Earth Observation Handbook 2023

SPACE DATA FOR THE GLOBAL STOCKTAKE

Earth Observation Handbook **2023**

SPACE DATA FOR THE GLOBAL STOCKTAKE

CONTENTS

At COP 21 in Paris, on 12 December 2015, Parties to the UNFCCC reached a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future. The Paris Agreement builds upon the Convention and – for the first time – brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so. As such, it charts a new course in the global climate effort.

The Paris Agreement's overarching goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." However, in recent years, the science has stressed the need to act faster and limit global warming to 1.5°C by the end of this century.

There are many aspects to such a significant and ambitious agreement. One of which – the Global Stocktake process – has an important milestone in 2023 with the accomplishment of the first Stocktake. This process will be repeated on a 5-year cycle to assess the collective progress towards achieving the purpose of the Agreement and to inform further individual actions by Parties. Data will play a crucial role in the Global Stocktake, with it being designed to be transparent, participatory, and science-based. Countries are required to report their progress towards achieving their nationally determined contributions and their efforts to adapt to the impacts of climate change. These reports will be based on data on greenhouse gas emissions, energy consumption, and other relevant factors. The quality and accuracy of this data will be essential for assessing progress and identifying areas where further action is needed. We are also working on data tracking and accountability for voluntary action through the Global Climate Action portal, ensuring a place especially for business, investors, subnationals and civil society to be recognised for their commitments and plans.

UNFCCC has long-recognised the importance of Earth observation satellite data to the significant information challenges we face in realising the Paris Agreement. Two-thirds of the 55 Essential Climate Variables are either exclusively or largely measured by satellites. We welcome the efforts of CEOS to coordinate the space agencies of the world to unite towards this common goal and recommend this EO Handbook to stakeholders of all kinds who are engaging in the climate policy process and wish to explore how satellite data can assist them in doing so.

Simon Stiell

Executive Secretary
UNFCCC

The Earth Observation Handbook that you are now reading has been provided for key international events of relevance to satellite Earth observations for more than 30 years, since the Rio UN Conference on Environment and Sustainable Development in 1992. In 2023 our motivation is stronger than ever as the countries of the world unite under the UN Framework Convention on Climate Change (UNFCCC) to undertake the first Global Stocktake of the Paris Agreement. The Global Stocktake is very much a data-driven process, seeking to use facts on key planetary indicators and on our collective efforts to reduce greenhouse gas emissions, to inform an improved and increasingly ambitious approach to our attempts to mitigate and to adapt to climate change.

Satellite Earth observations are absolutely fundamental to the generation of the facts and figures that are the objective of the Stocktake process, providing the main source of information for many key datasets that countries, policy-makers, and scientists will seek to accumulate and reconcile. So in 2023, the space agencies of the world, represented by the Committee on Earth Observation Satellites (CEOS), have sought to provide this plain language guide to the role for space data in the Global Stocktake and the Paris Agreement more broadly. So that stakeholders of all kinds may be supported in their understanding of its relevance to their roles and obligations, and have access to further information, tools, and resources to investigate further. This includes: national agencies and experts involved in the development of emissions calculations through national inventories; the policy community, including the many UN and national and international agencies and NGOs involved in the climate policy processes; and the scientists involved in the global syntheses, assessments, and reconciliation work that will ensure the rigour and accuracy of the Stocktake.

This edition of the Handbook is for you and we hope that it supports a deep understanding of the role of satellite Earth observation data and its effective uptake and application for the Paris Agreement.

Simonetta Cheli

Chair, Strategic Implementation
Team of CEOS

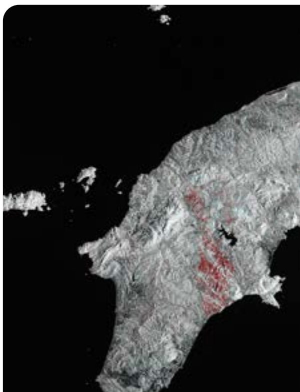
Director of Earth Observation Programmes,
European Space Agency

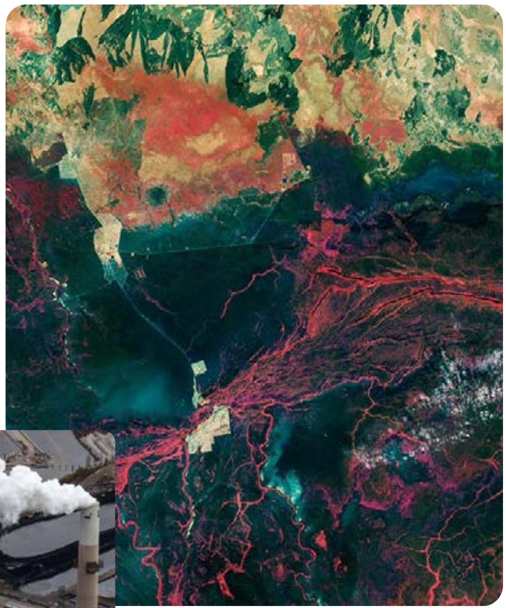
THE FIRST GLOBAL STOCKTAKE OF THE PARIS AGREEMENT IS HAPPENING THIS YEAR

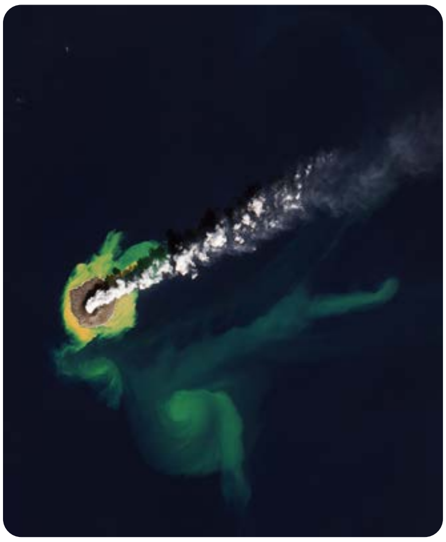
This edition of the Earth Observation Handbook is timed to coincide with this major event

This edition of the Earth Observation (EO) Handbook is timed to coincide with the first Global Stocktake (GST) in 2023 of the Paris Agreement, under the UN Framework Convention on Climate Change (UNFCCC). Its purpose is to help develop a broad understanding of the importance of satellite EO for all stakeholders in these processes. At its heart, the GST is an evidence-driven process, using data to power improved understanding of the global climate and an ambition cycle that seeks to leverage the data for increasing action by countries on the reduction of greenhouse gas (GHG) emissions.

The EO Handbook emphasises the questions faced by different user types when approaching the application of EO satellite data for their climate-related challenges and reporting obligations. The Handbook also aims to provide practical examples and leads for further investigation so that the potential of the data available from our EO satellites is fully realised. We hope to help the reader understand the power of the data, where to find it, and how to begin to learn to apply and benefit from it.







Part I explains the role of EO in support of the Paris Agreement and the GST and the different players and processes, including:

- agencies and experts involved in national GHG inventories and reporting emissions and national statistics into the GST;
- science and UNFCCC communities undertaking global assessments and reconciliation of the global picture of GHG emissions with national reports; all sectors and organisations undertaking adaptation planning and forecasting of climate change impacts;
- the finance and economic sectors and those engaged in loss and damage aspects of climate change and the Paris Agreement.

Part II comprises a range of articles by a variety of different organisation types related to the Paris Agreement and explains the role of EO data for their purposes. Each of these articles is intended to be a stand-alone narrative and they may be read in any order. It is hoped that readers might find inspiration and resources relevant to their own information needs and reporting obligations.

PART I

SPACE DATA FOR THE GLOBAL STOCKTAKE

1 THE PARIS AGREEMENT IN PLAIN LANGUAGE

If you are reading this, there is every chance that you are already familiar with the Paris Agreement and its main elements and objectives.

To achieve the goals of the Paris Agreement, we need a big-picture view of national and global greenhouse gas (GHG) emissions and the impact of mitigation and adaptation efforts. Satellite-based Earth observation (EO) is widely regarded as the most effective method to provide this synoptic view for keeping track of GHG emissions, monitoring the changes in Earth's climate over time and enabling reporting on the effectiveness of adaptation strategies.

In 2023, the first formal review of progress towards the goals of the Paris Agreement, known as the Global Stocktake (GST), will take place. EO will play a critical role in the GST process for assessing how effectively the Paris Agreement's goals are being met.

This section aims to give a brief and straightforward summary of the Paris Agreement and its key processes. It provides context for the rest of our explanation of why EO satellite data is crucial for implementing the Paris Agreement and, ahead of the 28th Conference of the Parties (COP 28) of the United Nations Convention on Climate Change (UNFCCC), as to how satellite-based EO will play a vital role in the GST process.

The Paris agreement key points

The historic pact, approved by 195 countries

Temperatures
2100

- Keep warming “Well below 2 degrees Celsius”
- Continue all efforts to limit the rise in temperatures to 1.5 degrees Celsius

Finance
2020 - 2025

- Rich countries must provide 100 billion dollars from 2020, as a “floor”
- Amount to be updated by 2025

Differentiation

- Developed countries must continue to “take the lead” in the reduction of greenhouse gases
- Developing nations are encouraged to enhance their efforts and move over time to cuts

Emissions Objectives
2050

- Aim for greenhouse gases emissions to “peak as soon as possible”
- From 2050: rapid reductions to achieve a balance between emissions from human activity and the amount that can be captured by “sinks”

Burden Sharing

- Developed countries must provide financial resources to help developing countries
- Other countries are invited to provide support on a voluntary basis

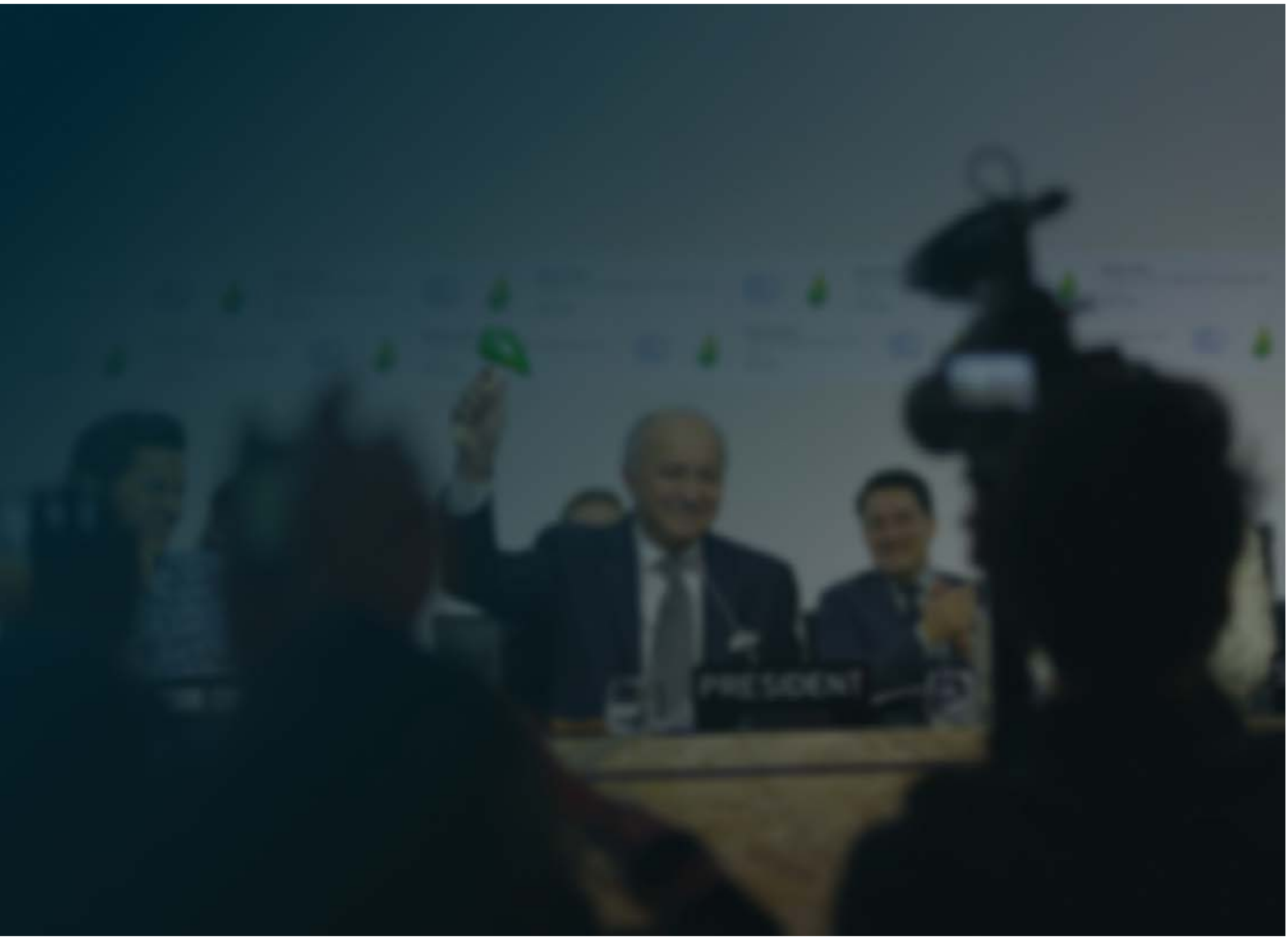
Review Mechanism
2023

- A review every five years. First world review: 2023
- Each review will inform countries in “updating and enhancing” their pledges

Climate Damage

- Vulnerable countries have won recognition of the need for “averting, minimising and adressing” losses suffered due to climate change

Figure 1: Key points of the Paris Climate Agreement which will be reviewed every five years.



THE FACTS ABOUT THE PARIS AGREEMENT

To minimise further negative human impacts on climate change (and the loss and damage they cause), countries have agreed to set ambitious targets for reducing global GHG emissions under an international treaty known as the Paris Agreement.

The Paris Agreement was negotiated and agreed to at the COP 21 of the UNFCCC in Paris on 12 December 2015. It entered into force on 4 November 2016, as a legally binding treaty. Currently, 195 parties (194 States, and the European Union) have joined the Paris Agreement, accounting for 98% of global GHG emissions.

It seeks to achieve a balance between GHG emissions (sources) and removals (sinks) through three main purposes:

Mitigation: Mitigate the effects of climate change by keeping global temperature change below 2°C and limiting any change to 1.5°C above pre-industrial levels.

Adaptation: Increase adaptation and resilience to adverse climate change impacts.

Means of Implementation: Use fiscal policy and investment to support the implementation of low GHG emissions technology and climate-resilient development.

Why is the Paris Agreement Important?

The evidence for human-induced climate change is overwhelming and has been extensively studied and documented by scientists over the past few decades.

The Intergovernmental Panel on Climate Change (IPCC) has released several reports, the latest being the Synthesis Report for the 6th Assessment in 2023, which unequivocally states that human-related emissions of greenhouse gases (GHGs) are causing a warming world.

This latest IPCC report shows that if we rely on policies implemented to date, or current nationally determined contributions out to 2030, it will not be possible to limit global warming to 1.5 degrees, and possibly not even 2 degrees.

Urgent action is needed to reduce GHG emissions and mitigate the impacts of climate change. **The Paris Agreement is the mechanism to bring about this change.**

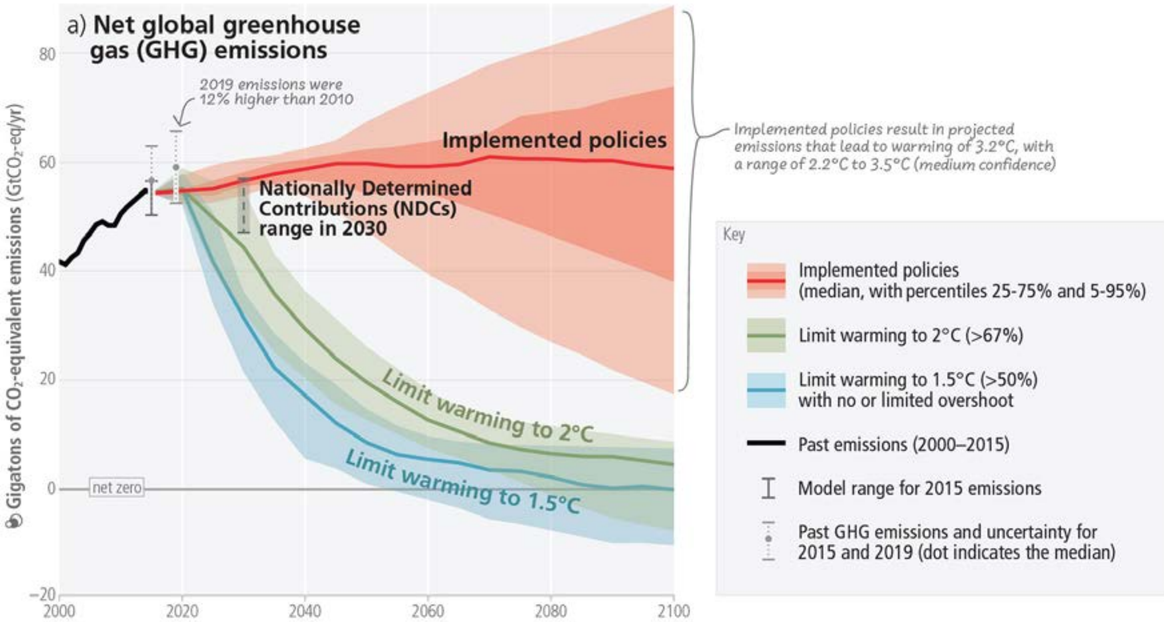


Figure 2: Net Global Greenhouse gas (GHG) emissions (IPCC 6th Assessment Report, Summary for Policy Makers)

Countries signed the Paris Agreement with the goal of capping human-induced temperature rises and limiting future climate change. Under the Agreement, this will be achieved by global peaking of GHG emissions as soon as possible, minimising further increases in global temperatures, and associated loss and damage.

Climate change is already causing significant economic (e.g., assets, resources, goods or services that are traded in markets) and non-economic (e.g., livelihoods, human health, territory, culture, biodiversity) loss and damage (IPCC, 2013).

Loss and damage are caused by climate change increasing the frequency of events that are either fast-onset (e.g., heatwaves, extreme rainfall, tropical cyclones, droughts, floods, and wildfires) or slow-onset events (e.g., desertification, glacial retreat and related impacts, land and forest degradation, loss of biodiversity, ocean acidification, salinisation, increasing temperatures and sea level rise), the full impact of which can be just as detrimental as sudden-onset events, but can take decades to fully manifest.

Seven key indicators all point towards the accelerating impacts of climate change

Earth observations from satellite are essential in monitoring all seven of these indicators of global warming

1	Increasing global mean surface temperature causing heatwaves, droughts, and wildfires in many parts of the world.
2	Increasing ocean heat content causing sea levels to rise and disrupting marine ecosystems.
3	Increasing ocean acidification caused by the absorption of CO_2 by seawater, which leads to a decrease in pH levels. This decrease in pH levels is harmful to marine life, particularly organisms that rely on calcium carbonate to build their shells and skeletons.
4	Reductions in glacier mass, caused by the warming temperatures. Glaciers are important sources of freshwater for many communities, and their melting is causing water shortages in many parts of the world.
5	Increasing atmospheric CO_2 leading to increasing temperatures.
6	Rising sea level caused by the thermal expansion of seawater and the melting of glaciers and ice caps.
7	Reduction in both summer and winter sea ice extent causing changes in the Arctic ecosystem, rising sea levels and affecting the livelihoods of indigenous communities.

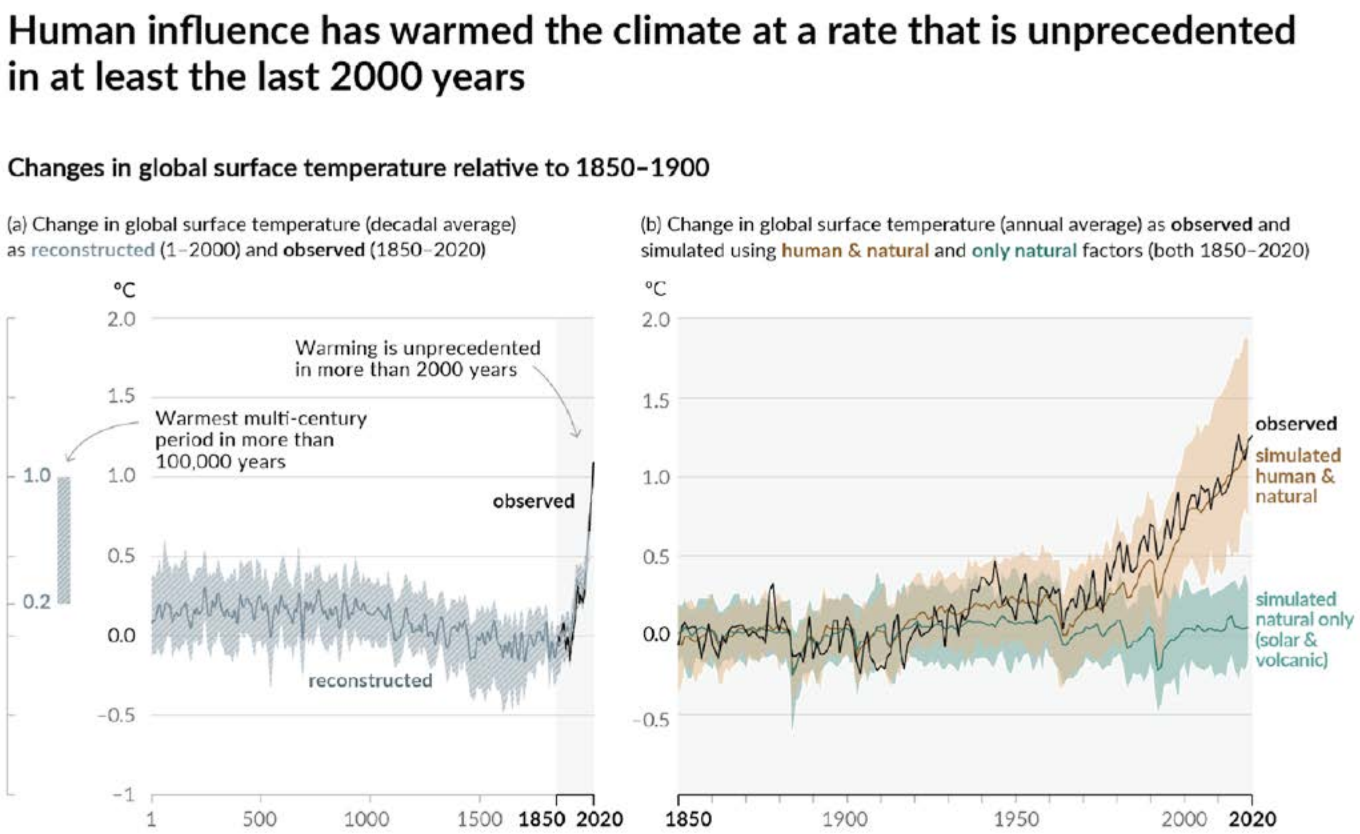


Figure 3: Changes in global surface temperature relative to 1850 - 1900 (IPCC 6th Assessment Report, Summary for Policy Makers)

HOW DOES THE PARIS AGREEMENT WORK?

The Paris Agreement implements an Enhanced Transparency Framework (ETF) with the benefit of providing a single approach to reporting emissions for all signatory countries commencing in 2024. Recognising countries have different capacities for reporting, the ETF allows each country to define its targets based on its circumstances and, the UNFCCC Global Stocktake process offers flexibility and guidance for developing countries in reporting. The primary ambition of the Paris Agreement and the timeframes for each part of the cycle are presented in the diagram below.

The Paris Agreement mandates that countries make 5-year pledges on emissions reductions, described in their Nationally Determined Contributions (NDCs), and report their emissions every 1–2 years in biennial or annual transparency reports.

Particular consideration is given to developing nations, where a longer time frame is expected before reducing GHG emissions can occur. Capacity development is also required in these nations to assist with technology for reporting and reducing GHG emissions. Finance flows are also necessary from external sources to support a reduction in GHG emissions, adaptation and resilience. In these countries, while reporting is voluntary, the majority have already submitted their first biennial report under the Enhanced Transparency Framework (ETF).

The GST will evaluate progress and trends related to the Agreement's objectives on a global scale, every 5 years. It is an evolving tool that aims to assess progress and aid countries in achieving their national climate commitments.

The initial GST is scheduled to be completed in 2023 and will be the highlight of the COP 28 meeting in Dubai, United Arab Emirates, on 30 November to 12 December 2023.

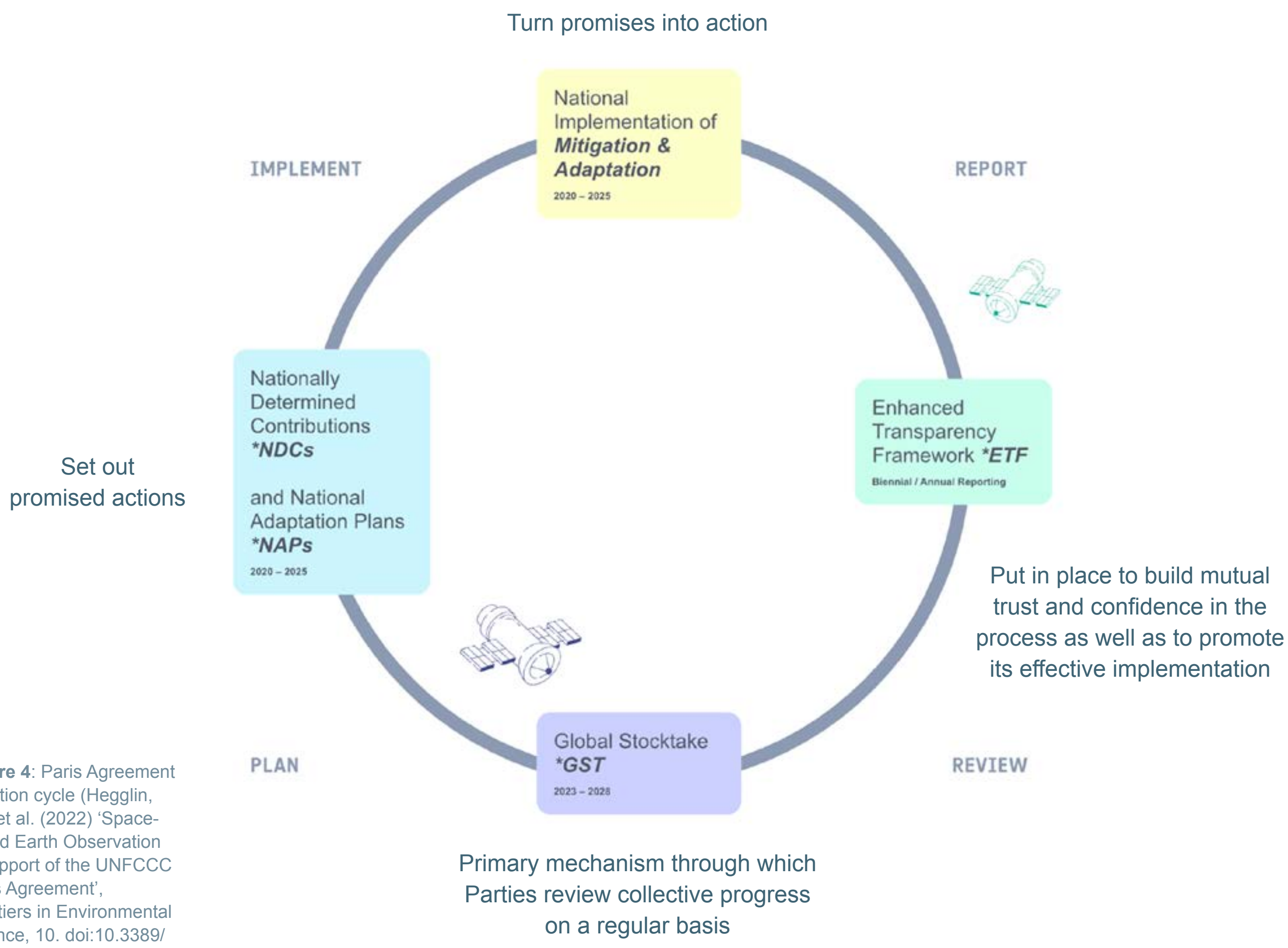


Figure 4: Paris Agreement ambition cycle (Hegglin, M.I. et al. (2022) 'Space-based Earth Observation in support of the UNFCCC Paris Agreement', Frontiers in Environmental Science, 10. doi:10.3389/fenvs.2022.941490)

MITIGATION

Parties to the Agreement are required to report on anthropogenic emissions for seven GHGs, including carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride. Developing countries must also report fluorinated gases (also known as F-gases) in their NDCs. Reporting guidelines are based on the Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines and IPCC Refinement 2019, which leverages technologies such as satellite-based EO. GHG emissions need to be reported across the Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU) and Waste sectors.

Emissions reporting typically involves a bottom-up approach, which estimates the emissions of individual activities by applying country-specific emission factors (EFs) based on the emissions typically produced by those activities. In some countries, a top-down approach is also included in reporting. This involves measuring emissions from observations such as space-based observations of GHG concentrations or modelling used to inversely estimate emissions from observed concentrations of GHGs in the atmosphere.

ADAPTATION AND RESILIENCE

The Paris Agreement emphasises the significance of adaptation measures taken by countries to counter the effects of climate change that are already happening or are anticipated. Effective adaptation includes building resilience against climate impacts, reducing vulnerability to climate hazards, and building capacity to respond to the anticipated effects of climate change. The Agreement also advises countries to develop and implement National Adaptation Plans (NAPs), outlining their strategies for mitigating and adapting to climate change.

MEANS OF IMPLEMENTATION (FINANCE, TECHNOLOGY TRANSFER AND CAPACITY BUILDING)

The Paris Agreement acknowledges the universal challenge of adaptation that necessitates international collaboration and assistance, particularly for developing countries. It recognises the need for financial flows to support the transition to a low-carbon economy and to help developing countries adapt to the impacts of climate change. Developed countries have committed to providing financial resources to developing countries to support their efforts to tackle climate change through the Green Climate Fund (GCF). Additionally, the Paris Agreement calls for the mobilisation of private-sector funding and the scaling up of climate finance flows.

2 THE ROLE OF EO FOR THE PARIS AGREEMENT AND THE GLOBAL STOCKTAKE

Satellite data has revolutionised how we understand the Earth as an integrated system, especially for climate.

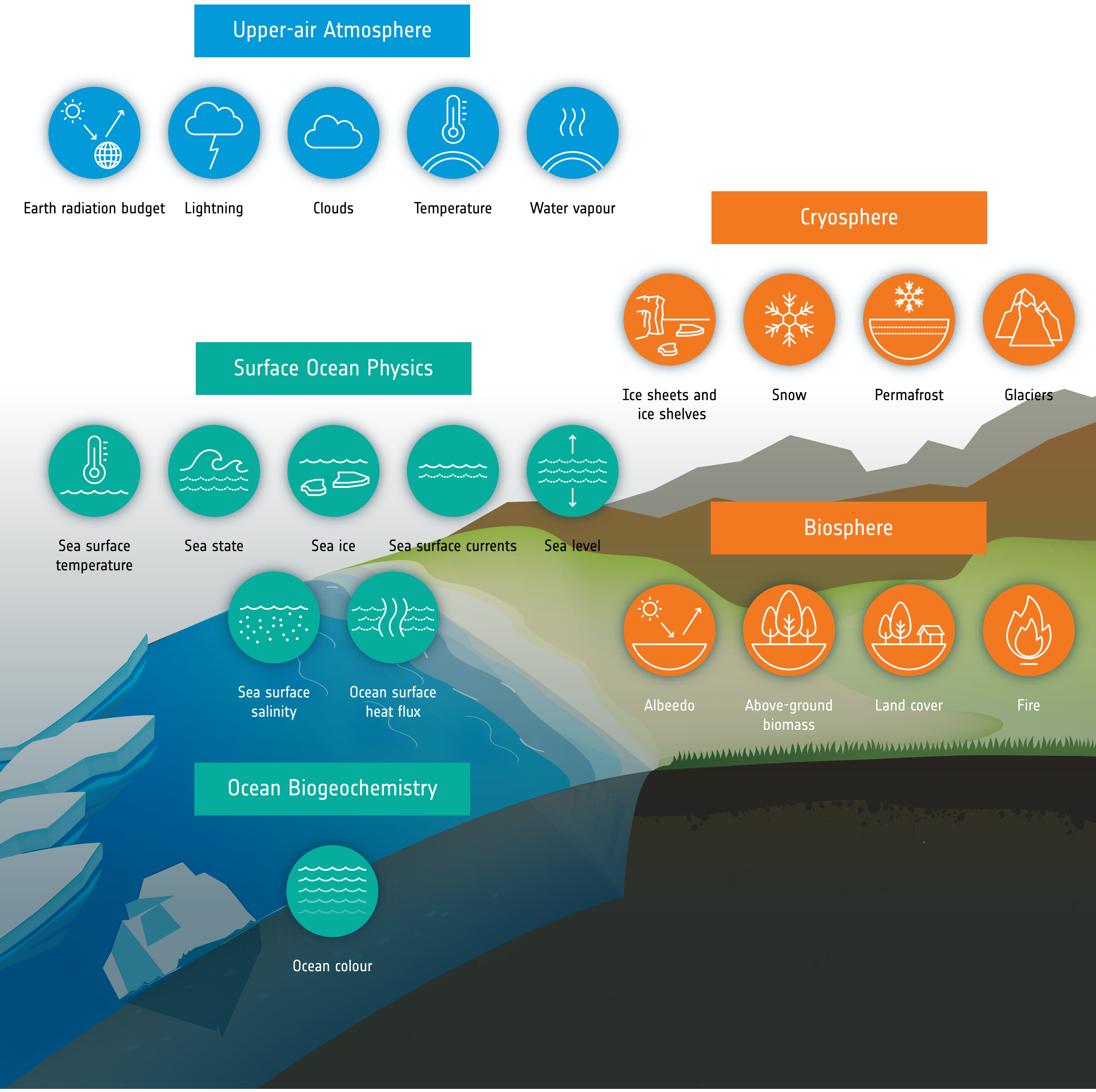
Satellites and complementary in-situ networks provide the global coverage needed to observe and document worldwide climate change. Satellite systems offer crucial insights on: agriculture and food security; El Niño and its impacts including floods and drought; deforestation and forest fires; urban development; sea ice and ice sheets; weather phenomena, extremes, and hazards such as cyclones; atmospheric composition including the ozone hole and greenhouse gases; solar fluctuations; snow and sea ice cover changes including in our polar regions; glacier changes; volcanic activity; tectonic plate motion and more.

SATELLITES AND THE ESSENTIAL CLIMATE VARIABLES

In order to monitor and fully understand the changing climate, we must observe key facets of the climate system on a sustained basis. The Global Climate Observing System (GCOS) is the authoritative source of scientific information and advice on global climate observational system requirements to inform processes and stakeholders

GCOS Essential Climate Variables

Space agencies provide data records for around two thirds of the 55 ECVs.



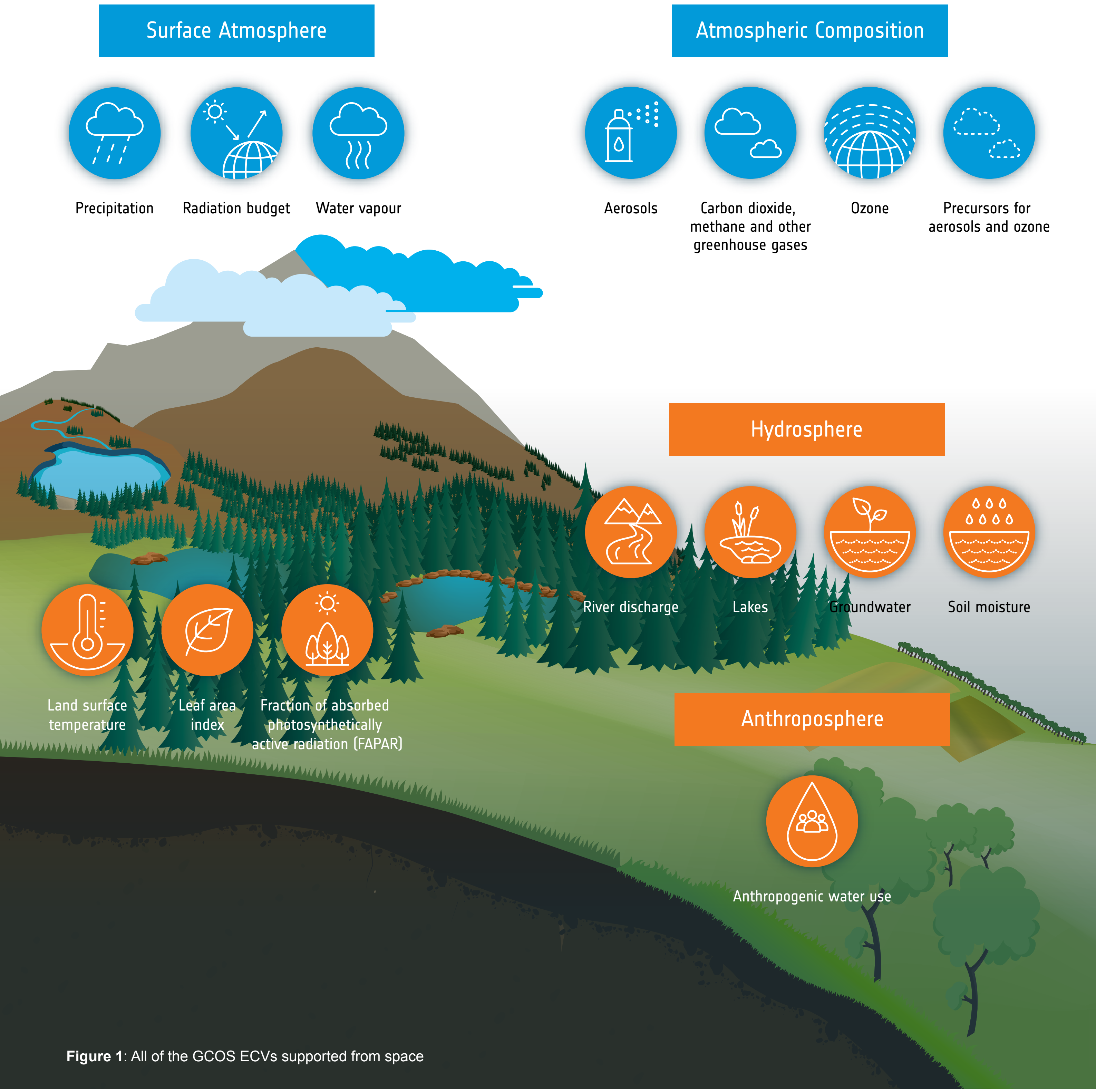


Figure 1: All of the GCOS ECVs supported from space

such as United Nations Framework Convention on Climate Change (UNFCCC), World Meteorological Organisation (WMO), Intergovernmental Panel on Climate Change (IPCC), and the global mitigation and adaptation communities. Its activities over the past 30 years have led to demonstrable improvements in the global observing system and the improved availability of observations to underpin climate science and climate applications in support of society.

To clearly present climate observational needs, GCOS has developed the concept of Essential Climate Variables (ECVs). An ECV is a physical, chemical or biological variable (or group of linked variables) that critically contributes to the characterisation of Earth's climate. These datasets offer the empirical evidence required to understand, predict, and mitigate climate change. GCOS has identified 55 ECVs, out of which satellite observations contribute to 38, with some being entirely dependent on them. Hence, the consistent, systematic, long-term data streams from satellite observations form the bedrock of climate science.

Significant efforts are underway within space agencies to develop and sustain the fundamental climate data records required to meet the information needs defined by GCOS. Examples include: the Climate Change Initiative of ESA; the EUMETSAT Climate Monitoring Satellite Application Facility (CM SAF) that generates high quality climate data records from long records of operational weather forecasting satellite information; the National Oceanic and Atmospheric Administration (NOAA) Climate Services Portal

The ECV Inventory

The Joint Committee on Earth Observation Satellites (CEOS)/Coordination Group on Meteorological Satellites (CGMS) Working Group on Climate (WGClimate) has been maintaining an ECV Inventory with inputs from many CEOS and CGMS space agencies. The ECV Inventory provides a comprehensive view of the systemic availability of Climate Data Records (CDRs) that are currently available and are being planned for the future from satellite missions of CEOS and CGMS members. It also assesses the compliance of satellite derived CDRs with the requirements defined by GCOS. The inventory is updated annually to provide the users with more up-to-date information, and to support gap analysis exercises. The latest version (V4.1) of the ECV Inventory contains 1251 fully verified CDRs, addressing almost all space observable GCOS ECVs.

The ECV inventory is a unique compendium that links CDRs to satellite instruments and space architecture and can be used by space agencies for mission planning to respond to the observational gaps identified by GCOS, UNFCCC, etc. It provides the status of the space observations and is a searchable library for users to identify available CDRs for each GCOS ECV. Data access is globally free and open without any constraint for more than 98% of the data records in the Inventory.

