Chapter 9

Greenhouse Gas Observation from Space

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9.1 GOSAT Mission Overview

The Paris Agreement was adopted at UNFCCC COP21 in Paris, France in December 2015 as a new international framework for greenhouse gas reductions in the post-2020 period. It is a fair agreement applicable to all Parties. The Paris Agreement has a long-term objective of holding the increase in global temperatures to well below 2 °C above pre-industrial levels, and each Party shall communicate or update its Nationally Determined Contribution (NDC) every 5 years. Each party is to regularly provide information and to participate in expert reviews and a multi-lateral consideration of progress. A 5-yearly ‘global stocktake’, a review of the impact of countries’ actions for the implementation of the agreement, will also take place.

CO₂ and CH₄ together account for more than 90% of the total warming effect (radiation forcing) caused by greenhouse gases (GHG) (IPCC 2013). More GHG in the atmosphere is thought to cause not only higher global average temperatures but also climatic change such as severe droughts and frequent floods, which may result in enormous damage. The Paris Agreement is a major step forward in addressing the climate change challenge. To do so, it is essential to obtain accurate information on GHG emissions on a climate zonal basis (and preferably a national basis) and to evaluate reduction measures based on this knowledge.

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Japan's focus on creating a uniform measure from space was driven by the Kyoto Protocol adopted in December 1997 at COP3, almost 20 years before the Paris Agreement. The Greenhouse gases Observing SATellite (GOSAT) became the world's first satellite designed exclusively to observe GHG. It has been operational since launch in 2009. The mission is jointly promoted by the Japan Aerospace Exploration Agency (JAXA), the Japanese Ministry of the Environment (MOE), and the Japanese National Institute for Environmental Studies (NIES). The administrative, technical, and scientific bodies working together on this mission have been a unique and highly effective scheme for achieving its goals.

The primary objectives of GOSAT are to estimate emission and absorption of GHGs on a subcontinental scale and to assist environmental administration in evaluating the carbon balance of the land ecosystem and in making assessments of regional emission and absorption.

GOSAT measures the concentrations of CO₂ and CH₄, the two major GHGs. The technical mission targets are to (1) observe columnar CO₂ and CH₄ concentrations at 100–1000 km spatial intervals, with 1% relative accuracy for CO₂ and 2% for CH₄, during the Kyoto Protocol's first commitment period (2008–2012) and (2) reduce subcontinental scale CO₂ annual flux estimation errors by half (Kasuya et al. 2009). GOSAT complements the approximately 320 existing ground and airborne CO₂ observation points with 56,000 further points around the globe, significantly enhancing the observation network capability and providing consistent global data over a long period.

9.2 Data Products and Recent Results

GOSAT carries the Thermal and Near-infrared Sensor for carbon Observation (TANSO), which is composed of two subunits: the Fourier Transform Spectrometer (FTS) and the Cloud and Aerosol Imager (CAI). The data from FTS and CAI are processed and used together to calculate column abundances of CO₂ and CH₄ and to estimate sources and sinks as well as the three-dimensional distributions of CO₂ and CH₄ concentrations using a global atmospheric tracer transport model.

GOSAT observational data are processed at the GOSAT Data Handling Facility (DHF) of NIES and the data products are distributed to general users through the GOSAT data product distribution website (GOSAT User Interface Gateway, GUIG). The GOSAT DHF collects the specific point observation requests from qualified researchers and the observation requests of NIES and transfers them to JAXA. JAXA coordinates all observation requests to prepare the satellite operation plan.

The FTS and CAI data are received and processed into Level 1B (L1B) data at JAXA Tsukuba Space Center. These data are then transferred to the GOSAT DHF. The GOSAT DHF also collects the reference data (e.g., meteorological information) necessary for higher level processing. Using the reference data, the FTS observations are processed into column abundances (Level 2, L2), spatially interpolated

monthly global distributions of column abundance (Level 3, L3), sources and sinks (Level 4A, L4A), and three-dimensional distributions of CO₂ and CH₄ (Level 4B, L4B). Reference data used for validating the products are also stored in the DHF.

