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# Research of $NO_2$ vertical profiles with look-up table method based on MAX-DOAS

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Obtaining the vertical distribution profile of trace gas is of great significance for studying the diffusion procedure of air pollution. In this article, a look-up table method based on multi-axis differential optical absorption spectroscopy (MAX-DOAS) technology is established for retrieving the tropospheric $NO_2$ vertical distribution profiles. This method retrieves the aerosol extinction profiles with minimum cost function. Then, the aerosol extinction profiles and the atmospheric radiation transfer model (RTM) are employed to establish the look-up table for retrieving the $NO_2$ vertical column densities (VCDs) and profiles. The measured $NO_2$ differential slant column densities (DSCDs) are compared with the $NO_2$ DSCDs simulated by the atmospheric RTM, and the $NO_2$ VCDs, the weight factor of $NO_2$ in the boundary layer, and the boundary layer height are obtained by the minimization process. The look-up table is established to retrieve $NO_2$ VCDs based on MAX-DOAS measurements in Huaibei area, and the results are compared with the data from Copernicus Atmospheric Monitoring Service (CAMS) model. It is found that there are nearly consistent and the correlation coefficient $R^2$ is more than 0.86. The results show that this technology provides a more convenient and accurate retrieval method for the stereoscopic monitoring of atmospheric environment.

**Keywords:** multi-axis differential optical absorption spectroscopy, look-up table method, the cost function, $NO_2$ vertical profile

**PACS:** 42.68.wt, 78.40.–q, 87.64.k–, 95.75.Rs **DOI:** 10.1088/1674-1056/ac1415

## 1. Introduction

With the rapid development of industrialization and urbanization, the pollutants concentrations, such as $NO_2$, have increased significantly in atmosphere, which lead to serious environmental pollution problems. The change in the proportion of air components will lead to a series of atmospheric environmental problems, holding a great influence on the survival and development of human beings.[1] Therefore, it is highly desired to obtain the tropospheric pollutants concentrations and vertical distribution through ground-based observation, which can benefit the pollution control and climate change research.

MAX-DOAS technology can be applied in remote sensing of multi-component air pollutants, in real-time, continuous, and non-contact conditions, which has been widely employed in the space of atmospheric environment monitoring. In recent years, different research groups have proposed various calculation methods for quantitative retrieval of aerosol and trace gas profiles based on MAX-DOAS technology. In general, there are two main methods: the optimal estimation method and the look-up table method. In 2004, Wagner *et al.*[2] put forward a method to retrieve aerosol extinction applying the absorption information of $O_4$. In 2008, Irie *et al.*[3] studied the parameterized retrieval algorithm of aerosol and trace gas vertical distribution based on the optimal estimation method. In 2013, Wang *et al.*[4] have retrieved aerosol optical depth and extinction profiles by using MAX-DOAS and nonlinear optimal estimation method, and they found that the optimal estimation method depends on prior profile and singular values may appear in the retrieval procedure. In order to eliminate the influence of prior profile, Li *et al.*[5] and Wagner *et al.*[6] proposed the look-up table method to retrieve aerosol profiles. In 2013, Wu *et al.*[7] have employed the look-up table method of MAX-DOAS to retrieve aerosol extinction profiles, but just with the focus on the noon period (09:00–13:00). In 2019, Mou *et al.*[8] used the look-up table method to retrieve the aerosol extinction profiles from 08:00–16:00, but they did not retrieve the trace gas profiles. In this article, the ground-based MAX-DOAS was applied to carry out continuous observation experiments in Huaibei area. Both of the aerosol extinction profiles and trace gas profiles information in the period of 08:00–16:00 from September 26, 2019 to September 30, 2019 were retrieved by applying the look-up table method, and the retrieved $NO_2$ vertical column densities are compared with the results of CAMS model.

## 2. Principles and methods

### 2.1. MAX-DOAS experimental instrument

The experimental instrument applied in this area is one-dimensional MAX-DOAS.[9] The experimental instrument is

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composed of prism, telescope, baffle and its driving device, temperature control system, optical fiber, spectrometer (HR2000+), and control computer.[10] The structure diagram is shown in Fig. 1. The prism starts to rotate under the drive motor, and the scattered light from different angles is introduced into the receiving telescope, and it will gather into the spectrometer through the optical fiber. In order to decrease the retrieval error due to the spectral drift brought by temperature change, a temperature control system is employed to ensure that the spectrometer works at constant temperature (20 °C). The measurement wavelength of the spectrometer is 290 nm–420 nm, and the spectral resolution is 0.54 nm.[11] The online monitoring platform automatically adjusts the integration time according to the intensity of the spectrum to obtain the spectrum with high signal-to-noise ratio. The elevation of the telescope changes with the rotation of the driving motor, and the elevation angle values are 1°, 2°, 3°, 4°, 5°, 6°, 8°, 15°, 30°, 90°, and the measurement cycle period is 15 minutes.

