Comparison of Satellite-retrieved NO2 Vertical Column Density with Ground-level NO2 concentration in a provincial scale region

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Abstract. Satellite remote sensing will have certain errors in data retrieval accuracy, which requires further ground observation verification. This paper examines and verifies 2019 Jiangsu provincial Ground-level monitoring data and TROPOMI data to evaluate the applicability of TROPOMI tropospheric NO2 Vertical Column Density (VCD) data and compares the results to OMI data analysis verification results. The results show that the correlation coefficient \( r \) between the TROPOMI NO2 data and Ground-level monitoring data at the monthly mean scale is as high as 0.9, and consistent seasonal cyclic changes are observed. The correlation between Ground-level monitoring data and OMI NO2 data is lower than TROPOMI (\( r=0.78<0.9 \)). Compared to OMI satellites, the TROPOMI attains a smaller deviation in tropospheric NO2 monitoring. Jiangsu Province had the highest monthly average concentration in January, which were 38.67 ug/m³ (Ground-level), 17.35×10¹⁵ molec/cm² (TROPOMI) and 20.04×10¹⁵ molec/cm² (OMI). The lowest concentration in August was 13.39 ug/m³ (Ground-level), 5.2×10¹⁵ molec/cm² (TROPOMI) and 7.03×10¹⁵ molec/cm² (OMI).

1. Introduction
With the rapid development of the social economy and industrialization, the nitrogen dioxide level in the atmosphere is increasing. Nitrogen dioxide (NO₂), as an important atmospheric trace gas, is one of the main atmospheric pollutants monitored by the environmental protection agencies of China and European and North and South American countries[1]. NO₂ causes the photochemical reaction of ozone (O₃) and the formation of secondary aerosols and affects the lifespan of methane (CH₄) and other greenhouse gases, thereby changing the Earth radiation balance and ultimately profoundly impacting human health and causing environmental changes[2]. Therefore, NO₂ concentration monitoring is of great significance to study its source and to formulate pollution control measures.

At present, NO₂ measurements are mainly performed via Ground-level and satellite remote sensing monitoring methods. The concentration information obtained by Ground-level observations has the advantages of a high accuracy, strong reliability, and all-weather monitoring characteristics. However, due to the limited number of national environmental air quality monitoring networks established in...
China and the uneven station distribution, NO2 cannot be monitored in real time via Ground-level observations on a large scale[3]. Since the 1990s, satellites have been widely applied in environmental remote sensing, and an increasing number of atmospheric components can be observed by satellites. Compared to the limited ground or Ground-level remote sensing observations, satellite remote sensing observations have the advantages of a wide coverage, real-time features, continuity, and a high resolution. Satellites can observe important parameters that cannot be obtained by conventional observation methods[4]. Therefore, they are becoming increasingly more prominent in NO2 monitoring. With the development of satellite sensor technology, a series of satellites capable of detecting NO2 has been launched. The European Space Agency (ESA) launched the Global Ozone Monitoring Experiment (GOME) instrument in 1995[5]. It was the first satellite capable of conducting global air-scale observations, thus greatly contributing to atmospheric research[6, 7]. The ENVISAT-1 launched by ESA in 2002 is equipped with a scanning imaging absorption spectrometer (SCIAMACHY) for atmospheric mapping, which is specifically used to monitor trace gases such as NO2 and SO2 in the troposphere and stratosphere[8]. With the launch of the In-orbit Demonstrator-1 Global Environmental Monitoring System (IOD-1 GEMS) satellite on April 17, 2019, satellite sensors have obtained global NO2 observation data for nearly 25 years.

As satellite data inversion is influenced by many factors, the data need to be verified to effectively ensure their accuracy[9]. Although there are many deficiencies in the application of Ground-level monitoring of the atmospheric composition, monitoring is more accurate and has been widely implemented. Zhang et al. performed linear fitting and found that the NO2 concentration measured at the national monitoring station in Beijing-Tianjin-Hebei and the NO2 Vertical Column Density (VCD) obtained by the Ozone Monitoring Instrument (OMI) are significantly and highly correlated as a whole. The R² values in the Shijiazhuang, Xingtai, Baoding, and Cangzhou areas all exceed 0.8, while that in the Qinhuangdao area is relatively lower, with an R² value of approximately 0.2[10]. Si et al. studied the correlation coefficient between monthly average OMI tropospheric NO2 VCD and and the Ground-level concentration was 0.73 in the North China Plain from 2006 to 2015. The correlation coefficients for cities, agriculture, forests and deserts are 0.69, 0.73, 0.67 and 0.76, respectively. The r values were ranked in desert>agriculture>city>forests[11]. However, the Tropospheric Monitoring Instrument (TROPOMI) sensor has significant advantages over the OMI in terms of the signal-to-noise ratio and spatial resolution and is expected to gain a greater application potential in further checklist verification and mode input. In addition, many research results have been obtained related to the verification of OMI NO2 inversion products, but there are relatively few TROPOMI verifications. This article will examine the differences between the tropospheric NO2 levels observed by the above two loads and Ground-level observations through comparative analysis.

