5</sub> concentration in eastern Canada. Ontario is burdened with \$9.6 billion in health and environmental damages each year due to the impact of ground-level fine PM and ozone (Yap *et al.*, 2005), which are generally attributed to the formation of smog. It therefore becomes a continuing priority for environmental researchers and government agencies (e.g. the Ontario Ministry of Environment) to develop a better understanding of the distributional patterns of these pollutants at multiple scales. There are only three AERONET sites (Windsor, Toronto, and Egbert) located in Ontario. It has therefore been a challenge for researchers to fully understand how aerosols are distributed across space in terms of concentration and size. Moreover, the increase of anthropogenic aerosols due to changes in land use and industrial activity has been found to have a significant impact on both the radiation budget and the hydrological cycle (Figuerasi Ventura and Russchenberg, 2008). The possible relationship between aerosol distribution and land use structure/topography has not been explicitly studied.



Fig. 1. Location map of the study area of southern Ontario



## 4. Data and Method

In this study, the MODIS aerosol product files (collection 5 data) from both Terra and Aqua have been collected for southern Ontario to cover the entire calendar year 2004. The collection 5 was chosen as its products were produced based on the most recent version of the retrieval algorithm. In total, over eight hundred MODIS aerosol image products of level 2 were collected from each platform (Terra and Aqua). These data were stored and provided in a standard hierarchical data format (HDF), which is a multi-object file format for sharing scientific data in multi-platform distributed environments. MATLAB programs have been developed to read the MODIS HDF files systematically and extract the parameters of AOD at  $0.47\mu\text{m}$  and AE over land. The utility of MODIS-derived AOD data was first checked based on the frequency of valid measurements and the effective data coverage in different months. Both the AOD data and the AE data were binned into a  $0.1^\circ \times 0.1^\circ$  grid. Typically, there are about 40 valid measurements (for both AOD and AE) available per grid cell for the study period. The number of valid MODIS-derived AOD values for each cell varies across space and time, so there will be some random differences associated with the observation frequency. The MODIS-derived AOD measurements were sampled to ensure a minimum of one day interval between the AOD values chosen for any averaging processing over each grid cell. This is mainly to reduce the possible temporal autocorrelation between the pixel values taken within a small time window (*e.g.* 3 hours). Yearly averaging and monthly averaging were performed for the grid cells and the municipal regions, respectively. The overall average and the standard deviation of AOD were calculated from the sampled AOD values for each month to reveal the seasonal variation.

The sampled AOD values were also aggregated by municipal regions, which often delimit the study area for local climate, air quality analyses. The monthly AOD means for the municipal regions were examined to capture seasonal distribution patterns. In space, the cities with a population greater than 100,000 have been selected and a statistical *t*-test was performed to find out those cities distinguishable from the general study area as a whole.

A detailed land use map and a digital elevation model were also collected as ancillary data for the study area. The land-use structure within the municipal regions and their corresponding AOD mean were also compared. Yet, only the municipal regions with land-use information were incorporated in our analysis due to the fact that complete land-use data were unavailable for the entire study area. The land-use types were aggregated into three major classes: Built-up Area, Vegetation Area, and Water Body. The yearly AOD means of the municipal regions were subsequently plotted against the fractions of the aggregated land uses within them. A correlation analysis was then performed to provide a quantitative description of the land use-AOD relationship. In addition, the digital elevation model (DEM) of southern Ontario was compared to its AOD distribution to help understand the impacts of the local topography on the aerosol dispersion or transportation.

## 5. Results and Discussion

### 5.1 Overall analysis

The observation of the collected data shows that, in southern Ontario, AOD generally varies between 0 to about 2.2 (unitless) and has an overall mean of 0.211 with a standard deviation

of 0.225. The frequency distribution of the collected AOD is shown in Fig. 2a. The availability of the valid AOD data from MODIS is highly season-dependent for southern Ontario. Due to the extremely limited number of valid AOD values (see Fig. 2b) and the lack of coverage for a great portion of the study area, MODIS can hardly provide a complete or unbiased picture of AOD for southern Ontario in January, February, March, or December. The data in these winter months were therefore excluded from the mean calculation to facilitate cross-space comparison. In other words, the yearly mean in the present study represents the AOD average over April though November.