GOSAT products are distributed through the GUIG. L1B data contain radiance spectra converted from raw data acquired by the satellite. The higher level products from L2–L4 store retrieved physical quantities such as the atmospheric columnar concentrations of CO₂ and CH₄. Users will be able to search and order these products using the GUIG (<https://data.gosat.nies.go.jp/>) by the end of 2016 or using the GOSAT Data Archive Service (GDAS, <http://data2.gosat.nies.go.jp/>) after January 2017.

To improve data quality, we updated the algorithm used for the estimation of XCO₂ and XCH₄ [column-averaged dry-air mole fractions (the ratio of the total amount of targeted gas molecules to the total amount of dry air molecules contained in a vertical column from the ground surface to the top of the atmosphere) for CO₂ and CH₄] and validated the retrieved values by comparing them to high-precision ground-based measurements. Using these L2 values, higher level data products such as monthly estimates of CO₂ and CH₄ regional fluxes were obtained. Based on these flux estimates, concentrations of CO₂ and CH₄ in three-dimensional space were simulated. These data have been made available to the public as GOSAT L4A (flux estimates) and L4B (three-dimensional concentration distributions). GOSAT data collected and archived for more than 6 years, can be used to map the seasonal variations and annual trends of XCO₂ and XCH₄ on regional and global scales.

The top images in Fig. 9.1 show the monthly mean GOSAT XCO₂ data gridded to a 5-degree by 5-degree mesh. The circles show GLOBALVIEW data (ground

Fig. 9.1 GOSAT monthly XCO₂ mean (*top*), CO₂ flux estimates (*middle*), and CO₂ flux uncertainties (*bottom*) for July 2010, 2011, and 2012

Fig. 9.2 Examples of GOSAT L4B data—model-simulated CO_2 concentrations for the same hour, date, and month in 2009, 2010, and 2011. Color denotes CO_2 concentration. 0.925 sigma-level represents about 800 m in the altitude of the mid-latitude atmosphere

observation, 212 sites). With this input, the middle images are generated (monthly flux estimates) and the bottom images show flux uncertainties (GOSAT L4A).

Figure 9.2 shows the L4B data product, which is the result of an atmospheric tracer transport model simulation based on the flux distribution (L4A) estimated from the ground-based and GOSAT-based concentration data. L4B products store global concentrations using a 2.5 -degree mesh in intervals of 6 h at 17 vertical levels, ranging from near the surface to the top of the atmosphere.

MOE, NIES, and JAXA issued a press-release on December 4, 2014 stating that GOSAT archive data has the potential to detect the origin of increased CO_2 concentrations. These analyses have progressed and have been performed for the Tokyo metropolitan area and other major cities around the world. The results, announced on September 1, 2016, demonstrated for the first time the possibility of using satellite observations to monitor and verify the emissions reported by countries, even at relatively small scales.

Figure 9.3a shows areas where high concentrations of anthropogenic CO_2 emissions were observed (average from June 2009 to December 2014). The color represents concentration. Figure 9.3b shows the correlation between the satellite data and inventory estimates for Japan.

These results demonstrate that satellite measurements have the potential to be used for Measurement, Reporting, and Verification (MRV)—especially verification for multilateral agreements—in combination with ground-based, airborne, and other measurements. For such purposes, it is critical that data are free and open.

Fig. 9.3 **a** Distribution of anthropogenic CO₂ concentrations higher than 0.1 ppm between June 2009 and December 2014, as estimated from observational data acquired by GOSAT. Red squares represent typical high emission areas (megacities). **b** Relationship between GOSAT estimates of anthropogenic concentrations and inventories in Japan

9.3 The Way Forward: GOSAT-2

GOSAT-2 is scheduled for launch in 2018. Developed jointly by JAXA, MOE, and NIES, GOSAT-2 is a continuation of the GOSAT mission with upgraded observation capabilities to meet the increased information demands of, for example, the Paris Agreement. GOSAT-2/TANSO-FTS-2 will also have full pointing capability, allowing cloud avoidance and targeted observations of large emission sources. GOSAT-2 will be able to observe carbon monoxide as a new observation target and aerosol pollutants such as PM_{2.5} or black carbon in the atmosphere.

