Committee on Earth Observation Satellites

CEOS/CGMS status on GHG monitoring

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An Architecture for Monitoring CO_2 and CH_4 from Space

- The CEOS Chair commissioned the Atmospheric Composition Virtual Constellation (AC-VC) to write a white paper that defines the key characteristics of a global architecture for monitoring atmospheric CO_2 and CH_4 concentrations and their natural and anthropogenic fluxes from instruments on space-based platforms to:
  - 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 (Nationally Determined Contributions, NDCs); and,
  - to track changes in the natural carbon cycle caused by human activities (deforestation, degradation of ecosystems, fire) and climate change

The CEOS AC-VC GHG White Paper

- **166-page document**
- **88 authors representing 47 organizations**
  - **Executive Summary (2 pages)**
    - **Overview of objectives and approach**
    - **Intended for policy makers, CEOS/CGMS Agency leads**
  - **Body of report (75 pages)**
    - **Science background and requirements**
    - **Current and near-term mission heritage**
    - **System implementation approach**
    - **Intended for program scientists and project managers**
  - **Technical Appendices (42 pages)**
    - **"Textbook" summarizing state-of-the-art in observation capabilities and analysis methods to justify system-level requirements**
    - **Intended for scientists, engineers, and inventory community**


CEOS
Committee on Earth Observation Satellites

A CONSTELLATION ARCHITECTURE FOR MONITORING CARBON DIOXIDE AND METHANE FROM SPACE

Prepared by the CEOS Atmospheric Composition Virtual Constellation Greenhouse Gas Team

Version 1.2 – 11 November 2018

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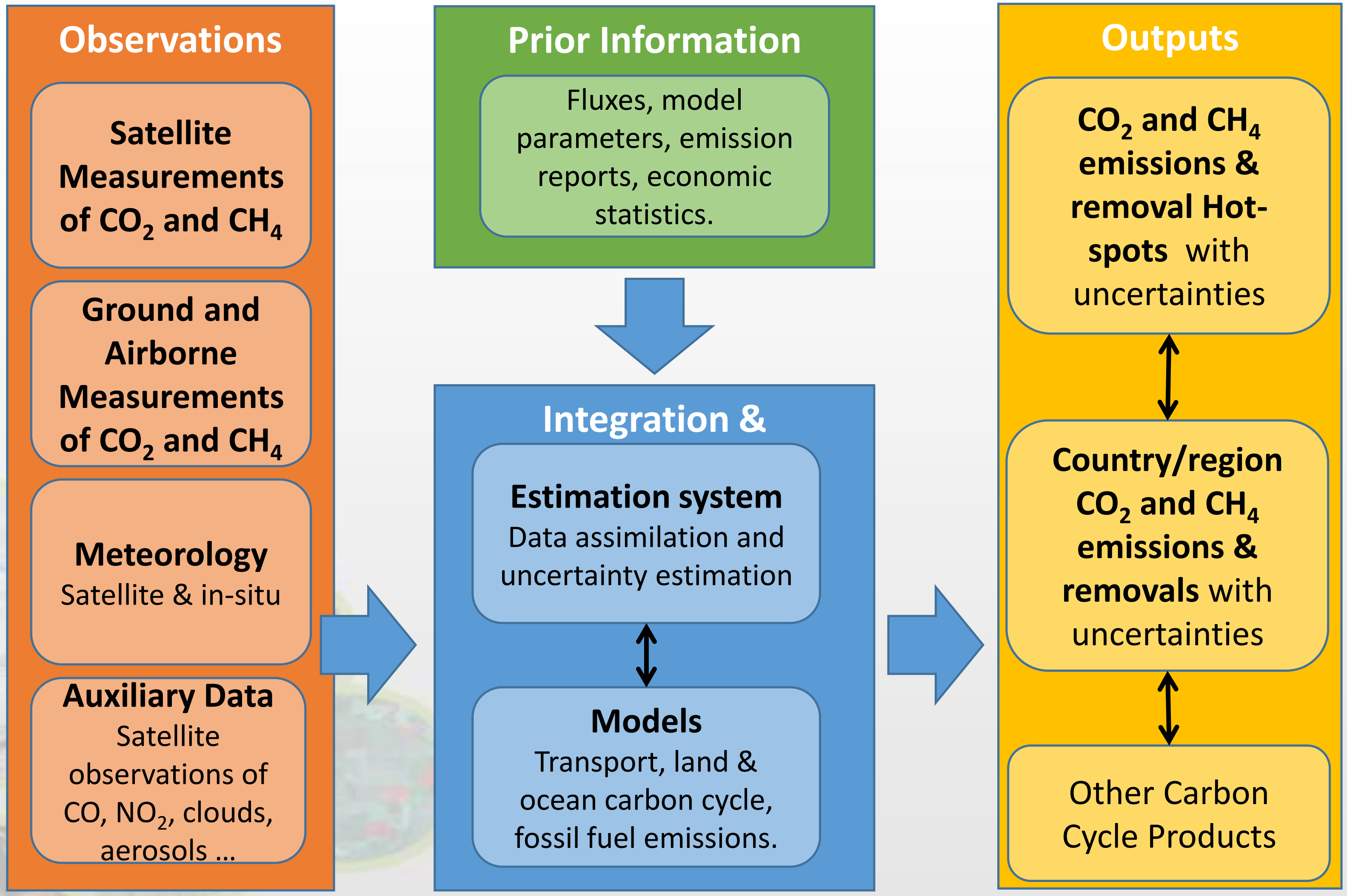
A System-Level Approach for Integrating Atmospheric Data

