Space Agency Response to GCOS Implementation Plan

WGClimate | CEOS | CGMS

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Executive Summary

The Committee on Earth Observation Satellites (CEOS) and Coordination Group for Meteorological Satellites (CGMS), in the form of the Joint CEOS/CGMS Working Group on Climate (WGClimate), are pleased to present a response to the 2016 GCOS Implementation Plan, reiterating their commitment to address the Actions required for the implementation of the Global Climate Observing System (GCOS). CEOS and CGMS, international organizations of 60 Members and Associates and 15 Members respectively, have had the honour to report on Space Agency activities to GCOS on several previous occasions.

Space Agencies have continued to evolve their systematic observation of the climate system, now spanning several decades, strengthening scientific knowledge on climate, and supporting the provision of knowledge-based information to climate services to under-pin informed decision-making. Space Agencies are framing their activities through the implementation of the *Strategy Towards an Architecture for Climate Monitoring from Space*, 2013 – developed by a team comprised of representatives from CEOS, CGMS, and the World Meteorological Organization (WMO).

The Role of the Architecture for Climate Monitoring from Space

In response to the continuing challenge of monitoring climate variability and climate change from space, CEOS, CGMS and WMO have accelerated development of the global *Architecture for Climate Monitoring from Space*. A recent, substantial, advance in the development of the Essential Climate Variable (ECV) Inventory has led to an unprecedented insight into the activities of Space Agencies across the ECV spectrum, resulting in the detailed characterisation of over 900 Climate Data Records (CDRs) that directly respond to the GCOS ECV requirements. The ECV Inventory enables the identification of existing and potential future gaps in the provision of the climate data requested by GCOS.

An analysis of the gaps between GCOS needs and the CDRs delivered by Space Agencies is currently underway, and will include the identification of actions to close any identified gaps. We are pleased to leverage this activity for the direct benefit of GCOS, thereby more accurately targeting, and responding to, GCOS needs.

The *Architecture for Climate Monitoring from Space* is central to our response to the GCOS Implementation Plan, and frames our response to both the Broad Context and Detailed Implementation actions articulated by GCOS.

Broad Context

Space Agencies are implementing programmes explicitly aimed at producing CDRs that respond to the ECVs requested by GCOS. Moreover, climate services directly benefit from the wealth of space-derived climate data products being systematically generated by Space Agency programmes. The continuing implementation of the global *Architecture for Climate Monitoring from Space*, and in particular the ECV Inventory, provides strong evidence of the on-going commitment of Space Agencies in terms of the application of sustained resources and investments.

Efforts have accelerated at a regional level also. For example, the WMO designated Regional Climate Centres (RCCs) are being implemented to generate and deliver more regionally-focused high-resolution data and products, as well as training and capacity building. The WMO has been making concerted efforts to implement RCCs, in close coordination with its Regional Associations, Commission for Climatology and Commission for Basic Systems.

On mitigation, CEOS continues to support the Global Forest Observations Initiative implementing the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation or REDD+.

Detailed Implementation including Preliminary Identification of Gaps

The overall response by Space Agencies to Atmosphere-related Actions is strong, although some important gaps remain. The meteorological satellite constellation, coordinated by CGMS, provides strong heritage and a backbone for satellite data characterising atmospheric physics, dynamics, and composition. Many agencies have launched programmes for generating satellite CDRs, and international coordination through Sustained Coordinated Processing of Environmental Satellite Records for Climate Monitoring (SCOPE-CM) has improved efficiency. Space Agencies are also enhancing coordination of a satellite constellation for monitoring CO_2 and CH_4, and are stepping up their investments. Unresolved gaps include the uncertain future of satellite-based measurements of precipitation, and no plans for continuing measurements of the upper tropospheric and stratospheric composition profile for better understanding the Earth's radiation balance, among other benefits. In addition, a space-based calibration mission could not be realized in full, and shortfalls have been identified in following up on key research missions that have revolutionised our understanding of atmospheric processes (e.g. CALIPSO/CloudSat for aerosol-cloud interaction by measuring the 3D structure of clouds and aerosol layers).

Our uncertainty of Terrestrial ECV products is a function of the temporal resolution of satellite data acquisition and the availability of *in situ* observations. Due to cloud cover, and low illumination conditions at high latitudes, significantly higher errors occur when optical data are used in isolation. Uncertainty is also difficult to assess, as *in situ* data are extremely limited and, in general, not consistent in space and time. Satellite multi-sensor and multi-product inter-comparisons have been minimal so far for lake temperature, as the availability of a reasonable set of overlapping products is a pre-requisite for such activities. Lake *in situ* monitoring and satellite observation targets need to be extended, and a common database derived on which to focus production and subsequent validation activities for all products. A higher spatial resolution is required for monitoring lake ice extent. Temporal resolution has considerably improved for many Arctic regions as more daily data are acquired. There is a strong need to establish lake sites for algorithm development and validation, for the purpose of long-term monitoring.

A major drawback for the true monitoring of constantly changing glaciers in steep high-mountain topography is the missing availability of Digital Elevation Maps (DEMs) from high-resolution sensors for ortho-rectification of the related satellite data. For Glacier Area the requirement for annual frequency is unnecessary because decadal change is sufficient. For glacier elevation change this is opportunistic and depends on DEM availability, quality and characteristics. For glacier flow velocity, observations on a sub-annual basis are possible using SAR and optical sensors especially for surge events, other instabilities, and seasonal velocity variations. Existing Fire ECV products (Brunt Area and Fire Radiative Power) are approaching target requirements for spatial resolution, although may not reach temporal requirements, but merged products derived from multi-sensor data may be close to satisfying both requirements. The International Land Surface Temperature and Emissivity Working Group (ILSTE[1]) has been initiated to bring developers and producers together to improve coordination and to make products more accessible to users.

Space Agencies intend a strong response overall to actions related to Oceans, with some gaps. Meteorological and operational optical and thermal missions will provide a strong instrumental backbone for sea surface temperature, with areas requiring stronger action focussed around maximising the quality of long records and integrating diurnal cycle observations from geostationary platforms. For SST and sea ice, the absence of plans across many agencies for low-frequency passive microwave radiometry remains concerning. An increased emphasis on evolving better ocean heat flux and sea surface dynamic state products constrained by observations needs to be sustained. Co-operation and continuity in sea surface height / sea level are strong, although validation and uncertainty estimation remain challenging. Observational continuity for ocean surface reflectance observation for ocean biogeochemistry looks secure from polar orbiting

[1] ilste-wg.org

platforms, and effort is strong in radiometric validation. Further product evolution is needed for phytoplankton biomass estimation and long-term climate data record stability. The global salinity record from L-band microwave frequencies is progressing, with multi-mission synthesis a priority. Salinity mission extensions are planned or under review that will extend the record beyond a decade, although no new salinity missions are in the pipeline thereafter.

As Agencies continue to invest in the efforts necessary to create CDRs from their archives of observations it is also understood that CDRs must have stringent quality characteristics that enable quantitative analysis of climate change and variability over decades. Therefore Space Agencies are addressing *in situ* fiducial reference measurements for verifying the accuracy and stability of satellite CDRs, integration of CDRs across evolving constellations of sensors for a particular ECV, assessment of consistency between variables, and reducing the knowledge gaps in the understanding of uncertainty in CDR products across all spatial/temporal scales relevant to climate. These activities have been applied across the atmospheric, oceanic and terrestrial domains, and substantial progress has been made for a significant number of CDRs.

1 Introduction

1.1 Background

The Global Climate Observing System (GCOS), a joint undertaking of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU), was established in 1992 to ensure that the observations and information needed to address climate related issues are obtained and made available to all potential users.

At the 7th Conference of the Parties (COP 7) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2001, the UNFCCC Subsidiary Body on Scientific and Technological Advice (SBSTA) invited GCOS to consider an integrated (satellite and *in situ*) approach, including the exploitation of new and emerging methods of observation to the measurement of climate change. At COP 9 in 2003, GCOS was invited to develop a phased 5–10–year implementation plan. COP 10 in 2004 invited Parties with Space Agencies to have those Space Agencies provide a coordinated response [2] to the recommendations in the 2004 Implementation Plan.

1.2 Purpose of this document

The purpose of this report is to provide a consolidated Space Agency response to actions from the Global Climate Observing System[3] in the form of GCOS 200, recently updated from GCOS 154[4]. Technical supplements responding to actions per ECV in detail will be provided in early 2018.

1.3 Approach to Responding to GCOS Implementation Plan

This document comprises the following parts:

- Introduction (§1).
- The Architecture for Climate Monitoring from Space (§2).
- Response to Part I: Broad Context (§3).
- Response to Part II: Detailed Implementation (§4).
- Acronyms (Annex A).
- Mapping from GCOS IP to Space Agency Response (Annex B),
- Contributors (Annex C).

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2 GCOS, 2006: Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC". GCOS-107, WMO, Geneva, September 2006.

3 GCOS, 2016: The Global Observing System for Climate: Implementation Needs. GCOS-200, WMO, Geneva, October 2016

4 GCOS, 2011: Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)". GCOS-154, WMO, Geneva, December 2011.

1.4 Terminology

Essential Climate Variable

An Essential Climate Variable (ECV) is a geophysical variable that is associated with climate variation and change as well as the impact of climate change onto Earth. GCOS has defined a set of ECVs for three spheres, atmospheric, terrestrial and oceanic[5,6].

ECV Product

Many GCOS ECVs are sub-divided into so called ECV Products. The term "Product" denotes long-term data records of values or fields of ECVs derived from FCDRs[7]. For instance, the water vapour ECV has 3 ECV Products: total column water vapour, tropospheric and lower-stratospheric profiles of water vapour, and upper tropospheric humidity, which describe different aspects of water vapour in the atmosphere. However, the definitions provided for ECV[7] are not always consistent for all ECVs. For some cases, e.g. the ECV Sea Ice, there is only one ECV Product that covers 4 different variables/parameters for which requirements are provided. The ECV Inventory and the associated questionnaire names each variable/parameter for which requirements are provided an ECV Product. A consistent mapping is provided in the ECV Inventory Questionnaire Guide[8].

GCOS Requirements

A GCOS Requirement as used in this document refers to the quantitative requirements provided for each ECV[7] They denote Horizontal Resolution, Vertical Resolution, Temporal Resolution, Accuracy and Stability.

Fundamental Climate Data Record

A Fundamental Climate Data Record (FCDR) is a well-characterised, long-term data record, usually involving a series of instruments, with potentially changing measurement approaches, but with overlaps and calibrations sufficient to allow the generation of products that are accurate and stable, in both space and time, to support climate applications[9]. FCDRs are typically calibrated radiances, backscatter of active instruments, or radio occultation bending angles. FCDRs also include the ancillary data used to calibrate them. The term FCDR has been adopted by GCOS and can be considered as an international consensus definition.

Thematic Climate Data Record

A Thematic Climate Data Record (TCDR) is the counterpart of the FCDR in geophysical[9]. It is closely connected to the ECVs but strictly covers one geophysical variable, whereas an ECV can encompass several variables. For instance, the ECV Cloud Properties includes at least five different geophysical variables, each of them constituting a TCDR. The term TCDR has been taken up by many Space Agencies and can be considered as de facto standard.

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5 Bojinski et al. (2014): The concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy https://doi.org/10.1175/BAMS-D-13-00047.1

6 GCOS-82, 2003: The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC, 74 pp, available at: http://www.wmo.int/pages/prog/gcos/Publications/gcos-82_2AR.pdf

7 GCOS-154, 2011: Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)". WMO, Geneva, December 2011.

8 WGClimate, 2016: ECV Inventory: Questionnaire Guide v2.4.

9 Dowell, M., P. Lecomte, R. Husband, J. Schulz, T. Mohr, Y. Tahara, R. Eckman, E. Lindstrom, C. Wooldridge, S. Hilding, J. Bates, B. Ryan, J. Lafeuille, and S. Bojinski, 2013: Strategy Towards an Architecture for Climate Monitoring from Space. Pp. 39, available at: www.ceos.org; www.wmo.int/sat; http://www.cgms-info.org/ GCOS, 2015: Status of the Global Observing System for Climate, GCOS-195, WMO, Geneva.

Interim Climate Data Record

An Interim Climate Data Record (ICDR) is a Fundamental or Thematic Climate Data Record regularly updated with an algorithm / system having maximum consistency to the FCDR or TCDR generation algorithm / system[10]. The update cycle depends on the user needs for climate extremes and might range from pentad to monthly.

10 WMO Workshop on Operational Space-based Weather and Climate Extremes Monitoring Geneva, Switzerland 15-17 February 2017 Meeting Report.

2 The Architecture for Climate Monitoring from Space

The space-based architecture for climate monitoring[11] forms the major international reference for the contribution of Space Agencies towards a fulfilment of GCOS goals. It is also reflecting the contribution of Space Agencies to the *monitoring and observation* pillar of the Global Framework of Climate Services (GFCS). The implementation of this architecture is coordinated by the joint CEOS/CGMS Working Group Climate (WGClimate) that was established in 2013.

2.1 Role of Satellites in a Global Climate Observing System

Earth observation satellites provide a vital means of obtaining observations of the Earth system from a global perspective and comparing the behaviour of different parts of the globe for many of the Essential Climate Variables. Their global nature distinguishes satellite observations from ground-based and airborne measurements that are more limited in spatial coverage, but nevertheless necessary to constrain and validate information derived from space, and provide data on variables not accessible from space.

Satellite climate data records that meet the GCOS requirements enable climate monitoring, studies of trends and variability, climate research, assimilation into numerical weather prediction models to produce long-term reanalyses of Earth System components, provision of boundary conditions for and verification of climate models, climate impact modelling, and, ultimately, decision making in many societal sectors including agriculture, water resource and coastal management, forestry, transportation, and insurance applications. Through this satellite observations play also an important role realizing the potential of Earth observations and geospatial information to advance the Group on Earth Observations (GEO) 2030 Agenda and enable societal benefits through achievement of the Sustainable Development Goals (SDGs).

In principle, reliable space-based observations can support authoritative statements on climate change by climate services needed to empower international organizations, governments and the private sector to make informed decisions on prevention, mitigation, and adaptation strategies (see Figure 1 for the value adding chain). However, the past and the current observing systems have not been primarily designed with a climate perspective, therefore inventories are needed to document the contributions of current and planned observing systems for climate purposes.

The architecture calls for a constellation of research and operational satellites, broad, open data-sharing policies and contingency planning. It includes agreements that are essential for bringing continuity to long-term and sustained climate observations that were established for weather observations. The sustained involvement of both research and operational agencies is a prerequisite for success. The Research and Operations paradigm envisioned by the architecture demands the sustained expert understanding of new and legacy sensors and many support activities to derive the needed ECV climate data records. This requires the continued effort of both research and operational agencies which is organized by the CEOS/CGMS Working Group Climate.

11 M. Dowell, P. Lecomte, R. Husband, J. Schulz, T. Mohr, Y. Tahara, R. Eckman, E. Lindstrom, C. Wooldridge, S. Hilding, J.Bates, B. Ryan, J. Lafeuille, and S. Bojinski, 2013: Strategy Towards an Architecture for Climate Monitoring from Space. Pp. 39, available at: www.ceos.org; www.wmo.int/sat; http://www.cgms-info.org/ GCOS, 2015: Status of the Global Observing System for Climate, GCOS-195, WMO, Geneva.

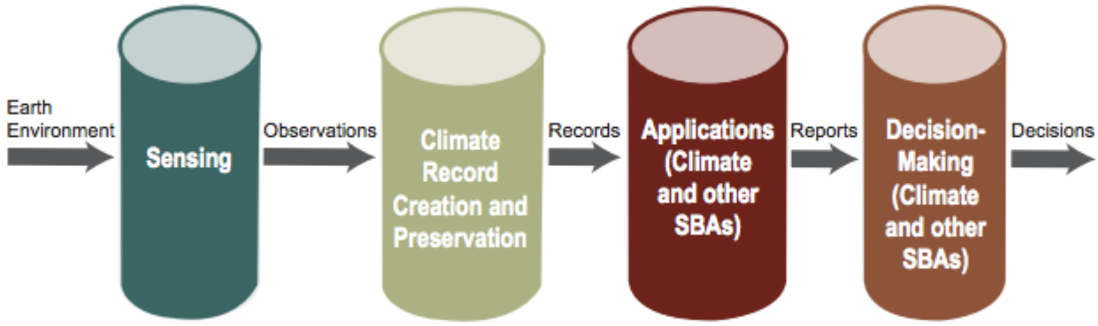

Figure 1 : Value adding chain schematically describing the use of satellite-based information for decision making (from Dowel et al., 2013).

2.2 The Joint CEOS/CGMS Working Group on Climate

A *Joint* Group and *Joint* Response

The Joint CEOS/CGMS Working Group Climate was founded in 2013 to enable all major Space Agencies to contribute via a coordinated CEOS and CGMS approach to the implementation of the *Architecture for Climate Monitoring from Space*. This joint working group, in addition to facilitating the implementation of the architecture, also provides a coordinated and unique voice for the response of Space Agencies to the GCOS and GFCS needs and plans.

The over-arching goal of the Joint CEOS/CGMS Working Group on Climate (WGClimate) is to improve the systematic availability of Climate Data Records including the GCOS ECVs through the coordinated implementation, and further development of the *Architecture for Climate Monitoring from Space*. More specifically, the coordination is designed to achieve three main objectives:

- Provision of a structured, comprehensive and accessible view as to what Climate Data Records are currently available from satellite missions of CEOS and CGMS members, or their combination;
- Creation of the conditions for delivering further Climate Data Records, including multi-mission Climate Date Records, through best use of available data to fulfil GCOS requirements (e.g. by identifying and targeting cross-calibration or re-processing gaps/shortfalls);
- Optimisation of the planning of future satellite missions and constellations to expand existing and planned Climate Data Records, both in terms of coverage and record length, and to address possible gaps with respect to GCOS requirements.

The first and third objectives are collectively fulfilled via the establishment of an ECV Inventory and the analysis of its content with respect to the needs of GCOS also addressing the level of compliance with the *GCOS Climate Monitoring Principles* and the *Guidelines for the Generation of Datasets and Products* and GCOS requirements as provided in the GCOS Implementation Plan.

The second objective is addressed both by single agency and multi-partner projects, in particular those implemented in the frame of the WMO SCOPE-CM and GSICS initiatives.

The WGClimate supports the work of GCOS in defining and delivering the ECVs required by the UNFCCC and supports the overall relation of CEOS to the UNFCCC, its subsidiary bodies, and to the Intergovernmental Panel on Climate Change (IPCC).

The WGClimate has also been tasked by CEOS and CGMS to coordinate the response of Space Agencies to the GCOS implementation plan, and to report to SBSTA/UNFCCC on CEOS/CGMS climate actions.

Moreover, WGClimate and its member agencies are committed to continuing to apply the GCOS Climate Monitoring Principles and guidelines. In addition to the space segment, Space Agencies resource data management systems that facilitate access, use and interpretation of data and products, treating these as essential elements of climate monitoring systems.

3 Response to Part I: Broad Context

3.1 Observations for Adaptation, Mitigation and Climate Services

3.1.1 Adaptation

Guidance and best practice for adaptation observations (GCOS Action G1)

Space Agencies are instrumental in providing capability to meet adaptation needs, by addressing the actions of the GCOS Implementation Plan via the *Architecture for Climate Monitoring from Space*. These capabilities include, for example, coordinating observation systems to inform adaptation stakeholders, providing public access to high quality and standardized data on the vulnerabilities to climate change impact, and operationalizing the addressing of adaptation at national, regional and local scales.

WGClimate will continue to support, and liaise closely with, GCOS on its continuing adaptation efforts as defined in GCOS-200 (§3.1), and spanning all adaptation action categories, namely requirements and guidance, acquisition of data, data, stewardship, climate services and international cooperation.

Specification of high-resolution data (GCOS Action G2)

WGClimate and its members continue to support specification of high resolution climate data requirements via their existing programmes. These activities typically include user consultation on space segment missions, user engagement on climate data production programmes and cooperation with users in provision of operational climate services. High-resolution data, together with various types of non-satellite data, continue to play a pivotal role in climate services as exemplified by the WMO report[12] supplement to the *Strategy Towards an Architecture for Climate Monitoring from Space*.

3.1.2 Climate Indicators

Development of indicators of climate change (GCOS Action G3) and Indicators for Adaptation and Risk (GCOS Action G4)

Establishment of Climate Indicators

Space Agencies are aware of the need to support the building of indicators of climate change. Many of the underlying climate data records are already available. What needs to be enhanced is a more systematic and correct consideration of uncertainty estimates.

Space Agencies are aware of the need to support the building of indicators for tracking climate change, based on the production of climate data records, including the systematic catering of uncertainties. To this end, planetary vital signs should be reliable, simple, have a long-term history, reflect a range of possible symptoms of climate change, integrate as far as possible many wider effects of change, be easily interpreted and conversely difficult to misinterpret, either by accident or intent[13].

12 WMO No. 1162. https://library.wmo.int/pmb_ged/wmo_1162_en.pdf

13 CEOS EO Handbook for COP-21 §5 p42

In addition, the Paris Agreement has led to the need for a new comprehensive set of climate indicators that should be forward-looking, i.e. aid decision-makers in assessing future climate change impact and the effects of measures to adapt to and mitigate impacts. Such indicators will rely on satellite and other observations, as well as modelling and forecasting capabilities, and are yet to be agreed internationally.

A number of parameters for tracking climate change such as sea level, snow cover, temperature, precipitation, ocean heat content and the cryosphere are covered by the WMO Statement on the Status of the Climate and supported by GCOS, and a WMO-GCOS position on indicators of climate change is established[14]. Many CEOS and CGMS agencies will continue to enable CDRs critical for the formation of climate change indicators. Some ECVs are depending on multi-agencies inputs, e.g. precipitation that needs a multitude of measurements provided by several CEOS and CGMS agencies. For those WGClimate will foster multi-agency activities to deliver high quality climate data records that stand up to the needs for detecting and understanding climate change.

