The 2022 GCOS Implementation Plan

ГЛОБАЛЬНАЯ СИСТЕМА
НАБЛЮДЕНИЙ ЗА КЛИМАТОМ
НЕУСТАННО СЛЕДИМ ЗА КЛИМАТОМ

SYSTÈME MONDIAL
D'OBSERVATION DU CLIMAT
NOUS VEILLONS SUR LE CLIMAT

النظام العالمي
لرصد المناخ
لنضع المناخ نصب أعيننا

全球气候观测系统
密切监视气候

SISTEMA MUNDIAL
DE OBSERVACIÓN DEL CLIMA
SIEMPRE VIGILANDO EL CLIMA

GLOBAL CLIMATE
OBSERVING SYSTEM
KEEPING WATCH OVER OUR CLIMATE

GCOS – 244
GOOS – 272

GLOBAL CLIMATE OBSERVING SYSTEM
KEEPING WATCH OVER OUR CLIMATE
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The 2022 GCOS Implementation Plan

GCOS-244
GOOS-272

The development of this report has received funding from the European Union.

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PREFACE

The World Meteorological Organization (WMO) is a specialized agency of the United Nations and is its authoritative voice for weather, water and climate. It sponsors and implements an integrated suite of programmes which encompass many aspects of climate: research, observations, assessment, modelling and services. Among these WMO programmes, the Global Climate Observing System programme (GCOS) - co-sponsored by the Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme (UNEP) and the International Scientific Council (ISC) – collects and documents the data needs for monitoring the climate system and assessing the impacts of climate variability and change. GCOS regularly produces status reports, which assess the progress and unmet requirements in the climate observing systems, followed by implementation plans, which propose actions for its improvement. These periodic reports are submitted every 5 years to the United Nations Framework Convention (UNFCCC) and are recognized by the Conference of the Parties (e.g. Decision 19/CP.22).

This 2022 GCOS Implementation Plan provides recommendations for a sustained and fit for purpose Global Climate Observing System. Global climate monitoring needs to cover the entire Earth system from the atmosphere to the oceans, from the cryosphere to the biosphere, and encompassing the water, energy and carbon cycles. The GCOS Implementation Plan supports and serves WMO Member States in addressing the challenges of climate change and the implementation of the Paris Agreement.

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report showed that the urgency of addressing climate change is inescapable. All successful actions to adapt to or mitigate climate change must be based on sound accurate information that can only be provided by a global climate observing system. Planning for the impacts of climate change, mitigating its impacts, predicting and understanding future risks, and protecting vulnerable populations and infrastructures all require the global information on the changing climate. This imperative to respond to climate change highlights additional information needs such as monitoring climate extremes and greenhouse gas fluxes.

WMO programmes provide much of this vital information. WMO strives to assist its Members in mitigating the risks of natural disasters, protecting food and water resources, safeguarding health and advising on the smart use of energy. This portfolio of activities needs to be underpinned by solid data and the GCOS Implementation Plan provides important guidance in this area. National Meteorological and Hydrological Services (NMHS) as well as other institutions running observational networks, together with governmental departments in charge of developing climate related policies, will benefit from the information on implementation needs described herein.

Indeed, many of the proposed actions in this Implementation Plan will be conducted by NMHSs. WMO supports this work through the WMO Integrated Global Observing System (WIGOS), the atmospheric constituent observing systems coordinated through the Global Atmosphere Watch (GAW), the WMO Information System (WIS), the World Hydrological Cycle Observing System (WHYCOS) and the Climate Services Information System (CSIS) of the Global Framework for Climate Services (GFCS). This report provides an excellent basis for developing more detailed activity plans that will ensure swift and effective support for operational services.

The Global Climate Observing System is dependent on strong partners and will need to be implemented through interrelated physical, chemical and biological observations of the atmosphere, ocean, the land-surface ecosystems, the hydrosphere and the cryosphere. This publication also highlights several important contributors to the Global Climate Observing

System: in particular, satellite observations coordinated through the Joint Committee for Earth Observation Satellites (CEOS)/Coordination Group on Meteorological Satellites (CGMS) Working Group on Climate and ocean observations coordinated by the IOC of UNESCO and the Global Ocean Observing System (GOOS). Other key observations are performed by a wide range of national and regional bodies.