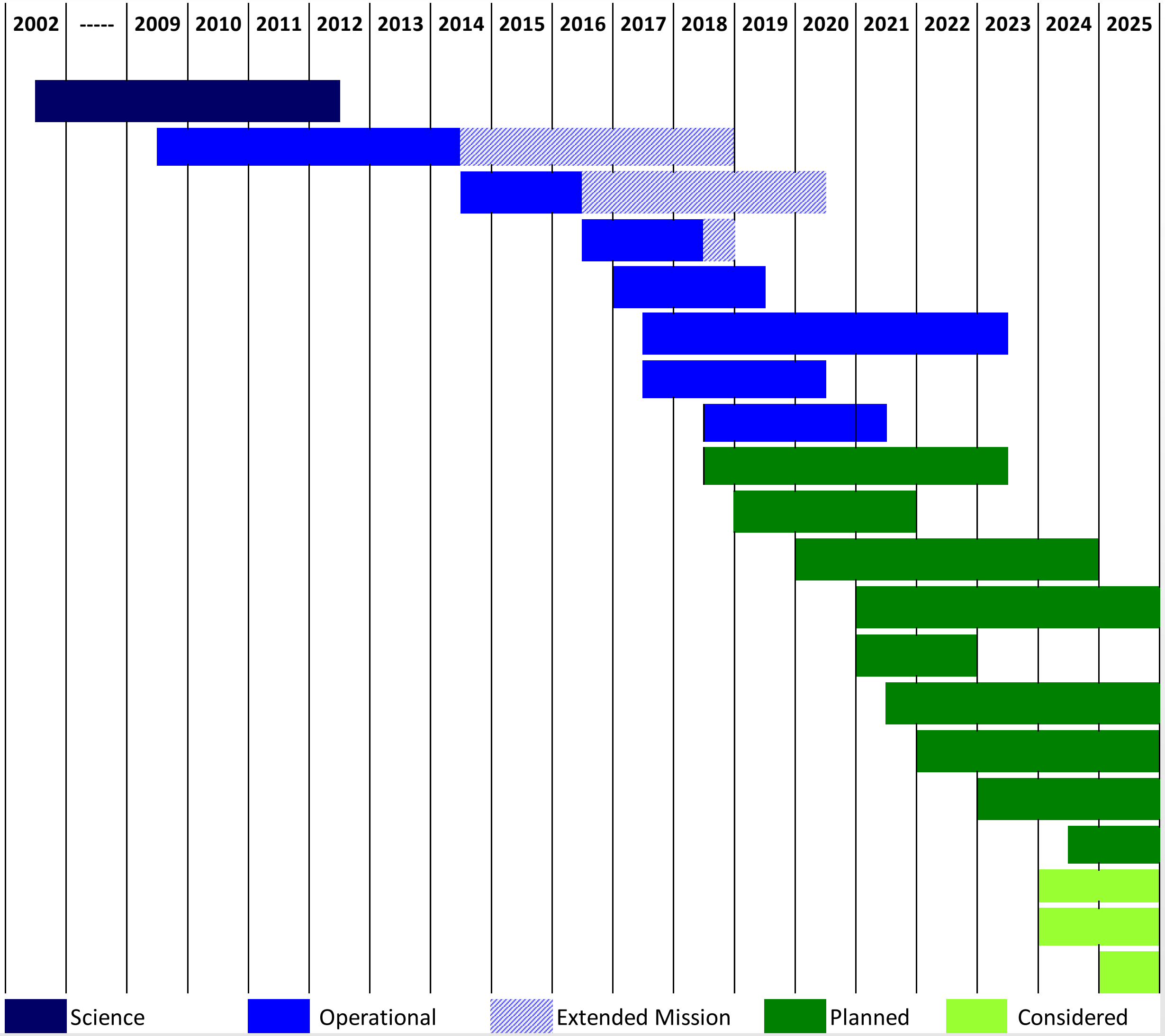


Actions Proposed in the AC-VC GHG White Paper

- **Proposes a series Actions to the CEOS Plenary for disposition:**
  - **Link atmospheric GHG measurement and modelling communities with stakeholders in national inventory and policy communities to refine requirements;**
  - **Exploit capabilities of the CEOS and CGMS member agencies and the WMO Integrated Global Greenhouse Gas Information System (IG^3IS) to:**
    - **integrate surface and airborne measurements of CO_2 and CH_4 with those from available and planned space-based sensors**
    - **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,**
  - **Use lessons learned from this prototype product to facilitate the implementation of a complete, operational, space-based constellation architecture that can:**
    - **quantify atmospheric CO_2 and CH_4 concentrations and**
    - **serve as a complementary system for estimating NDCs in time to support the 2028 Global Stocktake.**

