

Studying Air Pollution with Kitt Peak Solar Flux Atlas — Analysis Method and Results of Observation

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ABSTRACT

For the measurement of atmospheric NO₂ vertical column density (VCD), Kitt Peak Solar Flux Atlas can be substituted as an extraterrestrial solar radiation. Compared with differential analysis method, the Taylor expansion of integrated transfer equation underestimates the VCD. This underestimation is as large as 35% when the amount of NO₂ is $1 \times 10^{17} \text{ cm}^{-2}$ and observation is conducted with an air mass factor of 10. Even when the VCD is $2 \times 10^{16} \text{ cm}^{-2}$ and the air mass factor is 4, the relative error of the retrieved VCD is still no less than 3%. If the observation is restricted under the small air mass factor condition (≤ 4), with Kitt Peak Solar spectrum as an extraterrestrial solar radiation, only an atmospheric layer of 2 km thick from ground can be studied, which will make the absorption too weak to be detected by normal instruments.

The VCD in winter Tokyo area was observed and analyzed by differential method, which shows a good precision even when the absorption is as low as 3%. The largest average VCD was about $1.3 \times 10^{17} \text{ cm}^{-2}$, and the lowest was about $1.3 \times 10^{16} \text{ cm}^{-2}$. The trend of its variation was almost the same as the ground level observation by Saltzman reagent method.

Key words: Vertical column density (VCD), Extraterrestrial solar radiation, NO₂, Atmospheric contamination

1. Introduction

Two flights of the SAGE III instrument were planned being launched in June 2000 by Russian Meteor-3M and in 2002 by International Space Station (ISS). It is expected that they would offer information of almost global coverage. These instruments will utilize the self-calibrating solar occultation technique to measure profiles of aerosol extinction from 0 to 40 km, ozone from 6 to 85 km, nitrogen dioxide from 10 to 50 km, and water vapor from 0 to 50 km, and utilize lunar occultation observations to monitor the key nighttime species, nitrogen trioxide from 22 to 55 km and chlorine dioxide from 15 to 25 km^②. This provides an opportunity to investigate the air pollution in the lower atmosphere including metropolitan areas with the help of networks of ground-based instruments such as solar spectrophotometer.

Zhang et al. (1990) first used Kitt Peak Solar Flux Atlas as an extraterrestrial solar radiation in the absorption spectroscopic method for atmospheric NO₂ study. Unfortunately they gave no discussion about the extent to which it can substitute the radiation outside the atmosphere. In their study they supposed that NO₂ VCD in Beijing area was no more than $6 \times 10^{16} \text{ cm}^{-2}$ and the measurement was limited in the air mass factor of no larger than 5. They

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^②(<http://arbs8.larc.nasa.gov/sage3/objectives/dataprods.html>)

expanded the radiation transfer equation by the first order Taylor method with a relative error of 2%. Although this error of the first order approximation was relatively small, it could result in a relative error of larger than 10% of retrieved NO₂ VCD, leading to the underestimation of the real amount of NO₂ in Beijing area.

In this paper the differential optical absorption spectroscopy for monitoring atmospheric trace gases is discussed in detail. We compare two different analysis methods and point out that the method of the first order Taylor expansion of the integrated radiation transfer equation will introduce a large relative error in estimating the atmospheric NO₂ VCD in spite of the relative error of the Taylor expansion itself is not so large. It is also concluded that using Kitt Peak Solar Flux Atlas as an extraterrestrial solar radiation to study stratospheric NO₂ in a small air mass factor was not reasonable. This is because the Kitt Peak solar spectrum was taken at the height of only 2 km and air mass factor of about 1.8. Here we report the observational result of the high NO₂ VCD at Chiba city near Tokyo in the Kanto Plain from late autumn and early winter, 1996 to the beginning of 1997.

2. Kitt peak solar flux atlas

Zhang et al. (1990) and Xue et al. (1991, 1989) first used Kitt Peak Solar Flux Atlas (Robert, 1984) as an extraterrestrial solar radiation. Niu et al. (1997) discussed both its limitation and effectiveness in atmospheric absorption spectrometry. This spectrum is used as an extraterrestrial solar radiation in our NO₂ study.