Architecture – From Satellite Missions to Services

Satellites are critical in providing the observations of numerous such parameters. For example, arctic sea ice extent has been measured since the late 1970s by passive microwave imaging systems and for the last approximately 20 years by active radar imaging sensors also. In addition, dedicated satellites (ICESat, CryoSat) with specific relevant technologies have allowed measurements not only of the extent, but also the thickness and hence total volume of sea ice to be made. Sea level is now measured most accurately, and globally, by a series of precise altimeters; these measurements go back over 20 years and will continue into the future due to the Sentinel 6 series of missions.

Climate data record development is also geared by specification of indicators by GFCS and climate service providers. WGClimate and its agencies plan to continue dialogue with international and national climate service providers, with the aim of the Space Agencies highlighting, optimizing and shaping their climate data production to address the emerging needs of climate indicators. In this respect the European Commission, European Centre for Medium-Range Weather Forecasts (ECMWF), European Space Agency (ESA) and European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), for instance, are programmatically aligned to symbiotically address each other's needs, and this includes consideration of ECV product uncertainty in production of climate change indicators. WMO is planning to enhance its interaction with users of satellite-based CDRs and ECV products, as a contribution to the *Architecture for Climate Monitoring from Space*, the GFCS Climate Services Information System and User Interface Platform. These are being established to facilitate the dialogue between the providers of observations and monitoring products, climate modellers, and service providers.

In context to the development of climate services to express the changing climate, provision of climate services for responding to adaptation needs and growing risk are equally crucial. Already embedded and proactive within WGClimate, users of satellite-based climate data records and climate service providers will be performing a more pronounced role in the future in the working group in light of the Paris Agreement. This will benefit the highlighting, aligning and shaping of climate data products in support of downstream climate services.

The vehicle for this amplified collaboration between Space Agency climate data providers, direct users of satellite climate data records, and climate service providers is the *Architecture for Climate Monitoring from Space*[15]. The architecture, which logically and physically links space derived climate infrastructure and data to climate services and policy decision making support, has enabled productive dialogue across the variety of players within WGClimate.

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14 https://library.wmo.int/opac/doc_num.php?explnum_id=3418

15 M. Dowell, P. Lecomte, R. Husband, J. Schulz, T. Mohr, Y. Tahara, R. Eckman, E. Lindstrom, C. Wooldridge, S. Hilding, J.Bates, B. Ryan, J. Lafeuille, and S. Bojinski, 2013: Strategy Towards an Architecture for Climate Monitoring from Space. Pp. 39. Online: http://www.wmo.int/pages/prog/sat/documents/ARCH_strategy-climate-architecture-space.pdf

The expanded role in WGClimate of WMO, the European Commission, ECMWF and other parties involved in climate services for adaptation and risk will include leading consultative roles in the following:

- addressing the shortfalls in the ECV Inventory between status of ECV datasets and their associated ECV requirements in the GCOS Implementation Plan, therefore providing valuable climate adaptation and risk insight on the consequences of those shortfalls.
- mapping ECV Inventory records to any new indicators of climate adaptation and risk, and consequently informing Space Agencies in the prioritisation of space resources to optimally address downstream needs in light of such indicators.
- raising governmental, intergovernmental and non-governmental policy needs which emerge by means of new indicators of adaptation and risk, therefore supporting the development direction of the architecture.

These activities will be systematically addressed through the WGClimate development of the architecture, including the continued development of the ECV Inventory. Additionally, the ECV Inventory, provides future opportunities for intelligently and conveniently interrogating the mapping between climate data records and adaptation services.

3.2 The Broader Relevance of Climate Observations

This section addresses GCOS-200 Part I §4 ("The Broader Relevance of Climate Observations"). Although Action G5 is neither directly nor indirectly actionable by Space Agencies, WGClimate will remain vigilant in identifying opportunities for maximising benefit from ECVs in implementing the GEO SDG process. Any such insight will be shared with GCOS and SBSTA through existing reporting cycles.

With the adoption in September 2015 by the United Nations of the 2030 Agenda for Sustainable Development, a set of 17 "Sustainable Development Goals" (SDGs) were defined to be achieved in each country by 2030. Space Agencies, such as ESA[16], have confirmed their capabilities in the explicit support of these.

WGClimate recognizes the significant value in supporting the SDGs, both to inform, and be informed by, GCOS and SBSTA. This is particularly urgent in context to the Paris Agreement.

3.3 Consistent Observations Across the Earth System Cycles

This section addresses GCOS-200 Part I §5 ("Consistent Observations Across the Earth System Cycles").

The emergent need for holistic indicators of climate change following the Paris Agreement has magnified the need for WGClimate to adopt a similarly holistic forming to its climate data products and services, so informing observations across the Earth System cycles.

The analysis of the ECV Inventory content shows that many ECV Products needed to quantify the energy, water and carbon cycles are already provided from satellite data. CEOS and CGMS agencies already provided energy flux products at the top of atmosphere and surface (radiation and heat fluxes) before those became ECV Products.

16 ESA Activities Supporting Sustainable Development, Catalogue. 2016.

WGClimate member agencies attempt to demonstrate the usefulness of satellite products for considering energy and water budgets, e.g. the NASA MEaSURES programme[17].

Quantifying the global carbon cycle is essential to understanding many of the dramatic changes taking place in the Earth system, particularly those resulting from the burning of fossil fuel and land-use change. Forests absorb, store and release large amounts of carbon; therefore, they are a key component of the carbon cycle. Despite this crucial role, forest biomass is poorly quantified in most parts of the world and is an ECV currently labelled missing in the ECV Inventory. Responding to this challenge, ESA will start a CCI project dedicated to biomass using suitable satellite missions of today and the past to improve our current understanding of this ECV and prepare for future dedicated missions like NASA's GEDI/NISAR and ESA's Biomass missions set out to provide measurements of forest biomass and forest height. Reliable knowledge of forest biomass also underpins the implementation of the UN Reducing Emissions from Deforestation and forest Degradation, REDD+, initiative – an international effort to reduce carbon emissions from deforestation and land degradation in developing countries.

WGClimate will continue to actively support GEO carbon actions and strategy.

3.4 Capacity Development and Regional and National Support

This section addresses GCOS-200 Part I §6 ("Capacity Development and Regional and National Support").

The activities of WGClimate and its members are not entirely congruent with those GCOS actions focused on capacity development as defined by the GCOS Implementation Plan. Nevertheless, WGClimate can, and will, unreservedly support GCOS in its implementation of a GCOS communication strategy (Action G9), by raising awareness of the GCOS Implementation Plan and publicizing the need for sustainable climate observations, particularly for developing countries, in its own Space Agency communication strategies.

WGClimate member agencies are active in supporting capacity building initiatives focussed on climate services through the provision of access to climate data records and information, related user training and project management support. For instance, EUMETSAT has supported Africa through a Memorandum of Understanding signed with the African Union Commission and in the framework of the MESA programme funded by the 11th European Development Fund. EUMETSAT has in parallel supported the formulation of new projects expected to start in 2017-2018, i.e. the GMES and Africa and the ACP Climate Services projects, funded by different EU instruments.

Most agencies are strengthening their communication of climate monitoring activities, and these can be harmonized where possible with the GCOS communication strategy.

Building capacity of users to ingest satellite-based climate data and products into their operations and to interpret uncertainty is urgently required in many parts of the world where the competencies and infrastructure required are no match for the surging demand for high-quality climate information and services. The WMO-CGMS Virtual Laboratory for Education and Training in Satellite Meteorology (Vlab) is establishing a programme of virtual climate roundtables where experts and users, for example from WMO Regional Climate Centres, can interact regularly and address region-specific capacity needs. The European Commission through its ACP programme is implementing programmes to foster the uptake of satellite data and derived information.

17 L'Ecuyer, T.S., H.K. Beaudoing, M. Rodell, W. Olson, B. Lin, S. Kato, C.A. Clayson, E. Wood, J. Sheffield, R. Adler, G. Huffman, M. Bosilovich, G. Gu, F. Robertson, P.R. Houser, D. Chambers, J.S. Famiglietti, E. Fetzer, W.T. Liu, X. Gao, C.A. Schlosser, E. Clark, D.P. Lettenmaier, and K. Hilburn, 2015: The Observed State of the Energy Budget in the Early Twenty-First Century. J. Climate, 28, 8319–8346, https://doi.org/10.1175/JCLI-D-14-00556.1

3.5 Calibration and Validation of Satellite Data, Assessment and Intercomparison

Ground-based observing networks of sufficient quality and coverage (in terms of parameters, temporal and geographic space) are very important for validating satellite-based records, calibrating satellite sensors and thus for fully reaping the benefits of space-based systems. Space Agencies support calibration and inter-calibration of sensors through the Global Space-based Intercalibration System (GSICS) and dedicated activities in support of calibration such as innovative lunar calibration with dedicated instrumentation. Moreover, the maintenance of dedicated calibration and validation sites providing fiducial reference measurements are key.

Gaps in such networks have been identified for most ECVs. Space Agencies should step up their engagement with the operators of ground-based networks to address network gaps. Network design priorities should be established where appropriate, for example using Observing System Simulation Experiments or collocation studies.

Space Agencies will develop a comprehensive assessment of the adequacy of ground-based networks for validation of climate data records, including a gap analysis and the resources required to address issues related to the sustainability and geographic coverage of surface-based validation networks. This should build on work undertaken e.g. within the CEOS WGCV and the European GAIA-CLIM research project.

Space Agencies in collaboration with the operators of surface-based networks will invest in collocation studies demonstrating the value of using multiple data sources for estimating the uncertainty in atmospheric profiles.

Agencies continue to support the intercomparison of satellite data and derived products through international science working groups which unite leading experts in the field, and other users of satellite data. Intercomparisons foster product understanding including uncertainties, and guide the uptake of satellite data by users.

4 Response to Part II: Detailed Implementation

4.1 Overarching and Cross-Cutting Actions

4.1.1 Planning, Review and Oversight

Development of an ECV Inventory (GCOS Action G11) and Gap Analysis (GCOS Action G12)

The objectives associated with ECV Inventory development are intrinsic to the fulfilment of the core objectives assigned to WGClimate in its Terms of Reference, and form a pivotal asset in the implementation of the Climate Monitoring Architecture. The development of the ECV Inventory was implemented applying a cyclic approach as indicated in Figure 2 that was tied to the term of the Chair of the WGClimate.

The ECV Inventory provides a repository of verified information for the characteristics of two types of ECV Climate Data Records:

- Climate data records that already exist. This forms the current component of the inventory;
- Climate data records that do not currently exist, but are firmly planned to be delivered as part of an already approved programme. This forms the future component of the inventory.

A first version of the ECV Inventory had been developed in 2015 followed by a major redevelopment during the last two years that resulted in the ECV Inventory Version 2.0 which forms the basis for this report. ECV Inventory Version 2.0 describes the status on 31 December 2016 versus the 2011 GCOS Satellite Supplement but contains additional data records matching new ECV Products in the updated GCOS IP. WGClimate is committed to continue gradual updates of the ECV Inventory including an analysis of the content versus the GCOS needs. This analysis leads to recommendations and actions for CEOS and CGMS that allow an optimised planning for future satellite missions and constellations to expand the existing and planned ECV CDRs and to deliver the data records by single agency and multi-partner projects.

Besides the analyses performed by WGClimate, the ECV Inventory is seen useful to provide information to the users of climate data records, climate services and other applications on what is available for their work. For data providers and data record developers the Inventory can help to concentrate investments onto what is missing and to foster collaborative approaches at international level such as the WMO SCOPE-CM. In addition the ECV Inventory has the potential to become a resource for capacity building activities that rely on the access to climate data records. Relevant activities such as the WMO-CGMS Virtual Laboratory for Training and Education in Satellite Meteorology and CEOS Working Group on Capacity Building and Data Democracy have been informed about the publication of the ECV Inventory.

Entries for the ECV Inventory Version 2.0 have been received from 10 CEOS and CGMS Agencies. The entries are based on a Questionnaire that provides traceability to the GCOS principles, guidelines and requirements. The preparation of the ECV Inventory content involved almost 100 individuals which shows the high engagement of the agencies to provide high quality information to the ECV Inventory.

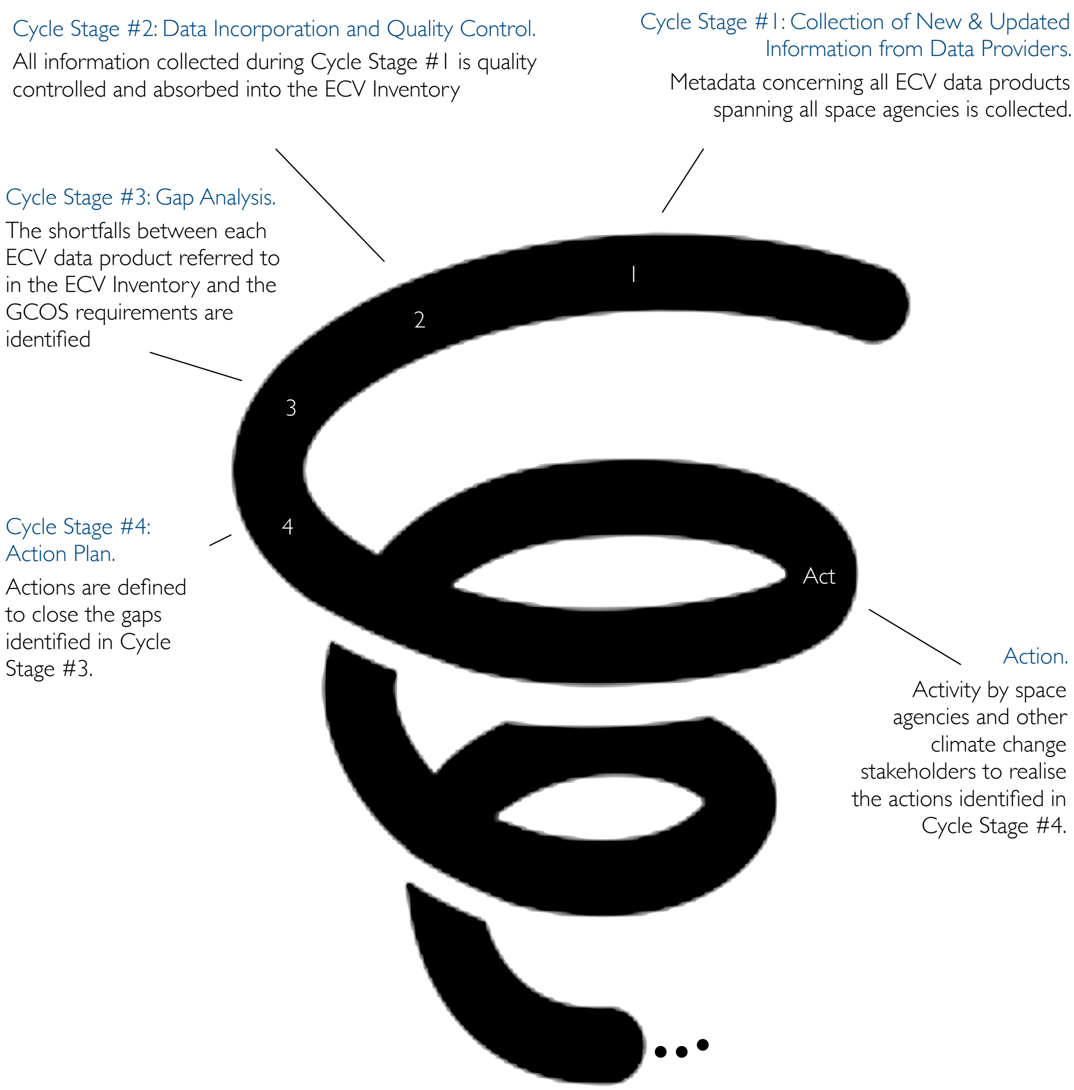

Figure 2 : Cyclic approach for the establishment of the ECV Inventory, the analysis of its content leading to the identification of gaps and derivation of recommendations and actions to mitigate such gaps.

Table 1 provides the number of climate data records in the ECV Inventory with a very large complement for the Atmosphere and smaller numbers for land and ocean. A first analysis on gaps related to ECVs and individual ECV Product as defined by GCOS (GCOS-200) reveals that for two (above ground biomass and sea surface salinity) no entry exist in the current and future part of the Inventory. As this reflects the status on 31 December 2016 we know today that both missing ECVs will be addressed by ESA in the future. In addition, no entries exist for lightning and ocean surface currents because the Inventory was established against the 2011 Satellite Supplement.

Domain	Total	Current	Future	Total (Cycle #1)
All	913	496	417	~200
Atmosphere	658	376	282	N/A
Land	135	56	79	N/A
Ocean	120	64	56	N/A

Table 1 : Number of data record entries in the ECV Inventory for Cycle#2

In terms of ECV Products with respect to the 2011 Satellite Supplement[18] in the current data holdings 3 ECV Products are missing for atmosphere (tropospheric ozone profiles, NO2 tropospheric column, SO2 and HCHO tropospheric columns), 5 are missing for the terrestrial part (fire radiative power, ice sheet elevation data and mass change, areas of Lakes and above ground biomass) and two for ocean (sea surface salinity and wave height).

The number of missing ECV Products in the future part of the ECV Inventory is shown in Table 2

Atmosphere	Land	Ocean
Ozone Profile in Upper Stratosphere and Mesosphere	Elevation Data	Ocean Colour - Chlorophyll-a Concentration
Ozone Profile in Upper Troposphere and Lower Stratosphere	2D Vector Outlines, Delineating Glacier Area	Ocean Surface Stress
Tropospheric Ozone Profile	Groundwater Volume Change	Sea-surface Salinity
Tropospheric CH4 Column	Ice Shelves	
Stratospheric CH4 Profile	Soil Moisture - Freeze/Thaw	
Aerosol Single-scattering Albedo	Fire Radiative Power	
Aerosol-layer Height	Moderate-resolution maps of Land-cover Type	
Aerosol-extinction Coefficient Profile	Above-ground Biomass	
NO2 Tropospheric Column		
SO2, HCHO Tropospheric Columns		
CO Tropospheric Column		
Solar Spectral Irradiance		
Total Solar Irradiance		

Table 2 : Missing ECV Products in the future part of the ECV Inventory.

Due to the large number of data records the gap analysis for the ECV Inventory Version 2.0 has not been finalised and a first comprehensive gap analysis report will become available in spring 2018. This will also contain specific recommendations and actions to mitigate found gaps.

4.1.2 Data Management, Stewardship and Access

Open Data Policies (GCOS Action G15)

18 GCOS-154, 2011: Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)". WMO, Geneva, December 2011.

Openness of space-derived climate data is crucial for the maximal uptake of such data by the user communities, for supporting unhindered collaboration in climate science, and promoting confidence in the data through transparency. Moreover, the integrity and quality of climate data products from space can only be fully realized when data from instrument to final climate data record along the traceability chain is open.

WGClimate has systematically collected and consolidated the climate data product access instructions of their constituent members by way of their ECV Inventory development. The ECV Inventory content shows that an open data policy is todays standard for climate data records from satellites. Many Space Agencies have enhanced and progressed their open climate data policies and have planned for ambitious uptake of their open climate data. ESA, EUMETSAT, JAXA, NASA and NOAA run data portals that ensure the provision of open, free and easily accessible ECV data records. Other Space Agencies are on their way to develop their data distribution in similar directions.

This activity is complemented by the Group on Earth Observation (GEO)'s mission to build the Global Earth Observation System of Systems (GEOSS) supported through a Common Infrastructure (GCI) and the GEOSS Portal, a single Internet access point for users seeking data, imagery and analytical software packages relevant to all parts of the globe. The GEOSS Portal brokers numerous climate data products.

Meaningful policy on open climate data is predicated on open and freely available tooling to act on the data. An Open Source cross-ECV toolbox[19] is being released under ESA procurement in late 2017, with plans for its continued service confirmed (CCI+, 2017 to 2026). Space Agency investment in open climate data tooling has generally grown strongly the last 5 years, for example at EUMETSAT, NASA, and NOAA, and evidence exists of its continued role in enabling open climate data.

Use of Digital Object Identifier for data records (GCOS Action G20)

The ECV Inventory and the continued development of the *Architecture for Climate Monitoring from Space*, will be capitalized on to assess which climate data records have missing DOIs. This practice will commence in Inventory Development Cycle #4 (2020 to 2022), with owners of non-DOI datasets being notified of this incomplete status, and accompanied by request for DOIs. This activity will similarly take place to ensure new DOIs for updated versions of existing data records in the inventory.

The emerging need for DOIs on climate data sets has emerged over the last 5 years, and they have become the de facto method for uniquely identifying data records and other research assets. The content of the ECV Inventory demonstrates that for more than 80% of the climate data records the DOI is already in use. This is also recognized by major programmes of WGClimate member agencies to deliver climate data records such as ESA, EUMETSAT, NASA, NOAA and JAXA.

4.1.3 Production of Integrated ECV Products

Preservation of early satellite data (GCOS Action G26)

Identification, recovery and curation of early satellite data are necessary activities for ensuring full capitalization of space-derived Earth observation data. These data are important because the

19 CCI Toolbox. https://cci-tools.github.io/

coverage with satellite data already started in the mid-1960s[20]. The major thrust in this sector is the usage of historical satellite data for global reanalysis.