GHG Mission Timeline

Satellite, Instrument (Agencies)	CO_2	CH_4	Swath	Sample
ENVISAT SCIAMACHY (ESA)	●	●	960 km	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	●	●	3 pts	10.5 km (d)
OCO-2 (NASA)	●		10.6 km	1.3x2.3 km^2
GHGSat (Claire)		●	12 km	0.0004 km^2
TanSAT (CAS-MOST-CMA)	●		20 km	1x2 km^2
Sentinel 5P TROPOMI (ESA)		●	2600 km	7x7 km^2
Feng Yun 3D GAS (CMA)	●	●	7 pts	10 km (d)
GaoFen-5 GMI	●	●	5-9 pts	10 km (d)
GOSAT-2 TANSO-FTS (JAXA-MOE-NIES)	●	●	5 pts	10.5 km (d)
OCO-3 (NASA)	●		11 km	4 km^2
Bluefield Technologies		●	25x20 km	0.0004 km^2
MicroCarb (CNES)	●		13.5 km	40 km^2
MethaneSAT (EDF)		●	200 km	1 km^2
MetOp Sentinel-5 series (Copernicus)		●	2670 km	7x7 km^2
Feng Yun 3G (CMA)	●	●	100 km	< 3 km^2
GEOCARB (NASA)	●	●	2800 km	4x4 km^2
MERLIN (DLR-CNES)		●	100 m	0.14 km (w)
TanSat-2 Constellation	●	●	3x100 km	2x2 km^2
GOSAT-3 (JAXA-MOE-NIES)	●	●	TBD	TBD
CO2 Sentinel (Copernicus)	●	●	3x250 km	2x2 km^2



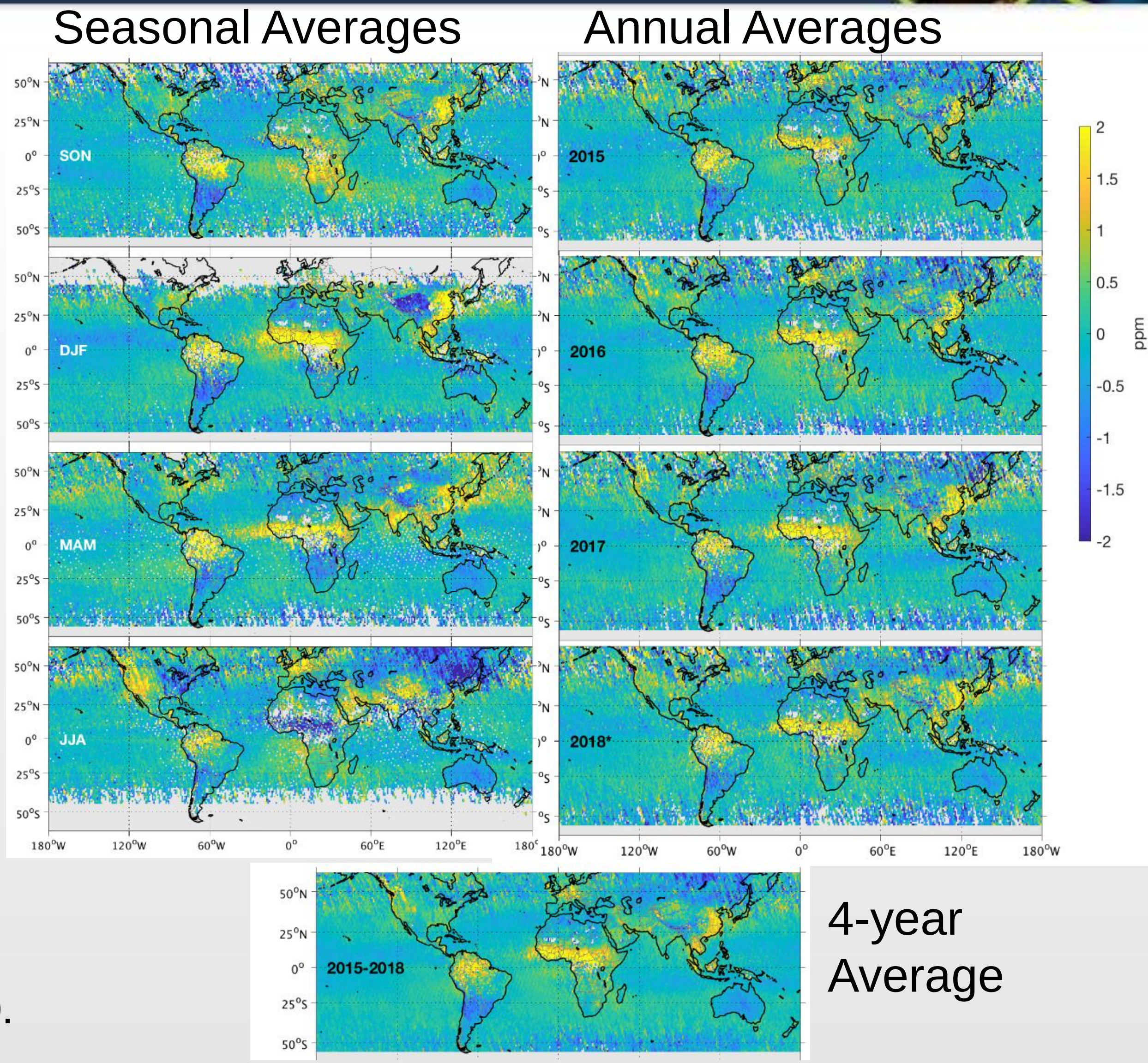
Endorsement of the AC-VC GHG White Paper