Kitt Peak Solar Flux Atlas provides the solar spectrum covering the wavelength range of 296 to 1300 nm with a resolution of 0.005 nm. This database in more convenient ASCII code is also provided recently by National Optical Astronomy Observatory's home page^① or from anonymous ftp service^②. It is observed with a high-resolution Fourier transform spectrometer at the Kitt Peak National Observatory (32°N, 111.5°W) located in the southern part of Arizona at an altitude about 2000 meters above sea level. The whole spectrum is divided into eight charts. The chart 1, observed from air mass factor of 1.01 to 1.05, covers a wavelength range of 290 to 329.897 nm involving a part of Hartley absorption band of ozone and a strong absorption band of SO₂. Chart 7, observed from air mass factor of 1.84 to 1.63, covers another wavelength range of 401.965 to 473.8 nm overlapping the NO₂ strong absorption band (430–450 nm). Considering the clean environment of the Kitt Peak observation site, this atlas can be substituted as an extraterrestrial solar radiation when an observation of trace gases conducted at large solar zenith angles (large air mass factor) (Niu et al., 1997a; Niu et al., 1997b; Niu, 1996).

The Kitt Peak spectrum is taken at the height of 2 km and at the air mass factor of about 1.8. These conditions contribute to minimize the residual NO₂ absorption in the spectrum. Nevertheless it contains the effect of stratospheric NO₂ absorption. Thus, generally speaking its use as the extraterrestrial solar radiation is reasonable only when the ground observation is made with a large air mass factor. However if the chart is applied to detecting high-level NO₂ contamination in the boundary layer, the ground observation could be conducted at a small air mass factor. Under such conditions the absorption will be very weak, and an instrument with very high precision will be required.

The atlas (Robert et al., 1984) is composed of two parts. One is a residual flux chart,

① <http://www.noao.edu/noao.html>

② <ftp://ftp.noao.edu/fts/>

which has been corrected for its pseudo-continuum corresponding to the slow change of solar intensity and the detector sensitivity according to the wavelength. In addition the atlas presents a calibration of the pseudo-continuum level in $\mu\text{W cm}^{-2} \text{nm}^{-1}$. One can convert the atlas from residual flux to an absolute irradiance by multiplying this pseudo-continuum by the residual flux chart.

3. The absorption cross-section information

Gregory et al. (1996) used a Fourier transform spectrometer to measure absorption cross-section of NO_2 at 200 ± 20 K in a wavelength range of 370–497 nm at resolutions of 2 cm^{-1} and 0.5 cm^{-1} . The overall error in this NO_2 cross-sections was estimated to be better than 27%. In the same year Vandaele et al. (1996) reported the absorption cross-section, measured at room temperature using a similar instrument in the visible range of 380–830 nm at 2 cm^{-1} and 16 cm^{-1} (0.03 nm and 0.26 nm at 400 nm) resolution. The accuracy on this new measurement is better than 4%. Unfortunately these data were not readily available when this work was conducted. Thus in this study we employed Johnston's cross-sections that had been used by a number of groups (Johnston et al., 1989; Zhang et al., 1990; Xue et al., 1991; Kondo et al., 1994). As summarized by Harwood and Jones (1994) that although the cross-sections exhibit no recognizable temperature dependence in the temperature range of 213–298 K, the peak to trough distance increases with decreasing temperature. Consequently, in the case of stratosphere, the use of room temperature values will result in an overestimation of the amount of NO_2 . In this study, however, the room temperature cross-sections bring about no systematic errors, since NO_2 amount near the ground surface is measured. Corcoran et al. (1992) and Amoroso et al. (1993) reported the measurement of absorption of NO_2 in the wavelength region longer than 440 nm.

4. Analysis method

When Zhang et al. (1990) used Kitt Peak solar spectrum as a reference spectrum in the observation of VCD of NO_2 , they employed the solar radiation transfer equation in integration form. Xue et al. (1991) and Niu et al. (1997a) used differential expression of the equation. Here we discuss the advantage and disadvantage of the two methods in the derivation of NO_2 VCD.

4.1 Integration method

The Beer-Lambert law describes the attenuation of a ray of incident intensity $I_0(\lambda)$ passing through the whole atmosphere and detected by a spectrometer at the ground level. The detector slit function is given as

$$f(\lambda') = 1 - \frac{|\lambda - \lambda'|}{\Delta\lambda}, \quad (1)$$

where $\Delta\lambda$ is the spectral resolution. Let $T_A(\lambda')$ and $T_R(\lambda')$ express the attenuation by aerosol and Rayleigh scattering, $k(\lambda')$ the instrument function describing the wavelength dependent response of the photomultiplier. Then the measured voltage $V(\lambda)$ can be expressed as integration in a very narrow band of $\Delta\lambda$

$$V(\lambda) = R \int_{\lambda - \Delta\lambda}^{\lambda + \Delta\lambda} f(\lambda') k(\lambda') I_0(\lambda') T_A(\lambda') T_R(\lambda') T'(\lambda') \exp[-\sigma(\lambda') m N] d\lambda'. \quad (2)$$

Here R is an instrumental constant, $\sigma(\lambda')$ the absorption cross-section of NO_2 , N the NO_2 VCD, and m the air mass factor. The influence of other atmospheric absorbers has been put into $T'(\lambda')$. In the limited wavelength region of 430–450 nm the λ dependence of the transmission factors $T_A(\lambda')$ and $T_R(\lambda')$ are assumed here to be linear. Similar argument holds also in the case of $k(\lambda')$ and $T'(\lambda')$. For the latter factor it is noted that though there remain the effects of other absorbers in 430–450 nm, none of the atmospheric gases exhibit absorption structures as prominent as NO_2 absorption.

