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## A WMO-COORDINATED GLOBAL GREENHOUSE GAS MONITORING INFRASTRUCTURE

*Concept Note*

*Working draft, 18 October 2022*

*WMO Joint Study Group on Greenhouse Gas Monitoring*

### Background

The three most important greenhouse gases (GHGs) influenced by human activities are carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). Increasing abundances of these gases in the environment are the cause of the observed climate change and other impacts according to the Intergovernmental Panel on Climate Change (IPCC, ref AR6, WG1). Recent (post-‑industrialization) increases in concentrations of CO2, CH4 and N2O have been documented to be driven by human activities. The Paris Agreement, adopted by 196 Parties at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties in 2015, sets specific targets for maximum rise in global mean temperature and indicates the means to achieve this target is through the reduction of GHG emissions.

At the 26th Conference of the Parties (Glasgow, November 2021), Parties recognized that “{…} limiting global warming to 1.5 °C by 2100 requires rapid, deep, and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 percent by 2030 relative to the 2010 level and to net-zero around mid-century, as well as deep reductions in other GHG {…}” (Decision 1/CMA3). Availability of information on the levels and budgets of GHG is critical in assisting countries in guiding their commitments and to monitor progress toward emission reductions targets.

### Need for improved quantitative knowledge of greenhouse gas cycles

The Paris Agreement (Article 13) requests Parties to regularly provide (...): “(a) A national inventory report of anthropogenic emissions by sources and removals by sinks of greenhouse gases, prepared using good practice methodologies accepted by IPCC and agreed upon by the Conference of the Parties serving as the meeting of the Parties to this Agreement”; and “(b) Information necessary to track progress made in implementing and achieving its nationally determined contribution under Article 4.”

According to Article 14 of the Paris Agreement, Parties will use these data to undertake a global stocktake every five years to monitor quantitative progress toward the goals and the purpose of the Agreement, and they will do so “in the light of {…} the best available science”. The first global stocktake is to be completed by November 2023. The reported anthropogenic emissions will be based on IPCC guidelines for national greenhouse gas inventories, involving methods of various levels of complexity and sophistication (currently classified by IPCC as tier 1, 2 and 3 methods).

As mentioned above, the largest part of the anthropogenic forcing to the climate system is caused by the changing atmospheric concentration of long-lived greenhouse gases. Therefore, global monitoring of these gases is of prime importance. However, these concentrations are not determined by anthropogenic emissions alone. GHG concentrations are strongly influenced also by the natural cycles, which in turn are influenced by climate and other environmental changes. Variations in natural emissions and uptakes of GHGs can interact with mitigation efforts to either increase or decrease their effectiveness. Our quantitative knowledge of some of the GHG sources and sinks has large uncertainties, both as they currently operate and the extent to which they will change in the future in response to for example climate change.

At present, most measurements of greenhouse gas (GHG) in the environment, and the processing of these observational data needed to support mitigation actions, rely primarily on research activities and funding. The time-limited nature of research funding and the uncertainty in its allocation lead to an inherent fragility of the GHG monitoring system that is difficult to reconcile with its critical and increasing importance as a policy driver.

A sustained, routine monitoring infrastructure of GHG concentrations and fluxes, using standardized protocols and methods akin to those used for monitoring of weather and climate, will provide a wealth of quantitative data to help improve our understanding of the GHG cycles. It will provide time-continuous global fields of the abundance of GHGs in the atmosphere, yielding unprecedented insight into geographic and seasonal distributions of GHGs, which will support the provision of monthly net flux estimates, for instance on a 1x1° (roughly 100 by 100 km) resolution. These quantities will constitute the main output of the proposed operational GHG monitoring. In addition, efforts are currently ongoing to develop capabilities to separate these net fluxes into source-apportioned emissions, which could lead to additional operational products in the future. Per WMO's data policy, the data will be made available to all interested users on a free and unrestricted basis.

The data products will be generated utilizing methodologies already developed by the research and operational communities, WMO Global Atmosphere Watch (GAW) has for instance 50 years of experience in developing the GGMT (Greenhouse Gas Measurement techniques) measurement guidelines that are implemented for example in the operational networks of Europe (ICOS) and the USA (National Oceanic and Atmospheric Administration (NOAA)). The flux product based on the observations will complement existing estimates of anthropogenic emissions. These products can assist Parties in the assessment of their individual emission reductions efforts and the global progress to achieve the mitigation goals of the Paris Agreement.