On behalf of all sponsors, I congratulate the GCOS programme and the climate observation community contributing to it for this important and timely publication.

I take this opportunity to urge all Parties to the UN Convention on Climate Change, GCOS sponsoring organizations and relevant national and international agencies, institutions and organizations, to collaborate and support the continued development of the Global Climate Observing System, which is critical to mitigate the magnitude of climate change and to adapt to changes that cannot be avoided.

Prof. Petteri Taalas
WMO Secretary-General

ACKNOWLEDGEMENT

We would like to express our sincere gratitude to all those who have assisted in developing this report, including technical experts, an editorial board, the writing team, the GCOS Secretariat and the many contributors to the public reviews. They are listed in Appendix 3.

This report has been compiled by the GCOS expert panels assisted by other experts, under the overall guidance of a writing team. The whole process has been conducted under the supervision of the GCOS Steering Committee.

The GCOS expert panels have consulted widely to ensure that as many views possible across the relevant communities are taken into consideration. We would also like to thank the Joint CEOS/CGMS Joint Working Group on Climate that read an early draft of the report and made many valuable comments.

The revised requirements for ECVs (see Chapter 4 and the 2022 GCOS ECVs Requirements, GCOS-245) were publicly reviewed in 2020 and the entire report, (including the ECVs requirements) publicly reviewed in May 2022. This process of public review and revision is one of the hallmarks of the success and acceptance of GCOS and ensures as wide as possible input into the process. We would like to thank all those who participated and made many valuable comments that have significantly improved this report.

We would also like to express our gratitude to the co-sponsors of GCOS, WMO, IOC of UNESCO, UNEP and the ISC for supporting this program. The work was also supported by financial contributions that enabled the work to be completed, especially those from the USA (US State Department and NOAA) and EU (Copernicus).

Prof. Han Dolman

Chair of the GCOS Steering Committee

Dr Anthony Rea

Director of the GCOS Secretariat

EXECUTIVE SUMMARY

This is the latest in a series of implementation plans produced by the Global Climate Observing System (GCOS) programme since its inception in 1992. It provides a set of high priority actions which if undertaken will improve global observations of the climate system and our understanding of how it is changing.

Climate observations have been very important: they have unequivocally shown that anthropogenic climate change is occurring, and they have informed the verification of the models and the projections needed to successfully adapt to and mitigate climate change. Climate services are underpinned by robust, accurate and timely climate observations.

This plan is mainly based on the following:

- The latest 2021 GCOS Status Report[1], released in 2021, that identified the successes and gaps in the existing observing systems.
- The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement that has highlighted the importance of both adaptation and mitigation. This puts additional requirements on the global climate observing system to support these climate services.
- The implications arising from the Intergovernmental Panel on Climate Change (IPCC) 6th assessment report and recent special reports.
- Recent scientific studies of how well the climate cycles of carbon, water and energy are monitored have identified additional observational needs that if addressed would improve scientific understanding, models and projections.

This plan aims to identify the major practical actions that should be undertaken in the next 5-10 years. It identifies six major themes that should be addressed. Within each theme, several actions are identified that are described below with the full details in the main body of the report. The GCOS panels will continually assess the implementation of each of the actions and report on progress in the next status report. The themes are:

A. Ensuring Sustainability. Sustained funding is essential to ensure the continuity and the expansion needed for many in situ observations of Essential Climate Variables (ECVs). While some observations have sustained long-term funding, many are supported through short-term funding, with a typical lifetime of a few years, leaving the development of long-term records extremely vulnerable. Satellite observations have been a major success in monitoring many ECVs, but the long-term continuity of some satellite observations is not assured. It is essential that consistent time-series are available across many missions. This theme, in particular, identifies those in situ and satellite observations that are particularly at risk. However, all current observations of ECVs need to be sustained.

B. Filling Data Gaps. This theme addresses gaps that have been identified in the existing observing system. In general, the current observations fulfil many requirements and provide the basis for many useful datasets and products of ECVs. However, in situ observations for almost all the ECVs are consistently deficient over certain regions, most notably parts of Africa, South America, Southeast Asia, in the deep ocean and polar regions, a situation that has not improved since the 2015 GCOS Status Report (GCOS-195).