Space Agencies such as NASA run dedicated programmes to make historical data available online for analysis and usage. In the United States the University of Wisconsin Wisconsin-Madison's Space Science and Engineering Center (SSEC) is rescuing early geostationary weather satellite data back to 1974[21]. During this activity also one year of data from Europe's first Meteosat satellite were discovered. The reconstruction of this data enables the first global composite from early January 1979 onwards and will allow extension of several time series backwards. In Europe, a series of dedicated research projects has fostered substantial data rescue and reprocessing activities of historical satellite data[22]. Moreover, the Copernicus Climate Change Service (C3S) will have a dedicated project on satellite data rescue that will be supported by EUMETSAT.

The future usage of such data for the delivery of ECV CDRs will be reflected in upcoming versions of the ECV Inventory. This will include engagement of the CEOS Working Group on Information Systems and Services (WGISS) to ascertain information on current and planned activities on the recovery of early space-derived data potentially relevant to climate data processing. WGClimate will use this information to perform an overlap analysis against the data needs of Space Agencies producing climate data products, on gaps existing between climate data products and GCOS requirements.

The overlap analysis may reveal opportunities for gap-filling in the ECV Inventory. WGClimate will engage relevant Space Agency climate teams to inform them of these opportunities and broker a relationship between WGISS and Space Agency team to support the gap-filling.

4.1.4 Ancillary and Additional Observations

Improve Gravimetric Measurements from Space (GCOS Action G31)

The gravity mission GOCE focused on measuring the static gravity field with high spatial resolution and accuracy, which is used e.g. for the unification of national height systems and, when combined with ocean mean dynamic topography from satellite altimetry, reveals geostrophic ocean currents. The gravity mission GRACE and the follow-on mission GRACE-FO, both flown by NASA, measure the time-variations of the gravity field that are due to mass transport in the Earth system. They give invaluable information required for the closure of the water cycle, including water mass balance at basin scale, the exchange of water mass between land and ocean, ice mass loss of the ice sheets, changes in ground water storage, etc. Mass transport observed through measurement of gravity changes thus contributes to a number of ECVs cross-cutting through the domains atmosphere, ocean and terrestrial hydrosphere/cryosphere. ESA is studying the concept of a Next-Generation Gravity Mission (NGGM) that can significantly improve the temporal and spatial resolution of mass transport observations. However, no mission is planned that would guarantee continuity of observations beyond the end of the lifetime of GRACE-FO in about 2023, which is required to arrive at a climate data record.

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20 Poli, P., D. P. Dee, R. Saunders, V. O. John, P. Rayer, J. Schulz, K. Holmlund, D. Coppens, D. Klaes, J. E. Johnson, A. E. Esfandiari, I. V. Gerasimov, E. B. Zamkoff, A. F. Al-Jazrawi, D. Santek, M. Albani, P. Brunel, K. Fennig, M. Schroeder, S. Kobayashi, D. Oertel, W. Doehler, D. Spaenkuch, S. Bojinski (2017), Recent advances in satellite data rescue, Bull. Amer. Meteor. Soc, doi:10.1175/BAMS-D-15-00194.1. http://dx.doi.org/10.1175/BAMS-D-15-00194.1.

21 https://www.eumetsat.int/website/home/News/DAT_3253427.html

22 Buizza, R. et al., 2017: The EU-FP7 ERA-CLIM2 project contribution to advancing science and production of Earth-system climate reanalyses. Bulletin Meteor. Amer. Soc., submitted.

Improved Bathymetry (GCOS Action G32)

Bathymetry is the measurement of water depth i.e. height from the seafloor to water surface. Better knowledge of seafloor topography and roughness is needed at every time and space scale, for nautical charts, navigation, water volume/transport computation, to understand and predict flow and mixing in the ocean, from tides to climate, and to recognize and exploit or protect habitats and resources. In particular, the impact of extreme events such as tsunami landfall or hurricane landfall and the associated storm surge requires good estimates of coastal bathymetry. *In situ* measurements of ocean depth (e.g. soundings, multi-beam/side-scan sonars, aircraft LIDAR flights etc.) cover less than 10 percent of Earth's ocean floor area.

Earth observation techniques that are capable of measuring bathymetry from space are varied and include estimates derived from optical multi-spectral sensors, synthetic aperture radar (SAR) and altimetry with varied degrees of success. Where the water depth is only a few meters deep, wave trains of surface swell are slowed and their crests refracted. Water depth may then be inferred if the swell refraction can be imaged using high-resolution optical satellite sensors or synthetic aperture radar imagery. However, this technique is limited to regions with favourable bottom topography and appropriate image availability and imaging conditions.

If the water is clear enough and the bottom reflective enough, imagers or lasers at optical wavelengths may "see" the bottom where it is only <50 m deep or less. (e.g. Sentinel-2, Worldview, IKONOS, Landsat etc.). Assuming that the ratio of bottom reflectance between two spectral bands is constant for all bottom types within a given scene, a bathymetric inversion is possible using two or more wavebands. The accuracy of the approach must be improved (e.g. ~2 m rmse. for clear water depths of 20m using IKONOS) to meet navigational requirements but, for other applications, such data are useful.

Ocean surface imprints of shallow-water bathymetry was one of the remarkable oceanic features observed in images from the first spaceborne SAR onboard SEASAT. Bathymetric mapping is not a direct measurement because it exploits the frequency dependent radar backscatter changes caused by ocean surface wave modulation induced by ocean current/bathymetry interactions. The technique is best suited to shallow coastal waters with strong currents and low wind. The technique has been demonstrated at all frequencies (C-, X- L- and P-band SAR). Qualitative preliminary results from an airborne campaign suggest that P-band is advantageous because it is less sensitive to wind driven roughness thus maintaining sensitivity at higher winds. The ESA ERS and ENVISAT SAR instruments have been used in demonstration bathymetry pilot projects. The Sentinel-1 C-band SAR mission has the potential for shallow water bathymetry mapping over large areas of the global coastline although little systematic progress had been made in this area to date. The ESA Biomass mission will explore this technique using P-band. However, SAR techniques are limited to regions with favourable bottom topography, low winds and appropriate image availability.

In deep and remote regions the topography of the seafloor has been inferred by using satellite altimetry. The global geoid derived from these data and its relationship to the structure of the seafloor provide global bathymetric maps of the world's oceans, revealing bottom features with wavelengths as small as 15 km. Ocean surface height structures measured by a satellite radar altimeter mirror gravity anomalies that are closely correlated to the shape of the ocean floor. To date, the horizontal resolution of this technique is about 10 km and the vertical accuracy around 100 m to 250 m. This has been enough to reveal major mountain ranges and other large-scale tectonic features of the seafloor, but is not enough to find seamounts that are significant habitats, obstacles to flow, and sites of enhanced mixing. It is estimated that there are perhaps 100,000 seamounts that have not yet been found but could be found using a dedicated satellite altimeter mission. Such a mission would not need absolute accuracy of sea level measurement, but would need very precise measurement of relative change in sea level over short distances, so that sea surface slope along-track could be measured to a few micro-radians over distances of a few km.

Such a mission would also need to collect data over a spatially dense network of ground tracks spaced only a few km apart. The new generation of delay-Doppler altimeter (DDA) such as Sentinel-3 and Sentinel-6 are well suited for global deep ocean bathymetry measurements along their ground tracks (the spatial coverage depends on the spacing of ground tracks). The DDA is able to measure the distortions of the ocean surface to a much higher degree of precision than a conventional altimeter. The precision and enhanced along-track sampling (~300 m) of a DDA altimeter allows the detection of deep ocean bottom features with wavelengths as small as a few kilometers, approaching a mapping capacity that today is reached using dedicated surface vessel-based surveys.

4.2 Atmospheric Climate Observing System

The Space Agency response to the GCOS IP 2016 Atmosphere-related actions is structured into three aggregate topics, covering all the thirteen[23] Actions with direct relevance to Apace Agencies. In addition, six Actions[24] mainly address individual surface-based networks which are "non-space" in nature but important to Space Agencies for the purposes of calibrating instruments and validating products. Action A31 calls for concerted action by Space Agencies to engage existing networks of ground-based remote sensing sites for validating satellite-based data. A generic Space Agency action is proposed to address these concerns (see section 3.5). The following provides a short summary of the detailed responses by Space Agencies to each relevant GCOS IP 2016 Atmosphere action.

4.2.1 Atmospheric Dynamics, Energy and Water Cycle Components

Reprocessing of atmospheric motion vectors (GCOS Action A19)

Tracking atmospheric motion is important for predicting weather systems, and for understanding atmospheric dynamics. For this purpose, satellite-based upper-air winds are derived at various scales and heights, with demonstrated impact on NWP and for climate applications.

Reprocessing of upper-air wind vectors derived from historical geostationary imagery (atmospheric motion vectors) is important for NWP and climate applications. Several Space Agencies have reprocessed parts of their archived data ranging back to the mid-1990s, coordinated internationally within a SCOPE-CM project. These activities will continue using state-of-the-art processing algorithms, encompassing AMV data derived from the early space-derived Earth observation (supplemented by current data preservation activities) to the present. Winds derived from polar-orbiting imagers and sounders are another important component of the upper-air wind record, especially in high latitudes.

Implementation of space-based wind profiling system (GCOS Action A21)

To pioneer 3D upper-air wind profiles based on lidar measurements, the ESA ADM-Aeolus mission has been developed, with launch planned in 2018. ESA and EUMETSAT are planning user workshops to facilitate user preparation, and to discuss a potential follow-on mission, pending success of this exploratory satellite.

Continuity of global satellite precipitation products (GCOS Action A25)

Precipitation is a very important ECV regarding direct societal impact. Satellite-based methods to estimate and quantify precipitation globally are improving. Concerns about the continuity of key missions for deriving global precipitation products (conical-scanning and other passive microwave

23 A16, A18, A19, A21, A25, A26, A27, A29, A30, A32, A35, A39, A40

24 A11, A15, A22, A31, A36, A37

(MW) imagers, precipitation radars) are recognized by several Space Agencies, as well as within the CEOS Precipitation Virtual Constellation and the International Precipitation Working Group (IPWG). The value of dedicated MW sounding to improve coverage of rainfall events in the tropical regions has been demonstrated and will be extended. Novel approaches based on precipitation radars and MW radiometers on cubesats are in development in single satellite or constellation configurations and microwave sounders in geostationary orbit are being studied. In addition, the Global Precipitation Measurement (GPM) mission provides global and regional rain and snow products and is a critical calibration standard for cross calibrating multiple MW for unified precipitation estimates GPM is expected to provide measurements until the 2030s and GPM continuity is being explored by NASA and JAXA. IPWG continues to pursue intercomparison and validation of global precipitation products using a common protocol.

Continuation of precipitation climatologies such as GPCP is of primary importance to detect trends and anomalies in precipitation; coordination and mobilization of resources should occur under SCOPE-CM.

Development of methodology for consolidated precipitation estimates (GCOS Action A26)

IPWG also promotes the development of methodologies to improve precipitation estimates based on various data sources (IR and MW satellite data, surface-based, models); to facilitate user uptake, IPWG could do more to consolidate the various approaches. Reprocessing of global satellite precipitation products is underway within several agencies, but requires enhanced international coordination and cross-sensor consistency. To this end, cross-calibration of MW and IR sensors is being addressed by the GSICS and GPM/X-CAL groups (see also A16).

Space Agencies will act to facilitate user uptake of precipitation products in societal applications. IPWG continues to foster the development of methodologies to consolidate precipitation estimates based on blended products using satellite, surface-based (gauge, radar) and model data.

Dedicated satellite Earth Radiation Budget mission (GCOS Action A27)

The Earth's energy balance (A27) and thus its climate is determined by the amount and distribution of the incoming solar radiation absorbed by the Earth and the outgoing longwave radiation (OLR) emitted by the Earth. The top-of-atmosphere (TOA) Earth radiation budget can only be measured from space, and continuity of observations is critical to interpret changes in surface and upper-air warming, and to constrain climate change predictions and projections. Total solar irradiance and spectral solar irradiance have been monitored since the late 1970s and are expected to continue, partly using the International Space Station (ISS) as host. TOA reflected shortwave and outgoing longwave radiation have been monitored since the late 1970s; continuity of measurement is secured through a payload on JPSS-1, but uncertain beyond 2024. Space Agencies need to address the potential gap in measuring TOA upwelling radiance to enable continuity in deriving the Earth radiation budget.

Space Agencies will act to address the potential gap in measuring TOA upwelling radiances (SW, OLR) to enable continuity in deriving TOA Earth radiation budget beyond 2024.

Lightning (GCOS Action A29)

Lightning, a recent addition to the list of ECVs, can be used as a proxy for monitoring severe convection and hence precipitation, and for improving estimates of severe storm intensity. Ultimately the data could be assimilated in NWP models and climate reanalyses to improve the representation of severe storms. The first lightning mappers in geostationary orbit operated by NOAA and CMA are entering operations in late 2017, and more will be added with the launches of GOES-S and MTG-I. Space Agencies will distribute products from these satellites (lightning events, groups, and flashes) in near real-time, and are expected to perform reprocessing of the new GEO-ring-based data in due time to extend the 20-year low-Earth orbit lightning dataset that is based on heritage lightning imagery from the Tropical Rainfall Measuring Mission (TRMM) and the extension of it through the LIS being flown on the ISS since February 28th, 2017. In developing application modules and proxy datasets, Space Agencies can assist as needed in the refinement of user requirements, as the application of lightning data matures.

4.2.2 Atmospheric Composition Including Greenhouse Gases

A number of atmospheric constituents have an important role in climate forcing and feedbacks, such as water vapour, CH4, CO2, O3 and aerosols. There is paramount importance for countries to monitor sources and sinks of greenhouse gases in the context of, for example, the 2015 UNFCCC Paris Agreement. Other gases, such as NO2, SO2, HCHO, NH3 and CO, are required to detect and attribute changes in ozone and aerosol in the troposphere and lower stratosphere, and for air quality monitoring.

> Water vapour and ozone measurement in upper troposphere and lower and upper stratosphere (GCOS Action A30)

Global high vertical resolution measurements of water vapour and ozone in the UT/LS by limb observations are essential for monitoring UT/LS fluxes of these constituents. This is important to better quantify their cycle and to better understand the causes of upper-air temperature trends, and related climate forcing/feedback mechanisms. There is currently no plan to fill the potential gap in ozone limb profiling between the Suomi-NPP and SAGE III missions in operation today, and the JPSS-2 missions planned to be launched in 2021. No follow-on to MLS on Terra/Aura or SMR on Odin is planned to provide MW limb profiling of water vapour, ozone and other constituents. No follow-on to OSIRIS on Odin is planned to provide UT/LS scattering limb profiling of ozone and aerosols. No sustainment of solar occultation soundings of atmospheric constituents is planned (such as from ACE-FTS and ACE-MAESTRO on SCISAT, or SAGE-III on ISS). Fig. 9 in the GCOS IP shows that most missions operate well beyond their anticipated lifetime.

Space Agencies will strive to sustain limb-scanning satellite missions for measurements of profiles of water vapour, ozone and other species from UT/LS up to 50 km altitude.

At the same time, GNSS-RO radio occultation-based measurements of atmospheric profiles should be maintained and their quality and coverage enhanced, given the demonstrated value of these data for NWP and climate applications.

> Develop a repository of water vapour CDRs (GCOS Action A22)

Building on significant efforts by the GEWEX climate research community to build a globally recognized repository of consistent surface-based GNSS zenith total delay and total column water datasets, satellite agencies should contribute satellite-derived water vapour climate data records to this repository. In addition to committing to exchange GNSS-RO data internationally, Space Agencies will act to maintain quality and coverage of the GNSS-RO constellation.

> Space-based measurements of CO2 and CH4 implementation (GCOS Action A35)

The complementary role of surface-based networks and satellite data for monitoring CO2 and CH4 within a comprehensive global observing system is increasingly accepted (cf. Actions A31 and A33). The quality of existing CO2 and CH4 satellite-based estimates has been assessed in the scientific literature as well as in operational contexts such as the European Copernicus Atmosphere Monitoring Service. Such estimates play an important role in quantifying the carbon cycle and to understand sources and sinks of these major GHGs.

Several Space Agencies have launches, or plan to launch a range of dedicated CO2 and CH4 missions (see Table below), both for monitoring these greenhouse gases globally, as well as for better estimating anthropogenic carbon emissions to the atmosphere, and to improve emission inventories. There are other missions allowing the derivation of trace gases which provide supplementary information. To validate satellite-derived products, surface-based networks for CO2 and CH4 (A33) and other GHGs, such as N2O, SF6 and halocarbons, need to be maintained and their coverage extended (see Actions A31 and A36).

Space Agencies, through CEOS and CGMS, will coordinate the space-based component of a global greenhouse gas observing system for marine and terrestrial components of the biosphere. Cross-linkage to the development of a global carbon monitoring system should be ensured (see Action T71).

Instrument	Agencies	Launch date	XCO2, XCH4	Instruments	Precision	Sampling (km)	Reference
Missions already launched							
SCIAMACHY	DLR / NSO / BelSpo / ESA		CO2 Total Column CH4 Total Column	UV/VIS/NIR/ SWIR – spectrometer	2.5 ppm 80ppb	30x60	Reuter et al. (2011), GHG-CCI (2017)
AIRS	NASA	May 2002	Mid-trop CO2 Mid-trop CH4	TIR spectrometer	2ppm	See AIRS web site[25]	Maddy et al. (2008) Chaine et al. (2008)
IASI	CNES-EUMETSAT	Oct. 2006	Mid-trop CO2 Mid-trop CH4	TIR Spectrometer	2ppm	Diam. 12	Crevoisier et al. (2009a)
TES	NASA	2004	Mid-trop	TIR spectrometer	10ppm	5.3 x 8.3	Kulawik et al. (2010)
GOSAT	JAXA / MOE / NIES	January 2009	CO2Total Column CH4 Total Column Mid-trop CO2 Mid-trop CH4	SWIR spectrometer and TIR	2 ppm 13 ppb	Diam. 10,5	Butz et al, (2011) Yoshida et al. (2013), GHG-CCI (2017)
OCO-2	NASA	Jul; 2014-…	CO2 Total Column	SWIR spectrometer	~0.5 ppm	1,29 x 2,25	Crisp et al. (2017); Wunch et al. (2017)
TanSat	MOST / CAS / CMA	Dec. 2016- ...	CO2 Total Column	SWIR spectrometer	4 ppm	2x2	
GHGSat ("Claire")	Canada	June 2016	CH4 Total Column	-	-	50 m/pixel over 12x 12 km field of view	www.ghgsat.com/
Decided missions (in phase B, C or D)							
MERLIN	CNES / DLR	2021	CH4 Total Column	SWIR Lidar	20 ppb	50 km	https://merlin.cnes.fr, http://www.dlr.de/rd/en/desktopdefault.aspx/tabid-2440/3586_read-31672/dlr%20merlin
OCO-3/ISS	NASA	2018	CO2 Total Column	SWIR spectrometer	1ppm	2 x 2	Basilio et al. (2013)
GOSAT-2	JAXA / MOE / NIES	2018	JAXA/MOE/NIES	SWIR and TIR spectrometer	0.5 ppm (CO2) 5 ppb (CH4)	Diam. 9.7	
Sentinel 5P	ESA / NSO	2017	CH4 Total Column	SWIR spectrometer	5 ppb	3.5*7	https://sentinels.cope

25 https://airs.jpl.nasa.gov/data/carbon_dioxide

							rnicus.eu/web/sentinel/missions/sentinel-5p
Sentinel 5	ESA / EUMETSAT	2021	CH4 Total Column CO2 Total Column as scientific product only	SWIR spectrometer	4 ppb	7.5*7.5	https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5
MicroCarb	CNES and UK Space Agency	2020	CO2 Total Column	SWIR spectrometer	1ppm	4,5*9 (2*2 demo)	https://microcarb.cnes.fr
GF5/GMI	CNSA	2017	CO2 Total Column CH4 Total Column	SWIR spectrometer		Diam. 10.3	
GAS/Feng Yun 3D	CMA	2017	CO2 Total Column CH4 Total Column	SWIR spectrometer	4 ppm	10x10	
HIRAS/Feng Yun 3D/E/F/G	CMA	2017-25	Mid-trop CO2 Mid-trop CH4	TIR spectrometer		16x16	
GASIII/Feng Yun 3G	CMA	2021	CO2 Total Column CH4 Total Column	Grating Spectrometer	4 ppm	3x3	
GeoCARB	NASA	2021	CO2 Total Column CH4 Total Column CO	SWIR spectrometer	1ppm CO2 4 ppbv CH4	3x6 at nadir	https://eospso.gsfc.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2 Polonsky et al. (2014)
Sentinel 7 – GHG Constellation (3 LEO satellites)	EC / ESA / EUMETSAT	2024-26	CO2 Total Column CH4 Total Column	SWIR spectrometer	0.5 ppm CO2 4 ppb CH4	2x2 (still tbc)	

The references are as follows :

- Chahine, M. T., L. Chen, P. Dimotakis, X. Jiang, Q. Li, E. T. Olsen, T. Pagano, J. Randerson, and Y. L. Yung (2008), Satellite remote sounding of mid-tropospheric CO2, Geophys. Res. Lett., 35, L17807, doi:10.1029/2008GL035022.
- Crisp, D., Pollock, H. R., Rosenberg, R., Chapsky, L., Lee, R. A. M., Oyafuso, F. A., Frankenberg, C., O'Dell, C. W., Bruegge, C. J., Doran, G. B., Eldering, A., Fisher, B. M., Fu, D., Gunson, M. R., Mandrake, L., Osterman, G. B., Schwandner, F. M., Sun, K., Taylor, T. E., Wennberg, P. O., and Wunch, D.: The on-orbit performance of the Orbiting Carbon Observatory-2 (OCO-2) instrument and its radiometrically calibrated products, Atmos. Meas. Tech., 10, 59-81, doi:10.5194/amt-10-59-2017, 2017.
- Basilio, R., et al. " Systems Design and Implementation of the Proposed Orbiting Carbon Observatory-3 On the International Space Station's Japanese Experimental Module." Science and Technology Series 114.20130000: 321-323, 2013.