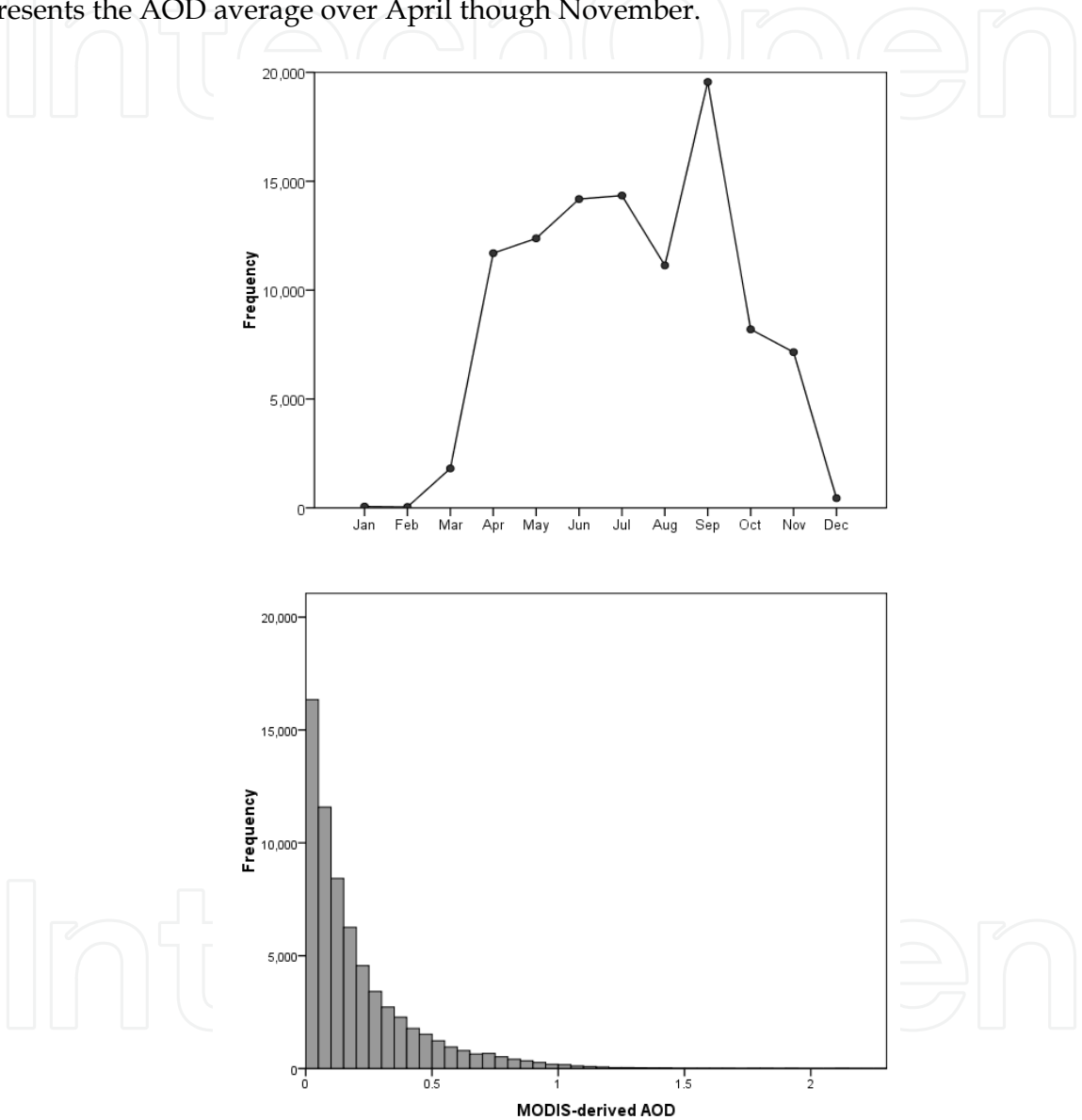


Fig. 2. Frequency distribution of valid MODIS-derived AOD measurements for the entire study period (a) and their utility for the different months (b) in southern Ontario.

Fig. 3 displays a heterogeneous distribution of the 2004 yearly AOD mean across southern Ontario. Relatively high AOD means are found in the densely populated and industrialized areas. Urban and industrial areas are considered to be the major sources of various anthropogenic aerosols, which often result in haze weather. Particularly high values are

found for Greater Toronto Area (A in Fig. 3), the belt connecting Niagara Falls, Hamilton, and London (B in Fig. 3), and the Greater Windsor Area (C in Fig. 3). This is largely attributed to their inherent high productivity of aerosol particles from manufacturing industry, heavy traffic, and geographic proximity to some U.S. cities (*e.g.* Detroit, Buffalo). Caution should be exercised when interpreting some high-AOD cells at the land/water boundaries, as applying the land algorithm to the pixels with sub-pixel water may lead to higher estimates than actual AOD values (Chu et al. 2003).