In view of the need for sustained, routine delivery of high-quality data products covering the entire global domain to support mitigation, this note outlines the case for developing an internationally coordinated, sustained, routine Global GHG Monitoring Infrastructure that would provide such data to the scientific community and to Parties on a more regular and sustained basis. The infrastructure will be developed through cooperation between different organizations that are already involved in the environmental monitoring of GHGs.

### A coordinated Global Greenhouse Gas Monitoring Infrastructure

In its initial configuration, a routine global GHG monitoring system would consist of four main components:

* 1. A comprehensive sustained, global set of surface-based and satellite-based observations of CO2, CH4 and N2O concentrations, total column amounts, partial column amounts, vertical profiles, and fluxes and of supporting meteorological, oceanic, and terrestrial variables, internationally exchanged in near-real time;
  2. Prior estimates of the GHG emissions;
  3. A set of global high-resolution models representing GHG concentrations, sources and sinks;
  4. Associated with these models, data assimilation systems that optimally combines the observations with the model background to generate products of higher accuracy.

The abundances of CO2, CH4 and N2O can be measured in situ in the atmosphere and aquatic environments with high precision (order 0.1% and better), allowing for determination of fluxes. In situ measurements at the surface and from airborne platforms have been widely used for many decades, providing high precision data at many locations around the globe. Over the last decade or two, space-based measurement capabilities, especially for CO2 and CH4, have significantly progressed, though precision of such observations is lower than that of in situ observations, but satellite platforms allow for global coverage.

The atmospheric component of this infrastructure will build on the various pre-existing elements of infrastructure for greenhouse gas observations and modelling supported by WMO since 1975, and on other relevant initiatives on the national, regional and global level.

The ocean observing component of the infrastructure will build on the research and monitoring infrastructure coordinated by the Global Ocean Observing System (GOOS). This includes the biological, physical, chemical, and geological components of the carbon and nitrogen cycles that are directly involved in biogeochemical processes that affect the GHG.

The current knowledge about anthropogenic emissions is documented in the form of inventories prepared at scale ranging from local to global. The inventories are based on input of various socioeconomic data, such as consumption of fossil fuels, and on emissions factors for different types of sources. These inventories are produced both by the academic sector (e.g. the widely used Emission Database for Global Atmospheric Research (EDGAR) and ODIAC inventories) and by public authorities for their national and sub-national reporting obligation. Inventories will remain pivotal as part of the GHG monitoring infrastructure as it is required for the modelling and data assimilation systems.

The modelling component will further utilize infrastructure and methodologies employed for more than 50 years for operational weather forecasting. Over the last decade, this infrastructure has evolved to embrace an Earth-System approach. State-Of-The-Art systems used for numerical weather prediction thus now increasingly incorporate detailed modelling of vegetation, ocean, atmospheric composition and the cryosphere. This provides an excellent basis to build upon for representing the cycles of key greenhouse gases. Direct coupling to land biosphere and ocean models will help further improve our understanding of the GHG cycles, how they may be changing, and the effectiveness of various mitigation strategies.

The key proposed output data provided by the GHG Monitoring Infrastructure will be:

* Routine timely global fields of GHG concentrations;
* Routine timely global monthly estimates of net GHG fluxes at a high horizontal resolution (for example at 1x1°).

Additional data products will be possible, depending on user needs and evolving requirements for GHG-related services (for instance estimates of anthropogenic emissions and of natural terrestrial and oceanic fluxes). Examples of potential downstream products and applications that can be built on the system output are provided in section 5.

As is the case for operational numerical weather prediction, a strong research component in parallel with operations will be required in order to continuously improve measurement techniques, GHG process understanding and model and data assimilation systems. Without such a sustained research effort, the infrastructure will be unlikely to deliver information that can meet evolving user requirements.

### Current and planned GHG monitoring capabilities and initiatives

Various efforts in quantitative GHG monitoring based on one or more of the system components outlined above have been underway for many years.

