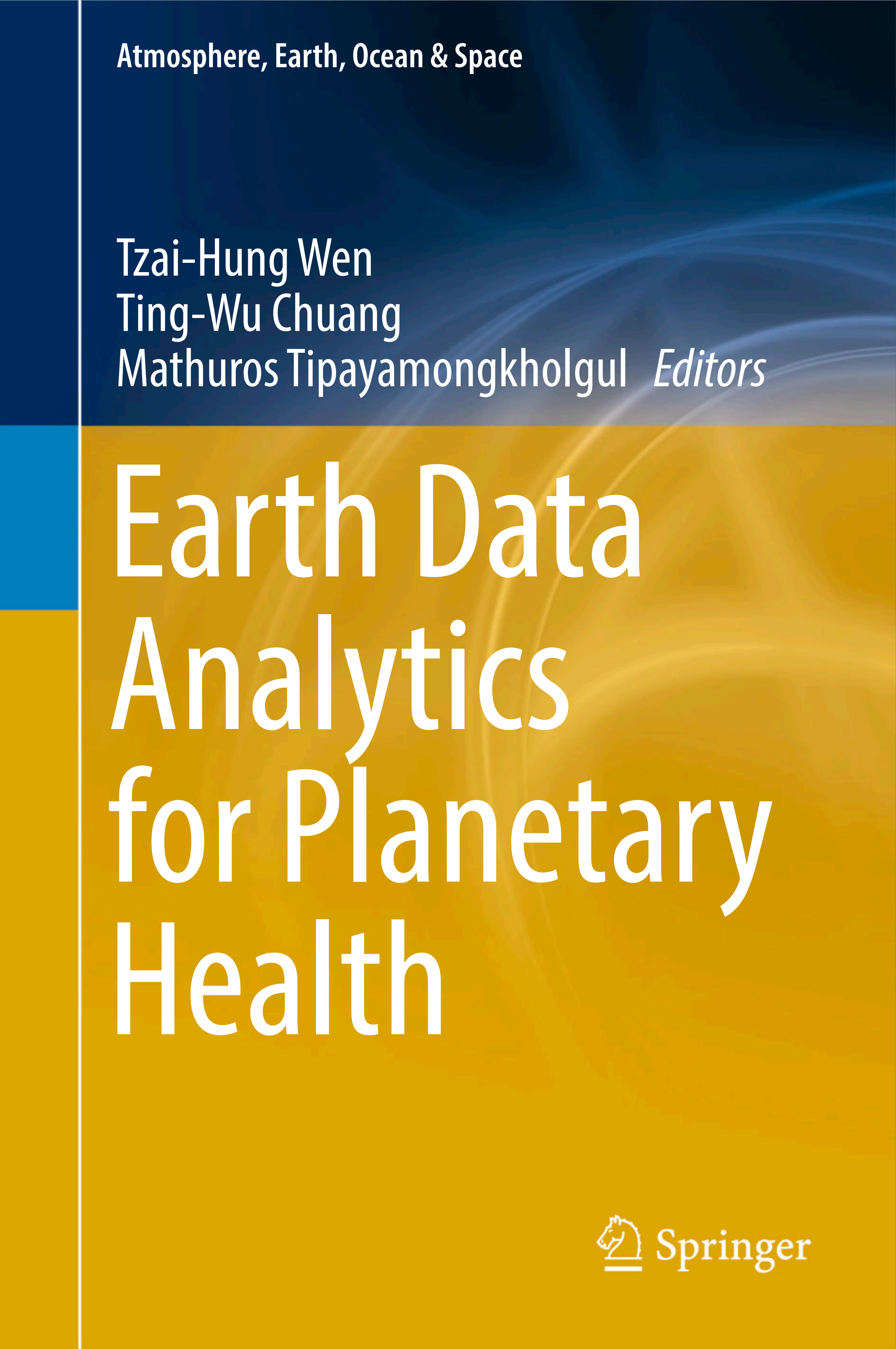

Atmosphere, Earth, Ocean & Space

Tzai-Hung Wen
Ting-Wu Chuang
Mathuros Tipayamongkholgul *Editors*

Earth Data Analytics for Planetary Health

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Contents

Part III Data and Methodological Issues for Health Studies

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Part I
Environmental Quality Monitoring