The inventory can be assessed at: https://climatemonitoring.info/ecvinventory/.
For any questions, please contact ecv_inventory@eumetsat.int.

10217		Atmosphere	Surface wind speed and direction	Surface wind speed and direction	Wind vector over ocean surface (horizontal)	Existing	EUMETSAT
10218		Atmosphere	Water vapour	Tropospheric and lower-stratospheric profiles of water vapour	Tropospheric and lower-stratospheric profiles of water vapour	Existing	NASA
10219		Atmosphere	Water vapour	Total column water vapour	Total column water vapour	Existing	NASA
10220		Atmosphere	Aerosol properties	Aerosol optical depth	Aerosol optical depth	Existing	ESA
10221		Atmosphere	Surface wind speed and direction	Surface wind speed and direction	Wind vector over ocean surface (horizontal)	Existing	EUMETSAT

Figure 2: Sample data entries from the ECV Inventory (https://climatemonitoring.info/ecvinventory/)

(climate.gov, including their climate dashboard that features a number of the ECVs) and extensive archives maintained by NASA in the US; as well as the Copernicus Climate Change Service (C3S), implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Union, and by JAXA in Japan - amongst others.

SATELLITES AND THE PARIS AGREEMENT

EO potentially provides valuable information on five out of seven of the most important objectives of the Paris Agreement, namely:

- mitigation;
- maintaining sinks and reservoirs;
- adaptation;
- protecting against loss and damage;
- capacity building.

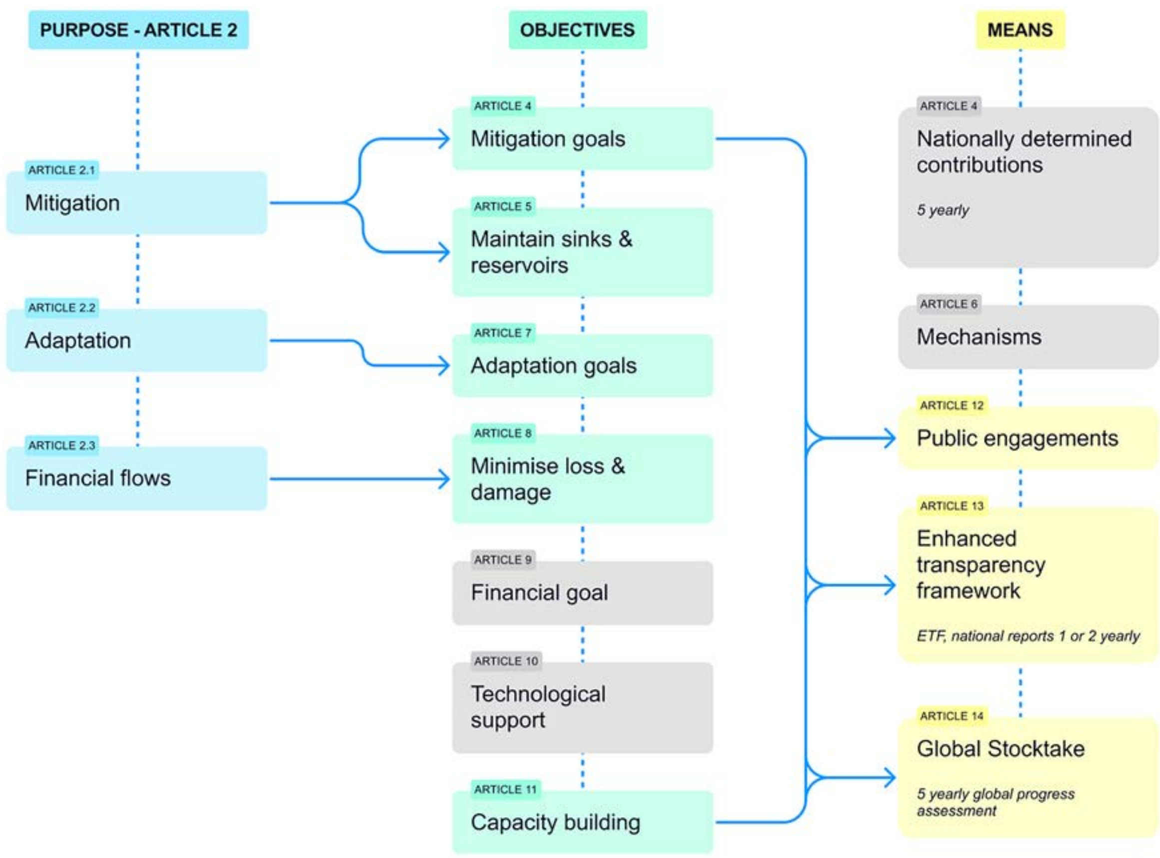


Figure 3: Where satellite EO can support the Paris Agreement. Contributions are shown in green for the Agreement objectives and in yellow for the Agreement means of implementation.

The contribution of satellite EO in relation to each of the Paris Agreement objectives and activities is elaborated in the following sections of this report and summarised in this table.

Element of the Paris Agreement	Opportunities for satellite data and derived products
Mitigation	Satellite measurements of surface and atmospheric temperatures provide the primary means of tracking increases in the global average temperature. Observations of atmospheric GHG concentrations can be analysed to track trends in their net emissions and removals, in accordance with the best available science.
Adaptation	Systematic observations are the foundation of a climate services value chain that connects observations to decision-making to support mitigation and adaptation action. Through this value chain, systematic observations provide the data that underpin climate models, forecasts on various timescales, and tailored products and services in support of mitigation and adaptation decision-making. Systematic observations of the Earth thus provide the scientific basis for identifying climate hazards and impacts and for designing, implementing and tracking the performance of adaptation investments and strategies.
Updating Nationally Determined Contributions (NDCs)	Satellite estimates of biomass can be used to provide quantitative targets and to derive GHG targets from non-GHG targets such as forest cover changes.
Reducing emissions from deforestation and forest degradation in developing countries (REDD+)	Estimation of activity data (land area change, AD) and emission/removal factors (biomass change, EF/RF) for establishing forest reference levels (FRLs) and report REDD+ results in a technical annex to the Biennial Transparency Report (BTR) in the context of accessing results-based payments. Assessment of drivers of forest changes and corresponding carbon fluxes for REDD+ strategies. Independent data sources for comparison by the assessment teams/ UNFCCC LULUCF experts or to constraint the estimates by the Party (verification).

Given the multiple ways in which satellite EO supports the Paris Agreement and its GST, they are relevant to the activities and obligations of a large number of participants and stakeholders in the process, including: **national agencies** responsible for GHG inventories and reporting to the UNFCCC; **scientific and UN bodies** undertaking assessments and synthesis on the state of the overall climate and its trends; **all participants to the GST process** including for the reconciliation of top-down global observations with the cumulative national reports and any ongoing differences.

Element of the Paris Agreement	Opportunities for satellite data and derived products
National reporting under the enhanced transparency framework (ETF)	High spatial resolution observations of land cover type, above-ground biomass and disturbances associated with fires, droughts, and severe weather can provide direct support for the development of bottom-up emissions inventories for agriculture, forestry and other land use (AFOLU). Estimation of carbon emissions and removals from forests, and non-forest areas with significant woody biomass (i.e., cropland/grassland) in the GHG inventory (GHGI) and BTRs (including AD and EF/RFs for all categories), and to track progress of the quantitative indicators of the NDCs. Supporting tools for Parties with lower Measurement, Reporting and Verification (MRV) capacity who will need to adapt to the more stringent reporting rules (previous non-Annex I Parties). Independent data sources for verification and to support assessment teams in the technical expert review of BTRs
Global Stocktake (GST)	Contribution to inputs to each cycle of the GST (taking place every five years), and its collective view on progress to achieve the objectives of the Paris Agreement, through country-Party submissions and independent estimates by non-Party stakeholders. Top-down budgets of GHG emissions and removals derived from atmospheric measurements can be used to assess the completeness and transparency of the bottom-up methods used to compile the biennial inventory reports.
Loss & Damage	Systematic observations are the foundation of operational climate services that can identify emerging climate hazards at sub-national to national scales and forecast their evolution on daily to decadal time scales to meet the goals of the Paris Agreement. Operational hydro-meteorological systems and services founded on systematic observations are proven technologies that assist to reduce loss and damage, strengthen resilience and reduce the overall vulnerability to climate change, contributing to the Means of Implementation objectives of the Agreement. Free and open access to these observations also supports the enhanced transparency framework.

Table 1: Examples of key uses and opportunities for satellite EO products in the core elements of the Paris Agreement (Source: Melo et al)

3 Phases of the Global Stocktake

As outlined in the Paris Rulebook, the GST will be carried out in three distinct phases, shown in Figure 4:

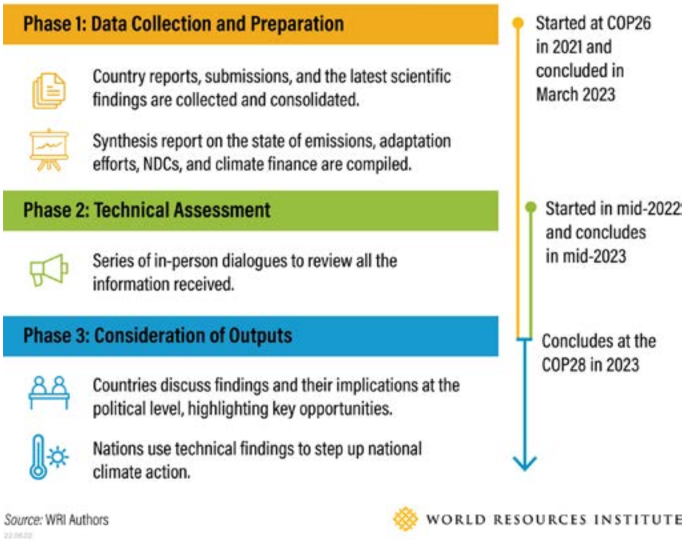


Figure 4: Phases of the Global Stocktake

1. **Information collection and preparation (2020-2021)**
   The UNFCCC will consider various sources of input, includind NDCs, scientific studies, country reports, tailored national submissions, and contributions from the systematic observation community, for the Global Stocktake (GST) in 2020-2021. Multiple synthesis reports will be prepared to inform the technical assessment.

2. **Technical assessment (2022-2023)**
   A technical dialogue will be organized to assess collective progress towards the PA's purpose and long-term goals, with a focus on three themes: mitigation, adaptation, and means of implementation and support. Other cross cutting themes may also be taken into account.

3. **Consideration of outputs (2023)**
   The COP will host this stage during the year of the stocktake, specially in 2023 and every five years following. The technical assessment findings will be presented at high-level events during this phase. It will summarize key political messages, good practices, and identify opportunities for enhancing action and support, as well as challenges.

SATELLITES AND THE GLOBAL STOCKTAKE

The GST is an essential tool to ensure that globally the Paris Agreement is on track to achieve its objectives by holding countries accountable for their NDCs and National Adaptation Plans (NAPs). It will also serve as an evidence base for scaled-up action where globally we are currently underperforming in the action needed to meet the Paris agreement goal of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. The initial GST is scheduled to be completed in 2023 and will be the highlight of the 28th COP meeting in Dubai, United Arab Emirates, in late 2023.

EO can assist in providing the evidence base for submissions under the GST. Broadly speaking, EO provides the evidence for monitoring, reporting and verification that is needed in the GST across **mitigation, adaptation and means of implementation**. It is an objective and independent data source that is able to provide the global picture, not constrained by country borders. Consistent, systematic, long-term data streams are the foundation of climate science. National and international research centres, universities, meteorological organisations, space agencies and intergovernmental and United Nations organisations are gathering and analysing all types of environmental data from local to regional and global scales, gathered by ground-based, airborne and space-based sensors.

EO IN SUPPORT OF MITIGATION

To support the first GST, Parties to the Paris Agreement are compiling national inventories of GHG emissions and removals from sectors defined in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. These sectors include Energy, Industrial Processes and Product Use (IPPU), AFOLU, and Waste. Each sector is subdivided into categories. For example, land uses (Forest, Cropland, Grassland, Wetlands, Settlements, and Other Land) are categories within the AFOLU sector.

For each sector and category, emissions and removals of GHGs are usually estimated in the GHG National Inventories by multiplying activity data by emission factors or modelling. For example, for the Energy sector, the activity data might indicate the number of tonnes of coal delivered to power plants while the emission factor specifies the expected number of tonnes of carbon dioxide (CO_2) or methane (CH_4) emissions produced per tonne of coal.

AFOLU

In the AFOLU sector, the activity data might specify the number of hectares of forest converted to cropland, while the emission factor specifies the loss of biomass carbon per hectare from that conversion. These methods usually provide accurate estimates of CO_2 emissions from fossil fuel use, but can have large uncertainties in other sectors, such as AFOLU and Waste. They aim to capture only the emissions and removals of GHGs resulting from human activities. The AFOLU sector is responsible for just under a quarter of anthropogenic GHG emissions, mainly from deforestation and agricultural emissions from livestock, soil and nutrient management (IPCC, 2014).

EO satellites have been acquiring data on the state and dynamics of the global landscape for over 40 years. The IPCC Special Report on Climate Change and Land, which highlights the multiple interactions between climate change and land use and the social dimensions of land degradation, desertification and food security in a changing climate, also references the strengths and limitations of EO data. The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories referred to the significant advancement of the use of EO data for monitoring land use and land change. The IPCC AR6 WGI report indicates that under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere. Because climate change can reduce the efficiency of land sinks, mitigation activities focused on AFOLU must include efforts to enhance the resiliency of these sinks.

CEOS has developed an AFOLU Roadmap to identify the substantive benefits of using Earth observation data and to provide the related satellite products in a form that addresses the needs of the policy community. A key focus of the CEOS effort to contribute to the land sector of GST is to ensure that the land data products derived from space-based EO are complete and accurate. Their EO satellite sensors operate in different domains of the electromagnetic spectrum (primarily optical, radar, thermal and lidar) and provide information on one or more properties of agriculture, forests and vegetation biomass. The primary expected outcome of the CEOS AFOLU efforts is an enhanced uptake of EO satellite data sets in support of the GST process on a global and country level. This new information should be of particular value to the developing world, where nations have less capacity to develop detailed bottom-up inventories and AFOLU is often the largest source of GHG emissions. It should also become increasingly important over time as fossil fuels are phased out and we approach a balance between anthropogenic emissions and removals.

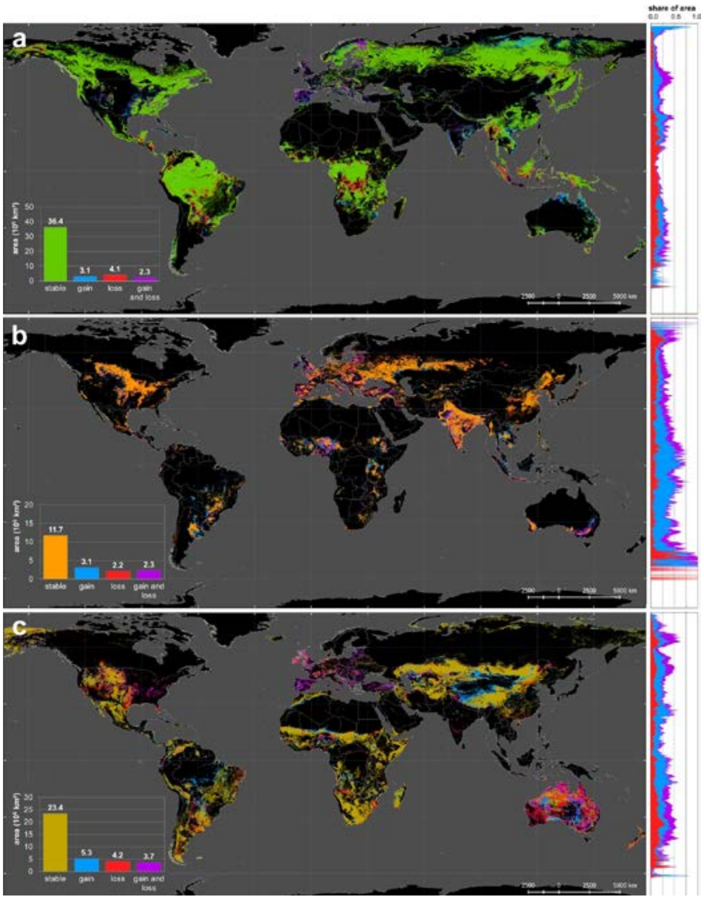


Figure 5: Global land cover change from 1960-2020 for (a) forest, (b) cropland and (c) Pasture and Rangeland and change (gain and loss) between 1960 and 2019 (derived from HILDA+ data, Winkler et al., 2021).

GHG MEASUREMENTS

The following sections and the case studies in Part II describe in detail the current state-of-the-art in top-down atmospheric GHG measurement and analysis methods and how they are being used to track trends in atmospheric GHG concentrations and to create budgets of net emissions and removals on local, national and global scales. Pilot, top-down budgets have been developed at national scales to encourage their use in GHG inventory development and assessment for the first GST.

Approaches to National Inventories of GHG Emission and Removals: Top-Down and Bottom-Up

There are two main approaches to monitoring greenhouse gas (GHG) emissions and removals: top-down and bottom-up. The bottom-up method uses the IPCC Guidelines to require annual reports of emissions and removals in specific sector and categories.

The top-down approaches involves time-resolved measurements of atmospheric CO_2 and CH_4 concentrations meadured from space, or derived by inversion modelling.

While bottom-up approach provide detailed insights into sector-specific emisions and removals, top-down approaches offer a broader, national-level overview of the largest sources and sinks of CO_2 and CH_4.

One significant advantage of top-down atmospheric measurements is the potential for transparency. Public and private sector missions collect the data, which is made freely available on publicly accessible archives. Although the analysis of this data is complex and computationally expensive, collaborative efforts by science teams around the world are working to assess the trade-offs between different methods. As a result, the value and transparency of top-down atmospheric emissions products will continue to increase.

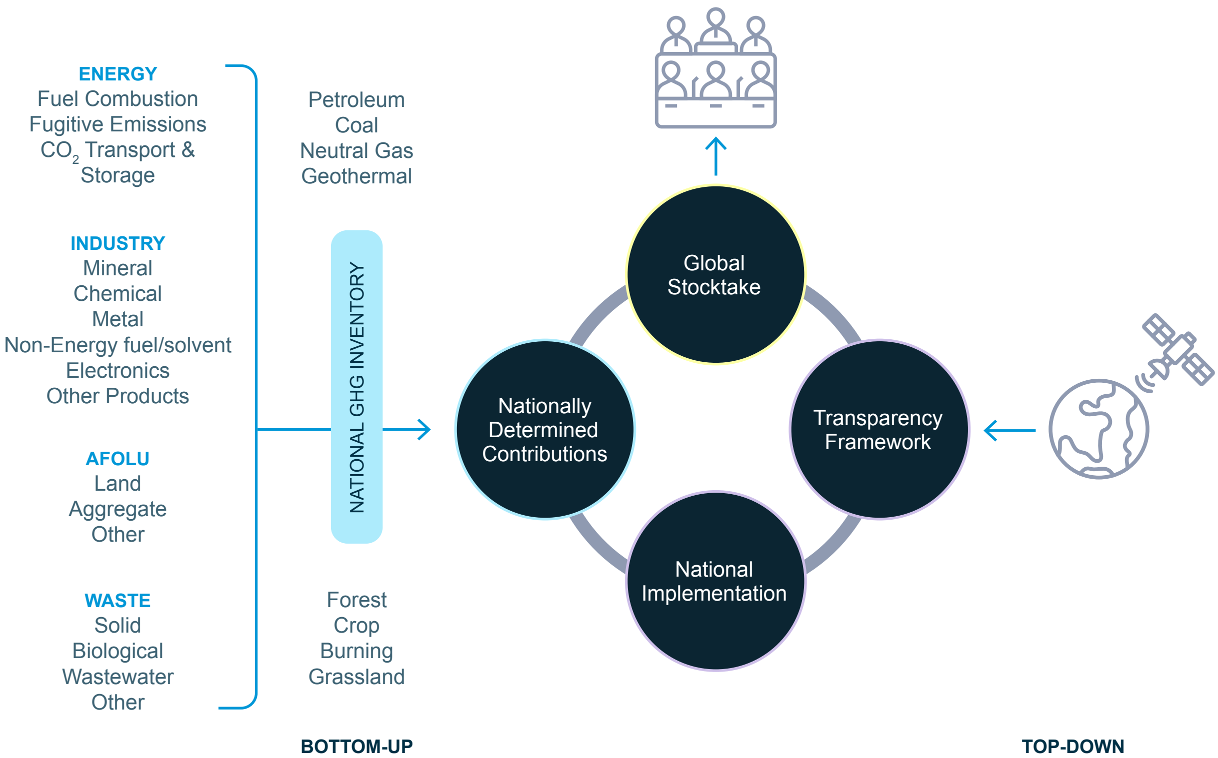


Figure 6: Bottom-up GHG inventories and top-down atmospheric GHG budgets provide independent information supporting the GSTs. (The Role of Systematic Earth Observations in the Global Stocktake, Version: 28 February 2022)

BIOMASS

Using data from space-borne instruments is the most efficient, reliable, and transparent method to estimate aboveground biomass (AGB) for accurate global carbon stock and change estimation. However, there are discrepancies in AGB estimates from different space data, methods and reference plot-level forest data. Global space agencies and researchers, coordinated by CEOS, are breaking new ground in aligning space-based AGB map estimates to inform national and sub-national reporting through the initiative of Biomass Harmonization:

1. A suite of products, including global AGB maps and continental maps, are displayed and comparable on the Biomass Harmonisation Dashboard (https://earthdata.nasa.gov/maap-biomass/). The science teams of these products are in dialogue to align on underlying definitions, assumptions and reporting of uncertainty estimates.
2. GEO-TREES is a parallel initiative that aims to establish high-quality global Biomass Reference Measurement sites with standardised and transparent measurement protocols to enhance space-based forest AGB estimation.

New products and EO satellites are expected to come online in the next half a decade that will significantly improve AGB estimates, however, harmonisation efforts and guidance on the use of these products will still be needed to ensure consistent and accurate AGB reporting for the UNFCCC GST.

AGRICULTURE

The AFOLU community is still in need of a system that can provide seasonal global agricultural monitoring information at field level. For this reason, the European Space Agency, in collaboration with stakeholders in global agriculture like GEOGLAM, FAO and AMIS, has initiated the WorldCereal project to demonstrate the feasibility of producing seasonal update cropland and crop type maps based on open and free data. The open source European Space Agency (ESA) WorldCereal system provides global seasonal updated maps for 2021 at 10m resolution based on Copernicus Sentinel-1 and Sentinel-2 and Landsat 8 data. The WorldCereal system produces 4 hierarchical products.

The WorldCereal crop type products provide binary

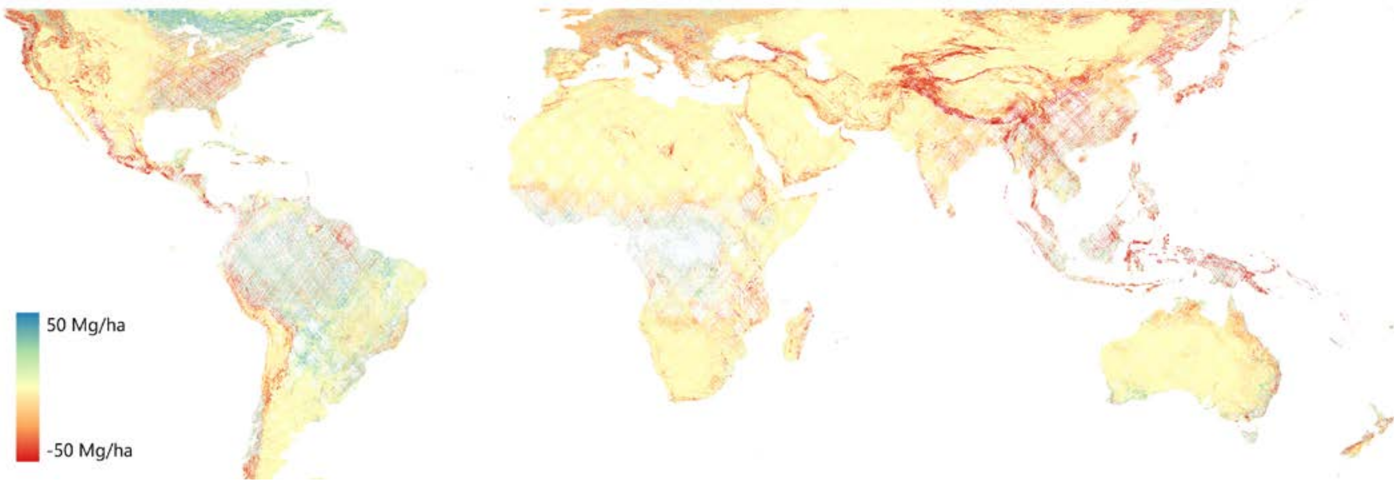


Figure 7: Difference in the aboveground biomass density (i.e. Mg/ha) estimated between two key satellite-derived global datasets: the ESA CCI Biomass 2020 v4product and the GEDI L4B v2 product at 1 km x 1 km grid cells (Hunka et al. (in review)). The largest differences are observed in the tropical belt.

Mission	Funding Agency	Launch Date (Expected)	Data Type (main obs mode)	Measurement Resolution	Geographic Domain
ALOS-2 PALSAR-2	JAXA	05/2014	L-band SAR (DP)	3-10 m stripmap 25-50 m ScanSAR	Global
ICESat-2	NASA	09/2018	532 nm photon counting lidar	13 m footprint aggregated to 100 m transect	Global
SAOCOM 1A/B	CONAE	10/2018 08/2020	L-band SAR (DP & QP)	5-10 m stripmap 30-100 m TOPSAR	Global
GEDI	NASA	12/2018	1064 nm waveform lidar	25m circular footprint	ISS (+/- ~51.6°)
ALOS-4 PALSAR-3	JAXA	2024	L-band SAR (DP & QP)	3-10 m stripmap 25 m ScanSAR	Global
NISAR	NASA-ISRO	2024	L-band SAR (DP)	3-10 m depending on mode	Global
BIOMASS	ESA	09/2024	P-band SAR (QP)	60 x 50 m with >6 looks	Global except W Europe and N America
MOLI	JAXA	2024	1064 nm waveform lidar	25 m circular footprint	ISS (+/- ~51.6°)
TANDEM-L	DLR	TBD	L-band SAR (DP)	Down to 5 x 7 m	Global
COPERNICUS HPCM ROSE-L	ESA / EC	2027	L-band SAR (DP)	TBD	Global

Table 2: A non-exhaustive list of current and planned biomass estimation missions.

maps for the maize and wheat growing seasons as defined by the global crop calendars, showing where maize and cereals are grown. Cereals include wheat, barley and rye, which belong to the Triticeae tribe. These crops were grouped together because their spectral signatures and growing seasons were too similar to reliably distinguish them at a global scale. The WorldCereal crop type maps are generated within the respective annual temporary crop mask.

Learn more about WorldCereal

EO IN SUPPORT OF ADAPTATION

Satellite and other systematic observations are vital for successful adaptation. They underpin the identification, planning, implementation and monitoring of adaptation measures. They are the first step in a chain linking observations through data exchange, global models supporting local models, warnings and planning and finally successful decision making. To understand and predict climate requires observations of the oceans, cryosphere, hydrosphere, and biosphere in addition to the atmosphere. Climate services that can identify emerging climate hazards at sub-national to national scales and forecast their evolution on daily to decadal time scales are needed to meet the goals of the Paris Agreement.

Section 4 has more detail on the use of EO for measuring and adapting to climate change impacts, with some examples in the case studies in Part II.

EO IN SUPPORT OF MEANS OF IMPLEMENTATION, INCLUDING FINANCE

Systematic observations - including from satellites - are being used to support improved access to climate finance by developing countries. Earth observations are being increasingly used to strengthen the climate rationale in funding proposals submitted to the Green Climate Fund (GCF), thus improving developing countries' access to public finance for mitigation and adaptation projects. Furthermore, private climate finance, including financial firms, insurance/reinsurance companies and businesses, are also employing EO to enhance climate risk assessments on their own assets, which creates more transparency and ultimately drives private sector investments in climate resilience globally.

The EO community has been working with global technology providers to enhance access to state-of-the-art cloud services including cloud computing, and building capacity to implement and use EO data systems and applications to enhance adaptive capacity and support sustainable development in the developing world. These efforts promote free and open access to user-friendly products and tailored, scalable solutions and climate services.

Section 5 has more detail on the topic of 'finance and climate' and the role for EO.

USE CASES FOR CLIMATE MONITORING FROM SPACE

The joint CEOS/CGMS Working Group on Climate together with the WMO are collecting use cases to demonstrate the value of EO satellites for societal benefit and decision-making. These aim to demonstrate the value of climate data records for decision/policy-making and to optimise their usage in applications relevant for climate services and science. The growing collection of use cases may be found here.

These use cases cover diverse applications. One example to highlight is the use of satellite data from NOAA geostationary weather satellites to produce estimates of precipitation and surface temperature. These products help inform food security managers (via FEWSNET – the Famine Early Warning Systems Network) on the extent and severity of drought and famine. Read more here.

LEARN MORE AND GET HELP

Much of our analysis above borrows liberally from the more detailed, technical, and comprehensive work of the Ad Hoc Coordination Group for the Systematic Observation Community's Contribution to the Global Stocktake. Their review of the role of systematic observations for the GST may be downloaded here.

CEOS Data Portal for the GST:
https://ceos.org/gst

The Essential Climate Variables:
https://gcos.wmo.int/en/essential-climate-variables

The ECV Inventory:
https://climatemonitoring.info/ecvinventory/

ESA Climate Change Initiative:
https://climate.esa.int/en/

NASA Earth Observation data:
https://www.earthdata.nasa.gov

USGS Earth Explorer:
https://earthexplorer.usgs.gov/

NOAA Climate Dashboard:
https://www.climate.gov/climatedashboard

JAXA climate data:
https://earth.jaxa.jp/en/data/products/index.html

3 MEASURING EMISSIONS

At the heart of the Paris Agreement is an understanding that governments will develop and meet greenhouse gas (GHG) emission reduction targets.

The global community recognises the need for urgent and collective actions on the mitigation of GHG emissions if we are to limit global warming. It is therefore fundamental to the implementation of the Paris Agreement that we better understand and accurately measure current levels, trends and sources of GHG emissions. Better information enables better-informed responses and better outcomes. As a result, data, information and their reporting by countries is integral by design to the Paris Agreement and to the Global Stocktake (GST) process. Every country has a responsibility to deliver national reports as a contribution to the assessment of aggregate progress under the GST. Under the Enhanced Transparency Framework (ETF) all countries will report on their National GHG Inventory and progress made on their stated commitments to emissions reduction. The first Biennial Transparency Reports (BTRs) are due no later than December 2024.

Data and knowledge around global GHG emissions, trends and sources will become increasingly important to support national and international climate policy-making. Transparent reporting processes will demand more and better data to satisfy society's needs, and satellite Earth observation (EO) has the potential to play a critical role to support policy-makers at the intersection between science and action. EO satellites are increasingly capable of monitoring GHG emissions with precision and scale and can support policy-makers at all levels, from the sub-national and national level for the establishment and operation of national GHG inventories, through to the global reconciliation and accounting processes that will seek to match aggregated national reports with the latest global observations.

Satellites provide us with new capabilities to measure and map GHG emissions on local, regional and global scales, and to identify specific emitting sources, leakages or hotspots, bringing a new level of detail and accuracy for data-driven decision-making. More accurate and policy-relevant GHG emissions data can inform local to global decision making, and facilitate more targeted and impactful climate action. For society to take full advantage of these capabilities, our policy-makers must understand these tools and data that are available to them to improve GHG reporting and strengthen climate mitigation policy. And it falls to the EO community to support awareness raising, accessibility, and capacity development to enable as many organisations and countries as possible to exploit this information delivered by EO satellites.

For that purpose, the Group on Earth Observations (GEO), in association with Climate TRACE and the World Geospatial Industry Council (WGIC) undertook a review in 2021 of the different satellite data sources available for GHG monitoring from space. This review has been updated in the course of preparing this EO Handbook to develop an entirely new and current resource detailing all satellite missions dedicated to the measurement and monitoring of greenhouse gases. The CEOS GHG Mission Portal may be reached here.

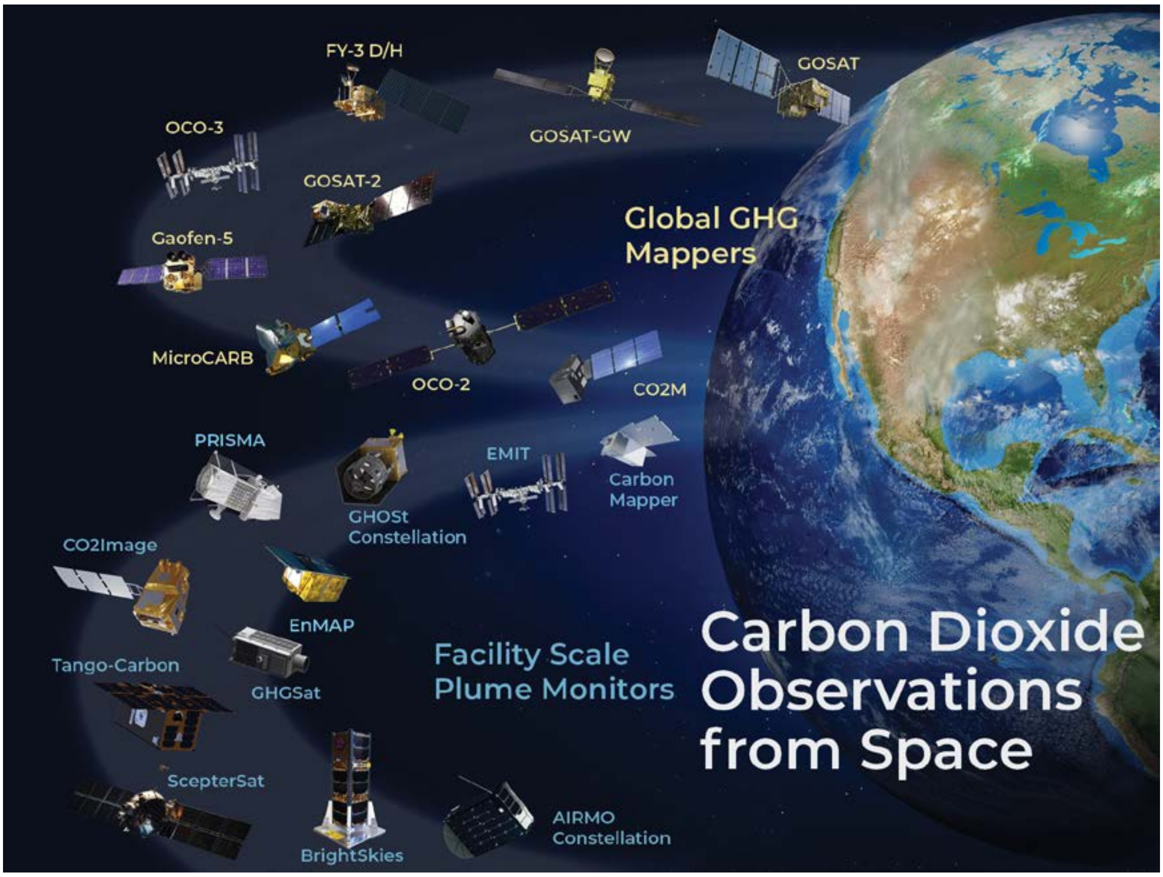


Figure 1: Satellite instruments for observation of methane. Area flux mappers are designed to quantify total methane emissions on regional to global scales. Point source imagers are designed to quantify emissions from individual point sources by imaging the atmospheric plumes

(Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane by Jacob et al)

These satellite missions have the potential to contribute to National GHG Inventories (NGHGIs) 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). The analysis also confirmed that:

- satellite observations reduce uncertainty in GHG emission monitoring by providing data across a range of spatial, temporal and spectral resolutions or scales;
- 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;
- private sector activity is increasing rapidly and bringing additional point-source emissions monitoring capabilities for specific GHGs;
- public-private models combining the strengths of the large public missions with the smaller and more targeted private missions are also emerging.

Download the PDF of the updated GHG satellite database here.

The timelines below show the outlook for different types of missions measuring GHG over a coarse area or at a facility level.

Space-based GHG estimates are less precise and accurate than their ground-based and airborne counterparts, but complement those systems with much better repeat measurement times and denser coverage of the globe. For example, NASA's OCO-2 and OCO-3 missions each collect about a million measurements over the Earth each day. On average, about 85,000 of these measurements are sufficiently cloud free to yield good measurements.

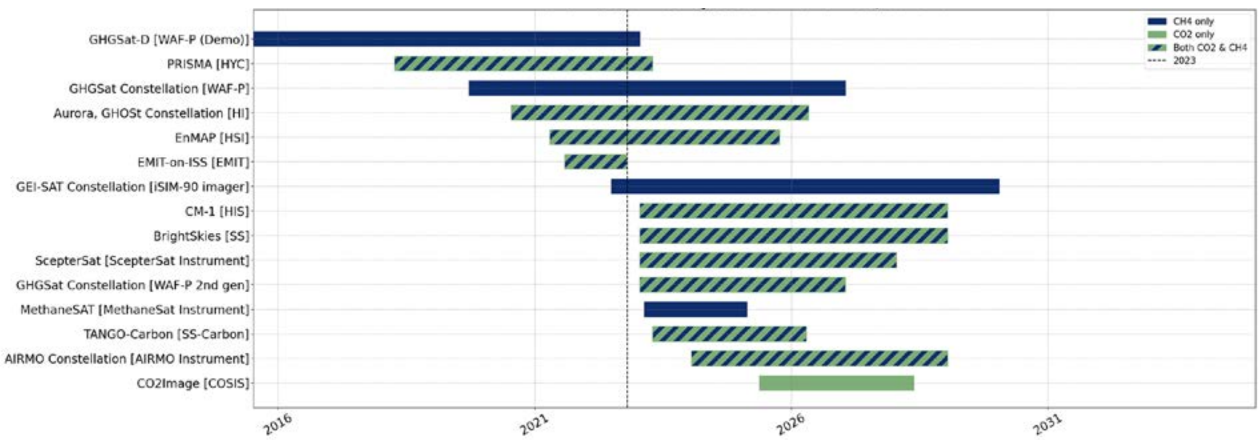


Figure 2: GHG Missions - Facility Scale Plume Monitors, CO_2 e CH_4

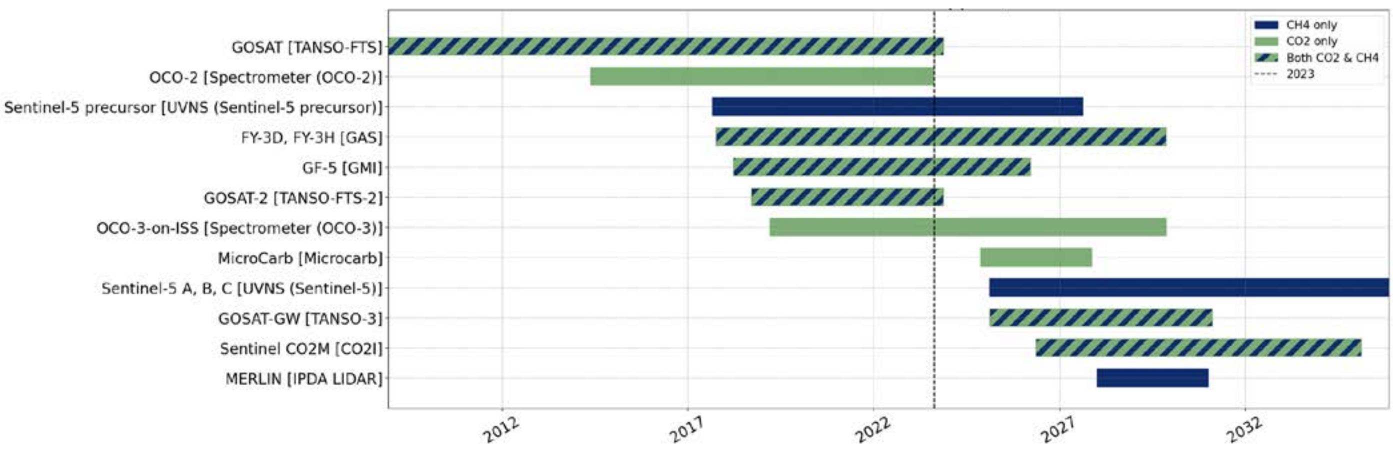


Figure 3: GHG Missions - Global GHG Mappers, CO_2 & CH_4

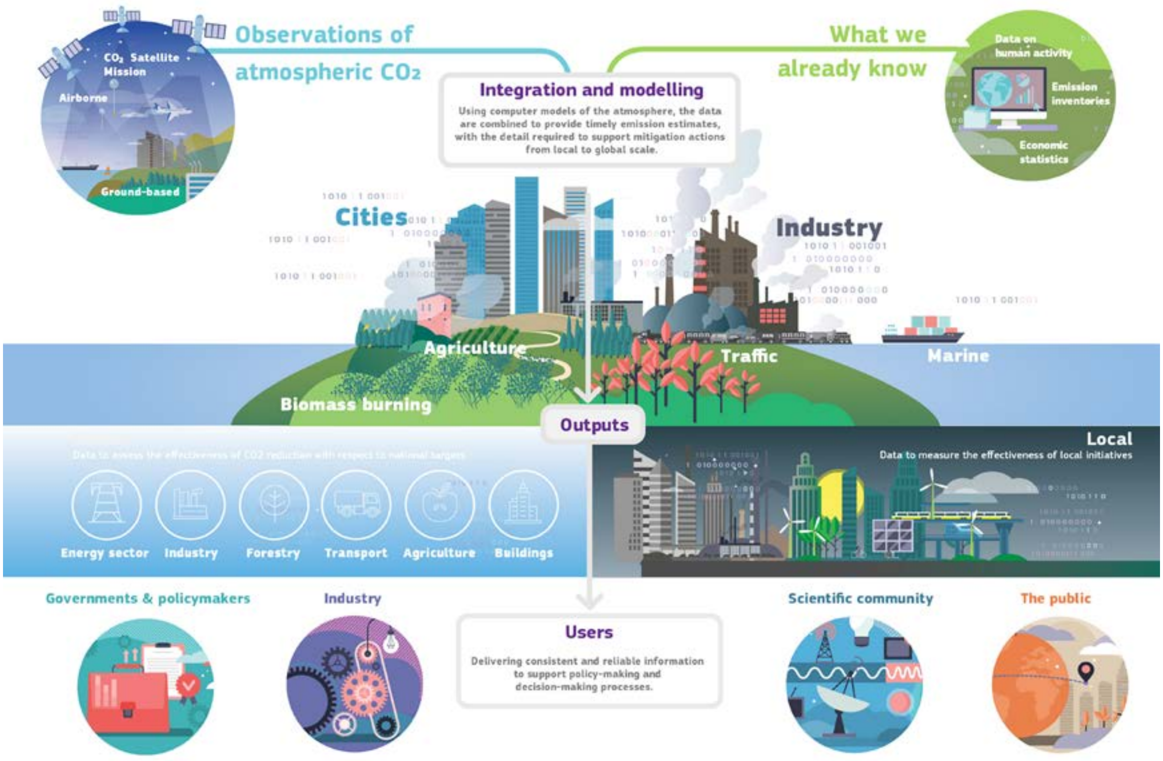


Figure 4: The new CO2MVS capacity will deliver unique information about anthropogenic emissions to support informed policy- and decision-making processes, both at national and European level (Copernicus Atmosphere Monitoring Service/ECMWF)

On monthly time scales, the measurements sample most of the globe, including areas that are too geographically or politically inaccessible to support ground-based observations.

