A New TanSat XCO₂ Global Product towards Climate Studies

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ABSTRACT

The 1st Chinese carbon dioxide (CO₂) monitoring satellite mission, TanSat, was launched in 2016. The 1st TanSat global map of CO₂ dry-air mixing ratio (XCO₂) measurements over land was released as version 1 data product with an accuracy of 2.11 ppmv (parts per million by volume). In this paper, we introduce a new (version 2) TanSat global XCO₂ product that is approached by the Institute of Atmospheric Physics Carbon dioxide retrieval Algorithm for Satellite remote sensing (IAPCAS), and the European Space Agency (ESA) Climate Change Initiative plus (CCI+) TanSat XCO₂ product by University of Leicester Full Physics (UoL-FP) retrieval algorithm. The correction of the measurement spectrum improves the accuracy (−0.08 ppmv) and precision (1.47 ppmv) of the new retrieval, which provides opportunity for further application in global carbon flux studies in the future. Inter-comparison between the two retrievals indicates a good agreement, with a standard deviation of 1.28 ppmv and a bias of −0.35 ppmv.

Key words: TanSat, CO₂, remote sensing, carbon flux, climate change

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The 1st Chinese carbon dioxide monitoring satellite mission, TanSat, which was supported by the Ministry of Science and Technology of China, the Chinese Academy of Sciences, and the China Meteorological Administration, launched in December 2016 (Liu and Yang, 2016; Ran and Li, 2019). The objective of the TanSat mission is to monitor carbon dioxide (CO₂) concentrations in the atmosphere over the globe to better understand carbon cycle processes. Since CO₂ has been recognized as the most important anthropogenic greenhouse gas owing to its significant impact on global warming and climate change, there are a substantial number of studies that have focused on investigating the status of CO₂ in the atmosphere in the past and present, and how it will change in the future. In support of the upcoming global stocktake in 2023, we require a new method to verify how much human emissions impact the global carbon cycle and climate change. The lack of global high-precision measurements of the CO₂ content in the atmosphere is a major limiting factor. Satellite measurements coordinated with ground-based observations will eventually lead to an improved anthropogenic CO₂ emissions MVS (monitoring and verification support) capacity (Pinty et al., 2017).

In order to improve our measurement of atmospheric CO₂, multiple satellite missions have been launched. The European Space Agency (ESA) Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) onboard ENVISAT which carried a space-based shortwave infrared CO₂ spectrometer and is recognized as a pathfinder of greenhouse satellites (Bovensmann et al., 1999). The first dedicated greenhouse gas satellite missions were the Japanese Greenhouse Gases Observing Satellite (GOSAT) and the U.S. Orbiting Carbon Observatory-2 (OCO-2),

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launched in 2009 (Kuze et al., 2009) and 2014 (Crisp et al., 2008) respectively. The TanSat mission is the 3rd mission launched that has the capability to provide CO₂ space-based measurements. The CO₂ instrument, the atmospheric carbon dioxide grating spectrometer, measures backscattered sunlight (Wang et al., 2018) in two CO₂ bands at 1.61 and 2.06 μm respectively. In addition, a 0.76 μm oxygen A-band channel is on-board in order to correct the light path modification by atmospheric scattering from aerosols and thin clouds (Chen et al., 2017).

The Institute of Atmospheric Physics Carbon Dioxide Retrieval Algorithm for Satellite Remote Sensing (IAPCAS) has been developed for space-based satellite measurement of greenhouse gases (Yang et al., 2015), and has been applied to TanSat retrieval. In IAPCAS, a well-known physical quantity, the column-averaged CO₂ dry-air mixing ratio (XCO₂), is retrieved using the Optimal Estimation Method (OEM) by iteratively analyzing and optimizing the spectrum residual between the simulation and measurement. We use a full-physics strategy in IAPCAS to ensure the retrieval accuracy. The 1st TanSat XCO₂ global map has been released (Yang et al., 2018), followed by the version 1 (v1) XCO₂ data product (Liu et al., 2018), which can be publicly accessed from the China GEO data service archive, the Cooperation on the Analysis of Carbon Satellites Data (CASA) at www.chinageoss.org/tansat, which is hosted by the International Reanalysis Cooperation on Carbon Satellites Data (IRCSD). Global validation by the Total Carbon Column Observing Network (TCCON) indicates a 2.11 ppmv (parts per million by volume) accuracy on average from March to July 2017 (Liu et al., 2018). Unfortunately, it is not accurate enough to estimate the anthropogenic CO₂ emissions in cities due to the fact that it only has a 1–1.5 ppm gradient across the urban area as shown in the ground-based measurements in Paris (Vogel et al., 2019).

