Space Agency Report in Support of the Paris Agreement

Prepared by:

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CEOS Virtual Constellation on Atmospheric Composition

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1 Introduction

The 2015 United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (UNFCCC, 2015a) came into force on 4th November 2016. It is expected that the Paris Agreement will drive climate policy during the next two decades and beyond. The agreement addresses climate change issues by asking all parties to the UNFCCC to reduce the total emission of greenhouse gases to the atmosphere (mitigation) and to increase the resilience of Parties to adverse effects of climate change (adaptation).

The Committee on Earth Observation Satellites (CEOS) together with the Coordination Group on Meteorological Satellites (CGMS) is regularly addressing the UNFCCC Subsidiary Body on Scientific and Technical Advice (SBSTA) reporting on specific CEOS and CGMS contributions to the systematic observation of the climate system. In particular, an annual statement on progress is provided at each Conference of the Parties (COP) SBSTA meetings.

This document is detailing existing and potential future contributions of space agencies in support of the implementation of the Paris Agreement that will foster the relation to UNFCCC. Section 2 provides a short summary of the Paris Agreement also considering the role that satellite data and derived products can play in the context of the Paris Agreement. Section 3 recapitulates analysis performed by other organisations, section 4 describes the CEOS contribution and section 5 provides some conclusions.

2 The Paris Agreement

The Paris Agreement defines three major aims (Art. 2):

1. Limiting the temperature increase to well below 2°C and targeting 1.5°C above pre-industrial levels;
2. Improving the ability to adapt to adverse impacts of climate change;
3. Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate resilient development.

The first two aims have a direct relation to needs for observations to which CEOS can make significant contributions. The consideration of the third aim is out of scope of this document and is not further addressed. While Article 2 of the agreement defines the major aims, Articles 3-15 specify the ways to achieve these aims. Articles 4-12 describe specific actions to be performed to implement the Paris Agreement and Articles 13-15 are describing the elements and the process to assess the progress on the implementation of the Paris Agreement. The remaining Articles cover procedural matters facilitating the implementation of the Paris Agreement.

The agreement addresses the topics mitigation including commitments made by the Parties (National Determined Contributions (NDCs)), adaptation, loss and damage, technology transfer, reporting and the financial support and capacity building needed to implement the actions. Systematic observations of the climate system are only mentioned once (Art. 7, paragraph 7(c)) on strengthening the cooperation on enhancing action on adaptation by strengthening scientific knowledge on climate to the benefit of climate services and support to decision making. However, many parts of the agreement can only be successfully implemented when underpinned by findings from systematic observations of the climate system. This is in particular true for the Global Stocktake that should lead to a progressive reduction of greenhouse gas emissions that will allow the Parties to reach the formulated aims over time. Inputs to the Global Stocktake are the NDC results, the state of adaptation efforts, and the mobilisation and provision of support. In addition, the reports of the Intergovernmental Panel on Climate Change (IPCC) and reports of the Subsidiary Bodies including SBSTA are considered.

Satellite data and derived products as well as reporting on their usage have the potential to support NDC reports, e.g., by contributing to the provision of global and regional constraints on greenhouse gas sources and sinks. They can also support assessment of progress in adaptation by monitoring changes on the Earth Surface, e.g., forestation, changes in disaster impacts, evolution of urban areas, etc. Results achieved through the analysis of satellite data provide significant information to IPCC reports via peer reviewed literature on the use of satellite data and products for GCOS ECVs fostering an improved understanding of the climate system. Finally this and the international coordination activities related to climate observations from space also provide significant input to SBSTA reports on the evolution of systematic observations of the climate system.

3 Analysis by GCOS and GEO

The Global Climate Observing System (GCOS) and the Group on Earth Observations (GEO) undertook exercises to analyse their current and potential future contribution and activities in support of the implementation of the Paris Agreement. Considering that CEOS is using GCOS as the major provider of observational needs for space-based climate monitoring, it is important that CEOS monitors the evolution of such needs and the initiation of new GCOS activities. Likewise CEOS is supporting many GEO initiatives including the cross-cutting climate theme.

A major outcome of the GCOS analysis (GCOS, 2018) is that observations are vital for a successful implementation of the Paris Agreement. Observational needs to support adaptation to climate change need to be developed and will form a dedicated new GCOS activity. Observations of many GCOS Essential Climate Variables (ECV) are seen as very important as they contribute directly and indirectly to mitigation and adaption questions by fostering an improved understanding of the climate system. In particular, atmospheric composition data together with suitable models for fluxes of greenhouse gases are seen as important for the support to the emission and removal estimates submitted to UNFCCC and also for providing information on the change of natural greenhouse gas sources and sinks.

Major outcome of the GEO analysis (GEO, 2018) is that GEO contributes to key areas of the Paris Agreement such as adaptation and loss & damage. However, a recent workshop called for a more integrated approach to climate across the GEO Work Programme, in particular to better address adaptation questions. The GEO community may play an important role in providing guidance to national adaptation planning processes on the use of Earth Observation data and information.

4 CEOS and CGMS Contributions to the Paris Agreement

Space agencies continue to improve their systematic observation of the climate system, now over several decades, strengthening scientific knowledge on climate, supporting provision of knowledge-based information to climate services and to support decision-making. Space agencies are doing this by implementing the Architecture for Climate Monitoring from Space (Dowell et al., 2013) – developed by a team comprised of representatives from CEOS, CGMS, and the World Meteorological Organization (WMO). This architecture involves the identification of existing and potential future gaps in the provision of the climate data requested by the UN's Global Climate Observing System Programme (GCOS) that will also address additional observational needs related to the Paris Agreement. CEOS and CGMS expect that additional observations and data products will be needed to support the monitoring of adaptation and that GCOS will provide new observational requirements for them.