A number of the current generation of GHG monitoring satellites were designed as a proof-of-concept, to demonstrate that space-based measurements of GHGs could yield measurements with the precision and accuracy required. In that context, they are a success but improvements are needed in satellite observation coverage and accuracy in combination with improvements in ground-based networks to satisfy the increasing information demands of society as the Paris Agreement ratchets up ambition via the stocktake process. In 2018, Committee on Earth Observation Satellites (CEOS) space agencies scoped out what it would take to have a future, purpose-built global greenhouse gas monitoring system that closely integrates ground-based, airborne and space-based measurements with Earth system models to yield both national-level top-down CO_2 and CH_4 inventories as well as estimates of hot-spot emissions from large power plants and urban centres. This integrated approach follows that used for operational numerical weather and air quality forecasting and has been adopted for planning and developing the European Copernicus CO2M constellation. CEOS anticipates that different nations will collaborate to support different ground-based, airborne and space-based elements of this GHG measurement system.

COPERNICUS ATMOSPHERE MONITORING SERVICE

Copernicus Atmosphere Monitoring Service (CAMS) scientists will be able to estimate and measure emissions of carbon dioxide and methane from anthropogenic sources with unprecedented accuracy and detail – and close to real time. CAMS, which is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission with funding from the EU, is working in partnership with other bodies and experts including the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), to provide the first European CO_2 Monitoring and Verification Support (CO2MVS) capacity on anthropogenic emissions.

In the lead up to the launch of a fully operational CO2MVS service the prototype currently being developed will be the result of worldwide expertise and innovations from a wide range of European and international players. A fully operational CO2MVS service is planned for launch by 2026. This initiative will come in time for the second GST of GHG emissions by countries participating in the Paris Agreement and to be concluded in 2028.

A constellation of dedicated satellites is being developed to measure concentrations of carbon dioxide and methane in the atmosphere with an unprecedented combination of coverage, detail, and accuracy. The satellites will even be capable of looking at individual carbon dioxide and methane sources such as power plants and fossil fuel production sites. Observations from these satellites will be assimilated through sophisticated computer modelling of the Earth's atmosphere and biosphere by CAMS scientists to be able to routinely quantify anthropogenic CO_2 emissions.

For the first GST, CAMS is already collaborating with EU-funded research projects to provide prototype products. The VERIFY Project has produced a first European annual synthesis, which includes CO_2 emission estimates from fossil fuel and managed land from all sectors reported to the United Nations Framework Convention on Climate Change (UNFCCC). The CoCO2 Project has supported the use of CAMS data to produce time series of CO_2 fluxes for the Agriculture, Forestry, and Other Land Use (AFOLU) sector in ten large countries or groups of countries around the world.

A full article on CO2MVS is in Part II of this document.

TOP-DOWN ASSESSMENTS OF GHGS

NGHGIs of emissions and removals submitted to the UNFCCC are generally estimated using "bottom-up" approaches to carbon measurement that rely on tallying and estimating how much carbon dioxide is being emitted across all sectors of an economy, such as transportation and agriculture. Bottom-up carbon inventories are critical for assessing progress toward emission-reduction efforts, but compiling them requires considerable resources, expertise, and knowledge of the extent of the relevant activities and this is why developing a database of emissions and removals via a "top-down" approach could be especially helpful for nations that lack traditional resources for inventory development.

As a complement to accounting-based inventory efforts, independent top-down assessments of CO_2 fluxes may be obtained from ground-based, airborne and space-based observations of atmospheric carbon dioxide. Such methods have undergone rapid improvements in recent years (as recognized in the 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories) and a number of countries (UK, Switzerland, USA and New Zealand) have adopted them for verification of national inventory reports.

Significant activity is underway in this direction within CEOS Agencies and their respective science communities. The case study in Part II of this document explains how satellite data has helped researchers track carbon dioxide emissions for more than 100 countries around the world. The pilot project offers a powerful new look at the carbon dioxide being emitted in these countries and how much of it is removed from the atmosphere by forests and other carbon-absorbing "sinks" within their borders. The findings demonstrate how space-based tools can support insights on Earth as nations work to achieve climate goals. Although the data in question (from NASA's OCO-2 mission) was not specifically designed to estimate emissions from individual nations, the findings from the 100-plus country study come at an opportune time as the first GST is underway in 2023. The data are available on the GST Data Portal developed by CEOS in support of the Stocktake. The pilot project was designed to start a dialogue between the top-down research community, inventory compilers and the GHG assessment community to identify ways that top-down CO_2 flux estimates can help inform country-level carbon budgets.

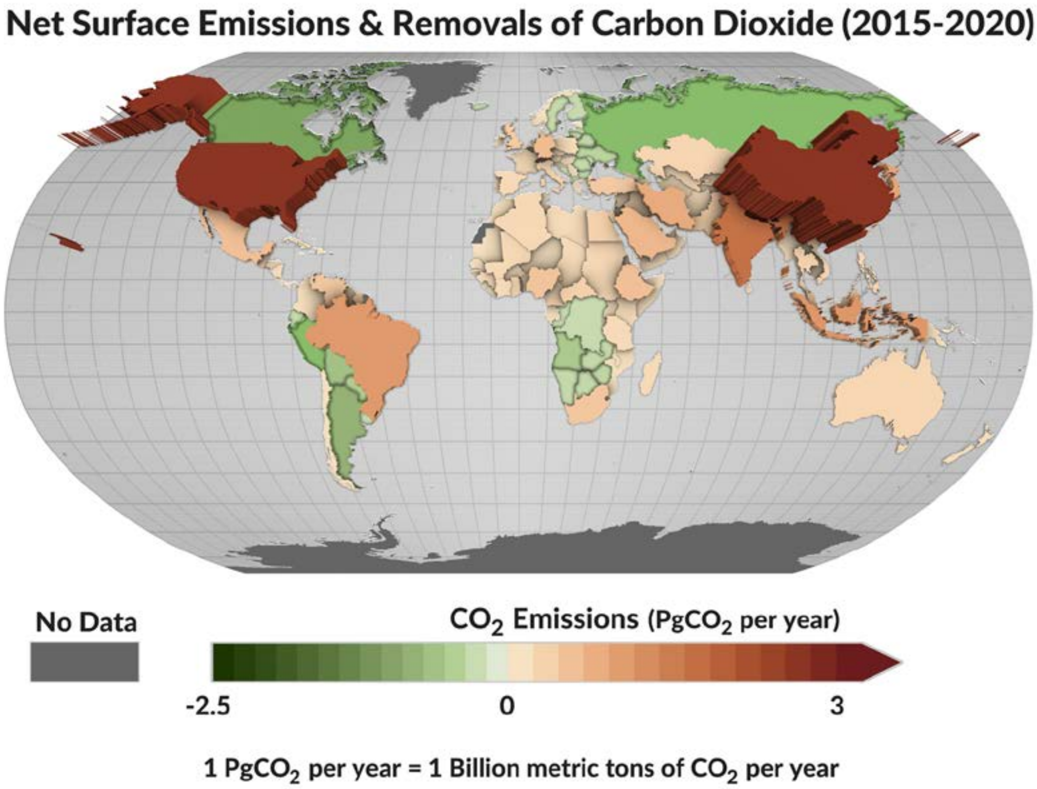


Figure 5: This map shows mean net emissions and removals of carbon dioxide from 2015 to 2020 using estimates informed by NASA's OCO-2 satellite measurements. Countries where more carbon dioxide was removed than emitted appear as green depressions, while countries with higher emissions are tan or red and appear to pop off the page (NASA's Scientific Visualization Studio)

METHANE EMISSION TRACKING FROM SPACE

Methane emissions are estimated to cause 25% of global heating today and have seen significant increases in the past decade. In 2021, methane levels were measured to have reached 2.6 times higher than before human activity started transforming the atmosphere. Fossil fuel exploration, production and transportation leaks account for about 40% of human-made methane emissions, with another 40% from agriculture (primarily cattle) and 20% from waste sites.

Methane has more than 80 times the warming power of carbon dioxide over the first 20 years after it reaches the atmosphere. Even though CO_2 has a longer-lasting effect, methane sets the pace for warming in the near term. Global heating could be reduced significantly if society can take fast action on the level of methane emissions, given its strong GHG effect but short lifetime. Estimates suggest that a methane emissions cut of 45% by 2030 could prevent 0.3°C of temperature rise and represents a uniquely effective and low cost opportunity to mitigate global warming risks. The UN's Global Methane Assessment estimated that measures to plug leaks and deliberate venting at 80% of oil and gas sites and 98% of coal mine sites would pay for themselves, by selling the extra gas captured.

A number of important initiatives are emerging to take advantage of the ability of EO satellite data to identify super-emitter sites and to quantify their emissions. Satellite data analysed by the company Kayrros through their Methane Watch programme identified more than 1,000 super-emitter events in 2022, mainly from oil, gas and coal sites. The events can last between a few hours and several months. Kayrros Methane Watch monitoring platform measures the methane footprint of companies, regions and countries on a global scale. Future methane emissions from fossil fuel sites are forecast to overwhelm the entire global "carbon budget" limit required to keep heating below 1.5°C. Scientific estimates suggest that just 112 of the largest super-emitters could represent somewhere between 80% and 200% of the remaining global carbon budget for that 1.5°C of heating. Satellite data gives us the ability to detect, measure and act

"This map - made possible by advancements in satellite technology - opens new possibilities for the acceleration of methane abatement. What we really look forward to is the day when, thanks to the success of the Global Methane Pledge, it will finally go dark"

Antoine Benoit at Kayrros

Figure 6: Map of Methane Emissions in 2022 (Kayrros Methane Watch, contains modified Copernicus data)

on these emission sources and provides the basis for urgent political action. At UNFCCC COP 26 in Glasgow in 2021, the Global Methane Pledge was announced, with some 150 countries having since signed up. Participants joining the Pledge agree to take voluntary actions to contribute to a collective effort to reduce global methane emissions at least 30% from 2020 levels by 2030. Participants also commit to moving towards using the highest tier IPCC good practice inventory methodologies, as well as working to continuously improve the accuracy, transparency, consistency, comparability, and completeness of NGHGI reporting under the UNFCCC and Paris Agreement, and to provide greater transparency in key sectors.

"Before the satellite technology, we didn't have a clue where these big events were happening but now, the good thing is at least we have some monitoring,"

Dr Lena Höglund-Isaksson, International Institute for Applied Systems Analysis in Austria

Part II of this document features a profile of the International Methane Emissions Observatory (IMEO) led by the UN Environment Programme (UNEP). Their Methane Alert and Response System (MARS) will use information provided by multiple satellites in near-real-time to identify super-emitting polluters and to initiate action to address them. MARS will publish data on leaks from the second half of 2023.

As highlighted in the GEO report on GHG

monitoring from space, there is an increasing supply of publicly funded EO satellite missions aimed at improving our ability to identify significant emitters of methane. At the same time we are seeing a large number of private and public-private programmes that are specifically designed to target point sources of methane and to be able to quantify them more accurately than the globally-focused missions can. Canadian company GHGSat launched a demonstrator mission in 2016 and now operates a constellation of five active satellites that can detect and measure methane emissions at high resolution worldwide. Further satellites are planned in the near future to bring new and extended capabilities.

Carbon Mapper, a new nonprofit organisation, and its partners – the State of California, NASA's Jet Propulsion Laboratory (NASA JPL), Planet, the University of Arizona, Arizona State University (ASU), High Tide Foundation and RMI – will launch the first of a constellation of satellites in 2023 with the ability to pinpoint, quantify and track point-source methane and carbon dioxide emissions. Carbon Mapper is also developing a public portal to make the data available for use by industry, governments and private citizens to improve GHG accounting, expedite repair of leaks, support disaster response and improve environmental resilience. Powered by philanthropy, Carbon Mapper convenes a unique coalition of private- and public-sector actors with the combined expertise and resources to deploy a science-driven, sustained and operational decision support service for maximum impact.

Further analysis of satellite capabilities and plans specific to measurement of methane emissions is covered in this 2022 paper, with a summary of the various contributing satellites in the graphic below indicating both systems that are capable of mapping wide area fluxes of methane and those that might be considered as point source imagers. Area flux mappers are high-precision instruments with 0.1–10 km pixel size designed to quantify total methane emissions on regional to global scales. Point source imagers are fine-pixel (<60 m) instruments designed to quantify individual point sources by imaging of the plumes.

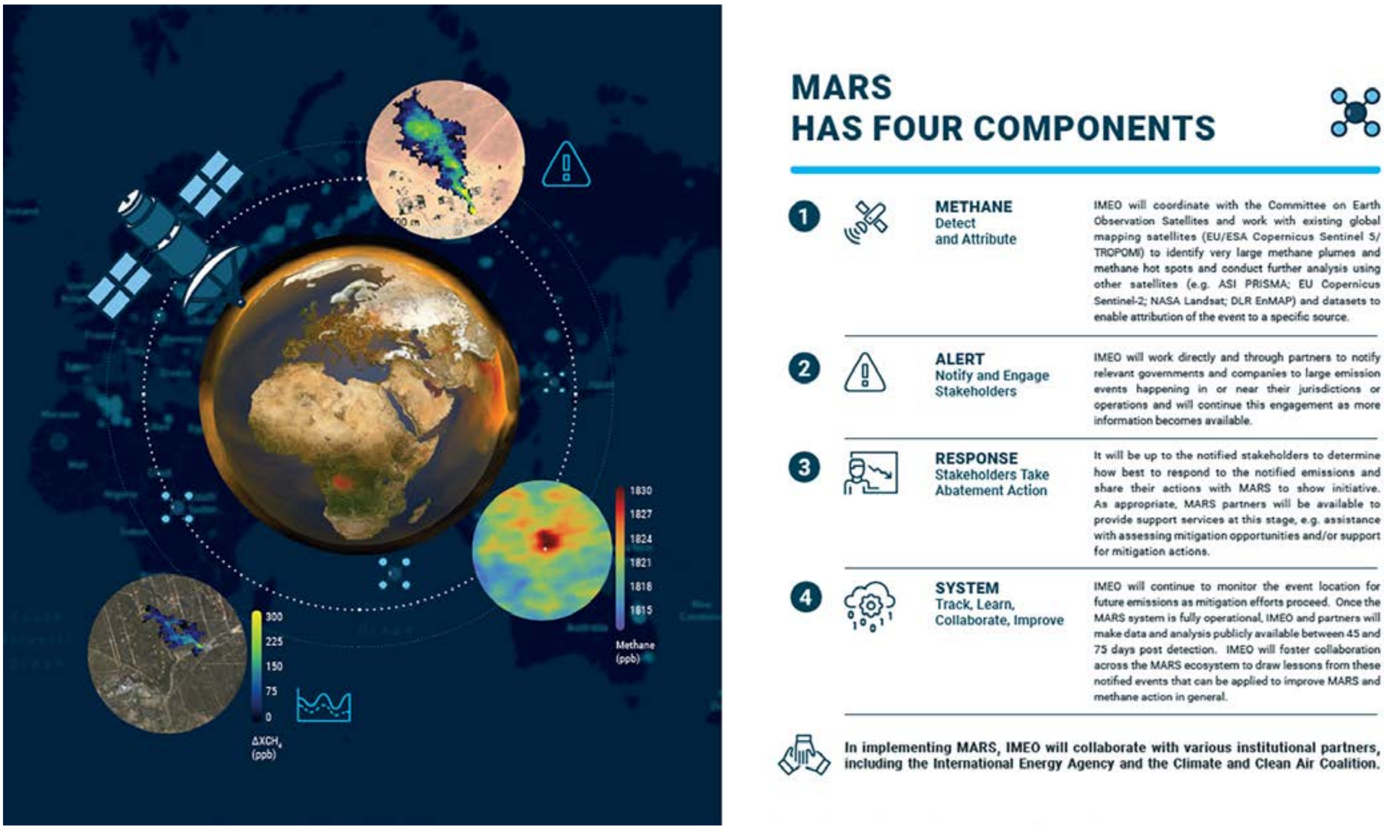


Figure 7: The four Components of MARS (UNEP)

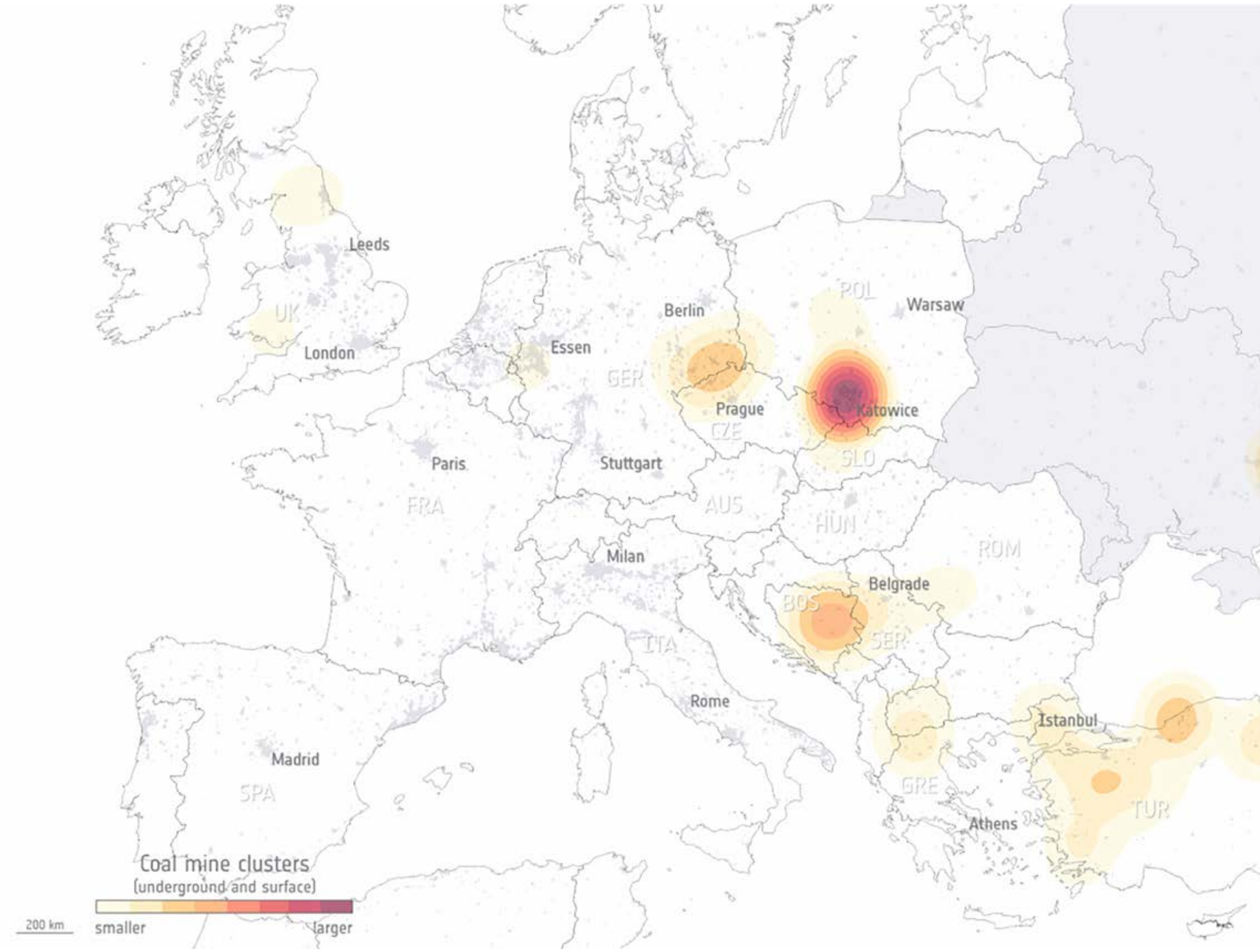


Figure 8: Sentinel-5P GHG Methane Monitoring Coal Mines over Poland. This map shows the clusters of both underground and surface coal mines in Europe (Contains modified Copernicus Sentinel data (2018-20) processed by University of Leicester)

As of May 2023, 150 countries have now signed the Global Methane Pledge of 2021 committing them to reduce their collective 2030 methane emissions by 30% relative to 2020 levels. Satellites can help to quantify national emission baselines for setting methane reduction goals, and can also monitor emissions over time to evaluate progress towards those goals, providing near real-time information on emissions.

FURTHER INFORMATION AND RESOURCES

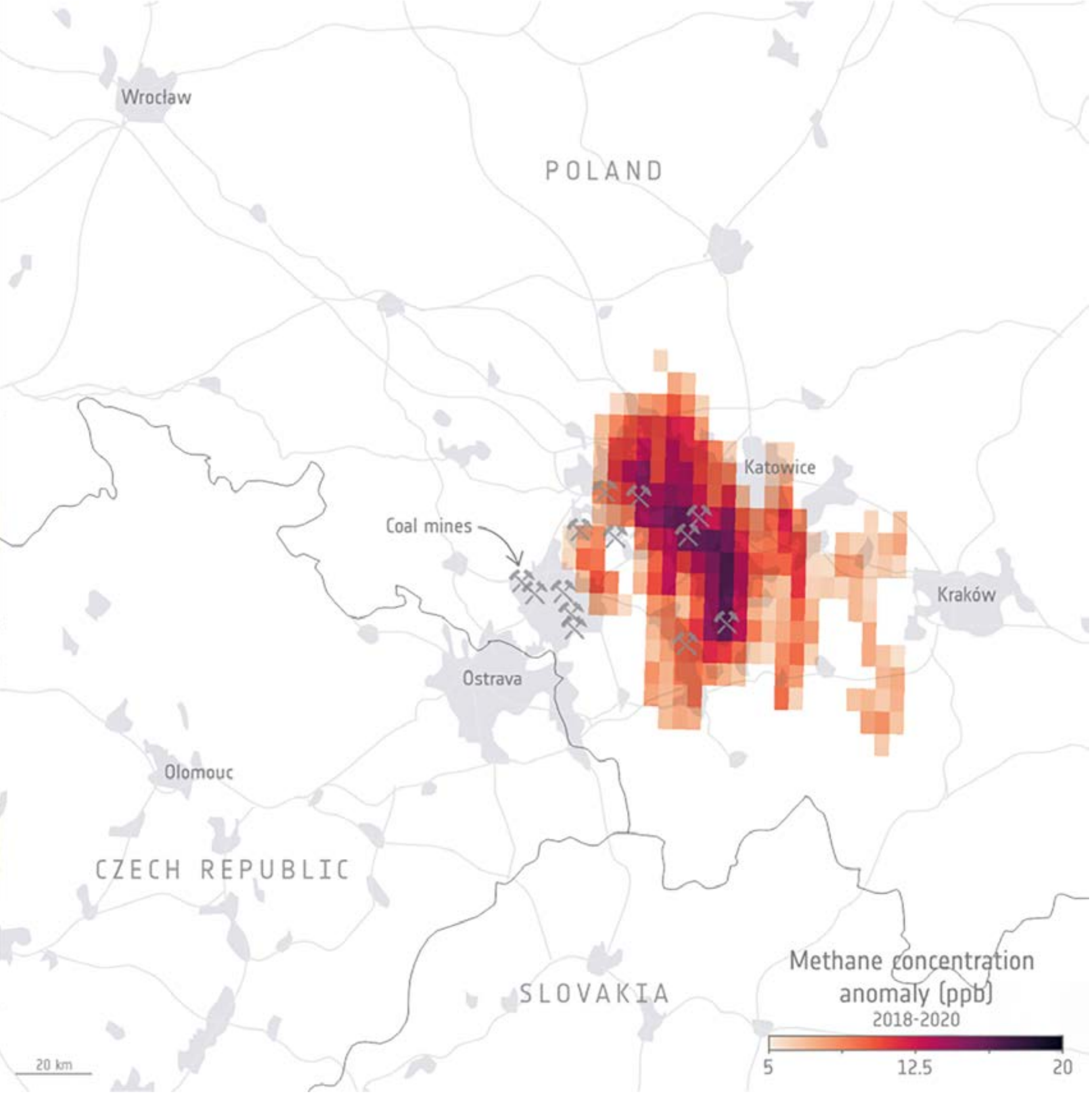
Updated database of GHG Satellites: GHG Monitoring from Space

CEOS GST Data Portal: https://ceos.org/gst/carbon-dioxide.html

Jacob et al paper on methane measurement from space: https://acmg.seas.harvard.edu/files/acmg/files/jacob2022.pdf

Global Methane Pledge: https://www.globalmethanepledge.org

Bill Nye explains MethaneSAT: https://www.youtube.com/watch?v=aiU-cSEGjqM


Wrocław
POLAND
Katowice
Coal mines
Kraków
Ostrava
Olomouc
CZECH REPUBLIC
SLOVAKIA
Methane concentration anomaly (ppb)
2018-2020
5
12.5
20
20 km

4 MEASURING AND ADAPTING TO CLIMATE CHANGE IMPACTS

Satellite Earth Observations (EO) provide a critical source of data that nations can use to understand and adapt to the risks and impacts of climate change.

By combining EO with socioeconomic data, we can discern the effects of climate change on populations and built environments. EO also provides the means to monitor the effectiveness of adaptation strategies, including infrastructure designed to combat the impacts of climate change, such as irrigation channels or sea walls and flood defences. It provides crucial data, allowing us to assess the performance and resilience of such infrastructure in real-time and over extended periods, thus providing valuable feedback for future design improvements and policy adjustments.

In this section we highlight how satellite EO can support countries in formulating and executing their National Adaptation Plans (NAPs). This contribution spans:

1. Modelling and forecasting climate and weather and their associated impacts.
2. Adaptation planning and implementation including vulnerability assessments, risk mapping, etc.
3. Monitoring and evaluation of adaptation policies and actions.
4. Early Warning Systems (EWS) for events such as floods, droughts, fires and cyclones.

This text is not intended to be comprehensive but rather to provide a glimpse of instances and suggestions for further exploration.

HOW CAN EO DATA SUPPORT CLIMATE CHANGE ADAPTATION?

While adaptation areas are often identified in countries' Nationally Determined Contributions (NDCs), and are largely related to changes in temperature, precipitation, evapotranspiration and extreme events, NAPs provide more specific information on vulnerabilities, adaptation strategies, contingency plans, and approaches to monitoring and evaluation. The process of formulating and implementing a NAP is iterative, and is captured in the following diagram. Satellite EO data has roles across the entire NAP formulation and implementation chain.

The integration of satellite EO data into climate services provides measurements that are comprehensive, spatially homogeneous, and consistent across scales. EO data is available in long time series, crucial for monitoring slow-onset climate impacts, such as droughts, and long-term adaptation trends like shifts in settlements. Long time series are also necessary for allowing consistent evaluation with the same or comparable data source, and for establishing baselines and prior conditions.

Satellite EO data is often available even for traditionally data-scarce regions, including areas that are hard to access or affected by conflicts, and fills gaps in existing terrestrial and ocean monitoring capabilities worldwide. It is also available in a timely manner, increasingly in near-real time, and can potentially support EWS and the assessment of real-time physical risk exposure. Furthermore, it is cost-effective, especially with the free and open EO programs promoted by the Committee on Earth Observation Satellites (CEOS) and Group on Earth Observations (GEO).

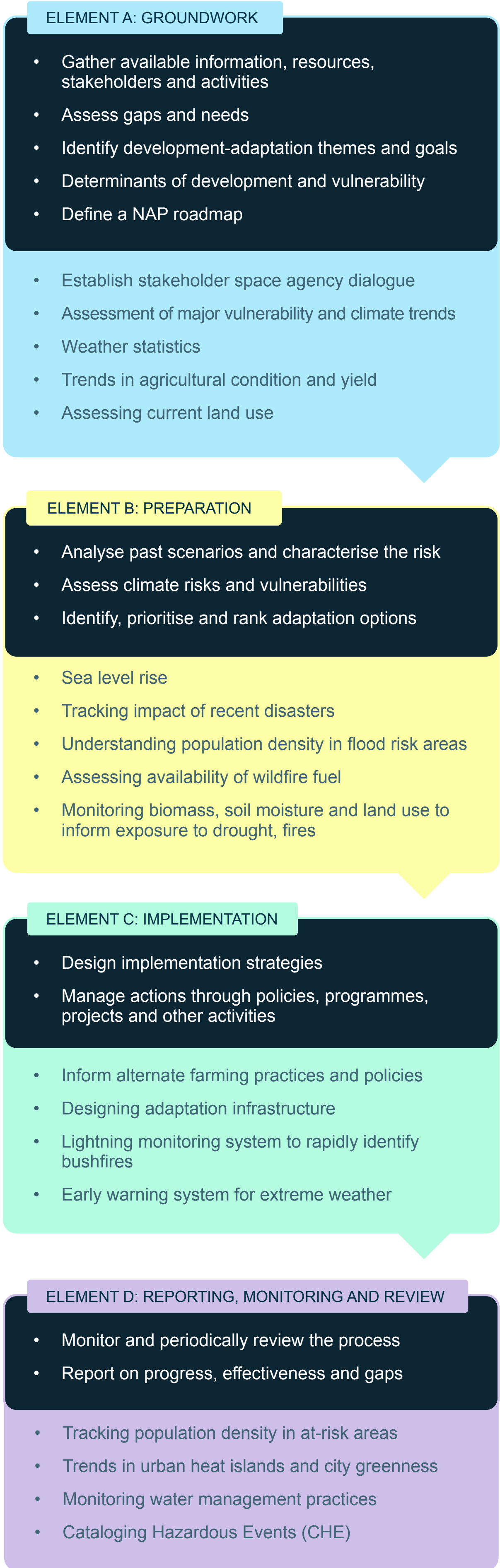


Figure 1: Major elements of a NAP formulation and implementation process with some potential contributions from EO identified (below each element, in colour). (Derived from 'Sample process to formulate and implement a National Adaptation Plan' by Paul V. Desanker, UNFCCC.)

MODELLING AND FORECASTING

As a major contributor to the ECVs, EO underpins climate modelling, forecasting and reanalysis with extensive, long-term climate data records. Modelling and forecasting the future of weather, climate and the biosphere allows us to assess climate change impacts and, when combined with socioeconomic data, risks to populations and infrastructure.

Sea-level rise is a fundamental climate change product, with the record from satellite altimetry missions TOPEX/Poseidon, the JASON series, and Sentinel-6 Michael Freilich providing a long-standing reference.

Long time series of images such as those from the Landsat series can provide more local level insights that complement the overall trend of global sea-

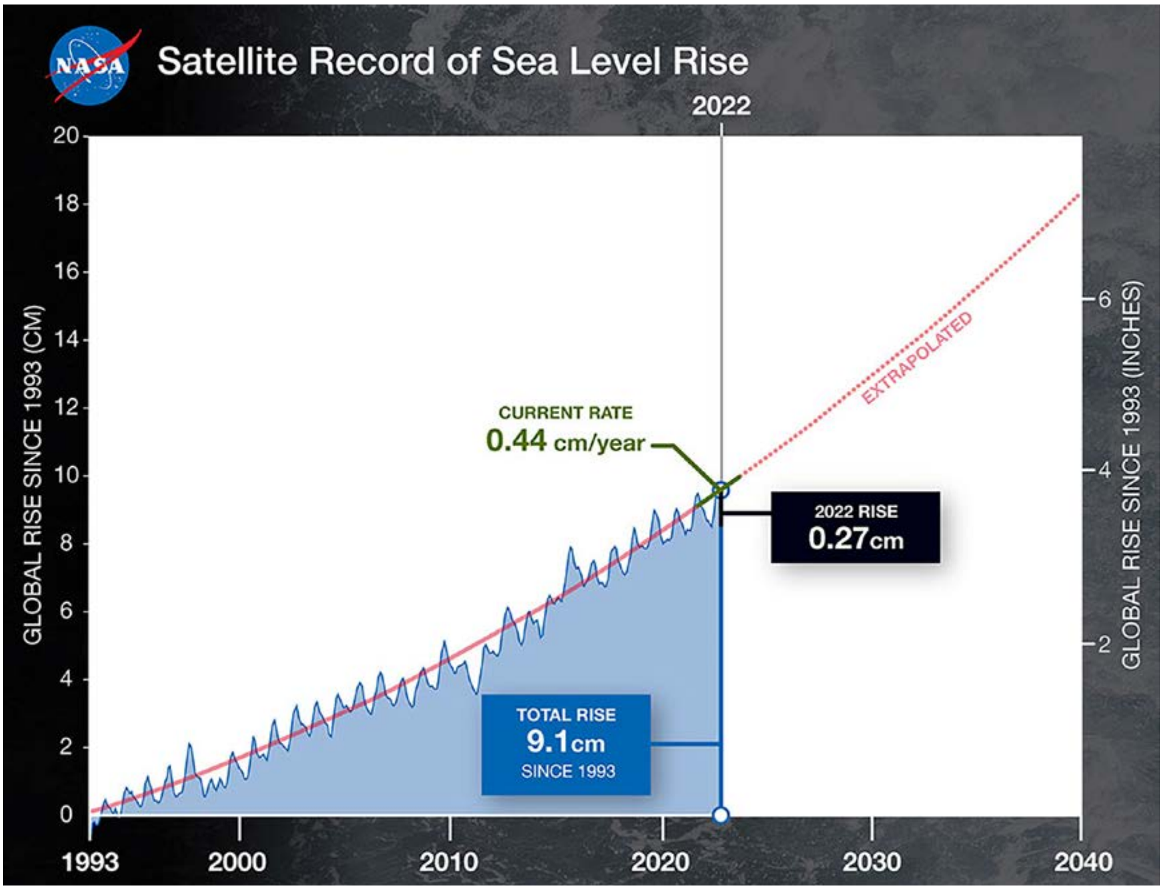
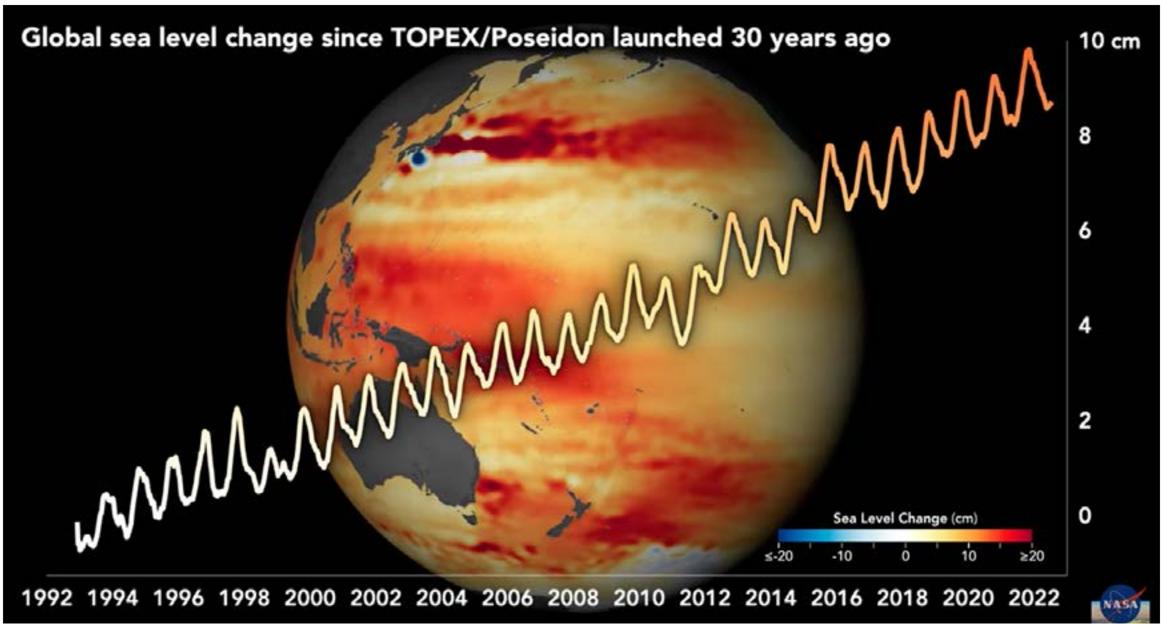


Figure 2: This graphic shows rising sea levels (in blue) from data recorded by a series of five satellites starting in 1993. The solid red line shows the trajectory of rise from 1993 to 2022, illustrating that the rate of rise has more than doubled. By 2040, sea levels could be 3.66 inches (9.3 cm) higher than today (NASA/JPL-Caltech)



Video

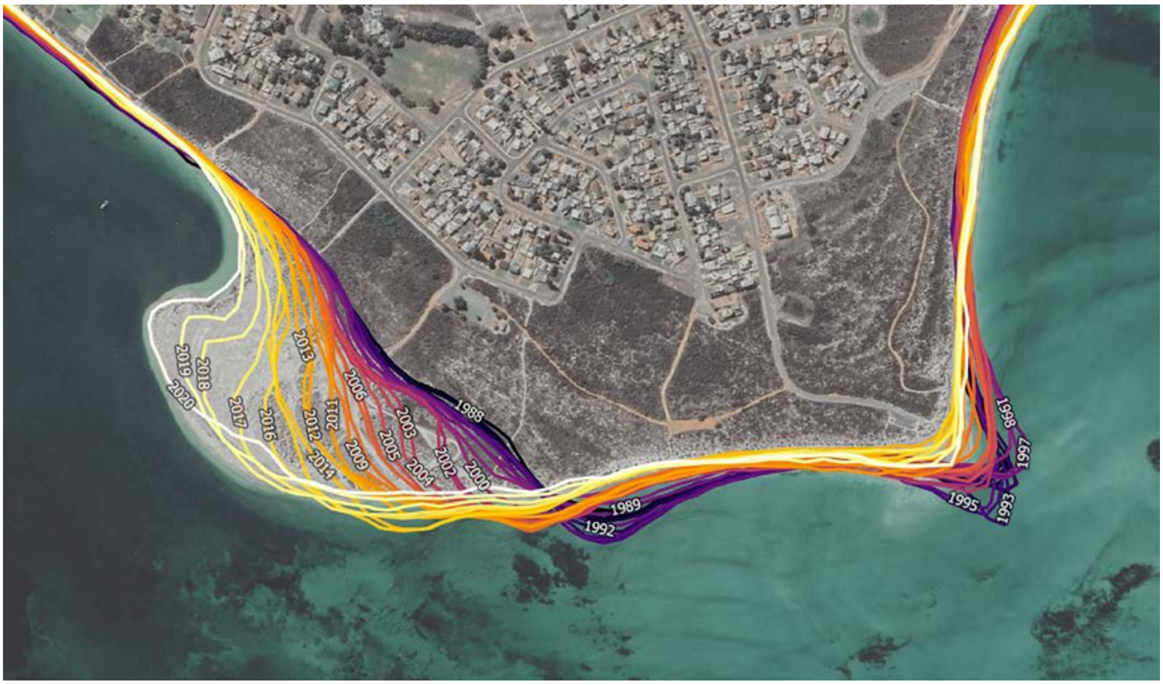


Figure 3: Coastline products derived from moderate resolution Landsat data provide forecasting information that is actionable at local levels. This modelled, historical data provides crucial insight on likely future scenarios for adaptation planning and implementation – for example, the construction of sea walls or sediment relocation.

level rise. The Digital Earth Australia and Digital Earth Africa Coastlines products demonstrate the power of decades of this data (from 1988) when stacked through time. The Coastlines products combine satellite data with tidal modelling to map the typical location of coastlines at mean sea level. The resulting shorelines and detailed rates of change show how beaches, sand spits, river mouths and tidal flats have grown and eroded over time. Animations of the data also reveal striking coastal dynamics that go unnoticed without long-term data.