This XCO₂ retrieval makes use of only the CO₂ weak band (1.61 μm) without any correction of aerosol and thin cloud scattering, which means the uncertainty of the light path modification directly induces retrieval errors, especially in areas highly impacted by aerosols, e.g., industrial regions and megacities. On the other hand, carbon flux inversion by assimilating the XCO₂ data, which is a popular technique to estimate land–atmosphere carbon exchange, also requires strict accuracy and precision of the XCO₂ data product (Miller et al., 2007).

A new approach has been developed to improve the retrieval accuracy by optimizing the TanSat measured spectrum, particularly, a wavelength-dependent continuum gain effect in O₂ A band, and hence we successfully include the O₂ A band in

Fig. 1. Global TanSat v2 XCO₂ distribution from March 2017 to May 2018 (land only). Colors indicate the values of XCO₂ in ppmv.

Fig. 2. Intercomparison of individual XCO₂ retrievals between the IAPCAS TanSat v2 data product (horizontal axis) and the CCI+ TanSat product (vertical axis) for a total number of 34 699 individual data points. Color coding is the number density of the data. The solid gray line indicates the 1:1 line, and the red dashed line shows the linear regression results, with quantitative results given in the upper-left of the plot. RMSE and STD denote the root-mean-square error and standard deviation of the differences of the two data products.

retrieval (Yang et al., 2020). Analysis of the fitting residuals and validation against TCCON measurements show that this new approach leads to a significant improvement in the retrieval quality, with an average bias of -0.08 ppmv and RMSE of 1.47 ppmv. Also, the retrieval precision is 53.6% better than for the TanSat v1 data product in individual validation studies (Yang et al., 2020). This new technique is used in TanSat IAPCAS V2 data processing.

The new TanSat XCO₂ data product is now retrieved by IAPCAS using the O₂ A-band and CO₂ weak band together. Fifteen months of the global XCO₂ distribution (Fig. 1; land only) is shown for each month, indicating the CO₂ seasonal variations in the Northern Hemisphere and the continually increasing CO₂ values in the Southern Hemisphere. The anthropogenic impact is visible in winter and spring around China, Europe and the U.S. The TanSat v2 XCO₂ data product can be obtained from the CASA TanSat data and science service (www.chinageoss.org/tansat). Information on measurement and retrieval quality, such as cloud clearing and post screening, is also provided in the data. Top-down carbon flux estimation research will be one of main objectives of the TanSat CO₂ data, and hence we produce a special lite version with only core elements (e.g., XCO₂, averaging kernel, and a priori CO₂ profile) toward climate change studies.

In January 2020, a protocol was signed between the National Remote Sensing Center of the China Ministry of Science and Technology of China (MOST/NRSCC) and the ESA regarding the intended coordination of their activities in the Remote Sensing of Greenhouse Gases and Related Missions. MOST/NRSCC and ESA intend TanSat to be a third-party mission of ESA, and TanSat data have been included in key ESA programs such as the Climate Change Initiative plus (CCI+) (Buchwitz et al., 2015) and Earthnet Data Assessment Pilot (EDAP). The preliminary CCI+ TanSat XCO₂ data product has been processed by the University of Leicester Full Physics Retrieval Algorithm (UoL-FP) (Bösch et al., 2006) for TCCON overpasses only, to evaluate the retrieval strategy and data quality, and is available to the public on the CCI+ data archive at <http://cci.esa.int/data>. Future plans will focus on the production of global TanSat retrievals, and those data will be part of the CCI+ data product.

The IAPCAS and UoL-FP algorithms use a similar OEM (Optimal Estimation Method) technique but a different forward model, physical module and strategy (e.g., pre-screening, post-screening and state vectors) in their retrieval. The intercomparison of TanSat XCO₂ retrieval between the two algorithms shows a good agreement for all TCCON overpass measurements with 34 699 individual measurements (Fig. 2). The dispersion between the two data products has a standard deviation of 1.28 ppmv, which mostly comes from noise error. There is a -0.35 ppmv overall bias between both, and this systematic error is probably induced by the differences of the two algorithms and bias correction method.

