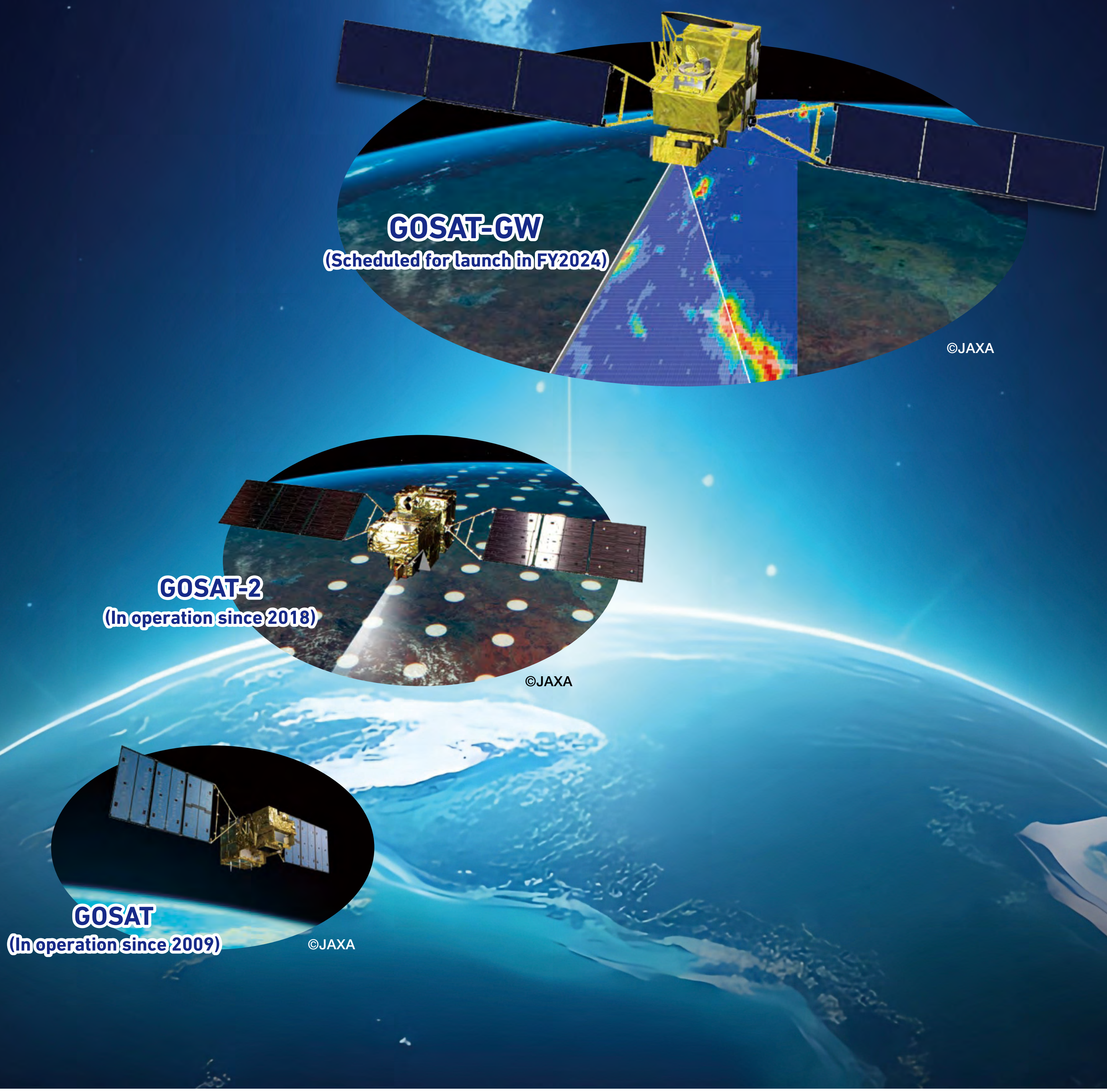
Observing Greenhouse Gases from Space

Long-term Satellite Observations since 2009 and the Future of the GOSAT Series



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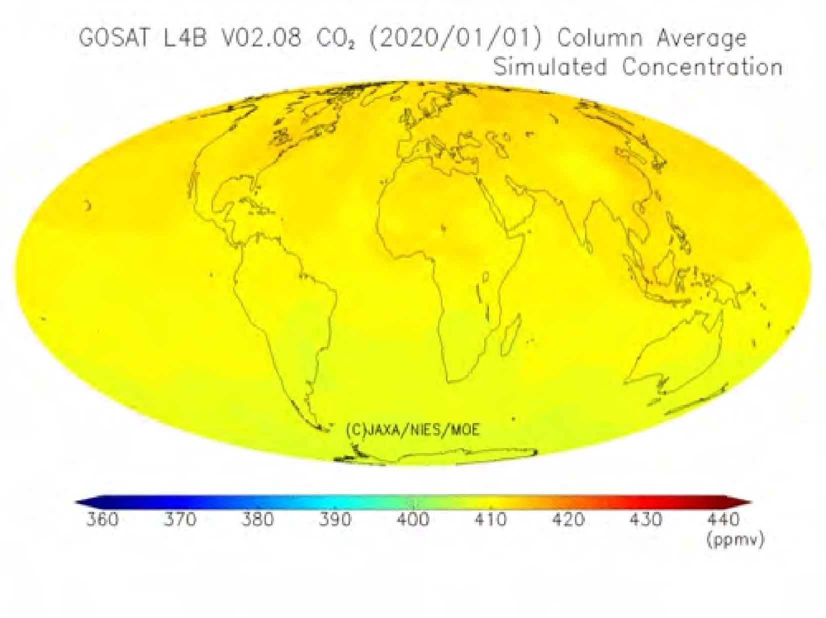
Executive Summary

- The Greenhouse gases Observing SATellite (GOSAT) series are the world's first dedicated greenhouse gas observation satellites. The data on greenhouse gases including carbon dioxide and methane, has been provided without compensation for 15 years since the launch of GOSAT, the first satellite of the series, in January 2009. The research findings based on GOSAT series data have been cited in reports of the Intergovernmental Panel on Climate Change (IPCC) and further utilized in climate change research and policies around the world.
- It is essential to consider and implement climate change countermeasures based on the "best available science", in particular scientific data. The GOSAT series plays a significant role within the international community in providing objective measurement data.
- Various studies utilizing data from the GOSAT series have revealed differences between the anthropogenic greenhouse gas emissions volumes estimated from GOSAT series satellite measurements and those estimated from official statistics on fossil fuel usage and reports submitted by each country to the United Nations Framework Convention on Climate Change (UNFCCC). These differences have been observed in certain regions such as East Asia.
- All countries shall submit, by the end of 2024, their biennial transparency reports detailing annual greenhouse gas emissions volumes under the Paris Agreement. In the leadup to their submission of these reports, it is essential that all countries enhance the accuracy and transparency of their emissions reporting and implement effective science-based countermeasures.
- More detailed monitoring and management of emission sources, such as emissions from cities and individual facilities will become increasingly important, as will monitoring and management of unintentional emissions such as atmospheric leaks connected with the use of natural gas.
- Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW) , the third satellite of the series scheduled for launch in Japanese fiscal year (JFY) 2024, will significantly enhance spatial resolution and increase the amount of data gathered considerably. The Government of Japan will utilize GOSAT-GW to continue providing objective scientific data to help the international community obtain a picture of current conditions. This will involve collaboration on various international initiatives, as well as collaboration with individual countries on efforts relating to satellite-based observation, ground-based observation, and modeling studies. The government also aims to utilize GOSAT-GW to help developing countries enhance the transparency of their emissions reporting through bilateral cooperation.
- Measures are also being implemented to prevent the GOSAT-1 and GOSAT-2 satellites from going out of control and continuing in orbit for a long term as part of efforts to address risks and threats that may impede the safe and sustainable utilization of space.
- Deliberations on a successor satellite to GOSAT-GW are to be held with the aim of contributing to the international community's efforts towards net zero by 2050.

Figure: Global GOSAT Carbon Dioxide Concentration Observation[1]



1 Global Gas Concentration Animations (nies.go.jp)

1 Aims and Background

In January 2009, Japan launched the first satellite of the GOSAT series, the world's first satellite series dedicated to greenhouse gas observation. Scientific and governmental use of GOSAT series data from the approximately 15 years of observations has facilitated a wide range of achievements. To enhance international efforts to reduce greenhouse gas emission, it is crucial to have objective and independent verification of effort of each country, and engage in reciprocal improvement of these efforts through the sharing of verification results within the international community. It is increasingly vital to increase the number of countries that engage in transparent reporting using satellite observation data that can ensure objective and independent verification.

This report compiles the GOSAT series research findings made during the 14 years of continuous global observations since the first GOSAT launch, as well as information on how GOSAT data is utilized in climate change policymaking, and outlines future challenges and directions. It is hoped that the report will also serve as a catalyst to further enhance collaboration between researchers, government officials, and business operators around the world following the launch of GOSAT-GW in JFY 2024 and its successor satellites, deliberations about which are currently underway.

2 Major GOSAT Series Achievements

During the 13 years between 2009 and 2022, more than 600 papers related to the GOSAT series were published, and 24 papers are referenced in the IPCC AR6 WG1 report. The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[2] mentions methods for using satellite data to improve the accuracy of each country's reporting on emissions volumes, and particular mention was made of the utilization of GOSAT data. There are also expectations for improved accuracy in reporting of national scale emission estimates through increased number of observation points and hot-spot data analysis by GOSAT-2 together with other satellites.

The major achievements with the GOSAT series of satellites are summarized below by category.

Global Observation

The SSP1-1.9 scenario used by the IPCC AR6 WG1, in which the rise in the average global temperature of this century is limited to 1.5°C, requires the average carbon dioxide concentration in the atmosphere to remain below approximately 440 ppm. To measure the global average concentration of greenhouse gases, a large number of sampling points need to be set. Measurements also need to include not only surface concentrations but also vertical distributions of concentrations in the atmosphere. Satellite observation enabling the measurement of column-averaged concentrations is therefore considered to be a useful method.

Ongoing Observation of Average Concentrations

GOSAT, the world's first dedicated greenhouse gas observation satellite, has been used to observe greenhouse gases continuously since April 2009. GOSAT data on greenhouse gases is shared without compensation, complementing each other with data from satellites of other countries. GOSAT has played an important role in ensuring the seamless gathering of long-term global greenhouse gas observation data, in particular through initiatives such as ascertaining coherence between GOSAT data and data from the SCIAMACHY imaging instrument onboard the European Space Agency's Envisat, launched in May 2002 (observation using SCIAMACHY continued until April 2012) [Heymann et al. (2015)][3], as well as conducting simultaneous observations of the same locations with other countries satellites like OCO-2, which was launched after GOSAT, for the purpose of data calibration. Furthermore, the results of the verification of measurement continuity between GOSAT and GOSAT-2 conducted by Yoshida et al. (2023)[4], indicate that GOSAT series has been providing consistent data on global greenhouse gas concentrations to the global community without compensation, from April 2009 to the present.