Chapter 1

Applications of Remote Sensing for Air Pollution Monitoring in Thailand: An Early Warning for Public Health

Arika Bridhikitti

Abstract There are also consistent findings on the adverse effects of air pollution on public health in Thailand. Small size particulate matter, or $PM_{2.5}$, is the most pronounced air pollutant during the haze crisis. $PM_{2.5}$ often comes along with other polluted gases, including carbon monoxide (CO), oxides of nitrogen ($NO_x = NO + NO_2$), sulfur dioxide (SO_2), ozone (O_3), and volatile organic compounds (VOCs). This chapter presents various applications of remote sensing technology for air pollution monitoring, warning, and forecasting. These applications can help assess human exposure to air pollution and determine health risks associated with air pollution. The presentation is divided into four sections. The first section provides an overview of Earth Observing Satellites and current remote sensing technology for air pollution observations. The second section is on assessing the magnitude of atmospheric pollutants and human exposure levels from remote sensing. The third section is on air pollution source identification using remote sensing technology. Finally, the fourth section discusses the possibility of employing satellite information for forecasting haze episodes as the early warning tool. The presentation is based on the recent deployment of remote sensing technology for air pollution monitoring, especially reported for the cases of Thailand and the Southeast Asian region.

Keywords Satellite · Remote sensing · Air quality forecast · Air pollution · Particulate matter · Southeast Asia

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1.1 Introduction

Air pollution in Thailand has become public attention nowadays. In the dry season from December to March, the pollution is often reported at harmful levels, exceeding the national air quality standard. Pinichka et al. [1] studied the burden of disease attributed to air pollution and found that NO_2 and $PM_{2.5}$ could account for 10% and 7.5%, respectively, of the disease burden for all mortality. The $PM_{2.5}$ could also contribute to 16.8% of lung cancer cases and 14.6% of cardiovascular cases, whereas the NO_2 was responsible for 7.8% of respiratory mortality [1]. Jenwitheesuk et al. [2] also showed evidence on $PM_{2.5}$-induced risk of colon cancer, with 15% risk increased for every ten micrograms $PM_{2.5}$ m^{-3} increased. Furthermore, US researchers have strong evidence showing that short-term exposure to $PM_{2.5}$ could significantly increase the risk of COVID-19 cases and death [3]. Not only the small-size aerosol, but the coarse-size particulate matter (PM_{10}) could also suddenly increase in hospital admissions as found a strong association between the PM_{10} level and the number of cardiovascular and respiratory admission in Bangkok, the most populated city in Thailand [4].

The Thai Government set up several policies and solutions to tackle haze pollution. The haze mitigation policy includes inspection and maintenance of vehicles, mandating higher quality fuel, and balancing productivity and environmental conservation in agricultural production [5]. During the haze episode, the policy relied on single command-and-control, framed by the central and provincial government [6]. The policies include prohibiting biomass burning, applying water sprays in public areas, roadside inspection on vehicle exhaust emissions, etc. [7]. Moran et al. [5] criticized that key issues of unsuccessful haze abatement in Thailand are low public participation and poor enforcement of laws or regulations. Scientists recommended policy outlines to minimize health effects from air pollution in the short term and eliminate the haze in the long run. The policy outlines included improvement of capacities to monitor, assess source inventory, and forecast air pollution, probably by incorporating applications of satellite retrievals in combination with ground measurements to fill spatial monitoring gaps [7, 8].