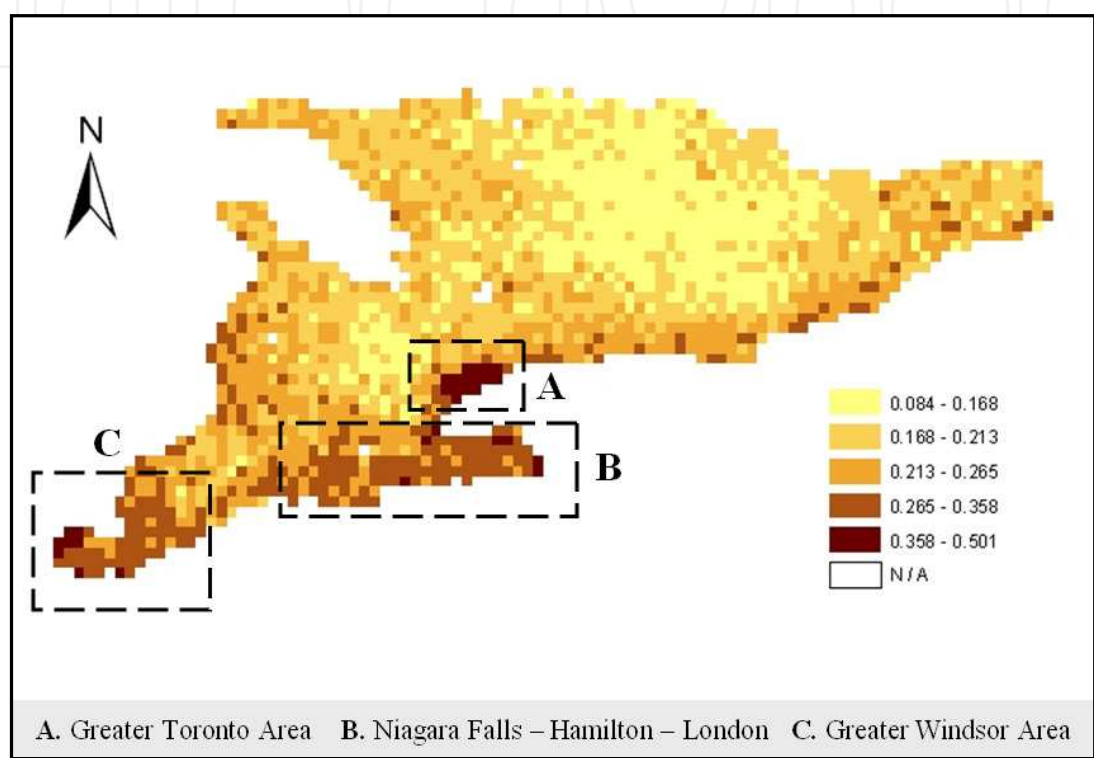


Fig. 3. Distribution of MODIS-derived aerosol optical depth (AOD) mean for the period from April to November (2004) in southern Ontario.

MODIS-derived AOD varies greatly over seasons. Fig. 4 presents the AOD mean and standard deviation as a function of month, revealing a seasonal pattern with a higher AOD level during the spring and summer months, and a lower AOD level during the fall and winter months. Accordingly, there seems to be larger variances in AOD during the spring and summer months. This is largely explained by the seasonality of atmospheric motion over the area. During summer months, weather conditions in southern Ontario are generally dominated by the Maritime Tropical air mass (highly unstable with strong turbulence) originating from the Gulf of Mexico and Caribbean Sea, bringing aerosols sourced in the U.S. In contrast, the Continental Polar air mass in winter moves over the area, bringing clean and stable air from the north and producing heavy lake-effect snows. Extensive snow cover is the main reason causing the inability to retrieve AOD in winter (Power et al., 2006). In addition, higher air temperatures tend to hold more water vapor that feeds aerosol to grow (Masmoudi et al., 2003). This is another reason causing the higher AOD levels in the summer time.



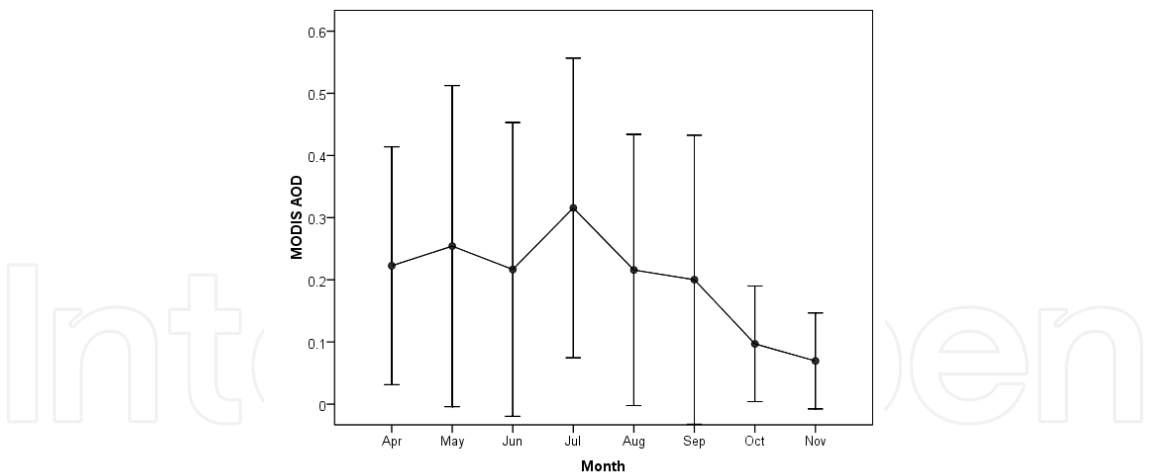


Fig. 4. Mean (point) and one standard deviation (bar) of monthly AODs for southern Ontario in 2004 (Note: January, February, March, and December are not presented because there were very few valid AOD values in these months).

