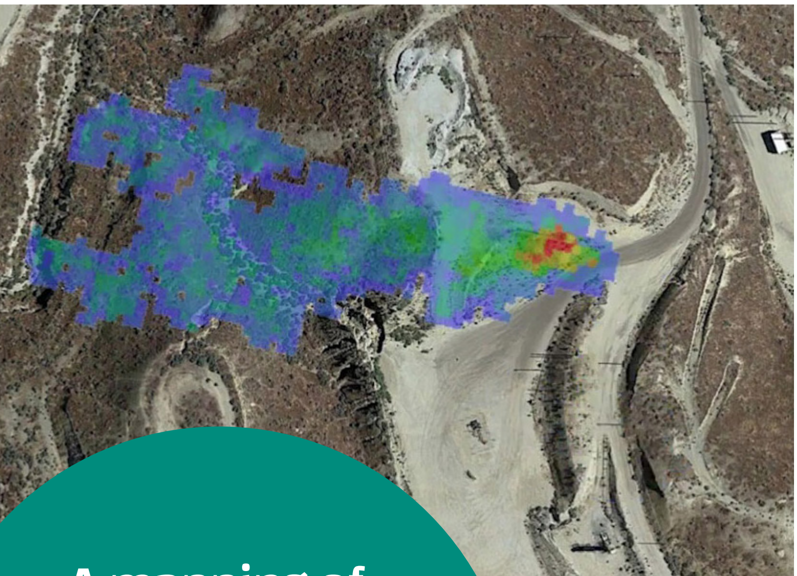
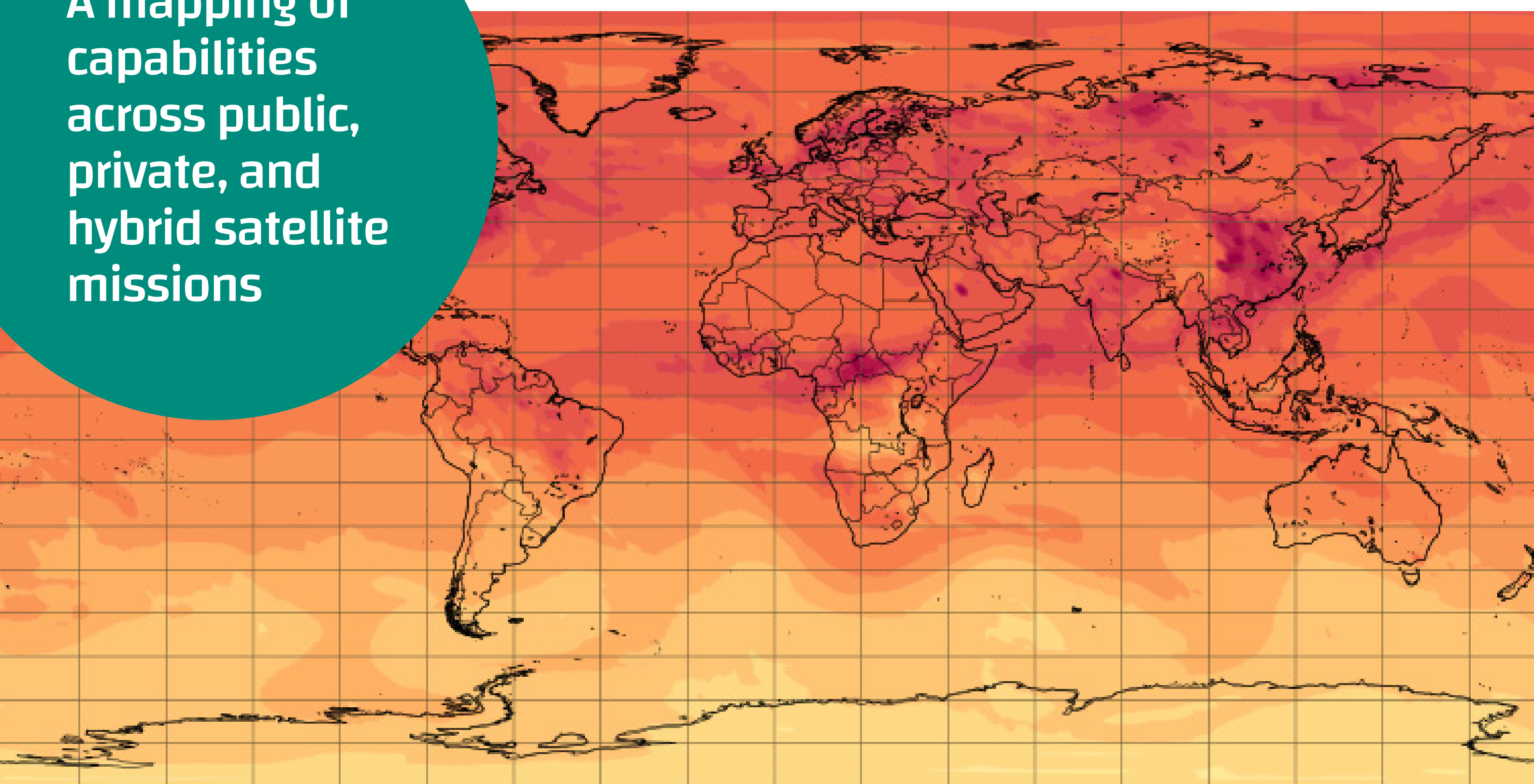
GHG Monitoring from Space

Joint report by the Group on Earth Observations (GEO), Climate TRACE and the World Geospatial Industry Council (WGIC)





A mapping of capabilities across public, private, and hybrid satellite missions

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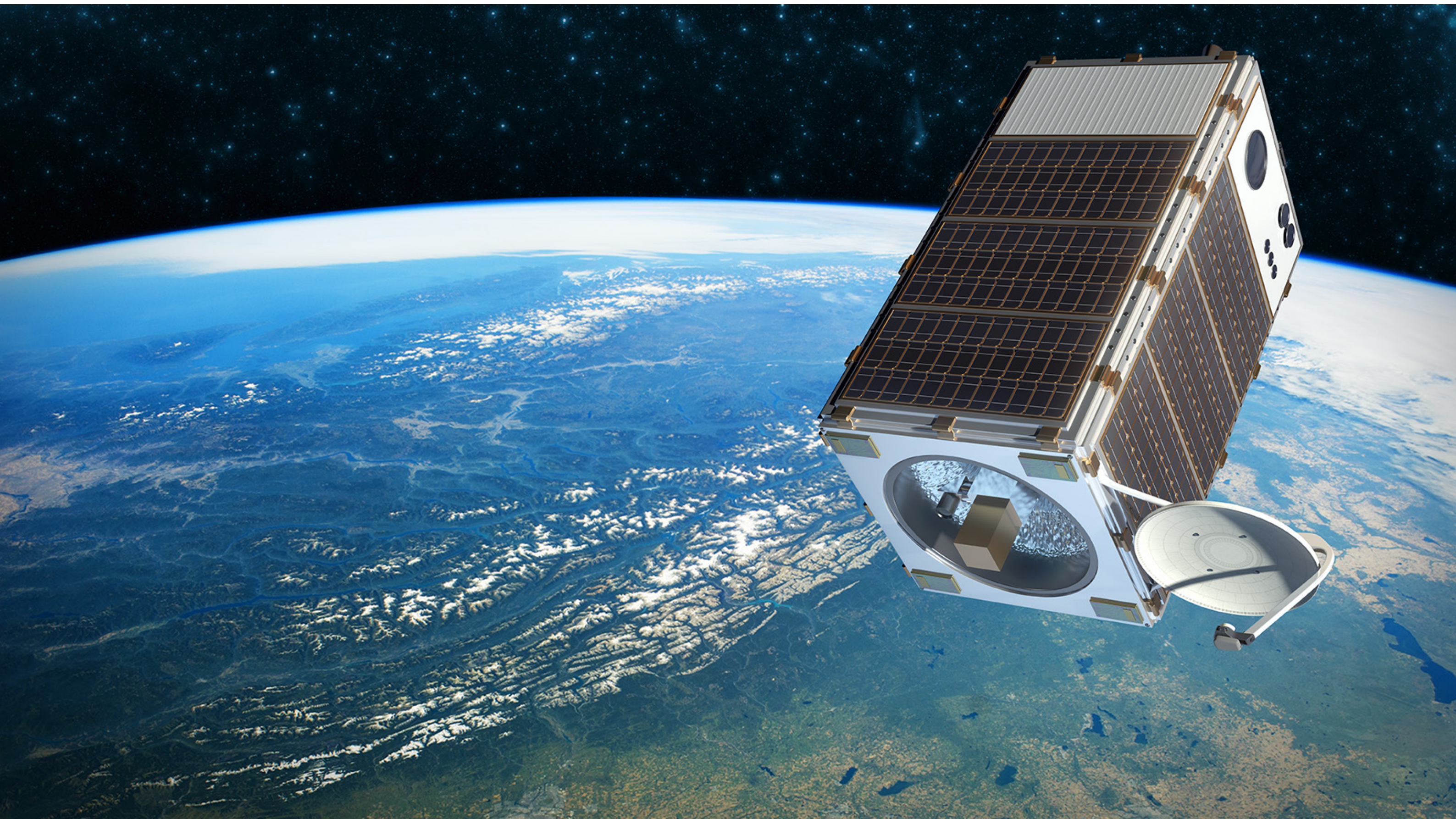

Abbreviations

AR6 - IPCC Sixth Assessment Report

ASI - Agenzia Spaziale Italiana / Italian Space Agency

BELSPO - Belgian Science Policy Office

BTR - Biennial Transparency Reports

CDTI - Centre for the Development of Industrial Technology

CEOS - Committee on Earth Observation Satellites

CGMS - Coordination Group for Meteorological Satellites

CH4 - Methane

CNES - Centre National d'Etudes Spatiales / French National Centre for Space Studies

CO_2 - Carbon dioxide

CSA - Canadian Space Agency

DLR - Deutsches Zentrum für Luft- und Raumfahrt/ German Aerospace Center

EC - European Commission

EC JRC - European Commission's Joint Research Center

ECMWF - European Centre for Medium-Range Weather Forecasts

EDF - Environmental Defense Fund

EO - Earth Observations

ESA - European Space Agency

EUMETSAT - European Organisation for the Exploitation of Meteorological Satellites

FAO - UN Food and Agriculture Organization

GCOS - Global Climate Observing System

GEO - Group on Earth Observations

GOOS - Global Ocean Observing System

GHG - Greenhouse Gas

GST - Global Stocktake

HFCs - Hydrofluorocarbons

IG3IS - Integrated Global Greenhouse Gas Information System

IMEO - UNEP's International Methane Emissions Observatory

IOC-UNESCO - Intergovernmental Oceanographic Commission of the UN Educational, Scientific and Cultural Organization

IPCC - Intergovernmental Panel on Climate Change

ISISpace - Innovative Solutions in Space

JAXA - Japan Aerospace Exploration Agency

JPL - NASA's Jet Propulsion Laboratory

KNMI - Royal Netherlands Meteorological Institute

MIM - CEOS Missions, Instruments, and Measurements Database

MOE Japan - Ministry of the Environment of Japan

MVS - Monitoring and Verification Support Capacity

N20 - Nitrous oxide

NASA - National Aeronautics and Space Administration of the United States

NDC - Nationally Determined Contribution

NIES - National Institute for Environmental Studies of Japan

NF3 - Nitrogen trifluoride

NOAA - National Oceanic and Atmospheric Administration of the United States

NRSCC - National Remote Sensing Center of China

NSMC/CMA - Chinese National Satellite Meteorological Center/China Meteorological Administration

NSO - Netherlands Space Office

PFCs - Perfluorocarbons

REDD+ - Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and forest carbon stock enhancement

RMI - Rocky Mountain Institute

SBSTA - Subsidiary Body for Scientific and Technological Advice

SDGs - Sustainable Development Goals

SEPI - Sociedad Estatal de Participaciones Industriales / State Society of Industrial Participations

SILO - Science and Innovation Link Office

SF6 - Sulfur hexafluoride

SRON - Netherlands Institute for Space Research

TNO - Netherlands Organisation for Applied Scientific Research

UKSA - United Kingdom Space Agency

UN - United Nations

UNEP - United Nations Environment Programme

UNFCCC - United Nations Framework Convention on Climate Change

WCRP - World Climate Research Programme

WGIC - World Geospatial Industry Council

WMO - World Meteorological Organization

WRI - World Resources Institute

Foreword

We are excited to introduce the report "GHG Monitoring from Space: A mapping of capabilities across public, private, and hybrid satellite missions" on behalf of the Group on Earth Observations (GEO), Climate TRACE, and the World Geospatial Industry Council (WGIC).

This report, prepared in advance of the 26th Session of the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP26), is an outcome of the "Forum on Innovation in Remote Sensing Technologies for Accelerated Climate Action" held on 14 December 2020, sponsored by the UK High-Level Climate Action Champion, Nigel Topping, and former United States Vice President, Al Gore, and the Climate TRACE Initiative, together with WGIC and GEO. More than 100 invitation-only diplomats, government officials, heads of commercial and not-for-profit organizations, scientists and financiers came together to discuss innovations in remote sensing technologies for accelerated climate action.

Several themes and key messages, and a commitment to prepare this report emerged from the dialogue. Firstly, no single country, organization, or sector can adequately address the challenges of the changing climate. We must work together in a coordinated manner to mitigate the effects of climate change. Secondly, public sector space agencies have made tremendous strides in observing greenhouse gases (GHGs) from space over several decades. Now we are seeing the emergence of the private sector bring additional observational capabilities and hybrid missions evolving out of public-private partnerships and philanthropic support for digital public goods.

This report primarily describes the use of space-based monitoring of GHGs around the world. It also lays the groundwork for enhanced contributions to the Global Stocktake effort under the Paris Agreement. Thus the report includes a database of GHG monitoring capabilities from space, characterized by public, private and hybrid missions. While observations from the ground will continue to play an essential role in climate studies, space-based observations mentioned in this report will increasingly become more available for climate mitigation and adaptation efforts.

We plan to update this report as appropriate based on additional feedback from the international community.