4.1 The ECV Inventory, gap analysis, and coordinated actions

The consolidation of space agency efforts through the establishment of the Joint CEOS/CGMS Working Group on Climate has resulted in a significant increase in efficiency in responding to the needs of

Systematic Observations as required by the Convention. Using the web-based Inventory of more than 900 existing and planned climate data records of Essential Climate Variables (ECV) observable from space published in 2017, the Working Group Climate consolidated its first gap analysis that covered three objectives:

1. Assessment of ECVs and their ECV Products where no data records exist or are not planned. ECV Products provide further detail of specific geophysical quantities that can be derived from satellite measurements;
2. Assessment of the existing and planned climate data records with respect to the fulfilment of the criteria, published by GCOS, that provide guidance to climate data record providers on the sustainable process to generate CDRs, and on the quality required to be able to serve known climate applications. The analysis has been performed for all GCOS ECVs and their ECV Products. The ECV Inventory was designed to assess against criteria in GCOS (2016);
3. Assessment of a more optimised use of past and current satellite measurements and an analysis of missing measurements in the future, which would prevent the generation of CDRs for specific ECV Products. Eight ECVs (Carbon Dioxide, Methane, Precipitation, Sea Surface Temperature, Sea Surface Salinity, Land Surface Temperature, Leaf Area Index, and Above-ground Biomass) and their associated ECV Products were addressed.

Results for the first objective indicate for atmospheric ECVs:

- All ECVs are partially covered, although a dense data population only exists for the period 2001-2010;
- For existing CDRs, five ECV Products (Temperature of Deep Layers, Tropospheric Ozone and CO_2 Profiles, and NO_2, SO_2 and HCHO Tropospheric Columns) are not covered. However, Temperature of Deep Layers does not constitute a real data gap because data records are known to exist for this ECV even though they are not currently registered in the inventory;
- For planned CDRs, very few plans exist for the extension of CDRs beyond 2020. For 4 ECV Products (Total Solar Irradiance, Tropospheric CO_2 Profile, Stratospheric CH_4 Profile, and CO Tropospheric Column) no entries exist in the ECV Inventory. In some cases, these gaps may not be real due to incomplete data holdings. This is improved for the next version due in 2019.

For terrestrial ECVs:

- Far less data records per ECV Product are present in the inventory for terrestrial ECVs compared to atmospheric ones;
- For the existing CDRs, 9 ECV products (Areas of GTN-L Lakes, Snow Water Equivalent, Glacier Elevation data, Ice Sheet Surface Elevation and Mass Changes, High Resolution maps of land cover type, Above-ground Biomass, Active Fire Maps, and Fire Radiative Power) have no entries in the ECV Inventory;
- For planned CDRs, for 6 of the 9 missing ECV Products plans exist to address them in the near future. Three ECV Products (Snow Water Equivalent, High Resolution maps of land cover type, and Active Fire Maps) remain missing and require further analysis.

For oceanic ECVS:

- Far less data records per ECV Product are present in the inventory for oceanic ECVs compared to atmospheric ECVs, with the exception of Sea Surface Temperature;
- The only missing ECV in the current data record holdings is Sea Surface Salinity;

- For the planned data records, major improvements in coverage will be achieved by addressing Sea Surface Salinity in the future and also by extending other data records, e.g. Sea Ice Thickness, backwards in time.

Significant findings for the second objective include, but are not limited to:

- Regarding the CDR generation process, in very few cases an independent assessment body, such as GEWEX, was used to perform a quality review. Some Quality Assurance process in general is applied to about 80% of the data records, which is, in most cases, normal product validation. A formal process is in place only for just over 25% of the CDRs, of which only about 5% implement the QA4EO process;
- For the GCOS uncertainty requirement, up to 70% of the data records fulfil the needs for their intended application, although only 20% fulfil GCOS requirements. For 30% of the data records there is no or only qualitative information on uncertainty provided. This could be due non-responsiveness of contributors to this question or could possibly constitute a real area for improvement;
- The temporal stability of the data records have not been assessed in about 75% of the cases, which is a concern as only high stability in CDRs would enable the detection of a change in the geophysical variable considered. From the remaining 25% of the data records, about one third fulfils the GCOS requirement and the rest seem at least good enough for their intended or realised application. Not many improvements are detected for the planned data records, pointing to substantial issues in demonstrating improvements in the absence of fiducial reference measurements, in particular for stability;
- With regard to data access, a positive finding is that for more than 80% of the data records the access point is an institutional help desk or similar. Only a few percent of the data records are available from individuals only, or the access point is unknown. Also positive is that for more than 98% of the data records the access to the data is without any constraint;
- For a little more than 50% of the data records a link to the used Fundamental Climate Data Record is provided. For a few percent, links to non-FCDR input data is provided, and for the remaining 40% this question remained unanswered. This is correlated to the finding that more than 30% of data producers seem not to know who is responsible for the provision of a best possible input data record (FCDR), including cross-calibration to reference sensors. Various interpretations of this result can be made. The most obvious analysis would be to assume that half of the data records in the inventory do not actually represent climate data records because the input data do not achieve the required quality. However, it is known that many Level 2 data production algorithms contain corrections of Level 1 data, the details of which are often not saved or accessible by others. For future data records there is slightly more awareness on the need for FCDRs, although in all cases it does not seem to be a part of the specific planning for a data record. From this, WGClimate concludes that a specific FCDR inventory would help to facilitate the usage of FCDRs and may make the provision of FCDRs more attractive;
- A clear weakness of the current ECV Inventory holdings is that for less than 50% of the data records a known metadata standard has been applied. This presents a barrier for international interoperability as this is needed for data exchange and automatic visualisation.