In Eq.(2) if all the factors $T(\lambda')$, $T_A(\lambda')$, and $T_R(\lambda')$ were set to 1, NO_2 VCD to 0, and $k(\lambda')$ to a constant, we obtain

$$V_0(\lambda) = R k \int_{\lambda - \Delta\lambda}^{\lambda + \Delta\lambda} I_0(\lambda') f(\lambda') d\lambda' . \quad (3)$$

This equation expresses a spectrum just outside the atmosphere observed by the same instrument as the ground observation.

Calculating the ratio of the ground observation $V(\lambda)$ to the spectrum $V_0(\lambda)$, one can obtain a sloped absorption spectrum of NO_2 . To eliminate this slope (effect of aerosol and Rayleigh scattering, absorption of other constituents, instrument function etc.) one can find two wavelength points in the 439 nm band at which the NO_2 absorption cross-sections are equal. Connecting these two points in the ratio spectrum, a linear function can be found. Dividing the ratio spectrum by this linear function most of the above effects can be eliminated (Zhang et al., 1990; Platt, 1994). Multiplying this corrected ratio spectrum by $V_0(\lambda)$, we can get the expression as follows:

$$V(\lambda) = \int_{\lambda - \Delta\lambda}^{\lambda + \Delta\lambda} I_0(\lambda') f(\lambda') \exp[-\sigma(\lambda') m N] d\lambda' . \quad (4)$$

Assuming the term $\sigma(\lambda') m N$ to be small enough, the exponential can be expanded into a Taylor progression. If we retain up to the second order, we have

$$V(\lambda) = \left[A(\lambda) - m N B(\lambda) + \frac{m^2 N^2}{2} C(\lambda) \right] , \quad (5)$$

where

$$A(\lambda) = \int_{\lambda - \Delta\lambda}^{\lambda + \Delta\lambda} I_0(\lambda') f(\lambda') d\lambda' , \quad (6)$$

$$B(\lambda) = \int_{\lambda - \Delta\lambda}^{\lambda + \Delta\lambda} I_0(\lambda') f(\lambda') \sigma(\lambda') d\lambda' , \quad (7)$$

$$C(\lambda) = \int_{\lambda - \Delta\lambda}^{\lambda + \Delta\lambda} I_0(\lambda') f(\lambda') \sigma^2(\lambda') d\lambda' . \quad (8)$$

The VCD of NO_2 can be determined by solving the quadratic equation of Eq.(5). The relative error of this method can be estimated by

$$\frac{\Delta N}{N} < \frac{[\sigma(\lambda) m N]^2}{6} . \quad (9)$$

Zhang et al. (1990) analyzed the VCD by first order Taylor expansion retaining the first two terms in Eq.(5), with subsequent least square method. Their method would lead to a

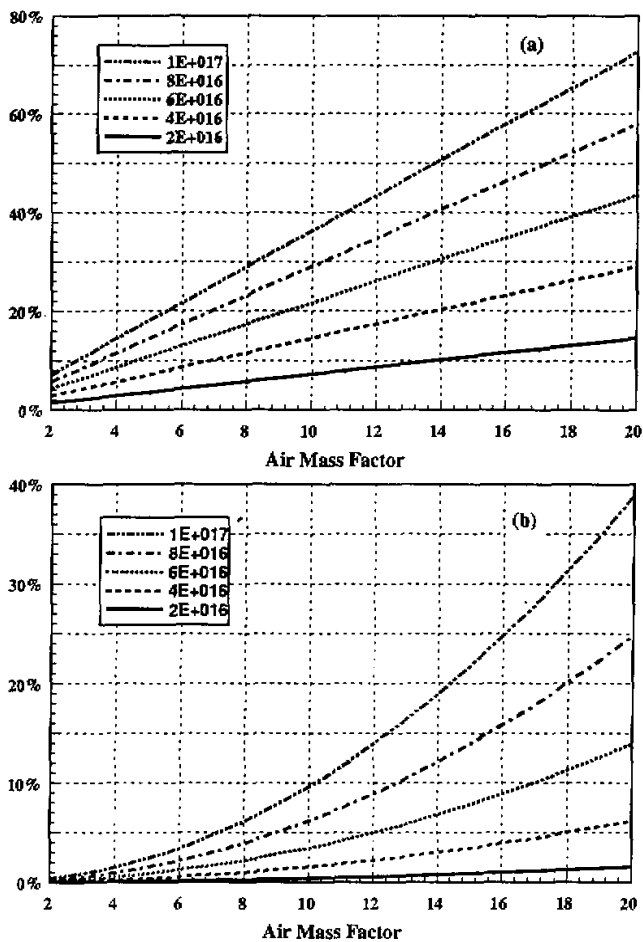


Fig. 1 (a) The relative error of VCD derived from the first order Taylor expansion method at different air mass factors for different NO_2 VCD. (b) The same error from the second order Taylor expansion method.