Yana Gevorgyan
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Gavin McCormick
Climate TRACE Co-founder and WattTime Executive Director

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WGIC Executive Director

Executive Summary

Data and knowledge around global greenhouse gas (GHG) emissions, trends and sources are becoming key levers to support national and international climate policymaking. Public and private sector efforts will help us collect and maintain accurate and relevant GHG emission datasets on all scales to unlock climate action.

As per the Sixth Assessment Report (AR6) by the Intergovernmental Panel on Climate Change (IPCC), the global community needs to take urgent and collective action on the mitigation of GHG emissions to stay within the planetary boundaries and limit global warming to well below 2 degrees Celsius, as stated in the 2015 Paris Agreement.

To enable sound GHG emission reduction, we need a more comprehensive understanding of current national and global GHG emissions contributing to global warming and the overall impact of mitigation efforts. Earth observations (EO), notably satellite-based EO, is recognized as the most powerful tool to provide a synoptic monitoring and reporting on Earth's changing climate over time.

EO are data and information collected about our planet, including atmosphere, ocean, land, and ice. Satellites placed in orbit carry sensors that detect and record reflected or emitted energy and gases from the Earth surface. As the field is rapidly evolving through technology and data processing innovations, EO satellites are increasingly capable of monitoring GHG emissions with precision and scale. Hence, EO data can support policymakers in the establishment of National GHG Inventories as well as the Global Stocktake (GST) process under the Paris Agreement.

Over the past several decades, the EO community has provided extensive support on these fronts. Governments and public entities have supported GHG emission monitoring by launching and financing satellite missions to collect national and global baseline data on GHG emissions. Through open access to these data, academia, government, and commercial entities have provided essential assessment functions to the broader community. As part of the evolution of EO, the private sector has taken on an increasingly important role, particularly concerning point-source monitoring by identifying emission sources and their hotspots or leaks. Numerous private sector and hybrid missions are currently in development, which will further drive innovation and new findings in the field.

To increasingly benefit from the rapidly evolving space-based monitoring capabilities, both governments and commercial sector entities must focus on innovation, financing and, importantly, collaboration, data availability and sharing, and cooperative knowledge creation. Examples are independent and credible platforms that can elaborate and combine massive amounts of data for knowledge generation.

A total of 33 relevant satellite missions and instruments both in orbit and in planning funded by public, private and not-for-profit entities were identified in the database of GHG monitoring capabilities from space underpinning the analysis. These missions have a potential to contribute to National GHG Inventories and the GST, focusing on the three major gases listed under the Paris Agreement for reporting purposes by Parties: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Of these 33 identified missions, most are driven by public entities (21, of which 13 in orbit and operational). In addition, there are 7 commercial missions (of which 1 in orbit and operational, and 1 in its final trial period before being fully operational in orbit) and 5 hybrid missions (all in development) with proposed launch dates until the 2040s. Aiming to provide a comprehensive overview, the database features specific mission information on the country or region where the mission is based, the contributing or coordinating organizations, the mission name and the related instrument, the mission status (in orbit, in development, end of mission), the mission goal and application, GHG data monitored directly (CO_2, CH_4, N_2O), potential policy-relevant application (point-source, national, and global level), and data access.

Photo credit:
NASA

Some key policy-relevant messages can be drawn from the analysis of the identified satellite missions:

1. Satellite observations reduce uncertainty in GHG emission monitoring by providing data across a range of spatial, temporal and spectral resolutions or scales.
2. Government space agencies have the capability to collect national and global baseline data for all relevant GHGs in a sustained manner with measurement availability ranging into the 2040s.
3. Private sector companies are speedily entering the market and bringing additional point-source emissions monitoring capabilities for specific GHGs.
4. Hybrid models are increasingly emerging and leveraging respective strengths.
5. Collaboration, innovation and financing are key levers for GHG monitoring from space.
6. Open data, open science and open knowledge are essential to drive on-the-ground solutions.
7. New opportunities are arising for analysing secondary remote sensing measurements with frontier IT technologies which call for transparency and capacity development.

Based on these findings, we call for continued cooperation between public and private sector entities to fully maximize complementary capacities and synergies to support policy makers in the race to net zero emissions going forward.

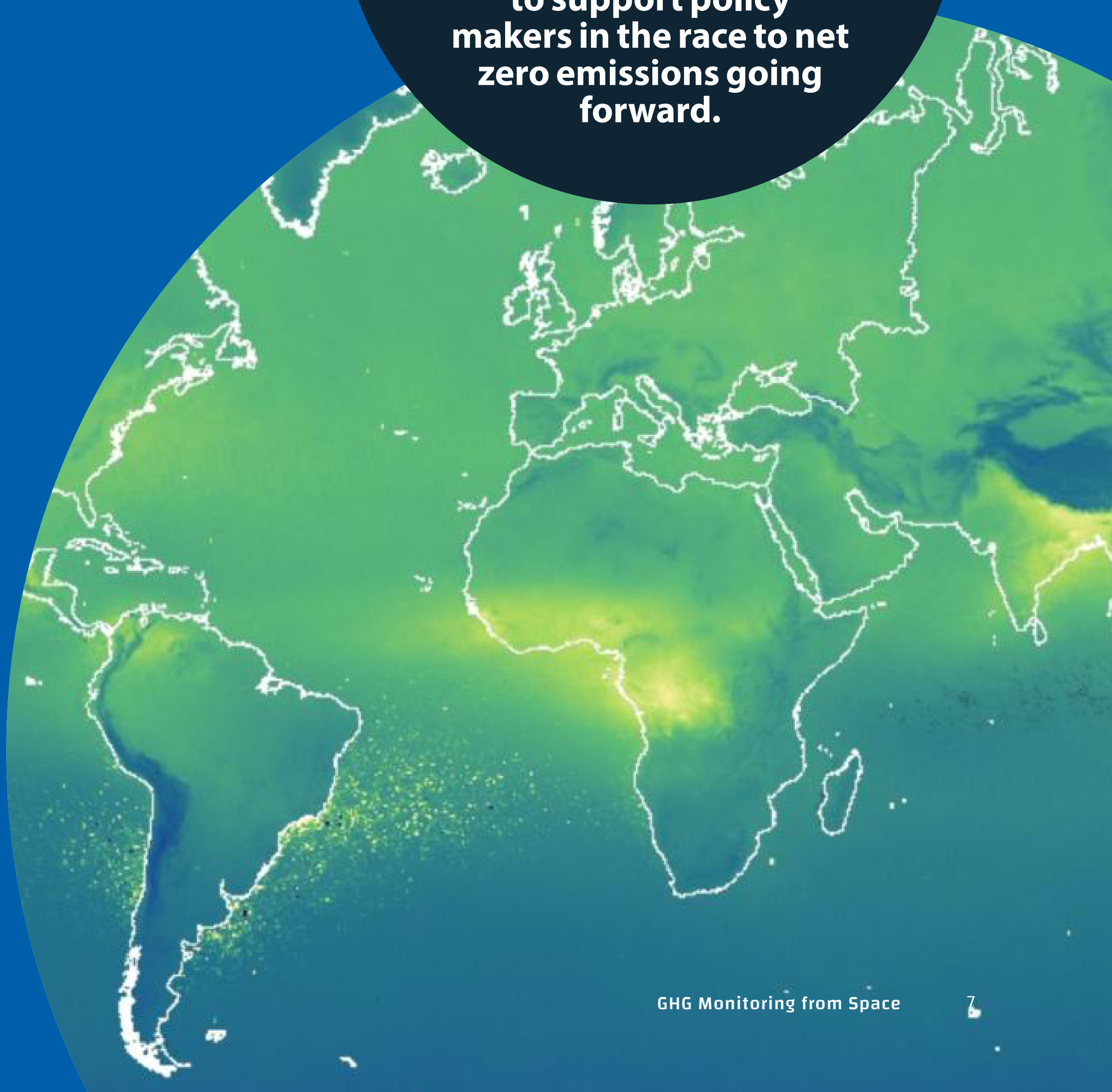


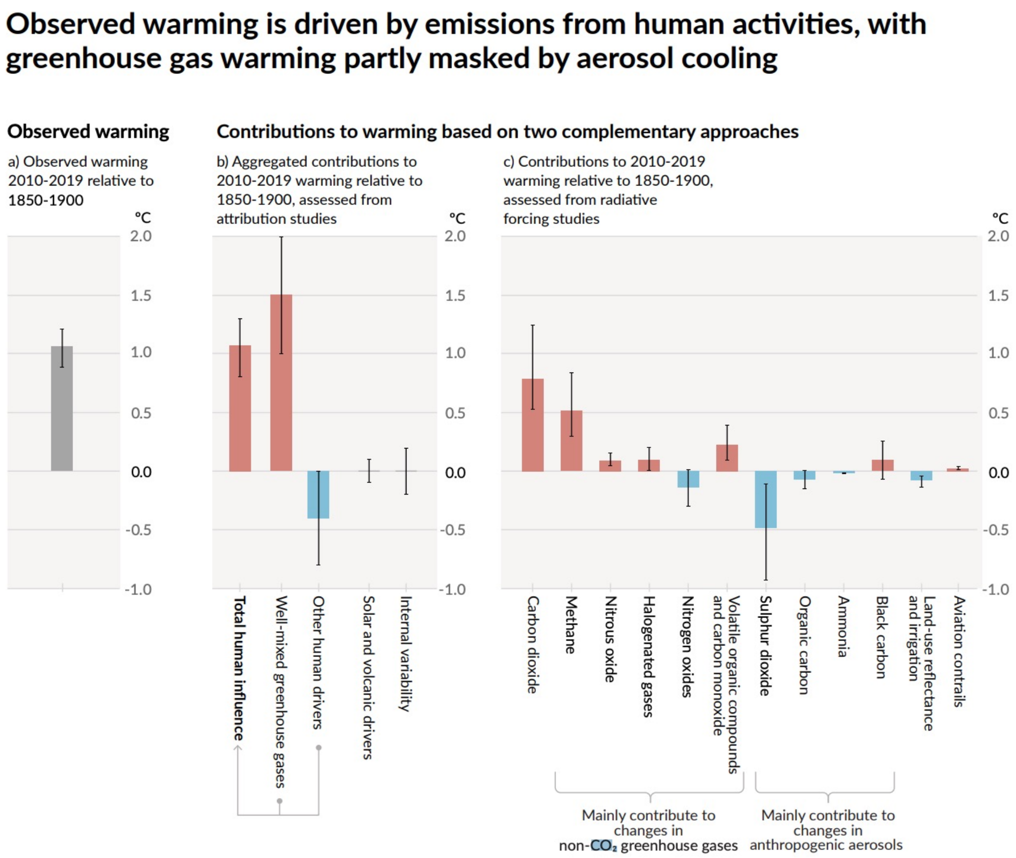
Photo credit:
ESA - Sentinel-5P

1. Climate policy and Earth observations

The United Nations declared the Decade of Action to deliver the Sustainable Development Goals (SDGs), including climate action, by 2030 (UN 2019).

Under the United Nations Framework Convention on Climate Change (UNFCCC), the 2015 Paris Agreement was a major milestone in climate policy in terms of global ambition, stating the importance of keeping global warming well below 2 degrees Celsius through planned national emission reductions. By cutting global greenhouse gas (GHG) emissions by about 50% by 2030 and reaching net zero by 2050, governments have a chance to halt climate change. However, the sum of current emission mitigation plans by 2030 still falls far short of the level of ambition needed to achieve this goal, according to the findings of the Intergovernmental Panel on Climate Change (IPCC). Based on current projections, released in the recent Summary for Policymakers of the Sixth Assessment Report (AR6) by the IPCC, the global surface temperature is very likely to be higher by 1.0 to 1.8 degree Celsius under the lowest GHG emissions scenario considered, by 2.1 to 3.5 degree Celsius in the intermediate scenario, and by 3.3 to 5.7 degree Celsius under the highest GHG emissions scenario, by the end of the century (IPCC 2021).

Fig.1 - IPCC (2021): Observed warming driven by emissions from human activities: carbon dioxide and methane emissions have contributed the most to climate change.



It is essential to better understand and accurately measure current levels, trends and sources of GHG emissions, in order to progress at the scale and speed required to combat global climate change. With the Paris Agreement, governments agreed to develop and meet GHG emission reduction targets as part of their Nationally Determined Contributions (NDCs), by providing country-level information through their National GHG Inventories, as well as aggregate information through a "stocktaking" process (see Fig.2).

The Global Stocktake (GST) is designed to assess the collective progress towards the purpose and the long-term global goals of the Paris Agreement. Understanding and measuring GHG emission data is critical for the successful establishment and implementation of the upcoming GST. The GST will assess collective progress on the following thematic areas: mitigation, adaptation, and means of implementation and support. It will be carried out for the first time in 2023 and every 5 years thereafter, but the collection of input from various sources and the related assessment to prepare for and inform the GST process has already started.

The "information collection and preparation" phase goes from November 2021 until June 2023 and will focus on gathering, compiling and synthesizing information and preparing for the subsequent technical assessment component.

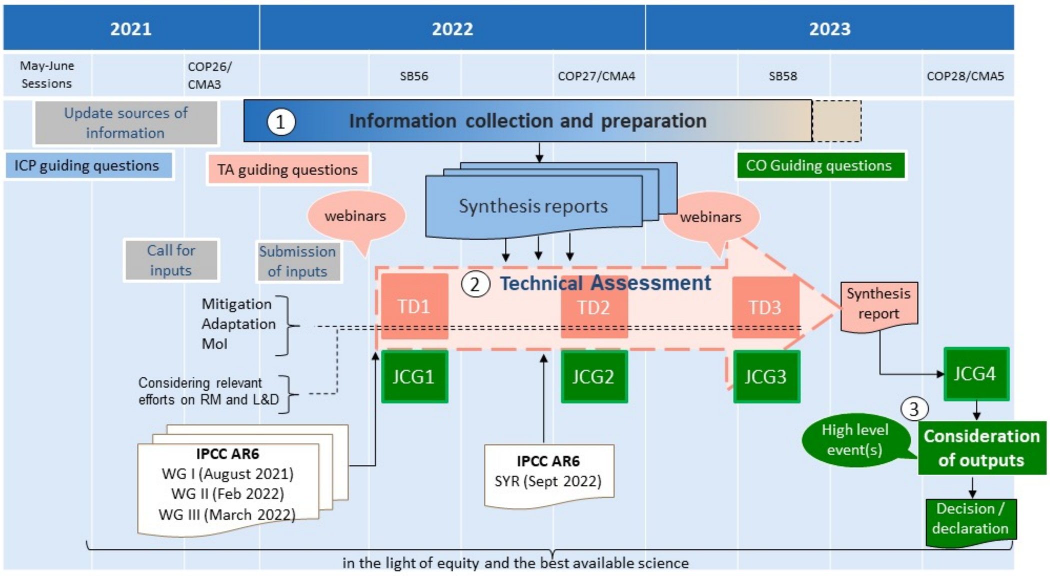
The "technical assessment" phase will focus on taking stock of the implementation of the Paris Agreement to assess collective progress on the key areas, including progress on reducing GHG emissions. This will be followed by the "consideration of output" phase, which will be the final component of the GST and will focus on discussing the implications of the findings and action to be taken by governments.