The assessment of the 8 ECVs has the following major findings:

- For CO_2, there are only very few data records existing and/or planned. It is recommended that CEOS and CGMS agencies commit to the generation of such data records;

- For CH_4, the gaps for climate data records mentioned above, in particular for stratospheric CH_4 profiles, should be closed. It is recommended that the AC-VC develop a plan to resolve this;
- For Precipitation, many potential additional entries for the ECV Inventory have been identified that provide several long-term, quasi-global, publicly available multi-mission precipitation datasets, which have a clear or potential relevance to climate. In addition it has been found that the number of microwave sensors will most likely decline over the next decade, inheriting the risk that the required temporal sampling (3 hourly) cannot be fulfilled in the future. Because of the number of satellites involved, the number and potential climate relevance of various products, and the general complexity to establish precipitation climatology from space-based measurements, it is recommended to the P-VC to identify a way forward on how precipitation climatology can be addressed in the future;
- For Sea Surface Temperature (SST), a couple of potentially missed opportunities have been identified that address the use of geostationary image data to improve temporal sampling. In particular, the use of the diurnal cycle compared to imagers in polar orbit, the potential contribution of IR sounders to SST accuracy and stability (particularly in the earlier decades), and the potential use of microwave SST that provide increased coverage albeit with greater uncertainty, are all potential measurement opportunities not currently being addressed. It is recommended that the CEOS SST-VC foster work on SST ECV data records with regards to the improvements possible by exploiting the aforementioned data sources. With regards to potentially missing measurements in the future, the continuation of all-weather capability originating from microwave C-band measurements is endangered. It is recommended that the life of operating instruments be maximised, that the possibility of an AMSR-2 on GCOM-W2 be prioritised, and full data sharing with regards to microwave imaging instruments on FY-3 series and HY-2B be enabled. In the longer-term, a sustainable plan with redundancy for C-band microwave conical scanning radiometers should be developed by agencies with an operational mandate.
- For Sea Surface Salinity (SSS), a single activity only is planned to generate a climate data record from the existing measurements, and this single activity will only represent a relatively short time series. It is evident that SSS is not adequately addressed in future missions and it is recommended that agencies address this shortfall as a priority. This has also been recognised by GCOS in the 2016 IP (GCOS, 2016) where GCOS Action 32 advocates for the continuation of salinity observations.
- For Land Surface Temperature (LST there is no apparent gap in the availability of future measurements, but virtually no plan exists to derive climate data records from the combined use of the multitude of individual instruments available. It is recommended that the CEOS LSI-VC devise a way forward for the combined use of past, current and future instruments to create sustained LST CDRs;
- For Leaf Area Index (LAI), it was observed that some known data records have not been registered within the ECV Inventory; this omission should be fixed in the next update. The total number of existing and planned data records currently in the ECV inventory is fairly low (two existing and three planned), even though plenty of satellite instruments that have very high relevance for Leaf Area Index are known to exist. Thus, it is recommended that the CEOS LSI-VC assess climate user needs for such products that are not currently exploited from existing missions. This should assist future planning for LAI CDRs;
- For Above-ground Biomass, there is currently a total gap in climate data record provision. However, it is known that ESA is now attempting to produce epoch estimates for given years. The maximum attainable length of this CDR will be about 10 years, with gaps, which is not suitable for longer-term climate analysis. The situation could be improved if more data, such as from PALSAR-2, would become available, as recommended by WGClimate. Regarding future measurements, two

experimental missions are planned with biomass as the primary mission aim. If they can be successfully executed (including combined use), plans would then be needed to ensure measurement continuity.

The results of the gap analysis clearly demonstrate the capability of the ECV Inventory for providing an end-to-end analysis of available and planned CDRs as derived from measurements from space. The investment made by many agencies into the Inventory, and the presented analysis here, has resulted in a great resource to support the establishment of those capabilities required to ensure that the requirements for observing the Earth's climate system on a routine and sustained basis can be met.

The recommendations made by the WGClimate resulted in a coordinated action plan for space agencies that will lead to a further improved delivery of climate data records and will also help to improve sustainability of measurements in the future. CEOS/CGMS Plenaries endorsed the plan have and it is implemented with support from many other CEOS and CGMS coordination bodies. The ECV Inventory will be updated annually always followed by a gap analysis and an update of the coordinated action plan. WGClimate provides oversight for the implementation of the coordinated actions and is controlled by the CEOS and CGMS Plenaries.

4.2 Adaptation (Article 7)

The planning of adaptation to adverse climate change impacts requires systematic observations for the whole climate system as well as specific information at local scales. The observations are used in very diverse applications at different space and time scales supporting adaptation measures. These include:

- Climate resilience requires to be prepared for dealing with climate related disasters such as flood and storms as well as disease outbreaks. Key elements are Early Warning Systems that use weather forecasts directly depending on satellite observations provided by CEOS and CGMS agencies, as well as higher resolution information at local scales (e.g. water resources, land cover and land use);
- Climate resilience on seasonal timescales, e.g., reacting to drought conditions needs long time series information, e.g., on soil moisture, plus actual development of drought related indicators, e.g., coming from crop monitoring as well as a reliable seasonal forecast. All mentioned elements strongly depend on CEOS and CGMS satellite data and products;
- Longer term changes in weather patterns can lead to extreme weather conditions, e.g., for temperature, precipitation etc., and can also lead to slow changes, e.g., shifts in wet season onset and duration in areas depending on Monsoon related rainfall. Longer term changes in ocean and land surface properties also have profound impact on climate resilience of countries. To monitor and understand such developments of the climate system, climate data records of GCOS ECVs with extreme high quality are needed. The continuous improvement of satellite-derived global, regional and local data records provided by CEOS and CGMS agencies is helping to establish facts that can be used to determine key impacts on vulnerable sectors, geographical zones, and also incurred cost resulting from impacts of extreme events.

