

Monitoring Air Pollution Using Satellite Data

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Abstract

Millions of people in the globe are suffering from series health problems that result from air pollution, which emphasizes the importance of monitoring air pollution. Satellite remote sensing is a valuable tool to facilitate a better understanding of the pollutants. Satellite data can be used to measure and map air pollution due to its capabilities of providing complete views of large areas in only one image regularly due to the good temporal resolution of various satellite sensors. The variety of satellites offers the opportunity to estimate different air emissions such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ammonia (NH_3), carbon monoxide (CO), some volatile organic compounds (VOCs), and aerosol optical depth (AOD), from which surface particulate matter ($\text{PM}_{2.5}$).

This paper presents a review of the capabilities of different satellite remote sensing in measuring air pollutants and the methods of processing and accessing satellite data for the mapping of pollutant concentrations.

Keywords

Remote Sensing, Satellite Data, Air Quality and Air Pollution

1. Introduction

Millions of people around the globe are suffering from series health problems due to extensive exposure to air pollutants such as nitrogen dioxide (NO_2), as particulate matter (PM), ozone (O_3), and sulfur dioxide (SO_2). In 2018, the World Health Organization (WHO 2018) reported that over 4.2 million people were dead because of air pollution. Also, according to WHO, about 90% of the world's population lives in places where the rate air pollutants are more than the WHO air criteria (WH, 2018). Therefore, air pollution attracted the attention of world. Many countries established ground stations to monitor the air quality, but the data collected by this station is not enough to map air pollution because air quality is spatially and temporal variable. Satellite remote sensing is a valuable tool for the management of air pollution as satellite images can cover a large area in one image, and due to its temporal resolution (Hadjimitsis et al. 2012).

Using satellite images in monitoring air pollution started in the 1970s by using the Advanced Very High Resolution Radiometer (AVHRR), Landsat, and GOES. Although the three instruments were designed to monitor the surface and meteorological field, they were used to detect some air pollutants such as particles over ocean and sulfate that results from volcanoes. Satellite remote sensing that was designed for trace tropospheric gases started in 1978 with the launch of the Total Ozone Mapping Spectrometer (TOMS) instrument onboard of Nimbus 7 satellite by NASA (Martin 2008). Satellite remote sensing offers different spatial and temporal resolutions. The spatial resolution ranged from 40x320 km for GOME to 0.25 km for MODIS, while the temporal resolution ranged from 9 days for MISR to 0.5 days for IASI.

There are several studies in monitoring and mapping air pollutants using satellite images. For example, OMI was used to monitor NO_x emissions in different areas, including Colombian territory (Grajales and Baquero-bernal 2014), mid-Atlantic US (Goldberg et al. 2017), United States (Boersma et al. 2008), Asia (Zhang et al. 2008), the Middle East (Beirle et al. 2011), and Europe (Curier et al. 2014). Also, OMI was used to measure the emissions of SO_2 in North America (Fioletov et al. 2011). The relationship between MODIS AOT and $\text{PM}_{2.5}$ was the core of other studies [11, 12].

This paper presents a review of the capabilities of different satellite remote sensing in measuring air pollutants and the methods of processing and accessing satellite data for the mapping of pollutant concentrations. Also, it discusses some applications of using satellite data in some case studies for estimates of surface concentrations of different air emissions.

2. Air Pollutants

Different air pollutants can be estimated using satellite remote sensing. This section focus on the most important emitted pollutants.

2.1 Carbon Dioxide (CO₂)

CO₂ is not considered a pollutant, but it is one of the most significant species due to its effect on the globe's climate (Ludwig et al. 1973) as it is considered major anthropogenic greenhouse gas. The growth of CO₂ has resulted from an increase in the use of fuel. According to the 2018 report of Emission Database for Global Atmospheric Research, CO₂ emissions, which are the main responsible for global warming, are still increasing yearly at world level. Global emission of CO₂ researched 37.1 gigatonnes in 2017 compared with 33.4 gigatonnes in 2011, which reflects an increase of almost 10% in six years (Leung et al. 2014).