Monitoring of aerosol properties (GCOS Action A39)

Aerosols remain a major source of uncertainty in estimating radiative forcing which is important for driving climate models and climate change projections. The latest IPCC AR5 report estimated that the direct aerosol radiative forcing (DARF) is -0.35±0.5 Wm-2. However, there remains considerable observational as well as modelling evidence that the actual uncertainty is a factor of two to four larger. The large uncertainty of DARF is caused by the combination of uncertainty in aerosol optical depth (AOD) retrieval from satellite observations, and the lack of accurate global characterizations of three-dimensional aerosol optical and microphysical properties. Current satellite instruments provide a global measurement of AOD and qualitative aerosol-type classification, but lack the capability of providing sufficient microphysical details to reduce the uncertainty in DARF and discriminating the anthropogenic components from the natural components. Space Agencies should aim to support the overarching goal to reduce the uncertainty in DARF by mapping the global 3D AOD distribution with an accuracy of 0.02 at the mid-visible wavelength. The retrieval of aerosol properties (types, shapes, size distributions) is also of high importance (e.g. for air quality and human health). A number of current and planned missions, feeding advanced multi-sensor analysis techniques, will contribute to progressing towards those objectives but more needs to be done.

Clouds and aerosols remain one of the largest factor of uncertainty in quantifying climate forcing and feedback. Satellite missions such as CALIPSO and CloudSat have revolutionized the understanding of 3D vertical profiles of clouds and aerosol layers, their composition (liquid/ice, chemical) and evolution over time. Continuity of space-based lidar observations beyond the CALIPSO and EarthCARE-type, and of limb scatter profiling observations (see A30) is essential for supplementing passive nadir-viewing sensors in terms of vertical resolution and coverage of the lowest atmospheric layers, however, mission continuity for aerosol and cloud vertical profiling beyond CALIPSO and EarthCARE is uncertain.

Space Agencies will act to coordinate the planning for a successor cloud and aerosol lidar mission beyond CALIPSO and EarthCARE.

Ground-based measurements (i.e. AERONET, GALION) of AOD and aerosol optical property retrievals are instrumental to validate the satellite retrievals of AOD and provide climatology for aerosol types (see Action in response to A31). Sub-orbital measurements will also play a role in better characterizing the microphysical properties of aerosols.

Fundamental Climate Data Records and Climate Data Records for greenhouse gases and aerosols ECVs (GCOS Action A32)

Many space agencies in Europe, the United States and Asia run major programmes devoted to the generation of climate data records for GHG amount and aerosol (A32) loading based on heritage instrument records. Significant efforts are going into cross-calibration and reprocessing of sensor records. Several current missions are providing CO_2 data, and there are plans to extend the CO_2 and CH_4 record by many agencies (see Table under Actions A35). In addition, solar-induced chlorophyll fluorescence (SIF) was first measured from space using high resolution spectral observations. Now a global and long-term SIF dataset is available for better understanding of CO_2 uptake. Continuation into the future to construct a long-term record for trend detection will require inter-calibrating and connecting heritage satellite sensor measurements with new generation of sensors, such as hyperspectral sounders, multi-spectral imagers, and multi-spectral multi-polarization instruments.

Ozone network coverage (GCOS Action A37)

Total column and profiles of ozone (A37) are routinely monitored using surface-based UV spectrometers coordinated globally through WMO Global Atmosphere Watch (GAW). Satellite-based retrievals of ozone parameters are a key contributor to the ozone climate record, and nadir-viewing ozone missions are secured in the long-term. Space Agencies should help addressing the decline in GCOS global baseline ozone networks through supporting network design experiments (see also A31).

Space Agencies will investigate the support of network design experiments (OSSE-type) to optimize the locations of Dobson-Brewer stations that are necessary for characterizing stratospheric ozone for climate research and applications (see section 3.5 and Action A31).

Continuity of products of precursors of ozone and secondary aerosols (GCOS Action A40)

For monitoring precursors of ozone and aerosols, a series of LEO and GEO orbiting satellite missions will ensure long-term satellite measurements of the precursors of ozone and secondary aerosols from space. Ground-based measurement networks (e.g. GAW) will insure the same for *in situ* measurements, and Space Agencies are supporting some of these activities. Observations of precursors of aerosols and ozone, such as NO2, SO2, HCHO, NH3 and CO, are required to detect and attribute changes in ozone and aerosol in the troposphere and lower stratosphere (see A30). They are also important variables for air quality monitoring.

The generation of emission inventories is currently mainly based on *in situ* data (e.g. EMEP, REAS), and Space Agencies are supporting the development of services to demonstrate the utility of satellite measurements for establishing more consistent emission databases.

4.2.3 Satellite Data Calibration, Validation and Reprocessing

This sub-section addresses Actions A11, A15, A16, A18, A31, and A36 related to enhanced satellite calibration and inter-calibration, data validation, and reprocessing of hyperspectral satellite records.

Implementation of satellite calibration missions (GCOS Action A16)

For "anchoring" the satellite-based climate record against an absolute standard, a dedicated in-orbit SI-traceable calibration mission is required against which other satellite instruments can be calibrated. This need was identified in the *Architecture for Climate Monitoring from Space*[26] (Dowell et al., 2013). However, there are no firm plans by Space Agencies for such mission, which would underpin and operate in the context of the WMO Global Space-based Inter-Calibration System (GSICS). Putting inter-calibration of VIS and IR sensors within GSICS on a more solid footing, and expanding GSICS to include passive MW sensors are interim objectives in the absence of progress with a fully dedicated satellite calibration mission. A partnership between Space Agencies and NMIs is required to foster the development of SI-traceable standards in the MW spectrum at the level of uncertainty required for climate.

A partnership between Space Agencies and relevant national metrology institutes (NMI) should be established to enable and promote the development of SI-traceable MW reference standards of sufficient quality to meet climate requirements.

Validation of satellite remote-sensing (Action A31), including: Operation of the BSRN (Action A11) Implementation of GRUAN (Action A15), N2O, halocarbon and SF6 networks (Action A36) and AERONET (Action A39) .

Validating satellite-based climate data products is necessary to characterize their quality and uncertainty, which are key elements for fostering user acceptance and serving as feedback to satellite operators. Several Space Agencies are investing substantially in surface-based networks for calibration and validation, such as BSRN (A11), NDACC, TCCON, GRUAN (A15), N2O, halocarbon and SF6 networks (A36), and AERONET (A39), through science programmes or

26 M. Dowell, P. Lecomte, R. Husband, J. Schulz, T. Mohr, Y. Tahara, R. Eckman, E. Lindstrom, C. Wooldridge, S. Hilding, J.Bates, B. Ryan, J. Lafeuille, and S. Bojinski, 2013: Strategy Towards an Architecture for Climate Monitoring from Space. Pp. 39, available at: www.ceos.org; www.wmo.int/sat; http://www.cgms-info.org/ GCOS, 2015: Status of the Global Observing System for Climate, GCOS-195, WMO, Geneva.

dedicated mission-based funding. However, despite these investments, many surface-based networks have insufficient resources to ensure sustained operations and to fill major geographical gaps (mainly in Africa, South America, Pacific region), and thus cannot adequately serve the needs for validation. Spatial gaps includes the oceans where surface-based measurements are sparse and often not adequately supported, for example, surface precipitation validation networks on research vessels or moored buoys. Collocation studies should be supported to demonstrate the benefits for estimating uncertainty using several data sources (satellites, surface networks, model). Building on existing activities (e.g. CEOS WGCV), Space Agencies will develop a plan how to strengthen the various surface-based networks to become a backbone for satellite data calibration and validation, and how to finance such measurements in all parts of the world. This requires on the one hand that some surface-based measurements become so-called fiducial reference measurements but also requires a long-term view on support and governance.

Space Agencies will act, together with meteorological agencies and science institutions, to develop a plan for a comprehensive validation of climate data records using surface-based data, including the resources required to address sustainability and sufficient geographic coverage of surface-based networks for calibration and validation.

Space Agencies will look, in collaboration with the operators of surface-based networks, into the possibility to invest in collocation studies demonstrating the value of using multiple data sources for estimating the uncertainty in atmospheric profiles.

Hyperspectral radiances reprocessing (GCOS Action A18)

Many space agencies such as EUMETSAT, NASA and NOAA have commitments to reprocess existing sensor data, including from their hyperspectral sounder instruments. Several activities are underway and efforts focus on more efficient, consistent and harmonized reprocessing across agencies, with international coordination envisaged through SCOPE-CM. This will result in a 20+ year FCDR of hyperspectral sounder radiances, representing a rich data resource for climate applications such as reanalyses. High-resolution IR sounders are expected to continue over the coming decades, improving the vertical resolution of satellite-derived upper-air water vapour and temperature profiles, and thus enhance monitoring of the atmosphere.

4.3 Oceanic Climate Observing System

This section addresses GCOS-200 Part II §4 ("Oceanic Climate Observing System").

The CEOS agency response to requirements for Ocean variables is structured into five aggregate topics, covering all the GCOS IP actions identified with a CEOS-agency relevance. The generic action O6 to continue to develop technology for satellite systems among others is implicit to all five topics. Some actions (O9, O11, O17, O23, and O29) are essentially non-space in content, but are addressed in the GCOS IP to CEOS (inter alia) because of their importance to integrated space-*in situ* observation and to satellite calibration; these non-space actions are included in the response below.

4.3.1 Physical – Sea Surface Thermodynamic State

Sea surface thermodynamic state includes activities addressing essential climate variables (ECVs) that quantify surface thermodynamic state (surface temperature and phase) and driving heat fluxes. This topic collects the CEOS agency response to actions O8 (sea surface temperature (SST) products), O17 (system for ocean surface heat flux observation), O29 (satellite validation, here for SST primarily), O31 (securing microwave SST missions) and O35 (sustaining sea ice products through active and passive microwave missions).

> Satellite SST Product Development (Action O8), Ocean-surface heat-flux observing system (Action O17), Satellite SST (Action O31), Satellite sea ice (Action O35), *in situ* data for satellite calibration and validation (Action O29).

Mission Continuity and New Missions

Regarding sea surface temperature (SST), infra-red surface-imaging missions with ~1 km spatial resolution on polar orbiting platforms are internationally well secured for continuity over the next decade, with relevant meteorological and environmental monitoring programmes across several agencies.

SST observation from geostationary sensors is at somewhat coarser resolution (2 to 10 km) and supports resolution of the diurnal cycle of SST, which is increasingly understood to be of climatological relevance particularly in the tropics. Himawari 8 is operational and Himawari 9 is on standby to ensure continuity of observation over the W Pacific sector. The first generation of Geostationary Operational Environmental Satellites (GOES) with Advanced Baseline Imagers (ABIs) will become operational between end 2017 (GOES-16) and circa 2020 and will restore diurnally resolved day-time (split-window) SST capability for the west Atlantic and east Pacific sectors. Several international geostationary programmes with diurnal SST capability address other longitudes/sectors completing the necessary constellation securely for at least 5 years according to published plans, with Meteosat-8 presently covering ~40°E until 2019.

A major concern for both SST and sea ice (SI) continuity of observation are the limited plans across many agencies for low-frequency passive microwave radiometry; the current plans are the JAXA AMSR3 hosted payload studies and early phase-0 studies by ESA/EC, neither of which currently have a commitment for an operational mission. There appears to be continuity of scatterometer missions, mainly directed at ocean vector wind determination but with SI capability, although with concerns about the consistency/stability of the climate data record over time from use of different techniques.

Product Evolution

Generation of long records of daily SST analyses is maturing, the main ongoing evolutions in progress being: improvement of true feature resolution at ocean mesoscales by methods that are more robust to the varying spatial resolution and gaps in coverage of input data streams over decades; and development of multi-decadal climate data records of high observational stability and quantified uncertainty, with scientific challenges in maximizing the benefit for climate data from the early record (1970s and 1980s). Evolution of diurnally resolved SST analysis is at an earlier stage and requires development of more subtle understanding of the sensitivity of SST observation (diurnal amplitude biases) and of inter-satellite SST errors (since the cycle is constructed from multiple overpasses), as well as developing computational capacity to integrate GEO and LEO data streams for long-term reprocessed climate data. Coastal zone SST analyses with higher resolution (<300 m) are desirable for climate impacts in coastal and estuarine environments. CMA are developing 250 m regional SST (from FY3D) and the NOAA VIIRS and JAXA SGLI sensors have nadir 300 m and 500 m SST capacity respectively.

Sea ice products such as concentration and extent are well established. As long as they are supportable by the observing system, sea ice type, drift and emissivity products will continue to be improved and evolved. Operational ice surface temperature products have emerged and will continue to evolve, and should be developed as climate data records within CDR programmes.

Global ocean surface heat flux products must rely on methods that indirectly constrain the fluxes: available satellite observations have negligible direct sensitivity to the fluxes themselves and the near-surface (e.g. 10 m) air temperature & humidity used in bulk formulae. Continued progress underpinned by investment should be addressed to further characterizing the ability of combined satellite observations to constrain fluxes, and should be pursued by agencies including ocean surface heat flux within CDR programmes[27].

Product Generation and Inter-comparison

Agencies will continue to generate and distribute SST and SI products at L2 and L3 from polar and geostationary instruments to meet operational (numerical weather, ocean and seasonal prediction) needs and monitoring of climate variability. NOAA will continue to generate and develop polar-geostationary-blended SST resolving diurnal variability, which can be compared with a UKMO diurnal analysis product.

GHRSST coordinates the inter-comparison of SST for operational products, analyses and climate data records and is an independent entity to the CEOS SST Virtual Constellation, which coordinates the agencies that provide the satellite SST data. CEOS SST Virtual Constellation maintains a strong and mutually supportive relationship and interface between CEOS and the activities of the Group for High Resolution SST (GHRSST). EUMETSAT financially supports the GHRSST Project Office. EUMETSAT and several other space and meteorological agencies (ESA, UKSA, CMA, KMA, SANSA, ISRO, JAXA, NOAA, NASA and BoM) are members of the CEOS SST Virtual Constellation.

Reprocessing Needs

The EUMETSAT Ocean and Sea Ice Satellite Application Facility will provide reprocessing of the MSG/SEVIRI archive from MSG/SEVIRI (2004 to 2012), and global SI concentration from Nimbus-7/SMMR, DMSP/SSM/I and DMSP/SSMIS (1978 to 2015) and from EOS AQUA/AMSR-E and GCOM-W/AMSR2 (2001-2015), the latter activity in co-ordination with ESA's climate change initiative (CCI) project on SI. ESA CCI will also provide a reprocessing and CDR of SST covering 1981 to 2016, with updates thereafter. CMA will reprocess FY3C VIRR SST, and JAXA will reprocess AMSR-E.

Validation, Metadata

Publicly available validation systems and data will continue to be provided by agencies, including NOAA's iQUAM[28] and ESA-funded Felyx[29]. Towards traceability to Système International standards and improved absolute stability of observation, ESA will continue to develop the concepts and deployment of Fiducial Reference Measurements for surface temperature[30] in international partnership.

4.3.2 Physical – Sea Level and Surface Dynamic State

Sea level includes activities addressing the climate-scale changes in sea surface height (SSH) some dynamic variability having been addressed within sea surface dynamic state. This topic collects the CEOS agency response to actions O9 (upper level observing system), O13 (sea level observation systems) and O31 (altimetry systems for SSH). The GCOS IP specifically calls Space Agencies to maintain and develop a global sea surface height observing system from the observational and satellite networks for annual assessment of sea level and sea level rise. Further it requires to ensure continuous coverage from one higher-precision, medium-inclination altimeter and two medium-precision, higher-inclination altimeters. Regarding the satellite altimetry reference mission, there should not be any gap between successive missions and an overlap period of 6-9 months to inter-calibrate each other (example of TOPEX/Poseidon and Jason missions). Care is required not to introduce bias in the data record due to the change from pulse-width-limited altimeters and

27 Bentamy et al., 2017, http://www.sciencedirect.com/science/article/pii/S0034425717303826

28 https://www.star.nesdis.noaa.gov/sod/sst/iquam/v2/about.html

29 http://hrdds.ifremer.fr

30 http://www.frm4sts.org

synthetic aperture altimeters. Sea surface dynamic state includes activities addressing ECVs that quantify ocean currents (horizontal) and sea state and the driving factor of wind stress. This topic collects the CEOS agency response to actions O12 (gridded current products), O16 and O34 (surface stress observations), O29 (satellite validation, for dynamic-state ECVs), and O33 (sea state from satellite). Theoretical and practical progress continues in estimating total and component surface current velocities by combinations of sea surface height, temporal evolution of features in SST and ocean colour, and/or *in situ* drifters and/or models.

> Upper-ocean temperature observing system (Action O9), Sea level observations (Action O13), Satellite sea-surface height (Action O31). Ocean current gridded products (Action O12), Ocean surface stress observations (Action O16), *in situ* data for satellite calibration and validation (Action O29), Satellite sea state (O33), Satellite ocean surface stress (O34).

Mission Continuity and New Missions

For Altimetry Reference High precision, Medium inclination Mission, European-US cooperation has ensured the continuity of the reference mission, without any gap, from TOPEX/Poseidon to Jason-3 (current). Sentinel-6A is planned to be launched in 2021 – in principle overlapping with Jason-3 for inter-calibration, the two successive S-6 with a planned life time of 5.5 years each fulfilling the mission continuity requirement without gap until 2030. Performance is expected to improve over the data record, e.g. an increase in precision is expected from SAR for Sentinel-6. Periods where two interleaved ground tracks are covered see an increase of the spatial resolution. A planned further contribution is China's HY-2C (planned in 2019). Care is required to ensure that the long-term record is not biased due to the very different data processing and sampling of a SAR altimeter. The Sentinel-6A Posiedon-4 altimeter introduces a new altimeter mode of operation (interleaved) that allows both SAR and pulse-width-limited measurements to be made at the same time.

Past contributions to Altimetry Higher Inclination Missions include ESA ERS-1, ERS-2, ENVISAT, ISRO-CNES Saral-AltiKa. Current and planned European contributions are: Sentinel-3 satellites, comprising the A + B constellation followed by the C + D, gap-free from 2016 to 2030; and Cryosat-2, whose main goal is to determine fluctuations in the mass of the Earth's major land and marine ice fields, and has demonstrated SAR observation above the ocean and contributed to high latitude coverage. The Sentinel A + B constellation will initially fly in a tandem phase enabling SAR and LRM altimeter inter-calibration following GCOS principles, before the B mission moves to an orbit plane configuration well-optimised relative to the A orbit for altimetry. Near identical precision to the reference mission is achieved using Synthetic Aperture Radar (SAR) mode observations. Sentinel-3 is the first satellite to operate a SAR altimeter 100% of each duty cycle. Chinese contributions in this category are HY-2A (2011-2016) and HY-2B (planned in 2018 for a 5–year life time).

The new swath altimetry mission SWOT (France-US-Canada-UK, planned in 2021) will characterize ocean mesoscale and sub-mesoscale sea surface height at spatial resolutions >15 km using interferometric SAR imaging techniques. This mission will not fly in the reference orbit.

For Surface Dynamic State, several agencies have committed plans for continuity of missions for ocean dynamics satellites. Scatterometer observations have planned continuity over the coming 5 to 10 years, providing ocean vector winds and co-derived variables. Altimetry missions ensure continuity of significant wave height products.

Product Evolution

Regarding sea level, the requirement for a Level 2 product, i.e. the Geophysical Data Record (GDR), is for 1-Hz sampling of the along-track signal of sea level, significant wave height and wind speed. The scope of the products keeps reaching closer to the coastal zone through improved tracking schemes and increase of the along-track resolution, the latter enabled by SAR observation (CS-2, S-3, S-6). However, access to full calibration is required. L1a products are now emerging (standard products for Sentinel-3 SRAL) that allow reprocessing by multiple users and greatly facilitate algorithm development in the new SAR altimeter era, supporting innovation to maximize the quality of data. Wider work on L1a products should be continued for all future altimeters, to broaden the range of processing techniques that are tested and applied to the data, and encourage innovation in aspects such as uncertainty estimation.

Regarding sea surface dynamic state, further progress is required and intended on combined analyses of data streams each giving complementary perspectives on surface currents and sea surface state. A challenge for product evolution is the development of stable long-term climate data records from an evolving constellation of sensors, particularly going back in time to maximize the record and combining where available relevant wave parameters from SAR. One initiative in this domain is the Sea State component of CCI+.

Product Generation and Intercomparison

Space Agencies all fulfil the requirements for GDR generation – although there is now a distinct break with the GDR concepts in the Sentinel-6 mission. The multi-mission products provided by CNES /AVISO, covering more than two decades, include corrections following systematic inter-comparisons at ground track cross-overs. Systematic inter-comparisons of lower-level data products and new geophysical corrections should also be systematically compared. For SAR altimeters, fully-focused SAR approaches may prove more lucrative than the simple "stack" noise reduction approaches currently used. Alternative and updated geophysical corrections are required using the best atmospheric model and other data in a systematic manner for time series. These corrections need to be consistent and updated based on the latest reanalysis products.

Reprocessing Needs

Multi-mission reprocessing of SSH records, fully taking inter-comparison into account, are regularly undertaken by the Agencies in particular CNES, ESA and NASA. Ongoing R&D in multi-mission reprocessing continues with the ESA CCI programme, forming the basis of a developing climate service within the Copernicus Climate Change Service (C3S) that will carry through to at least 2021.

Validation and Metadata

An essential aspect in the sustained success of sea level observation from space is the capacity for precise obit determination. The current capability uses the DORIS system and on GPS satellites, complemented by ground-based laser ranging stations.