The GST outcome shall inform Parties in updating and enhancing NDCs and international cooperation for climate action.

Every country has a responsibility to deliver their reports as a contribution to the assessment of aggregate progress under the GST. Under the Paris Agreement, an enhanced transparency framework has been adopted, which requires all Parties to report their National GHG Inventory and any progress made in implementing their NDC. This will be done through Biennial Transparency Reports (BTR), the first of which is to be submitted no later than December 2024. In addition to scientific research and findings by the IPCC, information reported by countries via the BTRs will be considered at a collective level as an important input into the GST.

Transparent reporting is a key component of impactful climate action: Earth observation (EO) has the potential to play a critical role to support policy makers at the intersection between science and action. EO are data and information collected about our planet, including atmosphere, ocean, land, and ice. Satellites placed in orbit carry sensors that detect and record reflected or emitted energy and gases from the Earth surface. As such, remote sensing can serve as an innovative approach to measure and map GHG emissions on a local, regional and global scale, and can also identify specific emitting sources and real-time data on GHG emissions, leakages or hotspots. The GST serves as the policy mechanism to raise global ambition on mitigation based on national efforts, where EO can bring a new level of detail and accuracy for data-driven decision making. The more accurate and policy-relevant GHG emissions data can inform local to global decision making, the more targeted and impactful climate action will become.

Fig.2 - UNFCCC Secretariat (2021): Global Stocktake process.

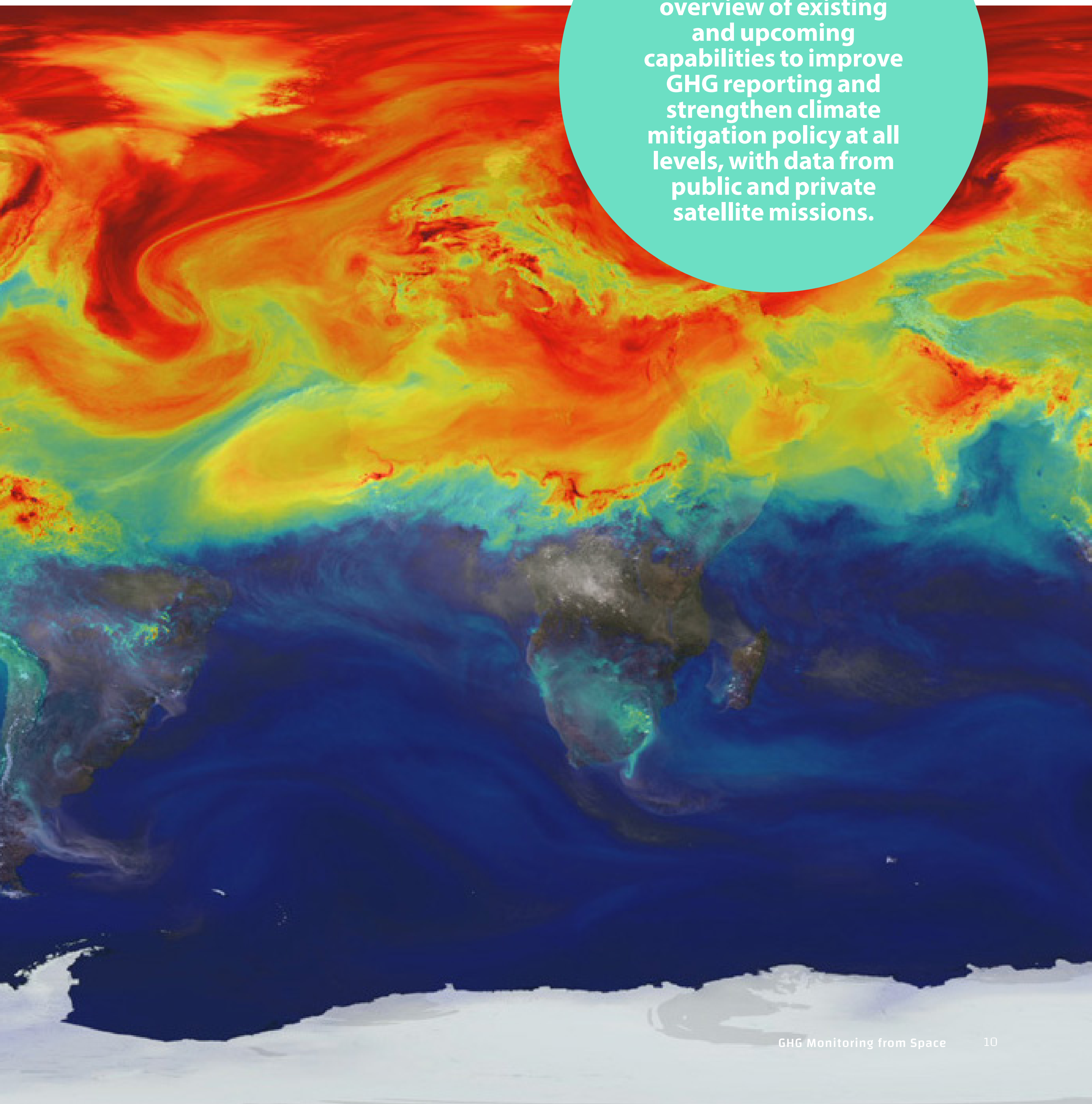


The EO tools, products and services to improve the accuracy of GHG reporting are increasingly provided by both public and private sector entities, offering a variety of services from data inventories, to maps, to strategic guidance. However, policy makers are not always aware of, or able to access or fully utilize the existing EO capabilities. It will be critical to support awareness raising, accessibility, and capacity development to enable scientifically-sound decision making on mitigation at the national and global level.

To respond to these challenges, this report represents the first joint and systematic effort by public and private sector entities to map existing and prospective GHG monitoring capabilities from space. It aims to provide a clear and comprehensive overview of current and future satellite missions and instruments that collect relevant data of GHG emissions in support of the NDC revision and BTR development, as well as the overall GST process, in a way that is accessible by policy makers.

Photo credit:
NASA's Scientific Visualization Studio / NASA's Global Modeling and Assimilation Office

It is crucial for policy makers to gain a full overview of existing and upcoming capabilities to improve GHG reporting and strengthen climate mitigation policy at all levels, with data from public and private satellite missions.



2. Building on the strength of existing Earth observation capabilities

Satellite-based observations contribute essential capabilities for a sustained gathering and assessing of GHG emission data in an accurate and timely manner, and increase transparency and accountability on contributions to mitigate climate change.

Space-based EO measurements provide a distinct opportunity given their capability of global coverage and continuous monitoring capabilities over time, thereby providing information about atmospheric concentrations of GHG (Hardwick & Graven 2016). One example of such large-scale GHG emission monitoring is OCO-3, a NASA instrument mounted on the International Space Station in 2019, which obtains high-resolution carbon dioxide measurements to characterize sources and sinks on regional scales and quantify their variability over the seasonal cycle, including across North America, Europe, and Asia. For the support of the GSTs in the future and for providing information on climate change in general it is very important to sustain the provision of EO data for a long time. Near future EO capabilities are of an operational nature and will provide observations at least into the 2040s.

The field of EO is advancing rapidly due to technical innovation, data policy, data processing capacity and new collaborations. Today, government space agencies are linking EO with cloud computing platforms (such as Amazon Web Services, Google Cloud, Microsoft Azure, etc.) leading to a big data system which enables complex computing of current emission data and forecast modelling (Nakalembe et al. 2021). These new big EO data processing capacities and the combination of different types of satellite data and ground data allow for GHG estimations in near-real time (hours, or for previous months and years) that are made available for the public and private sector by data platforms (such as Climate TRACE and Kayrros). Furthermore, a multitude of space companies are entering the market with new satellites which can provide distinct and sector-specific emission data: the first already operational commercial mission is GHGSat, which monitors specific sites and infrastructure for GHG emissions from point sources in the atmosphere.

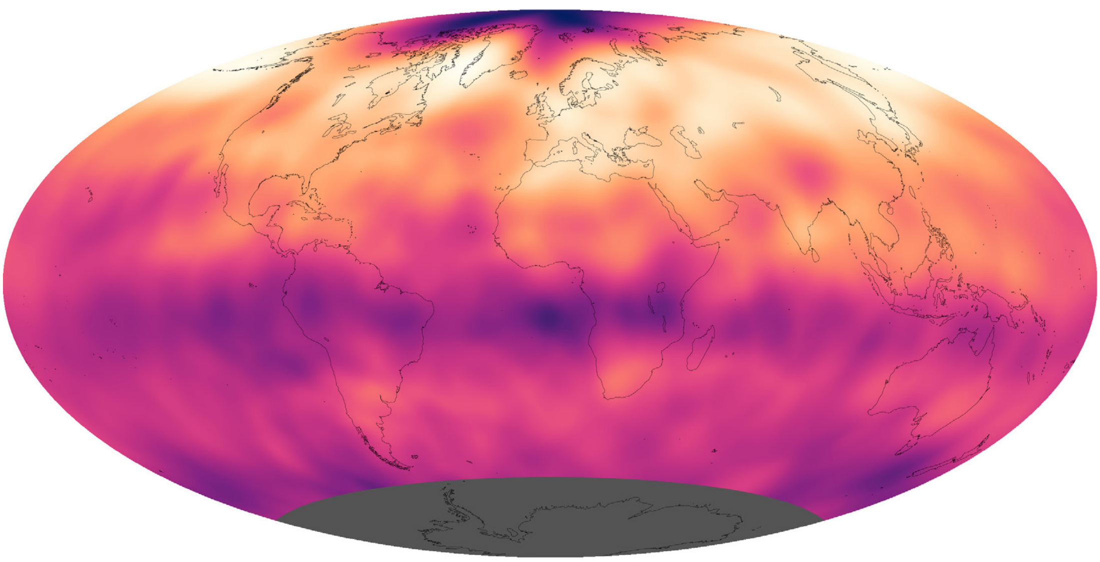


Photo credit:
NASA - OCO-2

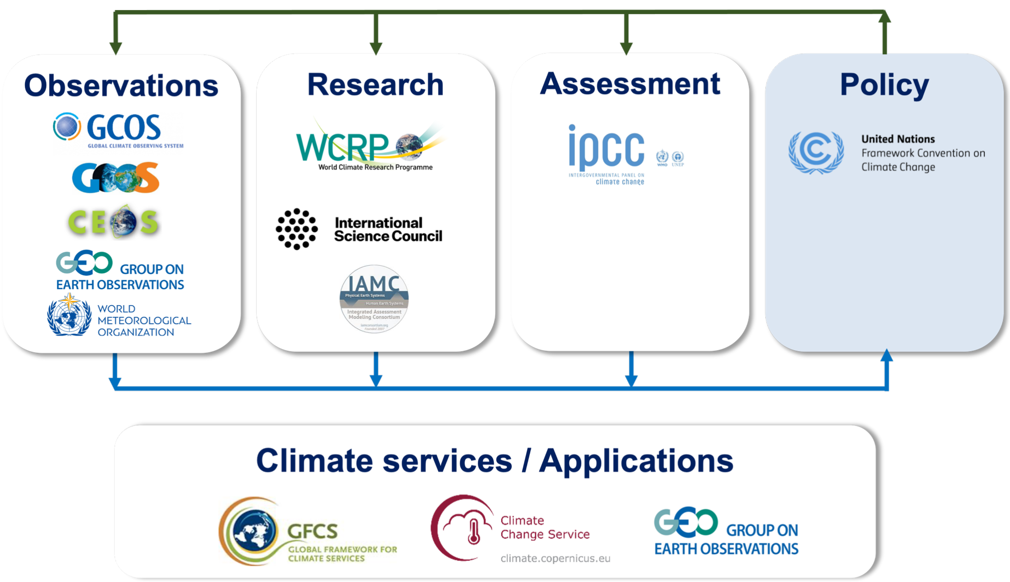
Additionally, analytical framework programmes can support major advances in establishing best practices, methods and standards for using top-down observation. One of the most relevant in the field is the Integrated Global Greenhouse Gas Information System (IG3IS), established in 2017 by the World Meteorological Organization (WMO), with the aim to expand the observational capacity for GHG, extend it to the regional and urban domains, and develop the information systems and modelling frameworks to provide information about GHG emissions to society.

The launch of a novel analytical framework aimed to engage with governments and companies around the world to accelerate GHG emission reductions was officially announced by the United Nations Environment Programme (UNEP) in March 2021. UNEP's International Methane Emissions Observatory (IMEO) will collaborate with a wide range of stakeholders to integrate data from company reporting, satellite data, and measurements from scientific studies to generate the best picture to date of global methane emissions levels and sources.

The EO community has been working toward increased integration and leveraging expert knowledge across disciplines. A multitude of international and national efforts have been driving the increased need and knowledge for GHG mapping. The establishment of the IPCC in 1988, by WMO and UNEP, created the first comprehensive international body for climate-related assessments, closely linked to the establishment of the UNFCCC in 1992. In the 2000s, the focus on international EO and GHG emission accounting was primarily driven by national efforts such as the United Kingdom's Stern Review (2006) and the United States' Decadal Survey (2007). Over this entire period, the international coordination of EO and requirements has been undertaken by a number of groups, and as time has progressed each has increased their capacities and know-how around climate monitoring.