- The 2018 CEOS Plenary endorsed the AC-VC GHG White Paper
  - The Plenary confirmed CEOS interest in continuing collaboration with CGMS through a specific task in WGClimate on GHG monitoring, with dedicated resources and activities based on the mapping table of the actions identified in the Way Forward chapter of the report
    - The 3-point plan and activities are interpreted as recommendations to the CEOS Agencies
  - Plenary also endorsed the revision of the Terms of Reference of the WGClimate to accommodate these changes
  - AC-VC will continue to support GHG constellation development and synergistic GHG and atmospheric composition observations and modelling efforts
  - The CEOS SIT Chair encouraged the publication of the white paper to facilitate citations and efforts to build on its content
    - WMO and Copernicus have agreed to jointly publish the white paper
    - Publication date ~June 2019

State of the Art – CO_2 Anomalies

Goal: Identifying persistent XCO_2 anomalies in OCO-2 data

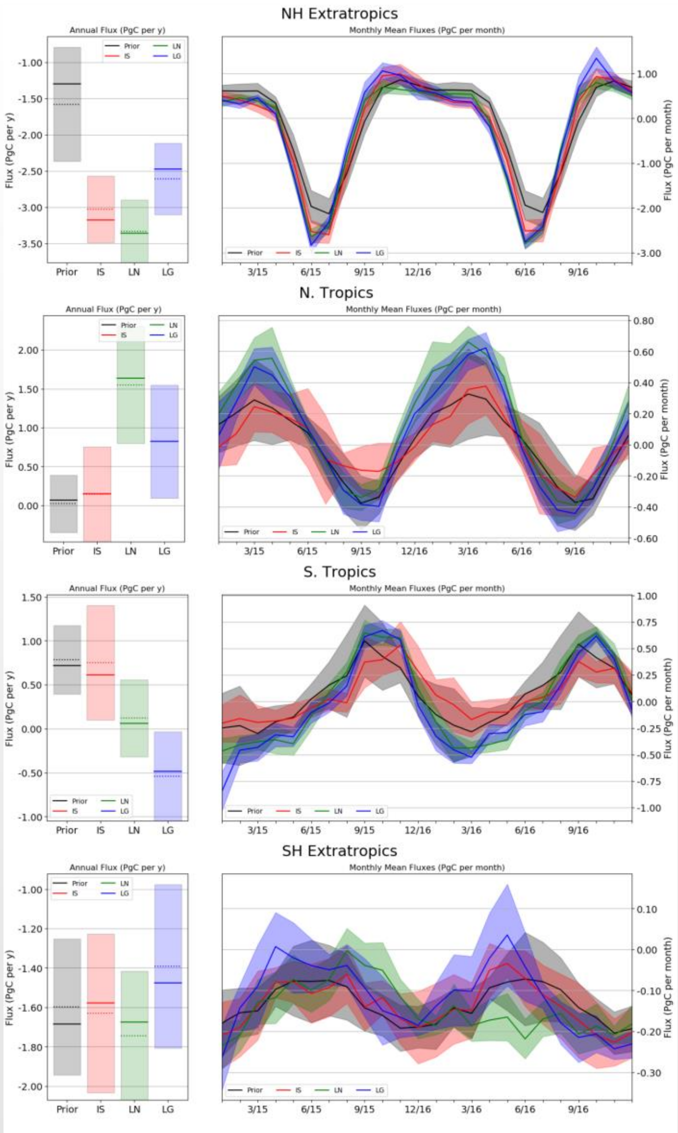
- **Seasonal (left) and annual (right) average anomalies derived for 2015-2018.**
  - **Positive XCO_2 anomalies dominate the tropics, except equatorial Africa during JJA – are the tropics now a net source of CO_2?**
  - **High latitudes land dominated by negative XCO_2 anomalies (strongest during JJA)**
  - **Biospheric CO_2 uptake reverses the positive XCO_2 anomalies over northeast U.S. and east Asia during JJA**



Hakkarainen, J., et al., Global XCO_2 anomalies as seen by Orbiting Carbon Observatory-2, Remote Sensing, in review, 2019.