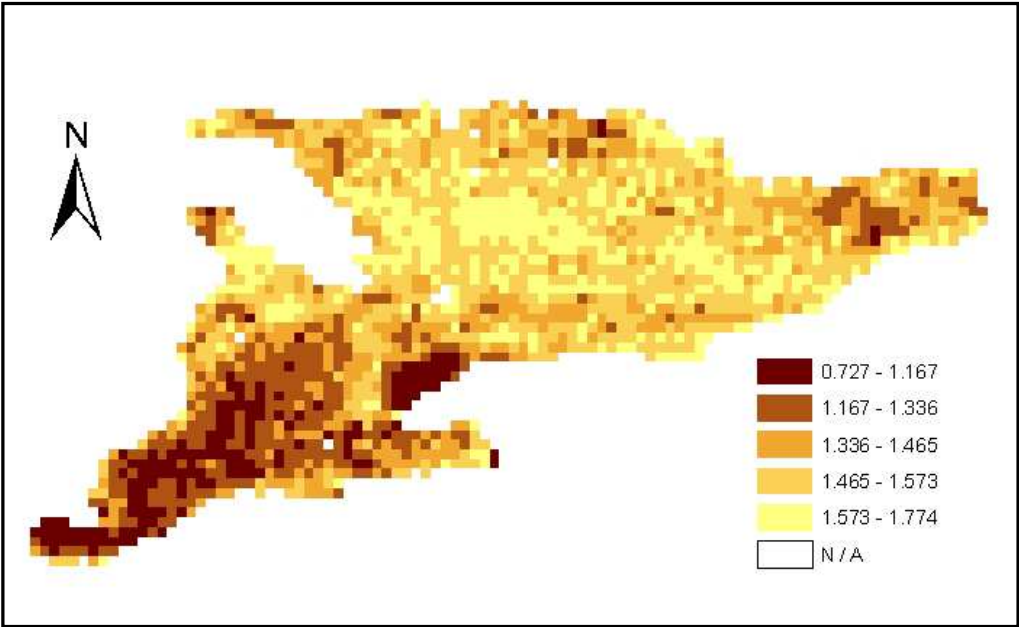


Fig. 5. Distribution of MODIS-derived Ångström exponent (AE) for the period from April to November (2004) in southern Ontario.

Fig. 5 depicts the distribution of the 2004 yearly AE mean across southern Ontario. In general, Southwestern Ontario and the Golden Horseshoe area appear to have smaller means (<1.34) of AE, indicating relatively larger sizes of the aerosols suspended over these areas. Such relatively coarser aerosols may originate and assemble from anthropogenic sources including industrial/constructional dust, soot, etc. Both the Canadian cities (local sources) located in the areas, and the U.S. cities across the Great Lakes (aerosol plumes can be transported downwind) are considered the contributors. There are large areas of concentrated agricultural lands in Southwestern Ontario. Physically produced agricultural dust is believed to account for the larger aerosol size over the area. Traffic emissions are perhaps another major source. In comparison, the northern areas (dominated by larger AE

means) are believed to be loaded with aerosols more from natural sources (*e.g.* sulfates from biogenic gases and organic matter from biogenic volatile organic compounds). Yet the result should be interpreted with caution because the AE here is a secondary derivative from MODIS AOD. MODIS-derived AE is not very accurate by comparison to AERONET AE (Remer et al. 2006); it may be biased for specific surface types or seasons (Koelemeijer et al. 2006).

5.2 Region-based analysis

The municipal regions with a low yearly AOD (0-0.2) were found to be spatially clustered, forming mainly two ‘clean’ zones (see A and B in Fig. 6). These regions are recognized as being more inland and including nearly no industrial or urban areas (further discussion is provided in Section 2.3.3). In contrast, the municipal regions with a relatively higher yearly AOD (0.2-0.3) are distributed around these two zones and take up most of the remaining portions in southern Ontario. Particularly Southwestern Ontario was recognized as having almost all the municipal regions with a relatively high yearly AOD. Moreover, there are some ‘hot’ regions (AOD>0.3) that can be clearly identified, including the Greater Toronto Area, the Niagara Falls Area, and the Greater Windsor Areas (see C, D, and E in Fig. 6, respectively).

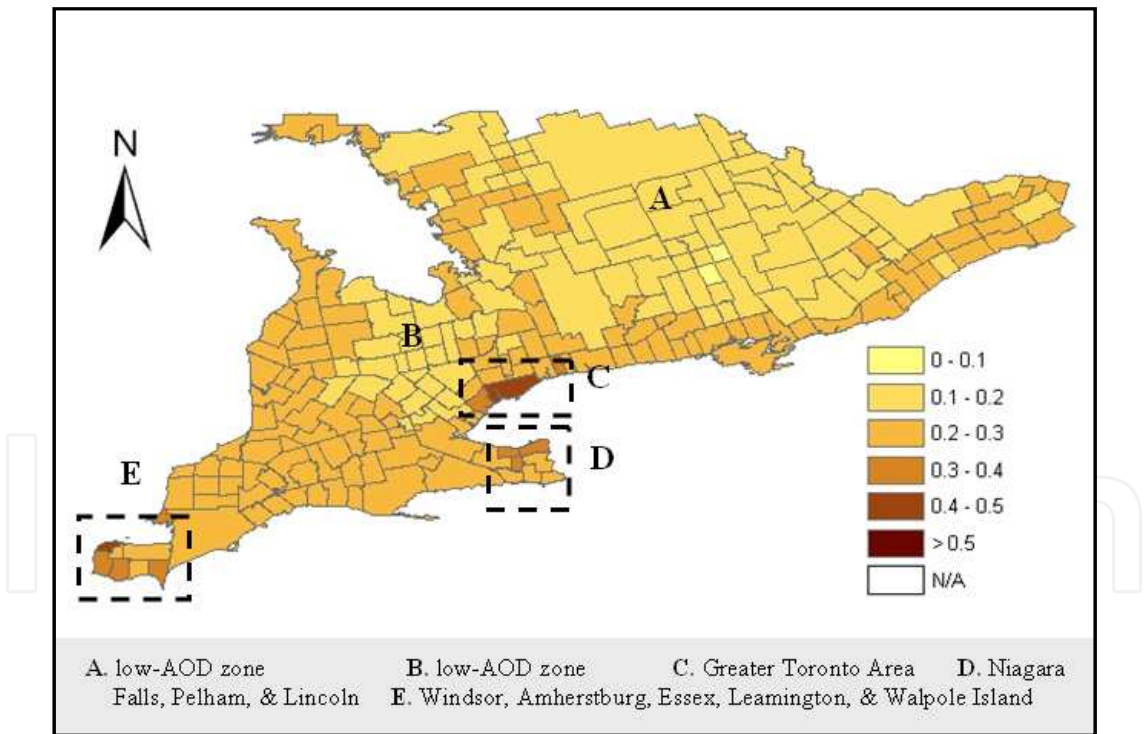


Fig. 6. 2004 yearly AOD mean over the municipal regions in southern Ontario.