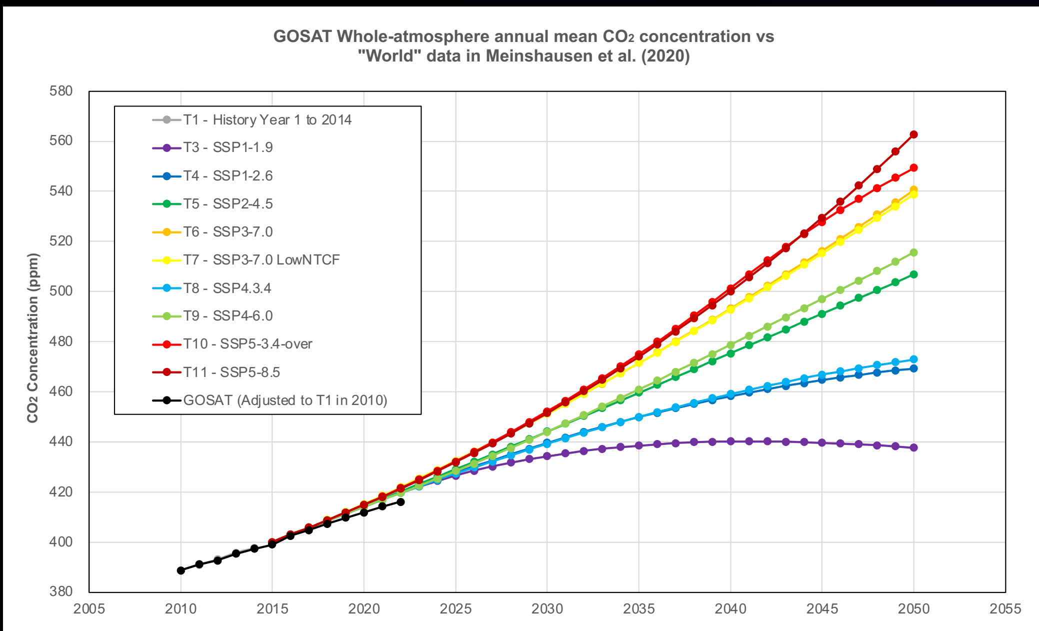
2 2019 Refinement to the 2006 IPCC Guidelines, Chapter 6.10.2.5 Satellite. "Local GHG concentration enhancements observed by the GOSAT satellite correlate well with transport model simulations, so that the anthropogenic emissions for large regions like the US or temperate Asia can be estimated by fitting model simulated enhancements to a large number of satellite observations. However, there was less success with country scale estimates due to a lack of observations. With the expected availability of GHG observations from new satellite sensors, such as TROPOMI, GOSAT-2, GeoCarb, TanSat and others, the limitations of observation numbers will be relaxed, and national scale emission estimates by hot-spot emission data analysis are expected to become possible."

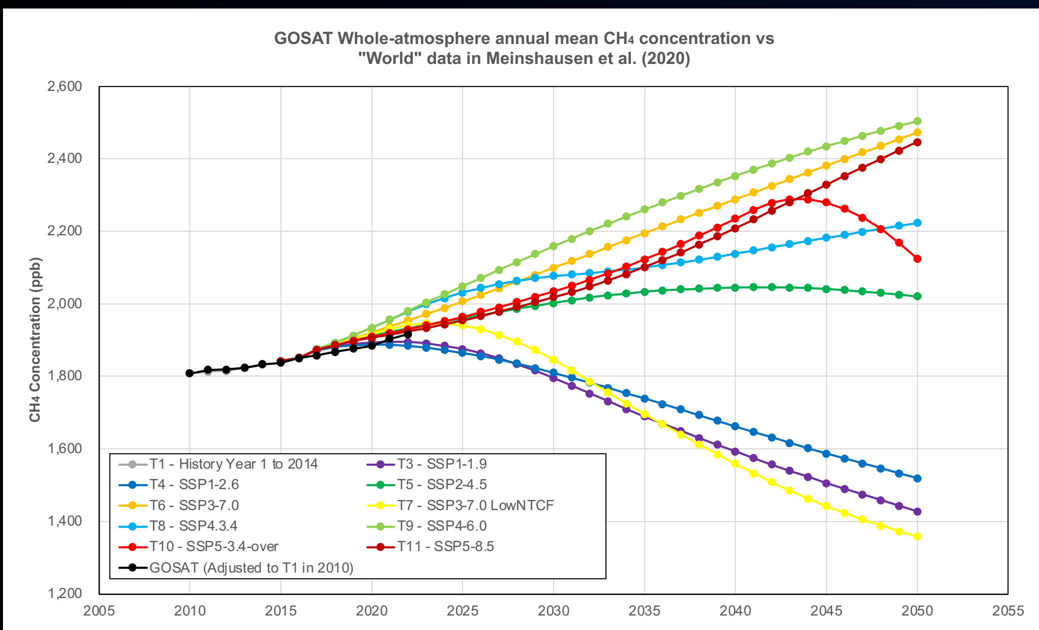
3 Heymann, J., Reuter, M., Hilker, M., Buchwitz, M., Schneising, O., Bovensmann, H., Burrows, J. P., Kuze, A., Suto, H., Deutscher, N. M., Dubey, M. K., Griffith, D. W. T., Hase, F., Kawakami, S., Kivi, R., Morino, I., Petri, C., Roehl, C., Schneider, M., Sherlock, V., Sussmann, R., Velazco, V. A., Warneke, T., and Wunch, D.: Consistent satellite XCO_2 retrievals from SCIAMACHY and GOSAT using the BESD algorithm, Atmos. Meas. Tech., 8, 2961–2980, https://doi.org/10.5194/amt-8-2961-2015, 2015.

4 Yoshida, Y., Y. Someya, H. Ohyama, I. Morino, T. Matsunaga, N. M. Deutscher, D. W. T. Griffith, F. Hase, L. T. Iraci, R. Kivi, J. Notholt, D. F. Pollard, Y. Té, V. A. Velazco, and D. Wunch, 2023: Quality evaluation of the columnaveraged dry air mole fractions of carbon dioxide and methane observed by GOSAT and GOSAT-2. SOLA, 19, 173– 184, doi:10.2151/sola.2023-023.

Comparison of Emissions Scenarios and Actual Observations

Long-term observation of global column-averaged greenhouse gas concentrations using GOSAT make it possible to determine[5] which socioeconomic scenario the world is currently tracking towards. According to the IPCC AR6 WG1 FAQ4.1, however, detection of reductions in atmospheric concentrations due to world mitigation action beyond natural variability requires observation over a prolonged duration although it depends on the scale and pace of the emissions reductions. Specifically, even if the two carbon dioxide emissions scenarios “SSP1-2.6” (low emissions) and “SSP-3-7.0” (high emissions) had hypothetically diverged in 2015, it would take approximately 5 to 10 years for reductions in atmospheric concentrations to be detected beyond natural variability. For other climate change indicators, such as changes in global average temperatures, it may take an additional 20 to 30 years, and for regional precipitation, which has larger natural variability, differences may not manifest themselves until the second half of the 21st century. Compared with these indicators, the observation of greenhouse gases allows for a relatively early understanding of the scale of impact and progress of reductions effects; , and continuing with this observation is highly meaningful for impact prediction and deliberations on global adaptation measures. The GOSAT series will continue to be utilized to observe global atmospheric concentrations of greenhouse gases.





5 NIES (2022) "Submission of Information to the 1st Global Stocktake - GOSAT and GOSAT-2 Standard Products and Related Data –" (NIES Feb. 2022) with the addition of data for 2022.

National to Continental Level Observation

Comparison of GOSAT Data and Each Nation's Reported Emission Volumes

According to the decisions[6] established under the Paris Agreement, by the end of 2024, all countries, including developing countries, shall submit their emission volumes based on the Paris Agreement to the UNFCCC as a part of their Biennial Transparency Reports (BTR) or as a stand-alone report.

The Ministry of the Environment and the National Institute for Environmental Studies are advancing research that compares data from the GOSAT series with carbon dioxide and methane emission estimated based on statistics from major emitting countries, or emission volumes reported by each country to the UNFCCC. By verifying the emission volumes from each country based on objective satellite observation data and making the information available to the international community, these projects contribute to improving the transparency of emission volumes reporting by each country. The following summary focuses on recent achievements by institutions using GOSAT series, led by the National Institute for Environmental Studies and other institutes, while also citing papers from other groups that address similar themes.

Carbon Dioxide

The following maps show the distribution of increments in carbon dioxide concentration from emission volumes associated with the burning of fossil fuels worldwide according to Janardanan et al. (2016)[7], and the values for increments in carbon dioxide concentration according to the emission source database (ODIAC) constructed from statistical data such as fossil fuel consumption location of power plants. If the two maps match, it would mean that observed values from GOSAT and the values projected from statistical data are aligned. However, if there is a significant discrepancy between the observed values and the statistical values, it could signify the presence of emission sources or sinks that are not accounted for in statistics. Discrepancies that lie beyond the margin of error are undesirable from the

Figure: Geographical distribution of increase in concentration due to carbon dioxide emissions originating from fossil fuels (a: GOSAT observations, b: emission source database ODIAC) [Excerpt from Janardanan et al. (2016)]

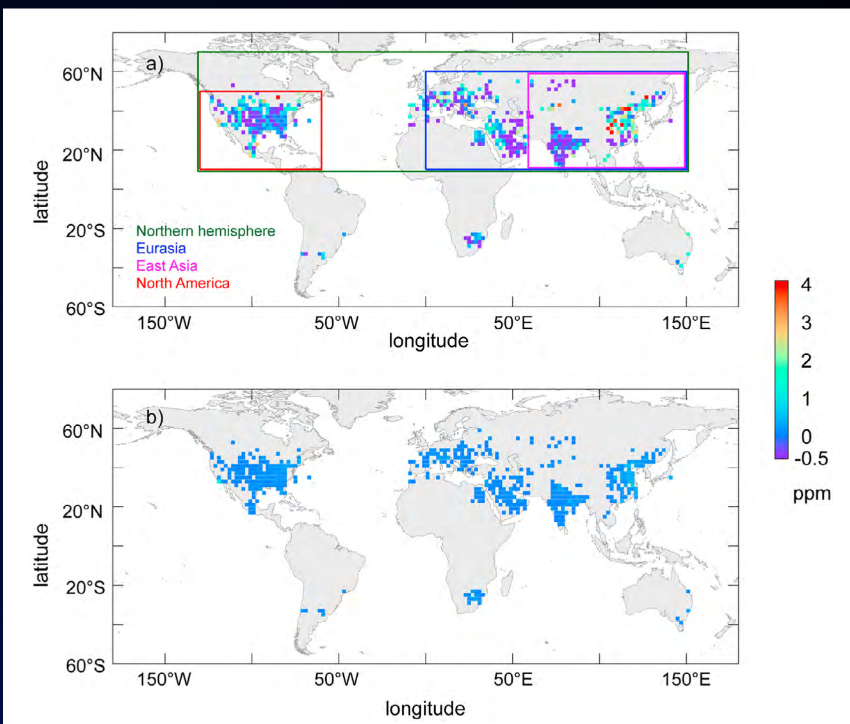


Figure 1. Observed and simulated total column CO_2 with significant fossil fuel signature averaged over 2° × 2° grid. (a) GOSAT-deduced fossil fuel enhancements in X_{CO2} ($\Delta X_{CO2,obs}$; color shading; ppm) averaged over 2° × 2° grid where at least 10 observations exist for 2009–2012. The macro regions—East Asia (10–60°N, 60–150°E), Eurasia (10–60°N, 0–150°E), North America (10–50°N, 130–60°W), and the Northern Hemisphere (10–70°N, 130°W–150°E)—used for regional regression between modeled and observed ΔX_{CO2} are shown by colored rectangles. Overlapping boundaries are drawn with 1° offset for visual clarity. (b) Simulated fossil fuel enhancements in X_{CO2} ($\Delta X_{CO2,sim}$; color shading; ppm).