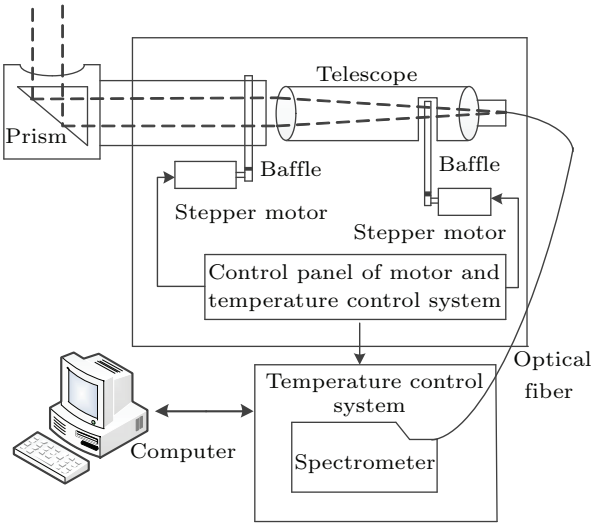



**Fig. 1.** Experimental setup of MAX-DOAS.

### 2.2. Retrieval principle of $NO_2$ profile

In this study, MAX-DOAS instrument is applied to measure the $O_4$ $DSCD_\alpha$ at different elevation angles. The $O_4$ VCD is constant in the troposphere, and we use $O_4$ $DSCD_\alpha$ divided by $O_4$ VCD to convert it into the $O_4$ $DAMF_\alpha$ (Differential Air Mass Factor). Then the $O_4$ $DAMF_\alpha$ and the look-up table method are applied to retrieve the aerosol profile information.[12,13] Finally the trace gas profile information is retrieved by the trace gas $DSCD_\alpha$ and look-up table method. The look-up table method[5,6] employs finite parameters to represent the aerosol extinction profile and trace gas vertical profile, which include aerosol optical depth (trace gas is VCDs), the boundary layer height, the weight factor of $NO_2$ in the boundary layer, *etc*. Then, combining with Monte Carlo atmospheric radiation transfer inversion model (McArtim), we can simulate the observed values of aerosol and trace gas at different elevation angles under different atmospheric conditions and observation geometry conditions, and thus establish the look-up table database. After that, the retrieval speed of aerosol or trace gas profiles becomes much faster, and the obtained results exhibit high stability. When retrieving aerosol or trace gas profiles, the measured values and the simulated values under various cases in the database are iterated with the cost function $\chi^2$ for many times, to find the aerosol or trace gas parameters corresponding to the minimum value of $\chi^2$. Due to the finite parameters of look-up table method, there is no need to assume the prior profiles in advance, which can eliminate the shortcomings of the optimal estimation method.

The trace gas profiles are assumed to be uniformly distributed near the ground (*i.e.*, boundary layer), and the trace gas profiles above the boundary layer decrease exponentially with the increase of height. Therefore the trace gas profiles $c(z)$ can be represented as two layers:

$$c(z) = \begin{cases} \omega \cdot \dfrac{\mathrm{VCD}}{h}, & z < h, \\ a \cdot \exp(-z/\beta), & z \geq h, \end{cases} \tag{1}$$

where $z$ is the height above the ground, $a$ is the normalized constant of the exponential function, $\beta$ is the height of the free troposphere, VCD is the $NO_2$ vertical column densities of 0 km–15 km, that is $\mathrm{VCD} = \int_0^{15\ \mathrm{km}} c(z) \cdot \mathrm{d}z$, $\omega$ is the weight factor of $NO_2$ VCDs in the boundary layer, and $h$ is the boundary layer height. Due to trace gas is mainly distributed in the boundary layer and the trace gas VCDs are not sensitive to $\beta$, therefore $\beta$ can be adopted to be 5 km, there are

$$c(z) = \begin{cases} \omega \cdot \frac{\mathrm{VCD}}{h}, & z < h, \\ \mathrm{VCD}\,(\omega - 1)\beta \left(\mathrm{e}^{-15/\beta} - \mathrm{e}^{-h/\beta}\right) \exp\left(-\frac{z}{\beta}\right), & z \geq h. \end{cases} \tag{2}$$

It can be seen from Eq. (2) that the $NO_2$ vertical profiles can be represented by VCD, $\omega$, and $h$. The $NO_2$ profile is shown in Fig. 2, and the $NO_2$ concentration on the ground is $c_1 = \omega \cdot \mathrm{VCD}/h$.