ADAPTATION PLANNING AND IMPLEMENTATION

Knowledge of the present coupled with long-term trends allows practitioners to understand potential future scenarios and to plan and implement strategies that mitigate identified impacts and risks.

Flooding is the most frequent type of natural disaster and affects more people than any other environmental hazard. Between 1998 and 2017, floods affected more than 2 billion people worldwide. A recent study used satellite EO to estimate that from 2000 to 2015 there was an increase of 20–24% in the proportion of the global population exposed to floods, ten times higher than previous estimates.

Historical flood data can be used to plan urban development (i.e., away from floodplains) or to help adapt areas that are already impacted, such as in the design of flood retention zones. These data are not only useful for flood adaptation planning, but also to understand overall water availability for settlements, and to inform water management and agricultural practices. Part II of this Handbook features a case study on the GEO Global Agricultural Monitoring (GEOGLAM) initiative and the integration of EO into NAPs for agriculture and food security.

Combining water and flood data with socioeconomic information provides insight on strategies to build climate resilience. Such an analysis was performed for the World Bank's Greater Monrovia Urban Review project through a pilot activity of the European Space Agency's Earth Observation for Sustainable Development (EO4SD) Climate Resilience Cluster. This pilot developed EO products that model coastal and inland flooding risk due to sea-level rise and coastal erosion and combined this information with population exposure to estimate the flood risk to the general population.

Launched in 2022, the new NASA / CNES / CSA / UKSA Surface Water Ocean Topography (SWOT) mission is revolutionising the mapping of water bodies from space. It measures the height of nearly

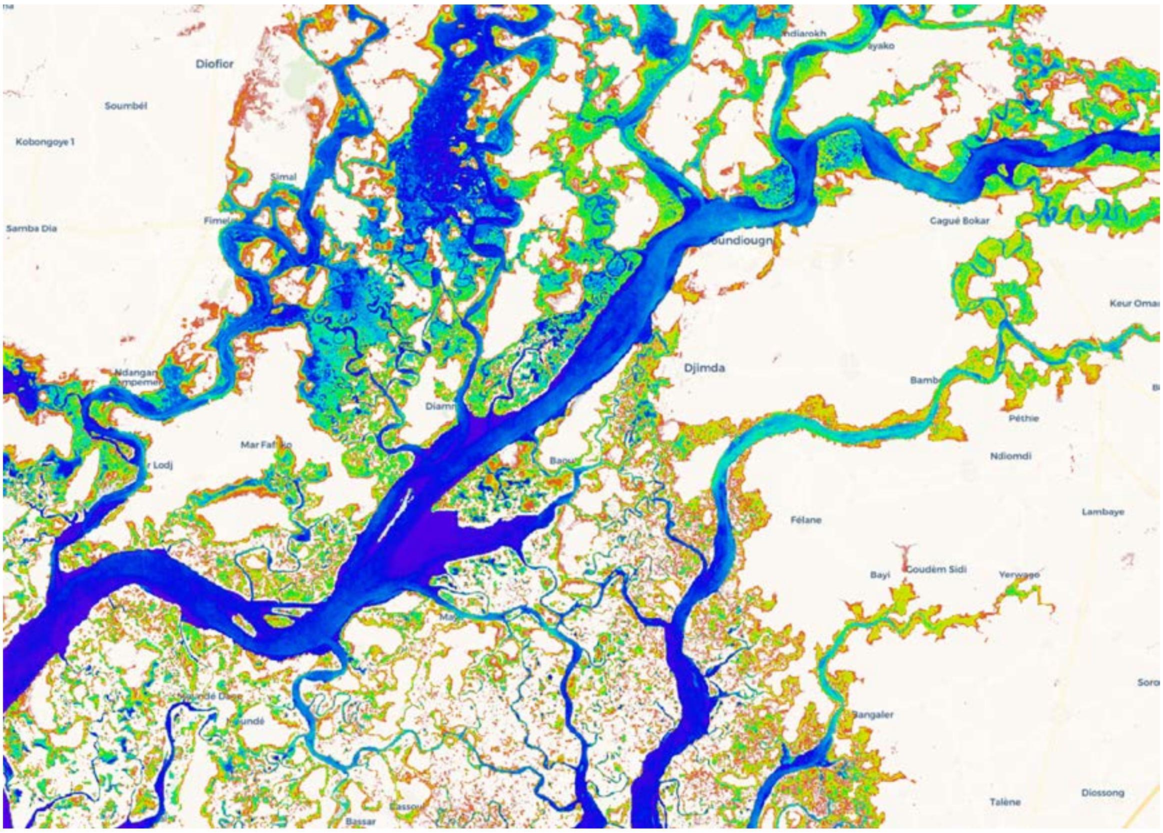


Figure 4: EO-derived historical water and flood extent maps can be found via online services such as the [The Global Flood Database] and the [Water Observations from Space (WOfS) of Digital Earth Africa / Australia], which stacks huge time series of USGS Landsat data to determine the frequency of water presence for particular surface locations. A Digital Earth Africa WOfS product for Senegal is shown to the right. (DEAfrica)

all water bodies, including large rivers, lakes, reservoirs and the ocean, filling gaps where surface water data are sparse or nonexistent, particularly in remote areas. Its wide swath altimeter is the first of its kind, allowing for wide area, frequent assessments of water bodies, which are critical to understanding water presence and its movement and change over time. Early adopters of SWOT are using the data for water management in the Nile Basin, improving hydrological models in Brazil and developing a flood vulnerability atlas, and establishing virtual stream gauges in the Lower Mekong Region and improving the accuracy of the regional drought and crop yield information system, among many others.

Information regarding the location, amount and dynamics of surface water is critical to climate change adaptation planning. Satellites readily provide water and flood extent maps and space agencies are providing operational near-real-time services in support of disaster response. Long archives of water extent data tell us where water has been and where it is moving. Improving technical capabilities reveal even more of these sources of surface water, including details of their heights and dynamics on a much shorter time scale than previously achievable. Implementation of solutions such as the construction of sea walls, design of infrastructure, and urban planning can also use satellite EO, e.g., high resolution optical data or digital elevation models.

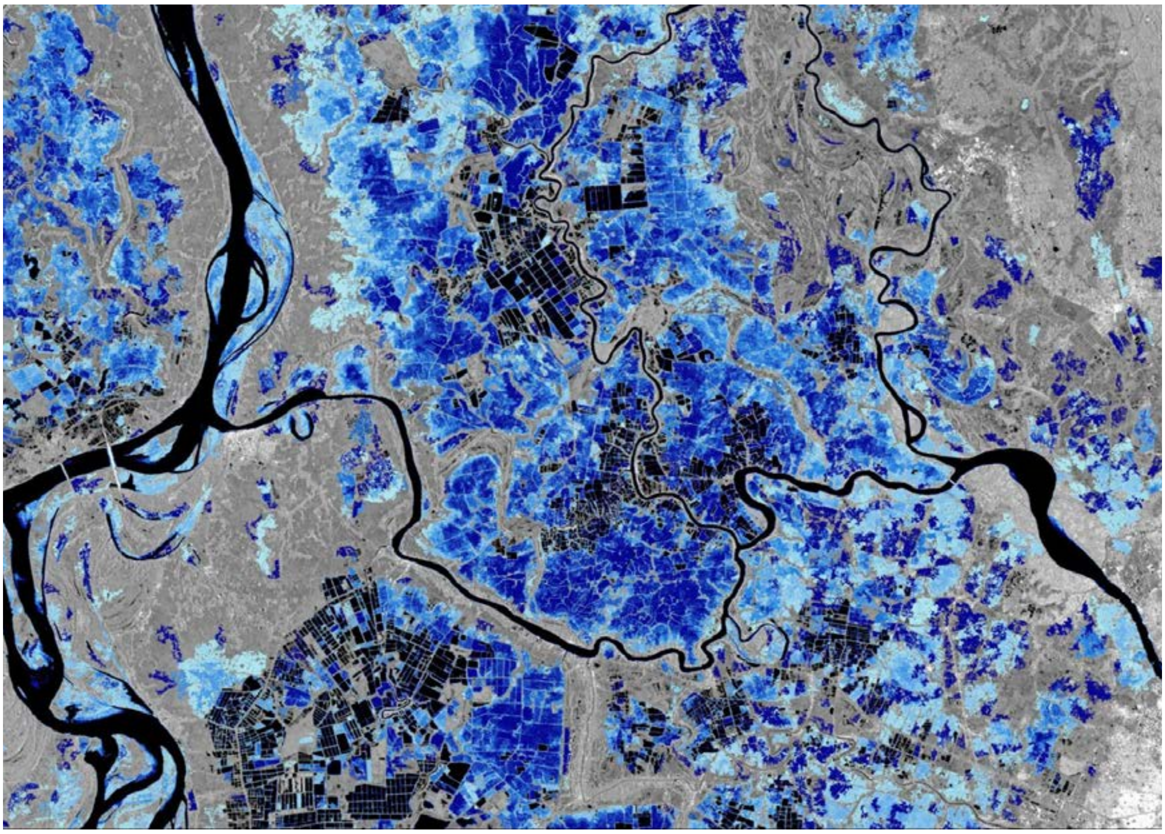


Figure 5: ESA GDA programme map showing flood frequency for a region of Myanmar, using time series data from the Copernicus Sentinel-1 radar mission. Areas of frequent water coverage are shown in darker shades.

Figure 6: Hotspot analysis of flood risk intersected with population density for Clara Town (Greater Monrovia). Risk severity depicted by red gradient colours. (EO4SD)

Harnessing Satellite Data for Heatwave, Drought and Wildfire Response
Urban Heat Islands

Satellite EO can inform exposure to droughts and fires by monitoring biomass, soil moisture and land use, and can help us understand the subsequent poor air quality. Together with floods, droughts represent the most destructive hydro-meteorological hazards.

Summer 2022 was Europe's hottest on record. Intense heat waves across many parts of the continent combined with unusually low rainfall led to widespread drought and wildfires. In many regions, the severe conditions continued into 2023, with experts warning that Europe could be facing its worst drought in at least 500 years.

Read about how observations by meteorological satellites are helping experts understand the complex factors underlying extreme heat, drought and wildfires, and to support community response in this case study by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

MONITORING AND EVALUATION

Monitoring and evaluation is crucial to understanding the effectiveness of climate adaptation measures. This knowledge informs future action as well as the iteration of NAPs. It also reduces the risk of practices resulting in maladaptation. The Global Stocktake (GST) of the Paris Climate Agreement does not include a comprehensive assessment framework for adaptation. While 75% of NDCs refer to adaptation, only 18% include quantified goals. Quantitative assessment requires a framework of indicators and metrics. EO offers some potential in this direction – covered further in the next section. There are different modes in which satellite EO can aid the monitoring and evaluation of climate adaptation measures.

Increasing temperatures are exacerbating the phenomenon of urban heat islands, where built structures absorb heat more readily and dissipate it slower than the natural surroundings, creating areas of increased temperature that are both uncomfortable and potentially dangerous to inhabitants. Climate change is anticipated to raise temperatures and is likely to increase heat-related human health morbidity and mortality risks. Annual heat-related deaths in the U.S. may increase by 28,000–34,000 additional deaths by mid-century. City planners can respond by increasing urban greenness – that is, by increasing the proportion of land covered by grass, trees, shrubs or other vegetation.

Optical satellite data can be used to directly quantify the greenness of cities. This has also been demonstrated at scale with the use of machine learning and the Copernicus Sentinel-2 mission. EO-derived canopy cover (from Lidar and SAR) can also be used.

Alternatively, we can use satellite observations in the thermal infrared spectrum, from missions such as USGS's Landsat (TIRS instruments, 100m resolution), NASA's Terra/Aqua (MODIS instrument, 1km resolution) to provide direct measures of Land Surface Temperature. MODIS also provides land surface temperature at night.

The image below demonstrates the utility of very wide swath (approx. 1675km), low resolution (1km) thermal infrared imagery from the Copernicus Sentinel-3 SLSTR instrument. The image was constructed by the National Center for Earth Observation (NCEO) and the University of Leicester to demonstrate the extent of the UK's record-breaking heatwave in 2022. The image reveals unique information on the spatial structure of the heatwave event and clearly demonstrates the urban heat island effect of the major cities.

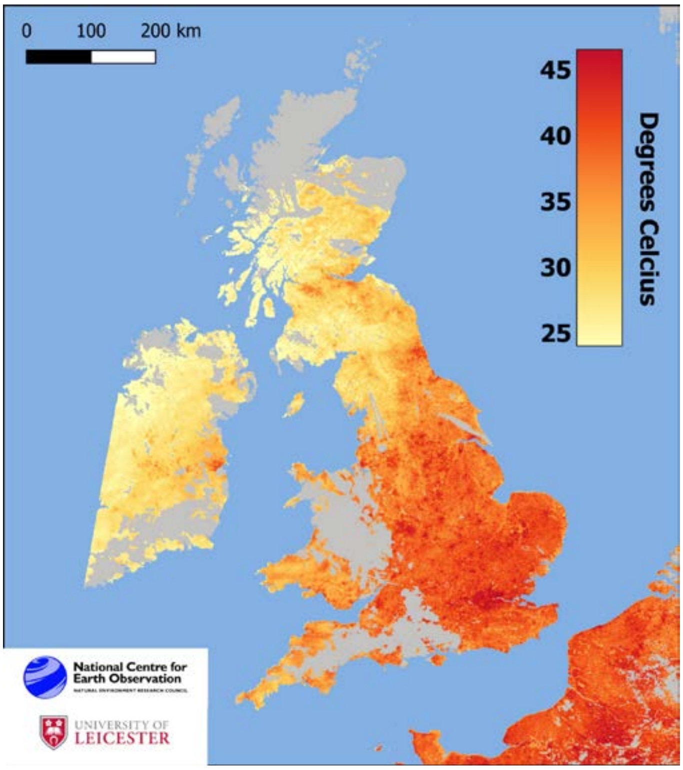


Figure 7: Land Surface Temperature recorded by ESA's Sentinel-3 SLSTR during the record-breaking UK heatwave in July 2022. (NCEO/University of Leicester)

Until now, due to the limited resolution of these existing sensors, data from ground-based networks often complements these sources of data. The NASA Applied Remote Sensing Training (ARSET) program demonstrates how socioeconomic data can be integrated with satellite imagery to derive Heat Vulnerability Indices (HVIs).

With improving technical capabilities, upcoming missions such as the NASA/JPL Surface Biology and Geology (SBG) Thermal Infrared Free-Flyer and the Copernicus Land Surface Temperature Monitoring (LSTM) mission will advance our ability to measure land surface temperature and trends at local scales. Such high resolution data will allow practitioners to directly evaluate efforts to reduce urban heat. The two LSTM satellites, operating as a constellation, will be able to image the Earth every 3 days at 50m resolution.

New commercial offerings are also emerging, such as those from Ororatech, Satellite Vu and Albedo, which are promising unprecedented detail for small area coverage, giving building owners, industrial site operators, etc. the ability to understand their footprint and take action to mitigate heat waste.

Figure 8: NASA's ECOSTRESS instrument on the International Space Station recorded land surface temperatures around Prague, Czech Republic, on 18 June 2022. ESA is using ECOSTRESS to simulate the data that will eventually be returned by LSTM.

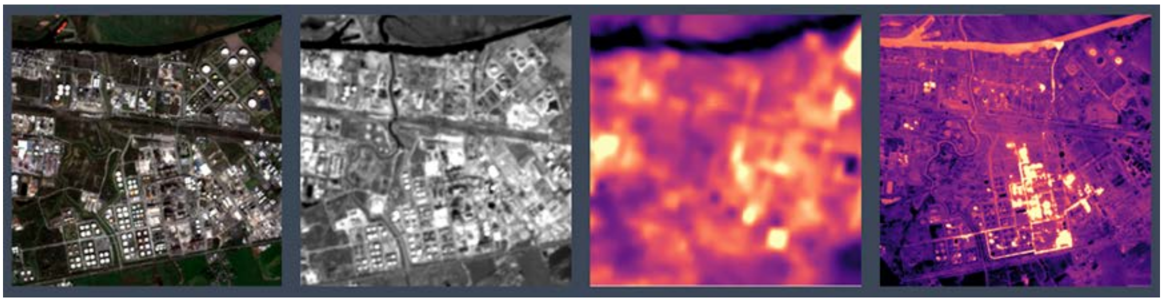


Figure 9: From left to right: Sentinel 2 RGB, Sentinel 2 SWIR, Landsat 8 TIRS, and Satellite Vu. (Satellite Vu)

EARLY WARNING SYSTEMS

Early warning systems (EWS) are a top adaptation priority for countries, with 88% of least developed countries (LDCs) and small island developing states (SIDS) highlighting EWS in their NDCs nationally determined contributions and NAPs. Data provided by 138 WMO Members, including 74% of LDCs and 41% of SIDS globally, show that just 40% of them have Multi-Hazard EWS, and one third of every 100,000 people in the 73 countries that provided information is not covered by early warnings (ESA, 2022).

EWS rely on short lead time information, which EO can support with frequent revisits and coverage of large geographical areas. Spatial disaggregation of global datasets can also be done in combination with in situ networks to further improve temporal resolution of information. Early warnings help mitigate climate risks, impacts and can act as triggers for support and recovery funding.

Some examples of EO-powered EWS and sources of near real-time EO data:

- GEOGLAM Crop Monitor 4 Early Warning (CM4EW): Developed in response to the pressing need for enhanced early warning of crop shortfalls and for better coordination across the various agencies responsible for crop assessments in regions most at risk to food insecurity.
- LANCE – NASA Near Real-Time Data and Imagery: NASA's Land, Atmosphere Near real-time Capability for EOS (LANCE) supports users interested in monitoring a wide variety of natural and human-created phenomena using near real-time (NRT) data and imagery that are made available much quicker than routine processing allows. NASA has provided a global flood product since 2011, with the latest iteration, the MODIS Near Real-Time Global Flood Product being released in 2022.
- Global Flood Monitoring (GFM): In 2021, this operational, near real-time system was released by the European Commission's Copernicus Emergency Management Service. GFM provides continuous monitoring of floods worldwide by immediately processing and analysing Sentinel-1 Interferometric Wide Swath radar data, which provides information day-and-night and regardless of cloud cover.
- WMO Climate Risk and Early Warning Systems (CREWS): The specialised Climate Risk and Early Warning Systems (CREWS) initiative saves lives, assets and livelihoods through increased access to early weather warnings and risk information for people in Least Developed Countries (LDCs) and Small Island Developing States (SIDS) – the world's most vulnerable countries.

SUMMARY

The range of applications for Earth Observation (EO) data in the arena of climate change adaptation is vast, with only a handful of examples outlined in this chapter. The critical aspect is that EO offers a wealth of data, which, when combined with socioeconomic information, can be processed to yield valuable insights that can guide the development of adaptation strategies and also monitor their progress.

However, the utilisation of EO data is not without challenges. The scale and complexity of the data can be daunting and necessitate sophisticated storage, processing and analysis techniques. Developing quantitative metrics and indicators from this data to gauge progress on climate adaptation and inform the iteration of NAPs can also pose significant difficulties. Simplified data access, tools, and support structures being championed by space agencies are working to address some of these aspects.

Despite these challenges, the opportunities and advantages EO data provides are invaluable. This rich data source is a key driver for our global resilience to climate change, illuminating our understanding of the planet's evolving climate system and aiding us in making informed, strategic decisions. As we advance our capabilities to navigate and interpret this data, the contribution of EO to our collective climate change adaptation efforts will only grow in significance.

LEARN MORE AND GET HELP

- SERVIR: A joint initiative of NASA and USAID, SERVIR partners with countries and organisations to address critical challenges in climate change, food security, water and related disasters, land use and air quality. Using satellite data and geospatial technology, SERVIR co-develops innovative solutions through a network of regional hubs to improve resilience and sustainable resource management at local, national and regional scales.
- Copernicus Climate Change Service (C3S): Implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the EU, provides access to a wide range of climate datasets via a searchable catalogue – the Climate Data Store (CDS). Satellite EO is a key contributor. Applications developed by users are also made available via the CDS for free without any restriction of use. A vast array of case studies demonstrate the value of Copernicus data for climate change adaptation.
- Copernicus Data Space Ecosystem: An open ecosystem that provides free instant access to a wide range of data and services from the Copernicus Sentinel missions and more on our planet's land, oceans and atmosphere
- Open Data Cube: An open source geospatial data management and analysis software project that helps users harness the power of satellite data. Open Data Cube seeks to provide an open and freely accessible EO exploitation architecture.
- ESA Global Development Assistance: A global partnership to mainstream the use of Earth observation into development operations. Includes a Climate Resilience thematic area.
- World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) Digital Earth Partnership: Aims to enhance the resilience of vulnerable countries and communities to climate change and natural hazard disasters through greater access to and adoption of frontier Earth observation tools and services. ESA is a key partner.

5 FINANCE, CLIMATE AND THE PARIS AGREEMENT

Earth Observation (EO) has a substantial role to play in directing finances towards climate change action, including capacity building.

Earth Observation (EO) has a substantial role to play in directing finances towards climate change action, including capacity building. The intersection of finance and climate change spans several sectors and affects numerous policy discussions. This ranges from funding mechanisms to reduce greenhouse gas (GHG) emissions and adapting to the inevitable future climate changes, to international funding management and steering private investments towards mitigating future climate change effects. EO can also contribute to managing the risk associated with climate damage insurance and reinsurance.

Key initiatives under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC) have been implemented to secure financial support for necessary actions to mitigate and adapt to climate change. The differing capacities of countries to contribute financially and the varied impacts they are likely to experience from climate change, particularly those countries classified as less developed, are central to these initiatives.

EO data can inform these financial decisions by providing accurate, real-time information about the state of the planet. This data can be used to identify the areas most in need of investment and to monitor the effectiveness of initiatives funded. By using EO data in this way, we can ensure that finances are being directed most effectively to combat climate change and to build the capacity of nations to respond to it.

In this section, we underscore how satellite Earth Observation (EO) can assist countries in both securing and utilising finance to facilitate climate change action in alignment with the Paris Agreement. We offer a concise overview of the financial mechanisms and expound on how EO can be employed under these mechanisms, with a special emphasis on areas such as Investment, Insurance, and Climate-related Financial Vulnerability. This includes initiatives like the Green Climate Fund, Loss and Damage Fund, the New Global Financial Pact 2023, private sector financing and investment, and the Task Force on Climate-Related Financial Disclosure.

A BRIEF HISTORY OF EO AND FINANCE ACTION UNDER THE PARIS AGREEMENT

In 2009, during the 15th Conference of Parties (COP 15), a significant commitment was made by developed nations. They agreed to collectively contribute US$100 billion annually by 2020 to aid climate action in developing countries. This pledge was made under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen.

From that time, contributions to this fund have generally been increasing, although they haven't yet met the annual goal of US$100 billion. The Organisation for Economic Co-operation and Development (OECD) has been keeping track of progress towards this goal. They've identified four main sources of these funds, with the bulk of these funds typically coming from the first two categories:

- direct aid from developed countries' institutions,
- financial support provided by global development banks and climate funds,

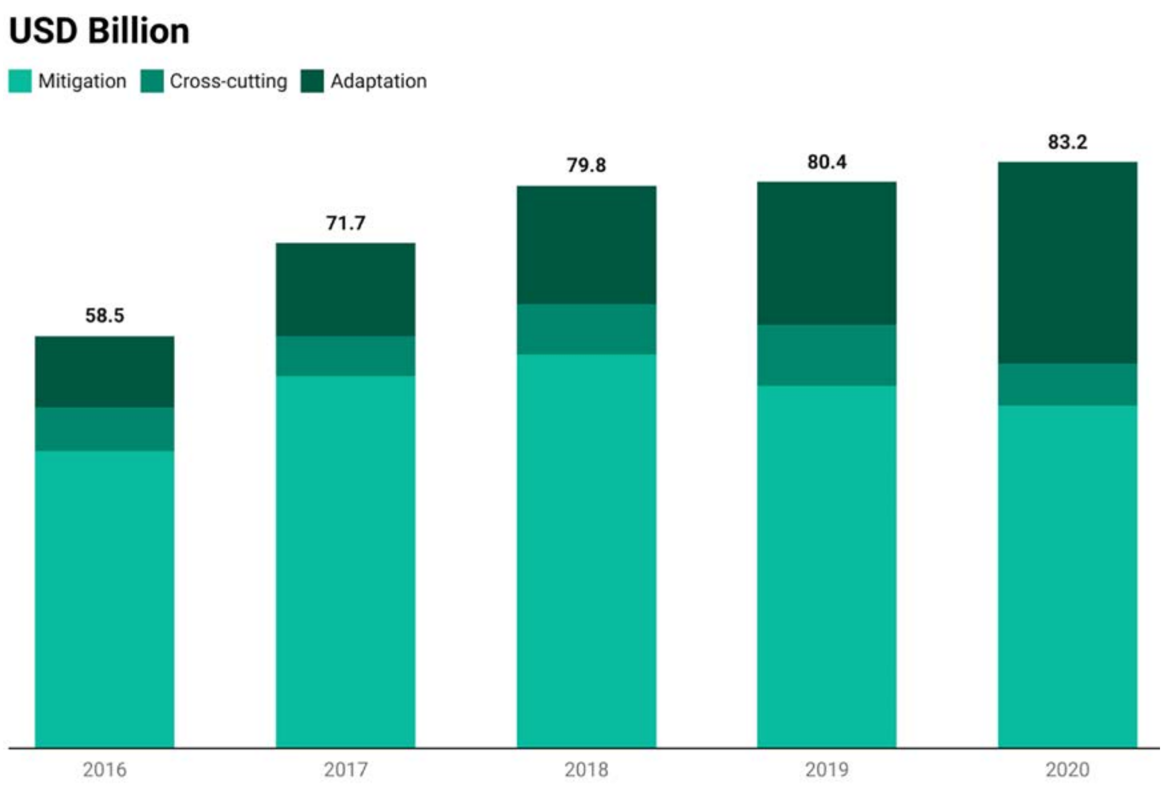


Figure 1: Climate theme and sectoral split of climate finance (US$Bn) provided and mobilised in 2016-2020 (Aggregate Trends of Climate Finance Provided and Mobilised by Developed Countries in 2013-2020)

- climate-related export credits from official agencies of developed countries,
- and private finance mobilised by public climate finance.

A common misconception about these funds is that they are primarily used to minimise the impact of climate change in the countries receiving the funds (adaptation). However, the majority of the funding has actually been used to reduce greenhouse gas emissions (mitigation) in these countries, often through changes in energy use, transportation, and agricultural and forestry practices.

During the period 2016-2020, the destination countries of funds were as follows: Asia (42%), Africa (26%), Americas (17%), Europe (non-EU/EEA, 5%), Oceania (1%), others (9%).

In relation to both mitigation of and adaptation to change funded through these mechanisms, satellite data and services have a fundamental role to play. Both implementation of actions in support of these and oversight of progress made in response to the provided funding can be supported through these services.

The UK Space Agency's International Partnership Programme (IPP) CommonSensing project employs satellite data as a vital tool to guide climate finance decisions, concentrating its efforts primarily in Fiji, Solomon Islands, and Vanuatu. The project's approach is twofold: first, it uses satellite-derived information to measure the impacts of climate change, such as extreme weather events or changes in land use, thereby establishing a strong, data-driven case for climate finance. Second, it applies these insights to the design and monitoring of climate resilience interventions. For example, in Fiji, satellite imagery is used to map mangrove coverage across various islands, with the data and methodology shared with local ministries for further application. This provides valuable information for designing and monitoring initiatives to protect coastal areas and enhance biodiversity. Similarly, in Vanuatu and the Solomon Islands, satellite data helps identify communities at risk from rising sea levels and supports the planning of potential relocation efforts, making a robust case for targeted climate financing. Through these applications, CommonSensing ensures that climate finance is directed where it can have the most impact.

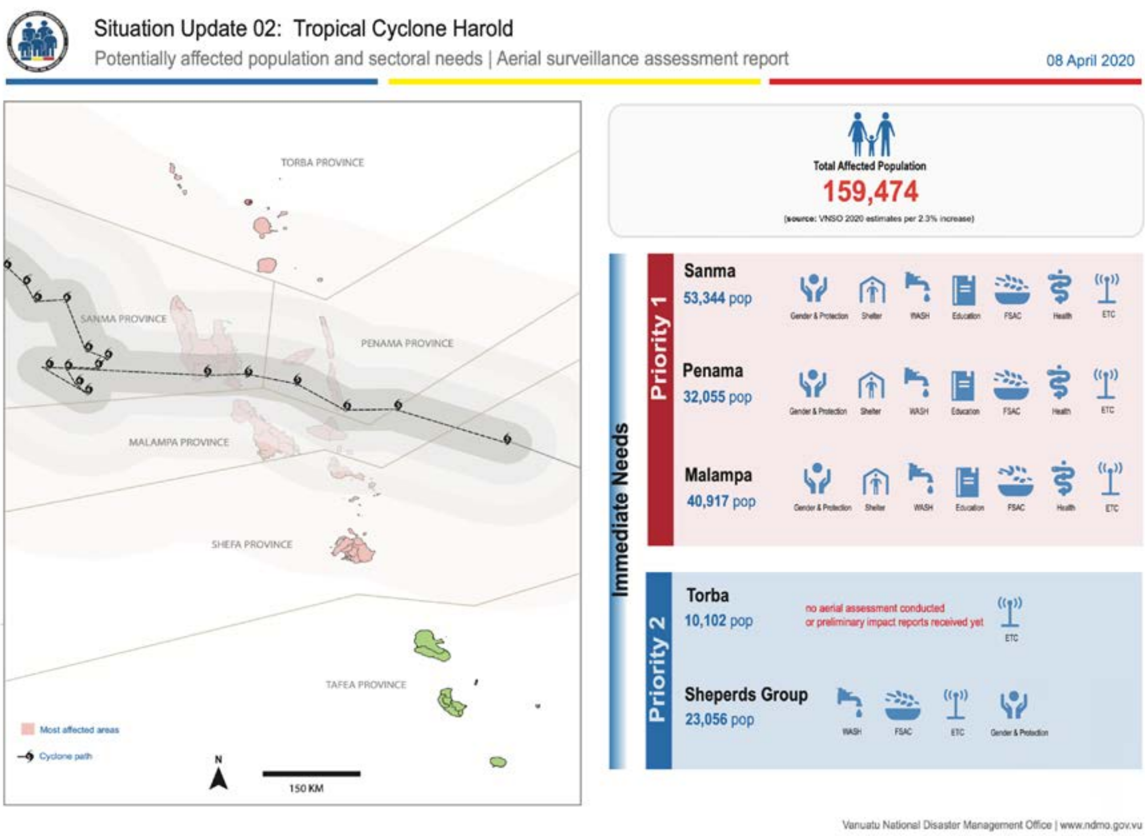


Figure 2: Vanuatu: Tropical Cyclone Harold Emergency Response Dashboard (Vanuatu NDMO)

Planet has announced a collaborative venture with the United Arab Emirates (UAE) Space Agency. Their joint initiative aims to create a regional satellite data-based atlas for evaluating loss and damage, and enhancing climate change resilience. This partnership is designed to offer data to a specified country highly susceptible to climate risk, with the intent of bolstering resilience, guiding policy decisions, and fuelling financial initiatives for climate change adaptation and mitigation. The facility's initial focus will be to gather data for a chosen country that is particularly vulnerable to climate change. This information will help quantify the damages incurred from extreme weather events such as floods and droughts, as well as aid in establishing early-warning systems. The partnership will leverage high-frequency, high-resolution satellite data and analytical tools to create foundational datasets. These datasets, accessible to governments, NGOs, and other relevant entities, will facilitate the development of insights into climate-related areas such as population dispersion, wildfire and flood threats, agricultural yield and food security, and physical assets.

ESA SUPPORTING CLIMATE FINANCE PROGRAMS

The ESA Global Development Assistance (GDA) program was launched in 2020 with the long-term objective of mainstreaming and operationalising the use of EO-based information for international development assistance projects and activities including:

1. **Agro-Climatic Resilience in Semi-Arid Landscapes (World Bank)**: This project uses Earth Observation (EO) to develop a Digital Soil Organic Carbon Measurement, Reporting, and Verification (MRV) system for agricultural landscapes in Nigeria, thereby helping to channel climate finance towards sustainable agriculture practices.

2. **Enhancing Differentiated Approaches in Context-Sensitive Situations (Asian Development Bank)**: The water availability and risk assessment web platform created through this project can inform water infrastructure investment decisions and climate resilience strategies in Afghanistan.

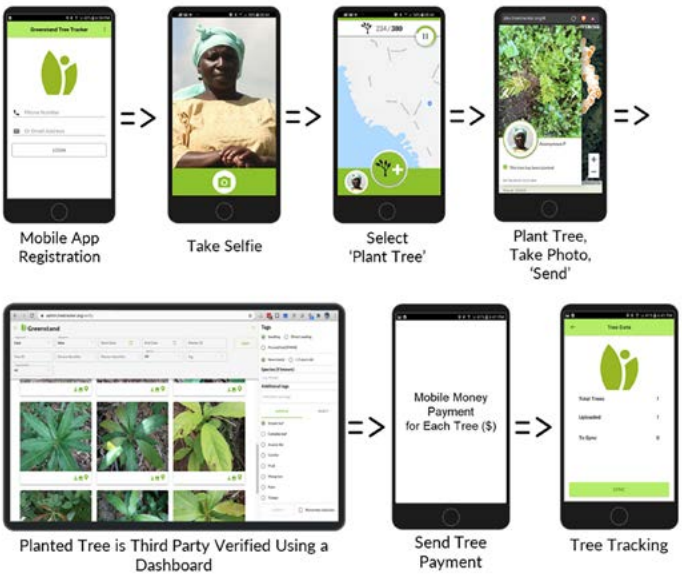
3. **South Sudan Climate Resilient Flood Management Project (World Bank)**: The use of satellite data to analyse flood trends and hazards can inform investments in flood management strategies and nature-based solutions in South Sudan.

4. **Global Program for Sustainability (World Bank)**: The sub-annual analysis of land cover dynamics using satellite data can support the allocation of finance towards projects that combat deforestation.

ESA has partnered with the World Bank on their Digital Earth Partnership, which aims to enhance the resilience of vulnerable countries and communities to climate change and natural hazard disasters through greater access to and adoption of frontier EO tools and services. This will be achieved by developing and transferring global knowledge, mobilising key partnerships and providing operational support to client-executed and Bank activities in the production and use of EO for resilience. Climate resilient development is especially reliant on stakeholders' abilities to use accurate and timely information about our changing climate, environment and livelihoods, for risk aware insights and risk reduction actions. Through knowledge building and partnership development, Digital Earth will focus on providing demand-driven data services for spatial monitoring, decision support and risk management activities prompted by client governments and their beneficiaries: activities that are locally appropriate, affordable, actionable, scalable, and sustainable.

FREETOWN THE TREETOWN: USING EO & AI TO DETECT AND MONITOR URBAN FOREST CANOPY FOR FREETOWN

Located at the brink of a dense forest area, Sierra Leone's capital, Freetown, faces the consequences of rapid urban expansion as its borders push deeper into the surrounding woodland, leading to a sharp decrease in tree canopy cover and escalating risks of landslides, flooding, and coastal erosion. In partnership with the World Bank, the Freetown City Council launched the #FreetowntheTreetown initiative, a tree-planting campaign that harnesses local involvement for sustainable tree cultivation with the ambitious target of planting and nurturing 1 million trees to increase the city's tree canopy cover by 50%. The campaign employs a TreeTracker app that enables community-based growers to plant, monitor, and care for new trees, rewarding them with micropayments for their contributions. Satellite EO is used to help monitor the tree plantings and individual tree locations are seen within the app https://map.treetracker.org/ Freetown the Treetown: Using EO & AI to Detect and Monitor Urban Forest Canopy for Freetown (YouTube)"



Spots on map of Greater Freetown area of Sierra Leone show where planted trees have been digitally tracked.

The remainder of this section discusses the major funding initiatives in relation to climate and different aspects of climate-related finance. Examples as to how EO satellite data is supporting these initiatives are provided. These initiatives related to climate finance are:

- The Green Climate Fund;
- Loss and Damage Fund;
- Private sector finance, clean investing and Environmental Social and Governance (ESG) under frameworks developed to support transparency for reporting;
- Taskforce on Climate Related Financial Disclosure (TCFD).

GREEN CLIMATE FUND (GCF)

The GCF has grown to be the largest multilateral climate fund. Fully operational since 2015, pledges to the GCF stand at over US$20 billion from countries, regions and cities. It is larger by far than any other multilateral climate fund. In September 2023, the GCF pledging conference will help set the scale and ambition of the multilateral climate funds for the 2024-2027 period (GCF-2) with strong signals of ambition for the New Collective Quantified Goal (NCQG) on climate finance to be set by the end of 2024. More info here.

GREEN CLIMATE FUND

Funding committed by countries through the agreements made at Copenhagen and beyond can be implemented through a wide range of financial mechanisms, both unilateral and multilateral. Unilateral funding is often through national development programme agencies such as USAID in the USA or GIZ in Germany.

There are also a wide range of options for multilateral funding, one of which is the GCF established by the UNFCCC. The GCF is a critical element of the Paris Agreement and is the world's largest climate fund. It is mandated to support countries to raise and realise their Nationally Determined Contribution (NDC) ambitions towards low-emission, climate-resilient pathways. Since 2019, the GCF portfolio of climate projects has more than doubled to US$12 billion of GCF finance, which when considering direct co-financing amounts to over US$45 billion under management. It currently manages over 200 projects in 129 developing countries.

GCF strives to increase access to climate finance, helping developing countries to turn their climate ambitions into bankable projects, moving from idea to action. For GCF, access to finance means providing more funding, quicker, simpler, with harmonised procedures, and delivered closer to local communities on the ground. It is about to embark on its second programming period GCF-2 (2024–2027) and an ambitious financial target has been set for its implementation.

An important factor in the future financing of a cleaner future is partnership with the private finance sector. Climate change offers businesses an unprecedented chance to capitalise on new growth and investment opportunities that can protect the planet as well. GCF employs part of its funds to help mobilise financial flows from the private sector to compelling and profitable climate-smart investment opportunities.

The EO community can both support and benefit from GCF funding. The science community is assisting the most vulnerable countries to improve the climate rationale of project proposals for adaptation and mitigation with EO data. At the same time, GCF is already financing a number of projects in developing countries that strengthen their use of climate information systems, and EO can be part of that investment.

LOSS AND DAMAGE FUND

In 2022, a crucial decision was made at the COP 27 conference to create a new fund to help developing countries deal with the fallout from climate disasters, a concept known as 'loss and damage'. This refers to the negative effects of climate change that are too severe for populations to adapt to, including loss of life, property damage, and economic losses.

Often, it's the most vulnerable groups like low-income communities, indigenous peoples, and small island states that suffer the most.

The issue of loss and damage has become a hot topic in climate talks, with developing nations asking for compensation from wealthier ones for climate change-related damage. However, these wealthier nations have been hesitant to accept this responsibility, citing legal and financial concerns. It's likely that some funding agreement will be reached, but connecting it to ideas like liability or blame might discourage the historically high-emitting countries from committing to it.

The COP 27 meeting led to a decision to set up funding structures to help vulnerable nations deal with climate change impacts. A fund was created specifically for this purpose, and a Transitional Committee was formed to outline its operation. They'll organise arrangements, define funding terms, and identify sources of funding. The committee will also explore current loss and damage strategies and potential funding sources. In 2023, they'll share their findings for a final decision on the fund.