2015-2016 Fluxes as seen by OCO-2 and the Global in situ Network

- **The OCO-2 team has been running a global multi-model intercomparison to improve our ability to retrieve CO_2 sources and sinks on regional scales from in situ and OCO-2 observations**
- **Results**
  - **OCO-2 v7 data and in situ data indicate a global annual carbon sink of 3.7±0.5 PgC**
    - o **Land contribution is 1.5±0.6 PgC**
  - **Agreement is best in northern hemisphere extratropics, which are well sampled by the surface networks**
  - **The largest difference occur over tropical Africa where there are few in situ measurements**



Crowell et al. Atmos. Chem. Phys. Discuss 2019

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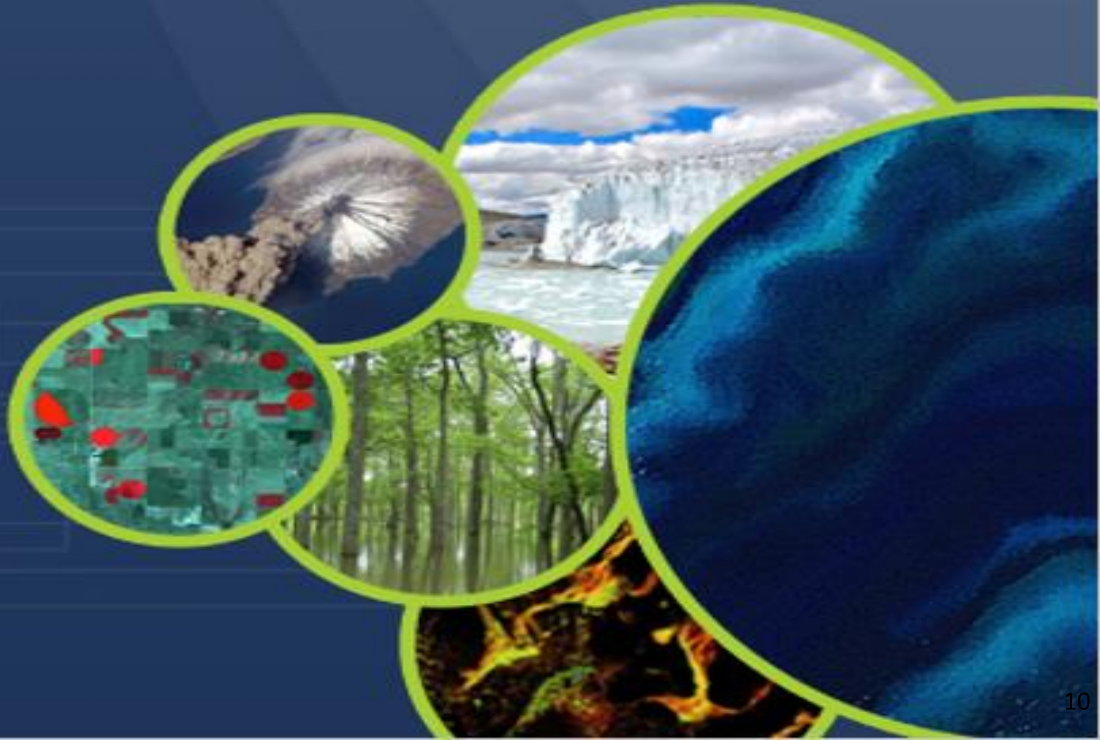
Implementation Approach

Ben Veihelmann

ESA ESTEC, AC-VC Co-Chair



Approach for Implementing GHG Actions

- **The CEOS Chair proposed that WGClimate coordinate the joint effort between CEOS and CGMS to monitor GHGs**
  1. Create a well-identified task within WGClimate addressing GHG monitoring (action WGClimate to decide how this would be implemented, by SIT-34).
  2. WGClimate to detail a roadmap based on activities from the AC-VC white paper and the outputs from the JRC GHG workshop (draft by SIT-34).
  3. WGClimate to establish appropriate links and cross-representation with AC-VC and the WGCV Atmospheric Composition subgroup.
  4. Relevant CEOS Agencies to dedicate appropriate resources.
  5. Task would also include the existing coordination layer for the CEOS Carbon Strategy.
  6. Update the WGClimate terms of reference (to also be confirmed by CGMS).
- **AC-VC will work with CEOS and CGMS to implement a (new) CO_2/CH_4 focus within WGClimate, using their existing interfaces with GCOS, WMO, IPCC, and UNFCCC. Mark Dowell has agreed to lead this activity.**