Satellite technology is widely applied for environmental monitoring since it provides spatial advantages for understanding the atmosphere and the land surface at the corresponding timeframe. Since air pollution is mainly released from surface activities, satellite observations could be helpful to provide strong connections between hot spots and pollution plumes or between urban land cover and heat island zone. The satellites could have multiple sensors onboarded, and each sensor was designed to capture specific radiative bands with certain viewing angles. Many Earth Observing Satellites detect solar reflectance and long-wave radiation from the Earth. These electromagnetic spectrums are appropriate for observing Ozone, Aerosol, Hydrocarbons, Greenhouse Gases, and Water vapor in the atmosphere. Some satellite sensors, such as Multiangle Imaging Spectroradiometer (MISR) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), provide aerosol optical properties, beneficial for aerosol source identification. Furthermore, ground-based remote sensing, such as Aerosol Robotic Network or AERONET, is typically used to validate satellite products. It can provide scattering and extinction properties of the atmospheric aerosols with a high temporal resolution by tracking direct sun and sky radiances.

1.2 Overview Earth Observing Satellites and Current Remote Sensing Technology for Air Pollution Observations

1.2.1 Earth Observing Satellites

By observing the Earth at the top of the atmosphere, satellite remote sensing can provide aerosol and gaseous compositions in the total atmospheric column basis. With approximately 1 μm and smaller, the aerosol highly scatters the energy spectrum in the visible to the near-infrared band from 300 to 1,000 nm. In addition, some types of aerosol absorb energy. The absorbing aerosols include black carbon (absorb both solar and thermal radiation) and mineral dust (scatter sunlight but absorb thermal infrared) [9]. The spectrophotometer is designed to observe solar radiation, and it can measure the extinction (both scattering and absorption) of the solar beam attributed to aerosol, called aerosol optical depth (AOD). Several satellite sensors have been previously employed for the studies of air pollution monitoring and assessment in Thailand. The summary of those sensors is detailed in Table 1.1.

Among the satellites, A-train (afternoon train) satellite constellation can be advantageous for atmospheric observation due to its combining multiple satellite remote sensors to better understand atmospheric and land dynamics. The constellation recently consisted of four satellites, orbiting in sequences, which are OCO-2 (launched in 2014), GCOM-W1 (since 2012), AQUA (since 2002), and AURA (since 2004) [10]. The satellites cross the equator around 1:30 PM local time with a 16-day repeating cycle.

The OCO-2 stands for Orbiting Carbon Observatory-2. The primary mission of OCO-2 is to quantify atmospheric carbon dioxide by its absorption of the visible band [11]. The GCOM-W1 stands for the Global Change Observation Mission-Water Satellite 1. It can explain the water cycle and climate change by observing the atmosphere and water bodies [12]. The GCOM-W1 is onboard with the Advanced Microwave Scanning Radiometer 2 (AMSR2), detecting microwave radiated from the ground, the water surface, and atmospheric gases, primarily greenhouse gases and water [12]. AQUA is designed to provide information about the Earth's hydrosphere. Furthermore, AQUA also enables the observation of aerosol via Moderate Resolution Imaging Spectroradiometer (MODIS) instrument and greenhouse gases via the Atmospheric Infrared Sounder (AIRS) along with the Advanced Microwave Sounding Unit (AMSU-A). AURA consists of four instruments to provide comprehensive studies on stratospheric and tropospheric compositions, including ozone,

Table 1.1 Summary of satellite sensors typically used for air pollution monitoring in Thailand