The EO community supports the implementation of the UNFCCC and the Paris Agreement through input to the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the Convention. The Committee on Earth Observation Satellites (CEOS) coordinates national space agencies to better link existing capabilities, as well as inform and assess new capabilities for GHG emission observations. In collaboration with CEOS and other partners, the Group on Earth Observations (GEO) focuses on creating a multi-stakeholder platform for the EO community,including almost 120 UN Member States, to develop applications, services and use cases for GHG data for a diverse range of users including at the regional and national level. WMO, UNEP, CEOS, GEO and other partners in the public EO domain - such as the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), the Coordination Group for Meteorological Satellites (CGMS), the World Climate Research Programme (WCRP), the UN Food and Agriculture Organization (FAO), and the Intergovernmental Oceanographic Commission of the UN Educational, Scientific and Cultural Organization (IOC-UNESCO) - regularly provide regular contributions to address complementary aspects of the systematic observation requirements needed to implement the UNFCCC and the Paris Agreement via the SBSTA.

Fig.3 - GEO (2021): The role of EO in the international climate policy process (authors'adaptation from: UNFCCC Secretariat, 2020).



Building on these existing engagement efforts, the private sector EO initiatives are being brought to the attention of policy makers as complementary input within the UNFCCC process.

Both policy makers and the EO community recognize the need for, and promote increased collaboration to develop a GHG emission monitoring approach that makes use of all currently available satellite data and tools. As part of the efforts established under the UNFCCC and SBSTA, in 2020 the EO community endorsed the development of a Greenhouse Gas Roadmap by space agencies that will "implement an operational atmospheric carbon dioxide and methane monitoring system to maximize contributions to the transparency framework, and the development and validation of NDCs and also for stocktaking" (UNFCCC 2020). According to this roadmap, the first ever GST in 2023 could be informed by a prototype of the atmospheric monitoring system based on available space-based assets, while the second GST in 2028 should be able to integrate learnings and a pre-operational system (UNFCCC 2020).

The EO community is expected to contribute data and information to the GST on aggregate progress in achieving the global mitigation target. EO partners are preparing to reflect their contributions to measure GHG and temperature trends and projections as well as support to Parties for their GHG monitoring and reporting, in a joint EO community's input that will feed into the "information collection and preparation" phase of the GST.

Coupling top-down and bottom-up approaches in GHG measurements will enable the development of more precise National GHG Inventories that underpin government mitigation goals set in NDCs. Currently National GHG Inventories submitted by Parties to the UNFCCC use "bottom-up" methods. These are sector-specific estimates of annual GHG emissions and removals made using data from national statistical offices, compliant with the 2019 Refinement of the 2006 IPCC Guidelines for National GHGs Inventories.[1] These bottom-up methods usually provide accurate estimates of emissions from fossil fuel use, but can include larger uncertainties in other sectors and are often restricted to emissions from managed lands. They therefore provide an often imperfect and incomplete picture of GHG emissions and removals (Crisp 2021).

GHG emissions and removals can also be estimated with "top-down" methods. These estimates are from measurements of GHG atmospheric concentrations (fluxes) determined in time/space, made using inverse models. Top-down atmospheric inventories are not as process-specific as bottom-up inventories, but complement those methods by providing additional datasets on a range of scales, spanning individual large power plants or urban areas to nations or the entire globe. They also track emission changes in the natural biosphere and ocean due to human activities and climate change.

Notably, nitrous oxide measurements from space are particularly relevant to improve the accuracy of emission estimates. Nitrous oxide emissions are extremely challenging to simulate and forecast based on in situ observations only. This is due to the fact that nitrous oxide emissions (natural and anthropogenic) are predominantly driven by microbial processes, which depend strongly on the environmental conditions (soil water content, temperature, oxygen availability, etc.) and management practices (Ricaud et al. 2021).

Satellite remote sensing measurements fill in the missing information related to the monitoring of all GHG emissions and work has begun in this space to answer these questions. Recognizing these developments, the IPCC Guidelines acknowledge the value of top-down methods for quality assurance and quality control of bottom-up inventories (Crisp 2021).

To demonstrate these advances in GHG monitoring, the EO community is starting a conversation with stakeholders and users to establish the utility and best practices for combining bottom-up and top-down methods to enable a more complete and accurate GST. Notably, this effort is led by the Joint CEOS/CGMS Working Group on Climate, bringing together ground-based, airborne, and space-based atmospheric GHG measurement and modeling communities to compile pilot top-down inventories of carbon dioxide and methane emissions and sinks for the 2023 GST (Crisp 2021).

As EO capabilities are becoming increasingly advanced in terms of accuracy and interpretability which provides a sound scientific basis for policy decisions. The The growing precision of EO data gives confidence to develop a robust and accurate accounting system for GHG emissions that reinforces National GHG Inventories and the overall GST process. This provides an opportunity to strengthen current policy processes under the Paris Agreement and at the national level.

The findings presented in the next section of this report are based on a comprehensive mapping of capabilities across public, private and hybrid missions that contribute to this objective.

[1] Sectors specified in the IPCC Guidelines include: Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), Waste and "Other".

3. Database of GHG monitoring capabilities from space

Definitions

CATEGORIES	DESCRIPTION
Country/Region	Country or region where the mission is based. In the case of public sector missions, the identified government funds the mission.
Organization	Contributing or coordinating entity/entities.
Mission (Instrument)	**Mission:** an object (satellite) launched into orbit around the Earth, with a capability (mission) to measure or monitor some characteristic or feature of the Earth and/or its atmosphere (i.e., land, ocean, or atmospheric change). **Instrument**: the name of the specific GHG monitoring instrument on the satellite.
Status	**In orbit:** describes a mission that is in orbit, collecting data and ensuring that users can gain access to the mission data. **In development:** describes missions planned and/or not yet in orbit. **End of mission:** missions that have completed their mission life cycle and are no longer collecting data. Data from the mission should still be accessible.
Mission Goal and Application	**Mission Goal:** identifies the overall objectives of the satellite mission. **Application:** identifies any mission objectives related to GHG monitoring and policy-relevant mitigation elements.
GHGs monitored directly	Atmospheric gases responsible for causing global warming and climate change as defined under the Paris Agreement. This report considers the main GHGs that are monitored directly through EO: **carbon dioxide (CO_2), methane (CH_4)** and **nitrous oxide (N_2O)**.
Potential policy-relevant application	Potential policy-relevant application of data refers to the utilization of EO data to support climate mitigation policy processes at different scales. **Point-source level:** refers to the monitoring of GHG emissions from large facility emitters (e.g. large-sized coal power plants). **National level:** refers to the monitoring of country-level information on GHG concentrations and distribution. **Global level:** refers to the monitoring of continental and global information on GHG concentrations and distribution.
Data access	Access to satellite datasets generally requires registration for individual users and affiliation with an organization. Once registered, the level of access varies by mission and the organization's data policy. **Open access:** full access to the satellite's dataset. **Limited access:** access to certain satellite data that may or may not include access to the GHG datasets. **Paid subscription:** private missions typically require a paid subscription to access their satellite data. Hybrid missions may have open access for their datasets and paid subscriptions for other selected services.

Database of the GHG Monitoring capabilities from space across Public, Private and Hybrid missions

COUNTRY/REGION, ORGANIZATION, MISSION AND INSTRUMENT					GHG MONITORED DIRECTLY			POTENTIAL POLICY-RELEVANT APPLICATION			DATA ACCESS
Country/ Region	Organization	Mission (Instrument)	Status	Mission Goal and Application	CO_2	CH_4	N_2O	Point-Source level	National level	Global level	Open access / Limited access / Paid subscription
PUBLIC MISSIONS: 21											
Canada	CSA ESA NASA	SciSat-1 (ACE)	In orbit	Mission Goal: To monitor and analyze the chemical processes that control the distribution of ozone in the upper troposphere and stratosphere. Application: SciSat-1 can measure the vertical resolutions of all major GHGs identified for monitoring under the Paris Agreement.	CO_2	CH_4	N_2O			Global level	Open access
China	NRSCC NSMC-CMA	FengYun-3D (GAS)	In orbit	Mission Goal: Operational meteorology with substantial contribution to ocean and ice monitoring, climate monitoring, atmospheric chemistry and space weather. Application: Retrieve GHGs in the atmosphere.	CO_2	CH_4	N_2O		National level	Global level	Limited access
China	CNSA	Gaofen-5 (GMI)	In orbit	Mission Goal: Hyperspectral observations of Earth's environments to track environmental impacts, water quality, and atmospheric change. Application: To measure carbon dioxide and methane in the troposphere and understand the source and sink processes that affect these GHGs.	CO_2	CH_4		Point-Source level			Limited access
China	NRSCC NSMC-CMA	TanSat (ACGS)	In orbit	Mission Goal: To retrieve the atmosphere column-averaged CO_2 dry air mole fraction (XCO_2) with precisions of 1% on national and global scales. Application: To improve the understanding on the global CO_2 distribution and its contribution to the climate change. Additionally, to monitor the CO_2 variation on seasonal time scales.	CO_2	CH_4		Point-Source level	National level	Global level	Limited access
Europe	EC ECMWF ESA EUMETSAT	Copernicus Carbon Dioxide Monitoring/ CO_2M	In development	Mission Goal: The CO_2M will focus on measuring carbon dioxide and methane emissions, which are released into the atmosphere specifically through human activity. Application: Reduce current uncertainties in estimates of emissions of CO_2 from the combustion of fossil fuel at national and regional scales. Produce an independent source of information to assess the effectiveness of policy measures, track their impact towards decarbonising Europe and meeting national emission reduction targets. Note- this mission will deploy a constellation of satellites.	CO_2	CH_4		Point-Source level	National level	Global level	Open access

LEGEND:

- CH_4 Methane
- CO_2 Carbon dioxide
- N_2O Nitrous oxide
- Open access
- Limited access
- Paid subscription
- In orbit
- In development
- End of mission
- Global level
- National level
- Point-Source level

Country/Region	Organization	Mission (Instrument)	Status	Mission Goal and Application	CO_2	CH_4	N_2O	Point-Source level	National level	Global level	Open access / Limited access / Paid subscription
COUNTRY/REGION, ORGANIZATION, MISSION AND INSTRUMENT					**GHG MONITORED DIRECTLY**			**POTENTIAL POLICY-RELEVANT APPLICATION**			**DATA ACCESS**
PUBLIC MISSIONS: 21											
Europe	EC ESA NSO	Sentinel-5P (TROPOMI)	In orbit	Mission Goal: To perform atmospheric measurements with high temporal (daily) and spatial resolution that can be used for air quality, ozone & UV radiation, and climate monitoring & forecasting. Application: The global monitoring of GHGs (i.e., CH_4) and their tracers and aerosols relevant to climate forcing.		CH_4		●	●	●	Open access
Europe	EC ESA EUMETSAT	Sentinel-5 1/2/3	In development	Mission Goal: To perform atmospheric measurements at daily and global coverage relating to air quality, climate forcing, ozone and UV radiation. Application: The global monitoring of GHG (i.e., CH_4) and their tracers and aerosols relevant to climate forcing.		CH_4		●	●	●	Open access
Europe	EUMETSAT	Metop-A/B/C (IASI)	In orbit	Mission Goal: Acquire a wide range of land, ocean, and atmospheric measurements serving operational services for nowcasting, weather forecasting and climate. Application: Profiles in middle atmosphere for CO_2, CH_4, and N_2O are derived from IASI measurements.	CO_2	CH_4	N_2O		●	●	Open access
Europe	EUMETSAT	Metop-Second Generation A/B/C (IASI-NG)	In development	Mission Goal: Acquire a wide range of land, ocean, and atmospheric measurements serving operational services for nowcasting, weather forecasting, air quality monitoring, and climate. Application: Profiles in middle atmosphere for CO_2, CH_4, and N_2O are derived from IASI measurements.	CO_2	CH_4	N_2O		●	●	Open access
Europe, Belgium Germany, The Netherlands	ESA BELSPO DLR NSO	ENVISAT (SCIAMACHY)	End of mission	Mission Goal: The global measurement of various trace gases in the troposphere and stratosphere. Application: The retrieval of atmospheric GHGs (CO_2, CH_4, and N_2O) and measurements in the troposphere related to biomass burning, pollution, forest fires, and industrial plumes.	CO_2	CH_4	N_2O		●	●	Open access
France Germany	CNES DLR	MERLIN (IPDA LIDAR)	In development	Mission goal: To obtain spatial and temporal gradients of atmospheric CH_4 columns with high precision and accuracy on a global scale. Application: To improve our knowledge of the global natural and anthropogenic CH_4 emissions.		CH_4		●			Open access
France UK	CNES UKSA	MicroCARB	In development	Mission Goal & Application: To map sources and sinks of CO_2 on a global scale, and the fluxes of CO_2 at the surface (natural or anthropogenic) between the atmosphere and the oceans and vegetation.	CO_2				●	●	Open access

COUNTRY/REGION, ORGANIZATION, MISSION AND INSTRUMENT					GHG MONITORED DIRECTLY			POTENTIAL POLICY-RELEVANT APPLICATION			DATA ACCESS
Country/ Region	Organization	Mission (Instrument)	Status	Mission Goal and Application	CO_2	CH_4	N_2O	Point-Source level	National level	Global level	Open access / Limited access / Paid subscription
PUBLIC MISSIONS: 21											
Germany	**DLR**	**EnMAP (HSI)**	In develop-ment	Mission Goal: To measure, derive, and analyze numerous diagnostic parameters which describe vital processes on the earth's surface relating to agriculture, forestry, soil and geological environments, as well as coastal zones and inland waters. Additionally, the mission will provide information about the status of different ecosystems and their response to natural or man-made changes in the environment. Application: Improve carbon emissions accounting and monitoring of land surface changes (i.e., forest degradation and deforestation).	CO_2	CH_4		✓			Open access
Italy	**ASI**	**PRISMA (HYC)**	In orbit	Mission Goal: To provide a global observation capability, monitoring of natural resources and atmospheric characteristic. The specific areas of interest to be covered are Europe and the Mediterranean region. Application: Carbon cycle monitoring and quantifying GHG emissions from sources.	CO_2	CH_4		✓			Open access
Japan	**JAXA MOE Japan NIES**	**GOSAT (TANSO-FTS)**	In orbit	Mission Goal & Application: To monitor the global distribution of GHGs (i.e., CO_2 and CH_4) at a sub-continental scale and verify the reduction of GHG emissions.	CO_2	CH_4			✓	✓	Open access
Japan	**JAXA MOE Japan NIES**	**GOSAT-2 (TANSO-FTS2)**	In orbit	Mission Goal & Application: To continue the monitoring record started by GOSAT by measuring the global distribution of GHGs (i.e., CO_2 and CH_4) at a sub-continental scale and verify the reduction of GHG emissions.	CO_2	CH_4			✓	✓	Open access
US	**NASA**	**Aqua (AIRS)**	In orbit	Mission Goal: A multi-disciplinary study of Earth's interrelated processes and water cycle (involving the atmosphere, oceans, ice, and land surface) and their relationship to changes in the Earth system. Application: AIRS measures CO_2 and CH_4 in the middle troposphere allowing for the study of the atmosphere's response to increased GHGs.	CO_2	CH_4			✓	✓	Open access
US	**NASA**	**GeoCarb**	In develop-ment	Mission Goal & Application: To monitor plant health and vegetation stress throughout the Americas, and probe the natural sources, sinks, and exchange processes that control CO_2, CO, and CH_4 in the atmosphere at a diurnal temporal scale. This is a geostationary satellite that will measure GHGs over North and South America only.	CO_2	CH_4		✓	✓		Open access