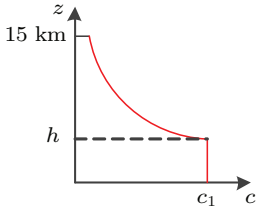



**Fig. 2.** $NO_2$ concentration profile.

The $NO_2$ profile is parameterized, and different shapes of $NO_2$ profile are obtained by setting different parameters of VCD, $\omega$ and $h$. These different $NO_2$ profiles and actual observation conditions are introduced into the atmospheric RTM to simulate and calculate the $NO_2$ DSCDs at different elevations with different $NO_2$ profiles. By minimizing the $NO_2$ DSCDs actually measured by MAX-DOAS and the $NO_2$ DSCDs simulated by look-up table method according to the cost function

$\chi^2$. The input parameter values corresponding to the current $NO_2$ vertical profiles can be reversed, including $NO_2$ VCD, $\omega$ and $h$.

The idea of retrieving aerosol extinction profiles by parameterized look-up table method is to get different aerosol extinction profiles by setting different $t$ (aerosol optical depth), $\omega$ and $h$. Combined with the actual observation conditions, different aerosol extinction profiles are brought into the RTM to simulate different $O_4$ DAMFs, and a look-up table is established using $O_4$ DAMFs under different aerosol conditions. Finally, the actual measured $O_4$ DAMF is compared with the simulated $O_4$ DAMF in the look-up table. After the minimization, the aerosol parameters ($t$, $\omega$, $h$) can be retrieved. The flow chart of retrieving aerosol extinction profile and $NO_2$ profile by look-up table method are shown in Fig. 3. The minimization process of $\chi^2$ is as follows:

$$\chi^2(\gamma,\omega,h) = \sum_\alpha \left( \frac{\mathrm{Meas}_\alpha - \mathrm{Sim}_\alpha(\gamma,\omega,h)}{\sigma(\mathrm{Meas}_\alpha)} \right)^2, \tag{3}$$

where $\mathrm{Meas}_\alpha$ and $\mathrm{Sim}_\alpha$ are the measured results and model results, respectively. The $\sigma(\mathrm{Meas}_\alpha)$ is the standard deviation of measured value. The $\gamma$ represents $t$ and $NO_2$ VCD in the different retrieval processes.

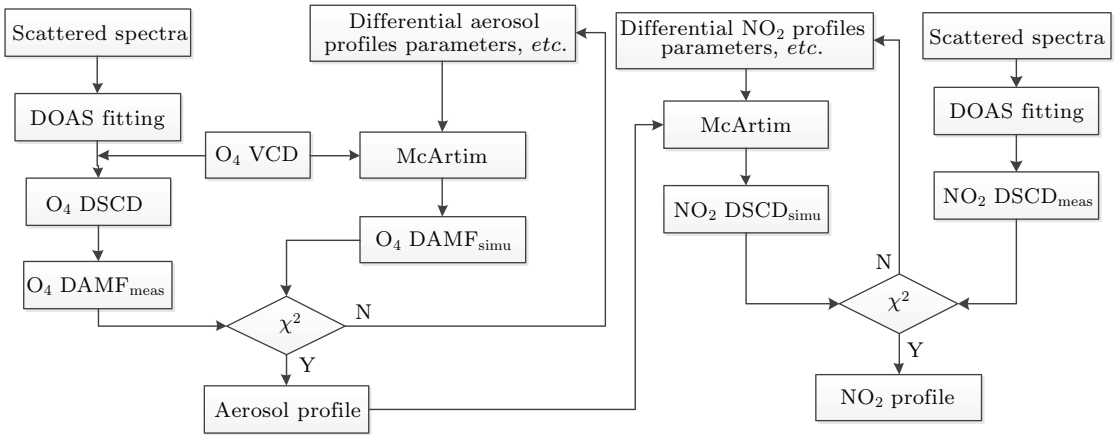



**Fig. 3.** The flow chart of retrieving $NO_2$ profile by look-up table method.

The tropospheric aerosol is complex when it is influenced by the emission of polluted gas, and the light transmission path is strongly affected by the scattering of particles and meters. Only when the aerosol state is accurately known, can the light transmission path in the troposphere be calculated. Therefore, the reconstructed aerosol profiles are input into the atmospheric RTM as the input to further retrieve the trace gas state.