relative error of

$$\frac{\Delta N}{N} < \frac{\sigma(\lambda)mN}{2} \quad (10)$$

Figure 1 shows VCD relative errors of first and second order Taylor expansion method at different air mass factors for different column amounts of NO_2 . If we suppose, somewhat arbitrarily that the first order approximation is accepted when the relative error of VCD is smaller than 3%, Fig. 1a shows that the air mass factor should be smaller than 4 with NO_2 VCD no more than $2 \times 10^{16} \text{ cm}^{-2}$. Even in the case of the second order approximation under the same criterion the air mass factor should be smaller than 5 with NO_2 VCD of about

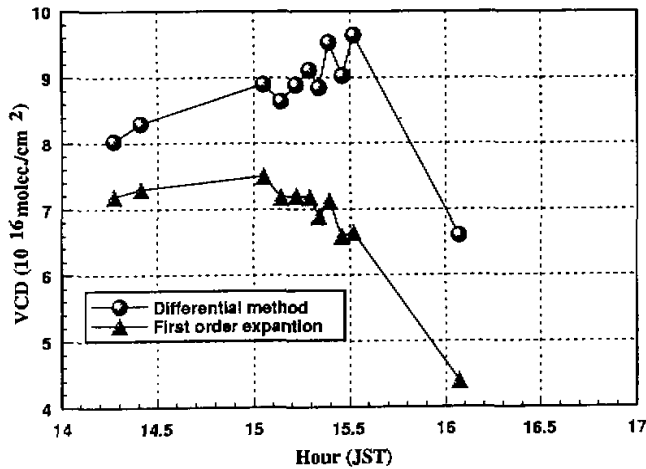


Fig. 2. The NO_2 VCD observed at Chiba city in Dec. 14, 1995 retrieved using the integration and differential methods respectively. The upper curve represents the result of differential method, the lower one the integration method with first order Taylor expansion. The larger the air mass factor and VCD becomes, the greater the difference of these two methods.

$1 \times 10^{17} \text{ cm}^{-2}$.

Figure 2 shows the comparison of the results from the first order Taylor expansion method and the differential method. The first order expansion method will largely underestimate the VCD of atmospheric NO_2 . Only the second order expansion method can be used in some limited conditions.

4.2 Differential method

This method has been well explained by Niu et al. (1997a). In a very narrow spectral band $\Delta\lambda$ (0.2 nm), the radiation absorption can be expressed as

$$V(\lambda) = V_0(\lambda)T_A(\lambda)T_R(\lambda)T'(\lambda)\exp[-\sigma(\lambda)mN], \quad (11)$$

where $V(\lambda)$ is the spectrum observed at the ground level in units of voltage, $V_0(\lambda)$ is the Kitt Peak spectrum of Eq.3, given as the absolute irradiance but not pseudo-residual flux.

In order to retrieve the NO_2 absorption signature, the ratio spectrum is calculated, which is defined as

$$R_s(\lambda) = \frac{V(\lambda)/V(\lambda_0)}{V_0(\lambda)/V_0(\lambda_0)}, \quad (12)$$

where λ_0 is a reference wavelength arbitrarily chosen in the relevant spectral region. The wavelength range of 438.2–442.2 nm for NO_2 retrieval contains 100 data points. Since other atmospheric absorbers and the Mie and Rayleigh scattering contribute as the slope of the observed spectrum, we can remove their interference by comparing two selected data points in the 439 nm absorption band with equal values of the cross sections. When these two data values are found to be different in the ratio spectrum, we renormalize them by using the slope of