Since 1989, WMO’s GAW program has coordinated the acquisition of measurements, quality management, capacity development, and the generation of downstream products and services related to atmospheric composition, including GHG. GAW provides the international framework for GHG in situ observations by organizing them from the Global to Local GAW stations. The framework also involves contributing GHG observation networks operated by many other organizations. For example, TCCON is used for the verification of GHG observations from space. The data are managed centrally by the World Data Centre for Greenhouse Gases supported by Japan to ensure consistency and high quality at the expense of a substantial time delay in data delivery. Attempts have been made to expand observing capabilities for GHGs into sparsely covered areas. However, over most of the globe the horizontal density of the surface observing network remains insufficient for effective monitoring, although regional higher density networks are found in Europe (Integrated Carbon Observation System (ICOS)), China, Northern America and a few other places. Open data exchange still remains a problem in some of the regions.

On the satellite side, NASA’s Jet Propulsion Lab has pioneered the ability to measure first CO2 and later CH4 from space. Starting with the Greenhouse Gases Observing Satellite (GOSAT) in 2009, through GOSAT-2, to be followed by GOSAT-GW, Japan has been steadily developing and refining its space-based CO2 and CH4 monitoring capabilities. China has had CO2 and CH4 monitoring capabilities on its FY-3D polar orbiter, on its dedicated TanSat mission, and on GaoFen-5, with additional space-based capabilities in the pipeline. Europe pioneered CH4 observation with SCIAMACHY instrument and currently operates Sentinel-5/Tropomi, and it has a set of CO2 missions planned, starting with Microcarb and followed by the EU Copernicus CO2M mission (CO2M) for launch in 2026. International coordination of these efforts takes place primarily via the Committee on Earth Observation Satellites (CEOS) (Virtual Constellations, the CEOS Working Group on Cal/Val) and to some extent via CGMS.

On the modelling and assimilation side, one of the most advanced efforts belongs to the Copernicus Program of the European Commission. The Copernicus Atmospheric Monitoring Service (CAMS) shares many of the goals listed in the previous section concerning quantitative monitoring of CO2 and CH4. There are plans to further expand the system and to develop a new global monitoring and verification support capacity of anthropogenic CO2 and CH4 emissions (CO2MVS), using the complementarity of observations and computer models. Similar efforts to model and assimilate CO2 observations have been underway also in the US, with both the National Aeronautics and Space Administration (NASA) and NOAA having capabilities in this area, especially with the CarbonTracker, while Japan has been advancing its efforts, including observations, ship and aircraft measurements, and China is also planning to develop its own capabilities over the coming years. Modelling efforts are building on long experience and pioneering work of the TRANSCOM community, of which many contributors are still involved in the mentioned modelling initiatives.

In addition to the efforts listed here, several other GHG-related initiatives are emerging, reflecting broad recognition of the need for improved GHG information. Given the vast political and economic implications of GHG monitoring, additional efforts are likely to emerge over the coming years. To maintain a credible information basis for climate change mitigation measures, it is vital that there is an enhanced coordination of these efforts in full transparency to all Parties.

### Potential downstream applications

Output from the proposed GHG Monitoring Infrastructure will be publicly available, GHG observations (surface- and space-based), modelled global GHG concentration fields at 1x1° resolution, and modelled surface fluxes at 1x1° resolution, globally. The initial list of potential application includes:

* Interpretation of the global product in the context of the Paris Agreement mandated global stocktake, including:
  + Global and/or regional aggregation of emission sources and sinks.
  + Methodologies for partitioning the global flux into sectors, gases, regions.
  + Uncertainties associated with aggregated products.
* Aggregation of 1x1° flux information to regional scales for interpretation of regional scale emission fluxes:
  + For evaluation of ocean fluxes not reported in national inventories and currently missed in the global stocktake. Note that these data will also add value to marine acidity reporting against the Sustainable Development Goal (SDG14.3.1).
  + For evaluation of regional scale land carbon fluxes, which are partially included in national inventory reporting. Monitoring of interannual variability (e.g. in response to drought) will be critical.
  + Anthropogenic emissions aggregated to national scale for nations which currently have little or no infrastructure to determine emissions from activity data, providing a starting point for development of improved emission information; may be particularly relevant for non-CO2 emission sources.
  + Analysis of uncertainties in these aggregate products.
* Provision of boundary conditions for regional, national and sub-national studies. This will typically utilize the GHG concentration fields rather than flux outputs. This will allow entities to develop finer scale emissions information for their domain of interest.
  + Uncertainty analysis for the derived boundary conditions.
  + Guidance on how such downscaling efforts should be conducted (utilizing other mechanisms such as IG3IS Good Practices).