Dedicated platforms (Harvest, Senetosa, Gavdos) are maintained by Space Agencies for calibration of the sea level signal, complemented by ground based transponders for range calibration. Validation further depends critically on the tide gauge network, an infrastructure outside the remit of the Space Agencies, but with a Space Agency role in improving the understanding needed to link the space and gauge networks. Multiple approaches to validation are required to access different parts of the uncertainty budget.

4.3.3 Physical – Sea Surface Salinity

Sea surface salinity includes activities addressing quantification of the ECV on salinity of the surface ocean. This topic addresses O11 (salinity observing system), O29 (validation of salinity) and O32 (continuity of satellite SSS record).

> Ocean salinity observing system (Action O11), *in situ* data for satellite calibration and validation, (Action O29), Satellite sea-surface salinity (Action O32).

Mission Continuity and New Missions

Three missions have pioneered the effort to observe SSS from space: ESA's Soil Moisture and Ocean Salinity (SMOS[31]) mission (November 2009-present), NASA/CONAE's Aquarius[32]/SAC-D mission (June 2011-May 2015), and NASA's Soil Moisture Active-Passive (SMAP) mission (January 2015-present). All three missions operate at L-band frequencies (~1.4 GHz), with SMOS having a radiometer and Aquarius and SMAP both having a radiometer and an integrated radar (the latter collects surface roughness measurements needed in SSS retrieval). Measuring SSS is part of SMOS' and Aquarius' mission objectives, but not part of SMAP's mission objectives. However, the similarity of Aquarius' and SMAP's sensors and the experience of SSS retrieval from Aquarius have enabled SSS retrieval from SMAP. ESA has approved SMOS' operation through the end of 2019 with further extension possible upon a review in late 2018. Aquarius/SAC-D suffered a spacecraft power failure in June 2015, which ended its extended mission that was approved by NASA. SMAP is currently in its prime mission, with a two-year extended mission plan submitted to NASA for review. Currently, neither ESA nor NASA have ocean salinity missions planned beyond SMOS and SMAP, and consequently space-based sea surface salinity measurements are not secure. These observations are critical for the understanding the Earth's water cycle and therefore high priority is required on securing on-going missions.

Product Evolution

The qualities of SSS products from SMOS Aquarius, and SMAP have been progressively improving as the retrieval algorithms become more mature, for example, in terms of the reduction of biases, correction of land contaminations, and mitigation of radio frequency interference (RFI) effects. Descriptions of the product evolution and latest products for SMOS SSS can be found[33,34]. Aquarius SSS have gone through four versions, with latest version (V4.0) being the latest version[35]. The Aquarius project will release version 5.0 in October 2017 towards the end of the Aquarius Phase-F. The versions 2 and 3 of SMAP SSS products are available[36].

Product Generation and Inter-comparison

Intercomparison among SMOS, Aquarius, and SMAP SSS products have been documented in various scientific publications for various regions and phenomena, for example, for the Gulf of Mexico[37,38], tropical Pacific[39], global and regional statistics[40].

The intercomparisons identified encouraging consistency of various satellite SSS products in depicting SSS structure in different regions and phenomena while revealing discrepancies that prompt for further understand in retrieval errors.

Reprocessing Needs

The discrepancies among satellite SSS illustrated by the ongoing intercomparison illustrate the need to further improve the satellite SSS retrievals through reprocessing. The recently available SMAP data also help improve the reprocessing of SMOS and Aquarius SSS data by capitalizing on

31 http://www.esa.int/Our_Activities/Observing_the_Earth/SMOS

32 http://aquarius.nasa.gov

33 http://bec.icm.csic.es/

34 http://www.catds.fr/

35 https://podaac.jpl.nasa.gov/aquarius

36 https://podaac.jpl.nasa.gov/datasetlist?ids=Measurement:Platform&values=Salinity%2FDensity:SMAP&view=list

37 Fournier et al. 2016, http://onlinelibrary.wiley.com/doi/10.1002/2016GL070821/full

38 Fournier et al. 2016, http://www.sciencedirect.com/science/article/pii/S0034425716300773

39 Yin et al. 2014, http://onlinelibrary.wiley.com/doi/10.1002/2014JC009960/abstract

40 Dinnat et al. 2014, http://ieeexplore.ieee.org/document/6929701/

the advantages of SMAP (e.g. better land correction tables and RFI detection). Within the ESA CCI+ programme, an effort on integrating SSS datasets to a CDR will commence in 2018.

Validation, Metadata

Validation of satellite SSS are typically performed by comparing with *in situ* near-surface salinity observations from the Argo array, tropical moorings, and shipboard measurements. The results of the validation have been documented through various publications as well as validation documents by the satellite projects (e.g. the validation documents in PO.DAAC for Aquarius[41]. Important issues related to the validation include the consideration of factors that contribute to the sampling differences between satellites and *in situ* platforms. These factors include (1) near-surface stratification (in the upper few meters) that can cause the difference between satellite SSS (for the upper 1-2 cm of the ocean) and *in situ* measurements (e.g. typically at 5-m depth for Argo and 1-m depth for moorings), and (2) average values within satellite footprint and time windows for satellite measurements and pointwise snapshot measurements from *in situ* data. These issues are discussed in a recent publication[42].

Capacity Building

NASA and ESA have sponsored various training workshops, webinars, and summer schools that intend to enhance the user base for satellite SSS.

4.3.4 Biogeochemistry and Biology / Ecosystems

Ocean biogeochemistry addresses ECVs quantifying water-leaving radiances or reflectances (“ocean colour radiometry”, OCR) and inferencing dissolved and particulate, living and dead constituents of the seawater, such as phytoplankton pigment concentrations (chlorophyll-a in particular), coloured dissolved organic matter (CDOM), particulate organic carbon (POC) and total suspended sediments (TSM), as well as water transparency, diffuse attenuation, and photosynthetically active radiation. Among emerging products are the structure and composition of phytoplankton community and associated particles, according to its size classes or functional types, and a variety of biogeochemical and ecosystem properties, as well as the potential to detail and quantify plankton characteristics. This topic collects the CEOS agency response to O23 (*in situ* OCR), O24 (OC algorithms), O25 (phytoplankton biomass) and O36 (OC climate data records).

> *In situ* ocean colour radiometry data (Action O23), Ocean colour algorithm development (Action O24), Satellite based phytoplankton biomass estimates (O25), Satellite ocean colour (O36).

Mission Continuity and New Missions

Geostationary Ocean Colour Imager (GOCI) of KARI/KIOST is a pioneering and thus far the only geostationary OCR mission despite the evidence of improved coverage and observations of diurnal and submesoscale dynamics in coastal waters and shelf seas. GOCI is providing complimentary time resolution to the polar-orbiting sensors at 128°E and an advanced GOCI-II is planned for launch in 2019 as a future geostationary platform covering the same area.

Significant research and management user interest in coastal and inland waters drives adoption of high spatial resolution sensors which are not designed specifically for OCR applications. The continuity of these instruments, such as USGS Landsat-8 OLI and EU Copernicus Sentinel 2 series, is supported through their individual programmes. They offer opportunity for high spatial resolution of ocean colour dynamics reflecting biology and coast zone geochemistry related to sedimentary loads, even if the sensors are not maximized for aquatic retrievals.

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41 https://podaac.jpl.nasa.gov/aquarius

42 Boutin et al. http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-15-00032.1

Product Evolution

OCR-VC agencies plan to support R&D to better exploit ocean surface reflectance measurements from satellite for constraining biogeochemical ECV quantities, particularly plankton and phytoplankton biomass (O25) and quantifying phytoplankton functional types that are key for research and management (e.g. HAB and fisheries) applications.

Product Generation and Intercomparison

Improvements in product generation and intercomparisons are goals of the INSITU-OCR initiative, which is working towards the development, validation and maintenance of consistent and accurate OCR data products from multiple missions, taking advantage of existing activities within CEOS agencies and across the broader community (INSITU-OCR White Paper, 2012). One of the activities is ESA Climate Change Initiative, which has developed a 20-year time series of consolidated OCR products following GCOS and user requirements and strict algorithm evaluation and intercomparison processes. NASA ESA, EUMETSAT and NOAA in concert with other Space Agencies through the OCR-VC and IOCCG maintain robust efforts to intercompare national and international mission data products. Additionally, NASA has been investing in the development of new instruments to ensure improved ocean colour instruments to be used in validation and vicarious calibration of new and planned ocean colour sensors, following the instrument and measurement observational requirements outlined in the INSITU-OCR white paper. The INSITU-OCR initiative also addresses a multi-agency network consisting of sea-based measurements for use in space-based sensor system vicarious calibration (SVC), data product validation, and algorithm development. SVC, in particular, has been jointly addressed as it requires a significant investment in field infrastructure and must be used to achieve the OCR product uncertainties required for climate and user applications. NOAA continues to maintain the Marine Optical BuoY (MOBY) system for sustained vicarious calibration efforts in support of all existing and forthcoming OCR sensors, along with other supporting data streams[43].

Reprocessing Needs

Multi-sensor integrated reprocessing is a high priority for ocean colour and biogeochemical products, an ongoing major challenge being the effects on multi-sensor time-series stability of the subtle differences between missions of channel suite specifications (O36). Ocean colour will continue to be an ECV addressed within ESA's Climate Change Initiative until 2023, and NOAA's JPSS program through 2023 and beyond.

Validation and Metadata

Fiducial reference measurements for ocean colour are being advanced on inter-calibrated *in situ* radiometry for example via FRM4SOC[44]. All OCR-VC agencies intend to continue the inter-calibration of *in situ* FRMs and the observational requirements of the INSITU-OCR white paper, including expanding engagement with national metrological (standards) institutes to work towards better quantification of errors and uncertainties associated with the *in situ* instrumentation needed for satellite data product validation. As such, agency groups such as NASA Ocean Biology Processing Group[45] (OBPG) maintains a local repository of *in situ* oceanographic and atmospheric data to support their regular scientific analyses. The SeaWiFS Project originally developed this system, SeaBASS, to catalogue radiometric and phytoplankton pigment data used their calibration and validation activities. To facilitate the assembly of a global data set, SeaBASS was expanded with oceanographic and atmospheric data collected by participants in the SIMBIOS Program, which has aided considerably in minimizing spatial bias and maximizing data acquisition rates. Archived data include measurements of apparent and inherent optical properties, phytoplankton pigment concentrations, and other related oceanographic and atmospheric data, such as water

43 https://coastwatch.noaa.gov/

44 https://frm4soc.org

45 https://oceancolor.gfsc.nasa.gov/

temperature, salinity, stimulated fluorescence, and aerosol optical thickness. Data are collected using a number of different instrument packages, such as profilers, buoys, and hand-held instruments, and manufacturers on a variety of platforms, including ships and moorings. Other Space Agencies maintain and are further developing similar capabilities in support of their OCR missions. The OCR-VC agencies pay constant diligence to assuring the quality of the *in situ* measurements and their metadata.

4.4 Terrestrial Climate Observing System

This section addresses GCOS-200 Part II §5 ("Terrestrial Climate Observing System").

4.4.1 General

> Improve coordination of terrestrial observations (Action T1), Develop joint plans for coastal zones (Action T2), Terrestrial monitoring sites (Action T3), Review of monitoring guidance (Action T4), Develop metadata (Action T5), Identify capacity development needs (Action T6).

The need for more coordination in the terrestrial domain has been recognised for some time. Improved coordination would benefit both the observing organisations e.g. Space Agencies as well as the end-user communities focused on meeting the Sustainable Development Goals (SDGs) and the goals and targets of other Multilateral Environmental Treaties (MEAs). The value of terrestrial coordination comes from several areas: reduced overlap in data collection; fewer gaps and denser observation networks from improved spatial and temporal coverage; and increased ability to share collected data due to greater standardization of methods and formats—all of which provides better observations at lower cost. A number of efforts have been initiated from different directions to achieve this, building on the work undertaken by the Global Terrestrial Observing System (GTOS) (e.g. TEMS database) and its technical panels such GOFC-GOLD, Coastal-GTOS). However, further coordination is required, driven by new needs and requirements related to the implementation of the 2030 Agenda and attainment of Sustainable Development Goals. The international science community focusing on Earth observations and sustainability issues calls for a dialogue to address this. Coordination between Space Agencies and *in situ* networks, in particular the exploitation of infrastructural investments such as Fluxnet, NEON, ICOS, TERN, TRACE, CERN and other regional flux networks has been initiated through WGCV LPV and through individual Space Agency efforts in support of individual missions (e.g. NASA GEDI, ESA BIOMASS). However this needs greater coordination.

A strategic meeting in March 2017, co-organised by GCOS, GEO and ICSU, brought together key players, including CEOS, to explore these coordination needs. The meeting initiated a process of exploring how best to fill the gap in terrestrial observation coordination. A White Paper[46] was developed describing an overall process to identify, agree on, and implement a coordination approach. It proposes improved coordination within various thematic layers (e.g. carbon, biodiversity, water) as well as across those layers. The process will start with a workshop (to be held in 2018) to bring together all relevant observation networks and Space Agencies, through CEOS, to discuss the ideas laid out in the White Paper.

Over the last two decades there has been an increased effort to extend the ecological network specifically in tropical forest through ForestPlots[47] which coordinates individual *in situ* activities e.g. RAINFOR[48] and AFRITRON[49]. These networks have made major investment in South America,

46 Terrestrial Observations for Sustainable Development: A Coordinated Path Forward. White Paper in preparation result of a GEO, ICSU, GCOS meeting held at ESRIN on March 13th, 2017.

47 http://www.forestplots.net/

48 http://www.rainfor.org/

49 http://www.afritron.net/

Africa and Asia building up data resources and capacity development. Also, their value for validation of satellite products is increasingly being recognised. However, there is a need to ensure their long-term continuity and optimise their data collection methods for satellite product validation. The latter also applies at various levels to the infrastructure investments in other parts of the world e.g. Fluxnet, NEON, ICOS, TERN, TRACE, CERN and other regional flux networks.

4.4.2 Hydrosphere

Lakes and Reservoirs: compare satellite and *in situ* observations (Action T8), Establish sustained production and improvement for the Lake ECV products (Action T10), Operational Groundwater monitoring from gravity measurements (Action T14)

Mission continuity for global lake water level, surface water temperature, ice coverage, and lake colour measurements is assured through the Sentinels, JPSS and Metop and the geostationary systems (Meteosat, GOES and Himawari). Higher resolution systems are research level e.g. Landsat 8 and have calibration challenges for temperature. While there is nothing dedicated currently planned for ice cover - SAR and Optical imagers provide sufficient information for product generation. Gravity approaches for groundwater will be served by NASA/DLR GRACE-FO and potentially ESA NGGM. A dedicated effort to merge different sensors (e.g. Landsat-8 and Sentinel-2 and RADARSAT-2 and Sentinel-1) would be very beneficial for the production of long-term records from overlapping satellites and multi-product and multi-sensor inter-comparison.

Algorithms for all lake products have been evolving rapidly with recent research efforts on colour, temperature and extent[50]. Further development is expected under ESA Lakes_cci, Copernicus and USGS Landsat Programme. CDR generation is being performed at the research level e.g. GloboLakes but there are plans under both Copernicus and ESA CCI to establish systems of production. Algorithm and satellite multi-sensor and multi-product intercomparison has been minimal so far. While the combination of *in situ* and satellite observations has just started through interaction between the HydroWeb and HydroLARE database organisers there is a pressing need to develop unified a satellite lakes database containing consistent LSWT, lake colour, lake height, lake extent and, where relevant, lake ice products. This should include *in situ* monitoring contributions although there is a need here to extend the *in situ* monitoring in both time and space (lake numbers and size distribution).

Satellite soil moisture data records (Action T15), Multi-satellite soil moisture data services (Action T16), Regional high-resolution soil moisture data record (Action T18)

Mission Continuity and New Missions

Microwave radiometers

Currently, there is a multitude of satellite radiometer missions suitable for soil moisture observations, in the first place the dedicated
L-band (1.4 GHz) soil moisture missions SMAP and SMOS. But, also observations made by C-band (AMSR2) and X-band radiometers (ASMR2, GPM GMI, and Fengyun 1B) are currently available for observing soil moisture. In case of failure of one of these missions, there is enough potential backup to reduce the impact of satellite failure on global soil moisture information on the short to mid-term. More worrying is the long-term continuation of L-band and C-band radiometer missions, since neither SMOS, nor SMAP nor AMSR2 has confirmed continuation. The planned Water Cycle Observation Mission (WCOM) of the Chinese Academy of Sciences has the potential to bridge the looming gap in L- and C-band observation time series from 2020 onwards. Nevertheless, at the last Satellite Soil Moisture Validation and Application Workshop (September

50 e.g. Pekel et al. 2014

2017) the international science community expressed large concern with respect to the continuity of non-restricted mission data that is consistent with current and historical missions.

Microwave scatterometers

Soil moisture is currently measured by the EUMETSAT Polar System (EPS) Metop-A and Metop-B ASCAT scatterometers.. Continuation is assured by Metop-C ASCAT. Continuation beyond the current EPS program will be provided by the approved EPS Second Generation (EPS-SG) program, which will start in 2021/22 and has the goal to provide continuation of C-band scatterometer and other systematic observations for another 21 years, i.e. at least until 2042. In combination with the earlier ERS-1 and 2 C-band scatterometers this would lead to a more than 50-year observation record of largely consistent properties.

Synthetic aperture radars

High spatial resolution systematic observations in C-band are being made by Copernicus' Sentinel-1A and B satellites (launched in 2014 and 2016, respectively) which have an envisaged minimum lifetime of 7 years. Continuation shall be provided by Sentinel 1C and 1D, which are expected to be launched in the 20121-2023 timeframe in order to extend the operational monitoring component of Copernicus at least until the end of 2030. The multi-satellite concept of Sentinel-1 overcomes the major limitation of other (mostly commercial) SAR missions for monitoring the highly dynamic behaviour of soil moisture, i.e. the long revisit times. Theoretically more suitable for observing soil moisture are the L-band SARs that were launched by JAXA (JERS-1, PALSAR, PALSAR-2 (only the latter still active), but these are hampered by the reduced revisit time. Other L-band SAR missions with restricted access are under preparation (e.g. Tandem-L by DLR).

Multi-satellite data services

EUMETSAT has performed repeated reprocessing of its Metop-A/B ASCAT level-1 and soil moisture products that have been used in ECMWFs ERA-5 reanalysis. ESA's Climate Change Initiative has supported the generation of a multi-mission multi-decadal soil moisture data record. In 2017, pre-operational production of this product has been transferred to the Copernicus Climate Change Service (C3S), with an endorsed continuation until 2021. Yet, there is no certainty regarding a potential continued support for scientific developments (e.g. needed for the integration of new missions like SMAP) beyond 2017.

Product Evolution

There has been significant algorithmic progress for single sensor surface soil moisture products (e.g. SMAP, SMOS, AMSR2, ASCAT) and derived products, e.g. SMOS and SMAP L4 Root-zone soil moisture and Carbon Net Ecosystem Exchange, and the ASCAT-based Soil Water Index. First evaluations of the new SMAP products have shown accuracies that in many places outperform existing products and meet the mission target requirements.

To reply to the user needs, algorithm developments increasingly focus on the derivation of soil moisture products with enhanced spatial resolution, either from SAR alone (mainly Sentinel-1), by fusing radiometer/scatterometer observations with SAR data (e.g. for SMAP and ASCAT), or by applying downscaling techniques using ancillary data (e.g. Thermal Infrared or topography data). Some downscaling algorithms exploit the oversampling of the sensor itself (e.g. for SMAP, AMSR2).

Significant progress has also been made for CCI multi-satellite soil moisture, e.g. by integrating the SMOS and Metop missions and by reducing the errors. Meanwhile, several Space Agencies (e.g. NASA, ESA) have supported the exploration of alternative approaches for combining multiple missions. The climate community has expressed a strong need for CCI soil moisture becoming totally independent of land surface models.

Product Generation and Inter-comparison

For several products, product generation has reached a high level of maturity and automation.

Accordingly, these products are produced and distributed by operational data centres, agencies, and services, e.g. NSIDC (SMAP, AMSR2), EUMETSAT/H-SAF (ASCAT), and Copernicus (CCI/C3S soil moisture, ASCAT Soil Water Index). Prototype development is primarily being performed by the science community with contributions coordinated by Space Agencies through major projects/programmes, e.g. SMOS EOP, ESA CCI and NASA JPL. Of concern are the usually long transfer times between prototyping and operational production, the coordination between evolving science and operational product updates, and the support for continued operations. From a user perspective, the diversity of distribution channels (which often distribute different data set versions and derived products) is often considered confusing.

Product intercomparisons are community-driven and mostly made by single scientist (group)s and/or studies. Consistent and transparent intercomparisons of datasets are currently lacking. Although mature evaluation protocols exist for individual missions or projects (e.g. for SMAP, ESA CCI soil moisture, SMOS) the limited accessibility of software, reference data (e.g. *in situ* observations) and procedures for preprocessing and validation, presently limit an objective intercomparison of products. This is further complicated by the large variety of product levels and versions per product, and the relatively long peer-review process, so that published results are mostly incomplete and do not apply to state-of-the-art product releases. Therefore, open, standardised, and online benchmarking protocols and tools are needed for achieving robust, transparent, and state-of-the-art intercomparisons. The evaluation procedures and metrics should not come from quality assurance teams of individual but need to be based on the consensus of the entire community. A first step towards a standardised protocol has been coordinated by the International Space Science institute and could be further coordinated e.g. by the CEOS Working Group on Calibration and Validation. Open-access tools and web interfaces required for a transparent and continuous benchmarking could be developed and coordinated by dedicated independent assessment panels, e.g. the WCRP GEWEX Data and Assessments Panel, where similar activities care currently being set up.