6 Para.3 of 18/CMA.1 "3. Decides that Parties shall submit their first biennial transparency report and national inventory report, if submitted as a stand-alone report, in accordance with the modalities, procedures and guidelines, at the latest by 31 December 2024;"

7 Janardanan, R., Maksyutov, S., Oda, T., Saito, M., Kaiser, J. W., Ganshin, A., Stohl, A., Matsunaga, T., Yoshida, Y., and Yokota, T. (2016), Comparing GOSAT observations of localized CO enhancements by large emitters with inventory-based estimates, Geophys. Res. Lett., 43, 3486–3493, doi:10.1002/2016GL067843.

perspectives of ensuring the accuracy and transparency of emission and absorption volumes by countries, as well as appropriate progress management toward the achievement of Nationally Determined Contributions (NDCs).

Janardanan et al. (2016) conducted regression analysis after extracting points from the range of 0.2 ppm to 1 ppm; that is, they excluded points greater than 1 ppm for which an adequate number of observation data could not be secured from the locations on the map shown, above, as well as points smaller than 0.2 ppm that could not be distinguished from background concentration. As shown in the following figure, in the analysis results for the respective regions of "Global," "Northern Hemisphere," "Eurasia," and "North America" obtained using this method, there is strong correlation between the anthropogenic carbon dioxide concentration values obtained by GOSAT

Figure: Comparison of increase in concentration due to carbon dioxide emissions originating from fossil fuels in each region (vertical axis: GOSAT observations, horizontal axis: emission source database ODIAC) [Excerpt from Janardanan et al. (2016)]

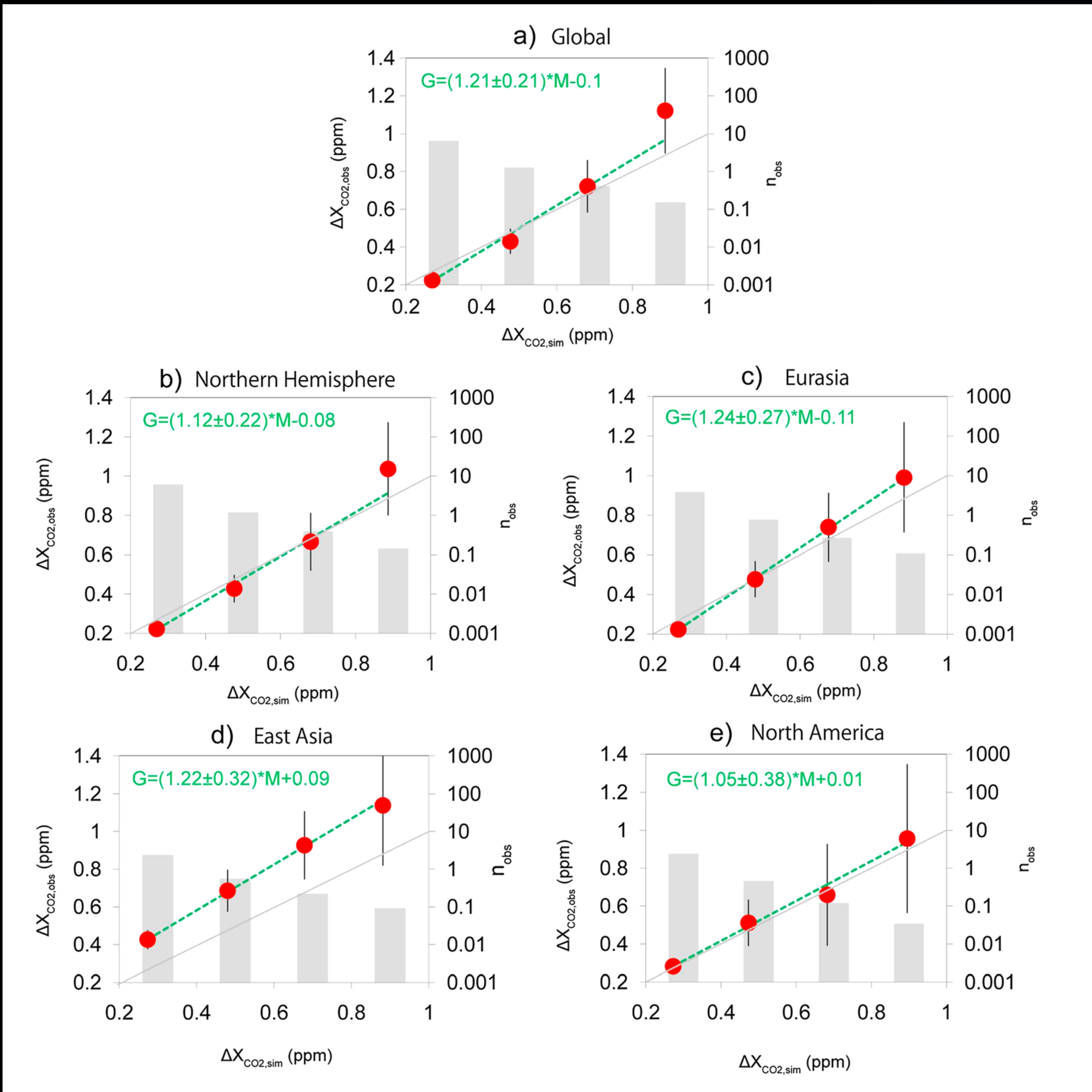


Figure 2. Mean observed ($\Delta X_{CO2,obs}$) versus simulated ($\Delta X_{CO2,sim}$) enhancements in 0.2 ppm bins for (a) Globe, (b) Northern Hemisphere, (c) Eurasia (d) East Asia, and (e) North America. Vertical thin lines show the standard error of the mean observed enhancements. Standard errors in the binning of simulated values are smaller than the symbol size. The grey dashed line is the identity line. The error-weighted regression between the modeled and observed X_{CO2} enhancements is shown as the green dashed line. The regression equation is shown at the top left of each panel (G, GOSAT; M, Model). The grey bars give the number of observations in thousands (right vertical axis, logarithmic scale; read n_{obs} as $n_{obs}\times 10_3$) in each enhancement bin.

and ones obtained from the emissions database are aligned within the margin of error. On the other hand, the results for "East Asia" ((d) in the figure below) shows that each point lies beyond the margin of error and is further upward than the straight line with a slope of 1, although the slope of the graph matches the straight line with a slope of 1 within the margin of error (1.22±0.32).

With regard to the fact that observed values are greater than statistical values in East Asia, Janardanan et al. (2016) points to inadequate statistics in China as the cause, citing several papers that had been published up to that point in time. For example, according to Guan et al. (2012)[8], the total annual carbon dioxide emission volumes for various regions in China in 2010 are estimated to be 9.08 billion tons, 1.4 billion tons more per year than the figure reported by China. Liu et al. (2015)[9] also reported that China's energy consumption, by their estimations, was 10% higher than China's national statistics. Zhao et al. (2012)[10], who recalculated China's carbon dioxide emission volumes using the energy statistics of some provinces (local governments), showed that the recompiled carbon dioxide emission volumes from fossil fuels and cement production were notably different (higher) from the estimated values that are obtained from widely used database.

The fact that observed values of carbon dioxide are greater than statistical values in China has also been verified in several recently reported studies that used ground observation. For instance, Zhong et al. (2023)[11] conducted a China-wide analysis using data from 39 ground observation stations located within the country from 2018 to 2021, and found that China's carbon dioxide emission volumes estimated based on the observation, were 15% higher than five widely used emissions databases. Guo et al (2023)[12] estimated total anthropogenic carbon emissions in Shanxi Province in 2019 from ground observation, and showed that these estimated values were approximately 30% (17% - 38%) higher than the average values from five emissions databases.

Additional analysis

To verify the results suggested in the abovementioned papers at the national level, an additional analysis was conducted by applying Janardanan's (2016) method to Japan in addition to China and the U.S., for which a large amount of data can be secured due to their large surface areas. The results showed that the GOSAT observation results for Japan and the U.S. corresponded to statistical values within the margin of error. On the other hand, the results for China suggested, as many of the abovementioned papers did, that the statistical values ware possibly lower than observed.

The observation data used was from 2009 to 2019 for Japan, and 2009 to 2022 for the U.S. and China (V02.95 and V02.96: Data from the first GOSAT). Additionally, for statistical values, a more recent version of ODIAC[13] was used, with improved data on locations of power plants and estimated emission volumes in the U.S. and China from the time of Janardanan et al. (2016). A total of 7,009, 104,694 and 76,795 GOSAT concentration data were analyzed for Japan, the U.S. and China respectively.

However, as can be seen from the width of the error bar on each graph, there is still room for improvement in the accuracy of estimates based on GOSAT observation data. Especially when conducting analysis at the national level for countries with a small area, it is necessary to further improve the methodology, accumulate more data, and enhance the accuracy of satellite observations. In this respect, further advance research will be conducted using satellites that can secure a larger amount of data, such as NASA's OCO2 and GOSAT-GW scheduled for launch in FT2024.

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8 Guan, D. B., Z. Liu, Y. Geng, S. Lindner, and K. Hubacek (2012), The gigatonne gap in China's carbon dioxide inventories, Nat. Clim. Change, 2, 672–675, doi:10.1038/nclimate1560.