### 2.3. The parameter setting of radiation transfer model

McArtim[14] model is based on Monte Carlo method and is adopted in this article. When McArtim model is adopted, the parameters such as solar zenith angle (SZA), temperature profile, humidity profile, pressure profile, solar relative azimuth angle (SRAA), trace gas profiles, and aerosol optical characteristics need to be input. Among the input parameters, the temperature, humidity, and pressure are calculated by using the American standard atmospheric profile, and the SZA and SRAA are calculated according to the measurement time and the longitude and latitude of the measurement point. A large number of studies have shown that,[4,5,15] asymmetric factor (AP) and single scattering albedo (SSA) with fixed values of 0.72 and 0.9, respectively, can well retrieve aerosol and trace gas profiles. The specific parameter settings are shown in Table 1.

**Table 1.** McArtim model parameters settings.

| Parameter | Value | Units |
|---|---|---|
| SZA | 61.48, 50.76, 41.98, 36.64, 36.34, 41.20, 49.69, 60.25 | degree (°) |
| SRAA | –65.81, –53.15, –36.27, –14.03, 11.32, 34.10, 51.54, 64.58 | degree (°) |
| AP | 0.72 | |
| SSA | 0.9 | |
| Surface albedo | 0.05 | |
| Photon number | 100000 | |
| Wavelength | 354 | nm |
| Elevation | 1, 2, 3, 4, 5, 6, 8, 15, 30, 90 | degree (°) |
| VCD | 5, 10, 15, 20, 25, 30, 40, 50 | $\times 10^{15}$ molec./cm$^2$ |
| $\omega$ | 0.1–1.0 (interval: 0.1) | |
| $h$ | 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.3, 1.5, 1.7, 2.0, 2.5 | km |

## 3. $NO_2$ profile retrieval results

### 3.1. Spectral retrieval

The measured solar spectrum is retrieved with DOAS method, and the $NO_2$ DSCDs at different elevation angles are obtained. In the course of wavelength fitting, small wavelength drift or squeezing is allowed to compensate for the error caused by the instability of the spectrometer.[8] The fitting band of $O_4$ and $NO_2$ is 337 nm–370 nm, and the reference spectrum is set as a fixed reference spectrum. The gas cross sections involved in the fitting are $NO_2$ (Vandaele *et al.* 298 K), $O_4$ (Thalman *et al.* 296 K), $O_3$ (Serdyuchenko *et al.* 223 K) and Ring structure. Figure 4(a) is the fitting diagram of $NO_2$ under the 15° elevation measurement spectrum at 14:16 on September 26, 2019, from which we can see the $NO_2$ $dSCD_{\alpha=15°}$ is $1.47\times10^{16}$ molec./cm$^2$, and the fitted residual is $1.49\times10^{-3}$, which is mainly originated from unknown structure and system noise. The time series of tropospheric $NO_2$ DSCDs in the observation period are obtained by retrieving the measured spectra from September 26, 2019 to September 30, 2019 (Fig. 4(b)). In order to decreased the error caused by spectral analysis and atmospheric instability, the hourly average of the measurements are measured out at each elevation angle.[8] It can be seen from Fig. 4(b) that the $NO_2$ concentration is basically high in the morning and evening, but low in the afternoon. In most cases, the high concentration is caused by traffic emissions during rush hours, while the low concentration is mainly concentrated at noon, which may be caused by the photolysis of atmospheric photochemical reaction.[9]

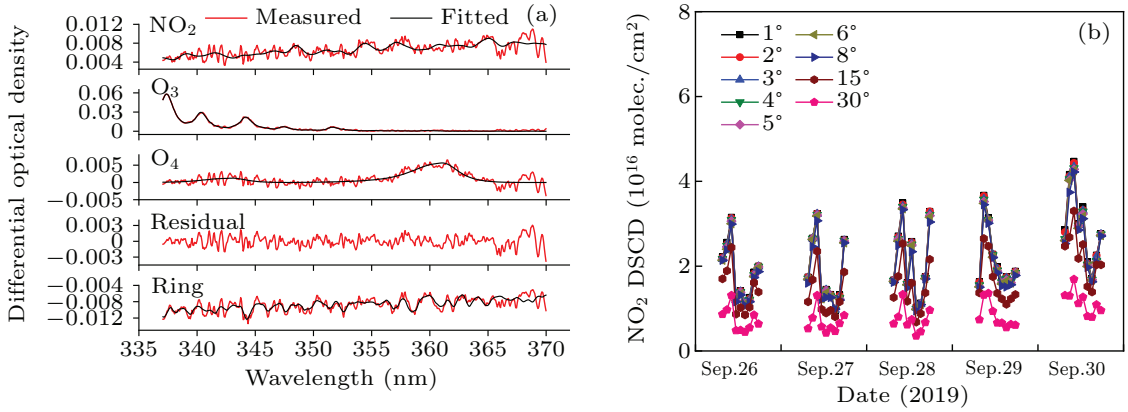



**Fig. 4.** Example of spectral retrieve of 15° elevation measured at 14:16 on September 26, 2019 (a) and the time series of $NO_2$ differential slant column densities at different elevation angles (b).

