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Satellite record of the transition of air quality over China

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ABSTRACT
The rapid development of atmospheric satellite instruments since 1990s provides unprecedented large amount of observational datasets concerning global atmospheric pollutants. The continuous and long-term large-scale satellite products such as aerosol optical depth, tropospheric NO\textsubscript{2} and SO\textsubscript{2} enable effective and objective evaluation of air quality. Satellite columnar aerosol optical parameters can be used to indicate particle pollution near surface after correction. By contrast, satellite results of trace gas pollutants such as NO\textsubscript{2} and SO\textsubscript{2} from fossil fuel combustion with short lifetime around half one day are used to estimate anthropogenic emissions. It is shown that the overall anthropogenic emissions in China have largely declined since strict emission reduction policy implemented since 2013. However, coarse pixel resolution of the trace gases, limited information and retrieval bias of aerosol properties tend to hinder further application of satellite in air quality research. Recently launched satellite missions with advanced detection abilities will greatly enhance global atmospheric observations with much more datasets available.

1. Introduction
Since the very first attempt of Landsat (Kaufman & Joseph, 1982), more and more sophisticated satellite sensors have been consecutively developed to obtain a comprehensive view of the global air quality concerning anthropogenic emissions, pollutant transportation, and their influence on public health. The twin moderate resolution imaging spectroradiometer (MODIS) sensors flying on Terra since 2000 and Aqua since 2002, create a valuable long-term observations of global aerosols (Levy et al., 2013), which have been widely used to answer scientific questions related to particle pollution (Engel-Cox et al., 2004; Wang & Christopher, 2003). As the development of hyperspectral satellite sensors since 1990s, global observation of atmospheric components such as NO\textsubscript{2}, SO\textsubscript{2}, and HCHO has greatly increased our knowledge in anthropogenic emissions (Burrows et al., 1999). Meanwhile, integrated satellite observations such as
A-Train (pass at close time as train after noon) satellite constellation since 2002 provides unprecedented data information to investigate air quality and corresponding regional processes from space (Tao, Chen, Su, & Tao, 2012). In particular, the recent launch of advanced satellite missions including Suomi National Polar-orbiting Partnership and TROPOspheric Monitoring Instrument (TROPOMI), and geostationary satellite Himawari-8 brings more chances in air quality research.

The large increase in anthropogenic emissions during the past decades has led to serious air quality problems in China (Feng, Chen, & Zhang, 2018; Tao et al., 2012), which are further complicated by regional processes such as pollutants transport and meteorological variations (Tao et al., 2016b) and environmental polices (Wang et al., 2016). Widespread haze pollution driven by anthropogenic pollutants and natural factors such as floating dust and moist airflows has greatly threatened public health and environment (Christodoulakis, Varotsos, Gracknell, & Kouremadas, 2018; Pope et al., 2002). Extreme pollution events with extensive influence area and high particle concentration usually occurred in eastern China during winter (Tao, Chen, Wang, Tao, & Su, 2013; Tao et al., 2014). The Chinese government implemented strict measures to reduce anthropogenic emissions since 2013, and there has been dramatic changes in the inhomogeneous distributions of atmospheric pollutants (Tao et al., 2016a), exerting large uncertainties on emission inventory and numerical simulations.

Here we present a brief overview of the large satellite data sets of atmospheric components and their application in evaluating air quality in China. Section 2 introduces the main satellite products used for air quality monitoring. The general characteristics of the air quality in China as well as effect of emission reduction policy is discussed in Section 3. Finally, we show some perspective of the potential application of advanced satellite missions in the near future.

2. Satellite data sets and retrieval methods

2.1. Aerosol dataset of the A-Train satellite constellation

Satellite aerosol retrieval over land is a challenging work due to more unknowns of aerosol and surface properties. The recent A-Train satellites (Aqua, Aura, PARASOL, and CALIPSO) provide an unprecedented opportunity to observe aerosol properties simultaneously from ultraviolet, multiple visible and shortwave bands, polarization, and active LiDAR detection (Hsu, Si-Chee, King, & Herman, 2006; Omar et al., 2009; Tanré et al., 2011; Torres et al., 2007). However, current A-Train satellite sensors such as ozone monitoring instrument (OMI), POLarization and Directionality of the Earth's Reflectance (POLDER), and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) are limited by coarse pixel resolution or narrow swath width. MODIS is one of the few sensors that provide daily operational retrievals of global aerosol optical parameters with 36 bands in 0.4–14.4 μm, a wide swath ~2330 km, and relatively fine resolution at 250–1000 m. MODIS aerosol retrieval over land was first realized over dense vegetation utilizing linear relationship of surface reflectance between visible and shortwave infrared bands (Kaufman et al., 1997), which is named as Dark Target algorithm. To obtain aerosol information over bright surfaces such as deserts and urban regions, Deep Blue algorithm utilizes pre-calculated surface reflectance database in blue channel with much lower reflectance relative to longer visible bands (Hsu et al., 2004).
The A-Train satellites crossing the equator in the same orbit after noon within a few minutes of each another (Figure 1), can provide comprehensive insights into atmospheric components and processes (Tao et al., 2012). Since the most commonly used satellite aerosol parameter, aerosol optical depth (AOD), is a columnar integration of particle extinction, which cannot directly express air quality index of particle matter (PM) near surface without consideration of the influence of humidity, aerosol component and profiles on AOD-PM relationships (Wang et al., 2003).