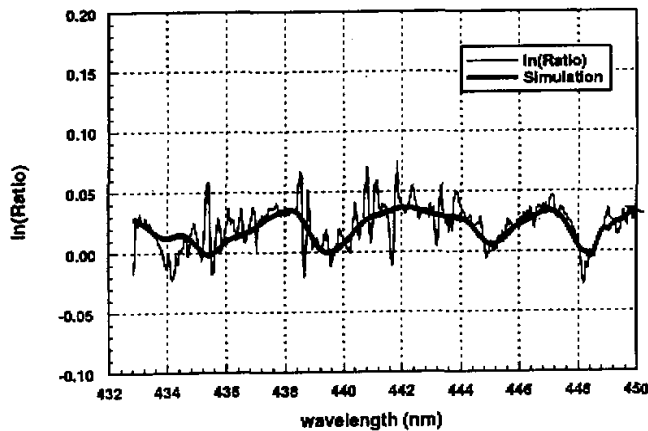


Fig. 3. Ratio spectrum and simulated spectrum based on retrieved vertical column density (3.6×10^{16}) at an air mass factor of 3.23 on Jan. 13, 1997.

a straight line connecting the two points, as in the case of the integration method. Taking logarithm of Eq.(12), the following equation can be obtained:

$$\ln R_s(\lambda) = [\sigma(\lambda_0) - \sigma(\lambda)]mN. \quad (13)$$

The value of N is determined by using the linear least-squares method. The resultant agreement between $\ln R_s(\lambda)$ and the right-hand side of Eq.(13) can be seen from Fig. 3.

The accuracy of the derivation of the NO_2 column density was discussed previously (Niu et al., 1997a). In order to estimate the relative error of this method, the Eq.(13) can be differentiated as

$$\frac{\Delta N}{N} \leq \frac{1}{N[\sigma(\lambda_0) - \sigma(\lambda)]} \left[\frac{\Delta I(\lambda)}{mI(\lambda)} + \frac{\Delta I_0(\lambda)}{mI_0(\lambda)} + N\Delta\sigma(\lambda) \right] + \frac{\Delta m}{m}. \quad (14)$$

The order of the relative error of the observed spectrum $\Delta I(\lambda)/I(\lambda)$ is 10^{-4} , the Kitt Peak solar radiation is 4×10^{-3} , the air mass $\Delta m/m$ is no larger than 2×10^{-2} if we assume the duration of observation to be about 1 min. Therefore, apart from the error of the absorption cross-section, we can estimate that the accuracy of determination of the column density is better than 4%. Another additional error is caused by imperfect wavelength matching, which is considered as about 15%.

5. Result

It is known that in the urban area on Kanto Plain the concentrations of NO_x and SPM (suspended particulate matter) often increase to very high levels in early winter (Mizuno, 1992). The observation of this phenomenon was made at the campus of Chiba University, located at the edge of Kanto Plain, from October 1996 to January 1997, whenever the weather was suitable for the measurement. Figure 4a shows the observed values of average NO_2 VCD in the afternoon of a series of days. Figure 4b shows the variation of NO_2 mixing ratio at the

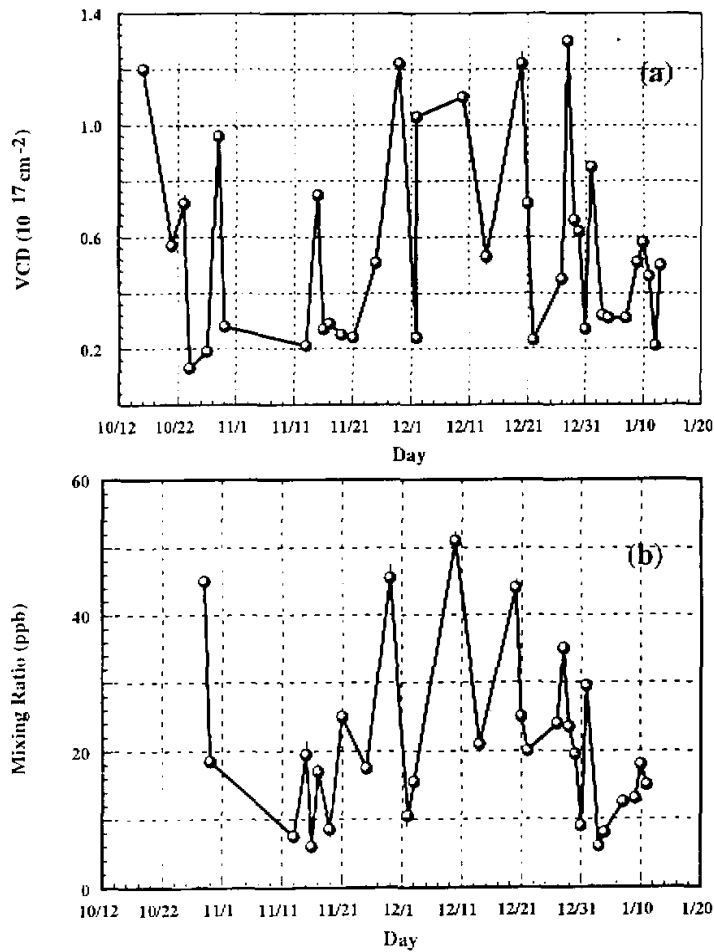


Fig. 4. (a) Day-to-day variation of NO₂ vertical column density measured at Chiba university in different days around 15:00 from October, 1996 to January, 1997. (b) Day-to-day variation of ground level NO₂ mixing ratio observed by Saltzman reagent method at the same place around the same time.