Japan has submitted to the IPCC a proposal for guidelines on the use of satellite data for verifying or validating carbon inventories, which may contribute to worldwide efforts to monitor the state of the global carbon cycle and the effect on the Earth's atmosphere and to help countries achieve their obligations. While satellite data cannot be expected to immediately replace existing methods, the possibility of applying satellite data to national inventories, or in the report and review process, is becoming more realistic.

As the sink and source distribution of CO₂ can be evaluated by the inhomogeneity of atmospheric concentration using diagnostic models, for accurate evaluation it is essential to enhance the current observation network, especially in areas where observations are sparse. Filling the existing spatial observation gaps would improve the quality of information and understanding of the long-term and general status of climate change, thus reducing the uncertainty of the scientific basis of treaties.

Over the long term, satellite observations might contribute to evaluating the sink and source distribution of CO₂ at a precision satisfactory to verify treaty effectiveness over long timeframes.

Satellite missions should aim to provide observations over a long period, so continuity is essential. Total column CO₂ observation missions are planned in a harmonized manner, and include GOSAT (Japan), OCO-2 (NASA), TanSat (China), GOSAT-2 (Japan), Microcarb (CNES), and possibly Carbonsat (ESA) and GOSAT-3 (Japan). A combination of measurement platforms (including in situ) is important to understand the status and change of GHG distribution and to estimate carbon sources and sinks.

Further work is needed to bridge the gap between observation methods and the policy framework. We need not only to enhance measurement accuracies, but also to develop and improve models that identify anthropogenic emissions. The results may be applied to the verification of national inventories or to estimating the effectiveness of measures taken, thus contributing to future treaty amendments and new institutional negotiations. By addressing the gaps between observations and the institutional frameworks, worldwide satellite missions may serve a significant role in the Paris Agreement and beyond.

Reference

Kasuya M et al (2009) Greenhouse Gases Observing Satellite (GOSAT) Program Overview and Its Development Status. https://www.jstage.jst.go.jp/article/tstj/7/ists26/7_ists26_To_4_5/_pdf. Accessed 7 Dec 2016

Author Biographies

Tatsuya Yokota received his Ph.D. in measurement and information systems engineering from The University of Tokyo in 1987. Since 1981, he has been working for the National Institute for Environmental Studies (NIES), Japan. His specialty is information processing and atmospheric remote sensing. He was engaged in several atmospheric satellite remote sensing projects in Japan, including ILAS, ILAS-II, and SOFIS, for polar ozone layer monitoring. He served as the project leader of the Greenhouse Gases Observing Satellite (GOSAT, *Ibuki*) at NIES and as the head of the Satellite Remote Sensing Research Section at the Center for Global Environmental Research (CGER) (2006–2016). Since April 2016, he has been a NIES fellow and the acting leader of the NIES GOSAT project.

Masami Onoda is currently the U.S. and multilateral relations interface at the International Relations and Research Department of the Japan Aerospace Exploration Agency (JAXA). As an academic, she is fellow of the Institute of Global Environmental Strategies (IGES) and she is also engaged in the private sector as an advisor to the Singapore-based space debris start-up Astroscale Pte. Ltd. since its foundation in 2013. From 2009 to 2012, Dr. Onoda was a scientific and technical officer at the intergovernmental Group on Earth Observations (GEO) Secretariat in Geneva, Switzerland. From 2003 to 2008, while pursuing her graduate studies, she was invited to the JAXA Kansai Satellite Office in Higashiosaka as a space technology coordinator to support technology transfer to SMEs for the small satellite project SOHLA-1. From 1999 to 2003, she worked in the field of Earth observations at JAXA (then NASDA), serving on the Secretariat of the Committee on Earth Observation Satellites (CEOS). In 1999, she was seconded to the UN Office for Outer Space Affairs (UNOOSA) for the organization of the UNISPACE III conference. She holds a Ph.D. in global environmental studies (2009) and a master's degree in environmental management (2005), both from the Kyoto University Graduate School of Global Environmental Studies. Her undergraduate degree is in international relations from The University of Tokyo.

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