Paired *t*-test between the monthly AOD for the entire southern Ontario and for each of the 17 cities with a population greater than 100,000 was conducted to determine which cities are significantly different from the study area average. A difference is considered to be significant when the associated *p*-value is less than 0.05. As can be seen in Table 1, Toronto,

Mississauga, Hamilton, and Windsor show to be significantly higher ( $t>0$ ) than the area average, while Ottawa and Cambridge are lower ( $t<0$ ). The relatively low AOD level for Ottawa, the national capital, may be explained by the large fraction of suburban and rural areas included within its municipal boundary. It is understandable that there exist significant spatial variations of AOD within such regions that hold both highly urbanized or industrialized areas and considerable suburban and agriculture/forest lands. The mean AOD over a municipal region like Ottawa tends to even off these differences and only represent the averaged level.

Municipal Regions	<i>t</i>	<i>p</i>	<i>r</i>
Toronto	5.768	0.001	0.969
Ottawa	-1.487	0.181	0.939
Mississauga	5.364	0.001	0.970
Hamilton	3.670	0.008	0.968
London	2.329	0.053	0.711
Brampton	2.872	0.024	0.938
Markham	2.263	0.058	0.830
Windsor	5.694	0.001	0.925
Kitchener	3.191	0.015	0.899
Vaughan	2.856	0.024	0.893
Burlington	1.765	0.121	0.861
Oakville	2.143	0.069	0.809
Oshawa	2.152	0.068	0.795
Richmond Hill	2.001	0.086	0.976
Kingston	1.768	0.120	0.882
Cambridge	-.305	0.769	0.662
Chatham-Kent	3.376	0.012	0.897

Table 1. Results of the paired *t*-test between the monthly AOD means of the cities with a population greater than 100,000 and those of the entire southern Ontario  
Note: *t* = *t*-value.  $p<0.05$  indicates sample means are statistically different from the study area means. *r* represents the correlation coefficient to the study area mean.

The spatial-temporal variability of MODIS-derived AOD has been investigated by mapping the monthly AOD mean of the municipal regions over April through November (Fig. 7). As there was very limited data coverage for January, February, March, and December (statistically sound mean could not be obtained for most municipal regions), their monthly AOD maps are not presented. It is clear that MODIS can not be relied upon for the aerosol data acquisition for southern Ontario during these four months. Again, this is mainly due to the extensive snow cover in winter, which greatly hampers the usability of the MODIS algorithm for AOD retrieval over land. Although there was relatively much more data available than the other winter months, data for the north part of the study area (approximately above 45°N) was widely missed in March.