COUNTRY/REGION, ORGANIZATION, MISSION AND INSTRUMENT					GHG MONITORED DIRECTLY			POTENTIAL POLICY-RELEVANT APPLICATION			DATA ACCESS
Country/ Region	**Organization**	**Mission (Instrument)**	**Status**	**Mission Goal and Application**	**CO_2**	**CH_4**	**N_2O**	**Point-Source level**	**National level**	**Global level**	**Open access / Limited access / Paid subscription**
PUBLIC MISSIONS: 21											
US	**NASA NOAA**	**Suomi NPP (CrIS)**	✓ In orbit	Mission Goal: Acquire a wide range of land, ocean, and atmospheric measurements for Earth system science while simultaneously preparing to address operational requirements for weather forecasting: clouds, oceans, vegetation, ice, solid Earth and atmosphere. Application: The CrIS sensor measures CO_2 and CH_4 concentrations in the middle troposphere.	CO_2				✓	✓	Open access
US	**NASA**	**OCO-2**	✓ In orbit	Mission Goal: To obtain high resolution CO_2 measurements to characterize sources and sinks on regional scales and quantify their variability over the seasonal cycle. Application: Improve our understanding of surface CO_2 sources and sinks at regional scales and difference between geographic regions.	CO_2			✓	✓	✓	Open access
US	**NASA**	**OCO-3**	✓ In orbit	Mission Goal: To obtain high resolution CO_2 measurements to characterize sources and sinks on regional scales and quantify their variability over the seasonal cycle. Application: Same as OCO-2 in addition to understanding the movement of fossil fuel plumes across North America, Europe, and Asia, and anthropogenic emissions over megacities.	CO_2			✓	✓	✓	Open access

COUNTRY/REGION, ORGANIZATION, MISSION AND INSTRUMENT					GHG MONITORED DIRECTLY			POTENTIAL POLICY-RELEVANT APPLICATION			DATA ACCESS
Country/ Region	Organization	Mission (Instrument)	Status	Mission Goal and Application	CO_2	CH_4	N_2O	Point-Source level	National level	Global level	Open access / Limited access / Paid subscription
PRIVATE MISSIONS: 7											
Canada/UK	GHGSat	GHGSat-D	In orbit	Mission Goal: The demonstration mission (GHGSat-D) is designed to detect vertical columns of both CO_2 and CH_4 in the atmosphere. Application: The satellite has 5 years in-orbit demonstrating advanced miniature hyperspectral SWIR imaging spectrometer, with a proven capability for monitoring point source emissions from industrial facilities (e.g., oil and gas, mining and landfills).		CH_4		✓			Paid subscrip-tion
Canada/UK	GHGSat	GHGSat-C1 and GHGSat-C2	In orbit	Mission Goal: GHGSat-C1 and GHGSat-C2 are optimized for measuring CH_4 from point sources, and/or over localized areas. Application: The satellite data is being used to gain insight about industrial CH_4 emissions. The insights can be integrated into industrial operations and government policy/regulations. In-orbit measurements of controlled CH_4 releases have validated performance of the instrument.		CH_4		✓			Paid subscrip-tion
The Netherlands	ISISpace	BrightSkies	In develop-ment	Mission Goal: Hyperspectral observations of Earth's environments to track environmental impacts, water quality, and atmospheric change. Application: To measure carbon dioxide and methane in the troposphere and understand the source and sink processes that affect these GHGs.	CO_2	CH_4		✓			Paid subscrip-tion
US	Bluefield	Bluebird	In develop-ment	Mission goal: Using a constellation of satellites, the primary application will be point source CH_4 gas detection. In the future tracking other GHGs such as SO_2, NO_2 and CO_2 is planned. Application: Bluefield aims to provide satellite data to investors in oil and gas companies, and to government agencies, environmental groups and insurance companies that want to monitor a company's progress in reducing emissions.	CO_2	CH_4	N_2O	✓			Part Open access Part Paid subscrip-tion
US	Orbital Sidekick	Aurora	In orbit Commis-sioning phase	Mission Goal: The Aurora mission is a precursor for the GHOSt mission and will capture 450 spectral bands in the visible to shortwave infrared light spectrum, and therefore capable of observing CO_2, CH_4, N20 and other GHGs. Application: Applications will include those in the energy, mining and defense sectors, including oil and gas pipeline monitoring, methane mapping, clean-energy resource exploration, sustainable mining practices and wildfire risk mitigation.	CO_2	CH_4	N_2O	✓			Paid subscrip-tion

COUNTRY/REGION, ORGANIZATION, MISSION AND INSTRUMENT					GHG MONITORED DIRECTLY			POTENTIAL POLICY-RELEVANT APPLICATION			DATA ACCESS
Country/ Region	Organization	Mission (Instrument)	Status	Mission Goal and Application	CO_2	CH_4	N_2O	Point-Source level	National level	Global level	Open access / Limited access / Paid subscription
PRIVATE MISSIONS: 7											
US	Orbital Sidekick	GHOSt Constellation (Satellites No. 1-6)	In development	Mission Goal: Building on the Aurora mission, the GHOSt constellations of satellites will collect data over the same spectral bands but at a higher spatial resolution (8 meters). Application: Applications will include those in the energy, mining and defense sectors, including oil and gas pipeline monitoring, methane mapping, clean-energy resource exploration, sustainable mining practices and wildfire risk mitigation.	CO_2	CH_4	N_2O	✓			Paid subscription
US	Scepter	ScepterSat	In development	Mission Goal: Using a suite of hyperspectral sensors, ScepterSat will observe emissions at point-source to regional scale for a number of air-quality parameters, including the major GHGs. Application: Combined with other data, ScepterSat will complement existing systems with higher spatial and temporal data for Energy, Transport, Agriculture and Health applications. Scepter's multi-sensor (more Species) approach will enable global legacy air-quality districts in more developed nations, and also developing nations who want an efficiently deployed remote sensing air quality and climate monitoring capability to minimize deploying unnecessarily high resource and costly airborne / terrestrial systems.	CO_2	CH_4	N_2O	✓	✓		Paid subscription
HYBRID MISSIONS: 5											
The Netherlands	<u>ISISpace-led consortium</u> ISISpace TNO KNMI SRON 3D PLUS	TANGO-Carbon	In development	Mission Goal: The Twin ANthropogenic Greenhouse Gas Observers (TANGO) Carbon mission will use breakthrough technology to monitor emissions of CH_4 and CO_2 at the level of individual industrial facilities and power plants. Application: TANGO-Carbon is aimed to complement the current and planned Copernicus monitoring missions such as Sentinel-5P and the CO2M High Priority Candidate Mission (HPCM) by providing high-resolution monitoring of the major anthropogenic GHG emissions on a regular basis at a spatial resolution of 300×300 m2 for CH_4 and CO_2.	CO_2	CH_4		✓	✓		Open access
The Netherlands	<u>ISISpace-led consortium</u> ISISpace TNO KNMI SRON 3D PLUS	TANGO-Nitro	In development	Mission Goal: The Twin ANthropogenic Greenhouse Gas Observers (TANGO) Nitro mission will use breakthrough technology to monitor emissions of N_2O at the level of individual industrial facilities and power plants. Application: The TANGO-Nitro mission is aimed to complement the current and planned Copernicus monitoring missions such as Sentinel-5P and the CO2M High Priority Candidate Mission (HPCM) by providing high-resolution monitoring of the major anthropogenic GHG emissions on a regular basis at a spatial resolution of 300×300 m2 for N_2O.			N_2O	✓	✓		Open access

COUNTRY/REGION, ORGANIZATION, MISSION AND INSTRUMENT					GHG MONITORED DIRECTLY			POTENTIAL POLICY-RELEVANT APPLICATION			DATA ACCESS
Country/ Region	Organization	Mission (Instrument)	Status	Mission Goal and Application	CO_2	CH_4	N_2O	Point-Source level	National level	Global level	Open access / Limited access / Paid subscription
HYBRID MISSIONS: 5											
Spain	**SATLANTIS** **Axis-ICO** **Basque Government** **CDTI** **Diputación Foral de Bizkaia** **Enagás** **Orza** **SEPIDES / SEPI** **Silo** **University of Florida**	**GEI-SAT (iSIM-90/ iSIM-179)**	In develop-ment	Mission Goal: iSIM-90 is a precursor instrument observing the Shortwave Infrared (SWIR) spectrum from 900-1700 nm, thereby providing for the detection of CH4 using the absorption band between 1600 and 1700 nm. Application: As part of a dedicated constellation, GEI-SAT will be able to provide near-continuous coverage of any sub-polar point on the globe (during daytime hours), and as a stand-alone platform, GEI-SAT, will be able to provide coverage for national or global applications, particularly when observations in the VNIR and SWIR spectral ranges are combined for more precise geolocation and accurate identification of CH4 emission sources.		CH_4		✓			Open access Paid subscrip-tion for certain services
US	**Carbon Mapper Partnership** **Carbon Mapper** **Planet** **NASA JPL** **State of California** **University of Arizona** **Arizona State University** **High Tide Foundation** **RMI** **Grantham Foundation** **Bloomberg Philanthropies** **ZEGAR Family Foundation**	**Carbon Mapper**	In develop-ment	Mission Goal: Is to pinpoint, quantify and track CH4 and CO2 emissions at facility scale; and to increase global accessibility, transparency, and understanding of methane and CO2 data. Application: To provide a rapid methane leak detection service to facility operators and regulators, and deliver independent data to help certify methane intensity for oil and gas supply chains.	CO_2	CH_4		✓			Open access Paid subscrip-tion for certain services
US	**MethaneSAT LLC** **EDF**	**MethaneSAT**	In develop-ment	Mission Goal: MethaneSAT will detect high-emitting point sources, with less spatial granularity, compared to point-source detectors. With its much broader swath, however, MethaneSAT will be able to revisit sites more frequently and cover a larger proportion of emission sources than a point-source satellite. This will enable MethaneSAT to capture a wide range of emissions, allowing for robust emission quantification encompassing both larger area- and point sources. Application: MethaneSAT will provide regular monitoring of regions accounting for more than 80% of global oil and gas production, identifying not only the location, but also quantifying the emissions rate, allowing changes over time to be monitored. Applications will include the oil and gas industry and agriculture.	CO_2	CH_4		✓	✓		Open access

4. Current scope of Earth observation capabilities from space

Establishment of the database

Under the Paris Agreement seven GHGs are listed for reporting purposes by Parties (UNFCCC 2019, Decision 18/CMA.1). Three GHGs are generally recognised as the critical drivers of climate change: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Additionally, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) are also accounted for through the process, although they are less prevalent.

The database underpinning the findings of this report (see pages 15-20) focuses on EO capabilities which are able to monitor directly one or more of the three major GHGs to simplify this first joint effort. Although challenges remain, technological breakthroughs are happening in the field of remote sensing that will enable capabilities to fully measure GHGs.

Aiming to provide a comprehensive overview, the database features specific information on: the country or region where the mission is based, the contributing or coordinating organizations, the mission name and the related instrument, the mission status (in orbit, in development, end of mission), the mission goal and application, GHG data monitored directly (CO_2, CH_4, N_2O), potential policy-relevant application (point-source, national, and global level), and data access.

A clarification is necessary with regard to "Potential policy-relevant application". In this report, this term is used to describe the utilization of GHG data collected from space to inform climate policy at different scales, including the global mitigation goal and the GST at the international level, mitigation targets and related National GHG Inventories at the country level, as well as mitigation targets and related reporting for cities or companies. The choice of this definition is justified by the existence of some complexities in the actual scale of application of GHG satellite measurements. There is an ongoing debate on what is feasible with satellite capabilities versus true spatial coverage, namely at what level data are actually collected. For instance, the definition of "global coverage" might vary depending on the provider and technology. Any satellite in a polar orbit has the capacity to target any location on the planet, however in practice the attainable spatial coverage is a function of field of view, spatial resolution (cloud clearing), agility, data system capacity, and sampling strategy. There are similar issues with "revisit rate" (orbit revisit does not equate to sample frequency), and "completeness" (percentage of emissions that can be detected, as a function of detection limit, spatial coverage and sample frequency). These assessments need to be accounted for and normalized in an independent manner, in order to be able to offer comparisons between platforms that might in reality represent different capabilities. Therefore, the database does not address technical capabilities per se but highlights the likely policy-relevance of the GHG data collected.

The database was compiled through a transparent and participatory review process involving public and private sector entities. To engage the public sector, GEO Secretariat, in collaboration with Climate TRACE, consolidated multiple information on government-led satellite mission and instrument data, primarily building on the CEOS Missions, Instruments, and Measurements (MIM) Database as well as mission-specific information, and peer-reviewed papers. To engage the private sector, the World Geospatial Industry Council (WGIC), a global not-for-profit trade association, collected information from partner and non-partner companies on existing and planned commercial GHG satellite missions, and compiled it to pair with the work done for public sector missions.