The UNFCCC Parties have identified flooding, sea level rise, drought and higher temperatures as main sources of concern for the future. It is expected that GCOS will derive specific requirements for the related ECVs being used for the described applications. Also the development of climate indicators derived from ECV data by GCOS provides some prioritisation to CEOS in terms of what ECVs need to be maintained to be useful for adaptation related applications. It is also expected that end products, in particular in high spatial and temporal resolution are provided directly from high-resolution satellite data records and by reanalysis outputs. It is important that CEOS provides the data important for the assimilation into models that are used for the reanalysis.

Of increasing importance in the context of adaptation is the monitoring of urban areas where more than 50% of the global population lives. CEOS will work with GCOS on how observations from space can support observations supporting the monitoring of the implementation and impact of adaptation and mitigation activities. For instance remotely sensed data may help with observations on urban greening and can also support sea level inundation through better information on local sea level rise.

4.3 Other Articles related to Observations

4.3.1 Global Temperature (Article 2)

On mitigation the Paris Agreement has formulated the aim of constraining the increase of global average surface air temperature to 1.5°C. This directly implies the need for global observations of surface air temperature, which is not possible to be derived from satellite data and is rather provided by station data today. However, satellite data can help to improve the quality of interpolation of surface air temperature between measurement stations, and supports the verification of model-extrapolations to unobserved regions, such as the Polar Regions, Africa, and the oceans.

To explain and predict changes of the global average surface air temperature an as complete as possible understanding of the Earth's energy budget is needed. GCOS has emphasised the importance of the climate system energy cycle in its last Implementation plan (GCOS, 2016) and CEOS using its inventory of ECV climate data records is analysing how well space based data have been used to provide information on energy cycle components. CEOS will work with GCOS to establish best possible ECV climate data records for energy cycle related ECVs.

4.3.2 Nationally Determined Contributions (Article 4)

Since the dawn of the industrial age, human activities have substantially increased the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and other greenhouse gases (GHGs). CO_2 and CH_4 are now the primary anthropogenic drivers of climate change and their impact is expected to grow unless their emissions can be dramatically reduced. To limit the increase in the global average temperatures to less than 2 °C above pre-industrial levels, the 21st session of the Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) agreed to implement an ambitious effort to reduce GHG emissions. Parties to the COP21 Paris Agreement defined nationally-determined contributions (NDCs) to a global GHG emissions reduction effort. Each party agreed to report GHG emissions and removals to the UNFCCC, which will evaluate progress toward the NDCs at 5-year intervals through global "stocktakes", the first of which is scheduled for 2023. These emission reports are based on "bottom-up" inventories that employ a statistical analysis of emissions and removals by known GHG sources and sinks. When fully implemented, bottom-up inventories can accurately quantify emissions sources and sinks within each country. However, some nations do not have the resources needed to compile comprehensive inventories due to rapid economic, social, or environmental change. Other sources and sinks are poorly constrained in bottom-up inventories due to uncertainties in the "activity data" or "emission factors" used in their derivation.

Atmospheric measurements of the CO_2 and CH_4 concentrations complement bottom-up inventory methods by providing an integrated "top-down" constraint on the net amount of each gas exchanged between the surface and the atmosphere. These data therefore provide additional information for compiling bottom-up inventories as well as a synergistic approach for assessing NDCs. At global scales, atmospheric CO_2, CH_4 and other well-mixed GHGs are characterized by precise, accurate, ground-based *in situ* measurements from a series of networks coordinated by the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) program. This network now includes about 145 stations that span the globe, but still does not have the spatial resolution and coverage needed to identify or quantify sources emitting CO_2 and CH_4 into the atmosphere on the scale of individual nations, or to quantify removals by natural sinks.

Recent advances in space-based remote sensing methods provide new opportunities to augment the spatial and temporal resolution and coverage of the ground-based GHG network. High spatial resolution measurements collected by space-based sensors can be analyzed to estimate the column-averaged dry air mole fractions of CO_2 and CH_4 (hereinafter XCO_2 and XCH_4, respectively) over the globe. The Subsidiary Body for Scientific and Technological Advice (SBSTA) of UNFCCC recently acknowledged the utility of these measurements for monitoring CO_2 and CH_4 emissions (SBSTA, 2017), The primary challenge of this approach is the need for unprecedented precision and accuracy to resolve the small (< 2%) XCO_2 and XCH_4 variations caused by surface emission sources and natural sinks.

Space agencies responded to these challenges by supporting a series of pioneering space-based instruments designed to estimate XCO_2 and XCH_4. These experiments include the European Space Agency (ESA) ENVISAT SCIAMACHY, Japanese GOSAT TANSO-FTS, United States (US) National Aeronautics and Space Administration (NASA) OCO-2, Chinese TanSat AGCS, Feng Yun-3D GAS and GaoFen-5 GMI, and ESA Sentinel 5 Precursor TROPOMI. These agencies are implementing six additional missions for launches between late 2018 and 2023 and several others are being planned by governments, private companies, and non-governmental organizations. Data from these space-based based sensors has fostered the development of end-to-end modelling systems for estimating surface CO_2 and CH_4 fluxes from atmospheric measurements on scales ranging from individual power plants to continents.