ground level observed at the same time and same place. From these two figures we can find that the trend of the VCD variation is basically similar to that of the mixing ratio at the ground level. The lowest VCD in this period is about $1.3 \times 10^{16} \text{ cm}^{-2}$ observed on October 24, 1996, while the highest levels are about 10 to 20 times higher than the lowest one. Usually it is expected that the emission of NO_x would become the lowest around the New Year's Day in the whole year in Kanto Plain because of the drastic decrease of the economic activities around this period. Although in the present observations the lowest NO₂ VCD was not detected, but the observed amount of $3 \times 10^{16} \text{ cm}^{-2}$ is close to the winter background level of

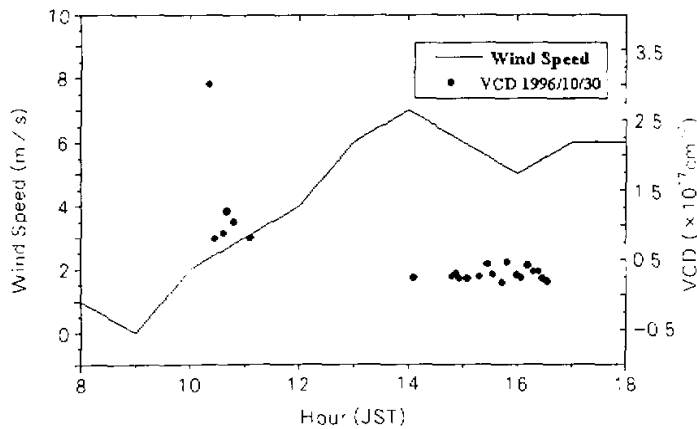


Fig. 5. Close relation between wind speed and VCD can be usually found in observation. In October 30, 1996, under the radiation cooling effect the inversion layer was formed in early morning. The contaminants stocked in this layer could not be diffused to the upper atmosphere, which caused the high-level air pollution. After 9 o'clock, with the gradually strong blowing wind, the polluted air diffused rapidly and the low level atmosphere became clear. The dark black circles show the VCD decreasing with the wind speed increasing.

VCD, $(1.5-4) \times 10^{16} \text{ cm}^{-2}$ (see Fig. 4). High levels of NO_2 usually happened in a foggy morning or in a very stable sunny day characterized by a yellowish-brown colored sky at the time of sunset.

The NO_2 VCD is closely related to the weather condition. In October 30, 1996, the weather condition was so stable in the morning that a very thick fog spread all over. Figure 5 shows that before 10:00am the wind was very weak, after that it gradually became stronger. The first measurement of this day was at 10:35am. As large as $3 \times 10^{17} \text{ cm}^{-2}$ of NO_2 VCD was recorded. But after that as the wind speed continually increased, the measured VCD abruptly decreased to about $1 \times 10^{17} \text{ cm}^{-2}$. At the time of about 14:00 the wind most strongly blew, which resulted in decrease of VCD to about $2.4 \times 10^{16} \text{ cm}^{-2}$. Another example shown in Fig. 6 is the observation on December 28, 1996. When the measurement began, a very thick contaminated layer covered the observation site and the measured VCD was stable (about $1.3 \times 10^{17} \text{ cm}^{-2}$). However, as the strong north wind began blowing after 15:00, the contaminated layer was gradually blown out. Thirty minutes later the atmosphere above the observation site became very clear, and the measured NO_2 VCD decreased to about only $4 \times 10^{16} \text{ cm}^{-2}$. However the observation in January 10, 1997 gives a very stable example. In spite of the wind speed over 3 m/s blew in the morning, the weather condition became very stable after 11:30 to the sunset with the wind speed of only 2 to 3 m/s. No sharp change of NO_2 VCD was detected.

