



# AEROCAN, the Canadian sub-network of AERONET: Aerosol monitoring and air quality applications



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## HIGHLIGHTS

- Higher AODs are observed at southeastern Canadian sites when winds come from the US.
- AOD and PM<sub>2.5</sub> are highly correlated on daily timescales in summer at polluted sites.
- AEROCAN sites with long records do not show significant AOD trends.
- Higher AODs are observed in Toronto on weekdays than weekends, indicating pollution.

## ARTICLE INFO

### Article history:

Received 7 March 2017

Received in revised form

15 August 2017

Accepted 18 August 2017

Available online 19 August 2017

### Keywords:

Remote sensing

Canada

Aerosols

## ABSTRACT

Previous studies have demonstrated the utility of AERONET (Aerosol Robotic Network) aerosol optical depth (AOD) data for monitoring the spatial variability of particulate matter (PM) in relatively polluted regions of the globe. AEROCAN, a Canadian sub-network of AERONET, was established 20 years ago and currently consists of twenty sites across the country. In this study, we examine whether the AEROCAN sunphotometer data provide evidence of anthropogenic contributions to ambient particulate matter concentrations in relatively clean Canadian locations. The similar weekly cycle of AOD and PM<sub>2.5</sub> over Toronto provides insight into the impact of local pollution on observed AODs. High temporal correlations (up to  $r = 0.78$ ) between daily mean AOD (or its fine-mode component) and PM<sub>2.5</sub> are found at southern Ontario AEROCAN sites during May–August, implying that the variability in the aerosol load resides primarily in the boundary layer and that sunphotometers capture day-to-day PM<sub>2.5</sub> variations at moderately polluted sites. The sensitivity of AEROCAN AOD data to anthropogenic surface-level aerosol enhancements is demonstrated using boundary-layer wind information for sites near sources of aerosol or its precursors. An advantage of AEROCAN relative to the Canadian in-situ National Air Pollution Surveillance (NAPS) network is the ability to detect free tropospheric aerosol enhancements, which can be large in the case of lofted forest fire smoke or desert dust. These aerosol plumes eventually descend to the surface, sometimes in populated areas, exacerbating air quality. In cases of large AOD ( $\geq 0.4$ ), AEROCAN data are also useful in characterizing the aerosol type. The AEROCAN network includes three sites in the high Arctic, a region not sampled by the NAPS PM<sub>2.5</sub> monitoring network. These polar sites show the importance of long-range transport and meteorology in the Arctic haze phenomenon. Also, AEROCAN sunphotometers are, by design and due to regular maintenance, the most valuable monitors available for long term aerosol trends. Using a variety of data analysis techniques and timescales, the usefulness of this ground-based remote-sensing sub-network for providing information relevant to air quality is demonstrated.

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## 1. Introduction

Aerosols are small airborne liquid or solid particles. They are of central importance throughout the atmosphere and affect meteorology, air quality, and climate. In the troposphere, aerosols are a significant source of uncertainty for radiative forcing (Myhre et al.,

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2013). Fine-grained particulate matter is also among the most important atmospheric parameters in terms of air quality (Stieb et al., 2008). Aerosols also indirectly affect air quality because they affect the photolytic flux reaching the surface (e.g. Parrington et al., 2013). Aerosol optical depth (AOD) is a unitless quantity representing the vertically integrated extinction of radiation, comprised of scattering and absorption terms. Extinction is a function of the aerosol number, size, and composition. Thus, AOD is only a qualitative indicator of aerosol surface area, however it serves as a valuable observational constraint for heterogeneous chemistry modelling, particularly since surface area or particle size information is more difficult to obtain remotely.

In order to validate and augment space-based remote sensing of aerosols, in which the primary retrieval quantity is AOD, the Aerosol Robotic Network (AERONET, <http://aeronet.gsfc.nasa.gov>) was established in the early 1990s (Holben et al., 1998). A federation of national ground-based remote sensing aerosol networks, AERONET consists of over 800 sunphotometers worldwide. The Canadian AEROCAN network is one such national network within AERONET and began in 1997. Sunphotometer measurements at sites now within the AEROCAN network began in 1994 with four Cimel instruments (<http://www.cimel.fr>) donated to the Université de Sherbrooke by the Canada Centre for Remote Sensing. Environment Canada gently took over the reins of this kernel of a network and, by 2004, had set it on a much more operational path with improvements in logistical, optical and human resources.

Recently, there has been an increasing effort to derive surface-level mass densities of particulate matter (PM) from satellite AOD measurements. Specifically, the mass density of PM with median aerodynamic diameter  $<2.5 \mu\text{m}$  ( $\text{PM}_{2.5}$ ) is now derived from satellite AOD measurements at a wavelength of  $\sim 500 \text{ nm}$  (e.g. van Donkelaar et al., 2006). This approach is especially valuable in locations where in-situ observations of ground-level PM are not routine (e.g. Chen et al., 2013). AERONET data, including AEROCAN sites, have served to quantify and correct for biases in simulated and satellite-observed AOD in such studies (van Donkelaar et al., 2013; van Donkelaar et al., 2016).