2.2 Carbon Monoxide (CO)

Carbon monoxide (CO) or the silent killer of the 21st century is one of the most poisonous gases. CO is formed through incomplete burning of compounds than contain carbon such as gasoline, natural gas, oil, coal, and wood. Usually, the largest source of CO is vehicle emissions. Breathing the high concentrations of CO has health effects such as headaches, increased risk of chest pain for persons with heart disease, and impaired reaction timing. Also to leads to reduced oxygen (O₂) transport by hemoglobin (Dey and Dhal 2019).

2.3 Nitrogen Compound (NO)

Nitrogen Oxide (NO) and nitrogen dioxide (NO₂) are generated from biomass burning, fossil fuel combustion, lighting, and soil. NO₂ is a vital contributor to the decay of ozone (O₃) in the stratosphere (Grajales and Baquero-bernal 2014). NO, and NO₂ are major predecessors in the chemical reaction chains that form O₃ in the troposphere (Curier et al. 2014). Tropospheric NO₂ converts to HNO₃ which is responsible for acid rain (Goldberg et al. 2017). The exposure to NO₂ a long time decreases lung function and causes a risk for respiratory diseases (Grajales and Baquero-bernal 2014). NO and NO₂ affect the global climate through increasing the levels of O₃, methane and greenhouse gases (Curier et al. 2014).

2.4 Ozone (O₃)

Ozone is gas contains three oxygen atoms. It is produced through chemical reactions between sunlight, volatile organic compounds (VOCs), and nitrogen oxides (Martin 2008). These compounds are formed through human activities such as burning fossil fuels. Ozone exists in the stratosphere to protect the earth from excessive ultraviolet rays. While the existence of ozone near the earth's surface causes plant damage and has a bad effect on human health as it reacts with lung tissue, which leads to injury to lung tissue and respiratory issues (National Research Council 2002). O₃ is a toxic air pollutant with a longer atmospheric lifetime (Goldberg et al. 2017).

2.5 Particulate Matter (PM)

Particulate Matter is a very tiny liquid, and solid particles result from smoke and dust. The smaller particles usually contain a higher amount of harmful compounds. Also, it can enter deeply into the respiratory system (Tan et al. 2008). PM₁₀ are particles with diameter less than 10 microns. It is considered a major component of air pollution and has threatened the environment and human health (Hadjimitsis et al. 2012). PM_{2.5}(particulate matter with diameter smaller than 2.5 microns) causes cardiovascular, respiratory diseases, and even early death (Guo et al. 2017).

2.6 Sulfur Dioxide (SO₂)

Sulfur Dioxide (SO_2) is an atmospheric constituent that is formed by the eruptions of volcanoes or the combustion of fossil fuel. It is quickly converted to sulfuric acid, which causes acidic pollution of lakes and streams and forms an aerosol that causes climate change. The lifetime of SO_2 in air ranges from hours in the boundary layer to days in the troposphere and a month in the stratosphere. The combustion of fossil fuel represents almost 80% of SO_2 ; however, the small amount of SO_2 produced by volcanic eruptions in the stratosphere remains for more than a year. The long-lifetime SO_2 produced by volcanoes causes a stronger effect on the global climate than SO_2 produced from combustion of fossil fuel. For air pollution, sulfate produces acid rain and causes environmental degradation. SO_2 affects human health. It causes shortness of breath, coughing and wheezing (Krueger et al. 2009).

2.7 Aerosol Optical Thickness (AOT)

Aerosol Optical Thickness (AOT) is considered the key parameter for evaluating atmospheric pollution. AOT is defined as “the degree to which aerosols prevent the transmission of light.” AOT values are related to the measurements of PM₁₀ and PM_{2.5} (Lee et al. 2011). High values of AOT are an indication of high air pollution (Hadjimitsis et al. 2012).

2.8 Ammonia (NH_3)

The existence of free ammonia in the atmosphere affects human health through its impact on air, although ammonia has an important function in the nitrogen cycle and aerosol formation. The sources of producing NH_3 are the agriculture sector, natural sources, fossil fuel burning, and biomass burning. NH_3 has a very short lifetime (about 11 hours). Therefore the main environmental effect of free ammonia is producing Particulate Matter (PM) as NH_3 reacts with acids such as sulfate and nitrate leading to increased PM (Kuai et al. 2019).

