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News & Views

Advancements in theory of GHG observation from space

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As a large developing country, China has the highest level of greenhouse gas (GHG) emissions. The Chinese government is seeking sustainable development and trying to reduce GHG emissions. From the scientific perspective, there are still many uncertainties in GHG budgets that make evaluating the success of climate change mitigation and adaptation strategies difficult. Therefore, there is an urgent need for a Chinese satellite-borne observation capacity to monitor CO_2 emissions at global, national, and regional scales. In the top-down atmospheric approach to estimating CO_2 emissions, the column-averaged CO_2 dry air mole fraction (XCO_2) is first measured directly by satellite, and the data-assimilation system then integrates atmospheric measurements with bottom-up information into consistent and accurate estimates of CO_2 emission flux. The Thermal And Near-infrared Sensor for carbon Observations-Fourier Transform Spectrometer (TANSO-FTS) on Greenhouse Gases Observing Satellite (GOSAT) from 2009 [1] and the Orbiting Carbon Observatory-2 (OCO-2) from 2014 have been designed to exploit this measurement approach [2]. OCO-2 carries a three-channel imaging grating spectrometer that collects high-resolution spectra of reflected sunlight in the 0.76-μm O_2 A-band and in the weak 1.61-μm CO_2 band (WCO_2) and strong 2.06-μm CO_2 band (SCO_2). The biggest challenge in satellite remote-sensing observation of XCO_2 is retrieval precision, as even the largest CO_2 sources and sinks produce changes in the background XCO_2 that are no greater than 2 %, and most are less than 0.25 % (1 part per million by volume (ppmv) compared with the 400 ppmv background). GOSAT and OCO-2 measurements have demonstrated tremendous improvements, and both have now achieved XCO_2 measurement precision of 1.5 ppmv and have reduced the uncertainties of regional CO_2 flux.

In 2011, the Ministry of Science and Technology of China and the Strategic Priority Research Program of the Chinese Academy of Sciences-Climate Change: Carbon Budget and Relevant Issues sponsored development of the Chinese Carbon Dioxide Observation Satellite (TanSat). TanSat will carry two instruments: the CO_2 monitoring instrument (a hyperspectral grating spectrometer) and a moderate-resolution polarization imaging spectrometer for cloud and aerosol observations (CAPI). With its launch in July 2016, TanSat will become the third satellite mission to monitor CO_2 from space [3].

Several advances in the science and technology of CO_2 observation from space have recently been made, including an XCO_2 retrieval algorithm, CO_2 flux inversion methods, and ground-based measurement for satellite product validation. Reports of most of these advances have been published recently, and we will review these achievements in the following sections, including the instrument design, retrieval method, validation, and flux inversion.

1 TanSat instrument design

The optimal design of TanSat instruments is the first step toward successful observation. As with the observation instrument of OCO-2, TanSat uses a grating spectrometer that has a small footprint and short sampling time, enabling it to collect more cloud-free data than the FTS onboard GOSAT. Another advantage of TanSat is that it will be complemented with the CAPI. This instrument will record images in five spectral channels (0.38, 0.67, 0.87, 1.38, and

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1.64 μm) with a spatial resolution of 0.5 km over a 400-km-wide swath, and it will have 0.67- and 1.64-μm polarization channels. CAPI will provide useful information to correct cloud and aerosol interference in XCO_2 retrieval.

The suitable spectral sampling rate and range of CO_2 absorption bands are critical for the design of the hyperspectral instrument. The effects of undersampling of spectra by the spectrometer were investigated, and it was found that XCO_2 error due to spectral undersampling could be up to 1 ppmv. The study also provides the optimal parameters of the CO_2 spectrometer, which were finally adopted during manufacture [4]. Further investigations that involved GOSAT satellite data made the conclusions more reliable, and the results emphasized the effectiveness of the coordination among the different parameters of the spectrometer.

2 Retrieval method

Retrieval algorithms link measurements to products. Most are full-physics retrieval algorithms that adopt optimal estimation theory [5]. Recent studies of the development of an XCO_2 retrieval algorithm have resulted in a significant improvement in precision from 4.0 to 1.5 ppmv [6, 7] (Fig. 1). To ensure such a high precision of XCO_2, a synchronous light path correction method was developed for the use of column-averaged O_2 (or surface pressure) measurements from the O_2-A band, and the aerosol optical depth, surface albedo, and temperature were also derived in the retrieval [8]. An accuracy of 4 hPa for surface pressure over bright surfaces has been achieved at different solar zenith angles and viewing geometries. This is a preliminary algorithm and before it can be applied to satellite measurements, more comprehensive studies are required to implement specific atmospheric scattering and absorption models. In particular, the aerosol micro physics parameters and bidirectional reflectance distribution functions require more study to improve the accuracy and reduce their interference on XCO_2. Further work on the vector radiative transfer calculation will lead to the optimization of the algorithm.