EO technologies can play a crucial role in supporting the Loss and Damage Fund by providing accurate and timely data on climate change impacts. EO, utilising satellites and other remote sensing instruments, can monitor climate parameters and track changes over time, capturing information on temperature changes, ice sheet dynamics, sea-level rise, and the frequency and intensity of extreme weather events. Such data can facilitate the estimation of loss and damage attributable to climate change, thereby enabling a more precise assessment and quantification of the financial needs of countries affected. Further, EO can aid in verifying claims of climate-induced loss and damage, thus enhancing transparency and accountability in the distribution and use of the fund. By integrating EO into the process, funds can be allocated efficiently and effectively to areas with the most urgent needs, fostering a more responsive and targeted approach to addressing the impacts of climate change.

As in the case of the funding under previous arrangements following COP 15, satellite data and services are key assets for the effective management of funds to address loss and damage. Satellite-based information can help assess the extent of damage suffered by countries due to climate change by reference to historical data. It can also optimise efforts to reduce or remediate damage through events such as flooding, storms or fire and help assess the losses due, for example, to loss of agricultural productivity, translated into economic costs – the GEO Global Agricultural Monitoring (GEOGLAM) project is a good example of this. Fuller examples of how this can be achieved are set out elsewhere in this document.

A key feature of the loss and damage funding would be to provide resources rapidly to remediate short-term and immediate damage caused by climate events, as opposed to long-term plans to improve resilience to future climate-related events.

NEW GLOBAL FINANCIAL PACT 2023

In November 2022, French President Emmanuel Macron announced an international conference in Paris in June 2023, separate from UNFCCC mechanisms, but aimed at enhancing financial solidarity with the global South. This decision resonates with the "Bridgetown Initiative" led by the Prime Minister of Barbados, Mia Mottley, intending to facilitate access to international financing for countries most susceptible to climate change, to better tackle climate challenges. The 2023 Paris Summit's objectives include restoring fiscal flexibility to heavily indebted countries, promoting private sector growth in low-income countries, encouraging investment in green infrastructure in emerging and developing countries, and mobilising innovative financing for countries vulnerable to climate change.

SUMMIT FOR
A NEW GLOBAL
FINANCING PACT

The Summit aims to amalgamate several agendas, including climate, development, and debt, and propose innovative solutions to these issues. Similar to the Bridgetown Initiative, this objective intends to provide less wealthy countries with the means to finance efforts to reduce the impacts of climate change within their territories and mitigate their contributions to increasing climate change by fostering low- and zero-emission economies.

EO is poised to play a key role in the New Global Financial Pact 2023, providing critical data for policymaking and financial decision-making by tracking and verifying climate change impacts. This data aids in identifying where funding is most necessary and assessing resource effectiveness. Additionally, EO can support the design, implementation, and monitoring of "green" infrastructure projects, ensuring environmental benefits are maximised and potential harm is minimised. EO also facilitates the monitoring and verification of project impacts, offering investors and stakeholders assurance about the effective use of funds and the delivery of intended project benefits. Thus, EO's role in the pact could significantly promote transparency, decision-making, and resource efficiency, contingent on the pact's specific provisions and their implementation.

PRIVATE SECTOR FINANCE, CLEAN INVESTING AND ENVIRONMENTAL, SOCIAL, AND GOVERNANCE (ESG)

Public sector initiatives have primarily driven the fight against climate change, but the private sector is increasingly contributing. Major players in finance, including Blackrock, the world's largest asset manager, are acknowledging that astute investment necessitates an understanding of companies' exposure to climate risk. The idea that "climate risk is financial risk" is gradually gaining traction and influencing investment decisions. This shift is encouraging corporations like Goldman Sachs, Wells Fargo, and Bank of America to devise more sustainable plans for their future activities. The production of Environment, Social, and Governance (ESG) reports is a growing trend in this realm, although the scientific robustness of these reports can vary.

In tandem with financial self-interest, there's a growing belief that large companies can affect positive behavioural change aligning with improved investment prospects and reduced future vulnerability to climate risk. This blend of self-interest and public image considerations has the potential to foster more sustainable practices in business. As an illustration, Goldman Sachs published a comprehensive document linking natural capital and finance in preparation for the 2022 Convention on Biological Diversity COP 15.

The relationship between finance and climate change is particularly evident in the insurance sector. The majority of insured losses from natural disasters stem from climate change-intensified events. In 2022 alone, weather events worsened by climate change resulted in about $320 billion in economic costs, only 40% of which were insured. This deficit, mainly in the developed world, is driving up insurance policy prices and leaving an increasing number of assets uninsured due to unaffordability. The number and cost of climate-related disasters have escalated dramatically over the last decades, with the USA experiencing 341 events each causing damages of $1 billion or more between 1980 and 2022. This trend only emphasises the financial consequences of climate change.

EO data, both archived and real-time, have become increasingly pivotal in shaping insurance and reinsurance strategies. These data can help insurers better understand, anticipate, and assess the implications of disasters on premiums and claim volumes. This utility is particularly noticeable in parametric or index-based insurance, which relies heavily on the quantitative, impartial, and objective nature of remote-sensed data. In regions like the developing world, where other sources of hazard data are limited, mixed in quality, or lack a lengthy reliable historical record, the real-time or near real-time accessibility of EO data becomes particularly valuable.

In parallel, EO technologies are a significant boon to private sector finance, clean investing, and Environmental, Social, and Governance (ESG) decision-making. By delivering comprehensive and timely information on environmental shifts and states, EO data can assist investors in pinpointing and evaluating the sustainability and climate-related risks and prospects tied to various investments. Furthermore, they can substantiate the environmental impact assertions made by corporations, thereby bolstering transparency in clean investing. EO can also monitor the tangible results of ESG campaigns, allowing companies and investors to evaluate the success of these efforts, make informed decisions, and accurately report their ESG progress to stakeholders. In essence, EO plays an instrumental role in aligning financial and investment activities with environmental sustainability objectives.

TASK FORCE ON CLIMATE-RELATED FINANCIAL DISCLOSURE

The Task Force on Climate-Related Financial Disclosure (TCFD), championed by former Governor of the Bank of England, Sir Mark Carney, marked a significant advancement in engaging the private sector in climate change matters. The TCFD devised guidelines on what companies should disclose to help stakeholders, such as investors and insurers, assess and price climate-related risks. This approach mirrors the improved financial risk reporting implemented post the 2008 financial crisis, but focuses on exposing a company's exposure to climate risk. EO data can provide the baseline information necessary for such disclosures. By incorporating climate risks into their risk management and strategic planning, companies can more accurately price these risks and opportunities, leading to more efficient capital allocation.

Furthermore, the TCFD encourages businesses to account for both direct and subtle climate risks in their valuation. For instance, a company might be reliant on a raw material that could become scarce or a manufacturing process sensitive to increasing energy costs. Additionally, certain industries like oil and gas, face potential devaluation due to societal shifts towards more sustainable options. Recognising this, there's a growing pressure to invest in renewable technologies and reduce reliance on fossil fuels. On a broader scale, the Task Force on Nature-Related Financial Disclosures (TNFD) has been established to assess businesses' dependence on natural capital, acknowledging that the accelerating global nature loss poses significant risks to businesses and financial institutions. This initiative is a global, market-led, science-based, and government-supported response to the urgent need to include nature in financial and business decisions.

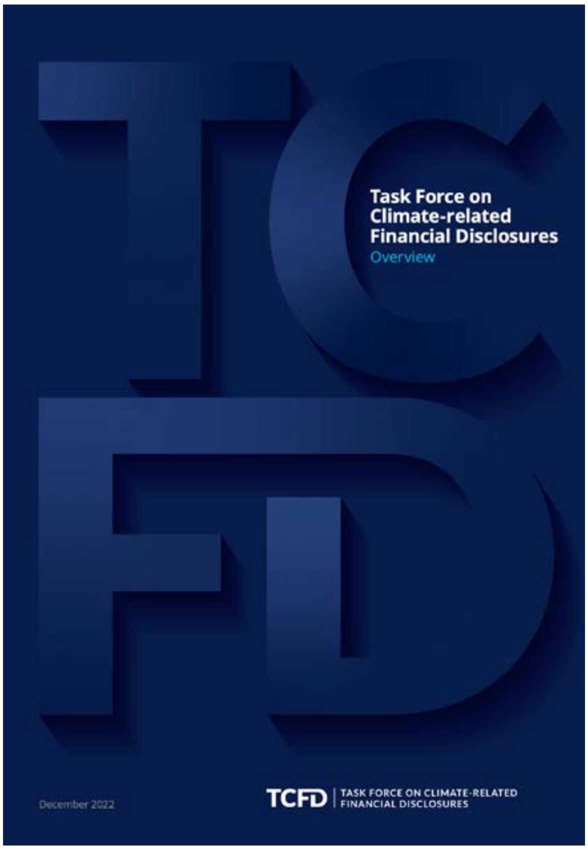


Figure 3: 2022 Overview Report of the Task Force on Climate-related Financial Disclosures.

EO can provide significant value to the work of the TCFD. The TCFD framework encourages companies to evaluate and disclose their climate-related risks and opportunities. Here's how EO can support this process:

1. **Risk Identification**: EO technologies can provide data that helps companies identify physical climate-related risks. For instance, satellite imagery can reveal areas prone to flooding, wildfires, or sea-level rise, which can pose significant risks to a company's physical assets or supply chains.

2. **Risk Assessment & Management**: Once risks have been identified, EO can assist in quantifying and monitoring these risks over time. For instance, data on changes in precipitation or temperature can help model future risks to agricultural yields, while information on deforestation can highlight risks related to reliance on certain supply chains.

3. **Opportunity Identification**: EO can also help identify opportunities related to climate change. For instance, companies looking to invest in renewable energy could use satellite data to identify optimal locations for solar or wind installations.

4. **Tracking & Reporting**: EO can support companies in tracking and reporting on their progress in managing climate-related risks and pursuing opportunities. This could include monitoring changes in land use related to a company's operations, or tracking the reduction of greenhouse gas emissions.

5. **Verification**: EO can provide an independent source of data to verify company disclosures. For instance, satellite data could be used to confirm a company's claims about its greenhouse gas emissions or the impact of its operations on deforestation.

In all of these ways, EO can provide valuable data that supports companies in aligning with the TCFD recommendations, enhancing their understanding of climate-related risks and opportunities, and communicating about these issues with their investors and other stakeholders.

CONCLUSION

The intertwining of climate finance and EO data is critical in our global quest to adapt to and mitigate the impacts of climate change. The evolution and augmentation of financial mechanisms, as demonstrated in the historical and ongoing developments within the UNFCCC, emphasise the vital role of finance in both adaptation and mitigation strategies. However, realising the full potential of these financial instruments demands effective decision-making and transparency, which in turn require reliable and comprehensive data - a need increasingly being met by EO technologies.

EO data has proven to be a significant asset in providing consistent, long-term, and spatially comprehensive information, assisting in the monitoring and evaluation of climate impacts and adaptation measures. These technologies allow us to better understand and forecast future climate risks, aiding in the design of more targeted and effective financial interventions. Furthermore, EO plays a crucial role in verifying the impact of climate investments and ensuring accountability, thereby increasing the attractiveness of such investments for the private sector.

While challenges remain in interpreting EO data and translating them into actionable insights, ongoing advancements in data science and the growing familiarity of financial institutions with these tools are steadily overcoming these barriers. Moreover, the recognition of climate risk as a material financial risk by influential financial institutions underscores the urgency of integrating EO data into financial decision-making processes.

Lastly, the growing use of EO data in assessing and managing climate-induced loss and damage highlights another important application of these technologies in directing climate finance. As the impacts of climate change intensify, the role of EO in helping countries navigate the difficult terrains of loss and damage will undoubtedly become increasingly critical.

In essence, the integration of EO data and climate finance has the potential to catalyse transformative climate action. As we continue to refine these tools and methodologies, their impact on the global response to climate change is poised to be profound. This is an evolving field, and as such, it invites further exploration and innovation.

6 FUTURE CAPABILITIES AND CHALLENGES

This Handbook has sought to demonstrate how fundamentally vital satellite observations are to our ability to measure, manage and adapt to climate change

- and to support the success of the Global Stocktake (GST) process of the Paris Agreement in particular. Satellite Earth observations (EO) provide:

- **climate data records** for 38 of the 55 Essential Climate Variables (ECVs);
- **more accurate measurement of greenhouse gas (GHG) emissions** and the development of national inventories on emissions;
- **more complete aggregated mitigation estimates for the GST** including through multiple contributions targeting the **Agriculture, Forestry, and Other Land Use (AFOLU) sector** to support the development of national inventories which are often incomplete in this challenging sector;
- **improved modelling and forecasting** of changes to our climate by the expert centres situated around the globe;
- **augmented early warning** capabilities for severe weather such as cyclones, heatwaves and flooding – phenomena that are increasing in frequency and severity as the temperature and humidity of the atmosphere rise;
- support for the **development and implementation of more effective and**

timely adaptation actions and preparation of adaptation communications across key socioeconomic sectors, including for agriculture as countries seek to evolve national practices with changing circumstances to ensure food security and resilient agricultural systems for their population and markets.

Part II of the Handbook goes into more detail for some of these capabilities. It features a number of case studies that can be read as stand-alone stories to inspire those who might benefit from satellite EO. Further study resources and contacts for assistance are provided in each case.

For all of the accomplishments in the EO satellite sector regarding its contribution to information for climate policy, much more could and should be done to harness and apply this incredible data in support of the information needs of the United Nations Framework Convention on Climate Change (UNFCCC), the GST process and the myriad of stakeholders who participate in it. The latest (2022) Implementation Plan from the Global Climate Observing System (GCOS) provides a supplement directed specifically at the space agencies coordinated by the Committee on Earth Observation Satellites (CEOS) and the Coordination Group on Meteorological Satellites (CGMS), offering a set of high priority actions (intended for a timescale of 5–10 years) which, if undertaken, will improve global observations of the climate system and our understanding of how it is changing. The GCOS requests to space agencies include:

- **ensuring sustainability**: long-term, continuous, in situ and satellite observations of the climate are necessary to understand and respond to the changing climate;
- **filling data gaps**: despite their successes, key gaps do exist in satellite observations;
- **improving data quality, availability and utility**: essentially to ensure that the original highly technical observational data is transformed into user-relevant information.

These themes and others are explored below as part of our future challenges.

ENSURING SUSTAINABILITY OF EO SATELLITE CONTRIBUTIONS

GCOS has noted that urgent actions are needed to ensure continuity of the following satellite observations:

- altimetry in the polar regions;
- gravimetry;
- biomass measurements;
- measurements of several ECV species in the upper troposphere and stratosphere areas of the atmosphere;
- sea surface salinity;
- wind lidar measurements;
- global scale ice surface elevation.

Further action is also needed to address medium- and long-term continuity of the following satellite observations: Earth radiation budget (ERB) measurements; cloud profiling; cloud lidar; global precipitation measurements to provide sufficient temporal and spatial sampling of rain areas; sea ice and icebergs. GCOS notes the real danger that some observations will stop in the next 5–10 years, or even sooner for missions that have already exceeded their expected lifetime.

The continuity of these measurements is essential to develop and extend the long time series needed for climate monitoring. CEOS and CGMS have established a process focused on the ECV inventory and a formal response to the GCOS Implementation Plan that seeks to ensure a comprehensive and effective institutional plan to all the actions identified periodically by GCOS for space agencies.

A fundamental commitment by governments investing in space-based EO is needed to ensure continuation of the required observations at an acceptable level of accuracy and coverage. Funding and execution of the individual satellite programmes remains the responsibility of individual governments and their space agencies, and CEOS will continue to be dependent on their funding and capacity to deliver the EO satellite programmes.

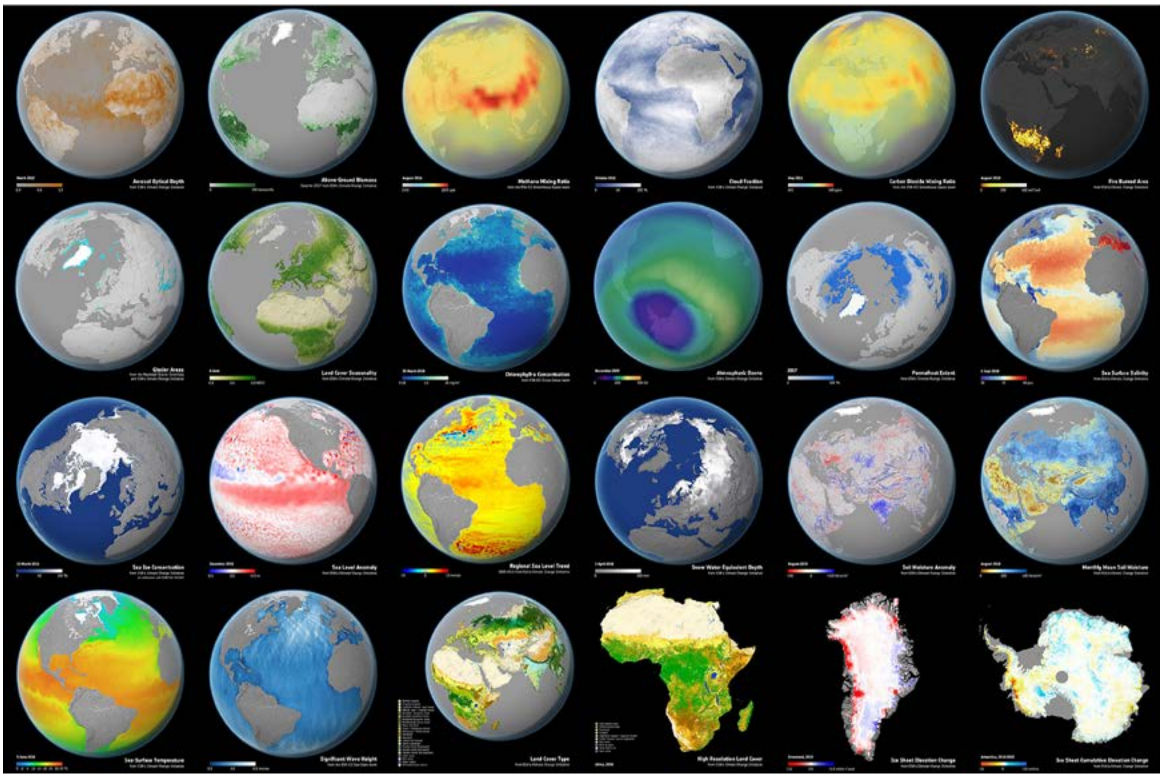


Figure 1:
ESA's Climate Change Initiative is developing satellite-derived data sequences for 22 of the 55 essential climate variables.

CEOS will aim to ensure continuity, consistency and inter-comparability of the priority measurements throughout the coming decades, consistent with the requirements of climate studies for trend monitoring and change detection. The CEOS Database documents all current and planned EO satellite missions of the world's civil space agencies. The eoPortal has details of many more commercially-funded missions.

FILLING DATA GAPS

Measuring long-term global climate change from space is a daunting task. The climate signals we are trying to detect are extremely small: temperature trends of only a few tenths of a degree Celsius per decade, ozone changes as little as 1% per decade and variations in the Sun's output as tiny as 0.1% per decade or less. Accuracy is an important attribute of a climate observing system and helps to advance the understanding of physical processes in the Earth's climate system. GCOS notes the need for 'reference quality' observations to ensure greater confidence in the assessment of future climate change and variability.

In response, CEOS space agencies foresee a series of highly accurate climate-reference instruments in order to measure with high spectral resolution the energy reflected and emitted by the Earth. These instruments would provide reliable long-term records of climate forcing, response and feedback to monitor climate change. Their records would also serve as the validation data needed to test and evaluate climate model predictions. The benchmark instruments would also constitute a reference standard, or calibration observatory, in space that can be applied to other environmental satellite sensors that are not as well calibrated. Examples include the CLARREO and TRUTHS missions. The improved climate change projections from these missions will enable more informed strategic planning and risk assessments by governments at all levels, and by the reinsurance industry, amongst others. Their high accuracy levels can detect small decadal trends sooner than is possible with current EO assets and reduce uncertainties in the long-term measurement of climate change.

GCOS has challenged space agencies to develop new missions to address other gaps in observing systems, including: GHGs; estimates of Earth's

Energy Imbalance (EEI); direct measurements of ocean surface currents from space; and permafrost extent.

IMPROVING DATA QUALITY, AVAILABILITY AND UTILITY

The variety and volume of the data required to satisfy society's climate information needs is staggering. It is potentially the ultimate Big Data challenge of our era. The good news is that a number of trends should continue to lower the barriers to entry for uptake and application of the relevant EO satellite data, including:

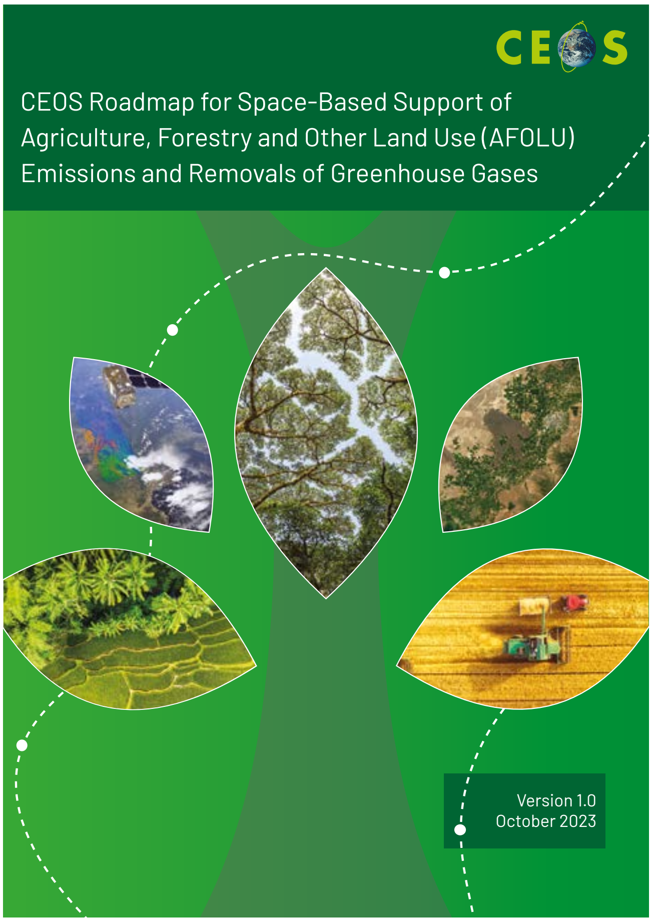
- **More accessible and affordable cloud computing, storage and analytics**: Tools such as Google Earth Engine, Microsoft Planetary Computer, Digital Earth Africa, AWS, the Copernicus Data and Information Access Services (DIAS), and NASA's Earth Data are revolutionising the ability of organisations and even individual citizens to acquire, manipulate and exploit large satellite datasets of relevance to their climate studies and applications. Such systems bring users to the data and provide simpler formats and means of analysis.
- **Reduced complexity** through initiatives and standards such as the CEOS Analysis Ready Data work: CEOS Analysis Ready Data (CEOS-ARD) are satellite data that have been processed to a minimum set of requirements and organised into a form that allows immediate analysis with a minimum of additional user effort and interoperability both through time and with other datasets.
- **Machine learning and Artificial Intelligence (AI) methods** for Big Data challenges: The application of EO satellite data to climate applications may be ripe to benefit from such technology. AI is becoming increasingly important in understanding climate impacts, being well suited to complex systems where fully inclusive geophysical models are not available. AI should allow increased application of EO data, including in combination with multiple other datasets such as socioeconomic data, in the areas of climate impacts, adaptation, loss and damage, or financial modelling where many different data types need to be investigated and combined. AI will also allow emulation of some complex climate model components, which in turn enables faster and more comprehensive investigation of scenarios. As the quantity and diversity of EO data available for climate purposes increases, we may expect more statistical models developed making good use of these massive datasets and reducing dependence on extremely complex climate models.

EFFECTIVE INSTITUTIONAL ARRANGEMENTS AND USER ENGAGEMENT

Effective institutional arrangements have been proven to be fundamental to the progress achieved to date in establishing consensus on climate information requirements and coordination in the provision of observations to address them. The cooperation between CEOS-CGMS and GCOS in support of the information requirements of the UNFCCC and its Parties is fundamental to the future success of the Convention and demonstrates the importance of strong partnerships between observation planners and global environmental governance frameworks like the UNFCCC. But given the data needs of the GST process, and the need for all countries to satisfy them, it is clear that space agencies need to increase their efforts in support of the current and potential users of EO satellite data so that its full potential is understood and national agencies are able to identify, locate and apply the data that they need for their national inventory development, national reporting, adaptation plans and more.

As part of a comprehensive strategy developed for space agencies to optimise their support to the GST, CEOS has resolved to work with capacity building organisations to help countries understand and develop satellite-based methods to assist them in their national reporting - particularly in relation to the AFOLU sectors. This work is led by SilvaCarbon

– an interagency technical cooperation program of the US Government to enhance the capacity of selected tropical countries to measure, monitor and report on carbon in their forests and other lands. Drawing on expertise and resources from multiple US Government agencies and partners such as the Global Forest Observations Initiative (GFOI), the program provides targeted technical support to countries in the process of developing and implementing national forest and landscape monitoring systems to support management decisions. SilvaCarbon leverages state-of-the-art science and technology to advance the generation and use of improved information related to forest and terrestrial carbon.



The Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) initiative seeks to strengthen the international agricultural community's capacity to utilise coordinated, comprehensive and sustained EO for the provision of timely and accurate information on agricultural production and food security.

Further, the new CEOS AFOLU Roadmap developed to steer space agency strategy in this area, emphasises the need for collaboration between the CEOS agencies engaged in land surface and carbon process observation and the domestic GHG inventory analysts and land measurement experts in the context of the UNFCCC, as well as capacity building programs and country practitioners. Regional workshops and development of case studies or demonstrations are planned ahead of the new cycle of submissions starting in 2024, which will be an input to the 2028 GST.

Although the supply outlook is strong for EO satellite data in support of multiple aspects of the GST, it does not necessarily follow that country and practitioner uptake of the resulting data and products will increase. Indeed some analysis suggests that, despite an increase in available satellite-derived global products, there is limited use by countries (from a sample of 56 tropical countries reporting to the UNFCCC in the period 2014–2022) of the majority of available global land EO products. **This underlines the need for developers of EO products to interact with groups responsible for GHG inventories and experts familiar with Intergovernmental Panel on Climate Change (IPCC) guidance (e.g., IPCC Task Force on National Greenhouse Gas Inventories) so that their products are suitable for national reporting, and thus contribute to more complete aggregated estimates in the GST.**

Of the sample of 56 countries reporting to UNFCCC, we see that all of them use satellite data for national Activity Data - emphasising the extreme importance of continuity of the data for effective operation of the national inventories and reporting. The request from GCOS of ensuring sustainability, addressing data gaps (e.g., spatial imbalance, cloudy areas), and improving data quality and adequacy are essential for climate monitoring (as highlighted above) but also for land monitoring. This data sustainability is essential to support national reporting for the land sector to the UNFCCC and to increase the confidence in the data used by the GST process.

Figure 2: Analysis of use of EO data in forest reference level submissions to the UNFCCC by developing countries between 2014 and 2022. The colour scheme in the quadrant charts shows the use of satellite data (e.g., Landsat imagery) and derived EO products (or global maps) to directly derive activity data (AD, left-hand quadrants in red and yellow respectively), and emission factors (EF, right-hand quadrants in teal and green respectively). Indirect uses of EO products are represented with a • mark in a quadrant (e.g. use for validation, to justify decisions) (Melo et al., 2023)

EMERGENCE OF NEW GHG MONITORING SYSTEMS

Major national and continental initiatives are underway to develop the capability to better monitor and measure our GHG emissions. These systems will be heavily reliant on the observations they harvest from EO satellites to provide the coverage and consistency needed to be useful. Some of these satellites will be custom-built for the purpose of serving these systems. The US is formulating its integrated GHG measurement and monitoring information system (GHG Center). Europe is developing the CO_2 Monitoring and Verification Support project (CO2MVS), driven by a new generation of highly accurate and precise passive and active CO_2 and CH_4 imaging satellites (CO2M and MERLIN) as part of the Copernicus Sentinel programme. Sustained, routine global monitoring of GHG concentrations and fluxes is required to support mitigation action taken by the Parties to the UNFCCC. The World Meteorological Organization (WMO) has plans for a new Global Greenhouse Gas Watch that will fill critical information gaps and provide an integrated, operational framework that brings together all space-based and surface-based observing systems, as well as modelling and data assimilation capabilities. Such system-led activities will help ensure that the space agency capabilities are suitably directed and that there are strong connections to potential users and policy processes. The CEOS GHG Portal explains the significant plans underway for new satellite missions dedicated to measuring GHG emissions.

LEARN MORE & GET HELP

The Committee on Earth Observation Satellites: https://ceos.org/

The Group on Earth Observations: https://earthobservations.org/

The CEOS Data Portal for the Global Stocktake: https://ceos.org/gst/

The CEOS satellite missions database: http://database.eohandbook.com/

SilvaCarbon: https://www.silvacarbon.org/

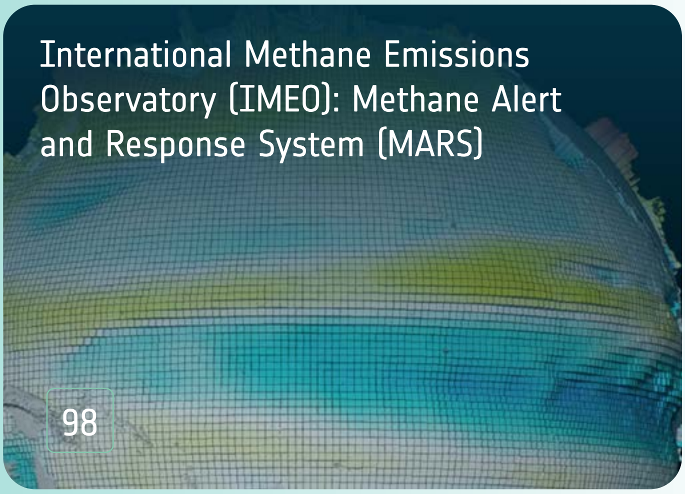
GFOI: https://www.fao.org/gfoi/

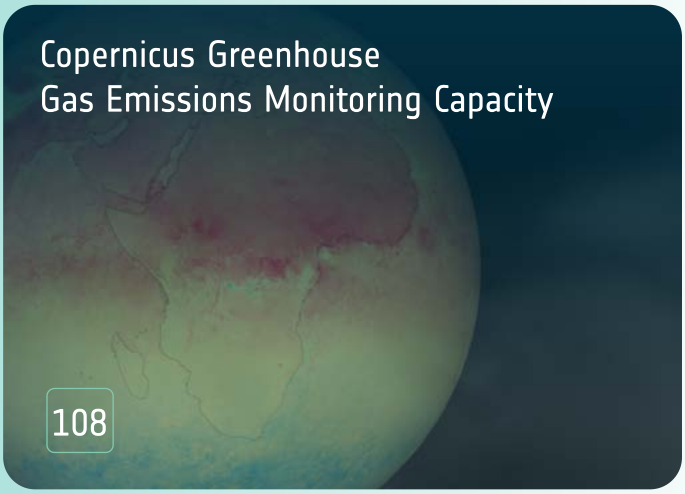
GEOGLAM: https://earthobservations.org/geoglam.php

ECV Inventory & Use Cases: https://earthobservations.org/geoglam.php

PART II

CASE STUDIES TO INFORM AND INSPIRE





SILVACARBON SUPPORT TO NATIONAL FOREST MONITORING SYSTEMS

CONTRIBUTED BY SILVACARBON (SYLVIA WILSON)

Robust National Forest Monitoring Systems (NFMS)-based on satellite observations are a prerequisite for countries participating in international forest carbon agreements and reporting frameworks of the United Nations Framework Convention on Climate Change (UNFCCC). To operate efficiently and sustainably, NFMS require a continuous, timely, and affordable supply of observations.

SilvaCarbon

The Committee on Earth Observation Satellites (CEOS) seeks to facilitate this data supply through partnerships like the Global Forest Observations Initiative (GFOI). In support of the GFOI, the SilvaCarbon program aims to strengthen the capacities of tropical countries by building regional partnerships and transferring information and knowledge. These tropical countries have pledged to reduce carbon emissions from deforestation and degradation as part of their Nationally Determined Contributions (NDCs) to the Paris Agreement and in exchange for results-based payments under the Reduction of Emissions from Deforestation and forest Degradation plus (REDD+) program. To do so, satellite-based forest monitoring has become an integral part of these commitments. Still, most country assessments are done annually or biennially and only detect deforestation *post facto*. However, satellite information can be a tool for achieving emissions reductions by generating forest cover change alerts that detect deforestation daily, weekly or monthly. Deforestation alerts' frequency and low latency make it possible for law enforcement and other actors to respond rapidly, potentially halting further forest clearing early on. In addition, these alerts identify areas where deforestation occurs and inform authorities and local communities so that appropriate action can be taken.

Figure 1: Deforestation alert site (Hai Pham Ngoc - FIPI, Vietnam)

In the Amazon, deforestation alerts are beneficial for identifying deforestation patterns along roads and highways. A combination of factors – economic opportunities, infrastructure development, population growth, and the expansion of agricultural frontiers – drives these patterns. Therefore, identifying deforestation patterns using real-time alerts is essential to prevent significant ecological and environmental impacts, including habitat fragmentation, loss of biodiversity and increased carbon emissions.

The SilvaCarbon program – a multi-federal agency program supported by the US Agency for International Development (USAID) and the US Department of State, implemented by the US Geological Survey (USGS) and the US Forest Service (USFS) – is committed to assist countries using Earth observation (EO) data to monitor deforestation and forest degradation and its associated carbon emissions. In addition, USGS has embarked on a broad range of activities in collaboration with CEOS to support countries using satellite data to achieve their commitments to the

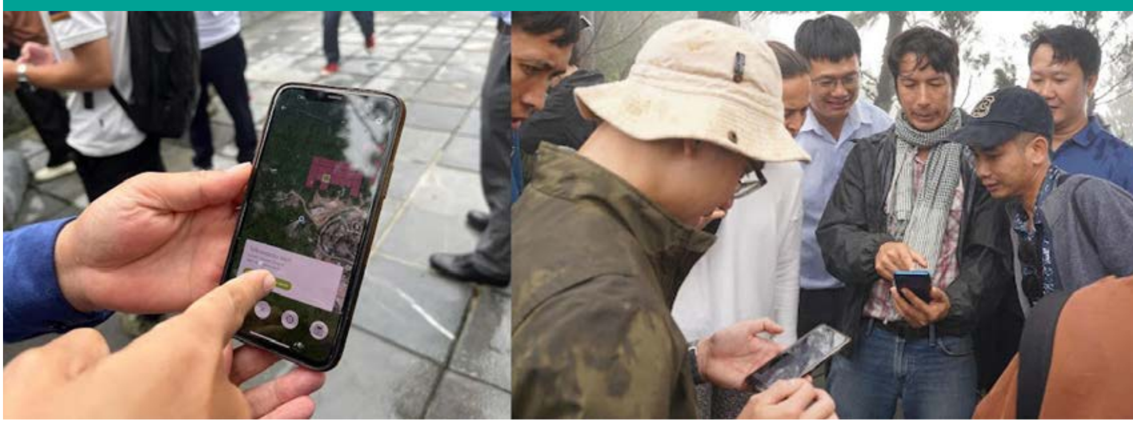


Figure 2: Participants validating deforestation alerts in situ at a SE Asia regional workshop on early warning systems (DaNang, Vietnam, November 2022)

Paris Agreement. SilvaCarbon has engaged with multiple countries since 2011, building the technical capacity to use EO data in their NFMS.

The program is currently working in 30 countries covering the tropics. SilvaCarbon's capacity-building plan for FY 2023 and 2024 has scheduled a series of regional workshops to discuss the value of deforestation alerts and early warning systems for carbon emission reporting forums, land management, and law enforcement. These workshops allow the exchange of experience from countries on the use of alerts and early warning systems and showcase different operational and research-stage methodologies that use data from a single sensor or multiple sensors.

LEARN MORE & GET HELP

If your NFMS could benefit from the kind of assistance described above, please get in touch with SilvaCarbon.

SilvaCarbon: www.silvacarbon.org

SilvaCarbon video: watch

CONTACT

Sylvia Wilson: snwilson@usgs.gov

Figure 3: Participants from Latin American countries at a SilvaCarbon Latin America regional workshop on implementation of early warning systems for deforestation

Figure 4: Presentation of Mexico's pilot early warning system at a Latin America regional workshop on implementation of early warning systems for deforestation

In FY 2023, CEOS, SilvaCarbon, and the World Research Institute hosted two regional workshops in Vietnam and Mexico. The outcomes of the regional workshops included:

- identifying stakeholders who would benefit from deforestation alerts, such as local communities, governments, and conservation organisations; and
- identifying the data sources and machine learning algorithms to produce alerts and developing a plan to deploy the deforestation alerts to the stakeholders, such as through a web-based platform or mobile application.

The next logical step is to monitor the effectiveness of the deforestation alerts and make improvements based on stakeholder feedback.

OPENFORIS AND SEPAL: ACCESS TO EARTH OBSERVATION DATA FOR ADVANCED ANALYSIS BY ANYONE, ANYWHERE

CONTRIBUTED BY FORESTRY DEPARTMENT, FAO (ERIK LINDQUIST AND INGE JONCKHEERE)

The goal of the Food and Agriculture Organization's (FAO) OpenForis Initiative and SEPAL is to remove the barriers to Earth observation (EO) and to allow data access and cutting-edge processing methods so that anyone, anywhere can produce sophisticated, useful and actionable results, especially where these results inform locally relevant decisions. By enabling better decision-making and targeted action, OpenForis and SEPAL will likely improve natural resource management and facilitate increased ecosystem and human resilience to otherwise high-impact environmental perturbations.

To ameliorate, manage and potentially reverse the negative impacts on human life and livelihoods caused by climate change, accurate information on natural resources is required to catalyse good decision-making. This information, data and methods need to be both consistent across large geographies and available to people *in situ*, at the point where decisions are being made. In many cases, people most vulnerable to changing environmental conditions and emergencies are also located in areas traditionally underserved by technology capable of increasing resilience and informing positive actions.

Figure 1. A Brazilian Amazon peat forest as seen from the European Space Agency Copernicus Program's Sentinel-2 sensor and enhanced for viewing using the SEPAL platform. SEPAL makes use of Copernicus and Landsat data to quickly provide analysis ready data on the fly.

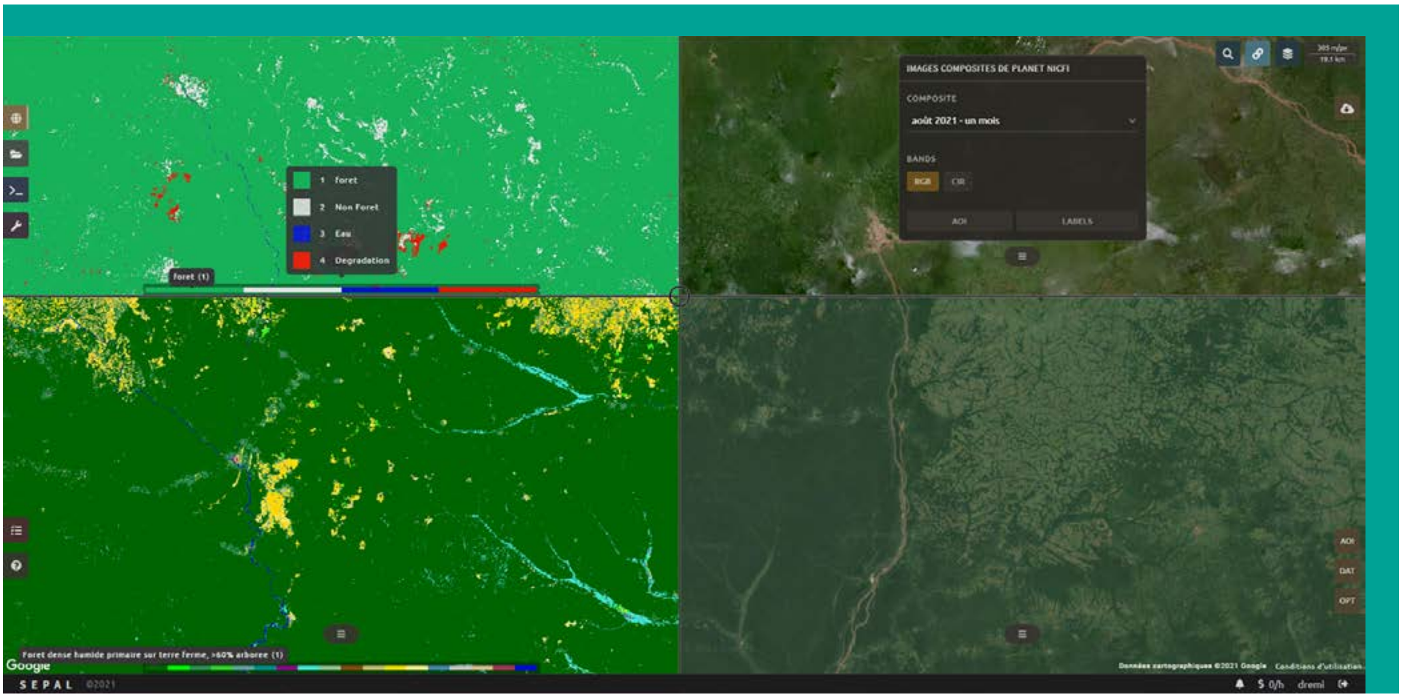
Figure 2: New Georgia, central Solomon Islands in 2021 from Landsat and enhanced for viewing and analysis in the SEPAL platform.