The database was shared in a feedback process receiving editorial inputs from reviewers. This effort marks a newly formed collaboration with the objective to facilitate the exchange of knowledge, create new opportunities, and increase the links to national and international policy making, ensuring that all existing and planned capabilities are used to the greatest extent possible.

Main findings

The database identifies a total of 33 relevant satellite missions and instruments funded by public, private and/or not-for-profit entities which are currently in orbit and/or planned for orbit to collect relevant GHG data. This database solely includes missions collecting EO data for the GHG categorized under the Paris Agreement and that have the potential to contribute to climate mitigation policies.

PUBLIC SECTOR MISSIONS

- **Countries and Organizations:** Overall, governments and related space agencies alone have been most actively contributing to the collection of EO data on GHG emissions and concentrations through national and collaborative efforts, with a total of 21 relevant satellite missions. Currently, 13 public satellite missions are in orbit, 1 has been completed and 7 new satellites are planned to be launched in this decade.

- **Missions & Instruments in Orbit:** Public entities of the United States are leading the field with currently 4 missions in orbit (Aqua/AIRS, Suomi NPP/CrIS, OCO-2, OCO-3), and 1 in development (GeoCarb) which will measure GHGs over North and South America. China currently has 3 missions in orbit (TanSat/GAS, FengYun-3D/ACGS, Gaofen-5/GMI), as well as Europe with 2 missions in orbit (Sentinel-5P/TROPOMI, and Metop-A/B/C IASI).

- **Upcoming Missions:** Europe is currently planning 3 upcoming missions (CO2M, Sentinel-5 1/2/3, and Metop-SG A/B/C (IASI-NG)); additionally there are 2 collaborations between France and Germany (MERLIN), and France and the United Kingdom (MicroCARB); as well as 1 stand-alone project by Germany (EnMAP) in development. As part of the work led by Europe, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) will continue its operational missions with the Metop-Second Generation (IASI-NG) that also carries the Sentinel-5 and will provide observations until 2045. The United States is working on the launch of satellite GeoCarb. China, and Japan have entered the field since the 2000s. China is planning to continue its FengYun series, currently in orbit. All the launches are planned between now and 2038.

- **GHG monitored directly:** Most satellites collect data on two or all of the three major GHGs under the Paris Agreement. SCIAMACHY by the European Space Agency (ESA), operated between 2002 and 2012. Japan Aerospace Exploration Agency (JAXA) currently has two satellites in orbit, GOSAT and GOSAT-2. OCO-3, a collaborative initiative by the United States' National Aeronautics and Space Administration (NASA) and JAXA, is targeting an improved methodology and data collection for the anthropogenic (human-induced) GHG emissions. The European Copernicus CO2M satellite constellation will use multiple instruments per platform to measure CO_2 and CH_4 even under conditions of air pollution with very high accuracy. It will target anthropogenic emissions by contributing to the European CO_2 Monitoring and Verification Support Capacity (MVS) currently established in support of the GST by the European Commission Copernicus programme.

- **Potential policy-relevant application:** Most of the public satellite missions have the ability to collect relevant GHG emission data from at least one or two specific levels, generally covering larger areas, including national or global scale applications. There are 3 public-sector missions in orbit which also have the capability to measure all three scales of application: the TROPOMI Instrument in Sentinel-5P (Europe, in orbit since 2017), OCO-2 and OCO-3 (United States, in orbit since 2016 and 2019 respectively). The satellite missions Sentinel-5 A/B (Europe) and MERLIN (Germany/France) with all three scale capabilities are planned for launch in 2022 and 2024 respectively and will be complemented by the European Copernicus CO2M constellation in 2026.

- **Data access:** The data from 18 out of 21 public missions are currently available openly, while data from 3 missions (FengYun-3D, Gaofen-5, TanSat) are available but with limited access.

PRIVATE SECTOR MISSIONS

- **Countries and Organizations:** Companies based in Canada and the United Kingdom (GHGSat), the Netherlands (ISISpace), and the United States (Bluefield, Orbital SideKick, and Scepter) have a total of 7 missions targeted at collecting selected GHGs from space.

- **Missions & Instruments in Orbit:** To date, GHGSat (Canada/United Kingdom) is the only commercial satellite company with on-orbit operational GHG monitoring capabilities involving two satellites, GHGSat-C1 and GHGSat-C2. Orbital Sidekick (United States) will follow shortly, as it has just completed its first data collection, downlink and processing of imagery from the recently launched Aurora satellite.

- **Upcoming Missions:** The Brightskies mission by ISISpace, the Bluebird mission by Bluefield, the ScepterSAT mission by Scepter, and the GHOSt constellation by Orbital Sidekick are under development.

- **GHG monitored directly:** GHGSat, through both a demonstration mission and an operational mission in orbit, currently detects and collects CH_4 data with plans to collect CO_2 data as well. ISISpace, while its mission is still under development, plans to monitor CO_2 and CH_4 data; Bluefield, Orbital Sidekick and Scepter also with missions still under development, plan to monitor all three major GHGs.

- **Potential policy-relevant application:** In almost all of the private sector missions, data is either being collected (GHGSat) or planned to be collected at the point-source scale. That is, relatively large individual facilities emitting or leaking CH_4 are being detected and measured from space.

- **Data access:** For all commercial missions (existing or planned), access to the data is usually through paid subscription. Bluefield plans to offer data partly through open access, partly through paid subscription.

Photo credit:
Microsoft

HYBRID MISSIONS

- **Countries and Organizations:** ISISpace (based in the Netherlands), SATLANTIS (based in Spain), CarbonMapper (based in the United States), and MethaneSat (based in the United States) have GHG monitoring missions under development, as part of public, private and/or not-for-profit partnership models:
  - ISISpace-led consortium: ISISpace, as mission prime, Netherlands Organisation for Applied Scientific Research (TNO), Royal Netherlands Meteorological Institute (KNMI), Netherlands Institute for Space Research (SRON), and 3D PLUS;
  - SATLANTIS: Axis-ICO, the Basque Government, Centre for the Development of Industrial Technology (CDTI), Diputación Foral de Bizkaia, Enagás, Orza, SEPIDES/Sociedad Estatal de Participaciones Industriales (SEPI), Science and Innovation Link Office (Silo), the University of Florida;
  - Carbon Mapper partnership: Carbon Mapper, as a not-for-profit organization, Planet., NASA's Jet Propulsion Laboratory (JPL), the State of California, the University of Arizona, Arizona State University, High Tide Foundation, RMI, the Grantham Foundation, Bloomberg Philanthropies, and other philanthropic donors;
  - MethaneSat: Methane Sat LLC is a wholly-owned subsidiary of the non-profit Environmental Defense Fund (EDF).

- **Missions & Instruments in Orbit:** Currently there are no hybrid GHG monitoring missions in orbit.

- **Upcoming Missions:** All of the 5 identified hybrid missions are under development with launch dates ranging from 2022 to 2025:
  - TANGO Carbon and TANGO Nitro (CO_2, CH_4, N_2O) by the ISISpace-led consortium;
  - GEI-SAT mission with 2 instruments with different revisit rates (CH_4) by SATLANTIS;
  - Carbon Mapper mission (CO_2, CH_4) by the Carbon Mapper partnership; and
  - MethaneSat mission (CO_2, CH_4) by MethaneSat LLC.

- **GHG monitored directly:** All of the hybrid missions described above will monitor CH_4. Of these, 2 missions (Carbon Mapper, MethaneSat) will also monitor CO_2, and another (TANGO) will monitor CO_2 and N_2O, in addition to CH_4.

- **Potential policy-relevant application:** Each of the planned hybrid missions will monitor emissions at the point-source scale. MethaneSat is also planning to develop capabilities that could potentially collect emission data over larger spatial areas, such as national or global.

- **Data access:** Among the planned hybrid models, 3 of them will be open access (TANGO Carbon, TANGO Nitro, and MethaneSat), while the other 2 will be open access (for instance, after limited hold or during natural disasters or emergencies) and may involve paid subscription for additional services (Carbon Mapper, and GEI-SAT).

Key messages

1. **Satellite observations reduce uncertainty in GHG emission monitoring by providing data across a range of spatial, temporal and spectral resolutions or scales:** More high-quality space-based observations will support a better understanding of national and global GHG emission levels, sources, and changes over time. Coupling top-down and bottom-up approaches in GHG measurements will enable the development of more informed National GHG Inventories that underpin NDCs. Moreover, GHG monitoring satellites can help identify GHG emission hotpots (e.g., emission anomalies such as methane leaks), and emission sources (e.g. power plants, forest fires; in combination with high resolution images or pre-existing assets location databases).

2. **Government space agencies have the capability to collect national and global baseline data for all relevant GHGs in a sustained manner with measurement availability ranging into the 2040s:** By creating baseline data, information, and knowledge on national and global scales for all relevant GHGs under the Paris Agreement, space agencies are continuously working to increase data accuracy, temporal coverage and innovation. These efforts, generally in a freely and openly available format, enable policy makers to access relevant data and information for improved decision making. Space agencies provide monitoring capabilities that can quantify a global total for CO_2, while beginning to trace CO_2 and CH_4 in a way that is complementary to ground-based networks. Space agencies are committed to providing demonstration products for the first GST in 2023, with a view to include significantly greater space-based information on GHG emissions at the sectoral and national level in future GSTs.

3. **Private sector companies are speedily entering the market and bringing additional point-source emissions monitoring capabilities for specific GHGs:** Private companies have been driving innovation around point-source emission monitoring, e.g., GHG peaks and leaks. Private sector missions, in orbit or in development, are generally focused on CO_2 and CH_4 emission detection. Although GHG measurements from private missions do not yet provide global coverage nor have global reach, their contribution to global assessments is significant since major GHG emissions that impact the Earth's climate come from a limited number of very large point-source emissions. Private sector entities are committed to contribute to global policy processes, such as the GST, by providing complementary and high-precision data on GHG emissions that will become available in the next few years.

Photo credit:
ESA

4. **Hybrid models are increasingly emerging and leveraging respective strengths:** Hybrid missions, i.e. partnerships between public, private, and/or not-for-profit organizations are becoming more and more common. These partnerships are designed to leverage the strengths of each participant contributing to the mission, for instance consolidating complementary capabilities to measure GHG at different scales, and develop new knowledge. Hybrid missions use a range of financing and governance models, and represent an opportunity for investors.

5. **Collaboration, innovation and financing are key levers for GHG monitoring from space:** There is a need for increased collaboration and innovation for public, private, and not-for-profit entities in order to provide comprehensive GHG data and information across multiple spatial, spectral, and temporal scales supporting global climate action. As the EO community at large (including both space-based and ground-based observations providers) is driving innovation, it will be critical for policy makers to identify their needs and knowledge gaps on GHG emissions for both the NDCs and related National GHG Inventories, and the GST process, so that these needs can be matched with future offerings. Large-scale funding is vital to sustain long-term investments in EO and applied research.

6. **Open data, open science and open knowledge are essential to drive on-the-ground solutions:** Data access and sharing are prerequisites for building effective communities to deliver open data, open science and open knowledge. In turn this will drive the application of data for on-the-ground solutions, as well as decision making for policy makers. Thus, stronger interactions between the public and private sector on open data can support increased innovation and collaboration, as well as financing.

7. **New opportunities are arising for analysing secondary remote sensing measurements with frontier IT technologies which call for transparency and capacity development:** Initiatives that apply big data analysis, data science and machine learning techniques to space-based and ground-based observations collected from multiple sources, including company asset data are emerging, and are being used to independently estimate GHG emissions. When this is done by sector or asset, e.g., for oil and gas or cement, this has a potential to support a stronger alignment between climate change mitigation efforts by governments, and emission reduction targets and actions by industry. EO metadata analysis platforms for GHG increasingly provide added-value through new forms of data aggregation and visualization, utilizing very high-resolution EO data. However, trust needs to be built for independent (non-Party driven) assessments to be integrated into official reporting under the Paris Agreement. Supporting capacity development to enable effective adoption, integration, and use of these new methodologies by Parties is therefore crucial.