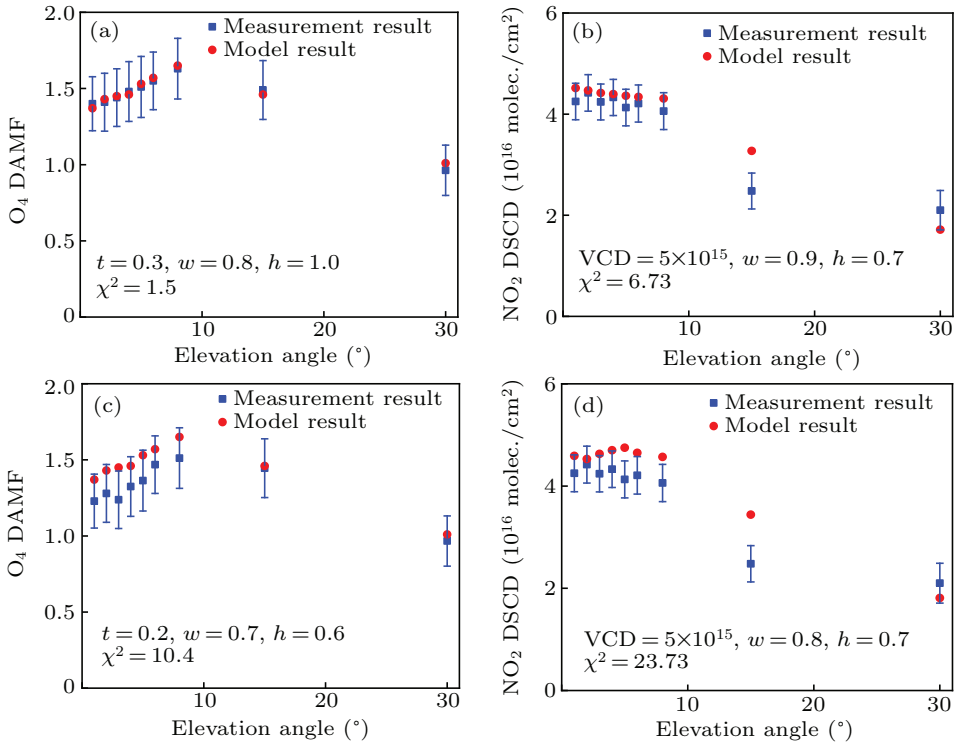



**Fig. 5.** Contrast between the measured and the modeled results of $O_4$ DAMF (a), (c) and $NO_2$ DSCD (b), (d) (September 30, 09:30–10:30, September 28, 2019).

### 3.2. Retrieval results and discussion of $NO_2$ profiles

The parameters settings in Table 1 are input into McArtim model, and the $NO_2$ DSCDs simulation values under nine different elevation angles are obtained through model simulation. By minimizing the cost function $\chi^2$ between the simulated $NO_2$ DSCDs and the measured $NO_2$ DSCDs, the $NO_2$ profile results that most conform to the real atmospheric state can be obtained. Figures 5(a) and 5(c) show the comparison between the measured and modeled results of $O_4$ DAMF, while figures 5(b) and 5(d) show the comparison between the measured and modeled results of $NO_2$ DSCDs. It can be seen from the figure that the smaller the difference between the measured and modeled results of $O_4$ DAMF, the closer the measured and modeled results of $NO_2$ DSCDs. Therefore, the more accurate the aerosol extinction profile in the input model is, the closer the $NO_2$ profile is to the real atmospheric state. In order to simultaneously obtain the aerosol profiles results of $NO_2$ measurement, the aerosol information is retrieved by using the spectrum in the same measurement cycle.