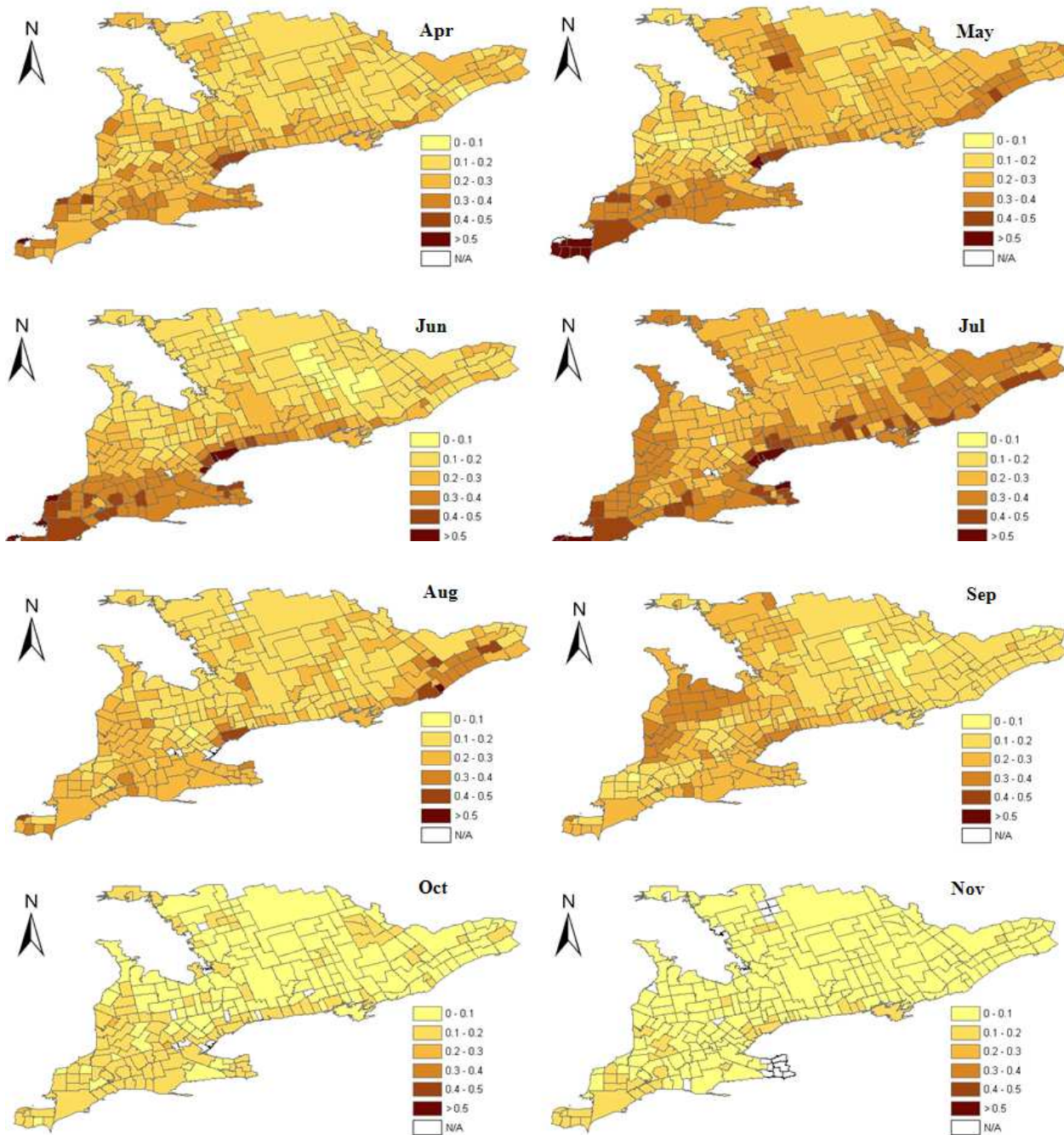


Fig. 7. Spatial and temporal variations of the monthly AOD mean over the municipal regions in southern Ontario

Visual examination of Fig. 7 showed that April experienced a moderate level of AOD overall (also supported by Fig. 4). May and June presented similar distribution patterns in Southwestern Ontario. The difference lies in that higher levels of AOD are observed for many municipal regions in Central and Eastern Ontario in May, compared with June. The reason for this remains unclear especially for some small towns with particularly high aerosol loading such as Huntsville. The Greater Toronto Area and Southwestern Ontario remain to be the areas with higher aerosol loadings in these two months, despite the inner-

section distributions of AOD were somewhat different. July exhibited the highest level of AOD in the year for most of the municipal regions. The monthly AOD mean for a large number of cities or towns reached a level of  $>0.4$  in this month. The coastal regions and the regions in Eastern Ontario widely experienced an elevated AOD level of 0.3-0.4. Due to the scope of this research, the discussion for such a phenomenally high level of AOD in July is not covered in the present paper. The AOD level dropped to its normal summer level for most municipal regions in August. The presence of relatively high levels of AOD at Eastern Ontario in July and August may be related to aerosol emissions sourced from major Québec cities such as Montréal. Although the spatial distribution of monthly AOD across the municipal regions differed in August and September, the overall study area mean remained at similar levels (0.2-0.22) for these two months (Fig. 4). Moreover, September seems to be a transition period towards a different meteorological air pollution regime at the synoptic scale, although more quantification may be needed in terms of air mass change. October and November exhibited a distinctly low level of AOD. More specifically, October saw no municipal regions with a monthly AOD of  $>0.3$ . Almost all the regions became dramatically reduced with their monthly AOD levels at this time. The overall AOD level appeared to be even lower in November, when only few municipal regions experienced a monthly AOD of 0.1-0.2, leaving the remaining regions to all have a value of  $<0.1$ . The above spatial-temporal distribution of AOD over months calls for a physical explanation. We tentatively suggest that the explanation may lie in the mesoscale meteorological processes.

As expected, the MODIS-derived AOD data appears to be patchy and lacks a consistent spatial coverage. This has greatly restricted its use in more detailed analysis, such as detection of short-term (*e.g.* one week) clusters of the municipal regions that were heavily loaded with aerosols. Attempts have been made to produce daily, weekly, and biweekly maps of AOD mean. Unfortunately, none of them have steady coverages with sufficient observations for each municipal region, even for the data-rich month of September.

### 5.3 Relate MODIS-derived AOD to land use and topography

Fig. 8 displays the land-use map (fully covering 62 municipal regions) available for the present study. The map was overlaid with the municipal region map for a zonal analysis of land-use structure. Descriptive statistics showed that the fraction of Built-up Areas (FBA) ranges from 0.1% to 78% for the municipal regions with land-use information. As can be seen from Fig. 9, regardless of seasonal changes, a municipal region's yearly AOD mean seems to be positively correlated ( $r = 0.7$ ) with its FBA. A fitted linear regression model between the two variables is able to explain almost 50% of the variability in AOD. Meanwhile, a municipal region's yearly AOD declines with the increase of its fraction of its Vegetation, although this negative correlation ( $r = -0.6$ ) is not as strong as that of the FBA-AOD relationship. These observations, to some extent, suggest that local and anthropogenic aerosols are a large contributor to the aerosol loading in southern Ontario. The urban heat island effect may be another reason; the lower albedo, higher heat capacity, and internal energy generated as a result of human activities in urban areas often causes atmospheric circulations towards the urban centers at urban/rural fringes, bringing in exogenous aerosols.