All OpenForis software developed by FAO Forestry is free and open-source, enabling autonomous processing and analysis of geospatial data for customised land and forest monitoring by a broad spectrum of stakeholders. The tools and platforms available through OpenForis empower users to process satellite data, create customised maps and detect land cover and land-use change. They also provide many other functions critical to effective land management without the need for coding skills. The tools work seamlessly with modern geospatial data infrastructures, such as Google Earth Engine, further driving the generation of high-integrity forest and land-use information that help users answer complex questions about any area of interest, land managers make more informed decisions, and countries attract finance for forest-related climate action.

As a global digital public good, the OpenForis initiative promotes and strengthens the collaboration between space agencies, intergovernmental and non-governmental organisations, research institutions and civil society to effectively deliver the services promised by Big Data analytics, including the dissemination and exchange of results, which can improve the accessibility and transparency of data.

Figure 3: OpenForis overview and SEPAL overview (web and mobile version)

Figure 4: The SEPAL multi-view interface showing (clockwise from upper left) a SEPAL-derived land cover classification, the associated NICFI/ Planet high resolution monthly basemap, Google high-resolution imagery, and a CEOS global land cover layer used to guide training for producing a more locally relevant land cover map.



OPENFORIS AND SEPAL USEFUL FOR AUTONOMOUS ANALYSIS AT MANY SPATIAL SCALES

AN INDONESIAN PEATLAND STORY: Innovative monitoring of Indonesia's peatlands

A collaboration of the BRGM (Peat Restoration Body of Indonesia), FAO and the key Indonesian institutions working on monitoring have developed an integrated system to monitor soil moisture, a key variable that helps with understanding and protecting Indonesia's peatlands.

Widayanto (53) has a small farm in Djabiren village, Pulau Pisang District, a town 125 km from Palangkaraya, the capital of Central Kalimantan. He never thought his routine work would contribute to protecting millions of hectares of peatlands across Indonesia. He has planted lowland fruits and native sengon trees in his ten-hectare peatland to rehabilitate the degraded land; the BRGM has installed some of its equipment to automatically monitor the peatland, including its groundwater levels (GWLs), on this land. Widayanto has been trained to maintain the equipment by checking its operation monthly, or as needed. His work helps to verify the satellite data that the BRGM displays as part of the Peatland Restoration Information and Monitoring System (PRIMS). The BRGM runs this system to display information on peatland conditions and the latest developments in peatland restoration across the provinces where it works. The PRIMS Platform has been supported by several international organisations, including WRI Indonesia and FAO, which has provided satellite data processing. Since 2016, FAO has also developed capacity within the BRGM and other key institutions to allow Indonesians to take advantage of the international guidance and tools for peatlands and peatland monitoring.

"I check the equipment to see the groundwater levels and report to the BRGM regularly. I also tell my friends about the peatlands' conditions, especially the water. If the groundwater level is low, meaning that the peatland is very dry, I tell my friends to be careful, for example not to throw their cigarettes to the ground. A burning cigarette can easily start a fire across our land when the soil is dry," Widayanto said. He is vigilant of forest fires. In 2015, he experienced huge forest fires that burned his land. Widayanto, who worked in the East Javanese plantations for 20 years before migrating to Central Kalimantan as a plantation farmer, said the losses were enormous. However, he managed to survive and is keen to see the rewetting of peatlands contributing to the reduction of large fires. In 2018, he agreed to support the BRGM by allowing the agency to install tools to monitor GWL on his land. This is a decision that he has never regretted. “Since we can monitor the condition of our land, we have not experienced forest fires anymore. We have been alerted from time to time of the condition of our land. If it is too dry and the situation too worrying, together we rewet our land to make sure it is wet enough,” he said. Widayanto is among the 154 Indonesian farmers who also work as BRGM “peatland watchers” in the seven priority provinces for peatland restoration. “Reports from the field help to verify the data that the satellites give us for the PRIMS. The satellite images help us to have an aerial view of the peatlands’ condition across the country. These monitoring systems also support early detection of issues, and finally to take action by working together with the local governments and farming communities on the ground,” explains Ahmad Syaugi, a specialist in geographic information systems at BRGM.

THE BACKBONE FOR PEATLAND MONITORING

FAO, jointly with BRGM officials, has been supporting peatland restoration monitoring in Indonesia, and in collaboration with academia, has developed a new satellite-based spatial data set for soil moisture.

This information is displayed on PRIMS as a map of soil moisture, which correlates well with the GWLs measured on the ground, such as on Widayanto’s land.

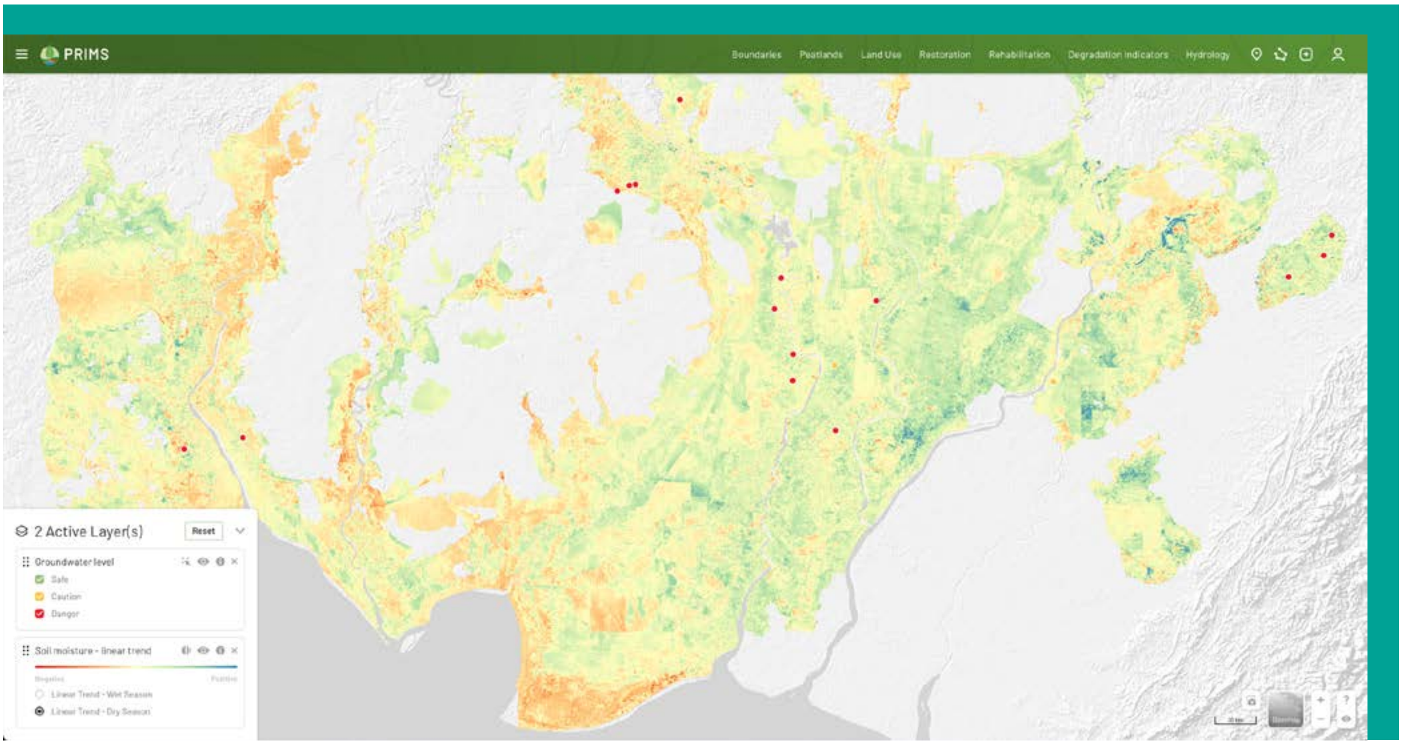


Figure 5: Soil moisture data as displayed in the PRIMS platform and GWL measurement points. Source: PRIMS Platform

“This is a new, fast, easily repeatable and frequent monitoring approach that allows the covering of huge areas and has never existed before. Previously there was information from a few field data points scattered across the peatlands, where soil moisture and GWL were measured; however, actors were lacking information on what was happening in between those measurements,” says Adam Gerrand from FAO’s office in Indonesia.

The soil moisture and other tools are now available as modules of the FAO-SEPAL system, also called “System for Earth Observation Data Access, Processing and Analysis for Land Monitoring”, an open-source platform offered by FAO to measure, monitor and report on ecosystems. Through SEPAL, anyone can gain free access to historical and new satellite data, including in high resolution. The platform allows its users to query and process satellite data quickly and efficiently, and to tailor their products for local needs. SEPAL is funded by the Government of Norway.

FAO has also developed an Excel-based tool, called the Peat-GHG tool, to easily estimate greenhouse gas (GHG) emissions from different land management options on peatlands. It has been specially tailored for Indonesia and follows international guidelines. “It helps Indonesian agencies and decision-makers to quickly assess and compare in advance different options for peatland interventions based on the carbon benefits,” says Maria Nuutinen, peatland specialist at FAO headquarters.

Since 2018, staff from the BRGM, together with colleagues at the Indonesian Ministry of Environment and Forestry and other officials from 16 institutions, have been participating in intense exchanges and capacity development in Rome, Jakarta and Bogor, as well as online, to effectively benefit from SEPAL and the Peat-GHG tool, and become proficient users of these tools.

“Our collaboration with FAO on the data processing of soil moisture and groundwater level monitoring on PRIMS is key for effective peatland restoration monitoring. If we see through the satellite imagery that soil moisture is decreasing, we talk to the local government and farmers in the field to check the real conditions, and then take action”, said Budi Wardhana, the former Deputy Head for Planning and Cooperation of BRGM.

PRIMS also alerts for possible forest fires in a given location. The combined data from GWL monitoring, weather prediction from the meteorology agency, and humidity index from SEPAL provide clues to possible forest fires. “We share the data with the local government and provincial disaster agencies for them to prepare,” Budi added.

The BRGM uses PRIMS to communicate with the public, as part of their accountability system. The agency has trained local government officials, civil society and journalists to monitor progress in peatland restoration across Indonesia through PRIMS.

"We want the restoration activities to not be just a central government activity. We want to restore our peatlands together with the local governments and the people," said Budi.

The Indonesian peatland area estimates vary, but it is estimated to cover between 15-26 million hectares, slightly bigger than the size of the Island of Java and contains three-quarters of the tropical peatlands' carbon storage.

"Before, we were blind. We did not have enough knowledge on how to manage our land. But now, since we have access to data about the condition of our land, we understand how to use it better. These are simple actions: Do not start fires and keep the land wet," Widayanto said.

LEARN MORE AND GET HELP

Further Use Cases

Forest Restoration Planning in Nepal (Video): https://www.youtube.com/watch?v=ZGbiCM1Yu-w&t=3694s

Assessing Land Degradation in Bangladesh: https://restorationmonitoringtools.org/sepal-assessing-land-degradation-bangladesh

Integration of SEPAL into Uganda's National Forest Monitoring System: https://www.fao.org/documents/card/en/c/cc4828en

Indigenous Communities using SEPAL for emergency planning: https://storymaps.arcgis.com/stories/0f8bb713657048568e496485fca066ca

OpenForis: https://openforis.org/

SEPAL: https://www.fao.org/in-action/sepal/en

POINT OF CONTACT

Erik Lindquist: Erik.Lindquist@fao.org

PILOT NATIONAL INVENTORIES FOR GREENHOUSE GASES

CONTRIBUTED BY NASA JPL (BRENDAN BYRNE, DAVID BAKER, JOHN WORDEN)

INTRODUCTION

A new dataset has demonstrated how emissions and removals of CO_2 from individual countries can be derived directly from atmospheric CO_2 measurements. The pilot project offers a powerful new look at the CO_2 being emitted in these countries and how much of it is removed from the atmosphere by forests and other carbon-absorbing "sinks" within their borders. The findings demonstrate how space-based tools can support insights on the Earth's environment as nations work to achieve climate goals. A detailed description of the dataset can be found in Byrne et al. (2023).

Traditional activity-based (or "bottom-up") approaches for estimating CO_2 emissions and removals rely on tallying and estimating how much CO_2 is being emitted across all sectors of an economy, such as electrical power generation, transportation and agriculture. These bottom-up techniques are used to develop national greenhouse gas inventories (NGHGIs) used to track national emissions and removals within the context of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. Bottom-up carbon inventories are critical for assessing progress toward emission-reduction efforts, but compiling them requires considerable resources, expertise and knowledge of the extent of the relevant activities.

This is why developing a database of emissions and removals directly from atmospheric measurements could be especially helpful for nations that lack traditional resources for inventory development. In fact, this pilot study includes data for more than 50 countries that have not reported emissions for at least the past 10 years.

To develop these atmospheric estimates, this study used measurements made by NASA's Orbiting Carbon Observatory-2 (OCO-2) mission, as well as a network of surface-based observations, to quantify increases and decreases in atmospheric CO_2 concentrations from 2015 to 2020. These data were combined with estimates of atmospheric transport by winds to infer the balance of how much CO_2 was emitted and removed by all processes within each nation's borders.

This atmospheric measurement-based (or "top-down") approach provides a new perspective by tracking both fossil fuel emissions and the total carbon "stock" changes in ecosystems associated with CO_2 emissions and removals by trees, shrubs and soils. These data are particularly useful for tracking CO_2 fluctuations related to land use and land cover change. Emissions from deforestation alone make up a disproportionate amount of total carbon output in the Global South, which encompasses regions of Latin America, Asia, Africa and Oceania. In other parts of the world, the findings indicate some reductions in atmospheric carbon concentrations via improved land stewardship and reforestation.

These top-down estimates provide an independent estimate of these emissions and removals, so although they cannot replace the detailed process understanding of traditional bottom-up methods, we can check both approaches for consistency to create a more complete, accurate and transparent global stocktake.

HOW TOP-DOWN ESTIMATES ARE PERFORMED

Top-down estimates of CO_2 emissions and removals (called "fluxes") are derived from atmospheric CO_2 observations. These data are obtained using both ground-based and space-based observing systems. Ground-based CO_2 measurements are collected across a network of surface sites spread across the globe. These data are complemented with measurements from ships and aircraft. Space-based observations retrieve column-averaged dry-air mole fractions of CO_2 (X_{CO2}) from

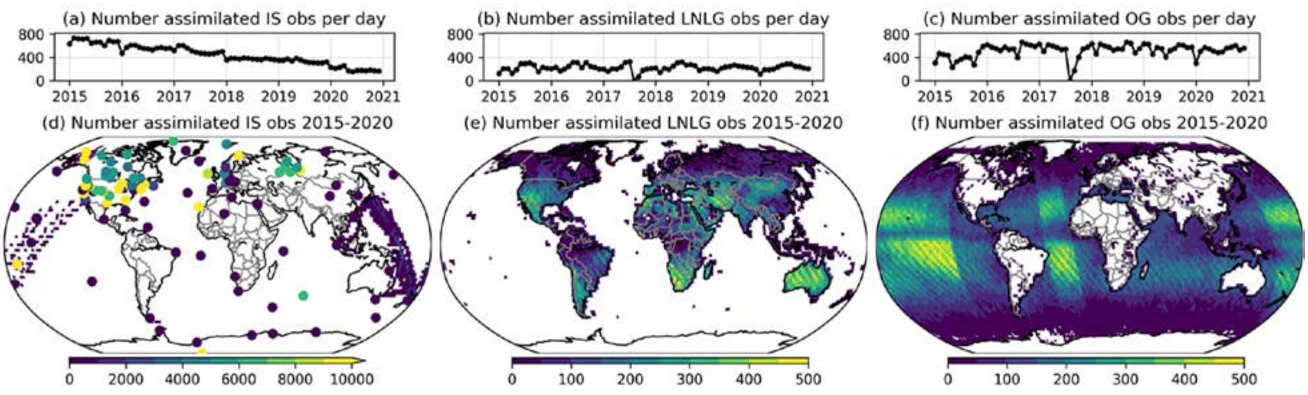


Figure 1: Distribution of atmospheric CO_2 observations for IS, LNLG and OG v10 MIP experiments. Number of monthly (a) in situ CO_2 measurements and (b) ACOS v10 OCO-2 land nadir and land glint X_{CO2} retrievals binned into 10 s averages and (c) ACOS v10 OCO-2 ocean glint X_{CO2} retrievals binned into 10 s averages. Spatial distribution of (d) in situ (e) ACOS v10 OCO-2 land X_{CO2} retrievals and (f) ACOS v10 OCO-2 ocean X_{CO2} retrievals over 2015–2020. Shipboard and aircraft in situ CO_2 measurements are aggregated to a 2° × 2° spatial grid, surface site measurements are shown as scattered points and ACOS v10 OCO-2 X_{CO2} retrievals are shown aggregated to a 2° × 2° spatial grid.

measurements of sunlight reflected off the Earth's surface. Figure 1 shows the distribution of ground-based in situ (IS) data, space-based X_{CO2} estimates derived from measurements collected over land (land nadir and land glint, LNLG) and over ocean (ocean glint, OG).

Top-down estimates of surface-atmosphere CO_2 fluxes are derived from atmospheric CO_2 observations using atmospheric CO_2 inversions. In this approach, an atmospheric chemical transport model (CTM) is employed to relate surface-atmosphere CO_2 fluxes to observed atmospheric CO_2 concentrations. As an inverse problem, the upwind CO_2 fluxes are estimated from the downwind observed CO_2 concentrations. The surface CO_2 fluxes are adjusted so that forward-simulated CO_2 concentrations better match the CO_2 measurements while considering the uncertainty statistics on the observations, transport and prior surface fluxes.

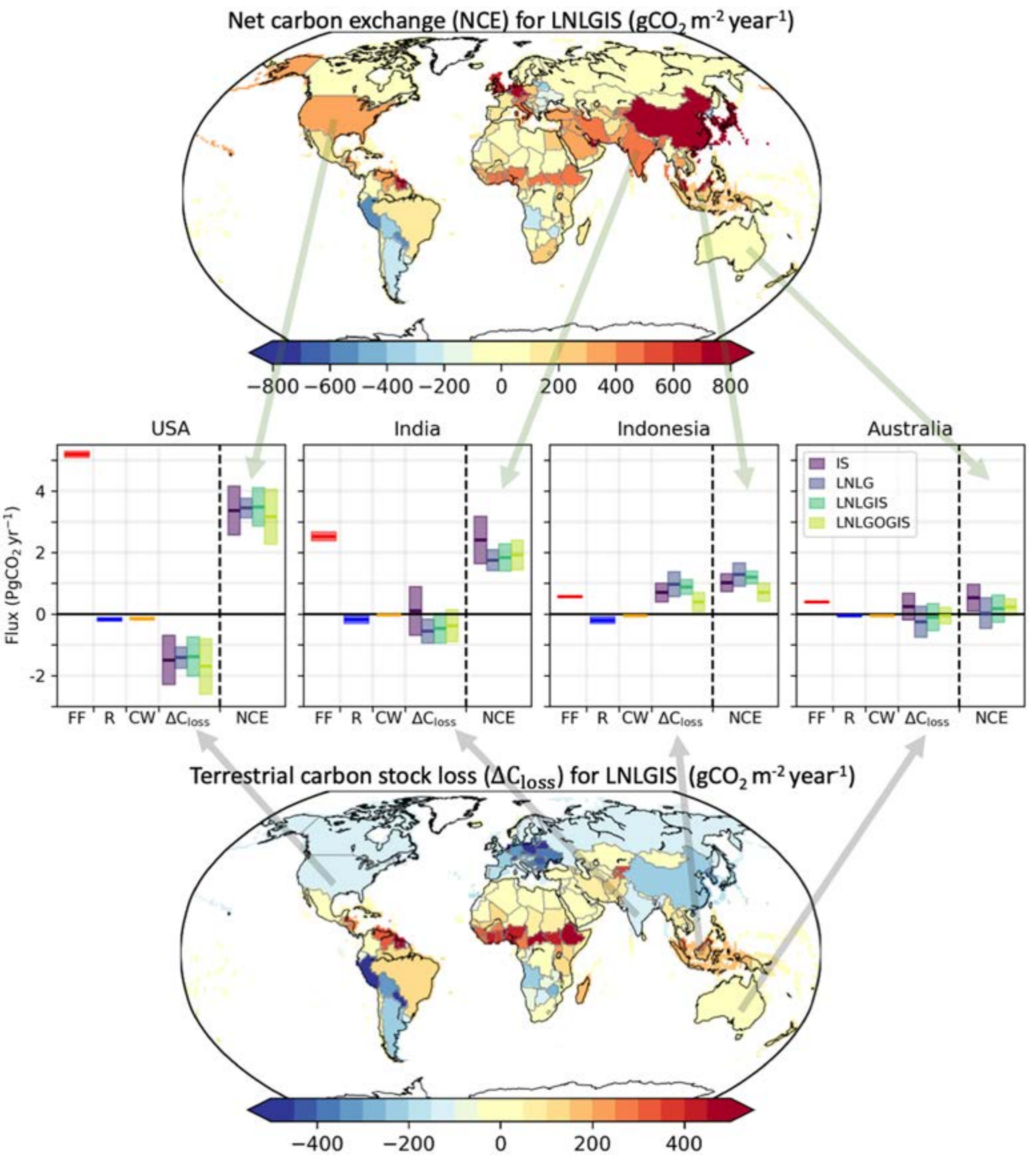


Figure 2: Top-down atmospheric measurements describe net changes in the atmospheric CO_2 abundance (Net Carbon Change, NCE). These estimates can be mapped to specific nations and combined with bottom-up estimates of fossil fuel emissions (FF) and carbon stock changes associated with river transport (R) and crop and wood exports (CW) to yield estimates of the net atmospheric carbon loss to the land biosphere (DC_{loss}). For northern mid-latitude nations, like the US, the land biosphere acts as a sink that reduces the net carbon increases from fossil fuel emissions. In subtropical and tropical countries (e.g., India, Indonesia and Australia), the land carbon sink is less efficient, and can even be a source (see Indonesia), adding to emissions.

Both ground-based and space-based observations have advantages and disadvantages for informing CO_2 flux estimates, based on their distributions in space and time, our ability to represent observations within a CTM and biases or random errors in the observations. For these reasons, flux estimates are commonly performed for each dataset individually and for combinations of these data.

To characterise systematic errors in atmospheric inversions (related to model transport and inversion set-up), groups or “ensembles” of inversions are often performed. The best estimate and uncertainty in estimated fluxes can then be derived from the distribution of flux estimates in this ensemble. In the pilot top-down dataset described in Byrne et al. (2023), the v10 Orbiting Carbon Observatory Model Intercomparison Project (v10 OCO-2 MIP) is used to generate an ensemble of CO_2 fluxes. The net CO_2 fluxes are then allocated to specific sectors, including fossil fuel use, lateral fluxes and terrestrial carbon stock changes using bottom-up estimates of fossil fuel emissions and lateral fluxes. A more detailed description of the methods can be found in Byrne et al. (2023).

HOW TO COMPARE TOP-DOWN AND BOTTOM-UP DATASETS

Top-down estimates of CO_2 fluxes can be compared with the bottom-up estimates of emissions and removals within the NGHGIs reported under the UNFCCC, which were downloaded from https://di.unfccc.int/flex_annex1 (last access: 6 February 2023). We also refer the reader to Chap. 6.10.2 in vol. 1 of IPCC (2019) for additional discussion of comparing top-down estimates with NGHGIs. Table 1 shows how NGHGI and top-down estimates can be compared. A more detailed discussion of this comparison can be found in Sect. 8 of Byrne et al. (2023).

Figure 3 demonstrates a comparison between top-down and bottom-up estimates of emissions and removals from terrestrial carbon stocks for the US, where nearly all land is considered managed. Averaged over the 2015–2020 period, we obtain statistically significant differences between the reported bottom-up inventories for the Agriculture, Land Use, Land Use Change and Forestry (LULUCF) and Waste sectors and the top-down estimates of changes in land carbon stocks (ΔC_{loss}) for the US (based on Student's *t* test at 0.05 significance level), with the top-down method suggesting greater carbon uptake. The reasons for these differences are unclear but are not expected to be explained by removals in unmanaged lands. It is possible that NGHGI methods miss or underestimate sink processes and/or that there are biases affecting the top-down estimates. We encourage further research and comparison between the NGHGI and top-down research communities to better understand the sources of these differences.

Table 1: How to compare NGHGIs and top-down estimates from Byrne et al. (2023).

NGHGI quantity	Top-down quantity	Consideration
Agriculture + Land Use, Land Use Change and Forestry (LULUCF) + Waste	Net terrestrial carbon stock loss (ΔC_{loss})	NGHGIs are only for managed land, while top-down estimates include both managed and unmanaged lands
Energy + industrial processes and product use	Fossil Fuel (FF) emissions	Top-down FF estimates are derived using bottom-up techniques.

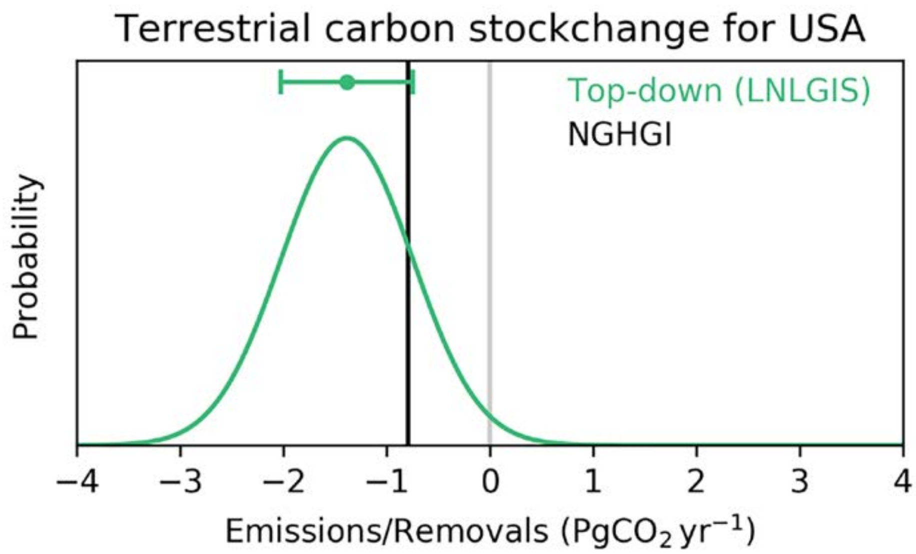


Figure 3: Comparison of top-down and NGHGI (bottom-up) terrestrial carbon stock changes over 2015-2020. The probability distribution of the top-down estimate is illustrated by the curve. The top-down estimate is determined to be significantly more negative than the NGHGI estimate based on Student's *t* test at 0.05 significance level.

LEARN MORE

NASA Applied Remote Sensing Training Program has developed a training course webinar series intended for stakeholders at local, regional, and national levels who are interested in managing GHG emissions to meet the climate change mitigation goals of the Paris Agreement, national inventory developers, and researchers who are interested in developing top-down atmospheric greenhouse gas budgets and working with the inventory development and assessment communities to support the Global Stocktake (GST) process.

The training course aims to help participants to:

- recognize the need to monitor CO_2, CH_4, and other GHGs to support efforts to reduce net emissions and mitigate their impact on climate;
- describe how top-down CO_2 and CH_4 budgets can be derived using atmospheric measurements and inverse models; and
- relate how the products and methods described can be combined with bottom-up inventories to identify opportunities for improving GHG inventories to support future GSTs.

The 3 x 2-hour webinar videos may be accessed [here]

Although this example has focused on CO_2, the second pilot project focuses on the CH_4 emitted by a broad range of natural processes and human activities. The NASA Carbon Monitoring System Flux (CMS-Flux) team analysed remote sensing observations from Japan's Greenhouse gases Observing SATellite (GOSAT) to produce national-scale CH_4 emission budgets. Unlike the pilot CO_2 inventories, these CH_4 budgets optimise emissions from fossil fuel extraction, transport and use as well as those from wetlands and inland freshwaters, agriculture, waste and fires.

Further information on the top-down pilot projects (in English, French, and Spanish): https://ceos.org/gst/ghg.html

POINTS OF CONTACT:

Brendan Byrne
NASA/JPL
brendan.k.byrne@jpl.nasa.gov

David Baker
CIRA, Colorado State University
David.F.Baker@noaa.gov

John Worden
NASA/JPL
john.r.worden@jpl.nasa.gov

NATIONAL ADAPTATION PLANS: TECHNICAL SUPPLEMENT TO THE UNFCCC GUIDELINES

CONTRIBUTED BY GEO GLOBAL AGRICULTURE MONITORING (IAN JARVIS, ESTHER MAKABE)

INTRODUCTION

Agriculture is highly sensitive to extreme weather and climate variability. In particular, the increasing frequency, intensity and severity of extreme weather and climate events significantly impacts smallholder farming systems in low- and middle-income regions of the world. Smallholders are often vulnerable to multiple hazards and less resilient to the drastic impacts of climate change. Timely, accurate and sustained Earth observations (EO) of the impacts of climate change on agriculture and food security can provide critical information to national adaptation and mitigation policies and programs, thereby enhancing the ability of policy-makers to make proactive decisions to mitigate impacts and take preventive measures to alleviate [further] loss and damage to agricultural systems. While key adaptation measures for short-term extremes include early warning, long-term changes require dedicated monitoring to measure the state and changes in the agricultural landscape over time. Monitoring and measuring these changes using EO can open the doors to longer-term adaptation measures at various scales ranging from sector-wide to site-specific responses.

Initiated and mandated by the G20 Agriculture Ministers in 2011, the GEO Global Agricultural Monitoring (GEOGLAM) initiative has been responding to and supporting food security efforts under multiple global policy drivers, including the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), the Sendai Framework on Disaster Risk Reduction and the UN Sustainable Development Goals, through the provision of timely, accurate and reliable EO evidence and information on agricultural conditions at global, regional and local scales.

The Essential Agriculture Variables (EAVs) characterise the state and change in the agricultural landscape for both crop and rangeland resources, using a simple suite of indicators, which are brought together to create fundamental knowledge and information to support the application of EO in responding to multiple policy challenges around agriculture production and food security. See below examples of EO applications for policy planning and/or action.

The technical guidelines on the use of EO in the formulation and implementation of National Adaptation Plans (NAPs) were developed supplementary to the UNFCCC NAP Technical Guidelines. The supplement draws on the rich knowledge and practical experience of the GEOGLAM community worldwide, to present the fundamental resources necessary to successfully leverage EO capabilities in implementing national and regional agriculture monitoring programs. These include, but are not limited to, robust institutional and technical frameworks, capacity development as well as financial resources to drive implementation forward.

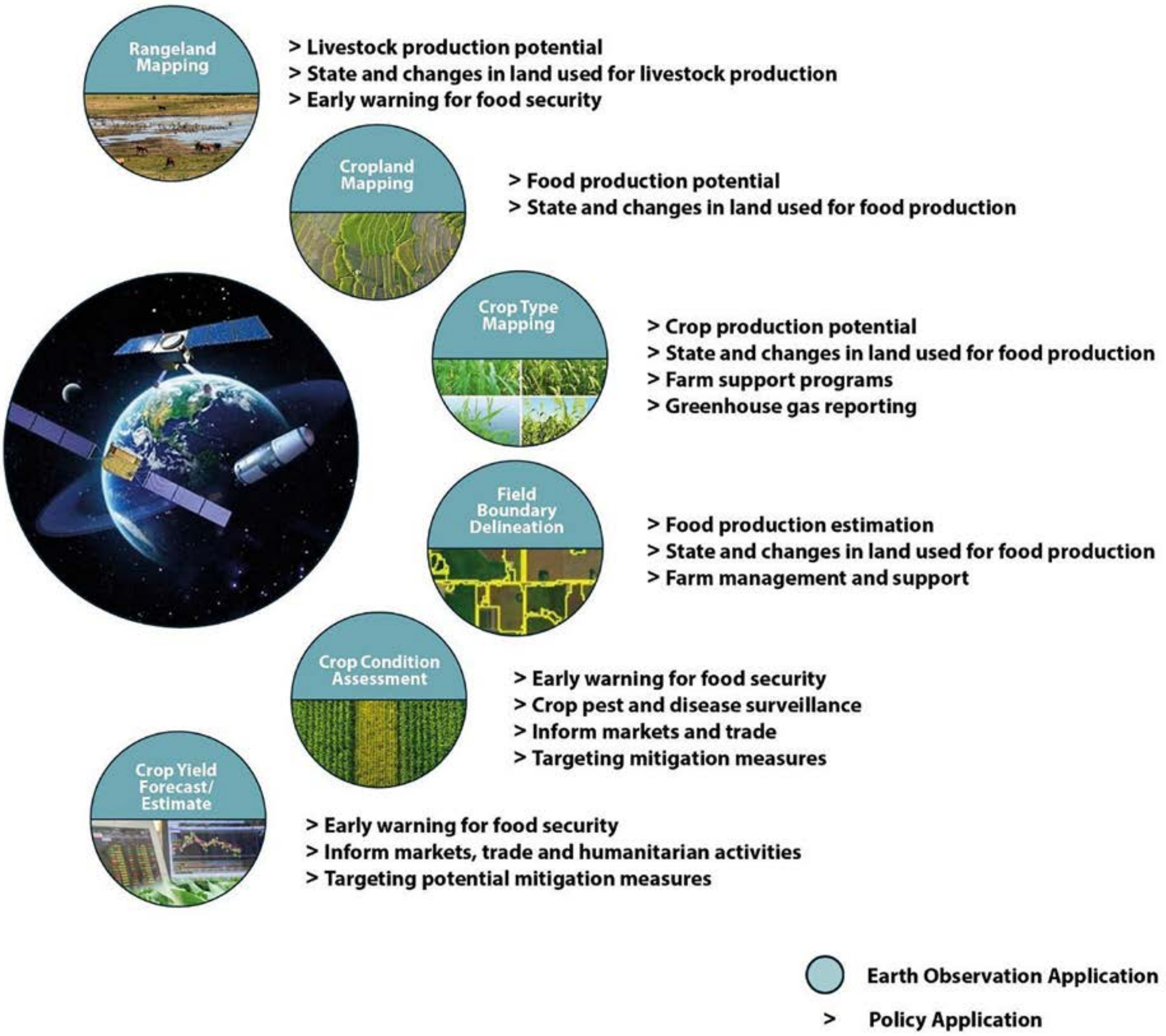


Figure 1: Essential EO information and applications from agriculture monitoring

INSTITUTIONAL FRAMEWORK

An effective institutional framework lays out the foundation for sustained policy and program support, providing a conducive and enabling environment for data collection and processing, product development,information dissemination, and decision-making. While there are common aspects, the framework must be responsive to local conditions.

Generally, the framework comprises a lead institution that provides the operational lifeline to the monitoring system and a home to the coordination team/centre, as well as a whole range of stakeholders who play different critical roles, and is supported by smooth flow and exchange of information at all levels of engagement. The example below, [Figure 2], emanates from the experiences of different national crop monitor implementation cases, while recognising the uniqueness of each country's context and set-up.

At the centre of the institutional coordination mechanism is the national coordination centre or team, responsible for aggregating, compiling and analysing data from different sources as well as producing information and evidence on agriculture production conditions across the country or region. The team – usually comprising multiple agencies and/or expertise including crop and livestock statistics, agriculture and food security analysts, and early warning, among others – handles the complex data from all the stakeholders including farmers and extension officers, private sector, and national and international partners. This data is integrated to produce information products and recommendations in the form of food

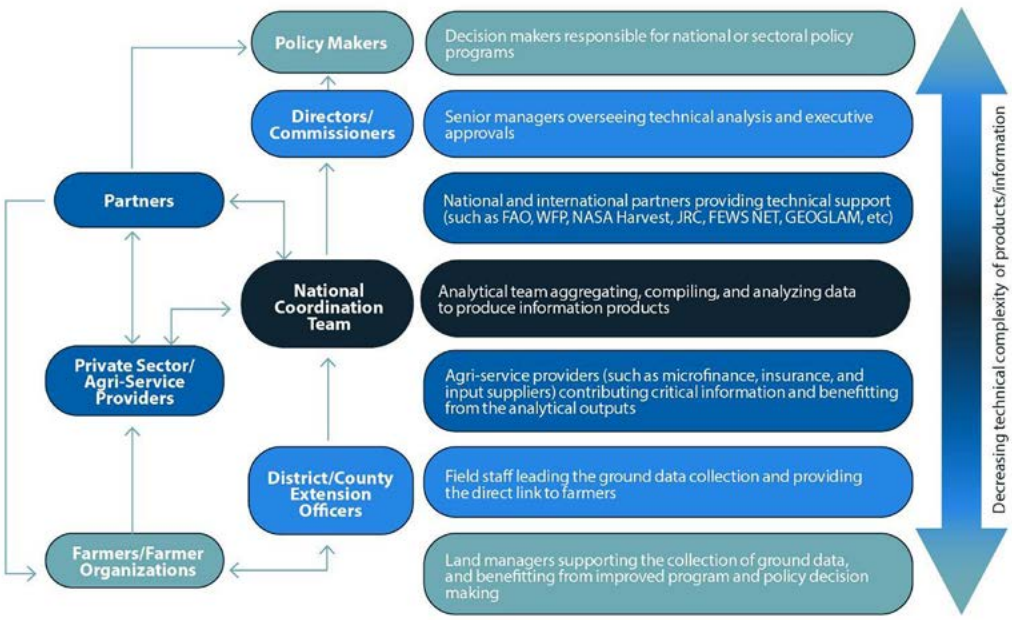


Figure 2: Institutional framework for an EO-based national agriculture monitoring system

Country	National coordination	Analytics platforms utilised	Ground data (tools and teams)	Main publication Programs supported Access to reports
Kenya	SDA, Ministry of Agriculture, coordinating with County Extension Officers	GLAM, EWX, Custom built Kenya Crop Monitor Kenya, Weather Forecasts from Kenya Meteorological Department	Via County Extension Officers	Kenya crop conditions bulletin, Crop Insurance program, rapid response to pest/ disease infestations
Uganda	National Emergency Coordination and Early Warning Center with inputs from Ministry of Agriculture, Uganda National Meteorological Authority, Ministry of Health, FAO, FEWSNET, Uganda Red Cross	Uganda Crop Monitor, GLAM, EWX, Weather Forecasts	Via District Extension Agents, and rapid food security assessments, OpenDataKit	UNIEWS Bulletin, Disaster Risk Financing
Tanzania	Ministry of Agriculture – National Food Security Division Coordinated with Tanzania Meteorological Agency (TMA), Ministry of Trade, National Bureau of Statistics (NBS)	GLAM, EWX, Tanzania Crop Monitor System	Via District extension agents, regional officers	Tanzania National Food Security Bulletin
Rwanda	MINAGRI with Rwanda Meteorology	GLAM, EWX, Rwanda Crop Monitor System	Via District extension officers	Rwanda Crop Monitor Bulletin

Table 1: Current crop monitor set-up examples

security bulletins, food balance sheets or crop monitor reports that are easily applied to decision- and policy-making.

Another essential element of the coordination mechanism is the feedback loop, especially between policy-makers and policy beneficiaries, including the farmers, private and public sector, as well as other stakeholders. This allows for smooth iterations of programs and policies, while at the same time evaluating the effectiveness of new policies.

Table 1 shows examples of different institutional set-ups and coordination frameworks in some of the countries that are currently operating and managing their own national crop monitoring systems through the GEOGLAM co-development support.

TECHNICAL FRAMEWORK

Highlighting the technical resources such as EO data, analytical tools, platforms and products, as well as technical human capacities, the technical framework provides a roadmap for the implementation of an EO-based national crop monitoring system, working in tandem with the institutional framework.