Figure 6 shows the correlation analysis between simulated and measured $NO_2$ DSCDs from September 26, 2019 to September 30, 2019. It can be seen from the figure that the simulated $NO_2$ DSCDs are very close to the measure at different elevations, indicating the cost function $\chi^2$ is sufficiently minimized. There is a good correlation between the measured and simulated below 15° elevation ($R^2 > 0.96$), the correlation decreases at 15° and 30° elevation ($0.9 > R^2 > 0.8$). Therefore, the low elevation observation results are more sensitive to the profile changes, and the low elevation observation should be added in the next research. In addition, it can be seen from the figure that the slope are between 0.77–1.00, so the simulated $NO_2$ DSCDs are slightly higher than the measured on the whole. This may be due to the errors of spectral fitting and model parameters.[7]

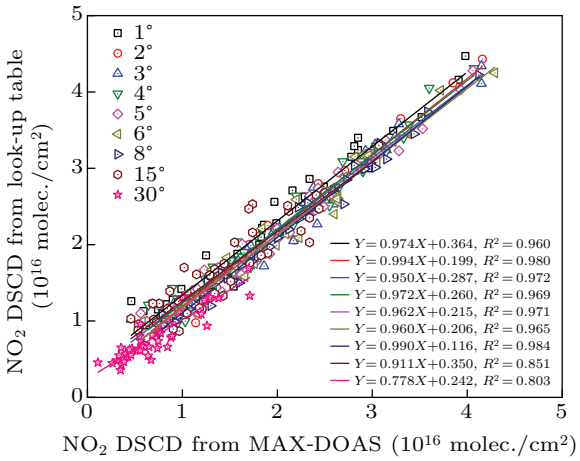



**Fig. 6.** Correlation analysis between simulated and measured values of $NO_2$ DSCDs.

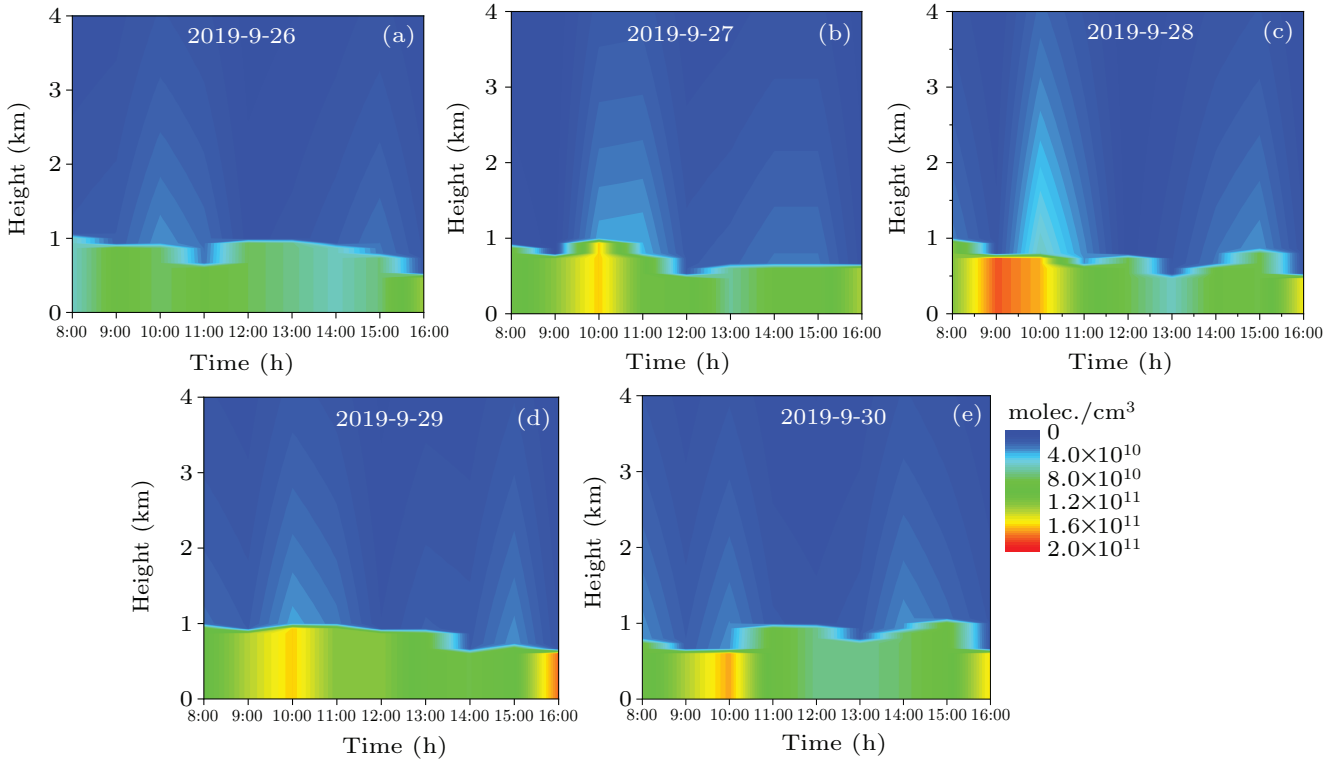



**Fig. 7.** $NO_2$ hourly mean profile and $NO_2$ VCDs hourly mean series from September 26, 2019 to September 30, 2019 (concentration unit: molec./cm$^3$).