Sensors	Satellite	Standard detecting air pollution products	Temporal resolution	Spatial resolution, m	Reference
Moderate Resolution Imaging Spectrophotometer (MODIS)	TERRA since 2000, AQUA since 2002	Aerosol optical depth with a combined land and ocean algorithms	Level 2: Daily Level 3: Daily, 8-day, Monthly	Level 2: 10 km × 10 km (at nadir) Level 3: 1° × 1°	NASA Atmosphere Discipline Team Imager Products, https://modis-images.gsfc.nasa.gov/products.html
		Aerosol optical depth with dark target and deep blue algorithm	Level 2: Daily Level 3: Daily, 8-day, Monthly	Level 2: 10 km × 10 km (at nadir) and 3 km × 3 km (at nadir) Level 3: 1° × 1°	
		Aerosol optical depth with Multi-Angle Implementation of Atmospheric Correction, or MAIAC, algorithm	Daily	Level 2: 1 km × 1 km (at nadir)	
Measurements of Pollution in the Troposphere (MOPITT)	TERRA since 2000	CO Total Column	Daily, Monthly	Level 3: 1° × 1° horizontally, 10-level vertical (surface, 900 hPa, 800 hPa, …, 100 hPa)	NASA TERRA, https://terra.nasa.gov/about/terra-instruments/mopitt
		CO Mixing Ratio for the layer above each pressure level			
		CO Mixing Ratio at the surface			

(continued)

Table 1.1 (continued)

Sensors	Satellite	Standard detecting air pollution products	Temporal resolution	Spatial resolution, m	Reference
Multi-angle Imaging Spectroradiometer (MISR)	TERRA since 2000	Aerosol Optical Depth at 550 nm (also *including absorption, non-spherical, small-mode, medium-mode, large-mode*) Ångström Exponent at 550 and 860 nm	Level 3: Daily, Monthly, Quarterly, and Yearly	Level 2: 4.4 km × 4.4 km Level 3: 0.5° × 0.5°	NASA Jet Propulsion Laboratory, California Institute of Technology, https://misr.jpl.nasa.gov/
Ozone Monitoring Instrument (OMI)	AURA since 2004	Total column ozone: DOAS technique	Level 3: daily, monthly	Level 2: 13 km × 48 km at nadir Level 3d: 1° × 1° Level 3e: 0.25° × 0.25°	[16]
		Total column ozone: TOMS version 8 method			
		Aerosol: near UV algorithm			
		Aerosol: multi-wavelength algorithm			
		Ozone profile			
		Total column SO_2, HCHO, BrO, OClO, NO_2			

(continued)

Table 1.1 (continued)

Sensors	Satellite	Standard detecting air pollution products	Temporal resolution	Spatial resolution, m	Reference
Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)	CALIPSO since 2006	Aerosol Profile	Level 2: ~ 2 to 3 times per month	Level 2: 5 km × 5 km horizontal, 60 m vertical in the troposphere and 180 m vertical in the stratosphere	NASA, https://www-calipso.larc.nasa.gov/
		Vertical Feature Mask (including aerosol subtype)		Level 2: 5 km × 5 km horizontal, 1 km vertical (from 0 to 30 km)	
		Tropospheric Aerosol Profile (similar to Vertical Feature Mask)	Level 3: Monthly	Level 3: 2° latitude × 5° longitude, 60 m vertical from 0.5 to 12 km	

(continued)

Table 1.1 (continued)

Sensors	Satellite	Standard detecting air pollution products	Temporal resolution	Spatial resolution, m	Reference
Visible Infrared Imaging Radiometer Suite (VIIRS)	Suomi NPP since 2011	Level 2 (or Environmental Data Record, EDR): aerosol optical thickness (AOT), aerosol particle size parameter (include Ångström exponent at 445 and 672 nm over land and at 865 and 1610 nm over the ocean), and suspended matter (include aerosol type and smoke concentration) Note: *available for Deep Blue and Dark Target algorithms as well*	Level 2: Daily Level 3: Daily, Monthly	Level 2: ~ 6 km × 6 km at nadir Level 3: $1^o \times 1^o$	[17–19]
		Aerosol data: Deep Blue Algorithm	Level 3: Daily, Monthly		

Note Level 1 is calibrated, and geolocated product, Level 2 is derived geophysical variables at the same resolution and location as Level 1 source data, or swath products, Level 3 is gridded variables in derived spatial and/or temporal resolutions water, greenhouse gases, halogen compounds, oxides of nitrogen, carbon monoxide, and aerosols [13]. The AURA sensors include the High Resolution Dynamics Limb Sounder (HIRDLS), the Microwave Limb Sounder (MLS), the Ozone Monitoring Instrument (OMI), and the Tropospheric Emission Spectrometer (TES) [13].