Methane (CH_4) is the second most important GHG. Its distribution and increasing concentration in the atmosphere also have a significant impact on global warming and climate change. As demonstrated by GOSAT, the 1.65-μm shortwave infrared (SWIR) measurements, sensitive to CH_4 in the lower atmosphere, can be used to retrieve column CH_4. Sensitivity studies have demonstrated the possibility of CH_4 retrieval in the SWIR band and have shown that the 1.65-μm band, associated with the 2.06-μm CO_2 band, retains more than 90 % of the CH_4, CO_2, and temperature information content [9]. Although this test retrieval using the GOSAT data indicated that retrieval errors were less than 1 %, there is still a need to correct the effects of aerosol and cirrus interference in XCH_4 retrievals. This can be done by applying the Cloud and Aerosol Imager (CAI) data simultaneously with the FTS on GOSAT. This study also demonstrates that it is possible to add the 1.65-μm CH_4 band in the second generation of TanSat to include CH_4 products.

Aerosols and clouds modify the light path by scattering and reflectance. Thus, they are the major source of errors in XCO_2 retrieval. CAPI simultaneously provides aerosol and cloud measurements with two polarization channels, which is extremely usefully for the correction of aerosol and cloud microphysics parameters. It is important to understand how the polarization measurement contributes to aerosol and cloud retrieval. Shi et al. [10] conducted a series of sensitivity studies of the polarized reflectance at the top of the atmosphere (TOA) with respect to the aerosol, atmospheric, and surface parameters. It was found that the TOA polarization reflectance at 0.66 μm is most sensitive to the real part of the aerosol complex refractive index and the mean radius of the fine-mode aerosol particles, as well as atmospheric pressure and temperature profiles; the TOA polarization reflectance at 1.64 μm is also sensitive to the volume ratio between the coarse-mode and fine-mode particles. This study demonstrates the potential of CAPI polarization channels to detect the aerosol size and complex refractive index, but more work is required before the retrieval algorithm is completed, including the selection of suitable aerosol parameters in the forward model, the application of more complete sensitivity studies to separate the effects of surface reflectance, the development of a cloud screening method, and the accumulation of ancillary data.

3 Validation

The satellite retrieval product should be validated with XCO_2 and XCH_4 obtained from ground-based measurements. The Total Carbon Column Observing Network (TCCON) is a ground-based network of FTSs that has been widely used in the calibration and validation of satellite measurements, such as GOSAT and OCO-2 [11]. Until recently there was no standard site the TCCON over China, but in Shenzhen there is a site using the same type of FTS as that used in the TCCON, which provides valuable measurements used to develop the retrieval algorithm. A preliminary retrieval study using differential optical absorption spectroscopy (DOAS) has been introduced [12], and the uncertainty of the retrieval was estimated to be 0.51 % (~ 2 ppmv) by comparing retrievals at two bands. This study also indicated that the DOAS has a limitation with regard to hyperspectral measurements, as is the case for IFS-125HR. To achieve a precision better than 0.25 % (~ 1 ppmv), which is similar to the TOCCN measurements, the full physical algorithm is required, and additional corrections, such as the vertical profile and air mass, are necessary.