The tropospheric of $NO_2$ vertical profiles from 08:00–16:00 on September 26, 2019 to September 30, 2019 are retrieved according to the Section 2.2 (Fig. 7). It can be seen from the figure that $NO_2$ is mainly concentrated below 1 km, which indicates that during the observation period, $NO_2$ is mostly generated by the city's own emissions, and the low

boundary layer height is not conducive to diffusion, resulting in pollution accumulation.[16] The high $NO_2$ concentration is easy to appear from 09:00 to 10:00, which is mainly due to the raise of traffic emissions during the rush hour. After 10:00 with the decrease of traffic emission and the enhancement of photochemical reaction, $NO_2$ is decomposed in large amount. In the afternoon, photolysis is weakened and $NO_2$ concentration begin to increase.

### 3.3. Comparison with CAMS model data

The vertical column density is a key parameter in the retrieval of $NO_2$ profiles. In order to check the correctness of the $NO_2$ vertical profiles obtained by the look-up table method, the $NO_2$ VCDs retrieved by the profile are compared with the results of the CAMS model. The data achieved from the CAMS model are at 00:00, 06:00, 12:00, and 18:00 UTC,[17] and the grid resolutions are $0.125^\circ \times 0.125^\circ$, $0.25^\circ \times 0.25^\circ$, and $0.5^\circ \times 0.5^\circ$. The average values of $NO_2$ VCDs in 07:30–08:30 and 13:30–14:30 from September 26, 2019 to September 30, 2019 are retrieved by the look-up table method and compared with the results of CAMS model at 00:00 UTC (08:00 LT) and 06:00 UTC (14:00 LT). The results of the two methods are consistent from the Fig. 8(a), and their differences are found to be ignored between the different grids. Compared with the results of look-up table method, the CAMS model overestimated $NO_2$ VCDs by $0.68\times10^{15}$ molec./cm$^2$–$2.71\times10^{15}$ molec./cm$^2$ ($0.125^\circ \times 0.125^\circ$), $0.31\times10^{15}$ molec./cm$^2$–$2.05 \times 10^{15}$ molec./cm$^2$ ($0.25^\circ \times 0.25^\circ$) and $0.19\times10^{15}$ molec./cm$^2$–$3.86\times10^{15}$ molec./cm$^2$ ($0.5^\circ \times 0.5^\circ$) at 08:00 LT and 14:00 LT, respectively. The correlation coefficient ($R^2$) between the CAMS model and the look-up table method are more than 0.86 (Fig. 8(b)). A comparison of the results show that the CAMS model and the look-up table method results are nearly consistent. In addition, the results show that the look-up table method based on MAX-DOAS can accurately retrieve the $NO_2$ profiles, and the error between the model and the measurement results may be brought by the limited number of input $NO_2$ profiles.

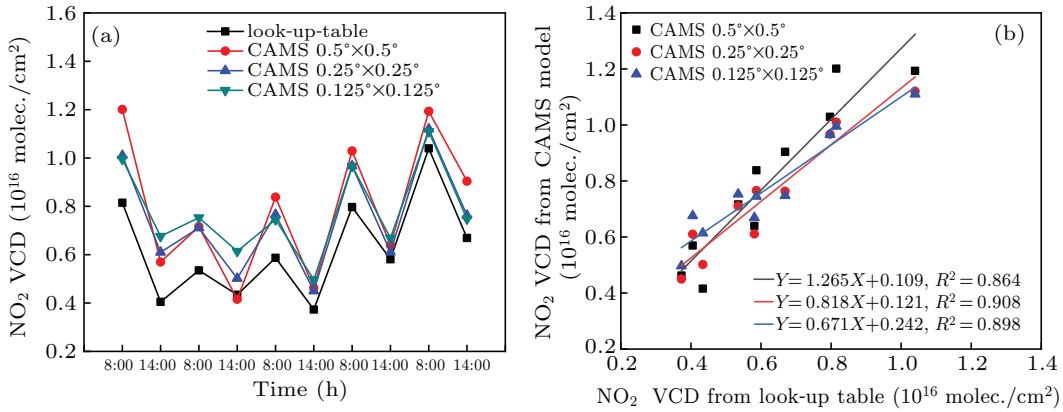



**Fig. 8.** Comparison of $NO_2$ VCDs time series (a) and correlation (b) between the look-up table method and CAMS model.