This paper analyzes Ground-level monitoring data in 13 prefecture-level cities in Jiangsu Province in 2019. The correlation and data consistency were verified by comparing ground NO2 concentration and satellite NO2 products. At the same time, the verification results of TROPOMI and OMI data are compared to verify the superiority of TROPOMI data.

2. Research area and data

2.1. Research area
Jiangsu Province is located in the middle of the coast of mainland China and the lower reaches of the Yangtze and Huaihe Rivers. It borders the Yellow Sea to the east, Shandong and Henan to the north, Anhui to the west, and Shanghai and Zhejiang to the southeast. All its 13 prefecture-level cities are among the top 100 cities in China, and it is the largest economic province in the Yangtze River Delta. It lies between 116°18'-121°57' east longitude and 30°45'-35°20' north latitude.
2.2. Data and processing method

2.2.1. Ground-level NO2
Ground-level NO2 concentration data source with the China National Environmental Monitoring Centre (CNEMC), and the CNEMC main functions are to perform state environmental monitoring and develop state environmental monitoring methods. Since the beginning of 2013, the CNEMC has established a network to monitor the Ground-level NO2 concentration across China[12]. By the end of 2017, China had established 1,597 atmospheric pollution monitoring stations[13]. The monitoring sites release ground SO2, NO2 and fine particulate matter (PM10) observations every hour. The CNEMC more accurately measures the NO2 concentration, but the associated construction and maintenance costs are high, and it is difficult to satisfy the requirements of real-time and accurate large-scale NO2 monitoring. The stations are mainly distributed in the central and eastern parts of China, and relatively little monitoring occurs in the western development areas. This paper adopts the NO2 concentration data of the 87 sites in Jiangsu Province in 2019 released by CNEMC. The site distribution is shown in Figure 1. The NO2 concentration measured at the environmental monitoring sites is expressed μg/m3, and the monitoring interval is 1 hour. Values with a poor continuity in terms of the observation time are eliminated from the environmental monitoring site data, specifically the observation data of certain ground stations with fewer than 20 observations in a day. The satellite transit time is approximately 13:00 local time, and the average of the ground station observation data of the environmental monitoring sites between 13:00 and 14:00 is selected as the daily average.

Figure 1. Distribution of 87 CNEMC sites in Jiangsu Province

2.2.2. OMI NO2
The Ozone Monitoring Instrument (OMI) is mounted on the AURA satellite. The OMI is an ultraviolet (UV)/visible light subsatellite point solar backscattering spectrometer. The transit time is generally 13:40~13:50 local time. It obtains daily global atmospheric tropospheric O3 and various other trace measurement results from which the distribution can be determined of gases such as NO2 and SO2[14]. The OMI applies push-broom imaging. Each push-broom row contains 60 pixels, and each pixel corresponds to the ground width perpendicular to the orbit from 24 kilometers at the subsatellite point to 128 kilometers at the pixel edge. The width is approximately 2600 kilometers. The track length along the ground is approximately 13 kilometers[15].
The OMI data used in this research were downloaded from the official NASA website (https://disc.gsfc.nasa.gov) and are satellite remote sensing data for public welfare purposes. This study uses the tropospheric NO2 VCD product, version number OMNO2 v003, in ESRI grid format, and the time span is from January to December 2019. OMI data has the row anomaly problem, which affects the quality of the level 1B radiance data at all wavelengths for a particular viewing direction of OMI. Since July 5, 2011, the abnormality of this line often shows only small changes, so comparisons for data for 2019 is unaffected by the row anomaly (http://projects.knmi.nl/omi/research/product/rowanomaly-background.php).

