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Detecting anomalous CO_2 flux using space borne spectroscopy

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ABSTRACT

Over the time-scale, earth's atmospheric CO_2 concentration has varied and that is mostly determined by balance among the geochemical processes including burial of organic carbon in sediments, silicate rock weathering and volcanic activity. The best recorded atmospheric CO_2 variability is derived from Vostok ice core that records last four glacial/interglacial cycles. The present CO_2 concentration of earth's atmosphere has exceeded far that it was predicted from the ice core data. Other than rapid industrialization and urbanization since last century, geo-natural hazards such as volcanic activity, leakage from hydrocarbon reservoirs and spontaneous combustion of coal contribute a considerable amount of CO_2 to the atmosphere. Spontaneous combustion of coal is common occurrence in most coal producing countries and sometimes it could be in an enormous scale. Remote sensing has already proved to be a significant tool in coalfire identification and monitoring studies. However, coalfire related CO_2 quantification from remote sensing data has not endeavoured yet by scientific communities because of low spectral resolution of commercially available remote sensing data and relatively sparse CO_2 plume than other geological hazards like volcanic activity. The present research has attempted two methods to identify the CO_2 flux emitted from coalfires in a coalmining region in north China. Firstly, a band rationing method was used for column atmospheric retrieval of CO_2 and secondly atmospheric models were simulated in fast atmospheric signature code (FASCOD) to understand the local radiation transport and then the model was implemented with the inputs from hyperspectral remote sensing data. It was observed that retrieval of columnar abundance of CO_2 with the band rationing method is faster as less simulation required in FASCOD. Alternatively, the inversion model could retrieve CO_2 concentration from a (certain) source because it excludes the uncertainties in the higher altitude.

1. Introduction

The earth's atmospheric CO_2 concentration has varied over the long time-scale resolved by several geochemical processes such as sedimentation of organic materials, wreathing of silicate rock and volcanic activity (Berner, 1993, 1997). It has observed from Vostok ice core samples that cover past four glacial/interglacial cycles (420 kyear), atmospheric CO_2 concentration was low during glacial period ($\sim$180 ppmv) and higher in interglacial period (300 ppmv) (Petit et al., 1999; Fischer et al., 1999). Several researchers suggested that the concentration of CO_2 in the atmosphere has unambiguously increased (from 350 to 375 ppmv) since the industrial revolution (Keeling and Whorf, 1999; Etheridge et al., 1996). Except industrialization, few geo-natural events such as volcanic activity, leakage from hydrocarbon reservoir and natural occurrence of coalfires could have significant contribution in global CO_2 budget.

The observational foundation of global carbon studies in the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostic Laboratory cooperate air sampling network of worldwide measurements for carbon cycle GHGs (Conway et al., 1994). Approximately 56 fixed base observatories complemented with ship and aircraft are distributed over the globe. Their *in situ* measurements are quite accurate but for assessing the global process their distribution is very limited over space and time. Based on this network the observed uncertainty of the global carbon budget is 2–3 GtC year^{-1} (Tans et al., 1990; Rayner and O'Brien, 2001; Gurney et al., 2002).

Numerous instruments such as Fourier transform spectrometer, lasers, hyperspectral sensors are being used, boarded on air/satellite-based platforms for estimation of different atmospheric gases with a proper analysis of atmospheric spectra and reliable retrievals. Few models (such as band rationing) are developed to retrieve columnar water vapour data from hyperspectral remote sensing data such as AVIRIS and have been standardized (Gao and

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Goetz, 1990; Schläpfer et al., 1998). The presence of several wide and distinct water vapour absorption bands in the visible near-infrared (VNIR) to short-wave infrared range (SWIR) of the electromagnetic spectrum (EMS) allow the estimation of atmospheric water vapour without much complication. The retrieval of atmospheric CO_2 is much more complex than water vapour as CO_2 has much narrower absorption features and frequently influenced by other atmospheric gases such as water vapour.

The problem of narrow absorption bands (>5 nm) can hardly be solved as most of the present remote sensing sensors typically have a band width of ~10 nm covering the whole visible and some part of the short-wave infrared region. To perform global measurements of trace gases in the troposphere and in the stratosphere SCIAMACHY (European Space Agency) was launched in 2002. The channel 7 of this satellite was specially designed for CO_2 observations, which unfortunately now non-operational due to ice formation on sensor (Buchwitz, 2006). There are only few remote sensing-based studies that deal with atmospheric CO_2 retrieval and they are either very coarse resolution (~100 km) or focused on specific atmospheric layers or ground based. Until now an ambitious project dedicated to atmospheric CO_2 retrievals has been taken up by JPL, NASA, namely Orbiting Carbon Observatory or OCO which will supposedly launch in 2008 (Miller et al., 2005).

The Hyperion pushbroom instrument (boarded on earth Observing 1 satellite) was designed to provide hyperspectral data of earth surface. Hyperion acquires spectra of 7.7 km across track with a spatial resolution of 30 m. It has two spectrometers, one in VNIR range (bands 8–57, 427–925 nm) and other in SWIR region (bands 77–224, 912–2395 nm). For the present research, from fast atmospheric signature code (FASCOD) simulated transmission spectra of atmosphere, two bands of Hyperion (acquired on 09.09.2003) were selected (B185 and B186) that are close to 2.0 μm.