9 Liu, Z., et al. (2015), Reduced carbon emission estimates from fossil fuel combustion and cement production in China, Nature, 524, 335–338.

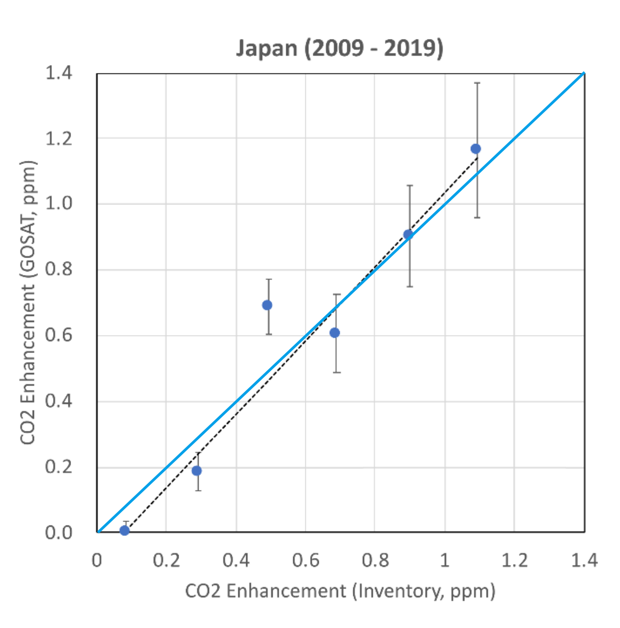
10 Zhao, Y., C. P. Nielsen, and M. B. McElroy (2012), China's CO_2 emissions estimated from the bottom up: Recent trends, spatial distributions, and quantification of uncertainties, Atmos. Environ., 59, 214–223.

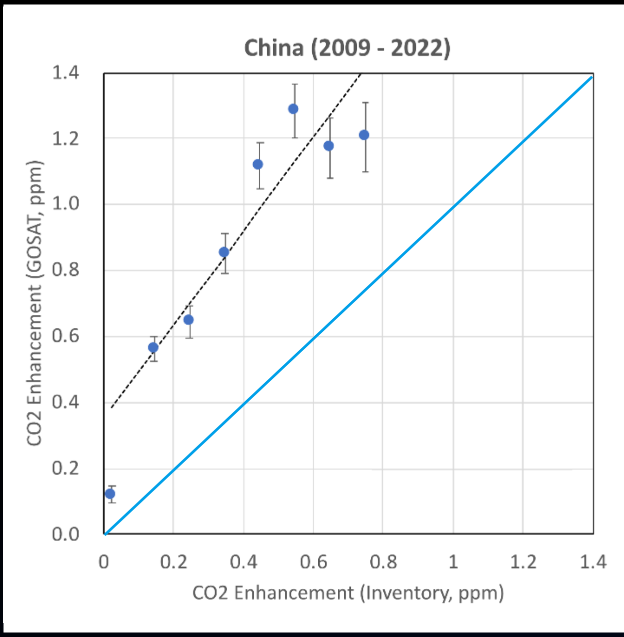
11 Junting Zhong, Xiaoye Zhang, Lifeng Guo, Deying Wang, Changhong Miao, Xiliang Zhang, Ongoing CO_2 monitoring verify CO_2 emissions and sinks in China during 2018–2021, Science Bulletin, 2023,(in press)

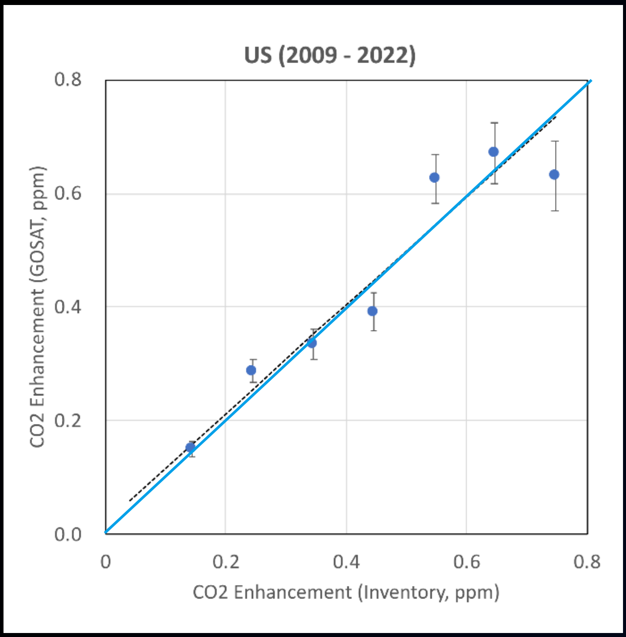
12 Lifeng Guo, Xiaoye Zhang, Junting Zhong, Deying Wang, Changhong Miao, Licheng Zhao, Zijiang Zhou, Jie Liao, Bo Hu, Lingyun Zhu, Yan Chen, Construction and Application of a Regional Kilometer-Scale Carbon Source and Sink Assimilation Inversion System (CCMVS-R), Engineering, 2023,

13 https://db.cger.nies.go.jp/dataset/ODIAC/ However, v2020b was used until 2018, and from 2019 onwards the monthly total value was corrected according to the method of Basu and Nassar (2021).

Figure: Comparison of statistical figures based on GOSAT satellite observations and ODIAC[14] of anthropogenic CO_2 emissions based on the method of Janardanan et al (2016).







Methane

The following map shows the difference between anthropogenic emission estimated by Janardanan et al. (2020)[15] derived from an inverse model using GOSAT data as an input, and the a priori values of emission volumes from the emission source database (EDGAR) constructed from statistical data, scaled with emission volumes reported officially by each country to UNFCCC. In the areas shown in green, including China, Eastern Europe, and Japan, observed values are smaller than a priori values. On the other hand, areas shown in red, including North America, Western Europe, and India, are areas where observed values are greater than a priori values.

14 Open source Data Inventory for Atmospheric Carbon dioxide (ODIAC v2020b, https://db.cger.nies.go.jp/dataset/ODIAC/DL_odiac2020b.html; DOI: 10.17595/20170411.001; Oda and Maksyutov, 2011, Oda et al., 2018)

15 Janardanan, R.; Maksyutov, S.; Tsuruta, A.; Wang, F.; Tiwari, Y.K.; Valsala, V.; Ito, A.; Yoshida, Y.; Kaiser, J.W.; Janssens-Maenhout, G.; et al. Country-Scale Analysis of Methane Emissions with a High-Resolution Inverse Model Using GOSAT and Surface Observations. Remote Sens. 2020, 12, 375. https://doi.org/10.3390/rs12030375

Figure: Difference between observed values from GOSAT and a priori values for anthropogenic absorption and emission volumes of methane [Partial excerpt of graph and explanatory text from Janardanan et al (2020) fig. 3]

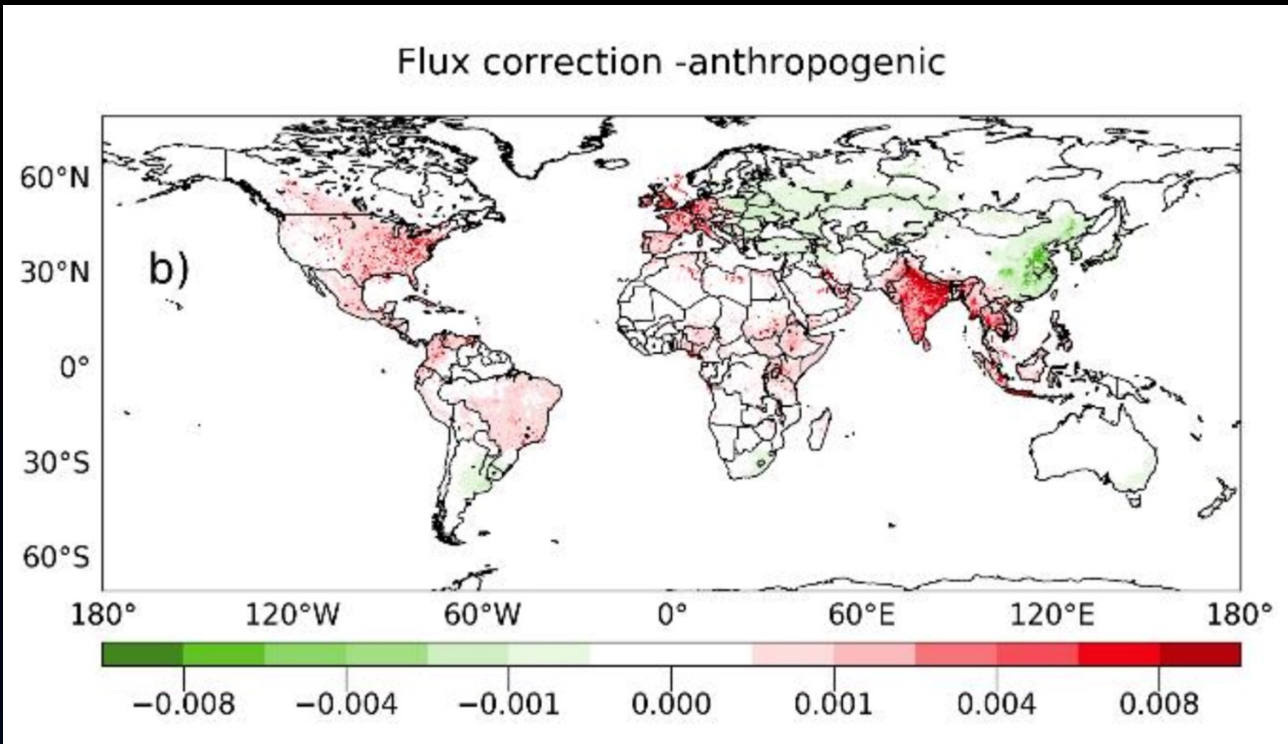


Figure 3. Flux correction **b** by inverse model, averaged for 2011–2017, for anthropogenic categories. The units are in g CH_4 m^{-2} d^{-1}. Note that the administrative boundaries depicted in the figure may not reflect the actual political boundaries.

However, a national-scale statistical analysis, as well as comparisons with those values and national inventory report submitted by each country to UNFCCC shows that these differences all lie within the margins of measurement error. The following is an excerpt of the results of estimations for the top five major methane emitting countries. For all countries on which the analysis was conducted, the figures[16] in the "Uncertainty" column are greater than the absolute values[17] in the "Posterior-Prior (Anthropogenic)" column. Hence, the difference between observed values and reported values lie within the margin of error.