6. Discussion

This study is conducted using a homemade spectrophotometer, which consists of a 12 cm heliostat and a grating spectrometer with a photo-multiplier sensor. Since it requires 3

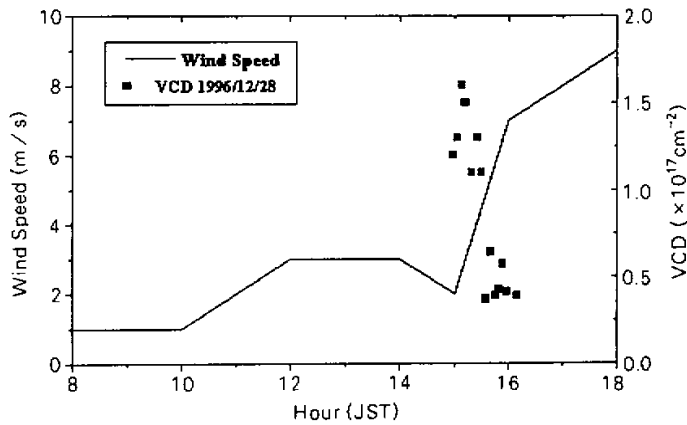


Fig. 6. The observation of December 28, 1996, shown by dark squares, gives another example of the VCD changing process with the weather condition.

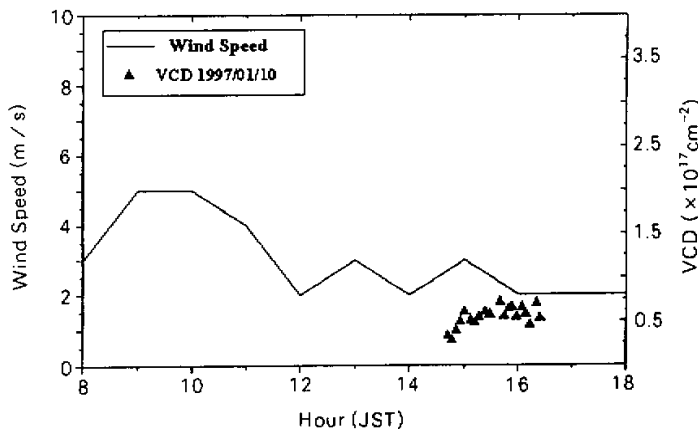


Fig. 7. Data on January 10, 1997, expressed by dark triangle, show nearly stable VCD, which were observed with a cloudless sky and a windless steady weather condition.

minutes to scan one piece of spectrum, some turbulence may affect the spectrum especially when the absorption is very weak due to the scintillation of atmosphere. To solve this problem another sensor should be introduced into the system to monitor the scintillation simultaneously, or change the sensor with a CCD detector, which can improve the quality of the observation and simplify the analysis method. Nevertheless Fig. 3 gives evidence that our method possesses sufficient precision to measure the VCD of a substance, which has absorption of 3%, even though the instrument is very simple.

The crucial point of this method is the calibration of the wavelength. In this work

peak-to-peak alignment has been adopted to match the wavelength between the observed and reference spectra. For further improvement the best fitting of each Fraunhofer line will lead to better eliminating of Fraunhofer structures. As a result the noise of the ratio spectrum will be reduced, and smaller amount of NO₂ absorption will become detectable.

We have analyzed NO₂ VCD by using the absorption signature at 439 nm with a narrow region including only 100 observation points for eliminating the effect of Mie, Rayleigh scattering etc. If a good model for estimating these effects could further be introduced into the analysis, and other absorption in this region be also considered, the whole 20 nm observation region with five absorption signatures can be utilized at the same time and the precision of analysis will be improved greatly.

The total amount of ozone is considered to be about 8×10^{18} cm⁻² in the Northern Hemisphere. The peak to trough of ozone absorption cross-section at about 328 nm is 3.8×10^{-21} cm². The absorption remaining in the chart 1 of the Kitt Peak Solar Flux Atlas is estimated to be no more than 3%. Considering the observation of stratospheric ozone conducted with an air mass factor of 10, 15 and 20, the relevant absorption will be 30%, 45% and 60% respectively. Under these circumstances the Kitt Peak spectrum can be reasonably used as a reference to study characteristics of stratospheric ozone.

Recent measurement (Ferm et al., 1997) suggested that in Beijing, China, SO₂ ground level mixing ratio changed from 16.5 to 72.4 ppbv during one year period from 1991 to 1992. Tanner et al. (1997) reported their results of Sichuan Province in China that at countryside the SO₂ mixing ratio can be as low as 2 ppbv, while in metropolitan area, for example in Chongqing, it can reach as high as 171 ppbv. Because SO₂ is concentrated in the populated area, the Kitt Peak spectrum can also be used as a reference spectrum to study sulfur in the lower atmosphere. Supposing the contaminant is homogeneously distributed in a layer of 1 km thickness near the ground level, 171 ppbv corresponds to a VCD of 4.2×10^{17} cm⁻². The peak to trough absorption cross-section of SO₂ at 301 nm is about 7×10^{-19} cm². The difference of absorption of solar radiation by SO₂ may reach as high as 29% even when the air mass factor is 1. Therefore one can also use Kitt Peak Solar Flux Atlas to monitor the pollutant SO₂.