Reprocessing Needs

A major concern for the consistency in climate data records from radiometers is the intercalibration between AMSR-E and AMSR2. Preliminary intercalibrations have proven to be insufficient to assure staying within the stability target requirements of GCOS.

Reprocessing of ERS-1 is needed for improved intercalibration and consistent spatial resolution with ERS-2 and later scatterometer missions.

Reprocessing of Metop-B NRT data prior to 2015-07-20 is needed for their consistency with observations after this date and to facilitate their integration into C3S soil moisture.

Validation, Metadata

Mature validation procedures have been established at the level of individual missions. Exemplary is the SMAP cal/val protocol, which is based on numerous *in situ* core validation sites with a high density of sensors, complimented with sparse validation sites. Based on this protocol it has been concluded that over most core sites SMAP fulfils the target requirements (0.04 m^3m^{-3} unbiased Root-mean-Squared-Error). However, larger uncertainties exist for densely vegetated areas. Comparable results are achieved for other operational products (e.g. AMSR2, SMOS, C3S, ASCAT) although skills depend on land cover. Generally, there is a lack of suitable reference data in the wet tropics and subarctic, i.e. in regions where soil moisture retrievals from satellites are difficult and uncertain.

The satellite soil moisture producers endorse the establishment of a common and transparent validation protocol. Such a protocol shall also allow for the assessment or more intricate data characteristics, e.g. trends and stability. Additional uncertainties, resulting from differences in scales between satellite and ground observations, shall be explicitly accounted for in such a protocol.

The satellite soil moisture community also expressed the need for evaluating the consistency and energy conservation between derived biogeophysical variables, e.g. between surface soil moisture and vegetation optical depth obtained from the same observation.

Other Comments (observations coming from the user community)

- Critical for the adoption of satellite soil moisture by operational users (e.g. weather centres) are long-term mission and service concepts, as well as accurate descriptions of error characteristics.
- A strong demand for satellite-derived root-zone soil moisture has been identified.
- An increased support for multi-sensor approaches needed, in particular for obtaining high-resolution products with appropriate revisit frequency and multi-satellite vegetation optical depth products supporting product consistency assessments.
- Cross-ECV activities are needed for assessing the consistency between products.

4.4.3 Cryosphere

Cryosphere includes activities addressing essential climate variables (ECVs) that quantify glacier and ice sheet state and dynamics and snow characteristics. The elements covered here comprise the CEOS agency response to actions with a clear satellite component, namely actions T21-T23 and T26 (glacier inventories), T24 (glacier geodetic products), T25 (glacier front location), T27 (glacier velocities), T29 (snow products), T32 (ice sheet observation continuity) and T38 (snow and ice albedo).

Existing albedo products have shown reasonable agreement over surfaces dominated by snow and ice. However, the simple radiative transfer models used are unlikely to capture the complexity of mixed surfaces, such as snow on trees. Products at coarse resolution have been developed for sea-ice, but are difficult to validate with field albedometers due to scaling issues. New 1km products have recently been developed that capture rapid changes such as snow melt and sea-ice motion, but continuity is limited due to a lack of suitable future multi-angular satellite instruments. To study the impact of soot, cyanobacteria (cyrobacteria) and plastics, new spectral bands need to be added which are tuned to these pollutants so that their impact can be better assessed.

> Improving multi-decadal glacier inventories (Action T21-23), Extending the geodetic dataset (Action T24), Glacier-front variation products (Action T25), Glacier observing sites (T26), Observations of glacier velocities (Action T27), Integrated analyses of snow (Action T29), Continuity of laser, altimetry and gravity satellite missions (Action T32), snow and ice albedo products (Action T38).

Mission Continuity and New Missions

For global glacier extent and velocity mission continuity is assured in the optical domain through Landsat 8 (follow on Landsat 9 planned for 2020) and Sentinel 2 with improved spatial resolution and in the SAR domain through Sentinel 1. Other very suitable SAR sensors currently in operation (TerraSAR-X, TanDEM-X, Radarsat 2, ALOS-2 PALSAR-2) have access restrictions and are only applied regionally.

For extending the geodetic dataset mission continuity using satellite data has never existed. The only DEM that is suitable (acquisition date known) and (nearly) globally available is SRTM. All other related data products have a regional scale using either national DEMs (NED) or self-processed DEMs from specific missions (SPOT, ASTER, TanDEM-X) as the second point in time (before or after SRTM). The ASTER GDEM v2 is good but does not have traceable acquisition information. New freely available datasets such as the ArcticDEM and the historic elevation dataset for Greenland have improved the situation regionally. A future free access to the TanDEM-X DEM would improve the situation dramatically, though with remaining uncertainties related to radar penetration and time stamp. Other options include radar and laser altimetry. These provide detailed information at point level, in particular Cryosat-2, but there remains difficulty, especially in regions of high mountain topography, in sample location and sufficient sample coverage on glaciers themselves. A follow-on for Cryosat-2 with interferometric capability is needed to extend the time period and coverage of these observations.

A major drawback for a true monitoring of constantly changing glaciers in steep high-mountain topography from EO satellites, is the missing availability of DEMs from high-resolution sensors for orthorectification of the related satellite data. This comes along with their unavailability for the science community (e.g. PlanetDEM, TanDEM-X). The latter is an absolute must-have for follow-on science applications (e.g. drainage divide calculation and digital intersection with glacier outlines to accomplish and product creation across sensors.

Mission continuity for ice sheet surface elevation change, ice velocity, grounding line location, and gravimetric mass balance is assured for:

- Surface Elevation Change: Cryosat-2 (until 2020), Sentinel-3, and ICESat-2 (launch 2018). Follow-up mission for Cryosat-2 is required.
- Ice Velocity: ALOS-2 PALSAR-2, Radarsat-2, Sentinel -1, TerraSAR-X and Cosmo-SkyMed (high resolution for fast flowing outlet glaciers).
- Grounding line location: Sentinel-1, TerraSAR-X, Radarsat-2, ALOS-2 PALSAR-2.
- Gravimetric mass balance: GRACE-F-O (launch within 2020 timeframe). Current GRACE-2 twin satellite is due to run out of fuel in November 2017. GRACE-F-O is required for continuity.

Good continuity is assured for snow extent (SE) products through operational satellite programmes, e.g. Copernicus Sentinel-3 SLSTR and JPSS VIIRS but there is no satellite mission specifically focused on the ideal measurements for snow water equivalent (SWE), which relies on passive microwave imaging instruments. Continuity of SSMI/S passive microwave instruments is uncertain after DMSP F18 satellite (which is already in-orbit). Sustained SWE measurements will in future be available from EUMETSAT Metop-SG MWI, but at slightly different frequencies than the heritage time series of SMMR and SSM/I. Concept studies for new missions are in progress at ESA ('SnowConcepts') and the Canadian Space Agency ('Terrestrial Snow Mass Mission'), and NASA's International Snow Working Group-Remote Sensing (iSWGR) is working toward preparing mission concepts for the 2017–2027 Earth Science Decadal Survey.

Product Evolution

A GLIMS executive board has been established to coordinate data production for glaciers to some degree. As glacier outlines are still science products (warranting a publication once created) the selection of a specific region and time frame is up to the analyst. The science community has expressed the wish to also have in the future a consolidated (frozen) globally complete dataset (e.g. an updated Randolph Glacier Inventory, RGI) for consistent global scale applications. Version 5.0 of the RGI has now been integrated in GLIMS and technical developments are under way to extract an RGI-like product directly from the GLIMS database. Efforts are also under way with the ECMWF Copernicus Climate Change Service (C3S) to collect and integrate already existing datasets in the GLIMS glacier database, following on from the effort made under ESA Glacier_cci. Poorly covered regions will likely be updated to obtain higher quality and/or additional glacier inventories for change assessment through increasing availability and improved spatial resolution of satellite data (e.g. Sentinel 2A/B).

New methods of automated data production (stack and cloud processing) are increasingly exploited for application of robust processing lines. For velocity such automated processing lines have already been established for SAR sensors as well as optical data (Landsat 8 project GoLIVE at NSIDC). Elevation change products will make a huge step forward once the TanDEM-X DEM has been applied in most regions currently covered with SRTM and NEDs.

The higher spatial resolution and more frequent availability of all datasets (satellite and DEMs) will allow detailed studies of short-term and local scale glacier dynamics that will likely also increase process understanding (e.g. of surging glaciers).

Improvements for SE & SWE retrieval are planned or currently ongoing in several projects, e.g. ESA Snow CCI, NOAA IMS, etc. Dedicated SWE retrieval development is only a small component of planned ESA Snow CCI, and largely relies on small nationally funded efforts (Finland, Italy, Canada, United States). Cloud clearing of optical snow products by means of multi-sensor or model data assimilation need to be evaluated and improved.

Until recently, Cryosat-2 had been the only altimeter system that provided ice sheet surface elevation changes since the end of the Envisat mission. With the launch of Sentinel-3 in 2016, new products are emerging. However, Sentinel-3 does not operate in SARIn mode, which is a crucial feature of Cryosat-2 that enables a measurement of the angle of the return signal and hence can distinguish sloped terrain and enables more precise elevation point positioning on the surface. This is important for the steep ice sheet margins. While Sentinel-3 is in a low inclination sun-synchronous polar-orbit, Cryosat-2 flies in a non-sun-synchronous drifting orbit to cover as much as the pole hole as possible.

Ice velocity products have matured since the Sentinel-1 two-satellite constellation. With its repeat cycle of 6 days a reduction in temporal decorrelation, prone to occur for the C-band SAR sensors, has been achieved. L-band SAR sensors are still needed as these provide better correlation, as well as high resolution SAR data to reliably monitor fast-moving outlet glaciers. There is a need to fill the polar hole over Antarctica to ensure product maturity[51].

Progress has been made regarding the determination of grounding line locations both using InSAR techniques, but also using Cryosat-2 to measure the break in ice sheet surface slope[52].

Product Generation and Inter-comparison

Product generation is primarily being performed by the science community with contributions coordinated by Space Agencies through major projects e.g. ESA Glaciers_cci, ECMWF C3S, NSIDC GoLIVE and national agencies. The key algorithms and processing lines for all products are publicly available and the science community is constantly working on improvements. Time-series analysis have started to become feasible as data density (Sentinel-1, Sentinel-2) has increased. Product inter-comparison is performed only occasionally as part of science studies. In general this is a difficult task due to differing temporal baselines and image conditions. Improved time stamps in products and accompanying DEMs would provide greater consistency. A dedicated data host is only available for glacier outlines (GLIMS database at NSIDC). Elevation change data (geodetic mass budgets) are collected by WGMS along with other data on glacier fluctuations (e.g. length changes, T25).

Measurements of snow lines, glacial lake outlines, velocities, and gridded products such as elevation changes can be stored in GLIMS as well, but few have been ingested to date. Decadal elevation change can be achieved[53]. A key concern of such elevation change studies is the variable sensor characteristics, such as radar penetration and lack of optical contrast.

Global SWE and SE products are routinely produced by multiple agencies: NOAA, NASA, EUMETSAT, JAXA, etc. An example is NOAA's Interactive Multisensor Snow and Ice Mapping System (IMS) which provides snow records back to 1972. ESA Snow CCI will improve on the existing GlobSnow SE and SWE products to deliver new snow CDRs integrating observations from multiple instruments. Regional/national snow melt extent products from SAR for mountains regions and flat areas are systematically produced by several groups, and work is ongoing to

51 http://www.wmo.int/pages/prog/sat/documents/PSTG-6_Final-Report.pdf

52 http://www.sciencedirect.com/science/article/pii/S0273117717301813

53 See example: http://www.nature.com/ngeo/journal/vaop/ncurrent/full/ngeo2999.html

develop a pan-European product[54]. Community endorsed protocols for product inter-comparison and validation have been established via the GCW/ESA Satellite Snow Product Intercomparison Experiment (SnowPEx; 2015-2017).

Regarding ice sheets, extensive algorithm assessments were undertaken within the ESA CCI programme based on community needs (e.g. for Greenland surface elevation changes[55]). ESA will continue to generate the relevant suite of CDRs for both the Greenland CCI and the Antarctica CCI. Experiments to evaluate the different satellite methods used to estimate ice sheet mass balance are undertaken by the ice sheet mass balance inter-comparison exercise (IMBIE) that is jointly supported by ESA and NASA.

Reprocessing Needs

An operational reprocessing of remote sensing derived glacier data is not performed. In part and regionally this is done within the framework of dedicated projects (e.g. C3S).

Glacier inventories derived from satellite remote-sensing and digital terrain information should be repeated at time intervals of a few decades. This can be accomplished with the Landsat archive aided by access to similar sensors (e.g. SPOT, ASTER, Sentinel-2). Consistency in processing, opening of archives and an easy-view interface is needed (e.g. GLOVIS, Earthdata Search). Within the framework of the Landsat Global Archive Consolidation (LGAC) initiative the USGS is currently collecting all available Landsat scenes from receiving stations around the world and reprocessing them to a common standard. This has large positive impacts on data availability and product generation for glaciers. Plans to process Landsat could benefit from the availability of the Sentinel-2 global mosaic. Common use of up-to-date DEMs for orthorectification of Landsat and Sentinel-2 would introduce greater consistency.

For flow velocity, access to interferometric SAR and optical pairs is necessary with an emphasis on open access for science. The target should be the key glacierized regions of the world with a special emphasis on regions with known surging-type glaciers or other flow instabilities.

For elevation change, improvements in swath altimetry (e.g. Cryosat-2) would be beneficial as well as correction in DEMs for effects of snow density and signal penetration (especially for SAR/radar altimeters).

For snow, product reprocessing is planned in a number of activities already mentioned - see sections above.

NASA JPL have recently undertaken Cryosat-2 processing efforts to produce more accurate ice sheet elevation changes with a focus on improved surface retrieval over the interior parts of the Greenland ice sheet. Further improvements to this product are anticipated given the release of ESA Baseline-C reprocessed data in January 2016[56]. Improvements for Sentinel-3 SRAL processing algorithms for ice sheets are being addressed by the ESA-SEOM Sentinel-3 Performance improvement for ice sheets (SPICE) project. Further results are expected in the upcoming phase II of the project.

Validation, Metadata

In general, all glacier outlines are validated visually by the analyst against the satellite scene used to derive them. In the case of disagreement, they are manually corrected (e.g. for debris, snow, shadow, water). Reporting of validation results or uncertainty assessments in meta-data is not standardized yet.

Missing reference data challenges validation of all glacier-related products. Appropriate reference data are only occasionally available and require careful consideration of inherent differences (e.g. snow conditions for glacier outlines). This is also due to the fact that remote sensing sensors

54 ESA SEOM S1-4Sci Snow project

55 http://www.tandfonline.com/doi/abs/10.1080/01431161.2014.999385

56 https://www.the-cryosphere.net/10/2953/2016/tc-10-2953-2016.pdf

provide information that is complementary to field observations. In consequence, glacier products are provided with an estimate of uncertainty from a range of methods rather than accuracy.

Field measurements of glacier mass balance are periodically inter-compared (and if required calibrated) using geodetic mass budgets over a longer time period (decade) derived from remote sensing. A more systematic distribution of benchmark glaciers, potentially derived using regional elevation differences, would improve representativeness and allow locations for new sites to be identified more effectively.

Elevation data from ICESat are a key dataset for validation of DEMs (off-glaciers) before differencing them and are applied globally for this purpose. ICESat-2 is expected to enhance this globally consistent elevation data source.

Reporting of metadata (e.g. on input datasets, processing methods, spatial coverage, analyst, funding source) is provided for datasets in GLIMS and observational data in the WGMS database on glacier fluctuations, but otherwise not standardized. The best source for this kind of information is a related journal paper.

Continuation of GCW/ESA SnowPEx product intercomparison on a regular basis is planned, and will bring together the snow product providers (e.g. through regular 2– 3–year validation and intercomparison activities)

International coordination of snow measurements from surface networks required for snow product validation is improving through the Global Cryosphere Watch (GCW) 'Snow Watch' working group. At present, only a few countries measure (and publish) SWE in a fashion suitable to be used for satellite validation.

The CRYOSat Validation Experiments (CryoVex) are based on regular field and airborne campaigns to retrieve independent data sets necessary for Cryosat-2 validation, including land ice validation campaigns in Greenland (latest effort October 2016).

NASA's Operation Ice Bridge has also performed underflights of Cryosat-2 and Sentinel-3 for intercomparison of Greenland ice sheet elevation changes[57].

Product Requirements

Frequency

For Glacier area the requirement for annual frequency is unnecessary - with decadal change deemed sufficient; this objective may require more observations within the decade (±5 years of reference year). For elevation change this is opportunistic and depends on DEM availability, quality and characteristics (voids etc.), and cross-matching, and on improvements in altimetric capabilities.

For flow velocity, observations on a sub-annual basis are possible using SAR (e.g. Sentinel-1) and optical sensors (e.g. Sentinel-2 and Landsat) and are important for surge events, other instabilities, and seasonal velocity variations. Optical pairs provide seasonal to annual observations. Both methods are complementary as optical and SAR tend to be better on different parts of the glacier.

Resolution

Resolution is dictated by availability of sensors and their spectral range - higher spatial resolution without key wavebands does not improve delineation for glacier area. 10-30 m is sufficient and will be provided by Landsat, SPOT, and Sentinel-2 series instruments.

Elevation change is dictated by availability of DEMs of appropriate quality over decadal timescales and their quality (especially voids, penetration limits etc.). Swath altimetry would be beneficial if the acquisition and processing could be improved for regions of high topography.

57 e.g. http://www.sciencedirect.com/science/article/pii/S0034425716304916

Operational snow extent products are generated using MODIS, AVHRR and VIIRS data (1 km and less) and Snow Water Equivalent (SWE) can be retrieved using passive microwave radiometers (< 25 km).

Uncertainty

Uncertainty of the estimation of area is dominated by the need for manual intervention in determining the glacier boundary. Inter-comparisons between operators gives some idea of its impact on final results.

State of the art SE retrieval performance of about 10-15 % is achieved on hemispherical scale, while for SWE the retrieval performance (hemispheric scale) is about 30 mm for shallow snow; 40 mm for most terrestrial snow conditions (shallow & deep snow).

Accuracy and Precision

Accuracy is difficult to assess given the limited availability of reference measurements. Assessment is generally against other products with their own limitations and hence is not translatable into an absolute accuracy, although uncertainties are provided in SI units. For elevation change and ice velocity accuracy can in some cases be defined fairly well (e.g. for DEM differences and velocities using stable ground, dense time series etc.).

The Global Cryosphere Watch SnowPEx initiative has led the determination of the retrieval accuracy of both SE and SWE datasets; while these efforts are still ongoing, there is now a quantitative baseline of SE and SWE inter-product agreement, performance, and constraints. Some significant disagreement in long-term trends between available snow CDRs has been identified and needs to be resolved. The efforts of SnowPEx are based on input and participation from the international snow remote sensing community, and this activity should be sustained.

Synergistic assessment/study of both SE and SWE is needed, and has been identified as a topic for a potential ESA SnowPEx follow-on.

Stability

Stability of observations is not yet considered. In some cases, accuracy assessment is a qualitative exercise since some sources of error lead to large qualitative uncertainties (e.g. presence of snow in an image from which glacier area is being mapped.

Length of Record

The record for glacier area can be extended back to 1980s with Landsat TM and to the 1960s if the Corona/Hexagon collection is opened including full reprocessing of the archive (e.g. for geolocation).

Snow Extent (SE) can be reliably detected using optical remote sensing means. Historical time series exist since 1967 (NOAA CDR, including weekly (1967-1999) and daily (1999-ongoing)) and since 1980 (AVHRR-based datasets). MODIS, AVHRR and VIIRS data are widely used for generating operational SE products.

Snow Water Equivalent (SWE) can be retrieved using passive microwave radiometers, but a first guess snow depth field generated from surface weather station observations is required (e.g. ESA GlobSnow). Historical time series is available since 1980.

4.4.4 Biosphere

> Ensure the consistency of the various radiant energy fluxes (T35).

The "system" that CEOS Working Group on Calibration Validation, Land Product Validation subgroup (WGCV LPV) is developing to meet this action to establish product data flows is the Land Product Characterization System (LPCS) being developed by NOAA and USGS, plus the Online Validation (OLIVE) tool for performing leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (FAPAR) product inter-comparisons. LPCS allows inter-comparison of higher-level data products derived from multiple sensors, and both systems enable comparison with *in situ* measurements.

Radiometric consistency of satellite-based land surface products (e.g. albedo, FAPAR, LAI) is being addressed through various approaches, including the assimilation multi-sensor satellite data into land surface models. Intercomparison of global products is routinely performed through methods such as triple collocation. Comparison of medium resolution (1 km) global satellite products with ground-based validation data is complicated by spatial heterogeneity within the satellite image pixels, but is being addressed through upscaling using higher resolution satellite data which is becoming much more widely available. Uncertainty estimates are now standard elements of satellite products and need to be validated as well.

Quality of Ground-Based Reference Sites for FAPAR and LAI (Action T37), Improve *in situ* albedo measurements (T39).

The WGCV LPV can recommend, or point to, current best practices for assessing the suitability of ground-based sites for the purposes of satellite product validation. This is already a task within each LPV validation protocol: more recently for LAI, and upcoming parameters such as Albedo and Land Surface Temperature[58]. As part of its ongoing efforts WGCV LPV is examining the quality of the sites that have been used to date for calibration and validation with the intention of identifying a set of core validation sites across all its current components groups. This includes consideration of the long-term viability of the site.

Production of CDRs for LAI, FAPAR, and Albedo (Action T40), Evaluate LAI, FAPAR, and Albedo (Action T41)

Daily albedo composited products are currently produced over all land surfaces and shallow continental shelves by single instruments or by fusion of multiple instruments, including both broad-band and spectral albedo and for polar regions. These composite products can be continued into the future with data from existing operational satellite missions. Future continuation of instantaneous products that capture rapid land surface variability will require new, and as yet unplanned, multi-angular instruments.