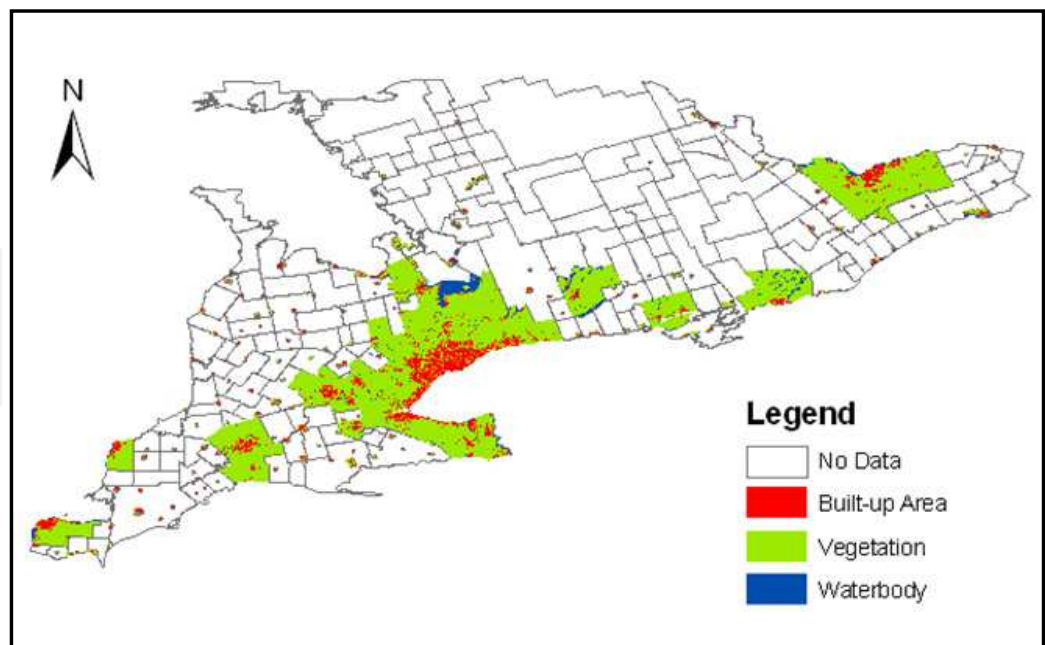


Fig. 8. Land use/cover map of certain municipal regions in southern Ontario.

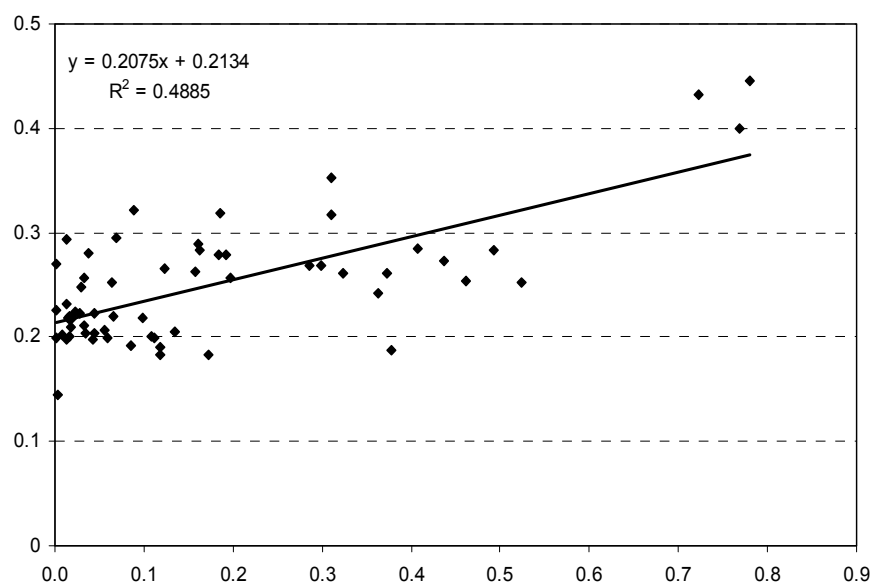


Fig. 9. Scatter plot of yearly AOD mean versus fraction of Built-up Areas (FBA) for the municipal regions.

Ideally, the land use/cover data should be weighted by their productivity of aerosols. More detailed information including road density, traffic volume, and pollution inventory are necessary in order to estimate such productivity. Another limitation with the current analysis is its exclusion of large areas of rural lands due to the lack of accurate land use/cover data for these areas. In summers, occurrences of forest fires in these areas may produce smoke aerosols and lead to short-time event-induced high levels of AOD. Such

aerosols are non-anthropogenic and can dominate the aerosol composition during the event period.

When compared with the digital elevation model (Fig. 10), the AOD distributions in southern Ontario seemed to be susceptible to topography. Interestingly, it is found that the low-AOD zones basically resemble the higher elevation upland areas (brown areas). The possible reasons to account for this observation include: (1) there are much less human activities or anthropogenic processes for aerosol production in these areas due to historic settlement; (2) the air circulations, either thermally induced (*e.g.* valley breeze) or mechanically forced (*e.g.* lee waves) by uplands, can possibly impel uptake of aerosols by posing more flux towards vegetated land surfaces, and the aerosol concentration can therefore degrade rapidly. The AOD values in these zones reflect the background aerosol loading level in southern Ontario, and may be valuable to the estimation of the net increase or decrease of local aerosol emissions.