Table: Difference between measured and reported values for natural/anthropogenic methane emissions from the top five methane-emitting countries [Partial excerpt from Janardanan et al (2020) Table 1]

Table 1. List of countries with annual emission (natural or anthropogenic) greater than 2.5 Tg CH_4. Annual prior and posterior emission for total, natural, and anthropogenic categories and their percentage difference after optimization are given. The final row corresponds to global values. Country codes are listed against country names in the appendix, Table A2.

Country Code	Total Prior	Total Posterior	Percentage Difference	Natural Prior	Natural Posterior	Percentage Difference	Anthropogenic Prior	Anthropogenic Posterior	Percentage Difference	Posterior-Prior (Anthropogenic)	Uncertainty (Tg)
CHN	60.1	52.0	−13.5	5.8	6.3	7.7	54.3	45.7	−15.8	−8.6	8.6
USA	51.6	55.7	7.9	23.8	25.9	8.8	27.8	29.8	7.2	2.0	7.8
RUS	47.8	45.2	−5.5	13.6	13.2	−2.7	34.2	31.9	−6.6	−2.3	7.8
BRA	45.6	56.2	23.3	29.2	39.8	36.1	16.4	16.5	0.6	0.1	10.0
IND	29.9	36.5	21.9	9.9	12.3	25.2	20.1	24.2	20.4	4.1	5.3

16 Margin of error for observed values from GOSAT.

17 Figures obtained by deducting figures from the inventory reports submitted by each country to UNFCCC, from the observed values of anthropogenic methane emissions from GOSAT. A positive difference shows that the observed value is greater than the reported value.

As described above, while the results of the global analysis (2011 – 2017) conducted by Janardanan et al. (2000) lie within the margin of error, a similar trend for each country and region has also been reported by other research groups. For example, concerning the smaller observed values than a priori values for China, the analysis by Qu et al. (2021)[18], using GOSAT data for 2019, yielded estimated values for anthropogenic emissions that were smaller than a priori values. Meanwhile, concerning the greater observed values than a priori values for the U.S., Cusworth et al. (2021)[19] conducted an analysis mainly for the U.S. using GOSAT data (2010 – 2015) and ESA's TROPOMI data (2018 – 2019). The results yielded estimated values for emissions that were greater than a priori values for the Permian Basin in Texas. Lu et al. (2022)[20] carried out an inversion mainly for North America using GOSAT data (2010 – 2017), and obtained estimated emission values for the U.S., Canada, and Mexico that were greater than the values reported by each country recently.

Support for Evaluation of Emissions Reports of Developing Countries Using GOSAT Data

The emission data calculated from statistical data does not include information of the geographical distribution of reported emission sources and seasonal fluctuations that are required for statistical evaluation. In view of that, the government of Japan provides support toward efforts to capture emissions in greater detail and compare them with data from the GOSAT series, in developing countries that have a desire to enhance the transparency of their greenhouse gas emissions reporting. Such support includes the implementation of ground observations and radiosonde observations to complement satellite observations, information on emission sources that is not reflected in global emission databases due to the inherent industrial and societal characteristics among countries, and detailed information on emission sources and emissions volume.

Recent outcomes include the development of carbon dioxide emissions estimation technology for Mongolia using GOSAT, published by Watanabe et al. (2023)[21]. The results of carbon dioxide emissions amount calculated using satellite observation data were published in the Second Biennial Update Report (BUR2) submitted by Mongolia in November 2023 for the first time in the world. Specifically, Watanabe et al. (2023) used GOSAT satellite data to estimate carbon dioxide emission from Mongolia's energy sector by combining results from analyses based on atmospheric transport models, inverse analysis, socioeconomic methodologies. Their results concurred with the reported values scheduled to be published by the Mongolian government in the Second BUR with a 1.5% margin of error. Furthermore, comparison with the global emissions database for atmospheric research, "The Emissions Database for Global Atmospheric Research (EDGAR)," yielded a low 4.2% result. The accurate matching of these datasets not only demonstrates the effectiveness of estimating carbon dioxide emissions using GOSAT data, but also shows that carbon dioxide emissions in the energy sector, estimated by Mongolia based on statistical data, have been estimated with a high degree of accuracy. Therefore, the report by Mongolia can be assessed as a highly scientifically transparent report.

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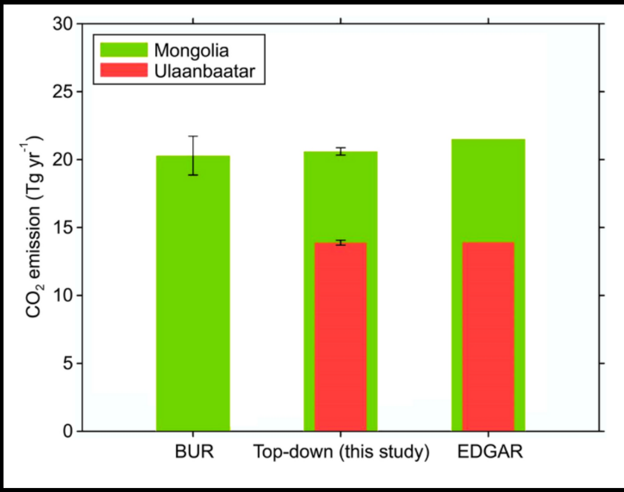
18 Qu, Z., Jacob, D. J., Shen, L., Lu, X., Zhang, Y., Scarpelli, T. R., Nesser, H., Sulprizio, M. P., Maasakkers, J. D., Bloom, A. A., Worden, J. R., Parker, R. J., and Delgado, A. L.: Global distribution of methane emissions: a comparative inverse analysis of observations from the TROPOMI and GOSAT satellite instruments, Atmos. Chem. Phys., 21, 14159–14175, https://doi.org/10.5194/acp-21-14159-2021, 2021.

19 Cusworth, D.H., Bloom, A.A., Ma, S. et al. A Bayesian framework for deriving sector-based methane emissions from top-down fluxes. Commun Earth Environ 2, 242 (2021). https://doi.org/10.1038/s43247-021-00312-6

20 Lu, X., Jacob, D. J., Wang, H., Maasakkers, J. D., Zhang, Y., Scarpelli, T. R., Shen, L., Qu, Z., Sulprizio, M. P., Nesser, H., Bloom, A. A., Ma, S., Worden, J. R., Fan, S., Parker, R. J., Boesch, H., Gautam, R., Gordon, D., Moran, M. D., Reuland, F., Villasana, C. A. O., and Andrews, A.: Methane emissions in the United States, Canada, and Mexico: evaluation of national methane emission inventories and 2010–2017 sectoral trends by inverse analysis of in situ (GLOBALVIEWplus CH_4 ObsPack) and satellite (GOSAT) atmospheric observations, Atmos. Chem. Phys., 22, 395–418, https://doi.org/10.5194/acp-22-395-2022, 2022.

21 Watanabe, M., Oba, A., Saito, Y. et al. Enhancing scientific transparency in national CO_2 emissions reports via satellite-based a posteriori estimates. Sci Rep 13, 15427 (2023). https://doi.org/10.1038/s41598-023-42664-3

Figure: Comparison of estimations of carbon dioxide emissions from Mongolia and the capital city of Ulaanbaatar based on BUR (left), GOSAT (center), and the database (EDGAR) calculated from publicly available statistics [Excerpt from Watanabe et al. (2023). Text has been partially edited.]



<Explanation> Comparison of results calculated using this method, with BUR2 and EDGAR. The results obtained using two methods of calculating how much carbon dioxide is emitted by Mongolia's energy sector in 2018, are compared. The bar graph shows the results from Mongolia's BUR2 (left) and EDGAR (right) calculated using the bottom-up approach, and the calculation results from this study (Watanabe et al. (2023)) (center) calculated using the top-down approach. The green bars show carbon dioxide emissions for the whole of Mongolia, while the red bars show emissions for Ulaanbaatar City. Note that with regard to the data from BUR2 and the top-down approach, the vertical lines indicate the reliability of the results, and there is a 95% probability that true values are included within the range of these lines.

This technology is currently being rolled out to Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan. MOUs were concluded with Uzbekistan in October 2022 and with Kazakhstan in March 2023, and several experts' meetings was held successively to advance discussions.

Going forward, we aim to continue contributing to enhancing the transparency of national inventory reports of developing countries through the use of Japan's observation and analysis technologies.

Municipal and Regional Scale Emission Sources

Municipal Carbon Dioxide Emission Volumes

The Sapporo G7 meeting in 2023 asserted that cities, which account for approximately 70% of global greenhouse gas emissions and two-thirds of global energy consumption, are at the forefront of making global efforts for transition to decarbonization. The promotion of emission estimates in each city hence should contribute to effective estimation of emission volumes and evaluation of the real effect of mitigation measures.

Kuze et al. (2022)[22] estimated CO_2 emissions from six megacities, including Beijing, New York, and Tokyo, using GOSAT data and compared these results with inventory prepared from fossil fuel consumption volume. This analysis demonstrated that GOSAT data can be utilized to estimate emissions from megacities. For the purpose of reducing variation and bias in estimate values, however, it is necessary to increase observation data with fair weather and separate CO_2 emissions from the background using simultaneous observation of nitrogen dioxide (NO2) emitted from high-temperature combustion of fossil fuels.

Above-mentioned Watanabe et al. (2023) compiled data obtained from concentrated observation of Mongolia's Ulaanbaatar using GOSAT-2's 14-point target mode. They also built an inverse analysis model based on the Bayesian Green's function that incorporated the 3D atmospheric chemical transport model WRFChem that includes CO_2 emission source and emission volume information estimated ahead of time from surface observations and statistical data. With these resources, they estimated annual CO_2 emissions from the entire area of Ulaanbaatar from GOSAT satellite observation data. Next, they easily estimated emissions from the entire country of Mongolia with excellent precision by utilizing the estimates and factoring derived from industrial structure and socioeconomic conditions.

Development of methods that facilitate efficient estimates by combining high-precision concentrated observation of cities and wide-area observation that covers the entire country in the cases of countries with a limited number of large cities with concentrations of anthropogenic emission sources, similar to Mongolia, is likely to advance. Furthermore, the IPCC's AR7 process currently taking place is scheduled to prepare a special report on climate change and cities. Japan intends to contribute to the report utilizing the scientific findings from GOSAT.

22 A. Kuze, Y. Nakamura, T. Oda, J. Yoshida, N. Kikuchi, F. Kataoka, H. Suto, K. Shiomi, "Examining partial-column density retrieval of lower-tropospheric CO_2 from GOSAT target observations over global megacities," Remote Sensing of Environment, Volume 273, 2022,

Methane Emission Volumes of Specific Regions

Another project develops a model that estimates methane absorption and emission at high spatial resolution and analyzes the relationship between estimated methane emissions and various social and weather parameters.

