Simulations of Aerosol Optical Properties to Top of Atmospheric Reflected Sunlight in the Near Infrared CO₂ Weak Absorption Band

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Abstract Over the Asian continent, high aerosol loading is critical to ensure the high accuracy of CO₂ retrieval in the near infrared absorption band. Simulations were performed to explore the effect of light path modification by aerosol on the atmospheric CO₂ near infrared band (6140–6270 cm⁻¹). The Vector Linearized Discrete Ordinate Radiative Transfer (VLIDORT) model and the Line-By-Line Radiative Transfer Model (LBLRTM) were used for forward calculations. The U.S. standard atmosphere was used for atmospheric profiles. The results indicate that the aerosols caused similar effects to increases in CO₂ Conflict depth was 0.1. This effect will cause an overestimation of XCO₂ retrieval. However, investigation of the optical properties of aerosols is valuable for improving CO₂ retrieval algorithm. Therefore, investigation of the optical properties of aerosols is valuable for improving CO₂ retrieval algorithm research. The results also indicate that the effect of urban and industrial aerosols is smaller than that of non-absorbing and dust aerosols because of the nearly constant absorption properties in the near infrared band.

Keywords: satellite remote sensing, CO₂, near infrared, aerosol

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1 Introduction

Carbon dioxide (CO₂) is a major anthropogenic greenhouse gas that remains significant uncertainties in global carbon cycle. Simulation studies indicate that the column-average CO₂ dry-air mixing ratio (XCO₂) requires a precision of 1% or better to improve our current knowledge of the surface CO₂ flux (Rayner and O’Brien, 2001). Existing ground-based measurements are too limited in spatial resolution to achieve required regional scale measurements; however, they can provide the highly accurate observations. Hyperspectral satellite remote sensing provides an efficient method to measure XCO₂. Thermal infrared instruments such as the Atmospheric InfRared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI) are less sensitive to CO₂ near the surface and will introduce an uncertainty larger than 1% into the XCO₂ measurement (Crisp et al., 2004). Near infrared (NIR) instruments such as the Thermal And Near-infrared Sensor for carbon Observation (TANSO) on board the Greenhouse Gases Observing Satellite (GOSAT) and the Orbiting Carbon Observatory (OCO), which is sensitive to column XCO₂, provide an opportunity to achieve highly accurate XCO₂ measurements (Liu et al., 2011).

Scattering of aerosols and clouds was a serious problem for satellite remote sensing in the NIR band. Multi scattering between aerosols and the surface could modify the light path and introduce uncertainty into the XCO₂ retrieval algorithm (Mao and Kawa, 2004). Over the Asian continent, high aerosol loading will be critical to construct high accuracy CO₂ retrieval algorithm. Therefore, investigation of the optical properties of aerosols is valuable for improving CO₂ retrieval algorithm research. The aerosol optical depth (AOD) is a major measurement of aerosol optical effects, such as scattering and absorption. In order to reduce the scattering effect of aerosols on XCO₂ retrieval, a medium resolution image spectrometer, the Cloud and Aerosol Imager (CAI), was onboard the GOSAT to approach distribution of AOD synchronous. However, the effect of aerosols on light paths was determined by the AOD and other properties. In this study, simulations were conducted to determine the effects of aerosol optical properties, particularly their vertical distribution, on the CO₂ NIR weak absorption band spectra.

2 Method

A hyperspectral forward model was built to simulate the solar radiance transform process in the atmosphere within polarization effect. The information collected by satellite observations mainly came from the CO₂ absorption lines in the NIR weak absorption band, and the line broadening varied with pressure and temperature. The Line-By-Line Radiative Transfer Model (LBLRTM) provided a high precision method to calculate line broadening and the absorption coefficient assuming a Voigt line profile (Clough et al., 2005). The line parameters were provided by High-resolution TRANsmission molecular absorption database (HITRAN) 2008 without considering any line mixing effects, which was more sensitive to O₂A band. The spectral range examined in this study was from 6140 to 6270 cm⁻¹ with 0.01 cm⁻¹ sampling spans. This range provided the most information for XCO₂.