The Committee on Earth Observation Satellites (CEOS) recognized that high-quality observations of atmospheric CO_2 and CH_4 from a constellation of space-based sensors will be an essential component of an integrated global GHG observing system designed to track progress towards NDCs and support global stocktakes. CEOS started to define a global architecture for monitoring atmospheric CO_2 and CH_4 concentrations and their natural and anthropogenic fluxes from space. This is to (i) reduce uncertainty of national emission inventory reporting, identify additional emission reduction opportunities and provide nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (NDCs); and (ii) track changes in the natural carbon cycle caused by human activities and climate variations.

To meet these goals, CEOS and CGMS performed a first comprehensive analysis (CEOS, 2018b) of the state-of-the art of space-based atmospheric greenhouse gas monitoring capabilities in support of international, regional and national climate policy. This analysis provides a reference for individual agencies planning satellite missions in this domain as well as for the broader coordination of virtual and dedicated constellations of space-based CO_2 and CH_4 sensors among space agencies through CEOS and CGMS.

CEOS (2018b) explains how estimates of XCO_2 and XCH_4 from space-based sensors can be integrated into a global carbon monitoring system and summarizes the state of the art in the space-based measurements and the tools needed to retrieve CO_2 and CH_4 fluxes from these data. It then provides a roadmap for existing and planned space-based CO_2 and CH_4 sensor types and performance, observing strategies, launch dates and operational timelines. It reviews the lessons learned from the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY, (SCIAMACHY), Greenhouse Gases Observing Satellite (GOSAT), and Orbiting Carbon Observatory-2 (OCO-2) missions and summarises the steps needed to transition from a series of scientific experiments to an operational constellation that can support an integrated global carbon observing system. To illustrate this transition, CEOS (2018b) documents the approach being used by the European Commission Copernicus Programme to define the requirements for a future operational constellation of CO_2 Sentinels. Finally, it proposes an architecture of a future greenhouse gas constellation designed to address the objectives listed above, and recommends a three-step plan to implement this architecture:

1. Link the atmospheric GHG measurement and modelling communities and stakeholders in the national inventory and policy communities (through UNFCCC/SBSTA), to refine requirements;

2. Exploit the capabilities of the CEOS member agencies, Coordination Group on Meteorological Satellites (CGMS) and the WMO Integrated Global Greenhouse Gas Information System (IG³IS) to integrate surface and airborne measurements of CO_2 and CH_4 with those from available and planned space-based sensors to develop a prototype, global atmospheric CO_2 and CH_4 flux product in time to support inventory builders in their development of GHG emission inventories for the 2023 global stocktake; and
3. Use the lessons learned from this prototype product to facilitate the implementation of a complete, operational, space-based constellation architecture with the capabilities needed to quantify atmospheric CO_2 and CH_4 concentrations that can serve as a complementary system for estimating NDCs in time to support the 2028 global stocktake.

To advance the state of the art and build a strong foundation for the space-based elements of an operational atmospheric CO_2 and CH_4 monitoring system that can be implemented within the next few years a series of specific steps are recommended to the space agencies:

1. A prototype system, based on available space-based and ground-based atmospheric measurement assets and modelling capabilities, should be designed and implemented in time to inform the first global stocktake in 2023. To support this stocktake, the initial global atmospheric CO_2 and CH_4 flux products must be available by 2021.
2. The initial operational system should exploit the lessons learned from the development and use of the prototype product as well as new space-based measurement and modelling capabilities to produce space-based CO_2 and CH_4 flux products in time to support the second global stocktake in 2028.
3. To meet these goals within a decade, it is imperative that individual research and operational space agencies work within CEOS, CGMS and other international coordination bodies (i.e. WMO IG³IS, GCOS, GEO-C) to define a roadmap with specific programmatic milestones for developing virtual and then dedicated constellations that can deliver harmonized, space-based climate data records for CO_2 and CH_4.
4. The preparation of CEOS (2018b) has demonstrated the benefits of the complementary viewpoints provided by CEOS and CGMS for advancing the implementation of system that incorporates both research and operational elements within the timeframe available. In particular, the CGMS partners could provide insight into the process of gathering user requirements for timeliness, reliability, traceability, reprocessing, quality assurance, and providing user support for an operational product. A continued engagement by both entities is required and some formalisation of the relationship would be advantageous. The joint CEOS/CGMS Working Group on Climate will lead this effort.
5. As recognised in the analysis, a broad system approach is required to develop a top-down atmospheric inventory approach that complements the bottom-up inventories. This system integrates the satellite observations, *in situ* (surface, aircraft, and balloon) measurements, modelling components (retrieval, inversion, biogeochemical processes and transport), prior information and ancillary data.
6. To ensure that the space agencies are working together and building the necessary partnerships with the relevant stakeholders (i.e. UNFCCC/SBSTA) to address the overall system implementation goals, they should work through CEOS and CGMS to strengthen the ties to these stakeholders.
7. The GCOS requirements were adopted as the basis in the formulation of a baseline operational CO_2/CH_4 constellation because GCOS provides an independent basis for the requirements. However, these requirements predated the Paris Agreement, which changed the focus of CO_2 and CH_4 monitoring efforts to anthropogenic emissions at national scales. Further analysis and revision of the space-based measurement and analysis requirements are needed to address this new focus. The CEOS and CGMS agencies will work with GCOS and other partner organizations and stakeholders in an iterative approach to further refine those requirements over the next few years.