Wang et al. (2022)[23] analyzed methane emissions from four areas in China from 2010 through 2018 using a high spatial-resolution inverse model based on GOSAT and ground observation. According to this paper, in the Northeast region of China (NE in the righ figure), which has an upward trend in methane emissions in recent years, annual fluctuation of total emissions of methane derived from GOSAT data (orange line in the lower plot: NG CH_4) changes in line with emissions estimated from natural gas usage and sales in the region (light blue line in the lower plot: NG CH_4). The authors suggested leaks of natural gas form production, transport, and consumption affected observed methane concentration of the region.

Figure : Estimated methane emissions in China during 2010-18 using GOSAT data, etc.

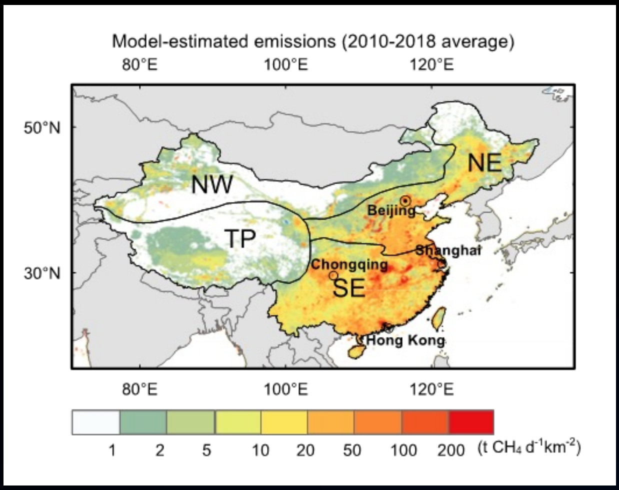
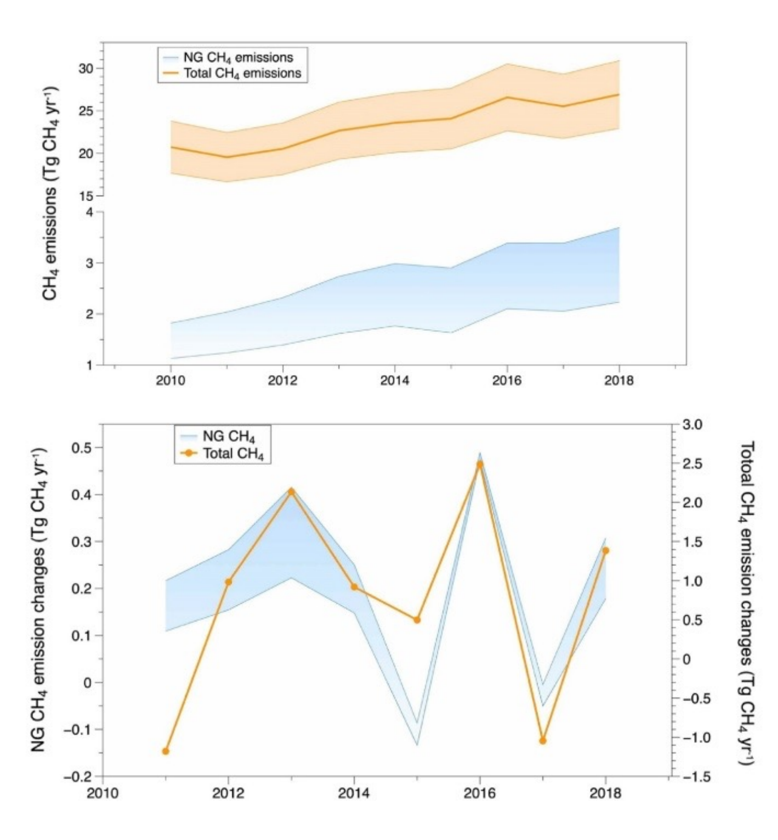


Figure : (Upper panel) Estimated CH_4 emissions from NG statistics and total CH_4 Emission observed by GOSAT in Northeast region of China during 2010–2018. (lower panel) CH_4 emission increment relative to previous year.



23 Wang, F., Maksyutov, S., Janardanan, R. et al. Atmospheric observations suggest methane emissions in north-eastern China growing with natural gas use. Sci Rep 12, 18587 (2022). https://doi.org/10.1038/s41598-022-19462-4

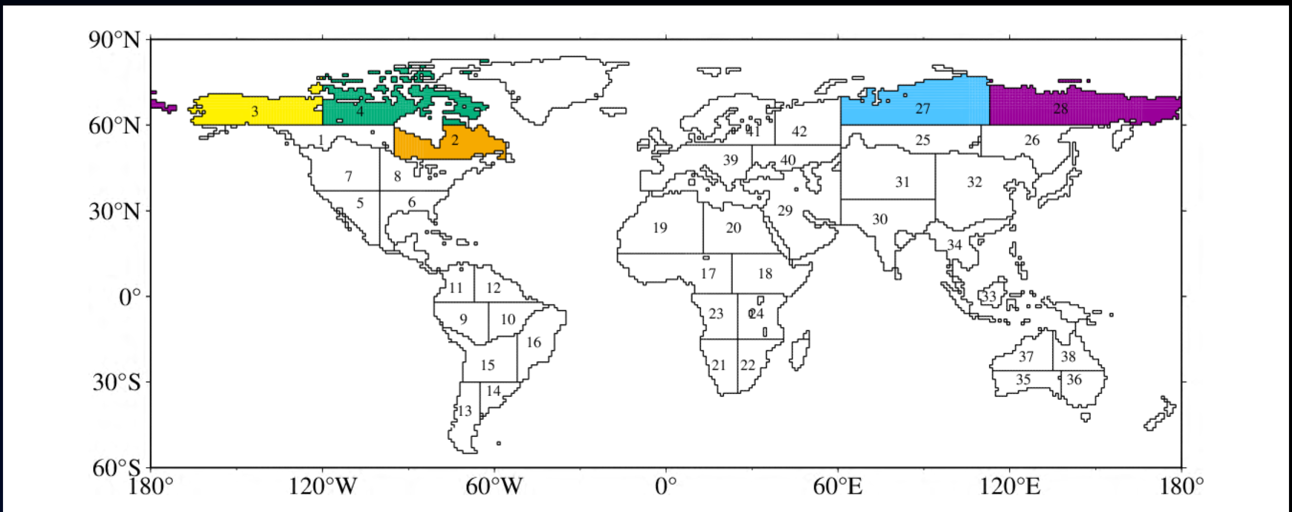
Methane Emissions from High-Latitude Regions in the Northern Hemisphere

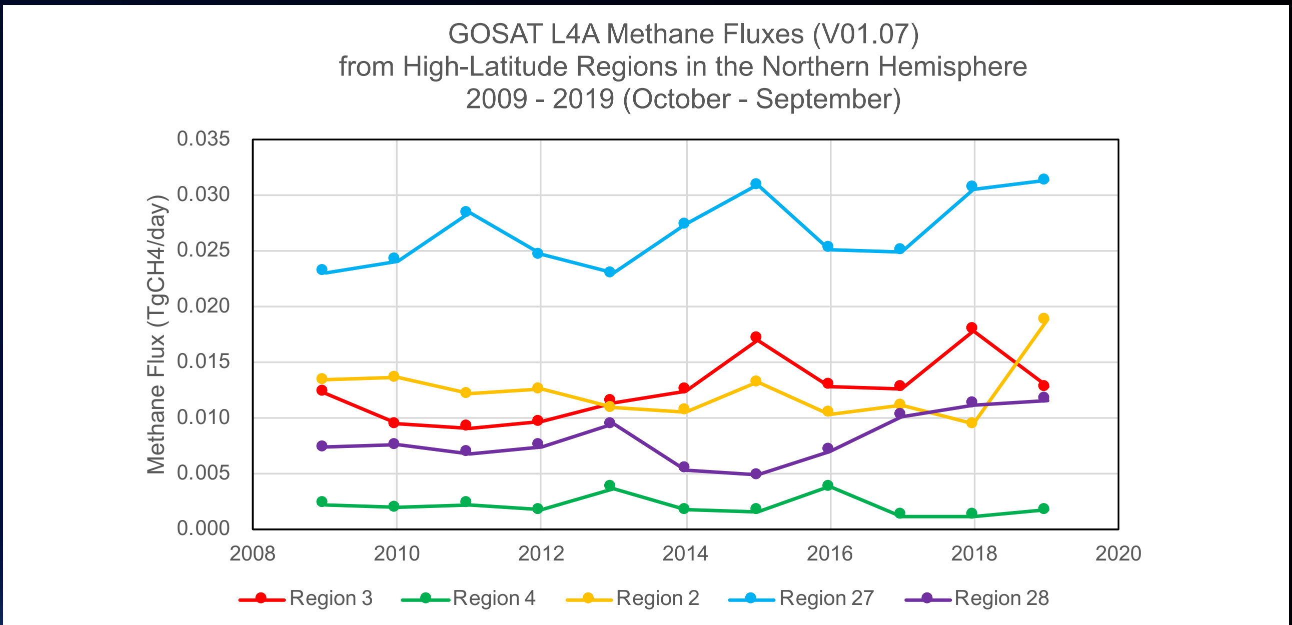
The IPCC AR6 WG1 report states that "Loss of permafrost carbon following permafrost thaw is irreversible at centennial time scales (high confidence)" (SPM:B.5.2) and "Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (high confidence)." (SPM:B.4.3), highlighting the possibility of larger feedback effect than anticipated.

In the data gallery for the GOSAT L4 product[24], NIES discloses time-series data of carbon dioxide and methane emissions estimated from global observation results, including regions with permafrost and monitors changes in emission volumes that could potentially occur in the future. The following diagram presents a graph of annual average methane emissions from five areas of high-latitude regions in the Northern Hemisphere with extensive permafrost, after calculation that includes multiplying the emission per area (disclosed as L4 product (June 2009 to September 2020)) by the surface area of each region.

Some regions already exhibit a long-term upward trend in methane emissions. Detailed analysis, such as removal of contributions from other sources of emission, should be conducted in the future.

Figure: Annual average methane emissions in Northern Hemisphere high-latitude regions (October through September of the following year)





24 NIES website (URL: https://data2.gosat.nies.go.jp/gallery/L4A/fluxts/fluxts.html)

Initiatives to Enhance Accuracy

Data Calibration Using Ground-Based Observation Instruments, etc.

Precision has improved through use of land observation, ships, and airplanes. Thanks to these activities, the measurement precision of land-area CO_2 (about 400 pm) improved from -0.51 ± 2.28 ppm (prior to calibration) to -0.02 ± 2.05 ppm (after calibration) (GOSAT Land H gain v03.05). This process carried out analysis of more than 15,000 sets of match-up data for satellite observations and land observations over a roughly 10-year period of 2009-19 on more than 30 sites located around the world[25]. The assessment of annual increase rates in greenhouse gas concentrations over a lengthy period also utilized observation data from airplanes and ships.