CEOS GHG Monitoring Actions

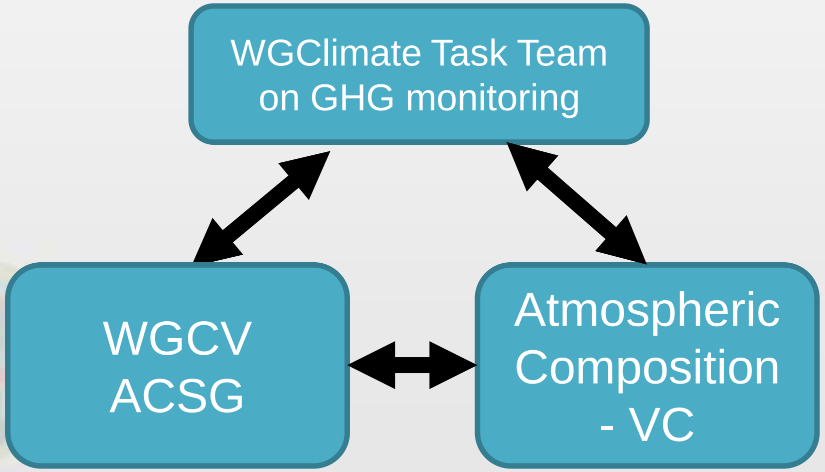
CEOS-32-05	WGClimate to report on internal implementation for the way forward on CEOS-CGMS coordination on GHG monitoring, including a roadmap based on the mapping of the GHG report recommendations and the JRC workshop conclusions.	**SIT-34**

- **A document mapping the recommendations from AC-VC white paper to different CEOS/CGMS working groups (WGClimate, WGCV) and virtual constellations (AC-VC) was distributed for discussion**
- **The process and governance on the GHG monitoring within WGClimate will be discussed at the joint GCOS/WGClimate meeting in Marrakech during the week of March 18th 2019**
- **A proposal will be presented to CEOS SIT-34**

Objective

The following slides

- **propose AC-VC activities and interactions with WGClimate and WGCV (dedicated sub-groups) to support the implementation of GHG monitoring system (Rec#1,2,3)**
- **are meant to serve as input for discussion with WGClimate and WGCV**
- **are meant to serve as input to the roadmap for the development of the GHG constellation (Rec#3)**



AC-VC GHG Activities and Interaction with WGClimate

WGClimate input for AC-VC (Rec#4, 7):

- Policy users' needs for GHG flux products from space
- ECVs and FCDRs needs for GHG L2 products from space
- Evaluation of satellite GHG products wrt related requirements

Support of AC-VC to WGClimate (Rec#7):

- Consolidation and refinement of satellite GHG product requirements, at various temporal and spatial scales (global, regional, national, local)

AC-VC input for WGClimate (Rec#1) Description of

- GHG Constellation and gaps
- GHG L1&2 data set, its consistency, and traceable data quality
- GHG flux data set and its consistency

AC-VC GHG Activities and Interaction with WGCV

Work with WGCV and GSICS to define cal/val needs (Rec#9)

- Identify available standards and techniques that can be used to cross-calibrate space based sensors prior to launch and on orbit (lunar, solar, vicarious)
  - Level-1: cross-calibration, common radiometric standards, vicarious calibration, ...
- Identify available standards and techniques that can be used to cross-validate space based estimates (TCCON, AirCore …) (Rec#11)
  - Level-2: cross-calibration, (fiducial) reference measurements, ...
- Discuss possible role of an active mission as flying standard in a GHG constellation (Rec#14)
- Surface flux products: validation approaches and reference estimates

AC-VC Coordination of Spaceborne GHG Sensor Development

- Implement a prototype system that incorporates products from a virtual constellation of sensors by 2021 (Rec#1)
- Define an operational system or dedicated constellations of sensors as long-term goal to as backbone for the Climate Monitoring Architecture (Rec#2)
- Define best practices and facilitate exchange and harmonization of approaches for instrument cross-calibration (Rec#10)
- Facilitate exchange of expertise and support in defining mission requirements (Rec#7)
- Coordinate discussion on auxiliary observations enhancing data quality (e.g., aerosol properties for light path correction) (Rec#15)
- Track implementation and operations of space-based GHG sensors (Rec#14)
- Identify and propose solutions for observational gaps (Rec#14)