3. Satellites: Platform and Instruments

The era of satellite remote sensing of aerosol started with the AVHRR, Landsat, and GOES. Although the three instruments were designed to monitor the surface and meteorological field, they were used to detect particles over ocean and sulfate that results from volcanoes. Satellite remote sensing that was designed for trace tropospheric gases started in 1978 with the launch of the Total Ozone Mapping Spectrometer (TOMS) instrument onboard of Nimbus 7 satellite by NASA. TOMS was designed to detect stratospheric ozone (O_3). TOMS was deactivated in 2007 (Martin 2008). This section focus on the main satellite that is used to monitor air pollutants. Table 1 lists the characteristics of major satellites that were designed for detecting aerosols. These satellites will be discussed hereafter.

3.1 European Remote Sensing 2 (ERS-2) satellite (GOME-1)

The monitoring of air quality in the lower troposphere using remote sensing began with the launch of the Global Ozone Monitoring Experiment (GOME-1) on the ERS-2 satellite in 1995 (Burrows et al. 1999). GOME-1 has a spectral coverage (230-790 μm) and a spectral resolution (0.2-0.4 μm). The typical nadir resolution is 320x40 km. The global coverage of GOME-1 is once every three days. The measurements of GOME-1 started in 1995 and ended by 2003 when it failed. GOME-1 was used to retrieve NO_2 , SO_2 , and tropospheric O_3 . The large spatial resolution of GOME observations effect on its validation with in situ measurements. However, limited validation of HCHO over the southeast of United States and Mediterranean is consistent with the expected uncertainty (Martin 2008).

3.2 ENVISAT (SCIAMACHY)

SCanning IMaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) has eight channels with spectral range 214-1750 μm and spectral resolution of 0.2-1.4 μm . It has a spatial resolution of 30x60 km. SCIAMACHY was used to retrieve NO_2 and SO_2 while retrieving CO from SCIAMACHY is challenging because of the weak signals (Martin, 2008). The temporal resolution of SCIAMACHY is six days (Streets et al. 2013). Contact with SCIAMACHY was lost in 2012 (Martin 2008).

3.3 Aura (OMI, TES)

Ozone Monitoring Instrument (OMI) was launched in 2004 on NASA Aura satellite to measure atmospheric emissions such as O₃, SO₂, HCHO, and NO₂ (Streets et al. 2013). OMI sensors have spectral range 270 – 500 μm and a spectral resolution is 0.5 μm. OMI has higher spatial and temporal resolution than GOME and SCIAMACHY (Zhang et al. 2017). At nadir, OMI has 13x24 km as a spatial resolution, but at the swath edges, spatial resolution became 26 km × 128 km. It achieves daily temporal resolution (Zhang et al. 2017). OMI is suitable for measuring small sources of SO₂ because of its high ground resolution and daily global coverage (Krueger et al. 2009).

The Tropospheric Emission Spectrometer (TES) instrument on the Aura satellite has a high spectral resolution (0.1 cm⁻¹) and a wide spectral range (650-3050 cm⁻¹). The spatial resolution of TES at nadir is 5x8 km (Martin, 2008), while its temporal resolution is two days (Streets et al. 2013). TES is used to estimate O₃, CO, and NH₃ (Martin 2008, Luo et al. 2015).

3.4 Terra (MOPITT, MODIS, MISR)

Terra satellite was launched on December 1999 by NASA. The Measurements Of Pollution In The Troposphere (MOPITT) instrument onboard Terra is a nadir-viewing gas correlation radiometer operating in the 4.7 mm band of CO. The spatial resolution of MOPITT is 22x22 km at nadir. MOPITT was able to retrieve CO with an accuracy of 10%. The measurements of MOPITT were validated with in situ measurements, and the accuracy was within the target. The Moderate Resolution Imaging SpectroRadiometer (MODIS) instrument has 36 channels with a spectral range from 410 to 14,200 μm. The spatial resolution is 250, 500 and 1000 m, depending on the channel (Martin 2008). The Multiangle Imaging SpectroRadiometer (MISR) has a spectral range of 20-40 μm and its highest spatial resolution is 275 m. The main application for MISR and MODIS is estimating AOT (Martin 2008). The temporal resolution ranges from 1-2 days of MODIS, nine days for MISR and three days for MOPITT (Streets et al. 2013).