In the measured spectrum of a sensor from top of the atmosphere (TOA) each atmospheric species leaves a specific absorption feature by which it can be identified and quantified (in required resolution). By exploiting differential absorption features till date several band rationing methods are being used to estimate columnar abundance of different atmospheric species. Among them Narrow-Wide (N/W: Frouin et al., 1990), Continuum Interpolated Band Ratio (CIBR: Green et al., 1989; Bruegge et al., 1990; Kaufman and Gao, 1992) and Linear Interpolated Regression (LIRR: Schläpfer et al., 1996) are being used by research community. The present study examines the possibilities of CO_2 columnar retrieval by using CIBR method (Green et al., 1989) because of its straightforward approach.

Another goal of this study is to investigate the relation between radiance at sensor and concentration of CO_2 plume emitted from certain event (in this case coalfire) to retrieve concentration of CO_2 (per pixel) from hyperspectral image. Based on FASCOD simulations a simplified atmospheric model was developed to retrieve the CO_2 plume related radiance and later this information was inversed to retrieve coalfire related CO_2 concentration up to a fixed altitude.

2. Study area

The study area, the Wuda coalmine area (or Wuda syncline), is located in Inner Mongolia autonomous region in north China. The area demarcated in north and west by Gobi desert, in east by the Yellow river, and south by the Helan Mountains. The extent of the Wuda coalmine area from north to south is 10 km and from east to west is 3–5 km, with a total area of 35 km^2. The Wuda mining region has subdivided into three mining zones: Wuhushan, Suhaitu and Huangbaici by the mining authority.

The first coalfire was recorded here in 1961 in a small coalmine pit. Before 1989, the coalfires in Wuda were isolated and scattered in different places, which gradually connected between 1989 and 1995. The connected fires are spreading rapidly since 1995. According to BRSC's (Beijing Remote Sensing Centre) estimation in 2002 that the total area affected by coalfires is 3.07 million m^2 covering 8.8% of the total area of the Wuda syncline (Source: Wuda Mining Authority). It has been estimated that CO_2 emissions from Chinese coalfires alone contributes about 0.3% of the total CO_2 emitted from fossil fuels (Voigt et al., 2004).

3. Research approach

Theoretically sun is the main energy source in optical remote sensing apart from the negligible thermal radiation. The earth's atmosphere modulates twice any signal before it reaches the sensor by means of absorption and scattering. As most of the remote sensing sensors are positioned in the middle or at the top of the atmosphere, the radiance at sensor is a combined effect of atmosphere and surface. The radiation of an incident beam is attenuated by both scattering and absorption in atmosphere. Aerosol particles, cloud drops and gases scatter and absorb energy as a function of wavelength.

As a chemically unreactive, well mixed and long lived gas, CO_2 has its main sources and sinks at the earth's surface. Depending on surface conditions, CO_2 concentration can vary in the planetary boundary layer (PBL), but at higher levels its mixing ratio is nearly constant below the dissociation level of molecular oxygen (~90 km) (Mao and Kawa, 2004).

As a polyatomic molecule, CO_2's three atoms lie along a straight line with the two oxygen atoms equidistant from the carbon atom. The stretching and bending of the bonds in the internal modes produces the infrared absorptions seen in CO_2 spectra. There are several CO_2 absorption bands in the incoming solar radiation and outgoing atmospheric thermal emission (i.e. infrared and thermal infrared zone of spectrum). The near-infrared absorptions of interest in this study are combination bands centred around 2.0 μm.

To estimate atmospheric CO_2 concentration from remote sensing sensors, it would be helpful to simulate same atmospheric conditions (as expected in study area) in controlled environment. Radiative transfer codes such as FASCOD are capable to simulate specific atmospheric conditions with variable atmospheric gas compositions and concentrations (Clough et al., 1986).

In the present study FASCOD was used that calculates spectral transmittance, radiance, optical depth for a given path by using line-by-line calculation for very high spectral resolution. FASCOD uses HITRAN2K (Varanasi and Nemtchinov, 1994) spectral database to simulate atmospheric models. To simulate atmosphere (as it is expected in study area), boundary layer aerosol 'desert extinction' with a 'fall–winter' seasonal aerosol profile was used and 'background stratospheric' aerosol profile was used. For cirrus clouds scattering calculation 'NOAA Cirrus Profile' was used with 'Cirrus Thickness' 1.0 km and 'Cirrus Base Altitude' 8.0 km in FASCOD.

In the present study two methods were evaluated for atmospheric CO_2 retrieval. The first method, namely CIBR is a well used method for atmospheric column averaged water vapour retrieval. However, it is worthy to mention that CO_2 has much narrower absorption bands than water vapour and frequently interfered by other atmospheric constituents. The second method attempts to establish a relation between CO_2 plume related radiance and CO_2 concentration. First, it identifies the different components of radiance at sensor and then extract the CO_2 plume related radiance from radiance at sensor. Finally, it delivers CO_2 concentration