## 4. Conclusion and perspectives

In this article, a fast method for retrieving the tropospheric $NO_2$ vertical profiles have been established by look-up table method based on MAX-DOAS. Taking the measurement of MAX-DOAS instrument in Huaibei monitoring point as an example, the look-up table is established under nine different elevation angles. By minimizing the cost function, the optimal $NO_2$ vertical column densities and $NO_2$ vertical profiles are obtained. It is found that $NO_2$ is mainly concentrated below 1 km. The high $NO_2$ concentration appeared from 09:00 to 10:00 in the morning, and after 10:00 the $NO_2$ concentration decomposed in large amount. The look-up table method results are compared with different grid resolutions results in CAMS model. The error of two methods is less than $4.00\times10^{15}$ molec./cm$^2$ and the correlation coefficient is more than 0.86. However, in the application of look-up table method, in the face of complex air pollution, it is necessary to further study the profile shapes of $NO_2$ gas, such as further optimization of the profile shapes of $NO_2$ gas and further improvement of calculation efficiency.

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## References


[1] Richter A, Burrows J P, Nüss H, Granier C and Niemeier U 2005 *Nature* **437** 129

[2] Wagner T, Dix B, Friedeburg C. V, Frieß U, Sanghavi S, Sinreich R and Platt U 2004 *J. Geophys. Res: Atmos.* **109** D22

[3] Irie H, Kanaya Y, Akimoto H, Lwabuchi H, Shimiza A and Aoki K 2008 *Atmos. Chem. Phys.* **8** 341

[4] Wang Y, Li A, Xie P H, Chen H, Mou F S, Xu J, Wu F C, Zeng Y, Liu J G and Liu W Q 2013 *Acta Phys. Sin.* **62** 200705 (in Chinese)

[5] Li X, Brauers T, Shao M, Garland R M, Wagner T, Deutschmann T and Wahner A 2010 *Atmos. Chem. Phys.* **10** 2079

[6] Wagner T, Beirle S, Brauers T, Deutschmann T, Frieß U, Hak C, Halla J.D, Heue K.P, Junkermann W, Li X, Platt U and Pundt-Gruber I 2011 *Atmos. Meas. Tech.* **4** 2685

[7] Wu F C, Xie P H, Li A, Si F Q, Xu J, Fang G Q, Liu J G and Liu W Q 2013 *Acta Opt. Sin.* **33** 0601002 (in Chinese)

[8] Mou F S, Luo J, Li S W, Shan W and Hu L S 2019 *Chin. Phys. B* **28** 084212

[9] Mou F S, Li A, Xie P H, Wang Y, Zhang J, Xu J, Wu F C and Chen H 2017 *Spectrosc. Spectral Anal.* **37** 1042

[10] Wang S S, Cuevas C A and Frieß U 2016 *Atmos. Meas. Tech.* **9** 5089

[11] Xu J, Xie P H, Si F Q, Li A, Wu F C, Wang Y, Liu J G, Liu W Q, Hartl A and Lok C K 2014 *Chin. Phys. B* **23** 094210

[12] Si F Q, Liu J G, Xie P H, Zhang Y J and Liu W Q 2005 *Chin. Phys. B* **11** 2360

[13] Tian X, Wang Y, Beirle S, Xie P H, Wagner T, Xu J, Li A, Dörner S, Ren B and Li X M 2021 *Atmos. Chem. Phys.* **21** 12867

[14] Deutschmann T, Beirle S, Frieß U, Grzegorski M, Kern C, Kritten L, Platt U, Prados-Román C, Pukīte J, Wagner T, Werner B and Pfeilsticker K 2011 *J. Quant. Spectrosc. Radiat. Transfer* **112** 1119

[15] Li X, Brauers T, Hofzumahaus A, Lu K, Li Y P, Shao M and Wagner T 2013 *Atmos. Chem. Phys.* **13** 2133

[16] Zhou H J, Liu W Q, Si F Q, Xie P H, Xu J and Dou K 2011 *Acta Opt. Sin.* **31** 1101007 (in Chinese)

[17] Tian X, Pinhua Xie P H, Xu J, Wang Y, Li A, Wu F C, Hu Z H, Liu C and Zhang Q 2019 *Atmos. Chem. Phys.* **19** 3375