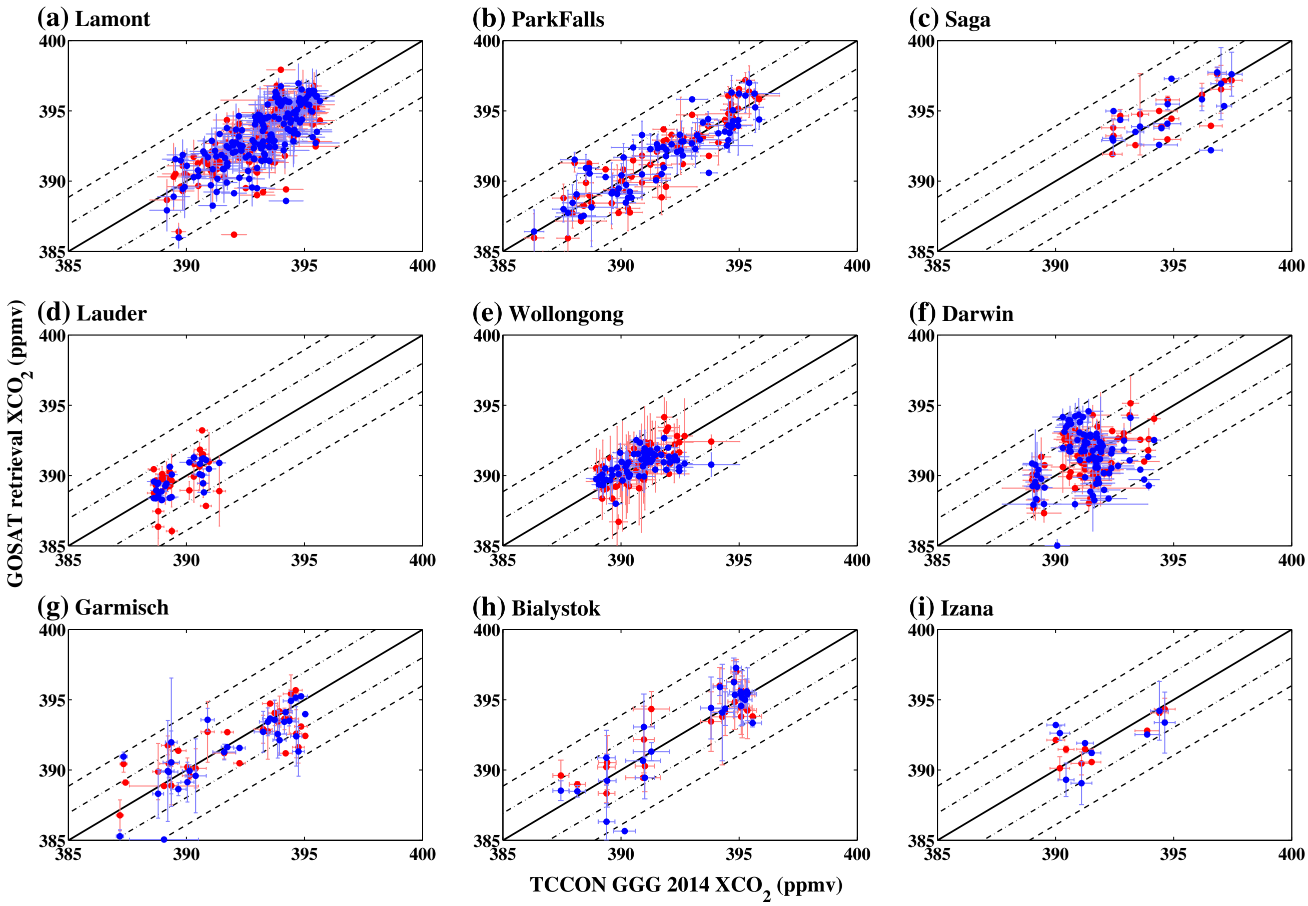

Fig. 1 Validation and inter-comparison of the Institute of Atmospheric Physics, Chinese Academy of Science—Greenhouse Gases Observing Satellite (IAPCAS–GOSAT) XCO_2 product with the Total Carbon Column Observing Network (TCCON) (**a**–**i**) and GOS OCFP (University of Leicester). Red and blue represent GOS OCFP V5.2 and IAPCAS-GOSAT XCO_2 products respectively. The black solid line is the 1:1 line. The dot-dashed line and dashed line indicate the 0.5 and 1 % error regions, respectively (selected from Ref. [5])

4 Carbon flux inversion and application

Currently the sources and sinks of CO_2 are determined by two different approaches, i.e., bottom-up and top-down. The top-down approach is based on the satellite observation of XCO_2 and a network of in situ boundary layer measurements. This approach is limited by the sparse spatial coverage of the sampling sites. To explain the satellite and surface measurements, numerical simulations play an important role. For this purpose, a three-dimensional global chemical transport model, GEOS-Chem, has often been applied to simulate the CO_2 concentration and its variation over global and regional scales. Wang et al. [13] used the GEOS-Chem model to investigate the variation of CO_2 concentrations, and compared the results with observations made at two eddy covariance flux observation towers in Beijing and Hefei. GEOS-Chem successfully captured the main aspects of the diurnal cycle of the CO_2 concentration in the boundary layer observed at both Beijing and Hefei. This work indicates that not only global models but also mesoscale models are necessary to reduce the discrepancies between the model simulations and tower observations.