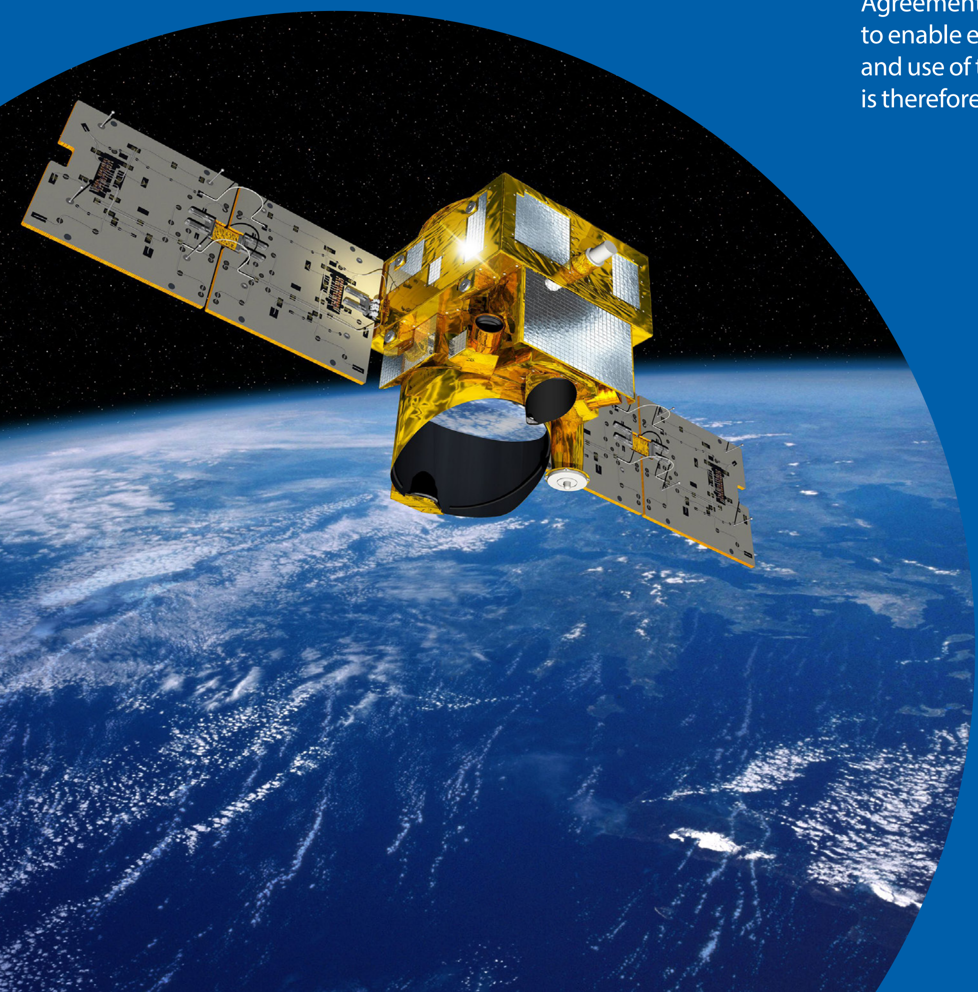


Photo credit: CNES

5. Case studies

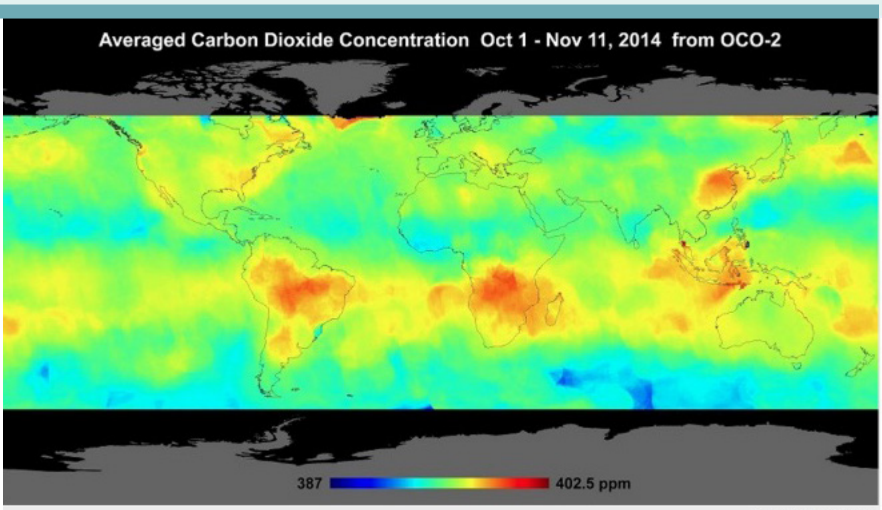
NASA OCO-2 and OCO-3 - Supporting a first collective effort to measure CO_2

Launched in 2014 by NASA, OCO-2 was the first dedicated Earth remote sensing satellite to study atmospheric CO_2 from space. Overall, OCO-2 aims to provide global measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize sources and sinks on primarily regional scales (NASA). OCO-3, following in 2019, has the same objective, with focus on growing urban populations and changing patterns of fossil fuel combustion (NASA).

OCO-2 and OCO-3 are able to showcase average CO_2 concentration, as well as highlight seasonal variations.

The illustration in Fig.4 shows the first ever assessment of atmospheric CO_2 levels measured through space-based technology, in Fall 2014 (Nature 2014). Fig.4 highlights an example of OCO-2 providing national-level and global-level information on monitored CO_2 distribution and concentration.

Additionally, OCO-3 has been monitoring areas such as the Amazon and Congo Basins to better understand the relevance of both areas as carbon sinks, by gathering data at different times of the day to reduce uncertainty of the data caused by cloud obscurity (Nature 2019).



NASA/JPL-Caltech

Data from the Orbiting Carbon Observatory-2 show atmospheric carbon dioxide levels measured between 1 October and 11 November.

Fig.4 - Nature (2014): OCO-2 Data of Average Carbon Dioxide Concentration, Oct 1 - Nov 11 2014.

GHGSat - Delivering point-source measurements and identifying leaks and hotspots

Founded in 2011, GHGSat is the first private sector satellite company contributing to GHG emission monitoring with dedicated commercial missions. The satellites are specifically designed to collect facility-level emissions from point sources, highlighted in Fig.5. The company has 3 satellites in orbit today with another 9 due to launch in 2023 and 2024. GHGSat is delivering emissions information to industrial operators, the financial services sector and governments. Through its unique data, GHGSat has supported new approaches to international climate diplomacy, while the company's science team works to identify/validate emission sources and improve data analysis techniques. The company meets with leading scientists every 3 weeks for an operational review of public and private data so operators can be notified of emissions problems; these reviews are based on longstanding collaborative relationships with international researchers from Harvard University and the Netherlands Institute for Space research, among others. As an additional contribution to global transparency, GHGSat launched Pulse, a free global data visualisation of CH4 available since 2020.

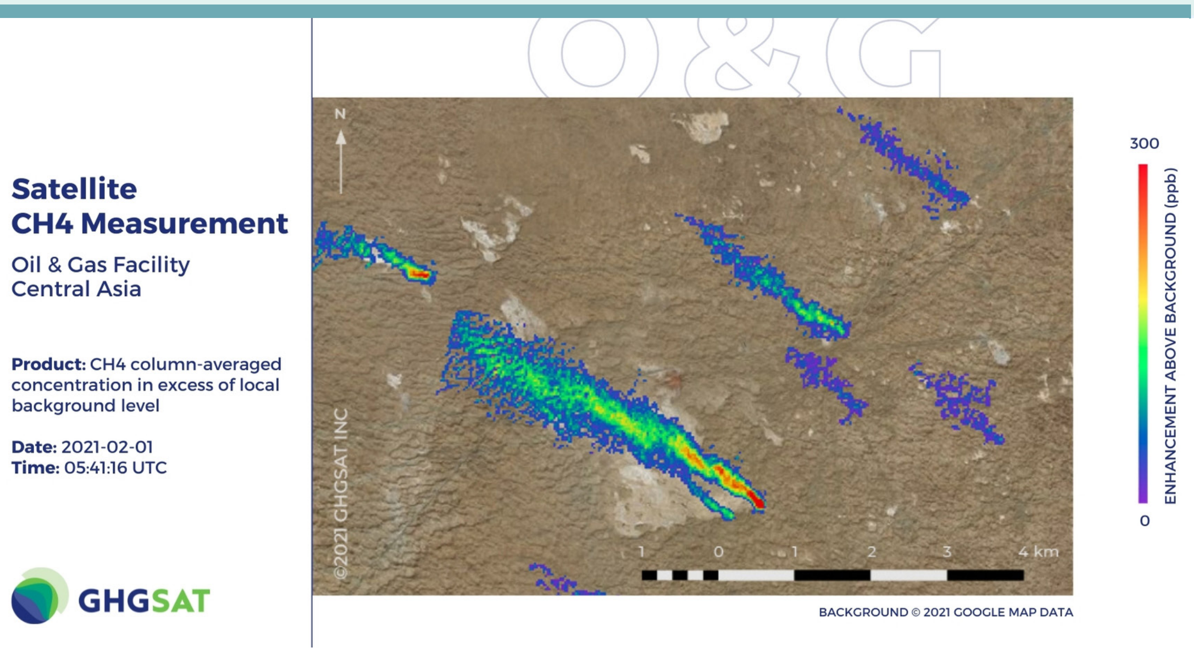


Fig.5 - GHGSat: CH4 emissions from oil and gas facilities in Central Asia, detected using satellites.

Carbon Mapper - Public and private sector strengthening innovation and collaboration

The satellite programme Carbon Mapper is an example of the evolving collaboration between public, private and philanthropic organizations to monitor GHGs from space. Set up as a non-profit foundation, Carbon Mapper aims to harvest the most critical expertise and know-how of the partnership with Planet, NASA's JPL, the University of Arizona, Arizona State University, the State of California, RMI (formerly the Rocky Mountain Institute), the High Tide Foundation, the Grantham Foundation, and Bloomberg Philanthropies, and other philanthropic donors.

The goal of the Carbon Mapper mission, with the first two satellites expected to be launched in 2023, is to pinpoint, quantify and track CH_4 and CO_2 emissions at facility scale; and to increase global accessibility, transparency, and understanding of CH_4 and CO_2 data. It will provide a rapid CH_4 leak detection service to facility operators and regulators, and deliver independent data to help certify methane intensity for oil and gas supply chains.

High-resolution satellite images provide an opportunity to not only identify hotspots, but clearly locate emission sources, which adds a point-source layer of transparency to the assessment of overall national and global emissions. As the technology is becoming more advanced, satellites can support in better understanding large emission sources, or sectoral and supply chain information.

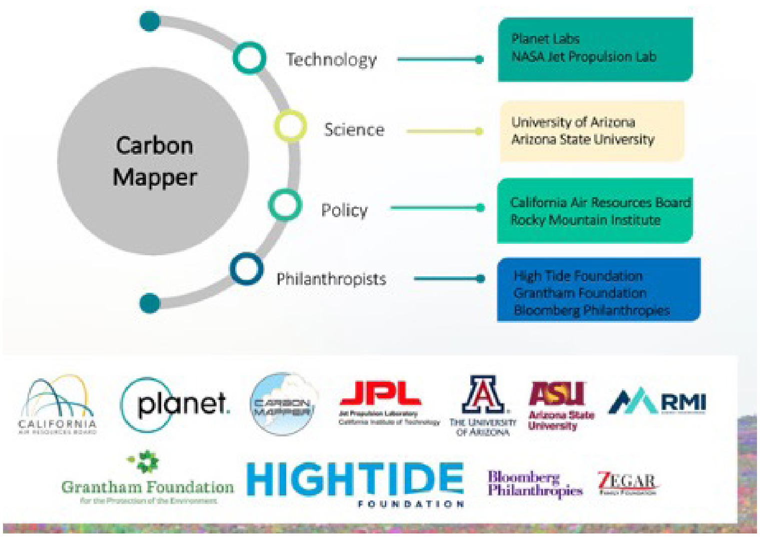


Fig.6 - Carbon Mapper: Overview of Partners for Carbon Mapper.

UNEP's International Methane Emissions Observatory - Focusing on high-impact projects and novel collaborations with the oil and gas industry

IPCC AR6 highlights the importance of CH4 mitigation for avoiding the worst effects of climate change. The fossil fuel sector is a major contributor of CH4 emissions and readily available mitigation measures could dramatically reduce emissions from both the oil and gas sector and the coal sector by 68% and 61% respectively by 2030. One key issue preventing targeted action on fossil fuel CH4 emissions is the lack of reliable and granular data about where and how much CH4 is emitted.

To address this problem, UNEP's IMEO will integrate data from various sources to produce a global public dataset of empirically verified CH4 emissions at an increasingly accurate and granular level.

The partnership outlines a multitude of satellites which are considered complementary for tracking global CH4 emissions (GOSAT, GHGSat, Sentinel-5P/TROPOMI, GOSAT-2, MethaneSAT, GeoCarb, and Carbon Mapper) that will be integrated based on integrity, transparency and relevance of data (IMEO 2021).

Satellite remote sensing data will be a key part of IMEO's data integration platform which - in conjunction with the company data from the Oil & Gas Methane Partnership (OGMP2.0), emission measurements from science studies, and inventory data, will provide a full characterization of methane emissions from global fossil fuel infrastructures. The OGMP2.0 itself is led by UNEP, in partnership with the European Commission, the UK Government, the Environmental Defense Fund, and leading oil and gas companies. Already 74 companies with assets on five continents representing 30% of the world's oil and gas production have joined the partnership (OGMP 2021).

Fig.7 - OGMP (2021): The Oil & Gas Methane Partnership was launched at the UN Secretary General's Climate Summit, in New York, in September 2014.

ESA - Sentinel-2, and potential use of Sentinel-5P, for climate change mitigation including REDD+

Utilizing remote sensing data will increasingly provide opportunities for more data-driven decision making, as well as link to cross-sector benefits. One example is the joint initiative by the European Commission's Joint Research Center (EC JRC), FAO, University of Maryland, Google, and the Global Forest Watch service of the World Resources Institute (WRI) on monitoring global deforestation in support of REDD+. REDD+ is a mechanism, enshrined included in the Paris Agreement, that refers to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. The project utilized various satellite imagery, including the ESA Sentinel-2 which focuses on a systematic global acquisition of high-resolution images to understand land changes as well as geophysical variables (Fig.8; ESA). Through the combination of different data sets and tools, the project was able to provide significant insight in deforestation, but also relevant information on climate change mitigation potential, with the opportunity to inform National GHG Inventories (CEOS/CGMS Working Group on Climate).

Efforts like this show the need for, and opportunity of innovation for satellite data to inform global policy frameworks. Sentinel-5P marks the most recent mission which aims to gather atmospheric measurements with high temporal and special resolution, with focus on monitoring GHGs, especially CH4. For example, Sentinel-5P was capable of measuring the average CH4 concentrations over the United States (Fig.9).

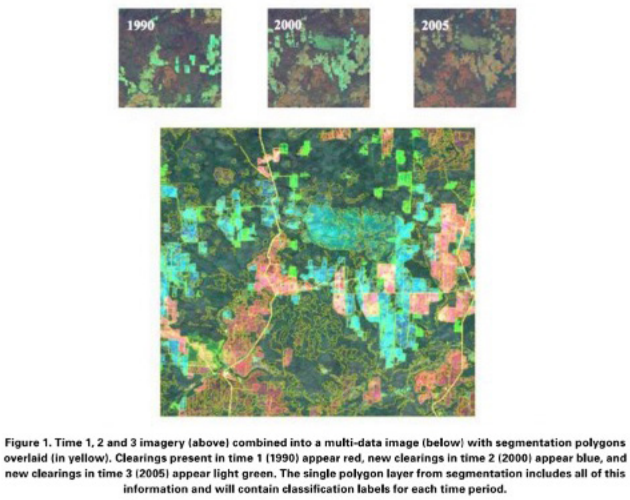


Fig.8 - CEOS/CGMS Working Group on Climate: Overview of land coverage data using multi-data approach, showcasing land coverage and forest clearing between 1990, 2000, and 2005 (top three images). Bottom image shows a composite image of each year, highlighting areas that have experienced land cover change.