2.2.3. TROPOMI NO2
On October 13, 2017, the ESA successfully launched the atmospheric measurement satellite Sentinel-5P with high temporal and spatial resolutions, which was equipped with the Tropospheric Monitoring Instrument (TROPOMI). The TROPOMI has similar advantages to those of SCIAMACHY, OMI and other advanced technologies in addition to a greatly improved sensitivity and spectral, spatial and temporal resolutions (https://sentinel.esa.int/web/sentinel/missions/sentinel-5p). The TROPOMI crosses the equator at approximately 13:30 local time[16], with an almost global coverage every day[17]. The TROPOMI UV-VIS spectral range is from 270–495 nm. Compared to the OMI launched in 2004, which is still in orbit, the TROPOMI possesses a fine-resolution NO2 detection capacity. Selecting NO2 products as examples, the resolution of OMI NO2 products is 13×24 km2, while the resolution of TROPOMI NO2 products reaches 5×3.5 km2. Moreover, the TROPOMI NO2 product data are based on the DOMINO-2 product algorithm and the OMI EUQA4ECV NO2 product algorithm prototype, which has been further optimized. The NO2 profile in the inversion algorithm relies on the 1°×1° latitude-longitude resolution product provided by the TM5-MP chemical transmission mode, which is an upgrade to the 2°×3° latitude-longitude resolution profile data used in the previous generation algorithm[18].

The TROPOMI data adopted in this study can be downloaded from the Tropospheric Emission Monitoring Network (http://www.te mis.nl/), the version is TM5-MP-DOMINO v1.2.x & v1.3.x OFFLINE, in ESRI grid format, and the time span is from January to December 2019.

3. Validation analysis of the TROPOMI and OMI tropospheric NO2 VCD

3.1. Comparison of TROPOMI to CNEMC NO2
The NO2 concentration data of the 87 monitoring sites in Jiangsu Province released by CNEMC from January to December 2019 were averaged on a monthly basis, and the monthly average value of the TROPOMI tropospheric NO2 VCD data was extracted. Linear fitting was performed to verify the accuracy of the TROPOMI data. Figure 2 shows a scatter plot of the monthly average TROPOMI tropospheric NO2 VCD and monthly average monitoring values at various CNEMC sites in 13 prefecture-level cities in Jiangsu Province. The fitting results reveal that the correlation coefficients between the TROPOMI tropospheric NO2 VCD and monitoring station NO2 concentration in Nanjing, Changzhou, Lianyungang, Nantong, Suzhou, Taizhou, Wuxi, Suqian, Yancheng and Zhenjiang are all above 0.9. Among them, Suqian and Zhenjiang exhibited the highest correlation, with a correlation coefficient r as high as 0.97. In Xuzhou, the lowest correlation was observed between the TROPOMI tropospheric NO2 VCD and monitoring site NO2 concentration, with a correlation coefficient r of 0.81, at p=1.27975E-72<0.05, which indicated a highly significant correlation. The tropospheric NO2 VCD data obtained by the TROPOMI sensor are significantly related to the Ground-level NO2 concentration data measured by CNEMC, and the correlation is very high. Therefore, TROPOMI data can be used to monitor the concentration of NO2 on urban scale.
Figure 2. Scatterplot of the monthly averaged NO$_2$ concentrations from CNEMC and TROPOMI NO$_2$ in the 13 prefecture-level cities in Jiangsu Province

3.2. Spatial Analysis

Spatial Analysis can better explore NO$_2$ seasonal variation and product discrepancy. The data is divided into four seasons, including spring (January, February and March), summer (April, May and June), autumn (July, August and September) as well as winter (October, November and December). Figure 3 illustrates the seasonal cycle of NO$_2$ based on TROPOMI (a1-a4), OMI (b1-b4) and CNEMC (c1-c4). The NO$_2$ concentration has a pronounced seasonal cycle over Jiangsu, which is high in spring and winter and low in summer and autumn. The concentration of NO$_2$ was higher in Wuxi and Suzhou, and lower in Yancheng and Huaian. At the same time, the three products show very similar NO$_2$ spatial structure and seasonal evolution. Due to the limited number of CNEMC sites, it can only reflect the level of NO$_2$ concentration in a small number of regions. TROPOMI and OMI data can clearly reflect the distribution of regional pollution and TROPOMI resolution is higher.
3.3. Comparison of the TROPOMI and OMI NO$_2$