2.2. Satellite dataset of key pollutant trace gases

Gaseous emission such as NO$_2$ and SO$_2$ from fossil combustion is main precursors of fine particles, which is also direct indicator of anthropogenic emission. Global zone monitoring experiment (GOME) launched in 1995 is a hyper-spectral ultraviolet-visible (UV-VIS) spectrometer with wide spectrum (240-490 nm) that provides measurement of trace gases with their absorption in the backscattered radiation. However, the GOME has a coarse pixel resolution at 40 × 320 km and narrow swath width ~960 km. The OMI instrument aboard Aura satellite since 2004 enables a much higher resolution of 13 × 24 km with daily global coverage. Currently, the main UV-VIS absorption satellite products of gaseous pollutants are NO$_2$, SO$_2$, and HCHO. According to absorption spectrum of trace gases, there have been several retrieval algorithms including differential optical absorption spectroscopy, iterative spectral fitting, and principle component analysis (Li, Joiner, Krotkov, & Bhartia, 2013). Compared to atmospheric composition such as NO$_2$ and HCHO with scattering and broadband interfering absorption approximately constant, these variations in the spectral fitting windows of SO$_2$ retrieval have to be considered. In addition, absorption in the shortwave infrared and thermal infrared bands is used to estimate amount of gases such as CO and NH$_3$.

3. Satellite view of the air quality in China

The global coverage of satellite remote sensing has a unique advantage in monitoring atmospheric environment. It can provide spatial distributions and temporal changes of
short-lived aerosols and gaseous pollutants. In particular, multiple remote sensing observations can get the characteristics of the atmospheric pollutants from a varied perspectives, which provides unprecedented opportunities for investigating the pollution formation and transportation from regional or global scales. Figure 2 shows variations of MODIS AOD during the last decade. High aerosol loading is prevalent in eastern China and the Sichuan Basin, the main urban and industrial regions in China. The annual mean AOD in northern China and Sichuan Basin exceeds 1.0, indicating that about one thirds sunlight cannot directly penetrate to land surface. While there is a slightly increase in the aerosol loading over northern China during 2012, annual mean AOD in eastern China decreased largely to ~0.8 in 2017 after 5 years emission reduction implemented by the Chinese government.

Atmospheric gaseous pollutants from fossil fuel combustion are the main precursors of particle pollutants with lifetime around half a day, which is much shorter than aerosol particles which originate from diverse sources with about 1 week lifetime. Therefore, satellite results of trace gases are widely used to estimate anthropogenic emissions. Tropospheric NO\(_2\) in China mainly comes from coal-burning and vehicle emissions, and is the main precursor of O\(_3\). It can be seen that NO\(_x\) emissions are concentrated in megacities of Beijing, Shanghai, and Guangzhou as well as the power plants in Hebei and Shandong (Figure 3). There is large increase in NO\(_2\) concentration in Shandong and Hebei from 2007 to 2012 but obvious decline in Guangzhou, where emission control measures have been implemented (Wang et al., 2016). The largely overall decline of NO\(_2\) concentration appears in 2017, when strict emission reduction has been widely realized in China.
SO₂ from coal-burning is one of the primary aerosol components due to its rapid transformation to particles. Different from variations of NO₂, SO₂ emissions continue to decline from 2007 since Chinese implements desulfurization policy in 2006 (Figure 4). SO₂ emissions are concentrated in Hebei and Shandong, where most coal-burning power plants are located. SO₂ concentration is also at relatively high level in Sichuan Basin, Shanxi, and Guangzhou in 2007. Despite large decrease in SO₂ emissions in 2012, there is a slight increase in Inner Mongolia. With emission reduction policy carried out since 2013, the overall SO₂ emissions in China decrease to low concentration. Satellite observations provide an effective and objective assessment of emission reduction effect of environmental policy in China.

4. Conclusions and perspectives

With the rapid development of atmospheric satellite sensors since 1990s, global observations of aerosol and gaseous precursors has been widely used in monitoring air quality. Satellite aerosol products such as MODIS AOD can provide regional information concerning particle pollution. Because gaseous pollutants such as NO₂ and SO₂ are usually concentrated near emissions sources due to their short lifetime, OMI gas results are directly used to estimate anthropogenic emissions. The integrated satellite data sets enable an effective and objective assessment of air quality. However, current satellite detection is limited by pixel resolution, information content or retrieval bias in certain extent. In the near future, the recently launched TROPOMI on Sentinel-5 satellite and GaoFen-5 satellite that plans to be launched in the first half year will largely enrich the existing atmospheric satellite data with finer resolution and higher detection ability.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the authors.
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