[1] GCOS (2021). The Status of the Global Climate Observing 2021: The GCOS Status Report (GCOS-240)

C. Improving data quality, availability and utility, including reprocessing. Many climate observations are currently underexploited because of the lack of consistency in their processing and usability. This theme looks at how the original observational data is transformed into user-relevant information. Standards are required throughout the phases of the processing chain that transform observations into user-relevant products. These should address uncertainty, the use of uniform metadata and quality attributes and also support the generation of sensor-agnostic gridded datasets. Further effort is required towards ensuring data could be readily used in reanalysis and is fit for purpose.

D. Managing Data. To address and understand climate change, the longest possible time series need to be preserved and made available in perpetuity. Every ECV needs to have one or more recognized global data repositories that are well-curated, provide free and open access to data, are sustainable and have clear guidance for users. Global Climate Data Centres should abide by defined principles such as the TRUST Principles[2] and FAIR Principles[3]. Data rescue from hard copy or archaic digital formats allows data series to be extended in the past and needs to be adequately planned and funded with the results openly and freely available. This theme aims to organise more efficiently data rescue, data sharing, data curation and data provision.

E. Engaging with Countries. Many climate observations are made by national bodies; however, these efforts need support and coordination. Some countries have national programmes that need to be connected regionally and globally to share and communicate issues and solutions. GCOS can help by linking these national efforts into the global system, providing information on observing needs, promoting needs for support and access to global information. Ultimately the benefits of climate observations need to be widely understood and the contributions of national observations to global datasets enhanced.

F. Other Emerging Needs. Stakeholder needs are evolving, and the actions in this theme address some of these needs. The GCOS Expert Panels have already identified several areas where emerging needs arising from response measures such as adaptation and mitigation need to be addressed in the short term. GCOS is looking at how observations more generally can support adaptation and will report these findings in coming years.

Global climate observations are made by a wide range of actors. Satellite observations are vital and are coordinated by the Joint Committee on Earth Observations Satellites/Coordination Group on Meteorological Satellites CEOS/CGMS Working Group on Climate (WGClimate). Ocean observations are performed by many countries coordinated thorough the Global Ocean Observing System, GOOS. The World Meteorological Organization coordinates National Meteorological and Hydrological Services (NMHSs) which provide many of the observations needed for monitoring the climate. Other observations are provided by a wide range of international and national bodies, and academia. This implementation plan will be followed by the publication of a series of supplements focusing on each of these constituencies providing guidance on the actions that they can implement. Table 1 provides links between the actions and the bodies expected to implement the actions.

The benefits of climate observations far exceed their cost. While no complete and comprehensive cost-benefit analysis of the global climate observing system has been conducted, analysis of its component parts shows its extensive benefits.

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[2] Lin, D., J. Crabtree, I. Dillo, et al., 2020: The TRUST Principles for digital repositories. *Scientific Data* 7, 144, DOI:10.1038/s41597-020-0486-7

[3] Wilkinson, M.D., et al., 2016: The FAIR guiding principles for scientific data management and stewardship. *Scientific Data*, 3, DOI:10.1038/sdata.2016.18

Revised observational requirements for the ECVs are provided in document 'The 2022 GCOS ECVs Requirements', (GCOS-245).