The scattering process was complicated, and the polarization caused by aerosols and molecules was serious and should not be neglected in the NIR band. Therefore a
vector radiation transfer model, Vector LInearized Discrete Ordinate Radiative Transfer (VLIDORT), was used to simulate the radiative transfer process (Spurr, 2006). The scattering parameters of atmospheric molecules were determined using the first principal of Rayleigh scattering theory (Bodhaine et al., 1999). Mie theory was used with a spherical assumption to determine aerosol optical properties. In this study, the 1976 United States standard atmosphere profile for pressure, temperature, and relative humidity was used to define the atmospheric parameters. Different atmospheric states, which could only induce numerical modifications, will lead to similar results to the 1976 U.S. standard atmosphere profile. This is because the scattering process has a small correlation with atmospheric state. The surface was assumed to be Lambertian with a constant albedo of 0.3, which is similar to a deciduous forest. The nadir observation with a 5° solar zenith angle was chosen as the calculation condition because it was general in satellite remote sensing simulation studies.

Aerosol and molecular scattering modified the light path in the radiative transfer process. The absorption strength increased or decreased as the light path extended or shortened, respectively. Therefore, modifications effects only affected the absorption region of the spectra. For the non-absorbing region, scattering only lead to a gentle modification of emergent radiance to the dimension of wavenumber. The total spectral change can be separated into two parts: flat variation through the whole band and rough variation in the absorption region. The relative changes between the absorption region and the non-absorbing region were important for the modification of the light path. In order to investigate these effects, we introduce an off-line to on-line ratio as follows,

\[
\text{Ratio} = \frac{I_{\text{off-line}}}{I_{\text{on-line}}}
\]

where \(I_{\text{off-line}}\) and \(I_{\text{on-line}}\) are the radiation with and without absorption, respectively. In this study, \(I_{\text{off-line}}\) was calculated using a linear fitting method for two non-absorbing points at 6140 and 6270 cm\(^{-1}\). The off-line to on-line ratio indicate the relative absorption of the CO\(_2\) lines, and positive variations indicate an extended light path.

3 Results and discussions

The CO\(_2\) mixing ratio in the Planetary Boundary Layer (PBL) is highly variable because it is closely related to carbon emissions that are unnatural, such as the production and combustion of fossil fuels. The change in the off-line to on-line ratio caused by CO\(_2\) PBL variation could act as a measurement for the aerosol scattering effect. Figure 1 shows the relative changes in the off-line to on-line ratio for CO\(_2\) increases in the PBL (<2km layer) of 3, 5, 10, and 20 ppm. The change in the ratio was positive and increased as the CO\(_2\) mixing ratio increased because higher amounts of CO\(_2\) lead to an increasing in absorption. A maximum ratio change of 1.4% was found for a 1% CO\(_2\) increase in the PBL. The maximum ratio change was near 2% for a 20 ppm CO\(_2\) PBL increase.

3.1 Non-absorbing aerosols

The aerosol optical properties vary because of their complex physical and chemical composition. We considered a simple type of non-absorbing spherical aerosol with a refractive index of 1.5–0.0i. A normal size distribution was used with a mode radius of 0.1 μm and a variance (\(\sigma\)) of 2.0. The aerosols were distributed uniformly in

![Figure 1](image-url) The off-line to on-line ratio changes for CO\(_2\) mixing ratio increases in the PBL of (a) 3 ppm, (b) 5 ppm, (c) 10 ppm, and (d) 20 ppm.
a single 0.5 km vertical layer. To investigate the effects of aerosols on the altitude uncertainty of the aerosol layer, the AOD was fixed at 0.1 for 6300 cm$^{-1}$. Figure 2 shows the relative changes of off-line to on-line ratios for different aerosol layer altitudes. The scattering effect becomes more significant as the aerosol layer increases in altitude. Compared to the ratio change caused by CO$_2$ in the PBL, a 1–1.5 km aerosol scattering effect was similar to a 5 ppm increase in the CO$_2$ mixing ratio, and a 1.5–2 km aerosol scattering effect was larger than a 20 ppm increase in the CO$_2$ mixing ratio.