### Role of WMO

There are two main reasons why WMO is well positioned to play a central role in coordinating a Global GHG Monitoring Infrastructure.

First, WMO has ongoing activities and experience in three of the four main areas listed in Section 3: Surface- and space-based observations of both basic weather variables and minor atmospheric constituents, international data exchange, relevant modelling and data assimilation efforts, and research. Via the Global Climate Observing System (GCOS) and its collaboration with the United Nations Environment Programme (UNEP), WMO has some activities in land-surface observations, and via GOOS and collaboration with the Intergovernmental Oceanographic Commission (IOC), significant activities in ocean observations and ocean modelling.

Second, as an intergovernmental organization, WMO has decades of experience in coordinating international efforts, establishing international systems, and setting standards and best practices in closely related areas such as weather and climate observations (WMO Integrated Global Observing System (WIGOS), GCOS, GOOS), numerical weather prediction (World Weather Research Programme (WWRP) and the Global Data-processing and Forecasting System (GDPFS)), and measuring and modelling concentrations of minor atmospheric constituents (GAW).

In addition, the World Weather Watch (WWW) is a useful paradigm for the infrastructure envisaged here, since it encompasses observations, data exchange, modelling and data assimilation and common verification methods. It is individual WMO Members that make observations, run models, and deliver data to users. The WWW establishes the collaborative framework for those countries (“infrastructure” in WMO terminology), within which its Members operate the various system components in a way that lets them complement and leverage each other for maximum impact. Under the auspices of the WMO Convention, the WMO Members (countries and territories) set requirements for the observing systems, the international exchange of data, the global modelling and assimilation efforts, and the dissemination and verification of the global model fields. The systems themselves are operated by the WMO Members, either individually or as groups of Members. This paradigm needs to be expanded to include many other institutions and parties within the Member countries and internationally to allow for the full implementation of the envisioned infrastructure.

Analogous to the role played by the WWW in the numerical weather prediction (NWP), the role of a common GHG Monitoring Infrastructure would be to establish:

* Requirements for an integrated surface-, aircraft and satellite- based observing system;
* A design of a comprehensive surface-based observing system and national observing requirements, along the lines of WMO’s Global Basic Observing Network (GBON), accompanied by a funding mechanism for implementation and operation in developing countries, along the lines of the Systematic Observations Financing Facility (SOFF);
* Improved and timely exchange of all satellite-, aircraft and surface-based GHG observations, including the coordinated planning for future satellite observing systems;
* Collaboration on common methodologies and practices for GHG modelling and data assimilation;
* Common file formats and practices for exchange of model fields;
* Common verification and validation methods;
* Common guidance on methods for postprocessing and down-streaming applications.

The WWW does not produce or disseminate weather forecasts, and similarly it would not be the role of the WMO GHG monitoring infrastructure to directly provide estimates or verification of anthropogenic emissions. This is the purview of individual Parties to the Paris Agreement, assisted where needed by targeted systems such as IG3IS or as developed under the Copernicus program.

### Next steps

At this point (September 2022), the WMO Executive Council has launched a comprehensive study to advance this WMO-coordinated Global GHG Monitoring Infrastructure. A broad interdisciplinary Joint Study Group has been tasked to develop its concept and submit a proposed architecture to the 19th World Meteorological Congress in May  2023.

At the same time, WMO is working with the broader GHG monitoring community to ensure that this development is embraced by the various entities that are already actively developing its main components (see Section 4).

Further details and developments related to development of this Global GHG Monitoring Infrastructure can be found on the [website](https://public.wmo.int/en/our-mandate/focus-areas/environment/greenhouse-gases/global-greenhouse-gas-monitoring-infrastructure).

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