Over the past two decades, a number of global moderate resolution LAI products have been produced with MODIS, MISR and GEOV1 produced operationally. Improvements in the quality of these products are necessary, specifically in algorithm performance, specification of uncertainty and optimisation for the temporal and spatial resolution of forthcoming missions. Further validation efforts are required to address the inadequacy in current validation, with a focus on the temporal behaviour of LAI products (see T1, T3, T37).

As with LAI a number of FAPAR datasets have been produced over the last two decades e.g. global FAPAR algorithms JRC-TIP, ESA/JRC MGVI and MODIS FAPAR. Since 2014 the Copernicus Global Land Service (CGLS) produces systematically LAI and FAPAR globally in coarse (1 km) and medium (300m) resolution based on Proba-V and SPOT-VGT. Differences in FAPAR estimates especially over forest highlight the importance of assumptions on structure and optical properties of land surfaces in remote-sensing-derived FAPAR products. Standardization frameworks quantifying the impact of different radiative transfer formulations on the estimation of FAPAR, independent uncertainty estimation methods and well-defined ground measurement protocols are all needed to improve FAPAR products[59]. Validation challenges include the need for a global

58 https://lpvs.gsfc.nasa.gov

59 D'Odorico et al. 2014, http://dx.doi.org/10.1016/j.rse.2013.12.005

distribution of spatially representative site locations; supported by global networks. The development and use of new measurement system such as wireless sensor networks[60] will help in this direction.

> Production of land surface temperature datasets (Action T43), Reprocessing land surface temperature (Action T44), Land surface temperature radiometric calibration (Action T46); Land-surface temperature: *in situ* protocols (Action T42), Land-surface temperature *in situ* network expansion (Action T45).

Collectively these actions would result in the development and provision of a suite of consistent, well-validated multi-mission land surface temperature (LST) products. Standard protocols for LST validation have been defined and are being widely adopted in Space Agency projects with the aim of providing consistent validation across multiple LST products. International science teams are being supported by the agencies to ensure coordination between different validation efforts. Future thermal infrared satellite data for global-scale LST production is assured via the existing operational polar and geostationary satellite programmes, but there is a lack of future continuity for passive microwave satellite data suitable for LST retrieval. Production of global long-term LST data sets is supported by several agency projects. Infrastructure for the ground-based validation of satellite LST is limited to just a few high-quality stations. There is still a need to expand the existing network, particularly into different land surface types. Current efforts to set up calibration and intercomparison exercises across this network need to be supported in the long-term.

> Land cover experts (Action T47), Annual land cover product (Action T48), Land cover change (Action T49), Land cover community consensus (Action T50), Deforestation (Action T51)

Annual land cover products have been produced by both NASA and ESA (LandCover_cci). The former is offered at 500m resolution and the latter at 300m. The validity of the latter has been tested by a network of land cover experts each contributing land cover interpretations for testing against the official product. Since it is unwise to address land cover change by comparison of individual land cover maps (based on the global accuracy and accuracy of individual classes), an alternative method has been adopted whereby the seasonal cycle of vegetation growth as indicated by the Normalised Vegetation Index is also provided. This allows an observed change to be confirmed through the consistency of the vegetation phenology.

The land cover community is increasingly converging on a consensus for specification of land cover, primarily focussing on two approaches a) the consistency with previous land cover classifications offered by IGBP scheme b) consistency with schemes established *in situ* and the associated cross-talk offered by the FAO Land Cover Classification System (LCCS). Both methods have been the subject of considerable work to cross-walk to Plant Functional Types required by Earth System models.

Deforestation and degradation requires higher resolution than that offered by moderate resolution sensors - approaches have been made to use the Landsat archive to extract information on both[61]. In additional considerable effort has been dedicated to understanding forest change through the Global Forest Observations Initiative (GFOI) where method and guidance were developed to provide methodological advice for countries wishing to make use of remotely sensed and ground-based data for forest monitoring and REDD+ reporting[62].

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60 http://www.enviro-net.org

61 Hansen et al. 2013 10.1126/science.1244693

62 http://www.gfoi.org/methods-guidance-documentation

Collaboration on above ground biomass (Action T52), Above ground biomass validation strategies (Action T53), Above ground biomass validation sites (Action T54), Above ground biomass data access (Action T55), Above ground biomass: forest inventories (Action T56)

Approaches to estimate aboveground biomass have been implemented by both NASA and ESA resulting in the production of biomass estimates primarily for forested regions. These estimates have been intercompared and while the overall values of biomass are consistent the spatial patterns are not. Satellite sensors are under development by both NASA (GEDI and, with ISRO, NISAR) and ESA (BIOMASS). Close collaboration has been established at the science level and also through discussion of collaborative activities. GEDI, a lidar, is due to be placed on the ISS while BIOMASS, a P-band radar, will be polar orbiting.

As part of these developments a partnership has been established with *in situ in situ* networks through the International Forest Biomass Network e.g. through the preparation of the BIOMASS mission with airborne campaigns e.g. AfriSAR and application projects like GlobBiomass, which is intended to continue through Biomass_cci. This provides a platform for discussion and collaboration with the *in situ* networks e.g. RAINFOR, AfriTRON, Smithsonian Institute. A future requirement on the Space Agencies is to improve the validity and spatial distribution of samples provided by these networks in coordination with these *in situ* teams to ensure the inventories are appropriate and supported long term to allow them to act as validation networks for both GEDI and BIOMASS.

Activities for intercomparison and integration of model-data like the International Land Model Benchmarking (ILAMB) project[63] are important to improve the performance of land models and, in parallel, improve the design of new measurement campaigns to reduce uncertainties associated with key land surface processes.

Historic fire data (Action T60), Operational global burned area and FRP (Action T61), Fire maps (Action T62), Fire validation (T63), Fire disturbance model development (T64).

For burned area observation continuity is assured through operational meteorological and environmental satellite programmes e.g. Copernicus supported by higher resolution data provision through Sentinel-2 MSI and Landsat OLI in the optical domain and SAR (e.g. Sentinel-1) for cloud covered regions. Very high-resolution imaging is a burgeoning commercial domain through e.g. Planet, Pleiades and in the SAR domain e.g. Cosmo-SkyMed, TerraSAR-X. Similarly, geostationary meteorological missions (MSG, MTG, GOES, Himawari etc.) and environmental satellite programmes e.g. Sentinel-3 SLSTR and JPSS/VIIRS with research support from MODIS, Landsat, ASTER and FireBIRD.

NASA has issued revisions to Burned area products are available from NASA, ESA (Fire_cci) and Copernicus, while FRP and active fire algorithms come from MODIS, Copernicus and EUMETSAT. These developments have brought the resolution for burned area down towards the GCOS requirement of 250m. Work on extending records back to 1982 through the consistent AVHRR record is ongoing using the NASA/NOAA LTDR record (ESA/CCI).

High spatial resolution products are also under development by both ESA and USGS using Landsat and Sentinel-2. This will help understand the impact of small fires, not detected by e.g. MODIS on emissions estimates. A major challenge remains uncertainty characterisation for burned areas along with activities on merging of existing products from moderate resolution satellite sensors. An approach to validation has been defined (WGCV-LPV Best Practices) and is being implemented and improved under ESA/CCI and NASA along with improvements in global burned area validation data spatial and temporal coverage.

[63] https://www.ilamb.org/

Fire shows a very strong diurnal cycle, so this must be considered when developing long-term active fire and FRP datasets from merging of data from multiple missions that may have different local overpass times.

4.4.5 Human Use of Natural Resources

Use of satellites for LULUCF emissions/removals (T68).

Satellite images provide spatially explicit tracking of land-use conversions over time and help to identify agricultural, silviculture and other land use activities. These activity data together with emission factors, either using IPCC default values or dedicated *in situ* knowledge provide estimates of overall emissions.

Systematic and frequent acquisitions from optical sensors like Landsat or Sentinel-2 (in 10 m – 30 m geometric resolution) enable the detection of LULUC in great detail. In most cases estimates of emissions and removals will be made using a combination of remotely sensed and ground based data. Landsat satellites provide a time series of remotely sensed digital images spanning 40 years and are being used widely in monitoring LULUF activities. The Sentinel-2 satellites increase the observation frequency and provide more detail. Joint working groups from ESA, NASA and USGS work on an improved interoperability of these datasets, which is a prerequisite for long-term analyses; e.g. reprocessing of the Landsat archive including Sentinel-2's Global Reference Image.

SAR data are complementary to the optical sensors and are particularly useful in areas of persistent cloud cover. With their capability to penetrate the vegetation cover, radar can provide estimates of biomass, where larger wavelengths saturate at higher biomass levels than shorter ones (e.g. L-band SAR (JERS, ALOS) has greater sensitivity to biomass than C-band (Envisat, Sentinel-1)), but still saturates at biomass levels of about 100 tons per hectare. Nevertheless, the accuracy levels are currently insufficient for use for GHG inventory estimates. New mission concepts like NASA's GEDI (high resolution lidar system on the ISS) or ESA's BIOMASS (first P-band radar in space) will improve the capability to estimate above-ground biomass from space in the future.

UNFCCC has recognized in its Paris Agreement the valuable information satellites data can provide for an accurate and transparent assessment of emission estimation. Mechanisms like REDD+ (Reducing Emissions from Deforestation and forest Degradation in developing countries, conservation of forest carbon stocks, sustainable management of forest land, enhancement of forest carbon stocks) are increasingly taking the use of satellite data into account. (GOFC-GOLD REDD+ Source Book[64], GFOI MGD and REDDcompass[65]). Finally, IPCC is working currently on a refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for 2019 were satellite data are expected to play an increasing role.

Prepare for a carbon monitoring system (T71).

Taking advantage of the remarkable achievements resulting from a number of satellites in recent years (e.g. SCIAMACHY, GOSAT, OCO-2, TanSat) in elucidating the synoptic distribution of greenhouse gas distribution over the last decade, CEOS, CGMS and their member agencies are coordinating a joint response to the Paris Agreement (COP-21).

Space Agencies recognise that high-quality greenhouse gas observations will be essential to track progress towards the achievement of Nationally Determined Contributions (NDCs) and for stocktaking, and recognise the added value of these observations, when combined with ground

64 http://www.gofcgold.wur.nl/redd/

65 http://www.gfoi.org/methods-guidance-documentation

based measurements and models (inversion and transport) through a fully integrated system in supporting the Transparency Framework.

Specifically, CEOS and CGMS will undertake, over the next few years, dedicated preparatory work in a coordinated international context, to provide cumulative added value to the specific programmatic activities of their member agencies. These activities will include:

- The definition of an architecture of space component elements to address the requirements of a CO_2 and GHG monitoring system, taking advantage of the existing competence of the CEOS Atmospheric Composition Virtual Constellation. This will provide a global holistic perspective both from the point of view of existing and planned space segment assets as well and that for an optimum global constellation.
- The documentation of best practices on the relationships between individual Space Agencies and their counterparts working on the modelling aspects, the inventories and *in situ* data provision, to better refine the required interfaces for the overall system implementation.
- The further consolidation of partnerships and collaborations between the relevant international entities including: the relationship between CEOS and CGMS on the space component aspects, the partnership with the WMO and GEO on the broader framework, and with specific attention on their possible role in coordinating the *in situ* data networks, and finally the relationships with GCOS itself, UNFCCC and IPCC TFI process in better defining the role for space-based observation in the inventory guideline process.

These efforts will continue to be implemented in the broader context of the comprehensive CEOS Strategy for Carbon Observations from Space, which is pursuing additional relevant activities to better constrain the natural carbon fluxes.

The agencies of CEOS and CGMS are endeavouring to advance the state of the art of prototype realisations of these integrated systems on timescales that are beneficial to the first Global Stocktake in 2023, with potential operational implementation of such systems (e.g. through the European Union's Copernicus Programme) around 2030.

Annex A. Acronyms

3D	Three Dimensional
BAMS	Bulletin of American Meteorological Society
BelSpo	Belgian Federal Science Policy Office
ABI	Advanced Baseline Imagers
ACE-FTS	Atmospheric Chemistry Experiment-Fourier Transform Spectrometer
ACP	UN African, Caribbean and Pacific (ACP) partner countries
ADM-Aeolus	ESA Atmospheric Dynamics Mission Aeolus
AERONET	Aerosol Robotic Network
AfriTRON	African Tropical Rainforest Observation Network
ALOS	Advanced Land Observing Satellite
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AMSR2	Advanced Microwave Scanning Radiometer 2 for GCOM
AMV	Atmospheric Motion Vector
AOD	Aerosol Optical Depth
AR	IPCC Assessment Report
ASCAT	Advanced Scatterometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASTER GDEM	ASTER Global Digital Elevation Map
AVHRR	Advanced Very High Resolution Radiometer
BIRD	Bi-Spectral Infrared Detection
BSRN	Baseline Surface Radiation Network
BUFR	Binary Universal Form for the Representation of Meteorological Data
C3S	Climate Change Service
CAS	Chinese Academy of Sciences
CCI	ESA Climate Change Initiative
CCI	WMO Commission for Climatology
CCI+	Extension to the ESA Climate Change Initiative
CDR	Climate Data Record
CERN	Chinese Ecosystem Research Network
CGLS	Copernicus Global Land Service
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
C-GTOS	Coastal-GTOS
CH4	Methane
CMA	China Meteorological Administration
CMRS	Climate Monitoring, Research and Service
CM SAF	Satellite Application Facility on Climate Monitoring
CNES	Centre National D'études Spatiales
CNSA	China National Space Administration
CONAE	Comision Nacional de Actividades Espaciales

COP	Conference of the Parties
CO	Carbon Monoxide
CO2	Carbon Dioxide
CryoVex	CryoSat Validation Experiments
DARF	Direct Aerosol Radiative Forcing
DEM	Digital Elevation Map
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOI	Digital Object Identifier
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DMSP	The Defense Meteorological Satellite Program
EarthCARE	Earth Cloud Aerosol and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EMEP	European Monitoring and Evaluation Programme
EO	Earth Observation
EOS	Earth Observing System platforms
EOS AQUA	Earth Observing System Aqua platform
EPS	EUMETSAT Polar System
EPS-SG	EPS Second Generation
ERB	Earth Radiation Budget
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAO	Food and Agriculture Organization
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCDR	Fundamental Climate Data Record
FMI	Finnish Meteorological Institute
FRP	Fire Radiative Power
FY3C	FengYun-3 C
FY3D	FengYun-3 D
GAIA-CLIM	Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring
GALION	GAW Aerosol Lidar Observation Network
GAS	Greenhouse-gases Absorption Spectrometer
GAW	Global Atmosphere Watch
GCI	GEOSS Common Infrastructure
GCOM	Global Change Observation Mission (JAXA)
GCOS	Global Climate Observing System
GCOS IP	GCOS Implementation Plan
GCW	Global Cryosphere Watch
GDR	Geophysical Data Record
GEDI	Global Ecosystem Dynamics Investigation
GEO	Group on Earth Observations
GEOV1	Geoland2
GEO	Geosynchronous Earth Orbit

GEOSS	Global Earth Observation System of Systems
GEWEX	Global Energy and Water Cycle Experiment
GF5	Gao Fen 5
GFCS	Global Framework for Climate Services
GFOI	Global Forest Observations Initiative
GHG	Greenhouse Gas
GHRSST	Global High-Resolution Sea Surface Temperature Project
GLIMS	Global Land Ice Measurements from Space
GMI	GPM's Microwave Imager
GNSS	Global Navigation Satellite System
GODAE	Global Ocean Data Assimilation Experiment
GOES	Geostationary Operational Environmental Satellite
GOFC-GOLD	Global Observation of Forest and Land Cover Dynamics
GOSAT	Greenhouse Gases Observing Satellite
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Measurement mission
GPS	Global Positioning System
GRACE-FO	Gravity Recovery and Climate Experiment Follow-on
GRUAN	GCOS Reference Upper-Air Network
GSICS	WMO Global Space-based Inter-Calibration System
GSN	GCOS Surface Network
GTN-G	Global Terrestrial Network for Glaciers
GTN-H	Global Terrestrial Network for Hydrology
GTN-L	Global Terrestrial Network for Lake Level/Area
GTN-P	Global Terrestrial Network for Permafrost
GTN-R	Global Terrestrial Network for River Discharge
GTOS	Global Terrestrial Observing System
GUAN	GCOS Upper Air Network
HCHO	Formaldehyde
HY	Hai Yang
HYDROLARE	International Data Centre on Hydrology of Lakes and Reservoirs
HYDROWEB	International Association for Environmental Hydrology
ICDR	Interim Climate Data Record
ICOS	Integrated Carbon Observation System
ICSU	International Council for Science
iLAMB	International Land Model Benchmarking
ILSTE	International Land Surface Temperature and Emissivity Working Group
IMS	Interactive Multisensor Snow and Ice Mapping System
INPE	Instituto Nacional de Pesquisas Espaciais
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IPMA	Instituto Português do Mar e da Atmosfera
IPWG	International Precipitation Working Group

iQUAM	*In situ* SST Quality Monitor
IR	Infrared
ISRO	Indian Space Research Organisation
ISS	International Space Station
iSWGR	International Snow Working Group-Remote Sensing
JAXA	Japan Aerospace Exploration Agency
JRC-TIP	Joint Research Centre Two-stream Inversion Package
JERS	Japanese Earth Resources Satellite
JPL	NASA Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JRC	Joint Research Centre
KMA	Korea Meteorological Administration
LAI	Leaf Area Index
LCCS	Land Cover Classification System
LGAC	Landsat Global Archive Consolidation
LEO	Low Earth orbit
LIDAR	Light Detection and Ranging
LPCS	Land Product Characterization System
LPV	Land Product Validation
LIS	Lightning Imaging Sensor
LS	Lower Stratosphere
LST	Land Surface Temperature
LSWT	Lake Surface Water Temperature
LTDR	Land Long Term Data Record
LULUCF	Land Use, Land-Use Change and Forestry
MAESTRO	Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation
MEA	Multilateral Environmental Treaty
MERIS	Medium Resolution Imaging Spectrometer
MGD	Methods & Guidance Documentation
MGVI	MERIS Global Vegetation Index
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOE	Ministry of the Environment
MOST	Ministry of Science and Technology
MSI	MultiSpectral Instrument
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
MW	Microwave
N2O	Nitrous Oxide
NASA	National Aeronautics and Space Administration
NED	National Elevation Dataset
NEON	National Ecological Observatory Network
NESDIS	National Environmental Satellite, Data, and Information Service