AC-VC Coordination of GHG Product (L1&2) Development

- Document the performance of existing and near term L1 and L2 products and their ability to meet WGClimate needs for ECV and FCDRs
- Establish product accuracy, precision, resolution, and coverage requirements needed to meet the flux requirements on various scales
- Coordinate between CCI and ACOS to identify best practices and develop a prototype product
- Pursue consistency in product content, format, units, variable names, …
- Pursue traceability of data quality
- Coordinate algorithm inter-comparisons to improve accuracy and speed of retrieval algorithms
- Facilitate exchange and harmonization of approaches to calibration and retrieval challenges
- Follow and provide recommendations on development of laboratory spectroscopy
- Define types of data (calibration, L1, L2) that must be exchanged to enable the integration of space based systems into a constellation

AC-VC Coordination of GHG Flux Estimation Development

- Coordinate research on flux estimation (local to national scale; Level-4 products) (Rec#3)
- Coordinate between CAMS/C3S and NASA OCO-2/CMS/GMAO (Rec#12)
- Coordinate OSSE studies dedicated to flux estimation (Rec#8)
- Identify synergies between observation strategies for GHGs and air quality gases and aerosols
- Consolidate mission requirements for auxiliary observations (e.g. plume tracers like NO_2) (Rec#14)
- Aim at accuracy and precision sufficient for policy applications
- Pursue consistency in the product content (Rec#12)
- Pursue traceability of data quality (Rec#12, 13)
- Define types of data that must be exchanged to derive and validate fluxes from a constellation of space-based sensors to facilitate open data access (Rec#11)

Near-term AC-VC Output

Deliverables needed by 2021 to demonstrate that satellites can support the 2023 stocktake (WP-Rec#1)

- Description of the virtual constellation consisting of the GHG satellite sensors that fly in 2021
- Prototype CO_2 and CH_4 product (spanning 2009-2021) from this virtual constellation, with traceable consistency and data quality
- Description of the quality of flux estimates derived from the prototype product on various spatial and temporal scales

Deliverables needed by ~2021 to prepare a future purpose-built, operational constellation to support future stocktakes (WP-Rec#2)

- Observational requirements for a future GHG constellation
- R&D plan for GHG retrieval and flux estimation schemes
- Action plan for validation and cross-calibration of GHG products aiming at traceable consistency and data quality

Progress with Interfaces in the GHG Communities

- **The White Paper proposes to link atmospheric GHG measurement and modelling communities with stakeholders in national inventory and policy communities to refine requirements**
- **Existing scientific conferences and workshops are being exploited to encourage interactions among these groups**
  - **17-20 Sept 2018: IG^{3}IS/TRANSCOM -** Ground and space-based measurement, flux modeling, and gridded inventory communities
  - **26-29 Nov 2018: ESA ATMOS** – Current/future Space based measurements
  - **10-14 Dec 2018: AGU** - Ground and space-based measurement, flux modeling, and gridded inventory communities
  - **4-8 March: GSICS** – Calibration and operational satellite communities
  - **12-14 March: CHE/VERIFY** - Ground and space-based measurement, flux modeling, gridded inventory and national (bottom-up) inventory communities
- **Principal Challenge – Interface with national inventory community**

Future Meetings

- The 15th International Workshop on Greenhouse Gas Measurements from Space (IWGGMS-15) will be held at Hokkaido University, Sapporo campus on 3-5 June.
  - The meeting announcement, registration, and abstract submission page here: https://www.nies.go.jp/soc/en/events/iwggms15/
  - Registration closes on March 28 and Abstracts are due on April 1,
- The CEOS AC-VC meeting webpage is posted here: http://ceos.org/meetings/ac-vc-15/
  - Venue: Nakano Sunplaza in Tokyo, Japan on 10-12 June.
    - The registration closes on May 3
  - We are still compiling the agenda, but the current plan is to focus on greenhouse gases on Monday, 10 June and air quality on 11-12.