Collaboration on Data Calibration with Overseas Space Agencies

The government of Japan cooperates in observations with various space agencies, including NASA (the U.S.) and ESA (Europe), to enhance the precision of GOSAT series observations and contributing to GOSAT use in international greenhouse gas measurements. Specifically, JAXA implements a joint field campaign annually in Nevada (the U.S.) to confirm precision by making observations and comparing data at the same time and same location by five satellites (including GOSAT and GOSAT-2). Removal of bias of the five satellites observations should boost precision of CO_2 absorption by oceans, an area with high uncertainty. These activities include correction of TROPOMI data (1,000 times more data points than GOSAT) with large disparities in measurement values in regions with high aerosol concentration, deserts, and oblique observation using GOSAT[26]. In this way, GOSAT, which has sustained high-precision observations over a long period, also contributes to improvement in the quality of global greenhouse gas measurement data.

Photos: Joint observations by NASA, ESA, and JAXA in Nevada (from the JAXA website[27])

25 Inoue, M., Morino, I., Uchino, O., Nakatsuru, T., Yoshida, Y., Yokota, T., Wunch, D., Wennberg, P. O., Roehl, C. M., Griffith, D. W. T., Velazco, V. A., Deutscher, N. M., Warneke, T., Notholt, J., Robinson, J., Sherlock, V., Hase, F., Blumenstock, T., Rettinger, M., Sussmann, R., Kyrö, E., Kivi, R., Shiomi, K., Kawakami, S., De Mazière, M., Arnold, S. G., Feist, D. G., Barrow, E. A., Barney, J., Dubey, M., Schneider, M., Iraci, L. T., Podolske, J. R., Hillyard, P. W., Machida, T., Sawa, Y., Tsuboi, K., Matsueda, H., Sweeney, C., Tans, P. P., Andrews, A. E., Biraud, S. C., Fukuyama, Y., Pittman, J. V., Kort, E. A., and Tanaka, T.: Bias corrections of GOSAT SWIR XCO_2 and XCH_4 with TCCON data and their evaluation using aircraft measurement data, Atmos. Meas. Tech., 9, 3491–3512, https://doi.org/10.5194/amt -9-3491-2016, 2016.
<REF: https://data2.gosat.nies.go.jp/doc/documents/ReleaseNote_FTSSWIRL2_BiasCorrCO2_V03.05_GU_ja.pdf (in Japanese)>

26 Balasus, N., Jacob, D. J., Lorente, A., Maasakkers, J. D., Parker, R. J., Boesch, H., Chen, Z., Kelp, M. M., Nesser, H., and Varon, D. J.: A blended TROPOMI+GOSAT satellite data product for atmospheric methane using machine learning to correct retrieval biases, Atmos. Meas. Tech., 16, 3787–3807, https://doi.org/10.5194/amt-16-3787-2023, 2023.

27 https://www.eorc.jaxa.jp/GOSAT/GHGs_Vical/index.html

3 Future Challenges and Directions

GOSAT-GW launch

GOSAT-GW, the third satellite in the GOSAT series, is scheduled for a launch in JFY 2024, according to the implementation timetable of the Basic Plan on Space Policy formulated in June 2023. It observes greenhouse gases as well as water cycles, including precipitation distributions and carries two instruments onboard: Total Anthropogenic and Natural Emissions mapping SpectrOmeter-3 (TANSO-3) and Advanced Microwave Scanning Radiometer 3 (AMSR3).

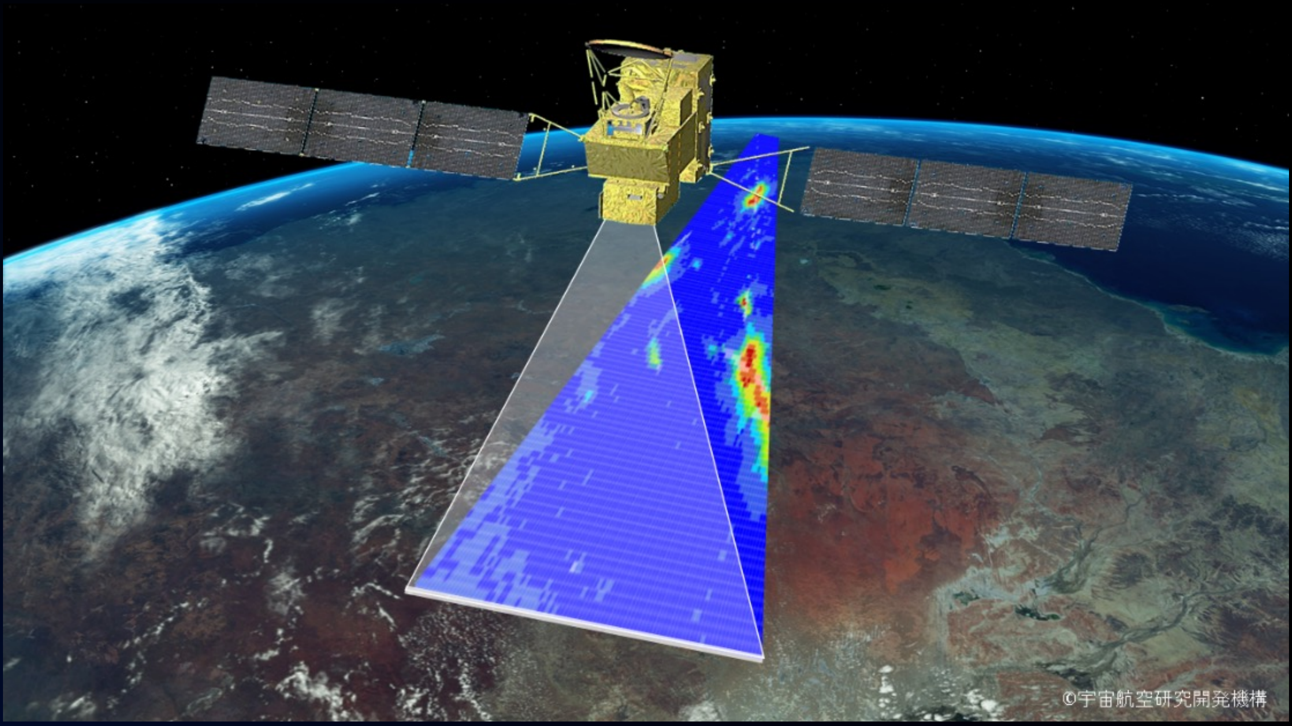


Figure: Image of observation by GOSAT-GW TANSO-3 (wide-area observation mode)

The observation sensors have been changed for the GOSAT-GW, so rather than performing point-based observation as had been done previously, it perform s surface-based observation. It also has two types of observation mode, namely Wide Mode and Focus Mode and both are capable of observing carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (NO_2) concentration.

In the Wide Mode, GOSAT-GW can seamlessly observe the entire globe in a planar manner with 911km observation width (10km*10km resolution). While continuing global greenhouse gas atmospheric concentration monitoring, it can also ascertain country-level emissions more precisely utilizing data that is 100-1,000 times the amount provided by GOSAT-2. Its observations will continue to ensure the transparency of country-level emission reports prepared and disclosed by countries based on the Paris Agreement.

In the Focus Mode, GOSAT-GW can implement detailed observation of locations seen as possible large-scale emission sources with 90km observation width and 3km*3km spatial resolution (target resolution of 1 km*1km). This feature aims to enhance emission estimates from large cities and large-scale emission sources.

NO_2, which is added to observation scope of TANSO-3, is emitted along with CO_2 by combustion of fossil fuels. Since it degrades in the atmosphere faster than CO_2 and methane, simultaneous measurements of these gases should facilitate identification of emission sources and high-precision emission estimates of CO_2 with an anthropogenic origin. GOSAT-GW will be the only satellite that can simultaneously conduct global observations of CO_2 and NO_2 in the mid-2020s. By analyzing GOSAT-GW observation data jointly with information on natural emission sources, such as wildfires, wetlands, and other spots, obtained from existing databases, it will be possible to estimate emissions from anthropogenic and natural origins. Furthermore, since NO_2 is an air pollutant, there should be opportunities to utilize GOSAT-GW data along with surface observations for air pollution measures.

Contributions to the Scientific Community

In addition to continuing global observations, further improving accuracy and increasing volume of observation data are necessary. In this respect, the precision of the GOSAT series data itself will be improved with calibration utilizing land, ship and aircraft observations, and contribution to improving accuracy of satellites observations in the whole world will continue to be promoted through joint observations with NASA, ESA, and other agencies. Furthermore, it is necessary to install more land observation devices in the regions with limited deployment as part of the effort to verify emission inventories of developing countries. Efforts for bolstering global greenhouse gas measurement capabilities include disclosing data from land observation devices installed to calibrate and verify GOSAT series data. IPCC is moving forward with the AR7 process, and this is likely to deliver advances in research in city, Short–lived Climate Forcer (SLCF), and other areas. Contributions to science using the GOSAT series will continue.

Governmental Application of Findings (country-specific emissions estimation, evaluation, and international standardization)

The Ministry of the Environment developed methodology to estimate country-level emissions from GOSAT observation data in Mongolia and Central Asia. The methodology is planned to be applied more broadly to other region such as India, the Himalayan region, the Caucasus region, and Asia from JFY 2024 through collaboration with partner countries and institutions. These efforts will contribute to improving transparency of developing country's emission inventories by including verification results based on GOSAT series data in the reports submitted to the UNFCCC such as BTRs and national inventory reports.

Additionally, these methods will be developed into international standards, thereby helping developing countries easily prepare their own emission estimates utilizing GOSAT data ensuring transparency of their reports as well as facilitating evaluation of the impact of their mitigation action. We also plan to comprehensively and periodically disclose estimated country-level annual emission and absorption volumes using the standardized method with GOSAT-series data. It will provide a scientific basis to understand objective country-level emissions and their mitigation efforts as well as to discuss to further improve the world effort.

We also seek to help alleviate administrative burden of developing countries such as LDCs by providing tools to easily verify the country emission reports using GOSAT series data and by support installation and management of grand-based observation facilities that enhance accuracy of their reports.

Commercial Uses

Towards realizing net zero and environmentally sustainable economic growth, the "Implementation Plan of the Basic Plan on Space Policy" adopted in June 2023 requires the government of Japan to promote satellite data usage and information provision by private companies through disclosure of satellite data. It also calls for consideration of a successor satellite after GOSAT-GW, taking business usage of satellite data by private companies into consideration.