3.2 Transported dust

One of the most well-known aerosol events in China is the transport dust from the Mongolian Gobi Desert or the Taklimakan desert. According to observations and simulation results, the transported dust could be classified by the altitude of the transport layer using a vertical normal distribution (Huang et al., 2008). Low-layer dust had a maximum concentration center at surface level and a $\sigma$ of 0.8 for the vertical dust dispersion region. Mid-layer dust had a maximum concentration center 3 km above surface and a $\sigma$ of 0.6 for the vertical dust dispersion. High-layer dust had a maximum concentration center 6 km above surface and a $\sigma$ of 0.2 for the dust dispersion region. The AOD of three types of transport dust was fixed at 0.1 for 6300 cm$^{-1}$, and the refractive index was fixed at 1.53–0.005i according to the Optical Properties of Aerosols and Clouds (OPAC) (Hess et al., 1998). Figure 3 shows the relative changes in the off-line to on-line ratios. The scattering effect became more significant as aerosol layer rose in altitude, which was similar to the results for A

Figure 2  The off-line to on-line ratio changes caused by a single layer non-absorbing aerosol with a layer altitude of (a) 0–0.5 km, (b) 0.5–1.0 km, (c) 1.0–1.5 km, and (d) 1.5–2.0 km.

Figure 3  The off-line to on-line ratio changes caused by (a) low-layer, (b) mid-layer, and (c) high-layer transport dust.
single layer aerosol. The effect of mid-layer dust was similar to that of a 20 ppm increase in CO$_2$ mixing ratio in the PBL.

### 3.3 Urban and industrial aerosols

Studies indicated that urban and industrial aerosols dominated the eastern regions of China, particularly the North China Plain (Yang et al., 2012). According to observations, the urban and industrial aerosols could be classified as different transport layers using a normal distribution in vertical (Xia, 2010). Low-layer urban and industrial aerosols had a maximum concentration center at surface level and a $\sigma$ of 0.8 for the vertical aerosol dispersion. Mid-layer urban and industrial aerosols had a maximum concentration center at 1.5 km above the ground and a $\sigma$ of 0.2 for the vertical aerosol dispersion. The AOD was fixed at 0.1 for 6300 cm$^{-1}$. The urban and industrial aerosols varied around the world, particularly in different industrial areas. Each aerosol’s composition was a key factor in determining its optical properties, such as the refractive index. Because of fossil fuel combustion, most urban and industrial aerosols were strong absorbers. Variations in the refractive index of high absorption aerosols in numerical produced to similar results. In this study, we used a fixed refractive index of 1.70–0.325i to represent urban and industrial aerosols according to OPAC (Hess et al., 1998). Figure 4 indicates the relative changes in the off-line to on-line ratio for two types of urban and industrial aerosols. The results indicate that the effect of urban and industrial aerosols was lower than that of non-absorbing and dust aerosols, and also lower than that of a 3 ppm increase in the CO$_2$ mixing ratio.

### 3.4 Discussions and explanation

Three types of aerosol scattering effects produced positive changes in the off-line to on-line ratio, an effect that became more significant for aerosols at higher altitudes. Modifications to the light path were caused by multi-scattering between aerosols and the surface. In general, greater distances between aerosols and the surface will cause more changes to light path. The effect of urban and industrial aerosols was smaller than for non-absorbing and dust aerosols because of its stronger near constant absorption properties throughout the band. The aerosol optical properties and vertical distribution were sensitive to the CO$_2$ NIR weak absorption band spectrum. Therefore, the effect should be considered in CO$_2$ retrieval. The uncertainty in the aerosol vertical distribution could cause an overestimation or underestimation to retrieval results.

### 4 Conclusions

This study investigated the effect of aerosol scattering on CO$_2$ NIR weak absorption lines. Three types aerosols were studied, including non-absorbing, dust, and urban/industrial aerosols. Results indicate that the aerosol scattering effect caused a positive change in the off-line to on-line ratio, which was similar to increasing the CO$_2$ mixing ratio in the PBL. The change in the off-line to on-line ratio was higher for aerosol layer sat higher altitudes.

Over a lower albedo surface, such as a deciduous forest, the effect could cause an overestimation of the CO$_2$ mixing ratio in retrieval process and an underestimation in the aerosol layer altitude. Although the information collected by passive remote sensing was limited, for CO$_2$ retrieval it was necessary to have information regarding the aerosol vertical distribution and optical properties, in addition to the AOD of the column. The information from the multi-instrument and chemical transport model was helpful for improving the accuracy for future XCO$_2$ satellite observations.

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### References