Besides the AQUA satellite, the MODIS instrument is also onboard the TERRA satellite to provide a higher temporal resolution of the atmospheric aerosol. The TERRA passes to tropic at around 10.30 AM (ascending) and 10.30 PM (descending), whereas the AQUA is around 1.30 PM (ascending) and 1.30 AM (descending). Thus, their combined product can be provided four times daily. Even though aerosol observation can only perform in the daytime due to the requirement of light scattering, the nighttime satellite imagery can provide helpful information on socioeconomic parameters, such as population density and gross domestic product, and greenhouse gas emissions [14]. Thus MODIS product quite temporally advantages over other instruments and is universally employed for ground-level air pollution monitoring.

1.2.2 Ground-Based Remote Sensing

With currently more than 1,000 stations (see Fig. 1.1) and the number is growing, the AERONET (Aerosol Robotic Network, https://aeronet.gsfc.nasa.gov/) provided good spatial coverage of aerosol and cloud in the atmosphere. It is widely used as ground truth measurement for satellite retrievals of aerosol around the world. Currently, a total of 21 AERONET sites are based in Thailand. The AERONET program was established by the National Aeronautics and Space Administration (NASA), and LOA-PHOTONS, the French National Observatory for Aerosol, has been operated for more than 25 years. The AERONET aerosol products are measured by sun and sky photometers to measure direct and diffuse radiation. Details on the AERONET products are in Table 1.2. The aerosol products include spectral aerosol optical depth (AOD) and aerosol inversions, which provide aerosol microphysical and radiative properties. In parallel, the NASA Micro-Pulse Lidar Network (MPLNET: https://mplnet.gsfc.nasa.gov/) operates in conjunction with the AERONET to provide vertical integration structures of aerosol and cloud. The MPLNET project started with full operation in 2000. The MPLNET has three active sites in Thailand—Princess Sirindhorn Astro Park in the North, Silpakorn University in the Central, and Songkhla Regional Observatory in the South. Nonetheless, the current aerosol model cannot sufficiently describe vertical aerosol extinction measured during field campaigns over the Indian Ocean [15].

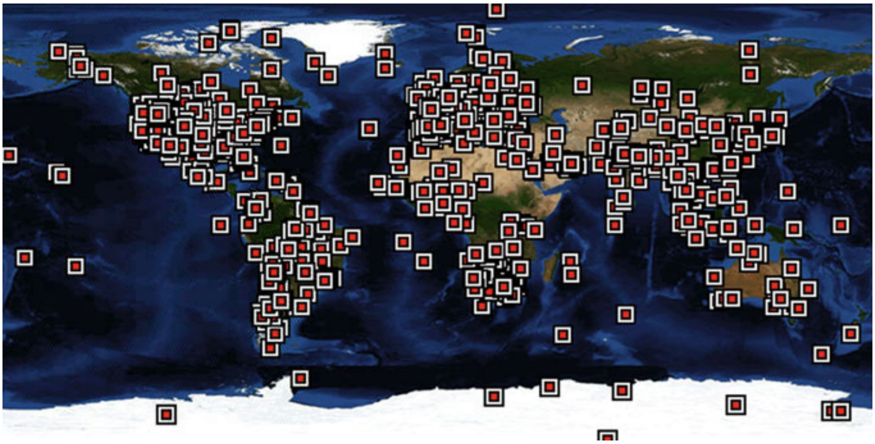

Fig. 1.1 AERONET sites (AERONET, 28 August 2021, retrieved from https://aeronet.gsfc.nasa.gov/)

Table 1.2 Products from direct sun measurements and aerosol optical properties from sun-sky photometers inversion products acquired from AERONET (https://aeronet.gsfc.nasa.gov/new_web/data.html)