8. CEOS, CGMS and their partners should continue to support the necessary OSSE experiments, which remain of critical importance in further refining the detailed requirements of the space-based elements of the constellation (sensor precision, accuracy, and resolution, orbit and mission coordination). The near-term objective is to develop a prioritized list of the required OSSE experiments and end-to-end system simulations to optimize the overall system design, resolve system-level uncertainties, and facilitate the coordination of activities among the CEOS and CGMS agencies. The output from these experiments should be made available to the CEOS and CGMS Principals periodically, in a format conducive to discussions with their mission and orbit planning organizations.
9. Over the last 15 years, research missions have provided considerable insight into instrument calibration, validation and the broader aspects of uncertainty quantification and quality control. Appendix 4 of [cite] summarizes the lessons learned from SCIAMACHY, GOSAT, and OCO-2. In the short-term, these lessons represent best practices that can be extracted and generalised by the CEOS/CGMS Working Group on Calibration and Validation (WGCV) and the Global Space-based Intercalibration System (GSICS) so that they are available as Cal-Val strategy "protocols" for space agencies that are now considering satellite missions.
10. The strategy for cross-calibrating the GOSAT and OCO-2 instruments has employed common standards, including observations of the sun, Moon, and surface vicarious calibration sites, such as Railroad Valley, Nevada, U.S.A. Additional effort by WGCV and GSICS is needed to maintain and improve the quality of these standards to better address the calibration needs of space-based CO_2 and CH_4 sensors.
11. The Total Carbon Column Observing Network (TCCON) has provided the primary transfer standard to relate space-based XCO_2 and XCH_4 estimates to the ground-based *in situ* standards maintained by the WMO GAW network. This network must be maintained and augmented using portable, ground-based remote sensing instruments, *in situ* sensors on fixed-wing aircraft (commercial aircraft, such as CONTRAIL, IAGOS) and balloons (AirCore), and airborne remote sensing instruments (MAMAP, CHARM-F etc.) to provide a more robust and accurate operational validation approach.
12. CGMS and CEOS should work with their member agencies to identify and promote standards in product specification, formats, pre-processing etc. and product inter-comparisons should be routinely undertaken and supported on a sustained basis to produce seamless, interoperable datasets that can be used in the broader system implementation.
13. Agencies should consider a centralized (but possibly geographically distributed) repository for hosting quality-controlled CO_2 and CH_4 products, with internal capability for product inter-comparison.
14. The capabilities required to meet the needs of the UNFCCC and the Parties to the Convention are already at the limit of the state-of-the-art for existing, space-based measurement technology. The CEOS and CGMS agencies should therefore continue to pursue complimentary technologies for both sensors (e.g. wide swath passive CO_2 and CH_4 imagers, active lidar) and mission design (e.g. HEO). These development efforts should be coordinated to keep the Principals updated on additional needs and capabilities that would be useful to consider for future mission opportunities.
15. There is a significant need for systematically produced ancillary measurements. These measurements are needed both to improve the accuracy of the XCO_2 and XCH_4 retrievals (i.e. coincident observations of clouds and aerosols) and to facilitate their interpretation within the context of the anthropogenic and natural carbon cycle (i.e. SIF, NO_2 and CO). Here, the proposed atmospheric CO_2 and CH_4 monitoring system could substantially benefit from the full scope of carbon cycle observations included in the CEOS Carbon Strategy. The CEOS partner agencies should therefore continue to support that strategy. The coordination mechanism identified to address follow-up to the current work should provide an assessment of prioritized products to be addressed in a coherent way, across agencies, to ensure seamless input to the system.

16. To ensure that the initial operational constellation and associated atmospheric CO_2 and CH_4 monitoring system can meet the sustained operational needs, a system engineering effort should be undertaken early in the implementation. This effort is needed to ensure that the requirement-reliability-traceability-fitness-for-purpose cycle is adequately planned and that the user uptake, user support and training and capability building elements are defined and prototyped. The CEOS and CGMS agencies and their partners at WMO have the necessary competences to start addressing these requirements and can help to assess the scope of these activities at the different levels of the implementation.

This summary describes some areas where initial efforts are required to ensure that the space agencies are ready to make the critical contributions needed on the timescale identified in point 1. above. These ambitious time constraints require substantial programmatic commitments at the level of individual space agencies. They also demand strengthened cooperation amongst space agencies (through CEOS and CGMS) as evidenced in point 2. as well as between CEOS/CGMS and the relevant external partners/stakeholders i.e. UNFCCC/SBSTA, WMO, GCOS and GEO. Finally, the CEOS and CGMS agencies should establish and nurture strong, continuous engagement with the national inventory agencies as well as the stakeholders listed above. Frequent interactions with the inventory community will be critical to ensure that the products CO_2 and CH_4 produced by the CEOS agencies are well understood, and can support the Transparency Framework and can serve as a complementary Measurement, Reporting, and Verification System for nationally determined contributions.

The CEOS agencies will exploit a number of existing elements and competences. These include:

- the all-encompassing CEOS Carbon Strategy which provides the broader template for CEOS' work on the Carbon Cycle;
- the Joint CEOS/CGMS Working Group on Climate which provides the direct link to the policy needs through UNFCCC/SBSTA and GCOS and for which the activities presented here represents a concrete example of the realisation of the Climate Monitoring Architecture from Space for atmospheric GHG monitoring;
- the Atmospheric Composition Virtual Constellation where there technical competences on the missions and instruments are located and other relevant competences for calibration (WGCV), information systems (WGISS) and capacity building and training (WGCapD). CGMS also has relevant working groups and expert groups, such as the Global Space-based Intercalibration initiative, which bring complimentary competences.

In summary, the needs are clear, the architecture implementation, though challenging, is within the means of space agencies and the coordination mechanisms. CEOS and CGMS have a clear understanding of how the activities fit into the broader system and with which external stakeholders we need to engage. CEOS and CGMS understand short-to-mid-term priorities that should be addressed to advance implementation. Most importantly, CEOS and CGMS have the necessary competences, and their technical working groups and other entities as well as their respective agencies, to address these priorities. With the appropriate decisions and direction from space agency Principals, CEOS and CGMS can strive to build the necessary constellation and associated system interfaces over the next decade.