Various start-up companies related to measuring greenhouse gas levels are recruiting investment funds worldwide. Considering the prospect of further expansion of such activities, provision of objective trustworthy data on greenhouse gas emission and absorption by the GOSAT series to these companies should enhance the reliability of information and data used in business related to cutting emissions. As a result, methods will be available for emission estimates at a city and the specific site such as thermal-fired power plants and factories as well as for absorption estimates, including forests and blue carbon. By leveraging these methods, we will not only eliminate green washing but also promoting divestment from projects with large greenhouse gas emissions. As a result, enhancing the investments in projects with genuine reduction effects, Japan will contribute to global-scale reduction of greenhouse gas emissions and increase in absorption volume toward realization of a net-zero society in 2050.

Space Debris Mitigation Initiatives

The Ministry of the Environment has been promoting efforts to manage the GOSAT series in order to prevent them from going out of control and continuing in orbit for a long term. Ministry of the Environment compiled an interim report on the issue in October 2020[28] states,

(1) Even if a satellite is still usable beyond its design life,
(2) After the mission of GOSAT has been successfully taken over by GOSAT-2,
(3) With the understanding of stakeholders and data users,
(4) Following discussions by the Ministry of the Environment, NIES and JAXA, they should start disposal process at an appropriate timing.

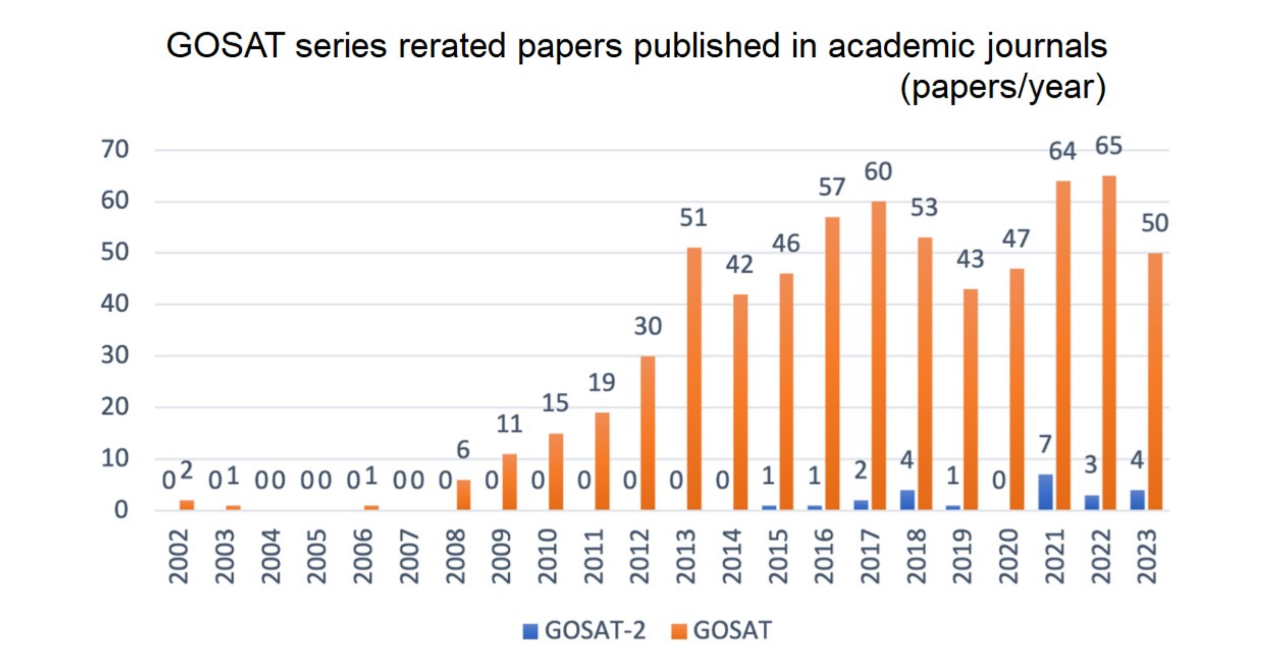
Based on this approach, these parties are regularly monitoring the satellite's state and conducting discussions. Points described below review the current situation.

Regarding (1), GOSAT-1 continues to operate properly at this time. It is transmitting data to the earth, and these data are utilized worldwide after processing by JAXA and NIES. Regarding evaluation of satellite soundness premised on continued operation, JAXA annually evaluates the soundness of GOSAT satellites, including the prospect a year later, based on Space Debris Mitigation Guidelines (JMR-003E) that reflect revisions from the 2019 version of ISO24113, the latest international rules. The most recent evaluation at the end of March 2023 confirmed that the conditional reliability of functions required for disposal process is not less than 0.9 from the end of March 2023 to a year later (end-March 2024). This means that GOSAT is not facing functional issues.

Regarding (2), in September 2023, Yoshida, et al (2023) examined the extent to which systematic differences that may exist in CO_2 and CH_4 concentration data between satellites vary over time and space by comparing CO_2 and CH_4 concentration data obtained from the GOSAT and GOSAT-2 satellites and found that they generally agree to within 1%, although there are slight regional differences. (Disclosure of improved GOSAT-2 concentration data discussed in the paper started in November 2022.) Based on this result, it is possible to conclude that GOSAT-2's succession of the GOSAT observation mission was completed as of September 2023.

Regarding (3), it is important to have GOSAT-2 replace GOSAT from the perspective of scientific and administrative use, which are the main users of the current GOSAT series data. Firstly, in scientific use, as shown in the following graph, GOSAT data is still overwhelmingly dominant, and this indicates that replacement has not occurred yet. One reason for this is that even though GOSAT-2 data have been available since the satellite launch, repeated improvement of the calibration method applied to GOSAT-2 concentration result in delayed guarantee of continuity between long-term data supplied by GOSAT from 2009 and GOSAT-2 data until September 2023. Secondly, for administrative use, comparison between emission reports submitted by countries and GOSAT series data is important. Official reporting is not yet in a situation where the replacement of GOSAT data with GOSAT-2 can be evaluated as complete, since the inventory reports to UNFCCC were supposed to be reported every year for developed countries and every four years for developing countries with two years behind, and the internationally used emissions databases such as EDGAR and ODIAC are also several years behind in development, so the utility of GOSAT data, which still continues to provide long-term data, remains high and the replacement to GOSAT-2 is not yet complete. Yoshida et al. (2023) confirmed the reliability of GOSAT-2 data in the past, and from the end of 2024, all parties including developing countries shall submit BTR and national greenhouse gas inventories every two years under the UNFCCC. As a result, the opportunities to utilize GOSAT-2 data are expected to expand in the future, as the 2020 emissions reports of each country that can be evaluated using GOSAT-2 data will become available sequentially.

28 "Initiative by the Ministry of the Environment to Address the Issue of Space Debris (Interim Report)" (Ministry of the Environment, October 2020); URL: English https://www.env.go.jp/en/earth/cc/debris.html Japanese https://www.env.go.jp/press/108494.html



GOSAT in the graph includes GOSAT-2.

Based on these points, GOSAT currently continues to deliver stable high-quality data inexpensively while retaining soundness as described in (1), and while it meets criteria of the "Interim Report" from the (2) perspective, the evaluation considering point (3) is that circumstances do not support transition to disposal process of GOSAT because the shift to GOSAT-2 is still taking place.

Hence, now is not the timing to proceed with a detailed consideration for (4), though preparation of an action plan for deorbiting and suspended operation as readiness to address unexpected risk of GOSAT becoming space debris. Reviews and coordination via discussions among Ministry of the Environment, NIES, and JAXA will continue.

Direction for Deliberations on Successor Satellites

GOSAT-GW will be beyond its design life 7 years in 2031, it is considered that efforts to achieve net-zero by 2050 will be underway amidst the increasing adverse effects of climate change, and more severe demands will be placed on measuring the effects of efforts (e.g., measuring the long-term effects of absorption technologies, confirming the fulfillment of reduction commitments by countries or companies, and confirming the validity of absorption calculations). It is necessary to envision the future image and a successor to the current observation system in order to respond to the future vision through satellite observation.

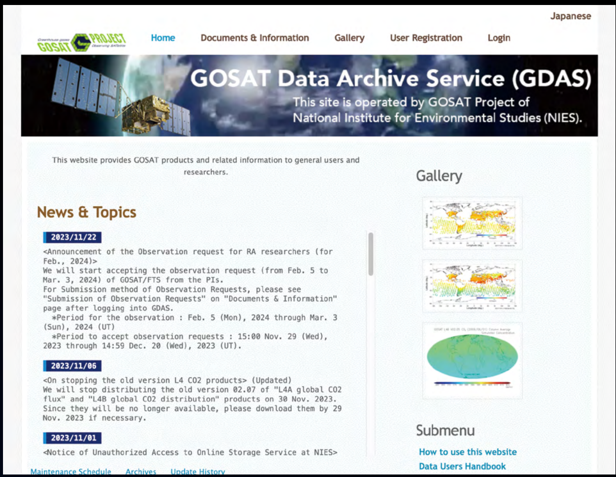
Ministry of the Environment is currently conducting a review from the above-mentioned scientific, administrative, and private utilization perspectives. Key points as contributions to science are securing seamless global observations with higher precision. From an administrative standpoint, topics are ensuring transparency of inventory reports and promoting mitigation efforts based on emission estimates by countries or companies. In data use by private sector, the review has started by identifying needs, such as quality guarantee of absorption credits and monitoring emissions from plants or facilities.

In particular, regarding greenhouse gas satellite observations, there have been multiple private-sector plans and launches, such as GHGSat, MethaneSat, and Carbon Mapper, and more activity is likely. The role of the GOSAT series operated by the government of Japan is to observe global trends while also searching for abnormal discharges and unknown large emission sources. If more detailed observations are needed, such as leak-site monitoring and continuous observation, it might let private-sector small satellites handle subsequent observations with economic incentives, as necessary. Assuming decreasing number of strong point-type emission sources, including emissions from fossil fuels, in line with implementation of net-zero policy over the next few decades, in the future when Japan launches the successor satellite, areal emissions related to changes in land use and unintended emissions from permafrost and other sites is likely to become important. Comparative examination in mitigation measures implemented to address these emission sources is an important perspective too.

In addition, Ministry of the Environment will also consider expanding the use of blue carbon and other sinks by combining GOSAT carbon dioxide data with other satellite data to evaluate the amount absorbed, changes over time, and the potential of these sinks, with a view to encouraging their expanded use in Japan and overseas.

Is it possible to use data from the GOSAT Series?

Data from the GOSAT Series can be downloaded from the following websites free of charge. For details, please visit the websites.



GOSAT
https://data2.gosat.nies.go.jp/index_en.html

GOSAT-2
https://prdct.gosat-2.nies.go.jp/index.html.en

In addition, videos regarding the GOSAT Series are posted on the websites. For details, please visit the video channel of the Ministry of the Environment.
https://www.youtube.com/kankyosho

YouTube

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