AERONET products	Unit	Range
Direct sum measurement products		
Aerosol optical depth (AOD) Levels 1.0, 1.5, and 2.0, AOD (λ)	unitless	Level 1.0 unscreened Level 1.5 cloud screened Level 2.0 quality assured
Angstrom parameter, AE at 440–870 nm	Unitless	
Total water vapor at 940 nm	cm^3/cm^2 or $g\ cm^{-2}$	
Aerosol inversion products		
Volume particle size distribution, dV(r)/dlnr	$\mu m^3/\mu m^2$	$0.05\ \mu m \le r \le 15\ \mu m$
Volume concentration, C_v	$\mu m^3/\mu m^2$	For total, fine, and coarse aerosol modes Note: the fine and coarse separation point is the minimum within 0.439 to 0.992 μm
Volume median radius, r_v (mean logarithm of radius)	μm	
Standard deviation from r_v	μm	
Effective radius, r_{eff}	μm	
Real-part refractive index, n(λ)	Unitless	$\lambda = 440, 675, 870, 1{,}020$ nm 83 scattering angles, $\sim 7^o \le \Theta \le \sim 170^o$
Imaginary-part refractive index, k(λ)	Unitless	
Single scattering albedo, SSA(λ)	Unitless	
Phase function for each scattering angle, P(Θ, λ)	Unitless	
Asymmetry parameter for each phase function, cos(Θ)	Unitless	

1.3 Assessing Magnitude and Extents of Atmospheric Pollutants and Human Exposure Level from Remote Sensing

1.3.1 Tropospheric Ozone O_3 and Its Precursors

Once the tropospheric O_3 is generated, it can disintegrate into OH-radical. Though both the O_3 and OH-radical have short-lived in the environment, they have high oxidation potential, which can harm the soft tissues of plants, animals, and humans. Several previous studies confirmed that the O_3 could significantly increase human mortality [20–22]. The ozone is not directly emitted from the sources. It is the product of the photochemical reaction, in which the precursors mainly are NO_x and non-methane volatile organic compounds.

In Southeast Asia, biomass burning is the key source of O_3 and its precursors [23, 24]. Mekaumnuaychai et al. [25] and Yimlamaid et al. [26] employed satellite retrievals to assess the ozone precursors across Thailand. They found that the formaldehyde (HCHO) retrievals from the OMI/AURA satellite may not well reach the ground level, but the NO_2 retrievals from OMI/AURA and other satellites can represent the ground levels well in dry seasons [25, 26]. Furthermore, the UV radiation product of OMI can infer surface UV radiation with aerosol correction [27, 28]. The UV radiation provides energy driving photochemical reaction for O_3 generation in the troposphere. However, since the OMI provides total-column-based O_3, it may not sufficiently represent the ground levels. Tropospheric O_3 can be estimated by subtracting the OMI total column ozone with the MLS stratospheric ozone, which both OMI and MLS sensors are onboard the AURA satellite [24]. Thus, the data acquired from the OMI/MLS is recommended for assessing variation in tropospheric ozone and suggesting mechanisms for surface ozone control.

1.3.2 Aerosol Loading

Aerosol optical depth (AOD) is one of the aerosol optical products retrievable from satellites with visible to near-infrared band detectors. Satellite remote sensing is advantageous for studying long-term aerosol trends in regional to global scales [29]. Mehta et al. [29] employ satellite retrievals (both MODIS and MISR-Multiangle Imaging Spectroradiometer) for studying regional trends of aerosol magnitude. Their finding showed a noticeable increase in annual AOD over Southeast Asia from September to May, covering post- and pre-monsoon season [29]. The CSR, United States, attempts to predict air quality from MODIS AOD observation and to isolate local sources from the long-range transport sources using ground observation networks [30]. Though AOD is strongly affected by the amount of aerosol scattering and absorption, the AOD may not reach the ground level. The performance of the