4.3.3 Greenhouse Gas Sinks/Reservoirs/Sources and REDD+ (Article 5)

CEOS continues to provide systematic satellite observations for forest monitoring through the Global Forest Observations Initiative (GFOI) and is supporting countries in the use of observations for their National Forest Monitoring Systems (NFMS) to provide fully measured, reported and verified (MRV) information for the United Nations initiative on Reducing Emissions from Deforestation and Forest Degradation (REDD+) in developing countries.

In addition, CEOS works on the provision of ECV climate data records for fire disturbance, soil carbon, wetlands, permafrost, land use and above-ground biomass which are linked to the new GCOS ECV (GCOS,

2016) on anthropogenic greenhouse gas fluxes. All of these ECVs are essential to better understand the global carbon cycle including all exchanges of matter between the atmosphere, ocean and land. Above-ground biomass has been identified as a gap in the first CEOS/CGMS gap analysis (CEOS; 2018a) and several recommendations have been made to enable the future production of a climate data record for this ECV.

4.3.4 Loss and Damage (Article 8)

The Paris Agreement emphasises the importance of averting, minimising and addressing loss and damage associated with the adverse impacts of climate including extreme weather and slow onset events, and the role of sustainable development in reducing the risk of loss and damage. The role of observations has already been discussed in section 4.1 on adaptation to climate change. In addition, observations can support the analysis of the linkage of events that lead to loss and damage to climate variability and change. Operational attribution systems are under development for the use in climate services and need all kinds of observations including satellite data. The analysis of GEO with respect to the Paris Agreement (GEO, 2018) indicates that a considerable number of GEO activities plan to contribute to the loss and damage mechanism including the development of early warning systems. Here a potential for increased collaboration between CEOS and GEO on the use of satellite data in such systems exists.

In addition, space agencies have initiated a series of activities supporting Disaster Risk Management (DRM), with a focus on Disaster Risk Reduction, more efficiently by optimizing and better coordinating satellite Earth observations. While improvements to the International Charter or Sentinel Asia for example can offer enhanced post-crisis support, it’s critical that space agencies invest in disaster preparedness and prevention. It’s in this context that CEOS created a specific Working Group on Disasters.

The overarching goals of CEOS are to increase and strengthen satellite Earth observation contributions to the various DRM phases and to inform politicians, decision-makers, and major stakeholders on the benefits of using satellite Earth Observations in each of those phases. To achieve these goals, CEOS Agencies have agreed to a series of objectives/actions that will improve the coordination of Earth Observations satellites, improve satellite Earth Observation data distribution, and foster the use of satellite data by DRM users. The Working Group on Disasters has defined a global satellite observation strategy for DRM and developed and strengthened relationships with stakeholders and end-users through a series of concrete actions addressed by single-hazard pilot projects.

Current activities addressed floods that is of high relevance to the Paris Agreement. Satellites offer the ability to map floods from space, enabling disaster responders to know what is happening in regions where they may not have information from people on the ground. This flood mapping, when combined with computer simulations of past floods, can also be used to assess the risk of flooding and the changes in that risk over time as climate changes, oceans rise, urban areas expand, and the land subsides. CEOS has worked for several years to move forward the state-of-the-art for satellite based flood risk reduction, designing new approaches and facilitating user uptake so that flood risk management can better benefit from satellite data.

Local administrations noted the benefits of the use of optical and radar images for flood mapping including access to the International Disaster Charter data. Equally important are the aspects of capacity building and access to new techniques for young professionals working for the local administrations. As a result of this work, a number of participating countries have developed or improved their capacity to not only use flood maps derived from EO imagery but also to develop their own products.

4.3.5 Global Stocktake (Article 14)

While the detailed content of the global stocktake and the model to conduct it is under development by the Parties it is evident that observations are needed to support it. In particular, what is already described under section 4.2.2 and other sections above is suitable to support the global stocktake. GCOS in its own analysis (GCOS, 2018) indicates that its climate indicators could be beneficial for the global stocktake.

Although the aim of the agreement is only formulated in terms of global average surface air temperature it is clear that a wide range of satellite-based data records will be needed to support the global stocktake.

The 47th session of SBSTA (SBSTA, 2017) noted the increasing capability of satellite and in situ data to systematically monitor greenhouse gas concentrations and emissions. CEOS has been active in the UNFCCC context in implementing its Strategy for Carbon Observations from Space (CEOS, 2014). In 2018, CEOS provided a first comprehensive analysis of the state-of-the art of space based atmospheric greenhouse gas monitoring capabilities in support of international, regional and national climate policy (CEOS; 2018b). This analysis provides a reference for individual agencies planning missions in this domain as well as for the broader coordination of virtual and dedicated constellations of space-based CO_2 and CH_4 sensors among space agencies through CEOS and CGMS. To build a strong foundation for the space-based elements of an operational atmospheric CO_2 and CH_4 monitoring system that can be implemented within the next few years and to maximize its impact towards the achievement of Nationally Determined Contributions (NDCs) and for stocktaking, a series of specific steps is recommended to space agencies. This includes the design and implementation of a prototype system, based on available space-based assets, in time to inform the first global stocktake in 2023 and an operational system in time to support the second global stocktake in 2028. This system shall integrate the satellite observing capability, in situ observations, modelling components, prior information and ancillary data. Space agencies will continue to work together through CEOS and CGMS to build and maintain the necessary partnerships with the relevant stakeholders to address the user needs and the overall system implementation goals.