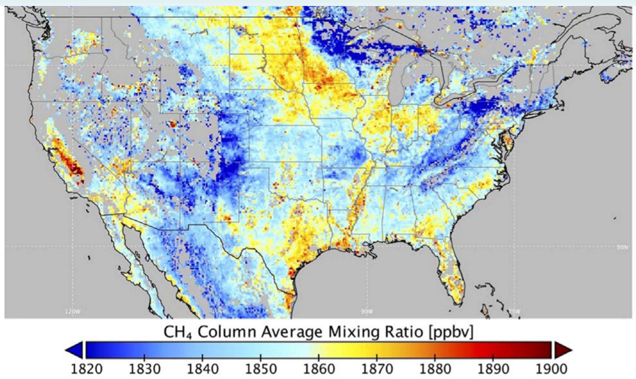


Fig.9 - Nature (2020): Average TROPOMI columns for CH4 over the United States from 1 Dec 2018 to 31 March 2019. Red areas indicate higher CH4 concentrations and blue areas indicate lower CH4 concentrations.

JAXA GOSAT-2 - Tools for trends and sectors of GHG emissions

The JAXA GOSAT series presents another important element to better understand and reduce uncertainty of climate data, especially with a link to also understanding regional changes. It aims to monitor the global distribution of GHGs (i.e. CO_2 and CH_4) at a sub-continental scale with a fairly high revisit rate (every three days) and verifying the reduction of GHGs emissions. In particular, GOSAT-2 focuses on collecting data on a sub-continental scale.

GOSAT and GOSAT-2 can observe both absorption of solar reflection and thermal radiation. These observations increase accuracy of CO_2 and CH_4 measurement, as well as accuracy on local level densities. "Leveraging these unique features, GOSAT and GOSAT-2 have been acquiring data on concentrations of CO_2 and CH_4 with their regional differences, seasonal variations and annual increase in the upper and lower troposphere" (JAXA).

Through GOSAT and GOSAT-2, JAXA has developed several different user tools such as GHGs Trend Viewer, showcasing long term trend viewer presents a quick view of CO_2, CH_4; or the Local GHG Emission Source Sectors, identifying GHG emission sources of Japan area (JAXA).

For example the GHG Trend Viewer provides a global map with regional or city-level information, based on several categories such as Aviation or Megacities (Fig.10). Fig. 11 presents an overview of the change of GHG emissions of CO_2 and CH_4 over time, starting from 2016.

Fig.12 and 13 represent products from the Local GHG Emission Source Sectors tool, which enables a concrete visual representation of local emitting sources, such as power plants or waste disposal facilities, intersected with GHG emission data, in this case CO_2.

Fig.10 - JAXA GHG Trend Viewer: Overview of datasets of GHG Trend Viewer.

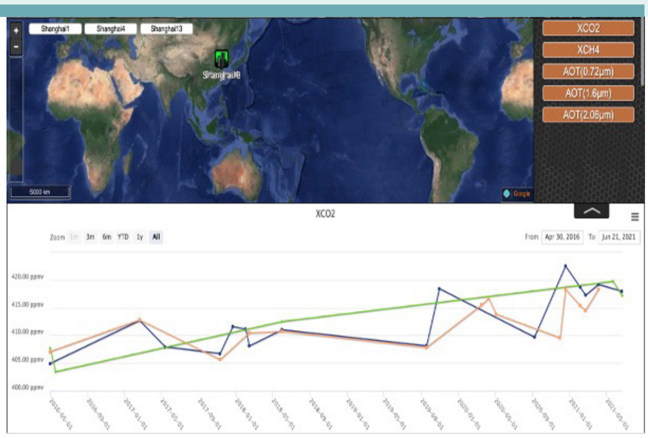


Fig.11 - JAXA GHG Trend Viewer: Overview of average increase in CO2 and CH4 since 2016 (three updates annually).

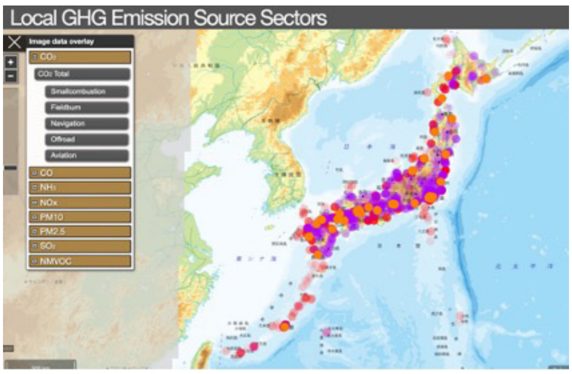


Fig.12 - JAXA Local GHG Emission Source Sectors tool: Facility Map with asset-level data of different industries, currently available only for Japan.

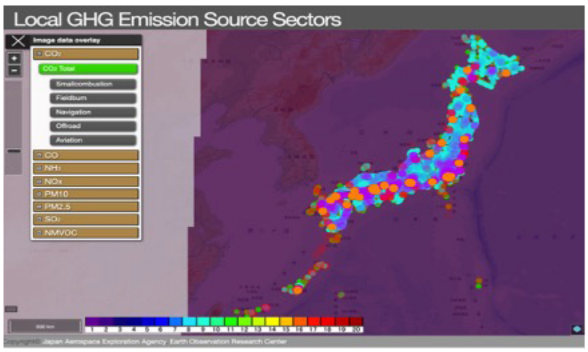


Fig.13 - JAXA Local GHG Emission Source Sectors tool: Intersection of asset-level data with total average CO2 concentration, currently available only for Japan.

Climate TRACE - A new approach to analyse existing satellite data

Climate TRACE is an initiative launched by a coalition of organizations which aims to monitor and publish GHG emissions worldwide. It aims to improve monitoring, reporting and verification of all major GHGs. The initiative is spearheaded by former United States Vice President Al Gore.

Climate TRACE highlights the utility of EO data and other state-of-the-art assessment tools to create an independent and publicly available GHG emissions database. The initiative uses artificial intelligence, visible and infrared satellite imagery, machine learning, and other remote sensing technologies to calculate and estimate global emissions data. Currently, Climate TRACE provides emission estimates for 10 sectors: power generation, forestry and land use, manufacturing, transport, agriculture, oil and gas, buildings, waste, maritime, and mineral extraction. In the future, sector coverage will expand beyond the ones currently monitored and will provide spatially and temporally granular data (Climate TRACE).

Fig.14 - Climate TRACE (2021): TRACE Places is a prototype of Climate TRACE's asset-level emission estimation tool that will provide emission data for all major emitting assets globally.

Kayrros - Building an integrated system for data processing, knowledge sharing and decision making

Complementary to EO data gathering through satellites, are new initiatives utilizing big Earth data processing capacities and the combination of different types of satellite data and ground data that allow for near-real time CO_2 and CH_4 estimations. Kayrros, a global asset observation platform, is an example to strengthen and improve the way businesses and governments currently access and utilize EO data. Kayrros focuses on "the integration of alternative and market data into unique solutions and customer product offerings while measuring environmental impact and delivering insight into climate and energy-transition risk" (Kayrros). It does so by harnessing satellite imagery, geolocation data, textual information and multiple sources of unconventional data with machine learning, natural language processing and advanced mathematics, Kayrros monitors and measures energy, natural resource and industrial activity worldwide.

For example, Kayrros Methane Watch is a monitoring platform that relies on satellite imagery and advanced algorithms to measure CH_4 emissions associated with the energy sector and other human activity, tracking CO_2 emissions in near real time and measuring changes in the carbon stock of forests.

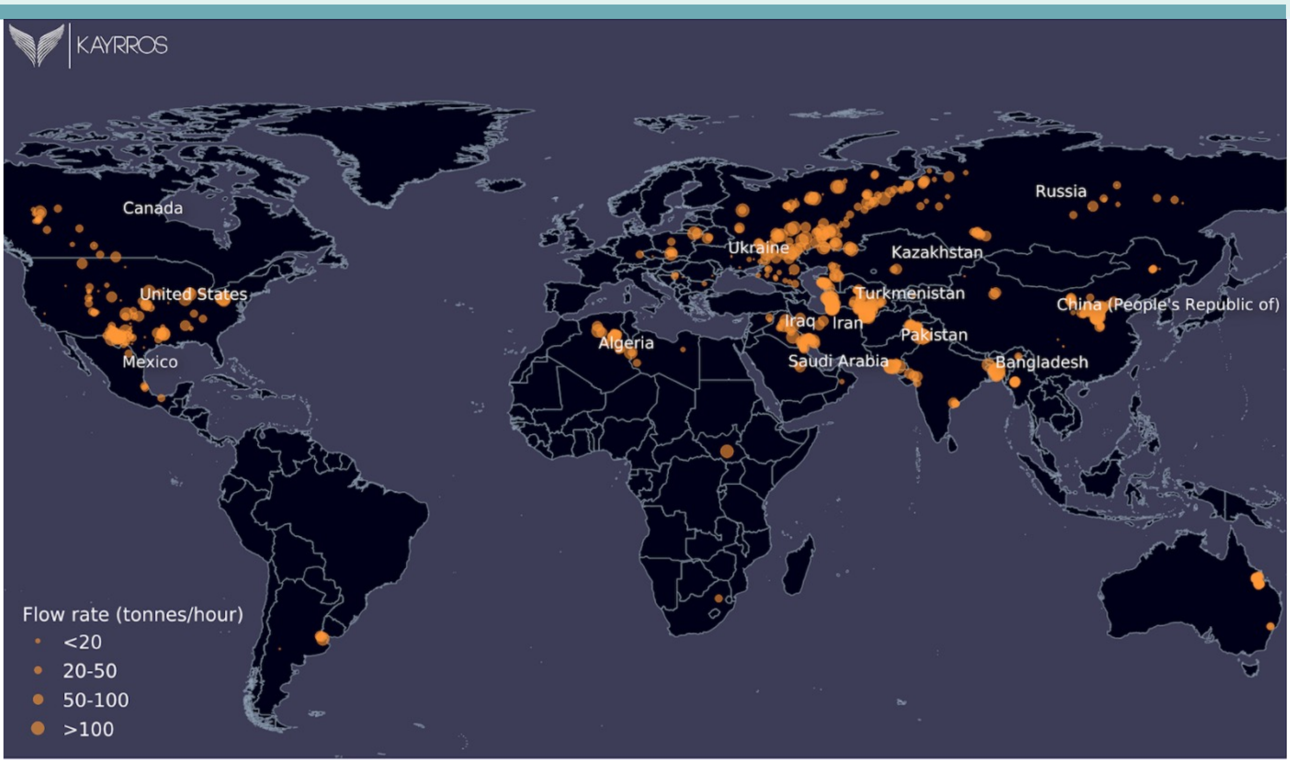


Fig.15 - Kayrros (2021): Kayrros analysis of Sentinel-5P methane data indicating flow rate at specific locations globally.

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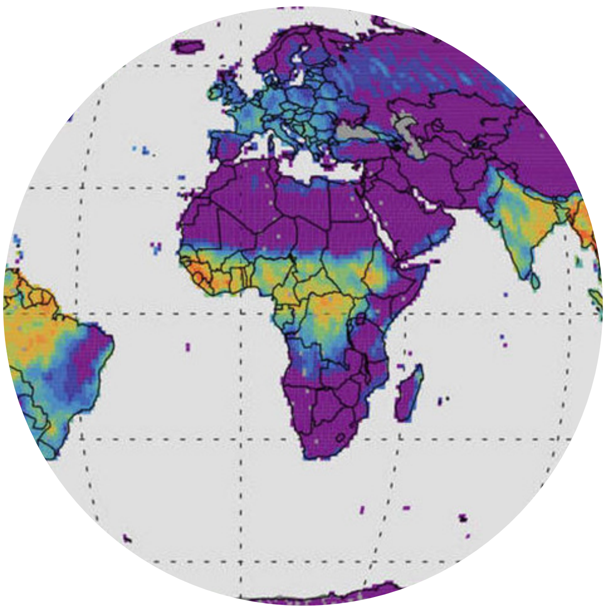
6. Conclusions and call for action

This report provides a comprehensive and objective overview of capabilities, and in doing so highlights the growing availability and accessibility of GHG data from space that have a potential to support national and global reporting underpinning climate mitigation policy.

The GST itself is at its onset where initial guiding questions have been identified to frame the process. How it will practically unfold will become clearer in the coming years. Meanwhile, it is important to continue strengthening the offerings from public and private satellite data providers, and ensure that these together match the demand from the local, national and global policy community.

The GST and the National GHG Inventories create a new demand for EO data, linking needs from policy makers for increased data monitoring on a national and global scale. As public sector missions have the capabilities to collect relevant baseline information, the private sector can potentially complement the information with actual use cases for peaks and leaks. Also, engaging with industry through existing or new partnerships is key to access first-hand data needed for a holistic understanding of and validation of satellite measurements. Furthermore, artificial intelligence and machine learning techniques can be applied to big EO data from secondary remote sensing measurements to obtain novel assessments on GHG emissions for different sectors or specific assets.

Photo credit:
NASA - OCO-3



The domain of satellite EO provides a multitude of opportunities, based on vast technical innovation, historic observations and engagement from a highly specialized expert community. Public efforts have been driving the EO agenda for many decades with the objective to better understand GHG emissions and potential impacts. We are, however, seeing more private sector investment and innovation that builds on, and complements, the benchmarks of government investment, providing essential and rapidly expanding services, which can support EO. While this domain has been dominated by scientists, engineers and technical experts - all still needed for future advancements - there remains a need for EO data, tools and applications to become more accessible for policy makers, and more integrated into decision making. This is true globally, and particularly critical for countries with limited capacity for EO data monitoring or assessment.

Public and private sector entities are urged to work together, leveraging their respective strengths in order to address the key issues associated with GHG monitoring from space. Noting that the public sector can bring a wealth of knowledge built on global data coverage, and long-term missions for data collection, as well as innovation around GHG emission monitoring. The private sector can bring capabilities with their missions: higher spatial, temporal or spectral resolution, speed to market and an integration into business processes for those needing the information. Still some capabilities may be missing or limited.

We call for continued cooperation between public and private sector entities to fully maximize complementary capacities and synergies and overcome these limitations. Innovation, finance and collaboration between the public and private sectors is already occurring to some extent in hybrid models, and will remain especially relevant to support policy makers in the race to net zero emissions going forward.

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