3.5 MetOP (GOME-2, IASI)

Two instruments, Global Ozone Monitoring Experiment (GOME-2) and Infrared Atmospheric Sounding Interferometer (IASI), are onboard of MetOP. GOME-2 is a nadir-scanning double spectrometer with spectral resolution of 0.26–0.51 μm, spatial resolution 40x80 km, and temporal resolution of 1.5 days. GEOM-2 is used to estimate the retrieval of NO₂, SO₂, AOT, and O₃. The IASI instrument consists of a Fourier transform spectrometer associated with an imaging system, designed to measure the infrared spectrum emitted by the Earth in the thermal infrared using a nadir geometry (Martin 2008). The IASI used to estimate the emissions of SO₂, CO, NH₃, NH₄, and CO₂. It has spectral range 3.6-15.5 μm, spatial resolution 50x50 km and temporal resolution is 0.5 days (Streets et al. 2013).

3.6 Sentinel-5P (TROPOMI)

European Space Agency (ESA's) Sentinel 5p was recently launched from Russia on October 13, 2017. Tropospheric Monitoring Instrument (TROPOMI) is onboard on Sentinel 5P. TROPOMI has eight bands: two ultraviolet with a spectral resolution 270–320 μm, two ultraviolet-visible with spectral resolution 320–500 nm, two near-infrared with spectral resolution 675–775 μm, and two shortwaves infrared with spectral resolution 2305–2385 μm. TROPOMI is used to monitor the emissions of O₃, NO₂, SO₂, CO, CH₄, and formaldehyde (El Khoury et al. 2019). TROPOMI has a spatial resolution of 3.5x7 km and daily global coverage (Butz et al. 2011).

Table 1: Summary of the characteristics of major satellite instruments

Instrument	Platform	Spatial Resolution	Temporal Resolution	Applications
GOME-1	ERS-2	320x40 km	3 days	NO ₂ , SO ₂ , AOT and O ₃
MODIS	Terra	0.25-1 km	1 – 2 days	AOT
MISR	Terra	0.275	9 days	AOT
MOPITT	Terra	22x22 km	3 days	CO and NH ₄

SCIMACHY	ENVISAT	30x60 km	6 days	NO ₂ and SO ₂
OMI	Aura	13x24 km	1 day	O ₃ , SO ₂ , HCHO, and NO ₂
TES	Aura	5x8 km	2 days	O ₃ , CO, CO ₂ , and NH ₃
GOME-2	MetOP	40x80 km	1.5 days	NO ₂ , SO ₂ , AOT and O ₃ .
IASI	MetOP	50x50 km	0.5 day	SO ₂ , CO, NH ₃ , NH ₄ and CO ₂
TROPOMI	Sentinel-5P	3.5x7 km		O ₃ , NO ₂ , SO ₂ , CO, NH ₄ , and formaldehyde

4. Application

There are two applications, estimating the pollutant emissions and Monitoring the long-term trend of ambient pollutant concentration.

4.1 Estimating of the pollutant emissions

Satellite remote sensing instruments can detect air pollutants such as NO_x, SO₂, CO, ammonia, PM_{2.5}, and PM₁₀. The relationship between NO₂ and AOT was the focus of many studies. For example, El Khoury et al. (2019) studied this relationship by using data from Sentinel-2 and Sentinel-5p in Lebanon. A significant correlation (up to $r^2 = 0.775$) was found between the natural logarithm (ln) of NO₂ and AOT in five images out of six.

OMI was used to estimate different species. Grajales and Baquero-Bernal (2014) used OMI data to map NO₂ for the Colombian territory. The results were validated with the corrected ground measurement of NO₂. A significant correlation (0.91) was found between ground and satellite measurements. By using OMI data, Fioletov et al. (2011) reported that the emissions of SO₂ in North American power plants are about 70 Gg per year. Ziemke et al., (2006) compared One year of daily observation of tropospheric ozone derived from Aura OMI and MLS (September 2004 to August 2005) with Global Modeling Initiative's COMBO CTM. The results indicated that there were no substantial calibration differences.