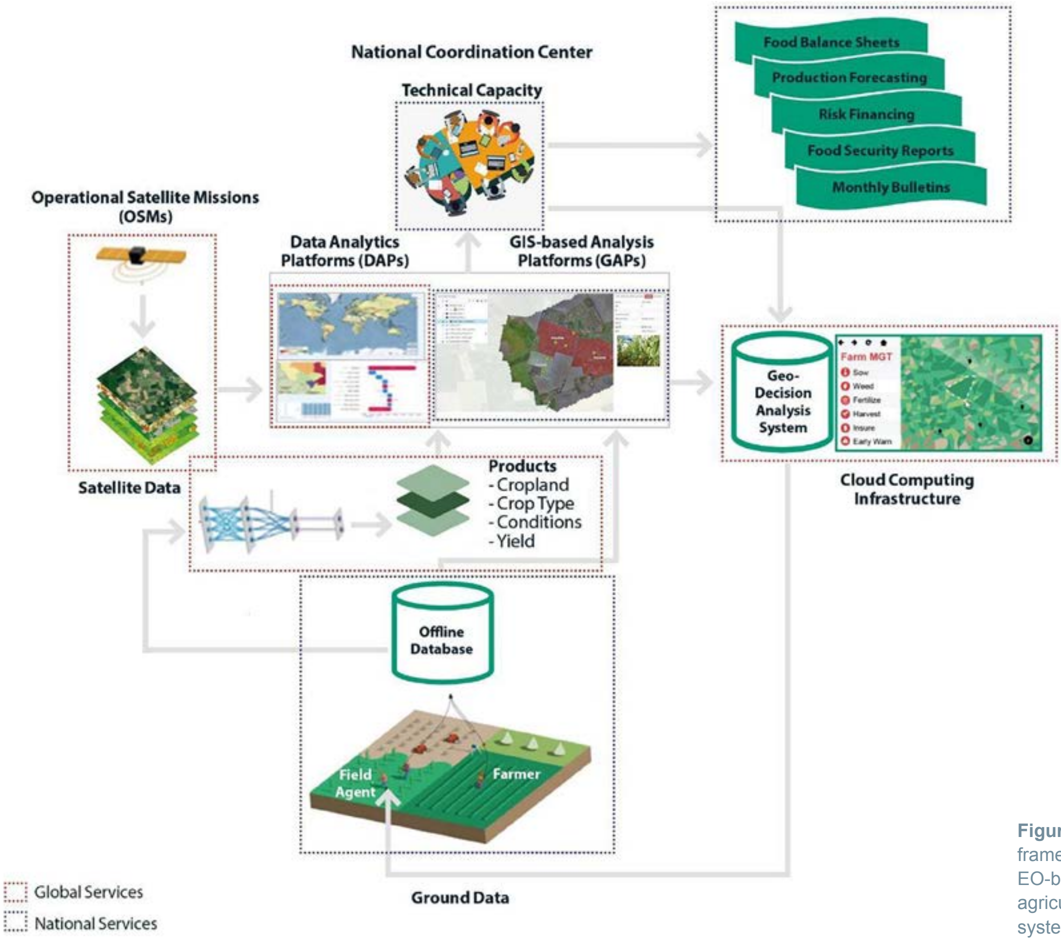


Figure 3: Technical framework for an EO-based national agriculture monitoring system

Recent advances in open data, analytical tools and computing have made the implementation of EO-based agricultural monitoring accessible to many organisations that might have been constrained by cost and capacity in the past. While most of the technical resources outlined in Figure 3 are open or can be accessed at low/no cost, countries need to make substantial investments in ground data collection as well as the technical capacity of individuals and institutions.

Ground data is necessary to train and validate EO data analysis, thus ensuring accuracy and assessing the reliability of derived remote sensing-based analytical products and information. In the advent of digital technologies, mobile data collection applications have made it relatively easy and faster to collect, disseminate and visualise information in near real-time, while realising huge savings on cost, labour and time, compared to manual/paper-based collections. Ground data is the most expensive aspect of the technical framework, and consequently it is advisable for countries to leverage and/or build on existing extension services, including ground data systems to sustain and ensure continuity of ground data collection efforts.

Similarly, it is essential that the national team is equipped with the necessary skills and knowledge to allow institutions to capitalise on the full potential of EO science, data, tools and other open resources.

CAPACITY CO-DEVELOPMENT

Capacity development is critical in strengthening existing or building new institutional and technical capacities, helping individual and organisations to:

- fully utilise EO in agriculture-related decision-making;
- adapt organisational workflows to exploit or improve the use of EO in agriculture;
- share good practices that showcase the value of EO;
- promote the engagement of institutional users; and
- strengthen the ecosystem in which the individuals and organisations operate.

Experience has demonstrated clearly that when countries develop and operate their own monitoring systems, the information generated is easily trusted and consequently easily absorbed and utilised for policy and program decisions much faster, compared to information coming from external sources. As such, GEOGLAM uses, promotes and advocates for a co-development approach to capacity building that is centred on, and driven by the unique needs, interests and existing capacities of the user or requesting entity right from the design to the implementation phase. This approach has so far proved its effectiveness in ensuring the suitability and sustainability of interventions, while achieving the greatest possible impact for enhanced societal benefit.

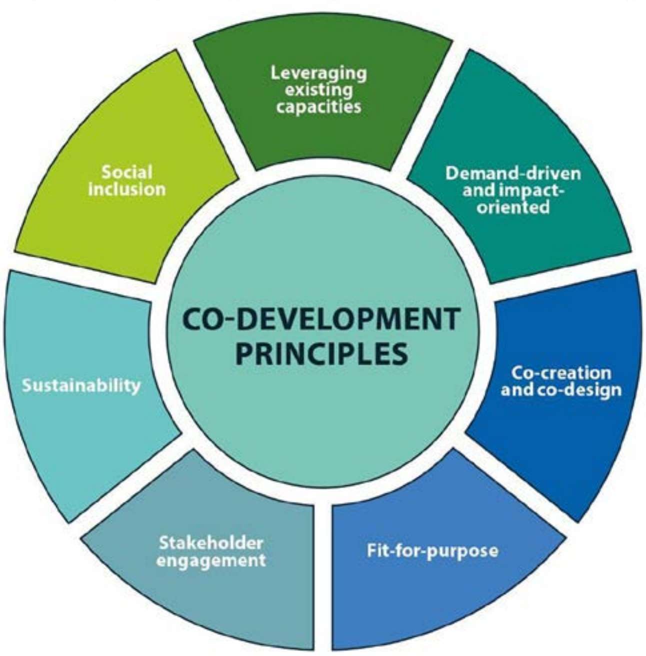


Figure 4: GEOGLAM's Principles for Capacity Development (adapted from the Digital Earth Africa capacity development strategy)

To sum up, in an era where livelihoods are persistently affected by multiple shocks, EO-based national monitoring approaches offer tremendous opportunities to governments and other stakeholders. By providing timely and accurate information, these approaches enable governments to take anticipatory and proactive actions to mitigate against risks to livelihoods, such as crop failure. Well-targeted proactive measures can also help governments achieve greater efficiencies and significant savings in terms of time and resources that would otherwise be spent on reactive emergency responses. Furthermore, these actions can boost the resilience of national systems against multiple hazards, while also enhancing food security.

Building on the extensive achievements and expertise of the community, GEOGLAM welcomes the opportunity to collaborate with countries that are eager to co-create their national crop monitoring systems.

EXAMPLES: NATIONAL CROP MONITORING

Through co-development partnerships, GEOGLAM has been supporting several countries to develop their national crop monitoring systems, downscaled and based on the experiences of setting up and operating the GEOGLAM global crop monitors: Crop Monitor for Agricultural Markets Information Systems (CM4AMIS) and the Crop Monitor for Early Warning (CM4EW).

The first GEOGLAM national crop monitor was set up with the Tanzania Ministry of Agriculture through the National Food Security Division (NFSD), which has the mandate for food security assessment and reporting, and Sokoine University of Agriculture. The Ministry had a national agriculture monitoring system, based on field data. Building on this system and through joint needs assessment and training, the NFSD identified remote-sensing data as a critical component to add onto the system to boost its capabilities for monitoring agricultural production as well as for early warning. Using readily available EO data from the Global Agriculture Monitoring (GLAM) data application system, the GEOGLAM and NFSD team customised the GLAM system to fit Tanzania's needs and context, complementing it with the national ground observations, to produce monthly or ad-hoc food security reports or bulletins. The NFSD team was trained on using remote-sensing EO inputs as well as agrometeorological data from the Early Warning Explorer (EWX), a web-based geospatial platform for monitoring and providing early warning for agricultural drought. Further, meteorological and relevant trade data are integrated into the reports.

The Tanzania crop monitor has been operational and producing regular reports since 2015, looking at the major crops (maize, beans, cassava and rice) significant for Tanzania's national food security from all regions across the country.

UNITED REPUBLIC OF TANZANIA
MINISTRY OF AGRICULTURE
NATIONAL FOOD SECURITY BULLETIN TANZANIA APRIL, 2020

Volume 36-2020	http://www.kilimo.go.tz	30 APRIL,2020

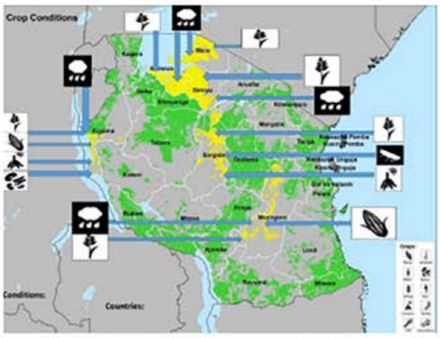


Figure 1: **This Crop condition map syntheses information for all crops as of 30th April, 2020.** Crop conditions over the main growing areas based on combination of national, regional and district crop analyst inputs along with remote sensing data and rainfall data provided by Tanzania Meteorological Agency. Crop with conditions other than favorable are marked indicated on the map.

NATIONAL HIGHLIGHTS

- Most parts of uni modal and bimodal regions experienced favorable conditions for most crops. However, water logging and flooding caused watched conditions for maize and paddy in some parts of uni modal regions i.e Morogoro, Kigoma and Kilimanjaro whilst in some parts of bimodal regions of Mwanza, Mara and Simiyu, paddy experienced the same condition for the same reasons.
- In Singida, paddy faced watch conditions due to pests' invasion. In bimodal areas, crops were in favorable condition in most part of the country except for paddy where watch conditions were observed in some parts of Mwanza, Mara and Simiyu regions due to flooding and water logging.
- Cassava continued to experience favorable conditions in most parts of the country and it is in different growth stages. Watch conditions were experienced in some parts of Kigoma due to Flooding while in some parts of Singida watch condition were observed due to presence of pest.
- Lindi, Mbeya and Mtwara had above average maize price while Musoma, Mpanda and Kibaigwa were all below average maize prices. However the lowest maize price were observed in the Musoma, Mpanda and Kibaigwa markets. Lindi, Ilala and Temeke had the highest prices for rice while Musoma, Shinyanga and Mpanda had lowest market prices.
- Temeke, Kinondoni and Lindi markets had the highest prices for beans while Sumbawanga, Musoma, Babati and Bukoba were all below average ranging from.

TABLE OF CONTENTS

Figure 5: Example of Tanzania National Food Security Bulletin

Similarly, in Uganda, the National Emergency Coordination and Operations Center (NECOC), under the Department of Disaster Preparedness, Relief, and Management (DPRM) in the Office of the Prime Minister, was the lead agency and co-development partner with GEOGLAM. Uganda adopted the GEOGLAM Crop Monitor as a system for synthesising crop conditions leveraging EO. NECOC officers (Disaster Management Officers) synthesise GLAM and EWX systems data to complement ground data from extension agents. These are further augmented by other auxiliary data such as meteorological reports from the Uganda National Meteorological Authority and food security status reports from relevant line ministries, including the Ministry of Agriculture and the Ministry of Health, and development partners, including FAO, WFP, and FEWSNET, to compile comprehensive assessments and reports on crop and pasture conditions, as well as information on any food security-related disaster risk for early warning and mitigation. The NECOC team comprises analysts from different fields of expertise, including disaster management, GIS/Remote sensing, and agricultural officers from the Ministry of Agriculture.

EO has been a critical component of the Uganda National Integrated Early Warning Bulletin (UNIEWS) since implementation of the system and has had tremendous positive impacts to Uganda's national social protection and food security efforts. For instance, in June 2017, normalised difference vegetation index (NDVI) values dropped below the pre-set threshold in five districts northeast of the country. Through continuous monitoring, the team was alerted well in advance (about 3 months lead time) of these anomalous conditions and the subsequent risk of crop failure. Equipped with this evidence, the government, through the Office of the Prime Minister, was able to trigger Disaster Risk Financing early enough to cushion the affected farmers of the poor harvest and prevent further loss and damage to their livelihoods. Between 2017 and 2020, the national crop monitoring system helped more than 90,000 households who were at risk of poor agriculture production, while saving the government up to US$11 million in reactionary food aid measures.

LEARN MORE & GET HELP

Integrating Earth Observations into the Formulation and Implementation of National Adaptation Plans: Agriculture and Food Security. GEO Supplement to the UNFCCC NAP Technical Guidelines. [earthobservations.org]

[Tanzania - National Food Security Bulletin example]

[Ugandan crop monitoring system enables early drought response]

POINTS OF CONTACT:

GEOGLAM Secretariat:
geoglam@geosec.org

Esther Makabe
Capacity Development Coordinator:
emakabe@geosec.org

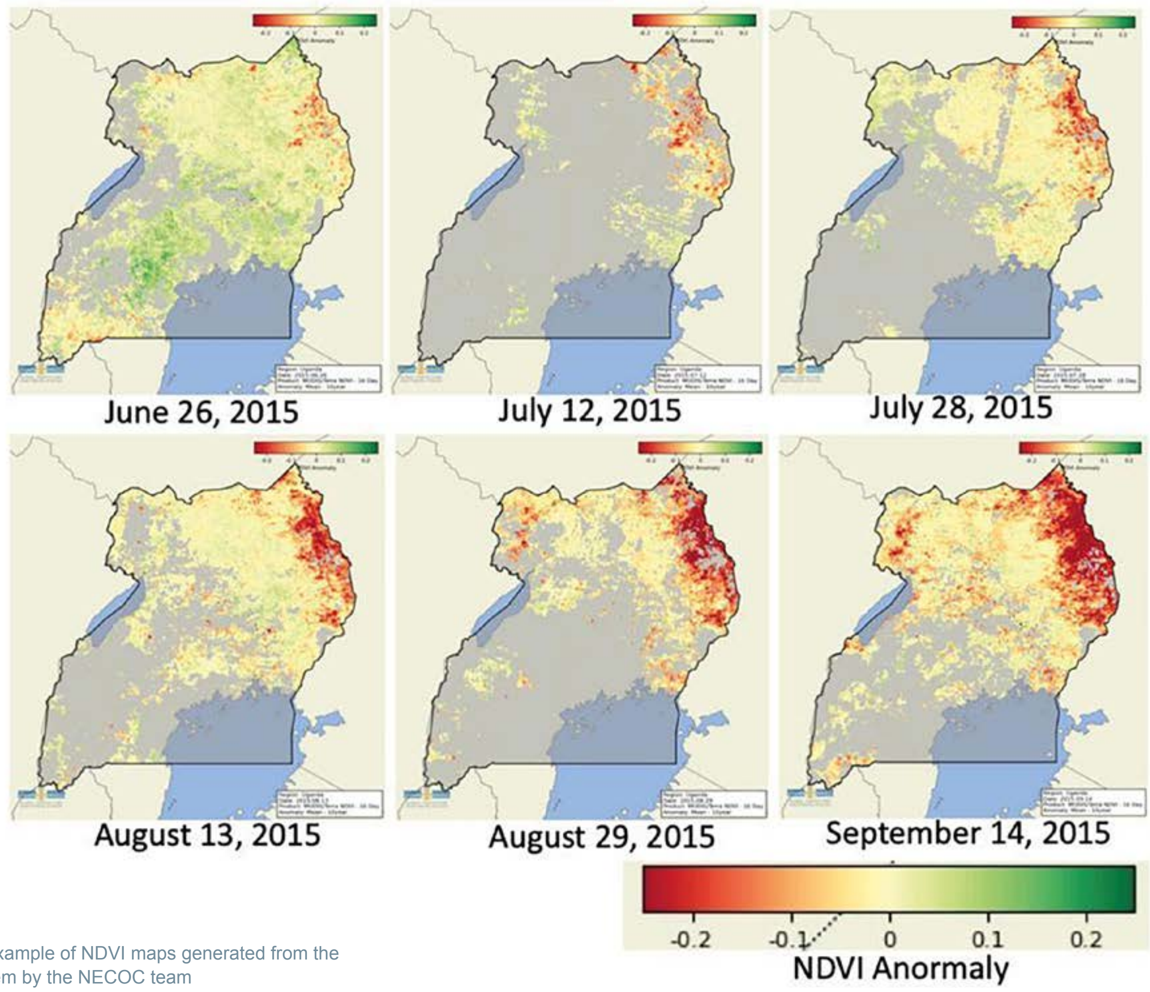


Figure 6: Example of NDVI maps generated from the GLAM system by the NECOC team

THE GEOGLAM CROP MONITOR: EARTH OBSERVATIONS FOR AGRICULTURAL DECISION-MAKING

CONTRIBUTED BY UNIVERSITY OF MARYLAND / NASA HARVEST
(CHRISTINA JUSTICE, KARA MOBLEY, BRIAN BARKER, INBAL BECKER-RESHEF)

Having accurate and timely information on how crops are developing around the world is essential for decision-makers to plan effectively and respond to potential production shortages. For countries that produce a large portion of the world's staple food supply, a poor crop can result in global production shortfalls and food price increases. For smaller-producing countries with a large population of subsistence farmers who largely depend on their own crops for their household food or income needs, poor crop conditions and reduced production can result in limited access to safe and nutritious food sources and increasing levels of food insecurity.

Satellite-based Earth observation (EO) data provides a highly efficient and cost-effective means of gathering crop condition information. By continuously monitoring large areas from space, EO data offers a more comprehensive view of crop conditions over time, enabling the analysis of current crop conditions compared to normal for a specific area. Additionally, the use of long time-series data provides a more robust analysis of trends in crop conditions. Scientists can use this data to remotely analyse crop health and predict potential production shortfalls for a specific country or region. In turn, governments, international organisations, humanitarian agencies, and other stakeholders can use this information to implement mitigation measures aimed at preventing production shortfalls or develop effective strategies to minimise the impact on economic stability and food security.

In 2007-08 and 2010-11, the world experienced significant spikes in global food prices. This triggered food riots and unrest in many countries, and the resulting food insecurity had severe consequences for millions of people worldwide. Under the 2011 G20 Action Plan on Food Price Volatility in Agriculture, the Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) initiative was created in response to the need for timely and science-driven information on global crop conditions to improve food security and market transparency.

The GEOGLAM Crop Monitor reports provide a monthly consensus on global crop conditions developed in partnership with national, regional and global food security monitoring agencies. The Crop Monitor for AMIS (CM4AMIS), established in 2013, provides crop condition information for the major producer and exporter countries, focusing on the four main food commodity crops (wheat, maize, soybean, and rice). In 2016, the GEOGLAM Crop Monitor for Early Warning (CM4EW) was established to provide crop condition information for countries at risk of food insecurity with a focus on each region's key food security crops. In 2022, the Global Crop Monitor was established, combining the results of the CM4AMIS and CM4EW to provide a global overview of crop conditions in a single report. The Global Crop Monitor reports connect major producing and exporting countries with countries that rely largely on food imports and whose population is susceptible to food insecurity.

HOW EO DATA IS USED IN THE CROP MONITOR REPORTS

EO data is a critical component of agricultural monitoring, allowing for a regular, repeatable and comprehensive view of crop conditions and development. This is especially true in countries where access to field information is limited and where crops are heavily reliant on rainfall. EO data is used by analysts to identify anomalies in agro-climatic factors that could potentially impact crop development, and in some cases, it provides the only source of information on crop conditions. Some of the critical EO data used for agricultural monitoring and related to crop condition and development include temperature, rainfall, vegetation greenness (normalised difference vegetation index or NDVI), soil moisture and Evaporative Stress Index (ESI), among other datasets related to detecting crop growth and health status.

Within the GEOGLAM Crop Monitor reports, EO data is a critical information source along with ground observations, national reports and climatic forecasts. While EO data is a valuable tool for assessing crop conditions, ground observations and national reports are also used to provide more detailed and specific information on local conditions, validate EO data and help improve the accuracy and reliability of crop health assessments. Additionally, climatic forecasts can help predict potential weather events or climate anomalies that may impact crop growth and health. Analysts use a combination of this information when available to provide a comprehensive and accurate assessment of crop conditions, enabling stakeholders to make more informed decisions about crop management and interventions.

Together, this information is used to help analysts categorise crop conditions into one of the following categories: "Exceptional" (above-average yields), "Favourable" (near-average yields), "Watch" (concern for potential yield declines), "Poor" (yield declines of 5-25% expected), and "Failure" (yield declines over 25% expected). Figure 1 provides the synthesis crop condition information for all current in-season crops analysed in the March 2023 GEOGLAM Crop Monitor reports.

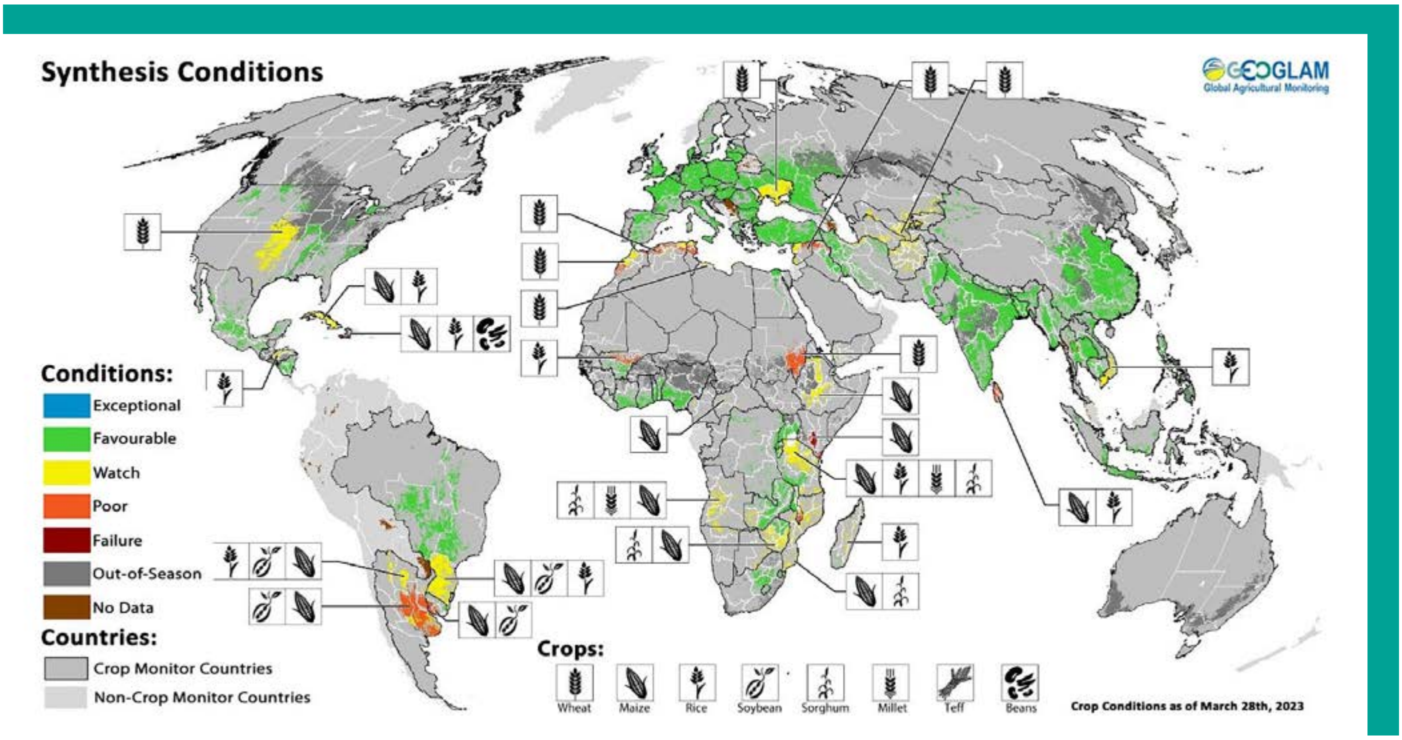


Figure 1: Global synthesis crop conditions from the GEOGLAM Crop Monitor reports as of March 28, 2023.

The GEOGLAM-NASA Harvest Agmet (Agrometeorological) EO Indicator graphics consolidate primary EO data for crop condition monitoring, providing valuable insights into in-season crop development and current crop conditions. These graphics are produced every 10 days at the subnational level for all Crop Monitor countries and are made available to the public as well as the GEOGLAM Crop Monitor partners to facilitate their assessments.

In Figure 1, the Central region of Kenya is shown to have "Poor" conditions as of March 2023 for the short Rains maize crop, indicating likely below-average yield outcomes for the end of the cropping season. Thanks to the use of EO data indicators, an early warning about the potential for a below-average seasonal yield outcome was provided as early as November 2022 in the CM4EW report. Since the beginning of the season, several EO indicators, including NDVI, ESI, precipitation and soil moisture, were all generally below average (Figure 2), indicating non-conducive agrometeorological conditions for crop growth throughout the season. Consequently, the Central region of Kenya was placed under "Watch" conditions from November 2022 to January 2023 and then downgraded to "Poor" conditions from February 2023, coinciding with the beginning of the harvest season.

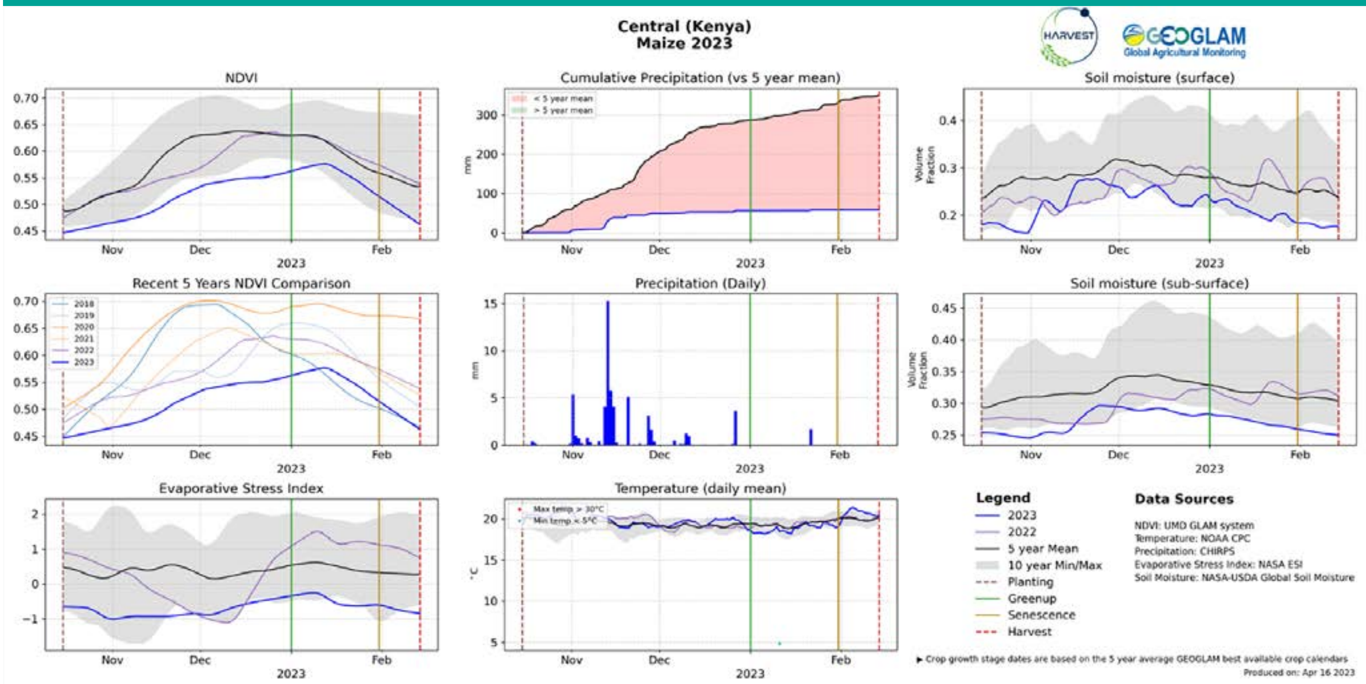


Figure 2: Agrometeorological EO indicators for the Maize 2 season in Central Kenya, produced on April 16, 2023. The EO indicators include NDVI (top-left graph), Recent 5 Years NDVI Comparison (middle-left graph), ESI (bottom-left graph), Cumulative Precipitation (vs 5-year mean) (top-centre graph), Precipitation (daily) (middle-centre graph), Temperature (daily mean) (bottom-centre graph), Soil Moisture (surface) (top-right graph), and Soil Moisture (sub-surface) (middle-right graph).

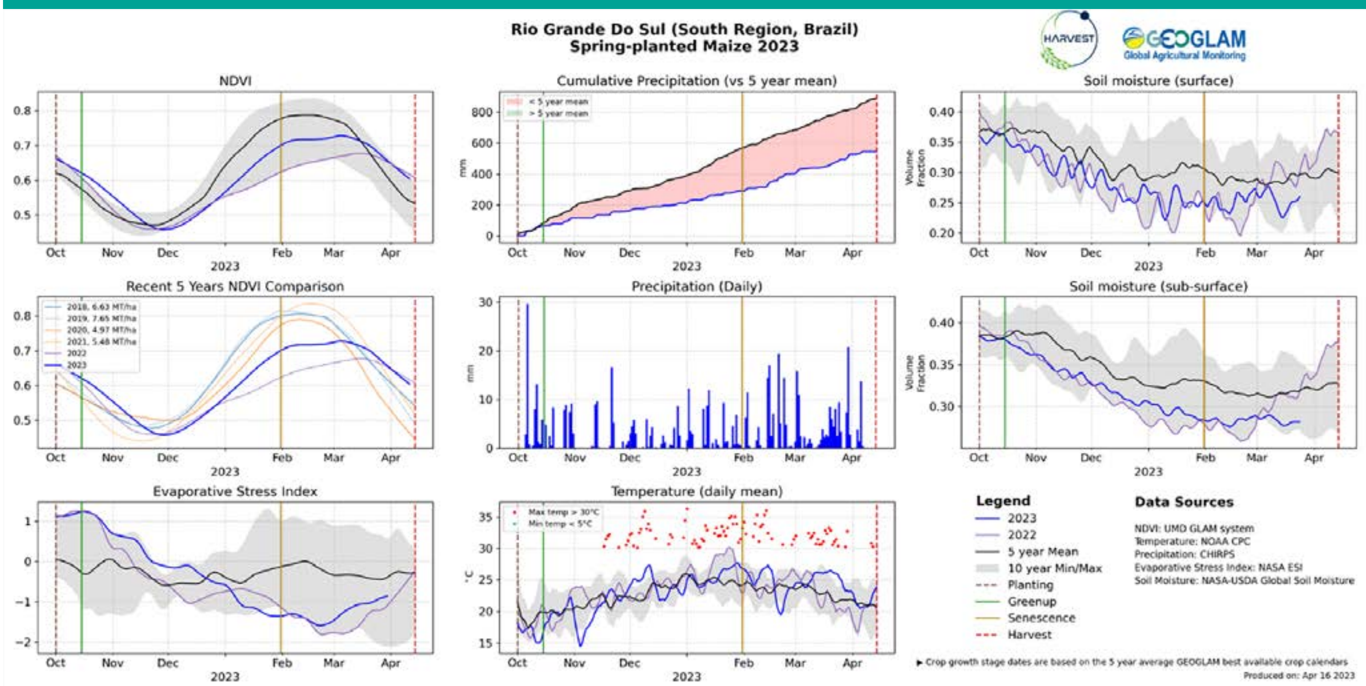


Figure 3: Agrometeorological EO indicators for the Maize 2 season in Rio Grande do Sul Brazil, produced on April 16, 2023. The EO indicators include NDVI (top-left graph), Recent 5 Years NDVI Comparison (middle-left graph), ESI (bottom-left graph), Cumulative Precipitation (vs 5-year mean) (top-centre graph), Precipitation (daily) (middle-centre graph), Temperature (daily mean) (bottom-centre graph), Soil Moisture (surface) (top-right graph), and Soil Moisture (sub-surface) (middle-right graph).

As another example, Figure 1 shows “Watch” conditions for spring-planted maize as of March 2023 over the South region of Brazil, which includes the state of Rio Grande do Sul, indicating concern about possible yield reductions. While the season started with generally near-normal NDVI, ESI, precipitation, temperature and soil moisture levels from October 2022, cumulative precipitation quickly dropped to below-average levels with high daily maximum temperatures. This in turn caused the NDVI to decline to below-average levels between late November 2022 and mid-March 2023 (Figure 3), suggesting a decline in vegetation health for spring-planted maize and potential yield reductions. As a result, the South region of Brazil began the season with "Favourable" conditions from September to November 2022, but was downgraded to "Watch" conditions from January 2022 due to a lack of rain and high temperatures.

CROP MONITOR IMPACT

The GEOGLAM Crop Monitor has gained widespread recognition as a reliable source for tracking global crop conditions, and it is frequently utilised by humanitarian and governmental organisations to inform decisions related to agriculture and food security. One notable example of its application is in Karamoja, Uganda, where in May 2017, the Office of the Prime Minister used satellite data analysis from the Crop Monitor to trigger Disaster Risk Financing funds. This funding was utilised to scale-up public works projects, which helped to offset agricultural losses and support 31,386 households, benefiting roughly 150,000 people. By providing timely, transparent, and consensus-based information on global crop conditions, the GEOGLAM Crop Monitor plays a critical role in supporting various stakeholders by informing decisions related to disaster relief as well as food security, trade and commodity markets.

LEARN MORE & GET HELP

GEOGLAM: https://earthobservations.org/geoglam.php
GEOGLAM Crop Monitor: https://cropmonitor.org/
GEOGLAM Crop Monitor Story Map: https://cropmonitor.org/index.php/crop-monitor-story-map/
AGMET EO Indicators: https://cropmonitor.org/tools/agmet/
AGMET EO Indicators Explained: https://cropmonitor.org/index.php/eodatatools/crop-conditions-plots/

POINTS OF CONTACT:

Christina Justice, GEOGLAM CM4EW Lead: justicec@geoglam.org
Brian Barker, GEOGLAM CM4AMIS Lead: bbarker@geoglam.org
Kara Mobley, GEOGLAM CM Lead Coordinator: mobleykara@geoglam.org

INTERNATIONAL METHANE EMISSIONS OBSERVATORY (IMEO): METHANE ALERT AND RESPONSE SYSTEM (MARS)

AN INNOVATIVE NEW SYSTEM TO TARGET METHANE EMISSIONS WITH SATELLITES

CONTRIBUTED BY IMEO (CYNTHIA RANDLES), UNEP (MANFREDI CALTAGIRONE)

The Methane Alert and Response System (MARS), designed by UNEP's International Methane Emissions Observatory (IMEO), is the first global system providing rapid, actionable and transparent data on methane emissions using satellite data.

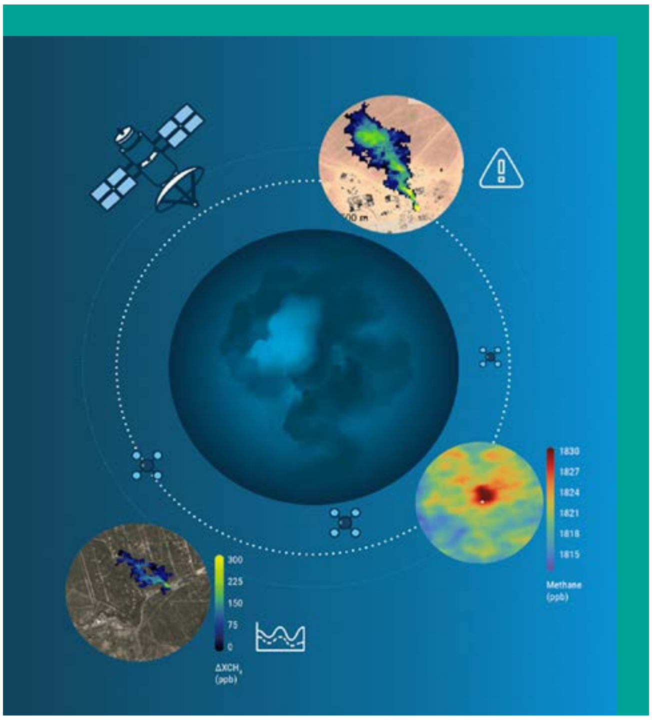


Figure 1: Illustration of IMEO's MARS using satellites to provide data to stakeholders (UNEP)

More accurate data will enable more targeted action. MARS harnesses existing satellite data to identify major emissions events, activate its partners to notify relevant stakeholders, and support and track progress towards mitigation. Data from these satellites is publicly available, though in some cases specialised remote sensing expertise is required to properly interpret these data. UNEP provides this expertise to the global community. This data is then made freely available to policy makers, businesses and the general public.

MARS will first focus on significant methane emissions sources from the energy sector. With more satellites coming on-line soon, MARS will be able to detect smaller sources, area sources, and make more frequent detections of methane emissions. These increased capabilities will later enable MARS to expand to cover other emitting sectors such as waste and agriculture.

FOUR CROSS-CUTTING COMPONENTS WILL LEAD TO REAL EMISSIONS REDUCTIONS

Component 1: Detect & Attribute
In coordination with CEOS and in partnership with Kayrros, Inc. and The Netherlands Institute for Space Research (SRON), UNEP's IMEO will work with existing global mapping satellites (e.g., ESA Sentinel 5P, JAXA GOSAT/GOSAT-2) to identify very large methane plumes and methane hot spots and conduct further analysis using higher-spatial resolution satellites (e.g., ESA Sentinel-2, NASA Landsat and EMIT, ASI PRISMA, DLR EnMAP) and other relevant datasets (e.g., visible imagery) to enable attribution of the emission to a specific source.

Component 2: Notify & Engage Stakeholders
UNEP's IMEO will work directly and through partners to notify relevant governments and companies to large emission events happening in or near their jurisdictions or operations and will continue this engagement as more information becomes available.

Component 3: Stakeholders Take Action
It will be up to the notified stakeholders to determine how best to respond to the notified emissions and share their actions with UNEP to show initiative. As appropriate, UNEP's partners will be available to provide support services at this stage, e.g., assistance with assessing mitigation opportunities or support for mitigation actions.

Component 4: Track, Learn, Collaborate, Improve
UNEP's IMEO will continue to monitor the event location for future emissions as mitigation efforts proceed. Once the MARS system is fully operational, UNEP will make data and analysis publicly available between 45- and 75-days post detection. UNEP will foster collaboration across the MARS ecosystem to draw lessons from these notified events that can be applied to improve MARS and methane action in general.

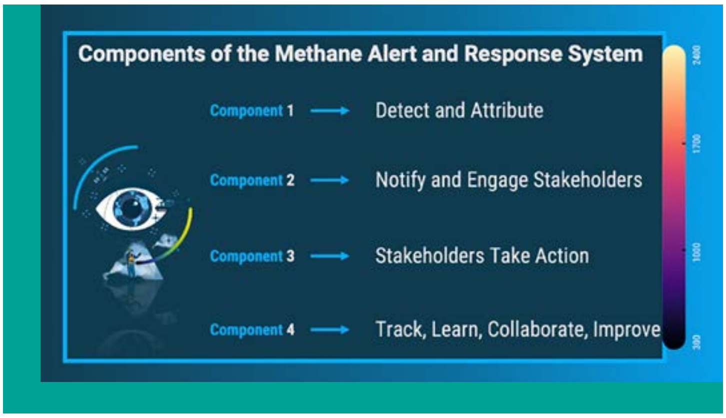


Figure 2: The Four Components of Methane Alert and Response System

MARS USES THE EVER-EXPANDING LANDSCAPE OF METHANE DETECTING SATELLITES

MARS uses the existing suite of Earth Observation satellites to detect, localise, and characterise large emission sources globally. Data from these satellites is publicly available, though in some cases specialised remote sensing expertise is required to properly interpret these data. UNEP provides this expertise to the global community to help further the goals of the Global Methane Pledge. MARS may also use other publicly available datasets, for example, to characterise facility types or determine site ownership.

MARS is designed to be flexible and adapt to satellite capabilities as they evolve. In the current iteration of MARS, a ‘tip-and-cue’ approach is used as follows:

1. Identify Regions of Interest (ROIs) through analysis of (for example):
    - ‘Hot Spots’ determined by averaging data from global methane mapping satellites such as ESA’s TROPOMI or JAXA/NIES GOSAT and GOSAT-2 instruments
    - Methane plumes detected by global mapping satellites or higher-resolution land imagers capable of methane detection (e.g., ESA’s Sentinel-2 or NASA’s Landsats, NASA's EMIT)
    - Aircraft data collected through scientific studies funded by UNEP IMEO or others
2. Map ROIs using high-resolution instruments such as ASI’s PRISMA and DLR’s EnMAP to look for recent emissions that can be attributed at the facility-level.
3. Use available public datasets to determine facility ownership and notify both governments and operators of detected emissions, and where possible, emission rates and their associated uncertainty.