In addition, CEOS agencies were actively engaged in the refinement process of the IPCC GHG Inventory guidelines. The Second Order Draft of IPCC GHG Inventory Guidelines was released in July 2018 for government and expert review and now contains information on the potential contributions of space-based observations to the quality improvement of GHG emission estimates, in particular with the planned new satellite missions.

CEOS will continue to work with GCOS, the UNFCCC, and emerging climate services to further develop what is needed to support the stocktake in the future.

4.4 Open Access to data

As described above observational data are needed in support of the implementation of the Paris Agreement. Many articles of the Paris Agreement (Articles 3, 7, 12, and 13) emphasise the importance of providing access to or sharing data. Open access to climate related observations has also been mandated by several WMO resolutions (25 (Cg-XIII), 40 (Cg-XII), and 60 (Cg-XVII)).

The CEOS Strategic Guidance (CEOS, 2013) states that within the scope of CEOS the agencies desire to provide and share high-quality data, as well as information tools, to an expanding global user community on a full and open basis, and in accordance with the principles of Data Democracy as enunciated by CEOS at its 2010 Plenary in Rio de Janeiro.

To facilitate open and easy access to space data, CEOS is improving discovery, provides interoperability arrangements, coordinates data access portals in specific topical areas, and promotes the use of open-source tools for data handling. CEOS has formed a specific Working Group on Information Systems & Services to better coordinate and incorporate standard data discovery and access mechanisms, and adaptation of these mechanisms to the tools employed by the user community. Similar activities are ongoing within CGMS.

4.5 Capacity Development (Article 11) and Education and Public Awareness (Article 12)

CEOS has a dedicated working group on capacity building and data democracy that builds upon the CEOS Data Democracy Initiative. This is an effort to increase the capacity of institutions in less developed countries for effective use of Earth Observation data for the benefit of society and to achieve sustainable development.

CEOS facilitate activities that substantially enhance international education and training in Earth System Science including climate and the observation techniques, data analysis, and interpretation skills required for the use and application of Earth Observation data to meet societal needs. The CEOS activities respond well to Article 11 and 12 of the Paris Agreement by exploiting the cumulative capabilities of CEOS Agencies establishing unified and unique capacity building activities. Thus is done by partnering with locally-based and managed regional partners to increase effectiveness and decrease duplication of efforts, by using threads such as disaster response or climate change to build capacity through discussion of a focused subject. The activities focus on user needs for data and capabilities, including information technology infrastructure, to inform actions/plans for delivering the appropriate data and training for the effective use of Earth Observation data.

CEOS entities are also working to increase data accessibility, especially in under-served communities. The work of several CEOS working groups is to ensure a seamless transition from the technical matters relating to data accessibility to the matters relating to systemic and individual capacity development. This includes publication of resources, datasets, and software made available to under-served communities, promotion of data dissemination systems to effectively reach areas that lack consistent internet access or redundant systems in case of emergencies, which is important in the light of disasters leading to loss and damage as described above. In addition, workshops and training activities to provide individual and institutional capacity to effectively use available Earth Observation resources is within the remit of CEOS.

4.6 The Transparency Framework (Article 13)

One of the aims of the Transparency Framework is to provide clarity and tracking of progress towards achieving Parties' individual nationally determined contributions. The observations discussed above are essential to support this aim because they enable evidence for progress or not. Information derived from observations including satellite data will form an important part of the reporting to the global stocktake. CEOS together with CGMS can play an important role providing data of a quality that is able to support the stocktake. However, it is expected that the process of implementing the Paris Agreement will lead to new requirements for observational data that will be incorporated into the GCOS Implementation plan.

5 Conclusion

The 2015 United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement will drive climate policy during the next two decades and beyond. The agreement aims at limiting the temperature increase to well below 2°C and targeting 1.5°C above pre-industrial levels, improving the ability to adapt to adverse impacts of climate change and to make finance flows consistent with a pathway towards low greenhouse gas emissions and climate resilient development.

The first two aims of the Paris Agreements require strong support from observations including satellite data. Systematic observations of the climate system will be needed to support NDC reports by contributing to the provision of global and regional constraints on greenhouse gas sources and sinks. They will also be needed to support progress in climate change adaptation by monitoring changes on the Earth Surface, e.g., forestation, changes in disaster impacts, evolution of urban areas, etc. Results achieved through the analysis of satellite data provide significant information to IPCC reports via peer reviewed literature on the use of satellite data and products for GCOS ECVs fostering an improved understanding of the climate system. Finally this and the international coordination activities related to climate observations from space also provide significant input to SBSTA reports on the evolution of systematic observations of the climate system. The described support to the implementation of the Paris Agreement involves new challenges, in particular in the use of space-based data in applications supporting adaptation activities and the specification of NDCs. CEOS and CGMS expect that GCOS will start a new activity on adaptation that will result in new observation needs and requirements that CEOS and CGMS shall respond to in the future.

The Joint CEOS/CGMS Working Group on Climate together with CEOS' working groups on Calibration/Validation, Disasters, Information Systems & Services, and Capacity Building, and the CGMS working groups are an established structure that is capable of efficiently responding to the needs that arise from the implementation of the Paris Agreement. The implementation of the Architecture for Climate Monitoring from Space (Dowell et al, 2013) plays a central role in ensuring:

- that the needed observations at the needed quality are also made in the future,
- that derived data products respond to the needs of applications, including climate services, for which the data are used, and
- that the applications provide the information needed by decision and policy making.

In the context of the Paris Agreement this means that space-based observations with undoubted quality used in the process of the global stocktake can play a strong role of providing evidence for the success of the implementation of the Paris Agreement.

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