Numerous studies have worked on finding correlations between PM and AOT using remote sensing. Nisantzi et al. (2011) reported a significant correlation between MODIS AOT and PM₁₀ over an urban area in Limassol, Cyprus. Also, the study reported a significant correlation between the estimated values of PM₁₀ with a ground measurement. Guo et al. (2017) studied the correlation between PM_{2.5} derived from MODIS AOT data and Ground-based meteorological observations in china for a period of three years (January 2013 to December 2015). As shown in Figure 1, the results indicated that the correlation between surface-level PM_{2.5} and MODIS varies spatially and temporally. Correlation in eastern China was stronger than the rest of the country. In a temporal aspect, MODIS AOT can better represent the surface PM_{2.5} in spring. Zeydan and Wang (2019) used MODIS derived AOT data and in situ measurement to estimate PM2.5 over Turkey.

Satellite data was used to study the chemical lifetime of NO_x. It ranged from 3 hours in summer to 13 hours in winter in Chinese urban areas retrieved from OMI and GOME-2 data (Mijling et al. 2012). In another study by Stavrakou et al. (2013), the lifetime of NO_x was found to be around ten hours in urban areas on the coast of India.

Luo et al. (2015) studied the distribution and the correlation between NH₃ and CO using TES satellite data. The study reported a strong correlation between NH₃ and CO in the regions where biomass burning is the main source of NH₃ and CO emissions. These results were consistent with the surface measurements taken over fires. While the correlation between NH₃ and CO was weak in TES observation if NH₃ and CO were produced from different sources.

Although the SPOT satellite is not designed to detect the air pollutant, it was used in several studies to detect PM_{2.5} and PM₁₀. Lim et al. (2008) were able to generate a map for PM_{2.5} in Penang Island, Malaysia, from visible and thermal infrared bands of SPOT data. While the visible bands of SPOT were used in PM₁₀ mapping in the same area. A correlation coefficient of 0.91 was found between PM₁₀ that estimated from SPOT satellite data and measured values (Tan et al. 2008).

Landsat satellite was used to detect aerosol before using satellites that were designed to detect air pollutants. However, some recent studies used the Landsat TM/ETM+ to retrieve AOT, CO, and PM₁₀. Band 1 of Landsat TM/ETM+ was used to retrieve AOT in Heathrow Airport (UK) and Paphos Airport in Cyprus. The retrieved AOT was satisfactorily validated using the ground measurements (Hadjimitsis et al. 2009). Also, a strong positive correlation was found between digital number (DN) of the thermal IR band of Landsat 7 ETM+ and CO and PM₁₀ in urban areas in Malaysia (Narashid 2010).