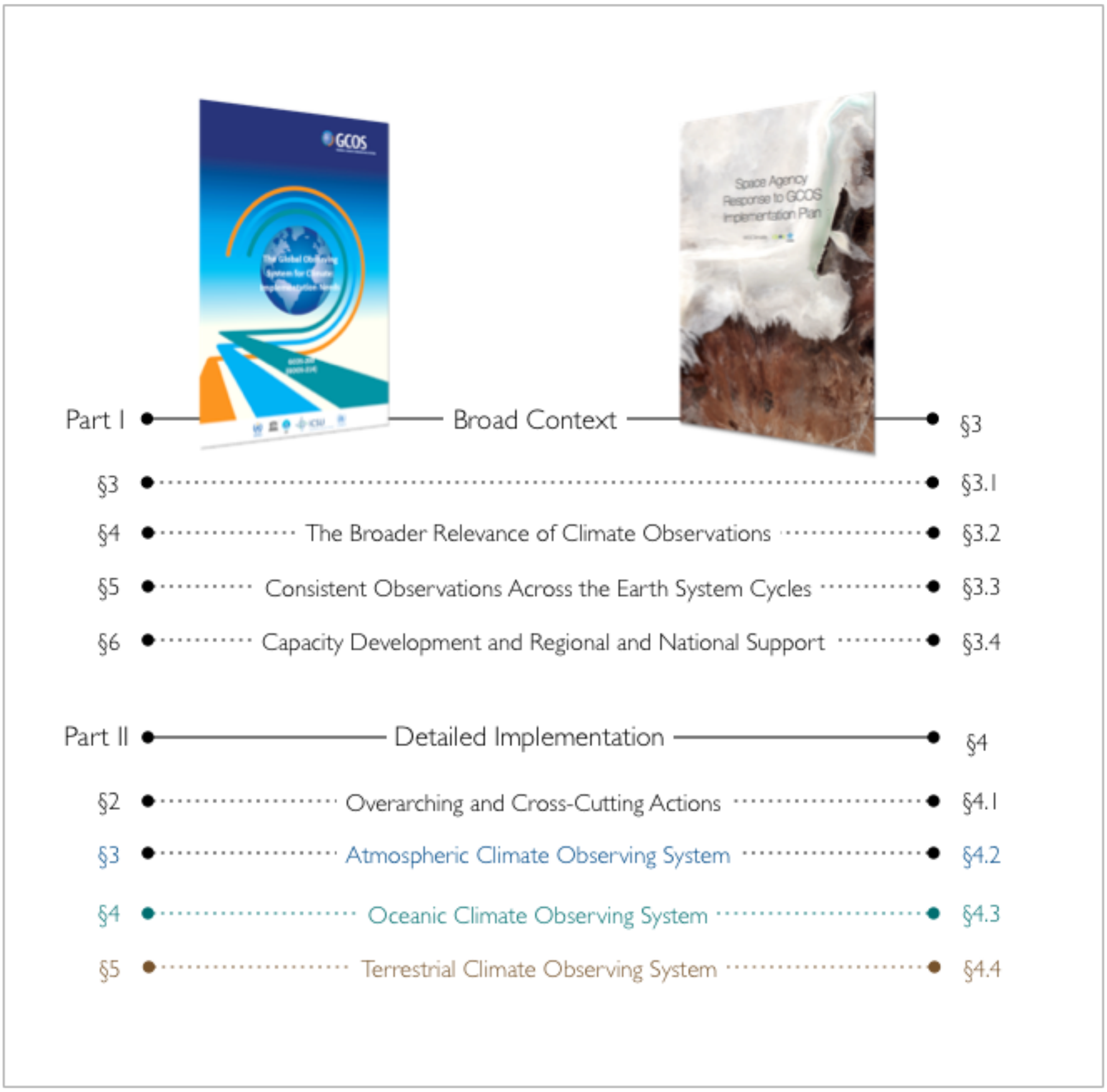
NISAR	NASA-ISRO Synthetic Aperture Radar
NMI	National Metrology Institute
NIES	National Institute for Environmental Studies (NIES)
NIR	Near-Infrared
NCEO	National Centre for Earth Observation
NDAAC	Network for the Detection of Atmospheric Composition Change
NGGM	Next Generation Gravity Mission
NH3	Ammonia
NO2	Nitrogen Dioxide
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NSIDC	National Snow and Ice Data Center
NSO	Netherlands Space Office
NWP	Numerical Weather Prediction
O3	Ozone
OC	Ocean Colour
OCO-2	Orbiting Carbon Observatory-2
OLI	Operational Land Imager
OLIVE	On-Line Interactive Validation Exercise
OLR	Outgoing Longwave Radiation
OSIRIS	Optical Spectrograph and InfraRed Imager System
OSSE	Observing System Simulation Experiments
PALSAR	Phased Array type L-band Synthetic Aperture Radar
pCO2	Partial Pressure of Carbon Dioxide
PO.DAAC	Physical Oceanography Distributed Active Archive Center
PPB	Parts Per Billion
PPBV	Parts Per Billion By Volume
PPM	Parts Per Million
RAINFOR	Amazon Forest Inventory Network
REAS	Regional Emission inventory in Asia
RCC	WMO Regional Climate Centre
REDD+	Reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (UNFCCC)
RFI	Radio Frequency Interference
RGI	Randolph Glacier Inventory
RO	Radio Occultation
SAC-D	Satélite de Aplicaciones Científicas-D
SAGE	Stratospheric Aerosol Gas Experiment
SAR	Synthetic Aperture Radar
SBSTA	Subsidiary Body for Scientific and Technological Advice
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SCOPE-CM	Sustained and Coordinated Processing of Environmental satellite data

	for Climate Monitoring
SDG	Sustainable Development Goals
SE	Snow Extent
SEOM	Scientific Exploitation of Operational Missions
SEVIRI	MSG Spinning Enhanced Visible and Infrared Imager
SF6	Sulfur Hexafluoride
SI	Système International; International System of Units
SIF	Solar-induced Fluorescence
SLSTR	Sea and Land Surface Temperature Radiometer
SMAP	Soil Moisture Active-Passive
SMMR	Nimbus-7 Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SnowPEx	Satellite Snow Product Intercomparison and Evaluation Exercise
SO2	Sulfur Dioxide
SPICE	ESA-SEOM Sentinel-3 Performance improvement for Ice Sheets
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SSH	Sea Surface Height
SSMI	Special Sensor Microwave Image
SSMIS	Special Sensor Microwave Imager/Sounder
SSS	Sea-surface Salinity
SST	Sea Surface Temperature
SW	Short Wave
SWE	snow water equivalent
SWIR	Short Wave Infrared
SWOT	Surface Water & Ocean Topography mission
SYNOP	Surface Synoptic Observations
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement
TBC	To Be Confirmed
TCCON	Total Carbon Column Observing Network
TCDR	Thematic Climate Data Record
TERN	Terrestrial Ecosystem Research Network: Climate
TFI	IPCC Task Force on National Greenhouse Gas Inventories
TIR	Thermal infrared
TM	Thematic Mapper
TOA	Top-of-Atmosphere
TOPEX	Ocean Topography Experiment,
TRMM	Tropical Rainfall Measuring Mission
USGS	United States Geological Survey
UT	Upper Troposphere
UN	United Nations
UK	United Kingdom
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific, and Cultural Organization

UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USGS	United States Geological Survey
UT	Upper Troposphere
VGT	Vegetation
VIRR	Visible and Infrared Radiometer
VIRRS	Visible Infrared Imaging Radiometer Suite
VIS	Visible Imaging Spectrometer
Vlab	WMO-CGMS Virtual Laboratory for Education and Training in Satellite Meteorology
WCOM	Water Cycle Observation Mission
WGClimate	The Joint CEOS/CGMS Working Group on Climate
WGCV	CEOS Working Group on Calibration & Validation
WGISS	CEOS Working Group on Information Systems and Services
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organization
XCTD	Expendable Conductivity Temperature Depth
XBT	Expendable Bathythermograph

Annex B. Mapping from GCOS IP to Space Agency Response

This Annex provides a mapping from the GCOS IP to the content herein, and comprises (1) document mapping from GCOS Implementation Plan (GCOS 200) sections to sections of this document, and (2) an Actions map denoting all relevant GCOS Actions responded herein.



GCOS IP			➔	Space Agency Response	
Adaptation (§3.1)	G1	Guidance and best practice for adaptation observations	-	§3.1.1	Adaptation
	G2	Specification of high-resolution data	-	§3.1.1	Adaptation
Climate Indicators (§3.3)	G3	Development of indicators of climate change	-	§3.1.2	Climate Indicators
	G4	Indicators for Adaptation and Risk	-	§3.1.2	Climate Indicators
Sendai Framework (§4.4)	G5	Identification of global climate observation synergies with other Multilateral Environmental Agreements (MEA)			
GCOS Cooperating Mechanism (§6.1)	G6	Assisting Developing Countries to maintain or renovate climate observation systems and to improve climate observations networks			
National Coordination (§6.2)	G7	GCOS Coordinator			
Regional Activities (§6.3)	G8	Regional Workshops			
Information & Communication (§6.4)	G9	Communications strategy			
Requirements for Climate Observations (§2.1)	G10	Maintain ECV Requirements			
Planning, Review & Oversight (§2.2)	G11	Review of CDR availability	-	§4.1.1	Planning, Review & Oversight
	G12	Gap-analysis of CDR	-	§4.1.1	Planning, Review & Oversight
	G13	Review of ECV observation networks			
	G14	Maintain and Improve Coordination			
Data Management, Stewardship & Access (§2.3)	G15	Open Data Policies	-	§4.1.2	Data Management, Stewardship & Access
	G16	Metadata			
	G17	Support to National Data Centres			
	G18	Long-term accessibility of data			
	G19	Data access and discoverability			
	G20	Use of Digital Object Identifier for data records	-	§4.1.2	Data Management, Stewardship & Access
	G21	Collaboration with WMO CCl on climate data management			
Production of Integrated ECV Products (§2.4)	G22	Implementation of new production streams in global reanalysis	-		
	G23	Develop coupled reanalysis			
	G24	Improve capability of long-range reanalysis			
	G25	Implementation of regional reanalysis			
	G26	Preservation of early satellite data	-	§4.1.3	Production of Integrated ECV Products
	G27	Recovery of instrumental climate data			
	G28	Register of data recovery activities			
	G29	Scanned records			
	G30	Historical data records sharing			
Ancillary & Additional Observations (§2.5)	G31	Improve Gravimetric Measurements form Space	-	§4.1.4	Ancillary & Additional Observations
	G32	Improved Bathymetry	-	§4.1.4	Ancillary & Additional Observations
Atmospheric Domain - Near-Surface Variables (§3.1)	A1	Historical GSN availability			
	A2	Land database			
	A3	International exchange of SYNOP and CLIMAT reports			
	A4	Surface Observing stations transition to automatic			

	A5	Transition to BUFR			
	A6	Air temperature measurements			
	A7	Atmospheric pressure sensors on drifting buoy			
	A8	Provide precipitation data to the Global Precipitation Climatology Centre			
	A9	Submit Water Vapour data			
	A10	National sunshine records into Data Centres			
	A11	Operation of the BSRN	-	§4.2.3	Satellite Data Calibration, Validation and Reprocessing
	A12	Surface Radiation Data into WRDC			
Atmospheric Domain - Upper-Air (§3.2)	A13	Implement vision for future of GUAN operation			
	A14	Evaluation of benefits for GUAN			
	A15	Implementation of GRUAN	-	§4.2.3	Satellite Data Calibration, Validation and Reprocessing
	A16	Implementation of satellite calibration missions	-	§4.2.3	Satellite Data Calibration, Validation and Reprocessing
	A17	Retain original measured values for radiosonde data			
	A18	Hyperspectral radiances reprocessing	-	§4.2.3	Satellite Data Calibration, Validation and Reprocessing
	A19	AMV reprocessing	-	§4.2.1	Atmospheric Dynamics, Energy and Water Cycle Components
	A20	Increase the coverage of aircraft observations			
	A21	Implementation of space-based wind profiling system	-	§4.2.1	Atmospheric Dynamics, Energy and Water Cycle Components
	A22	Develop a repository of water vapour CDRs	-	§4.2.2	Atmospheric Composition Including Greenhouse Gases
	A23	Measure of water vapour in the UT/LS			
	A24	Implementation of archive for radar reflectivities			
	A25	Continuity of global satellite precipitation products	-	§4.2.1	Atmospheric Dynamics, Energy and Water Cycle Components
	A26	Development of methodology for consolidated precipitation estimates	-	§4.2.1	Atmospheric Dynamics, Energy and Water Cycle Components
	A27	Dedicated satellite ERB mission	-	§4.2.1	Atmospheric Dynamics, Energy and Water Cycle Components
	A28	*In situ* Profile and Radiation			
	A29	Lightning	-	§4.2.1	Atmospheric Dynamics, Energy and Water Cycle Components
Atmospheric Domain - Composition (§3.3)	A30	Water vapour and ozone measurement in UT/LS and upper stratosphere	-	§4.2.2	Atmospheric Composition Including Greenhouse Gases
	A31	Validation of satellite remote sensing	-	§4.2.3	Satellite Data Calibration, Validation and Reprocessing
	A32	FDCRs and CDRs for GHG and aerosols ECVs	-	§4.2.2	Atmospheric Composition Including Greenhouse Gases
	A33	Maintain WMO GAW CO2 and CH4 monitoring networks			
	A34	Requirements for *in situ* column composition measurements			
	A35	Space-based measurements of C02 and CH4 implementation	-	§4.2.2	Atmospheric Composition Including Greenhouse Gases
	A36	N2O, halocarbon and SF6 networks/measurements	-	§4.2.3	Satellite Data Calibration, Validation and Reprocessing
	A37	Ozone networks coverage	-	§4.2.2	Atmospheric Composition Including Greenhouse Gases

	A38	Submission and dissemination of ozone data			
	A39	Monitoring of aerosols properties	-	§4.2.2 §4.2.3	Atmospheric Composition Including Greenhouse Gases Satellite Data Calibration, Validation and Reprocessing
	A40	Continuity of products of precursors of ozone and secondary aerosols	-	§4.2.2	Atmospheric Composition Including Greenhouse Gases
Oceanic Domain - Overview (§4.1)	O1	Coordination of enhanced shelf and coastal Observations for climate			
	O2	Integration and Data Access			
	O3	Data Quality			
	O4	Development of climatologies and reanalysis products			
	O5	Sustained support for ocean observations			
	O6	Technology development			
	O7	Observing System development and evaluation			
Oceanic Domain - Physical (§4.2)	O8	Satellite SST Product Development	-	§4.3.1	(Oceanic) Physical - Sea Surface Thermodynamic State
	O9	Upper ocean temperature observing system	-	§4.3.3	(Oceanic) Physical - Sea Level
	O10	Full depth temperature observing system			
	O11	Ocean salinity observing system	-	§4.3.4	(Oceanic) Sea Surface Salinity
	O12	Ocean current gridded products	-	§4.3.2	(Oceanic) Physical - Sea Surface Dynamic State
	O13	Sea level observations	-	§4.3.3	(Oceanic) Physical - Sea Level
	O14	Contributing to Sea State climatologies			
	O15	*In situ* sea ice observations			
	O16	Ocean Surface Stress observations.	-	§4.3.2	(Oceanic) Physical - Sea Surface Dynamic State
	O17	Ocean surface heat flux observing system	-	§4.3.1	(Oceanic) Physical - Sea Surface Thermodynamic State
Oceanic Domain - Biogeochemistry (§4.3)	O18	Surface pCO2 moorings			
	O19	Building multidisciplinary timeseries.			
	O20	Nutrient observation standards and best practices.			
	O21	Sustaining tracer observations.			
	O22	Develop sustained N2O observations			
	O23	*In situ* ocean colour radiometry data	-	§4.3.5	(Oceanic) Biochemistry & Biology / Ecosystems
	O24	Ocean Colour algorithm development.	-	§4.3.5	(Oceanic) Biochemistry & Biology / Ecosystems
Oceanic Domain - Biology / Ecosystems (§4.4)	O25	Satellite based phytoplankton biomass estimates	-	§4.3.5	(Oceanic) Biochemistry & Biology / Ecosystems
	O26	Expand Continuous Plankton Recorder and Supporting observations.			
	O27	Strengthened network of Coral Reef observation sites.			
	O28	Global networks of observation sites for Mangroves, Seagrasses, Macroalgae.			
Oceanic Domain - Key Elements of the Sustained Ocean Observing System for Climate (§4.5)	O29	*In situ* data for satellite calibration and validation.	-	§4.3.1 §4.3.2 §4.3.4	(Oceanic) Physical - Sea Surface Thermodynamic State (Oceanic) Physical - Sea Surface Dynamic State (Oceanic) Sea Surface Salinity
	O30	Satellite SST by passive microwave	-		

	O31	Satellite SSH	-	§4.3.1 §4.3.3	(Oceanic) Physical - Sea Surface Thermodynamic State (Oceanic) Physical - Sea Level
	O32	Satellite SSS	-	§4.3.4	(Oceanic) Sea Surface Salinity
	O33	Satellite Sea State	-	§4.3.2	(Oceanic) Physical - Sea Surface Dynamic State
	O34	Satellite Ocean Surface Stress	-	§4.3.2	(Oceanic) Physical - Sea Surface Dynamic State
	O35	Satellite Sea Ice	-	§4.3.1	(Oceanic) Physical - Sea Surface Thermodynamic State
	O36	Satellite Ocean Colour	-	§4.3.5	(Oceanic) Biochemistry & Biology / Ecosystems
	O37	Argo Array			
	O38	Development of a BioArgo Array			
	O39	Development of a Deep Argo Array			
	O40	GO-SHIP			
	O41	Develop fixed point time series			
	O42	Maintain the Tropical Moored Buoy system			
	O43	Develop time-series based biogeochemical data			
	O44	Meteorological Moorings.			
	O45	Wave Measurements on moorings			
	O46	Observations of Sea Ice from buoys and visual survey			
	O47	Sustain drifter array			
	O48	Underway observations from Research and Servicing Vessels			
	O49	Improve measurements from VOS			
	O50	Improve measurements of Underway thermosalinograph data			
	O51	Sustain Ship-of-Opportunity XBT/XCTD			
	O52	Coordination of underway pCO2 observations and agreed best practices			
	O53	Underway biogeochemistry observations.			
	O54	Continuous Plankton Recorder Surveys			
	O55	Maintain tide gauges			
	O56	Developing a global glider observing system			
	O57	Developing a global animal tagging observing system			
Terrestrial Domain - General (§5.2)	T1	Improve coordination of terrestrial observations	-	§4.4.1	(Terrestrial) General
	T2	Develop joint plans for coastal zones	-	§4.4.1	(Terrestrial) General
	T3	Terrestrial monitoring sites	-	§4.4.1	(Terrestrial) General
	T4	Review of monitoring guidance	-	§4.4.1	(Terrestrial) General
	T5	Develop metadata	-	§4.4.1	(Terrestrial) General
	T6	Identify capacity development needs	-	§4.4.1	(Terrestrial) General
Terrestrial Domain - Hydrosphere (§5.3)	T7	Exchange of hydrological data			
	T8	Lakes and Reservoirs: compare satellite and *in situ* observations	-	§4.4.2	(Terrestrial) Hydrosphere
	T9	Submit historical and monthly lake level data			
	T10	Establish sustained production and improvement for the Lake ECV products	-	§4.4.2	(Terrestrial) Hydrosphere
	T11	Confirm GTN-R sites			
	T12	National needs for river gauges			

	T13	Establish full scale Global Groundwater Monitoring Information System (GGMS)			
	T14	Operational Groundwater monitoring from gravity measurements	-	§4.4.2	(Terrestrial) Hydrosphere
	T15	Satellite soil moisture data records	-	§4.4.2	(Terrestrial) Hydrosphere
	T16	Multi-satellite soil moisture data services	-	§4.4.2	(Terrestrial) Hydrosphere
	T17	International soil moisture network			
	T18	Regional high-resolution soil moisture data record	-	§4.4.2	[#] (Terrestrial) Hydrosphere
Terrestrial Domain - Cryosphere (§5.4)	T19	Maintain and extend the *in situ* mass balance network			
	T20	Improve the funding situation for international glacier data centres			
	T21	Encourage and enforce research projects to make their ECV-relevant observations available through dedicated international data centres	-	§4.1.3	(Terrestrial) Cryosphere
	T22	Global glacier inventory	-	§4.1.3	(Terrestrial) Cryosphere
	T23	Multi-decadal glacier inventories	-	§4.1.3	(Terrestrial) Cryosphere
	T24	Allocate additional resources to extend the geodetic dataset	-	§4.1.3	(Terrestrial) Cryosphere
	T25	Extend the glacier front variation dataset both in space and time	-	§4.1.3	(Terrestrial) Cryosphere
	T26	Glacier observing sites	-	§4.1.3	(Terrestrial) Cryosphere
	T27	Observations of glacier velocities	-	§4.1.3	(Terrestrial) Cryosphere
	T28	Snow-cover and snowfall observing sites			
	T29	Integrated analyses of snow	-	§4.1.3	(Terrestrial) Cryosphere
	T30	Ice sheet measurements			
	T31	Ice sheet model improvement			
	T32	Continuity of laser, altimetry, and gravity satellite missions	-	§4.1.3	(Terrestrial) Cryosphere
	T33	Standards and practices for permafrost			
	T34	Mapping of seasonal soil freeze/thaw			
Terrestrial Domain - Biosphere (§5.5)	T35	Ensure the consistency of the various radiant energy fluxes	-	§4.4.4	(Terrestrial) Biosphere
	T36	Climate change indicators for adaptation			
	T37	Quality of ground-based reference sites for FAPAR and LAI	-	§4.4.4	(Terrestrial) Biosphere
	T38	Improve snow and ice albedo products	-	§4.1.3	(Terrestrial) Cryosphere
	T39	Improve *in situ* albedo measurements		§4.4.4	(Terrestrial) Biosphere
	T40	Production of CDRs for LAI, FAPAR, and Albedo	-	§4.4.4	(Terrestrial) Biosphere
	T41	Evaluate LAI, FAPAR, and Albedo	-	§4.4.4	(Terrestrial) Biosphere
	T42	Land surface temperature: *in situ* protocols	-	§4.4.4	(Terrestrial) Biosphere
	T43	Production of land surface temperature datasets	-	§4.4.4	(Terrestrial) Biosphere
	T44	Reprocessing land surface temperature	-	§4.4.4	(Terrestrial) Biosphere
	T45	Land surface temperature *in situ* network expansion	-	§4.4.4	(Terrestrial) Biosphere
	T46	Land surface temperature radiometric calibration	-	§4.4.4	(Terrestrial) Biosphere
	T47	Land cover experts	-	§4.4.4	(Terrestrial) Biosphere
	T48	Annual land cover products	-	§4.4.4	(Terrestrial) Biosphere
	T49	Land cover change	-	§4.4.4	(Terrestrial) Biosphere
	T50	Land cover community consensus	-	§4.4.4	(Terrestrial) Biosphere
	T51	Deforestation	-	§4.4.4	(Terrestrial) Biosphere
	T52	Collaboration on above ground biomass	-	§4.4.4	(Terrestrial) Biosphere
	T53	Above ground biomass validation strategies	-	§4.4.4	(Terrestrial) Biosphere
	T54	Above ground biomass validation sites	-	§4.4.4	(Terrestrial) Biosphere

	T55	Above ground biomass data access	-	§4.4.4	(Terrestrial) Biosphere
	T56	Above ground biomass: forest inventories	-	§4.4.4	(Terrestrial) Biosphere
	T57	Soil carbon: carbon mapping			
	T58	Soil carbon change			
	T59	Soil carbon – histosols			
	T60	Historic fire data	-	§4.4.4	(Terrestrial) Biosphere
	T61	Operational global burned area and FRP	-	§4.4.4	(Terrestrial) Biosphere
	T62	Fire maps	-	§4.4.4	(Terrestrial) Biosphere
	T63	Fire validation	-	§4.4.4	(Terrestrial) Biosphere
	T64	Fire disturbance model development	-	§4.4.4	(Terrestrial) Biosphere
Terrestrial Domain - Human Use of Natural Resources (§5.6)	T65	Anthropogenic water use			
	T66	Pilot projects – anthropogenic water use			
	T67	Improved global estimates of anthropogenic GHG emissions			
	T68	Use of satellites for LULUCF emissions/removals		§4.4.5	(Terrestrial) Human Use of Natural Resources
	T69	Research on the land sink			
	T70	Use of inverse modeling techniques to support emission inventories			
	T71	Prepare for a carbon monitoring system	-	§4.4.5	(Terrestrial) Human Use of Natural Resources
Terrestrial Domain - Potential (§5.7)	T72	Prepare for a latent & sensible heat flux ECV	-		

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