Figure 4 shows that the monthly average value of the tropospheric NO$_2$ VCD in the troposphere retrieved from the TROPOMI and OMI satellite data is basically the same as that of the NO$_2$ concentration retrieved from CNEMC sites, with consistent seasonal periodic changes. In urban areas, the concentration value of OMI is higher than TROPOMI. The NO$_2$ concentration in Jiangsu is high...
in spring and winter and low in summer and autumn. Jiangsu had the highest monthly average concentration in January, which were 38.67 ug/m³ (CNEMC), $17.35 \times 10^{15}$ molec/cm² (TROPOMI) and $20.04 \times 10^{15}$ molec/cm² (OMI). The lowest concentration in August was 13.39 ug/m³ (CNEMC), $5.2 \times 10^{15}$ molec/cm² (TROPOMI) and $7.03 \times 10^{15}$ molec/cm² (OMI). The air quality in Jiangsu in February improved significantly from the previous month and was lower than that in March. This may be related to the reduction in pollution emissions in Jiangsu during the Spring Festival. The ban on fireworks and firecrackers, the use of fewer cars during the Spring Festival, and the production reduction of industrial and mining enterprises have all improved the air quality. Comparing CNEMC, TROPOMI and OMI measurement results reveals that the two datasets are highly correlated, and TROPOMI and OMI data can be used to reflect the concentration and pollution in other nonmonitored areas.

Figure 4. The concentration of NO₂ at the CNEMC was compared with the monthly average of TROPOMI and OMI NO₂ in 2019

Figure 5 shows the scatter plot between the monthly monitoring values of NO₂ concentration and the average TROPOMI tropospheric NO₂ VCD of 13 prefectural-level cities in Jiangsu Province. The number of matching points is 156 and the correlation coefficient is 0.90. Figure 6 is the scatter plot of monthly monitoring values of NO₂ concentration at the CNEMC sites and monthly average OMI troposphere NO₂ VCD. The number of matching points and correlation coefficient are 137 and 0.78 respectively. Due to the different pixel sizes of TROPOMI and OMI satellites, the number of matching points with CNEMC data is also different. The resolution of TROPOMI is higher than that of OMI, so it has more matching results.

Figure 5. Scatterplot of the monthly averaged NO₂ concentrations from CNEMC and TROPOMI NO₂

Figure 6. Scatterplot of the monthly averaged NO₂ concentrations from CNEMC and OMI NO₂
In 2019, the correlation coefficient $r$ between TROPOMI tropospheric NO2 VCD and the CNEMC NO2 concentration in Jiangsu Province was 0.90, which was greater than that between OMI tropospheric NO2 VCD and CNEMC NO2 concentration at 0.78. This demonstrates that the TROPOMI has more advantages than the OMI satellite in monitoring the tropospheric NO2 VCD.

4. Summary and Conclusions
In order to verify the NO2 products of TROPOMI and OMI satellites, this paper uses the Ground-level NO2 concentration data from CNEMC in Jiangsu Province in 2019 for comparison and analysis. Concluded as follow:

1. The NO2 concentrations at the CNEMC in the 13 prefecture-level cities in Jiangsu Province in 2019 are highly correlated with the tropospheric NO2 VCD obtained by the TROPOMI and OMI. The correlation coefficient $r$ between the TROPOMI and CNEMC data in Jiangsu Province is 0.9, of which Suqian and Zhenjiang exhibit the highest correlation ($r=0.97$), and Xuzhou attains a slightly lower correlation ($r=0.81$). TROPOMI data can be used to monitor the concentration of NO2 on urban scale.

2. The NO2 concentration has a pronounced seasonal cycle over Jiangsu, which is high in spring and winter and low in summer and autumn. At the same time, the three products (TROPOMI, OMI and CNEMC) show very similar NO2 spatial structure and seasonal evolution.

3. The monthly average value obtained with the TROPOMI basically exhibits the same distribution trend as that of CNEMC data. Due to the reduction in pollution emissions in Jiangsu during the Spring Festival, the ban on fireworks and firecrackers, the use of fewer cars before and after the Spring Festival, and the production reduction of industrial and mining enterprises, the air quality has improved. The NO2 concentration in Jiangsu in February is lower than that in January and March.

4. The correlation between CNEMC data and TROPOMI data is higher than that of OMI ($r=0.9>0.78$). The TROPOMI has more advantages than the OMI in tropospheric NO2 VCD monitoring.

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