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REFERENCES

- Amoruso, Antonella, Luca Crescentini, Giorgio Fiocco, and Massimiliano Volpe, 1993: New measurements of the NO₂ absorption cross section in the 440 to 460 nm region and estimates of the NO₂-N₂O₄ equilibrium constant. *J. Geophys. Res.*, **98(D9)**, 16,857-16,863.
- Corcoran, Timothy C., Edward J. Beiting, and Mark O. Mitchell, 1992: High-resolution absorption cross section of NO₂ at 295, 573 and 673 K at visible wavelengths. *Journal of Molecular Spectroscopy*, **154**, 119-128.
- Ferm, Martin, and Henning Rodhe, 1997: Measurements of air concentrations of SO₂, NO₂ and NH₃ at rural and remote sites in Asia. *Journal of Atmospheric Chemistry*, **27(1)**, 17-29.
- Frost, Gregory J., Lisa M. Goss, and Veronica Vaida, 1996: Measurements of high-resolution ultraviolet-visible absorption cross sections at stratospheric temperatures. *J. Geophys. Res.*, **101(D2)**, 3869-3877.
- Harwood, M. H., and R. Jones, 1994: Temperature dependent ultraviolet-visible absorption cross sections of NO₂ and N₂O₄: Low-temperature measurements of the equilibrium constant for 2NO₂ ⇌ N₂O₄. *J. Geophys. Res.*, **99(D11)**, 22,955-22,964.
- Johnston, P. V., and R. L. Mckensie, 1989: NO₂ observations at 45°S during the decreasing phase of solar cycle 21, from 1980 to 1987. *J. Geophys. Res.*, **94(D3)**, 3473-3486.

- Kondo, Y., W. A. Matthews, S. Solomon, M. Koike, M. Hayashi, K. Yamazaki, H. Nakajima, and K. Tsukui, 1994: Ground-based measurements of column amounts of NO₂ over Syowa station, Antarctica. *J. Geophys. Res.*, **99(D7)**, 14,535–14,548.
- Mizuno, Tateki, and Hiroaki Kondo, 1992: Generation of a local front and high levels of air pollution on the Kanto plain in early winter. *Atmospheric Environment*, **26A(1)**, 137–143.
- Niu Jianguo, 1996: *Optical Absorption Spectrometry Applicable for Studying Air Pollution*. PhD thesis, Chiba University.
- Niu Jianguo, Yasushi Sakurada, Hiroaki Kuze, and Nobuo Takeuchi, 1997a: Measurement of atmospheric NO₂ column density with Kitt Peak Solar Flux Atlas as a reference. *Optical Review*, **4(1B)**, 240–245.
- Niu Jianguo, Daisuke Tanaka, Xue Yanqun, Yasushi Sakurada, Hiroaki Kuze, and Nobuo Takeuchi, 1997b: Application of Kitt Peak Solar Flux Atlas for studying air pollution in Tokyo area. In *IGASS 1997 IEEE International Geoscience and Remote Sensing Symposium Proceedings*, Vol. 1, 55–57, Singapore.
- Platt, U., 1994: Differential optical absorption spectroscopy (DOAS). In *Air Monitoring By Spectroscopic Techniques*, Vol. 127 of *Chemical Analysis, A Series of Monographs on Analytical Chemistry and Its Applications*, chapter 2, 27–84.
- Robert, Kurucz L., Ingemar Furenliid, James Brault, and Larry Testerman, 1984: *Solar Flux Atlas from 296 to 1300 nm*. Harvard University.
- Tanner, Peter A., Lei Hengchi, Huang Meiyuan, and Shen Zhilai 1997: Acid rain and below-cloud scavenging in south-western China. *Journal of Atmospheric Chemistry*, **27(1)**, 71–78.
- Vandaele, A. C., C. Hermans, P. C. Simon, M. Van Roozendael, J. M. Guilmot, M. Carleer, and R. Colin, 1996: Fourier transform measurement of NO₂ absorption cross-section in the visible range at room temperature. *Journal of Atmospheric Chemistry*, **25**, 289–305.
- Xue Qingyu, Niu Jianguo, Zhao Xuepeng, and Guo Song, 1991: Remote sensing of atmospheric constituents and the multi-function spectrophotometer. *Acta Meteorologica Sinica*, **5(3)**, 352–359.
- Xue Qingyu, Niu Jianguo, Zhao Xuepeng, and Guo Song, 1989: Development of a solar and skylight spectrophotometer for trace gas and aerosol studies. In *IGASS 1989 IEEE International Geoscience and Remote Sensing Symposium Proceedings*, 2946–2950, Canada.
- Zhang Chengxiang, Zhao Bolin, and Mao Jietai, 1990: Study on atmospheric trace gas NO₂. *Science in China (Series B)*, **33(9)**, 1124–1135.