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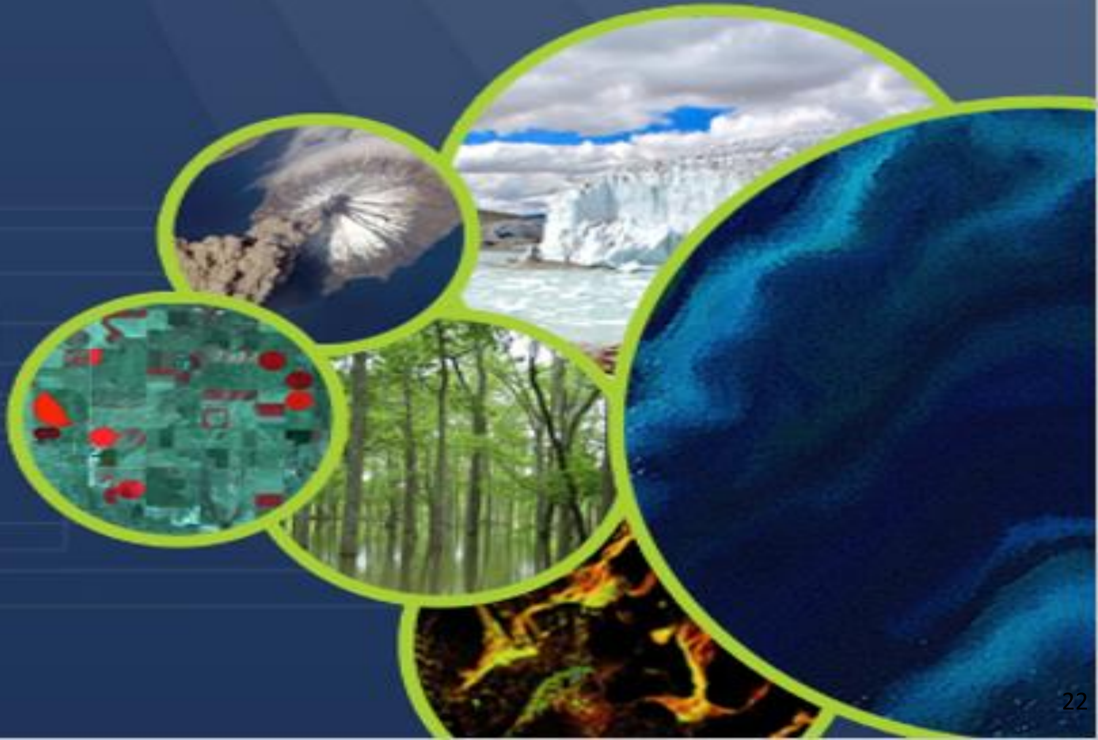
Backup



A Candidate Operational CO_2/CH_4 Constellation Architecture

The coverage, resolution, and precision requirements could be achieved with a constellation that incorporates

- A constellation of 3 (or more) satellites in LEO with
  - A broad (> 200) km swath with a mean footprint size < 4 km^2
  - A single sounding random error near 0.5 ppm, and vanishing small regional scale bias (< 0.1 ppm) over > 80% of the sunlit hemisphere
  - One (or more) satellites carrying ancillary sensors to identify plumes (CO, NO_2) or to detect and mitigate biases (CO_2 and/or CH_4 Lidar)
- A constellation with 3 (or more) GEO satellites
  - Monitor diurnally varying processes (e.g. rush hours, diurnal variations in the biosphere)
  - Stationed over Europe/Africa, North/South America, and East Asia
- This constellation could be augmented with one or more HEO satellites to monitor carbon cycle changes in the high arctic

Other Needs: Calibration Advances

- Space based sensors for CO_2 and CH_4 must be
  - calibrated to unprecedented levels of accuracy to detect and quantify the small XCO_2 and XCH_4 changes associated with surface fluxes
  - cross-calibrated against internationally-accepted standards prior to launch and in orbit so that their measurements can be integrated into a harmonized data product that meets the accuracy, precision, resolution, and coverage requirements for CO_2 and CH_4
- Efforts by the ACOS and GHG-CCI teams have demonstrated the feasibility of this approach for SCIAMACHY, GOSAT, and OCO-2
  - Rigorous pre-launch and in-orbit calibration methods demonstrated
- Substantial improvements will be needed to meet the much more demanding requirements of anthropogenic emissions monitoring
  - Cross-calibrating a more diverse range of spacecraft sensors
  - Reducing calibration-related biases across multiple spacecraft

Other Needs: Validation Advances

XCO_2 and XCH_4 estimates across the constellation must be cross validated against internationally-recognized standards to yield a harmonized integrated product that meets the demanding precision, accuracy, resolution, and coverage requirements

- The Total Carbon Column Observing Network (TCCON) currently serves a critical transfer standard between the space based measurements and the *in situ* standard maintained by WMO GAW
- TCCON must be maintained and expanded meet the much greater demands of anthropogenic emissions monitoring on national scales
  - Biases must be reduced by a factor of 5-10 from 0.25% on regional scales to < 0.025 to 0.05% to improve inventories
- Additional validation methods must be developed to support validation emissions estimates on scales ranging from that of individual large power plants to that of a large urban area.

Other Needs: Science advances needed to support GHG monitoring

Two types of analysis tools are needed to estimate CO_2 and CH_4 fluxes (sources and sinks) from space-based observations:

- Remote sensing retrieval algorithms used to estimate the XCO_2 and XCH_4 from space based observations
- Flux inversion models are used to estimate the surface fluxes needed to maintain the observe XCO_2 and XCH_4 distributions in the presence of the prevailing wind field

- These methods are now being successfully used to study emission hot spots and regional-scale natural CO_2 sources and sinks
- A substantial amount of additional development is needed to support applications as demanding and diverse as
    - supporting urban- to national-scale GHG emission inventories
    - monitoring the natural carbon cycle response to climate change
- CEOS should work with its partners to meet these needs