Assimilation of the carbon data is the final step in deriving surface carbon flux from satellite observations. To achieve this end, a carbon data assimilation system Tan-Tracker was developed based on the GEOS-Chem model. Tan-Tracker is a dual-pass data-assimilation system in which both CO_2 concentrations and CO_2 fluxes are simultaneously assimilated from atmospheric observations [14]. This research developed a strong basis for data-assimilation, with a highly efficient computing performance, and simultaneous assimilation of CO_2 concentrations and CO_2 fluxes, but it should be implemented with a supporting database and pre- and post-processing in order to produce CO_2 fluxes of satellite observations.

Based on the global monthly CO_2 flux data product from the GOSAT (June 2009–May 2010), the magnitude and patterns of China's terrestrial carbon flux were investigated; the results show that China's terrestrial ecosystems provide a carbon sink of -0.21 Pg C a^{-1} [15]. Because this study only used one year of GOSAT data, it provides

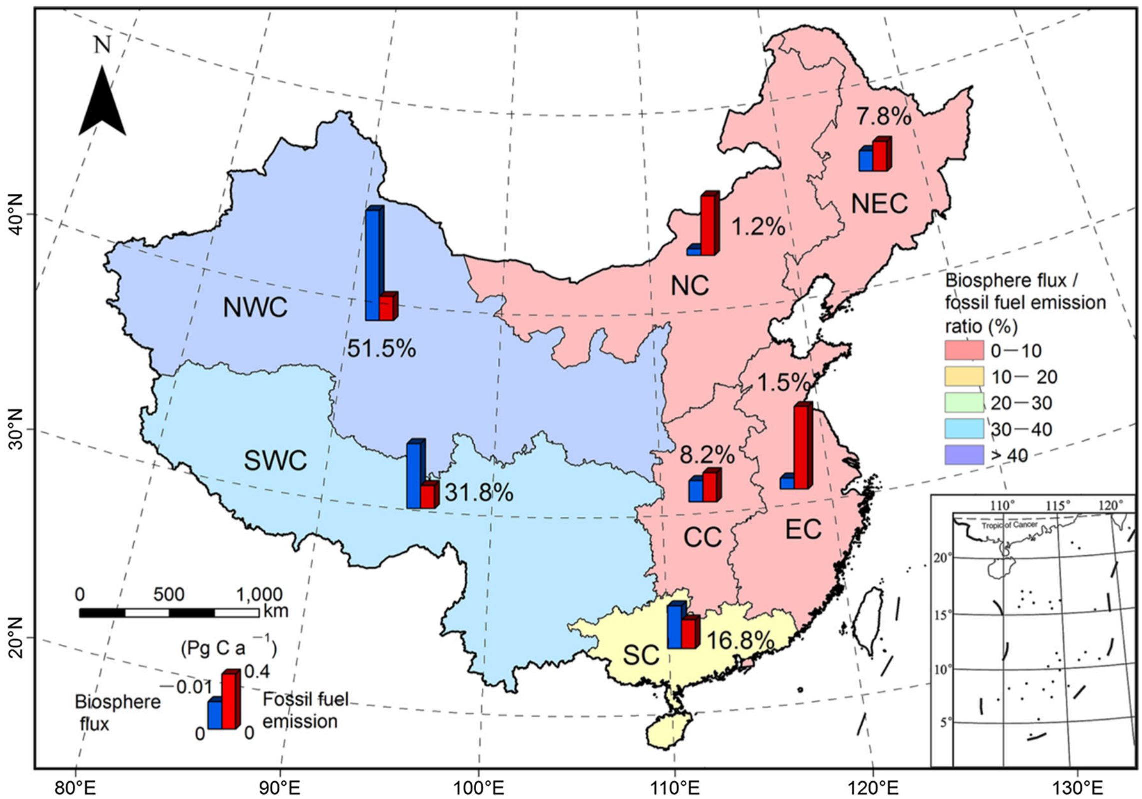

Fig. 2 Regional carbon sinks and fossil fuel emissions in China. The ratios indicate the percentages (%) of fossil fuel emissions that were offset by the biosphere carbon sink (selected from Ref. [15])

preliminary results for the Chinese carbon flux. More satellite data and Chinese in situ validation data are required to verify the satellite observations of the CO_2 flux in China (Fig. 2).

In general, recent studies have established the theoretical basis for XCO_2 retrieval, CO_2 flux inversion, and validation for satellite observations. This can be applied not only to the TanSat mission but also to other Chinese GHG measurement satellites, such as the instrument onboard the GaoFen-5 satellite.

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