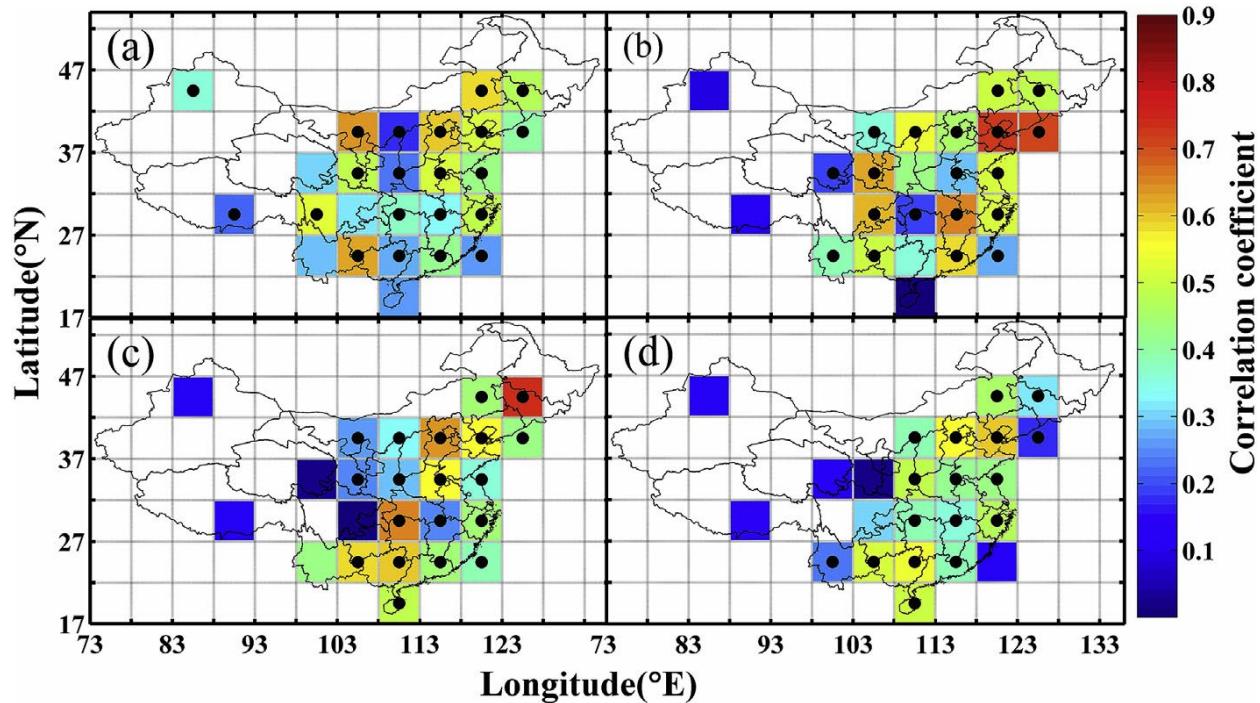


Figure 1. The spatial distribution of correlation coefficients between ground-based PM_{2.5} and MODIS-Aqua AOD in (a) spring, (b) summer, (c) fall, and (d) winter over China (Guo et al. (2017)).

4.2 Monitoring long-term trend of ambient pollutant concentration

Qiang et al. (2012) used SCIAMACHY and GOME data to study the changes in NO_x emissions over China from 1996–2010. This study was able to identify the high pollution regions and its expansion over time as well as identify the new polluted area that formed throughout China. Qin, et al. (2016) used the products of MODIS were used to create a map for AOT from 2003-2012 in Beijing-Tianjin-Hebei (BTH) region, China. Zhang et al. (2017) analyzed the trend of NO₂ and SO₂ levels in long term (2005-2014), by using OMI data. The results of NO₂ showed a continuous increasing rate of 6.4% per year from 2005 to 2011 then a decreasing rate of 10.6% per year from 2012-2014. While the increasing rate of SO₂ was about 16% per year from 2005 to 2007 then a decreasing of 7% per year from 2007 to 2014. Ul-Haq et al. (2017) used data from OMI and MODIS to study the relationship between NO₂ and AOT in South Asia during 2005–2015. The correlation coefficient (r) between the two parameters was 0.49 but with large variations as it ranged from 0.32 in 2008 to 0.86 in 2009. Also the correlation coefficient was different from place to another. The highest correlation was achieved in eastern regions of India and Bangladesh. In another study in Europe. Curier et al. (2014) used OMI NO₂ tropospheric columns to study the trends in the tropospheric NO₂ concentrations during 2005–2010. Barkley et al. (2017) used OMI data to assess the changes in air quality over 1000 locations in the Middle East for the period 2005-2014. The 1000 locations were chosen in urban, oil refinery, oil port, and power plant. The study focused on nitrogen dioxide (NO₂), formaldehyde (HCHO), and sulfur dioxide (SO₂). It was found that the highest level of these traces was over oil ports and refineries. Over urban areas, NO₂ increased by almost 12% per year while it increased by 2-9% per year in oil refineries, oil ports, and power plants. HCHO increased by 2-7% per year over urban areas and power plants and by about 2-4% per year over refineries and oil ports. SO₂ did not show a specific trend.

5. Conclusion

The 1978 launch of the TOMS instrument onboard on Nimbus 7 satellite initiated the era of observation of air pollutants from space. Since then, the improvement and developing of the space instruments designed to observe air pollution emissions have been remarkable. In 2017, TROPOMI, launched with spectral range 270-775 μm , high spatial resolution 3.5x7 km, and daily global coverage. The variety of spectral resolution of the space instruments enabled the observations of different species of air pollutants. The space observations of air pollutants are valuable to monitor the status of air quality and to study the long-term trend of ambient pollutant concentration.

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