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REFERENCES

- Bösch, H., and Coauthors, 2006: Space-based near-infrared CO₂ measurements: Testing the Orbiting Carbon Observatory retrieval algorithm and validation concept using SCIAMACHY observations over Park Falls, Wisconsin. *J. Geophys. Res.*, **111**, D23302, <https://doi.org/10.1029/2006JD007080>.
- Bovensmann, H., J. P. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. V. Rozanov, K. V. Chance, and A. P. H. Goede, 1999: SCIAMACHY: Mission objectives and measurement modes. *J. Atmos. Sci.*, **56**, 127–150, [https://doi.org/10.1175/1520-0469\(1999\)056<0127:SMOAMM>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<0127:SMOAMM>2.0.CO;2).
- Buchwitz, M., and Coauthors, 2015: The Greenhouse Gas Climate Change Initiative (GHG-CCI): Comparison and quality assessment of near-surface-sensitive satellite-derived CO₂ and CH₄ global data sets. *Remote Sensing of Environment*, **162**, 344–362, <https://doi.org/10.1016/j.rse.2013.04.024>.
- Chen, X., D. X. Yang, Z. N. Cai, Y. Liu, and R. J. D. Spurr, 2017: Aerosol retrieval sensitivity and error analysis for the cloud and aerosol polarimetric imager on board TanSat: The effect of multi-angle measurement. *Remote Sensing*, **9**(2), 183, <https://doi.org/10.3390/rs9020183>.
- Crisp, D., C. E. Miller, and P. L. DeCola, 2008: NASA orbiting carbon observatory: Measuring the column averaged carbon dioxide mole fraction from space. *Journal of Applied Remote Sensing*, **2**(1), 023508, <https://doi.org/10.1117/1.2898457>.
- Pinty B., and Coauthors, 2017: An Operational Anthropogenic CO₂ Emissions Monitoring & Verification Support capacity—Baseline Requirements, Model Components and Functional Architecture, European Commission Joint Research Centre, EUR 28736 EN, DOI: 10.2760/39384.
- Kuze, A., H. Suto, M. Nakajima, and T. Hamazaki, 2009: Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring. *Appl. Opt.*, **48**(35), 6716–6733, <https://doi.org/10.1364/AO.48.006716>.
- Liu, Y., and D. X. Yang, 2016: Advancements in theory of GHG observation from space. *Science Bulletin*, **61**(5), 349–352, <https://doi.org/10.1007/s11434-016-1022-1>.
- Liu, Y., and Coauthors, 2018: The TanSat mission: Preliminary global observations. *Science Bulletin*, **63**, 1200–1207, <https://doi.org/10.1016/j.scib.2018.08.004>.
- Miller, C. E., and Coauthors, 2007: Precision requirements for space-based X_{CO₂} data. *J. Geophys. Res.*, **112**, D10314, <https://doi.org/10.1029/2006JD007659>.
- Ran, Y. H., and X. Li, 2019: TanSat: A new star in global carbon monitoring from China. *Science Bulletin*, **64**(5), 284–285, <https://doi.org/10.1016/j.scib.2019.01.019>.
- Vogel, F. R., and Coauthors, 2019: XCO₂ in an emission hot-spot region: The COCCON Paris campaign 2015. *Atmospheric Chemistry and Physics*, **19**, 3271–3285, <https://doi.org/10.5194/acp-19-3271-2019>.
- Wang, L., C. Lin, Z. H. Ji, Y. Q. Zheng, and Y. M. Bi, 2018: Preflight diffuser's calibration of carbon dioxide spectrometer of TanSat. *Optics and Precision Engineering*, **26**(8), 1967–1976, <https://doi.org/10.3788/OPE.20182608.1967>. (in Chinese with English abstract)
- Yang, D. X., Y. Liu, Z. N. Cai, J. B. Deng, J. Wang, and X. Chen, 2015: An advanced carbon dioxide retrieval algorithm for satellite measurements and its application to GOSAT observations. *Science Bulletin*, **60**(23), 2063–2066, <https://doi.org/10.1007/s11434-015-0953-2>.
- Yang, D. X., Y. Liu, Z. N. Cai, X. Chen, L. Yao, and D. R. Lu, 2018: First global carbon dioxide maps produced from TanSat measurements. *Adv. Atmos. Sci.*, **35**, 621–623, <https://doi.org/10.1007/s00376-018-7312-6>.
- Yang, D. X., and Coauthors, 2020: Toward high precision XCO₂ Retrievals from TanSat observations: Retrieval improvement and validation against TCCON measurements. *J. Geophys. Res.*, <https://doi.org/10.1002/essoar.10502909.1>.