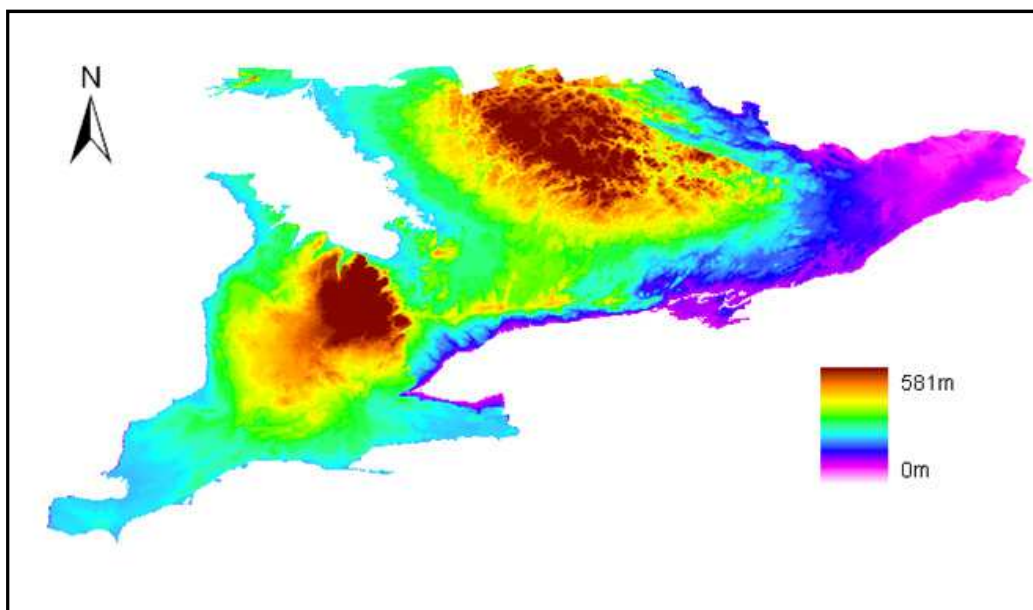


Fig. 10. The digital elevation model of southern Ontario.

## 6. Summary

This study has investigated the spatial-temporal distribution patterns of aerosols over a year in southern Ontario. It has been found that MODIS-derived AOD varies greatly across space and time in the region. In general, the Greater Toronto Area and the Greater Windsor Area experience the highest level of yearly AOD average. Summer months relate to elevated levels of AOD and stronger variations, compared to the other months. Among cities with a population greater than 100,000, Toronto, Hamilton, Mississauga, and Windsor experience a significantly higher yearly AOD than the study area average. Aerosols in Southwestern Ontario are mainly composed of relatively larger particles, resulting smaller values of Ångström exponent. The regional topography is also found to have a role to play in affecting the aerosol distribution. The two low-AOD zones identified clearly resemble the two major high elevation upland areas in southern Ontario. Moreover, AOD seems to be related with the underlying land-use structure: a higher fraction of built-up area within a

municipal region tends to correspond to a higher value of AOD. This somewhat proves the local and anthropogenic nature of a large portion of aerosols in southern Ontario, especially for the urbanized and/or industrialized areas, and can inform land-use management aiming to improve aerosol-oriented air quality. An in-depth understanding of the aerosol distribution across municipal regions in southern Ontario is expected to support decision-making for regional air quality protection or the establishment of compensation under transboundary air pollution agreements. This study is based on one year MODIS-derived AOD data in 2004. A multi year analysis should be conducted in the future to confirm or modify findings in this study.

## Acknowledgement

This research is partially supported by National Science and Engineering Research Council of Canada through a discovery grant.

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## **Air Quality**

Edited by Ashok Kumar

ISBN 978-953-307-131-2

Hard cover, 382 pages

**Publisher** Sciyo

**Published online** 18, August, 2010

**Published in print edition** August, 2010

Air pollution is about five decades or so old field and continues to be a global concern. Therefore, the governments around the world are involved in managing air quality in their countries for the welfare of their citizens. The management of air pollution involves understanding air pollution sources, monitoring of contaminants, modeling air quality, performing laboratory experiments, the use of satellite images for quantifying air quality levels, indoor air pollution, and elimination of contaminants through control. Research activities are being performed on every aspect of air pollution throughout the world, in order to respond to public concerns. The book is grouped in five different sections. Some topics are more detailed than others. The readers should be aware that multi-authored books have difficulty maintaining consistency. A reader will find, however, that each chapter is intellectually stimulating. Our goal was to provide current information and present a reasonable analysis of air quality data compiled by knowledgeable professionals in the field of air pollution.

### **How to reference**

In order to correctly reference this scholarly work, feel free to copy and paste the following:

DongMei Chen and Jie Tian (2010). Monitoring Spatial and Temporal Variability of Air Quality Using Satellite Observation Data: a Case Study of MODIS-Observed Aerosols in Southern Ontario, Canada, Air Quality, Ashok Kumar (Ed.), ISBN: 978-953-307-131-2, InTech, Available from: <http://www.intechopen.com/books/air-quality/monitoring-spatial-and-temporal-variability-of-air-quality-using-satellite-observation-data-a-case-s>

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Phone: +86-21-62489820  
Fax: +86-21-62489821



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