Similar to what has been done using satellite AOD, AEROCAN AOD data have been used to investigate the seasonal and spatial correlation with  $\text{PM}_{2.5}$  (van Donkelaar et al., 2006) and the spatial correlation during a 5 week summer period (Drury et al., 2010) over North America. Li et al. (2015) also investigated how AERONET-measured AODs over North America (Canada and United States) capture the spatial variability in  $\text{PM}_{2.5}$  on a monthly timescale. AERONET data in general have been used to relate AOD to ground-level PM on shorter timescales, including correlations of individual  $\text{PM}_{10}$  and co-located 440 nm AOD measurements (Bennouna et al., 2016), as well as correlations of  $\text{PM}_{2.5}$  and AERONET AOD measured or interpolated to various visible or near-infrared wavelengths (Green et al., 2009; Crumeyrolle et al., 2014; Chen et al., 2013; Sano et al., 2010). There have also been efforts to make  $\text{PM}_{2.5}$  inferences using individual satellite-based AOD measurements, although the correlation between individual AODs and ground-based  $\text{PM}_{2.5}$  in some locations tends to be too low to be useful for air quality monitoring (e.g. Sioris et al., 2017). Accounting for the boundary layer height and relative humidity can improve the correlation considerably (Zheng et al., 2015). The meteorology and the altitude dependence of the particle shape and size distribution are implicitly taken into account when the  $\text{PM}_{2.5}$ /AOD ratio from a chemical transport model (CTM) is used to convert observed AOD into  $\text{PM}_{2.5}$  (Drury et al., 2010). AERONET AOD measurements are inherently more accurate than those from satellites because of the simpler viewing geometry and higher signal-to-noise ratio of the spectral information. Because of the higher accuracy and temporal

frequency relative to satellite AOD measurements, this paper focusses on the relationship between surface-level  $\text{PM}_{2.5}$  and observed AOD using a variety of AEROCAN sites.

Total column AOD measurements such as from AEROCAN are also useful for detecting long range transport of aerosols from episodic phenomena such as forest fires, dust storms, and volcanic eruptions. Volcanic sulfate droplets are sub-micron in size whereas ash can be coarser. Dust also tends to be coarse but can be bimodal (McKendry et al., 2007), with the fine mode being relevant for air quality (Hsu et al., 2016). Forest fire smoke tends to be fine-grained.

The main focus of the paper is to investigate the ability of AEROCAN network to provide information relevant to Canadian air quality. While aforementioned studies have indicated that AERONET AODs are significantly correlated with  $\text{PM}_{2.5}$  over North America on monthly to seasonal timescales, here the focus is on Canadian sites exclusively and shorter timescales (hourly, daily, and weekly variations). To that end, statistical analyses such as the weekly cycle of AOD and the dependence of AOD on wind direction are presented below. Regional variations in AOD also provide insight into the origin of the enhanced particulate matter concentrations observed by sunphotometers. This paper also shows examples of how boundary layer height variability complicates the AOD-PM relationship.

## 2. Data sources

### 2.1. AEROCAN

The AEROCAN sub-network consists of twenty sites across Canada as shown in Fig. 1 and Table 1. AERONET sunphotometers (Cimel model CE318) operate autonomously in direct sun and skylight measurement modes (Holben et al., 1998), but this study focusses mainly on the former. In the direct sun mode, measurements are made at eight wavelengths, typically 340, 380, 440, 500, 675, 870, 940 and 1020 nm. Instrumental gain and offset are determined through a calibration (Holben et al., 1998). Using Langley's (1904) extrapolation method, the voltage for an air mass of zero (top-of-atmosphere) is determined for each wavelength, with Mauna Loa serving as a reference location (Holben et al., 1998). Long-term stability is monitored and filters are replaced every two years. The temperature sensitivity of the 1020 nm detector is also adjusted through the use of a reference temperature. The 940 nm channel is used to measure the column abundance of precipitable water vapour (PWV). The ability to simultaneously measure PWV can be useful for diagnosing whether sampled air masses originated from lower latitudes (with higher specific humidities) and for correlating AOD with air mass provenance (Holben et al., 2001). In this study, we use version 2.0 Level 2 AOD data, which have a latency of several months, obtained from the AERONET website (<http://aeronet.gsfc.nasa.gov>). AOD measurements at 500 and 340 nm are used herein. Note that Level 1.5 (cloud-screened) data are available only hours after the measurement occurs, but only Level 2 data are quality-assured. Cloud screening and quality control are described by Smirnov et al. (2000).

The wavelength ( $\lambda$ ) dependence of AOD is expressed using the Ångström exponent  $\alpha$  (Ångström, 1929) and is of the form  $\lambda^{-\alpha}$ . Recognizing that the particle size distribution generally tends to be bimodal, O'Neill et al. (2003) developed a spectral deconvolution algorithm (SDA) based on the AOD spectral dependence and higher order spectral derivatives (e.g.  $\alpha$ ,  $\alpha'$ ) to quantify fine and coarse mode components of the AOD (reported at a reference wavelength of 500 nm) and applied it to AERONET data. SDA outputs are currently an operational product of AERONET and version 2.0 of the SDA product is used here. This separation of AOD modes is relevant

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