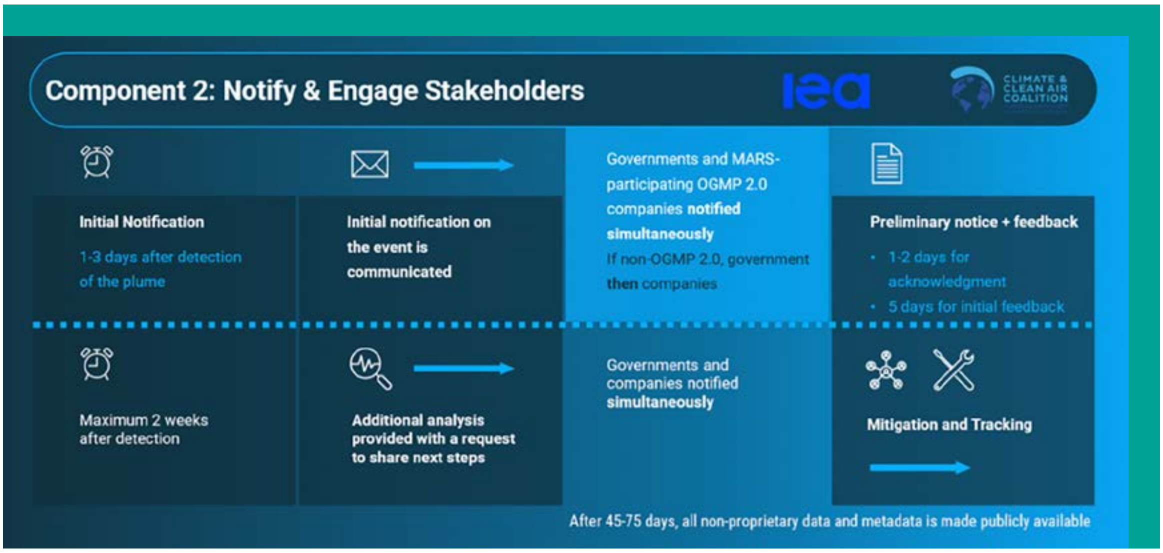


Figure 3:
MARS Component 1 - Detect & Attribute

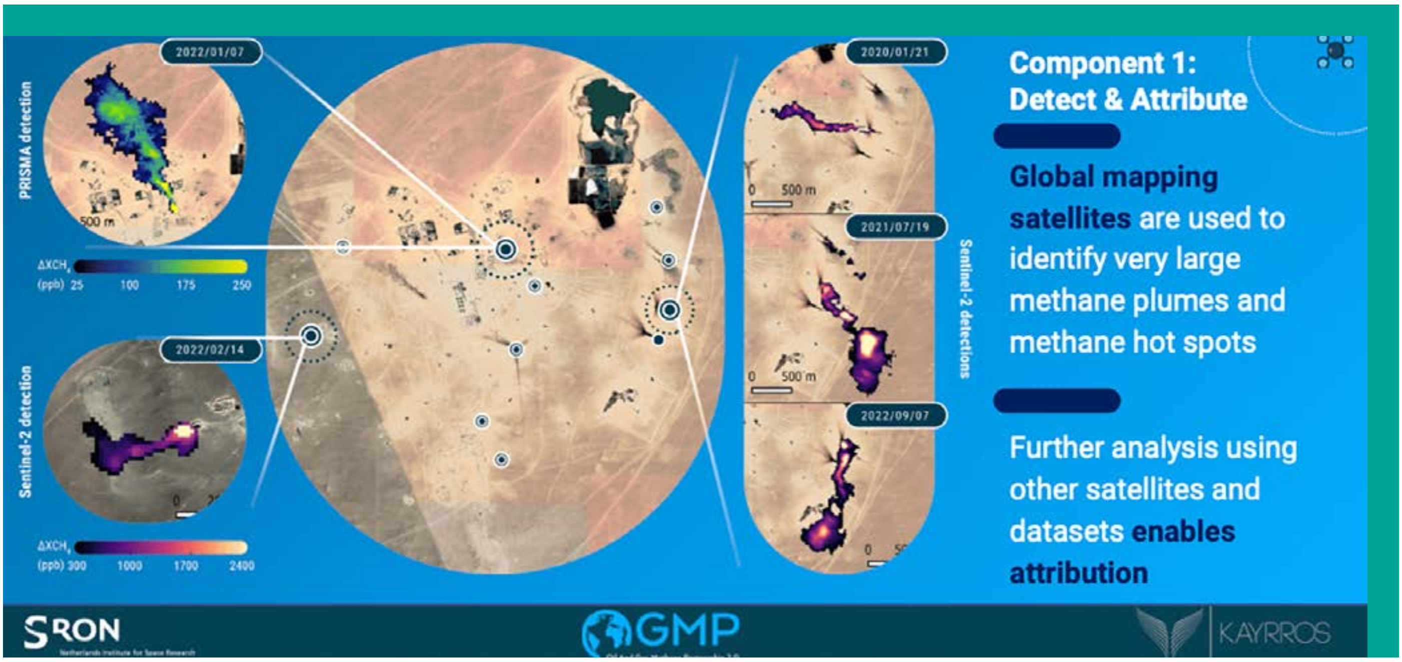


Figure 4: MARS Component 2 - Notify & Engage Stakeholders

MARS CONNECTS DATA TO ACTION BY NOTIFYING STAKEHOLDERS OF EMISSIONS

Once UNEP IMEO has linked a methane emission to a facility through use of high-spatial resolution satellite data, that emission is a candidate for notification. If there are many emissions detected within the same ROI during the same time frame, multiple emissions from multiple facilities may be batched together within a single notification.

Notifications are always sent to national-level government contacts in the appropriate ministry (e.g., Ministry of the Environment, Ministry of Oil and Gas, etc.). If UNEP IMEO is able itself to link the emitting facility to an operator, and that operator is also in OGMP2.0 and has provided UNEP IMEO with a MARS contact, the notification will be simultaneously sent to the government and the operator. Otherwise, UNEP IMEO will request that the government assist it in notifying and gaining the contact information of the operator.

UNEP IMEO requests that governments and operators first quickly – within 2 days – acknowledge receipt of the MARS notification. Then, UNEP IMEO requests that governments assist in notifying and gaining contact information for non-OGMP2.0 operators. For operators, UNEP IMEO requests initial feedback including the type of emitting facility, and any preliminary information regarding the emission event (e.g., if it was associated with a known operation or malfunction). After providing this initial feedback, the operator is requested to provide more detailed final feedback, including mitigation plans, no later than 45 days post notification. At any time during the process, operators are encouraged to communicate with UNEP regarding the notification, and UNEP and its partners stand ready to aid with mitigation efforts as requested.

MARS IS DESIGNED TO PROMOTE MITIGATION WHILE INCREASING TRANSPARENCY

MARS was designed to incentivise corporations and governments to credibly reduce their methane emissions and contribute to limit the rise of global temperatures to well below 2°C in line with the Paris Agreement. To that end and to increase transparency around global methane emissions and accelerate the implementation of the Global Methane Pledge, after 45-75 days post detection, all MARS data is publicly available. The publicly available data includes:

- All IMEO-gathered satellite data and related metadata (e.g., visual data).
- A summary of operator and/or government response(s) to the notification process.
- A summary description of mitigation efforts and/or plans.
- Any past or future MARS detections linked to the event location.

FURTHER INFORMATION AND GET HELP

International Methane Emissions Observatory: https://www.unep.org/explore-topics/energy/what-we-do/imeo

Methane Alert & Response System (MARS): https://www.unep.org/explore-topics/energy/what-we-do/methane/imeo-action/methane-alert-and-response-system-mars

MARS video: https://youtu.be/AypbO1IjaMQ

POINT OF CONTACT:

Cynthia Randles: cynthia.randles@un.org

TRACKING THE EVOLUTION OF GLOBAL AND REGIONAL GHG BUDGETS – EARTH OBSERVATIONS AND THE GLOBAL CARBON PROJECT

CONTRIBUTED BY JOSEP CANADELL (CSIRO, AUSTRALIA), BENJAMIN POULTER (NASA, USA), ANA BASTOS (MAX PLANCK INSTITUTE FOR BIOGEOCHEMISTRY, GERMANY), PHILIPPE CIAIS (LSCE, FRANCE), MARIELLE SAUNOIS (LSCE FRANCE), PIERRE FRIEDLINGSTEIN (UNIVERSITY OF EXETER, UK), HANQIN TIAN (BOSTON COLLEGE, USA), ROBERT B. JACKSON (STANFORD UNIVERSITY, USA)

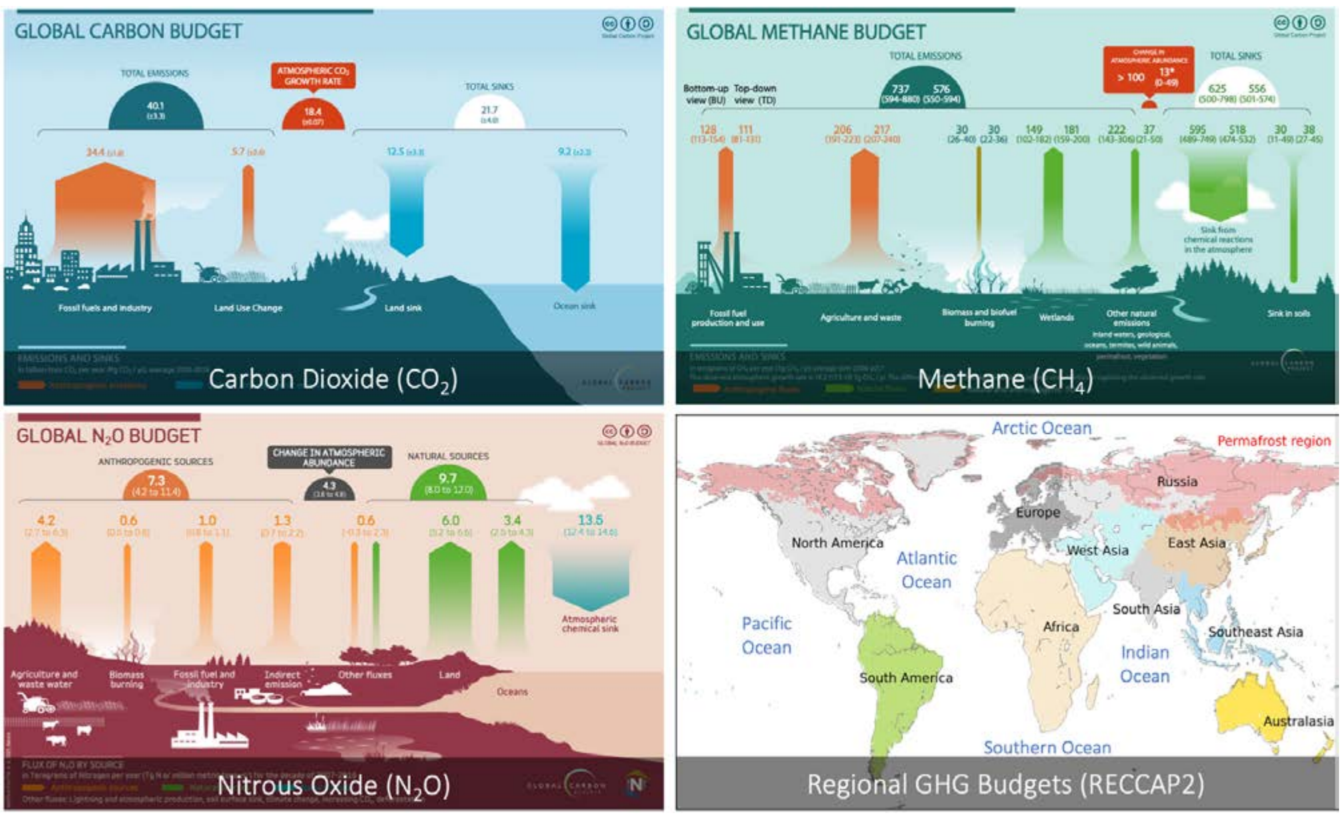
The Global Carbon Project (GCP) has coordinated and assessed the annual global carbon budget since 2005, a quasi biennial global methane (CH_4) budget since 2013 and a global nitrous oxide (N_2O) budget since 2020 (Figure 1). The budgets provide a comprehensive quantification of the anthropogenic and natural sources and sinks for the land, freshwater systems, the ocean and atmosphere using data from direct observations, inventories, remote sensing and modelling. A unique feature of the development of these budgets is the use of a broad set of complementary top-down and bottom-up methodologies that contribute to assessing the magnitude of sectorial fluxes, both natural and anthropogenic, their uncertainties and areas of further research.

These global greenhouse (GHG) budgets are used in the assessments of the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO), and increasingly support national GHG inventories by providing a scientific and independent accounting of greenhouse gas emissions and removals. Given their global coverage and periodic updates, these budgets are now an essential benchmark for tracking progress towards climate goals and supporting the global stocktake of the Paris Agreement. A key ongoing research focus is enabling the scientific approaches and the national GHG inventories to exchange information, constrain each other and ultimately integrate mulitple flux quantities in a globally constrained approach (Deng et al. 2021; Grassi et al. 2023).

In 2019, the GCP launched the Second REgional Carbon Cycle and Processes study (RECCAP2) to increase the resolution and attribution of the global budgets to the level of regions and large nations. RECCAP2 includes regional assessments (for the land and ocean) of CO_2, CH_4 and N_2O emissions and removals for the time period 2010–2019. The assessment includes 10-land regions, 5-ocean regions (Figure 1), and 10-special topic areas including permafrost, polar regions and the land-ocean-aquatic continuum (LOAC). Using both top-down and bottom-up methodologies (Ciais et al. 2022), a key goal of RECCAP2 is to reconcile differences between the approaches and develop regional capacity to assess budgets at regular intervals. For instance, RECCAP1 showed that large differences between estimates from top-down and bottom-up approaches could be reconciled when the lateral transfers of carbon from aquatic flows and trade are integrated into the regional budgets (Ciais et al. 2021). Each RECCAP2 assessment will be published in a special journal collection of the American Geophysical Union.

As Earth observations (EO) from remote sensing missions have expanded to include spaceborne lidar, GHG retrievals, and new proxies for biomass, i.e., vegetation optical depth (VOD), their use has similarly increased in GCP assessments. The Global Carbon and Methane Budgets include atmospheric inversions that use satellite retrievals of column concentrations of carbon dioxide and methane, respectively, and passive radar missions are the basis for determining global wetland area and dynamics used to estimate wetland methane emissions. Satellite-based biomass estimates are combined with land cover change information to provide independent estimates of emissions from deforestation. Remote

Figure 1: The three GCP global GHG budgets and their regionalization through RECCAP2's 25 regions and focus areas (Friedlingstein et al. 2022; Saunois et al. 2020; Tian et al. 2020)



sensing data products contribute additional constraints on land-surface models that have traditionally been used in 'prognostic' mode to estimate land-atmosphere fluxes, relying only on meteorological and land-use data to drive numerical representations of biogeochemistry.

EVOLVING USE OF REMOTE SENSING IN RECCAP2

Remote sensing data are used for the land, ocean, cryosphere and atmospheric components of RECCAP2. Many of the emissions and removal processes and products are traceable to a suite of satellite missions led by NASA, ESA and JAXA. Figure 2 illustrates the workflow of how remote sensing data are used to estimate net biome production (NBP) for the North American land region. NBP is the balance between carbon uptake from photosynthesis and losses from respiration and fire, land use change, and depending on whether top-down or bottom-up approaches are used, NBP can include sources from chemical weathering, losses from aquatic transfers, and losses or gains from trade. The different estimates by top-down, bottom-up or remotely sensed flux/stock approaches for the North American region can, for the most part, be reconciled through an understanding and adjustments due to lateral transfers and differences in terminology and definitions, which is largely the motivation of RECCAP2. Unreconciled fluxes and regions drive the evolution of development of new methodologies and data for the next generation of budget assessments. A comprehensive discussion of methods, data products and top-down and bottom-up approaches for regional GHG budgets is discussed in Poulter et al. (2022).

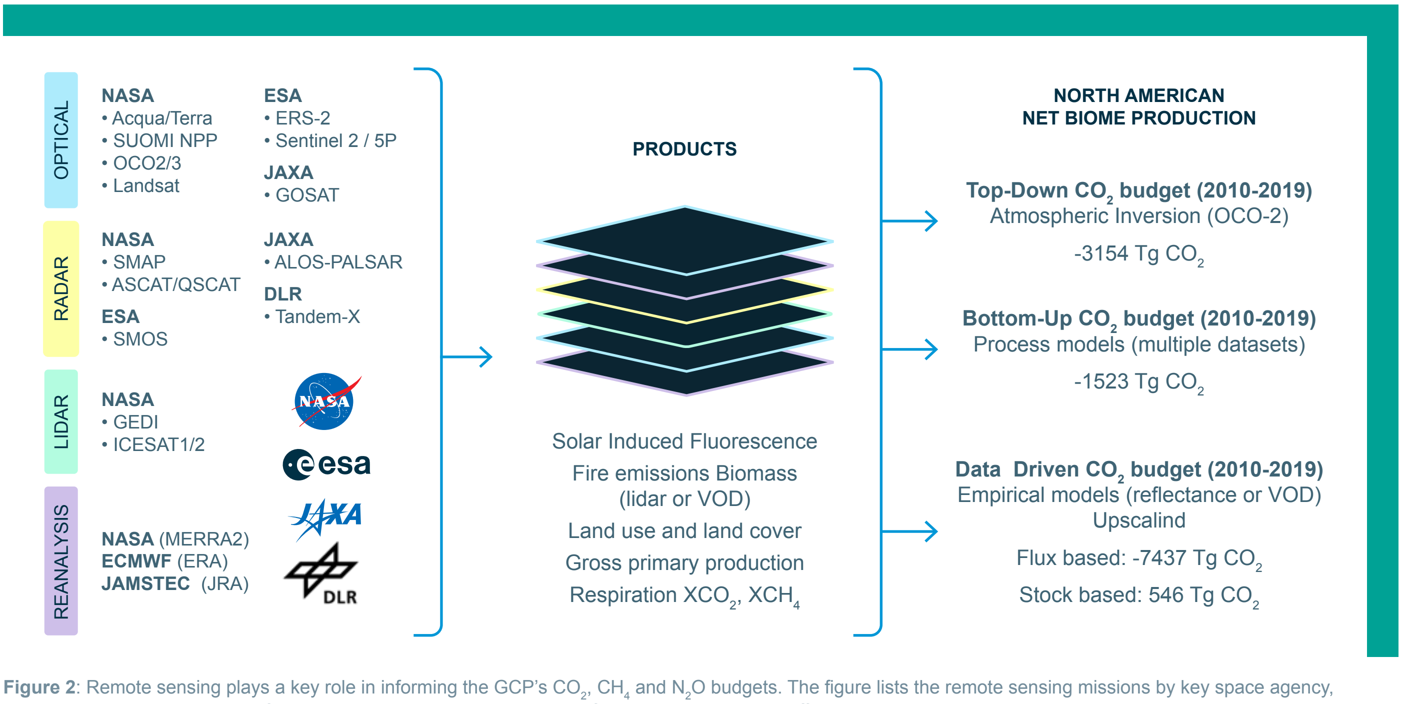


Figure 2: Remote sensing plays a key role in informing the GCP's CO_2, CH_4 and N_2O budgets. The figure lists the remote sensing missions by key space agency, the products, and an example of preliminary land net biome production for North America. The differences between top-down, bottom-up and data-driven approaches are reconciled in activities such as RECCAP2 through accounting of lateral aquatic and trade fluxes and addressing definitions that lead to double counting or missing processes.

EXPANDING THE USE OF EO DATA FOR THE GCP

Remote sensing observations of land cover change, biomass, GHG concentrations and other geophysical parameters are playing an increasingly important role in the GCP's GHG assessments. For remote sensing data to continue to be used, the GCP requires:

1. low-latency product delivery,
2. continuity in measurements,
3. free and transparent access to data,
4. quantification of data uncertainties,
5. support in data access and analysis systems, and
6. support in model development and data assimilation.

The Copernicus Expansion Missions are critical in providing GHG concentration data for use in atmospheric inversions, as well as biomass information to be used in stock change assessments or in land surface model development. New hyperspectral and thermal imaging missions are expected to improve land surface processes related to estimating gross primary production, the largest flux component in NBP. Currently, the nitrous oxide budget relies on in-situ measurements of GHG concentrations in the absence of any space-based mission. As the Expansion Missions become operational and as NASA's Earth System Observatory evolves, the use of EO data can be expected to reduce uncertainties and contribute to the objectives of the GCP to monitor Earth system processes and support policies to mitigate and reduce GHG emissions.

REFERENCES:

Ciais P et al. (2022) Definitions and methods to estimate regional land carbon fluxes for the second phase of the REgional Carbon Cycle Assessment and Processes Project (RECCAP-2). GMD 15: 1289-1316. https://gmd.copernicus.org/articles/15/1289/2022/

Ciais P et al. (2021) Empirical estimates of regional carbon budgets imply reduced global soil heterotrophic respiration. National Science Review 8 (2), nwaa145. https://academic.oup.com/nsr/article/8/2/nwaa145/5868251

Deng et al. (2022) Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions. ESSD 14: 1639-1675. https://essd.copernicus.org/articles/14/1639/2022/

Friedlingstein P et al. (2022) Global Carbon Budget 2021. Earth System Science Data 14:1917-2005. https://essd.copernicus.org/articles/14/4811/2022/

Grassi et al. (2023) Harmonising the land-use flux estimates of global models and national inventories for 2000–2020. ESSD 15: 1093-1114. https://essd.copernicus.org/articles/15/1093/2023/

Poulter B, Canadell JG, Hayes D, Thompson R (2022) Balancing Regional Greenhouse Gas Budgets. Elsevier, pp.503. https://shop.elsevier.com/books/balancing-greenhouse-gas-budgets/limbert/978-0-12-814952-2

Saunois M et al. (2020) The global methane budget 2000–2017. Earth System Science Data 12 (3), 1561-1623. https://essd.copernicus.org/articles/12/1561/2020/

Tian H et al. (2020) A comprehensive quantification of global nitrous oxide sources and sinks. Nature 586 (7828), 248-256. https://www.nature.com/articles/s41586-020-2780-0

LEARN MORE AND GET HELP

Global GHG Budgets: https://www.globalcarbonproject.org

RECCAP2: https://www.globalcarbonproject.org/reccap

POINT OF CONTACT:

Josep (Pep) Canadell: Pep.Canadell@csiro.au

COPERNICUS GREENHOUSE GAS EMISSIONS MONITORING CAPACITY

CONTRIBUTED BY ECMWF (RICHARD ENGELEN, NICOLAS BOUSSEREZ, JOE MCNORTON), LSCE (FRÉDÉRIC CHEVALLIER), EUMETSAT (RUEDIGER LANG), EC JRC (MARK DOWELL), ESA (YASJKA MEIJER)

INTRODUCTION

To enable the EU to move towards a low-carbon economy and implement its commitments under the Paris Agreement, the European Commission committed to cut its emissions by at least 55% by 2030. This was further consolidated with the release of the Commission's European Green Deal setting the targets for the European environment, economy and society to reach zero net emissions of greenhouse gases (GHGs) in 2050. To independently assess the progress of countries towards their targets, the European Commission indicated that an objective way to monitor anthropogenic CO_2 emissions and their evolution over time was needed. Such a capability would provide consistent and reliable information to support informed political and decision-making processes. The European Commission is therefore establishing an operational observation-based anthropogenic CO_2 emissions monitoring and verification support capacity (**CO2MVS**) as part of its Copernicus Earth observation (EO) programme (Figure 1).

The CO2MVS concept combines information from satellite and in situ observational datasets and from existing knowledge about emissions, together with detailed computer models of the Earth system. Its statistically robust framework enables exhaustive emission estimates of anthropogenic CO_2 and CH_4 at different scales with a similar level of mathematical rigour that has proven critically important in other applications, such as numerical weather prediction and air quality prediction.

As an observation-based system, the CO2MVS receives, as its main inputs, observations collected by satellite and in situ sensors. Satellite data are from existing or new Copernicus Sentinel satellites (such as Sentinel-5P, Sentinel-5, and CO2M) and various other sensors from national and international space agencies. In situ data are provided

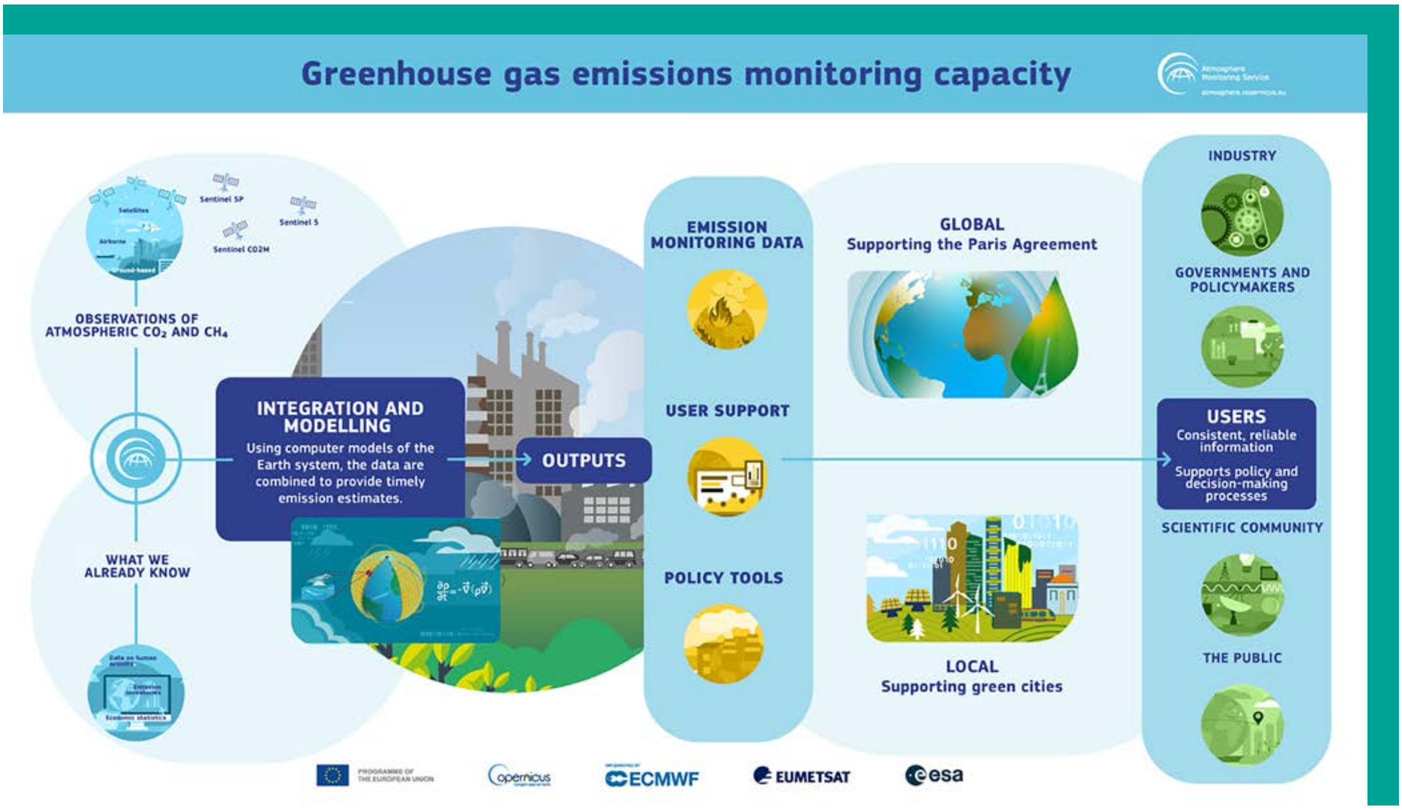


Figure 1: CO2MVS

by various surface networks, coordinated by national, European, or international efforts. None of these observation systems directly measure anthropogenic emissions, but instead provide information on atmospheric CO_2, CH_4, and co-emitted gases, which result from anthropogenic emissions. Observations can also provide information about the processes that are responsible for the exchange of CO_2 and CH_4 between the Earth's surface and the atmosphere such as photosynthesis or human activity.

The signal of anthropogenic emissions in the variables we can observe, like atmospheric CO_2, is weak compared to the signal of natural emissions and removals between land and ocean surfaces and the atmosphere, especially on time scales shorter than a year. Moreover, the variability of atmospheric CO_2 concentrations due to human activity is small compared to average background concentrations and large-scale variability. To address these challenges, the CO2MVS needs state-of-the-art computer models of the Earth system capable of simulating observed variables based on prescribed or modelled emissions and removals. Advanced data assimilation methods can then make adjustments to emissions and removals that are consistent with information from observations and constrained by the physical knowledge encapsulated in the models.

The CO2MVS will include and connect models and observations at three different scales:

1. a global integration and attribution system will provide global coverage integrating all available observations;

2. local hotspot integration and attribtion systems will directly assess emissions from individual plumes; and

3. regional systems will focus on specific areas with very dense observing infrastructure around them to provide a reference for the global system.

The CO2MVS will translate the generated data into user-friendly services. For some users, this could mean providing raw production data; for other user sectors specific tools need to be developed and implemented. The main objective of the CO2MVS is to serve the policy sector at international, national and local scales, to help countries develop their own specific emission monitoring capabilities and to stimulate adoption by businesses and the finance sector within the framework of a green economy.

The CO2MVS capacity is planned to become operational in 2026 as part of the Copernicus Atmosphere Monitoring Service (CAMS), implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), aligned with the planned launch of the CO2M satellite constellation, currently being prepared by the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

The operational provision of well calibrated and continuously monitored satellite data by ESA for Sentinel-5P and EUMETSAT for the future Sentinel-5 and CO2M missions is key for the CO2MVS capacity service to become operational in 2026.

The initial European CO2MVS is being developed through a range of EU-funded research projects, most notably the current Prototype System for a Copernicus CO_2 service (CoCO2) project funded by the Space 2018–2020 Work Programme of the European Union for a 3-year period (2021–2023).

As part of the ramping-up activities towards the operational CO2MVS, CoCO2 has been contributing to the first Global Stocktake (GST) data and information collection by providing accurate information about anthropogenic emissions based on current prototype systems that best exploit available observations. In what follows, two examples are given of current capabilities, one focused on CO_2 fluxes from the Agriculture, Forestry, and Other Land Use (AFOLU) sector using an offline atmospheric inversion system and one focused on CH_4 emissions using the newly developed online emission estimation system.

ESTIMATES OF AFOLU EMISSIONS FROM CO_2 ATMOSPHERIC INVERSIONS

Observations of atmospheric CO_2 from satellites or based on direct measurements of air samples provide information on the emissions and removals of CO_2. As outlined above, combining these observations with atmospheric transport models and prior information provides independent estimates of emissions and removals to compare with national inventories. All of these ingredients are still the topic of active research, but the domain has reached enough maturity in recent years to allow first comparisons with estimates reported for the AFOLU sector by some of the United Nations Framework Convention on Climate Change (UNFCCC) Parties in their National Inventory Reports (NIRs). For a like-for-like comparison, some emission and removal terms not included in the NIRs need to be subtracted from the inversion estimates (carbon absorbed by crop, emitted by human or animal respiration, or emitted by lakes and rivers) and the terrestrial biospheric carbon input to the inland water network needs to be added to the inversion system. These correction terms are estimated from the scientific literature and from living databases like that maintained by the Food and Agriculture Organization (FAO).

This example from CoCO2 post-processes the time series of the sum of emissions and removals estimated by the operational atmospheric inversions of CAMS provided by the Laboratoire des Sciences du Climat et de l'Environnement (LSCE). CAMS provides estimates based on surface air-sample measurements, from 1979 onwards, and based on satellite CO_2 soundings, from 2015 onwards. In line with the UNFCCC reporting guidelines on annual inventories, the sum of emissions and

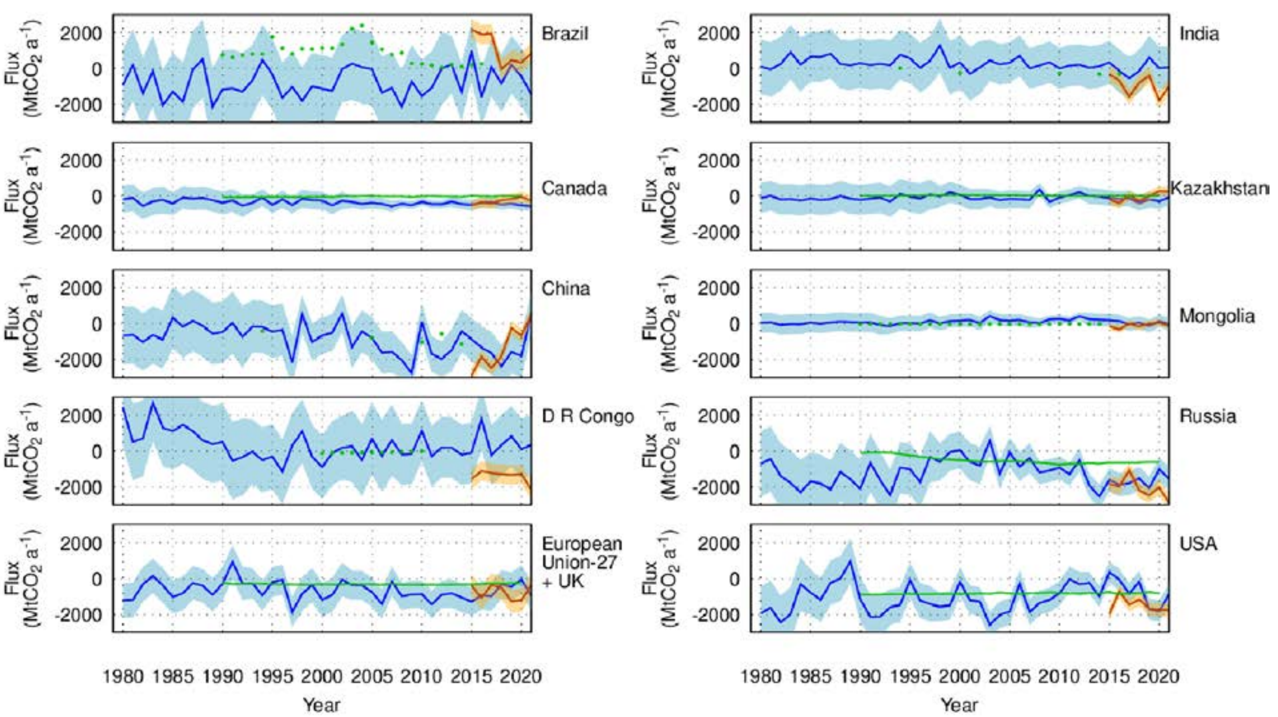


Figure 2: Annual CO_2 flux (the sum of emissions and removals) from the AFOLU sector in ten large Parties to UNFCCC estimated by the Parties themselves (green lines for the Annex-I parties, green disks for the non-Annex-I parties when available) and from the 1-σ uncertainty envelope of the two latest CAMS inversions (blue for the air-sample-driven inversion and orange for the satellite-driven inversion). Positive values indicate that the party is a source of CO_2 to the atmosphere. For a fair comparison, the surface fluxes from the inversions have been corrected for crop and river fluxes.

removals of managed areas in each grid point and their uncertainty at the annual national scale were aggregated, corrected to fit UNFCCC definitions as explained above, and compared with the numbers reported in the NIRs by ten Parties with very large geographical areas, a spatial scale at which these CAMS products are most robust: Brazil, Canada, China, the Democratic Republic of the Congo, the 27-member EU and United Kingdom together, India, Kazakhstan, Mongolia, Russia and the United States. From the NIRs, the sum of the net CO_2 emissions and removals from the agriculture sector and the land-use, land-use change and forestry sector were used.

Figure 2 shows the time series of net fluxes for the AFOLU sector in these ten large Parties to UNFCCC. The values have been estimated by the Parties themselves (green points and curves) or by the two CAMS products (blue for the air-sample-driven estimates and orange for the satellite-driven estimates).

The comparison to UNFCCC numbers reveals some similarities for the mean value and some consistent variations, but also a larger variability and some offsets. An important issue is the absence of a mask that unambiguously defines the land areas (plots) considered by each Party as managed from year to year. The lack of exhaustiveness of the NIRs, which unevenly report the evolution of the carbon stocks, is another issue, in particular for less accessible or not dominant carbon pools. Finally, the temporal support of the values reported in the NIRs for a given year, blurred by interpolations between infrequent plot measurements, sometimes separated in time by large natural disturbances, is another important limitation for the comparison. Nevertheless, some countries (e.g., Germany) have now started to make use of the CAMS estimates in their national reporting as part of the additional information to be considered as part of the NIR submission.

ESTIMATES OF CH_4 EMISSIONS FROM THE EXTENDED COPERNICUS ATMOSPHERE MONITORING SERVICE GLOBAL MONITORING SYSTEM

In CoCO2, the CAMS global monitoring and forecasting system is being extended to form the core of the global component of the CO2MVS. This system is a configuration of the Integrated Forecasting System at ECMWF that can monitor atmospheric concentrations and surface fluxes of GHGs and atmospheric pollutants in addition to the comprehensive meteorology that is already available for ECMWF's Numerical Weather Prediction services. The so-called online approach ensures full consistency between the different elements that are relevant for the monitoring of GHG fluxes (e.g., modelling of atmospheric transport, temperature, land surface, chemical reactions, etc.). In this example, preliminary results from the first version of the prototype are presented for CH_4 emissions.

Similar to the offline example above, prior knowledge of the GHG emissions is updated using satellite observations, taking into account the errors associated with each source of information. The prior knowledge consists of the CAMS-GLOB-ANT anthropogenic emission product and a combination of prescribed or modelled natural fluxes. The observations are retrievals of the CH_4 atmospheric column or partial column from the GOSAT, IASI, and Sentinel-5P satellite instruments. The prior global CH_4 emissions and removals are then rescaled to find the best fit between the full global atmospheric model and the satellite retrievals.

Figure 3 shows both the average monthly posterior CH_4 anthropogenic emissions (x-axis) and the corresponding correction to the prior inventory (y-axis) for top emitting countries for the first half of 2019. While the corrections to the prior emission inventories are small (< 1%) for most countries at this temporal scale, they are more significant for India and China, with a decrease by 3 and 5%, respectively. This overestimation in China's CH_4 emission inventories agrees with previous findings.

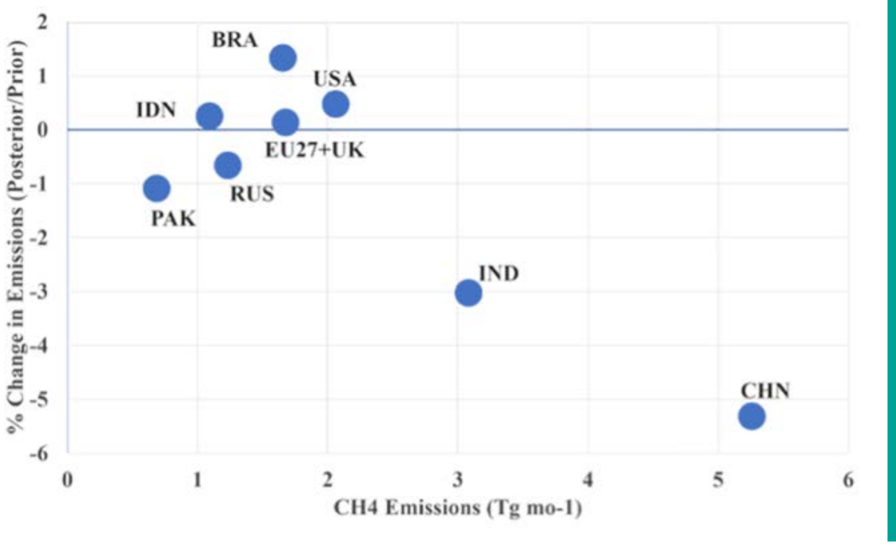


Figure 3: Posterior CH_4 emissions (x-axis) for several major emitting countries and difference between posterior and prior emissions (y-axis) averaged between January and June 2019, derived from the global IFS prototype system. From McNorton et al. (2022, https://doi.org/10.5194/acp-22-5961-2022)

LEARN MORE AND GET HELP

Copernicus Atmosphere Monitoring Service: https://atmosphere.copernicus.eu

Copernicus CO_2 service project: https://coco2-project.eu

POINT OF CONTACT:

Richard Engelen
Richard.Engelen@ecmwf.int

Compiled & edited by: Symbios

Layout by: ESA – EOGB
(Earth Observation Graphic Bureau)