Table 1. List of Themes, Actions, and Implementers in GCOS Implementation Plan

Theme	Actions	Implementing Bodies											
		WMO	NMHS	Space agencies	GOOS	Reanalysis Centers	Global Data Centers	Research organizations	National Agencies	Parties to UNFCCC	Academia	Funding Agencies	GCOS
A: ENSURING SUSTAINABILITY	A1. Ensure necessary levels of long-term funding support for in situ networks, from observations to data delivery	x	x					x			x	x	x
	A2. Address gaps in satellite observations likely to occur in the near future			x									
	A3. Prepare follow-on plans for critical satellite missions			x									
B: FILLING DATA GAPS	B1. Development of reference networks (in situ and satellite Fiducial Reference Measurement (FRM) programs)	x	x	x				x				x	x
	B2. Development and implementation of the Global Basic Observing Network (GBON)	x	x		x								x
	B3. New Earth observing satellite missions to fill gaps in the observing systems			x									
	B4. Expand surface and in situ monitoring of trace gas composition and aerosol properties		x					x	x			x	
	B5. Implementing global hydrological networks	x	x	x			x						
	B6. Expand and build a fully integrated global ocean observing system		x	x	x			x	x		x		
	B7. Augmenting ship-based hydrography and fixed-point observations with biological and biogeochemical parameters				x			x					
	B8. Coordinate observations and data product development for ocean CO_2 and N_2O	x			x			x	x				
	B9. Improve estimates of latent and sensible heat fluxes and wind stress		x	x	x			x			x		
	B10. Identify gaps in the climate observing system to monitor the global energy, water and carbon cycles							x				x	x
C: IMPROVING DATA QUALITY, AVAILABILITY AND UTILITY, INCLUDING REPROCESSING	C1. Develop monitoring standards, guidance and best practices for each ECV	x		x	x								x
	C2. General improvements to satellite data processing methods			x				x			x		
	C3. General improvements to in situ data products for all ECVs		x					x			x		
	C4. New and improved reanalysis products			x		x					x		
	C5. ECV-specific satellite data processing method improvements			x		x							
D: MANAGING DATA	D1. Define governance and requirements for Global Climate Data Centres	x					x						x
	D2. Ensure Global Data Centres exist for all in situ observations of ECVs	x	x		x				x			x	x
	D3. Improving discovery and access to data and metadata in Global Data Centres						x					x	x
	D4. Create a facility to access co-located in situ cal/val observations and satellite data for quality assurance of satellite products	x	x	x				x					
	D5. Undertake additional in situ data rescue activities	x	x							x		x	x
E: ENGAGING WITH COUNTRIES	E1. Foster regional engagement in GCOS	x			x					x			x
	E2. Promote national engagement in GCOS		x							x	x		x
	E3. Enhance support to national climate observations									x		x	x
F: OTHER EMERGING NEEDS	F1. Responding to user needs for higher resolution, real time data	x	x	x				x			x		x
	F2. Improved ECV satellite observations in polar regions			x				x			x		
	F3. Improve monitoring of coastal and Exclusive Economic Zones		x	x	x			x			x		
	F4. Improve climate monitoring of urban areas	x	x					x	x		x		x
	F5. Develop an Integrated Operational Global GHG Monitoring System	x		x				x	x		x		x

1. INTRODUCTION

Climate observations[4] are critical for understanding and responding to climate change. This report was produced in response to an invitation from the United Nations Framework Convention on Climate Change (UNFCCC) to update the 2016 GCOS Implementation Plan in light of the 2021 GCOS Status Report[5].

The 2021 GCOS Status Report was informed by experts from the three GCOS panels[6] who provided the technical information and assessments. Each Panel appointed "ECV Stewards" to monitor the performance of the observing system for specific Essential Climate Variables (ECVs). Similarly, experts were appointed to report on each of the actions on the 2016 Implementation Plan (IP Actions). All assessments have been internally and externally reviewed, with the entire report undergoing a public review. Finally, the report was approved by the GCOS Steering Committee. The Executive Summary of the 2021 GCOS Status Report can be found here GCOS-239.

There has been substantial progress in many areas of the Earth's climate observing system, made after the release of the 2016 GCOS Implementation Plan[7]. However, the 2021 Status Report identified a number of outstanding issues that are now addressed in this 2022 GCOS Implementation Plan[8].

This 2022 GCOS Implementation Plan has a different form to earlier plans: it has fewer, more focused, and integrated actions, with clearer means of assessment, and identification of the stakeholders who need to respond to the actions. Furthermore, the updated ECVs requirements are presented in a separate document called GCOS-245 -The 2022 GCOS ECVs Requirements.

An Editorial Board agreed on the outline and reviewed the final document. The actions described in Chapter 6 were compiled by experts of the GCOS panels in consultation with their respective communities. A Writing Team ensured consistency and completeness of the actions and drafted the remaining chapters. The draft was publicly reviewed in May 2022. The GCOS Secretariat supported the entire process; a complete list of contributors is presented in Appendix 3.

The remainder of this report is structured as follows:

- Chapter 2 discusses the evolving needs for climate observations.
- Chapter 3 looks at the future vision and evolution of GCOS responding to these evolving needs.
- Chapter 4 describes the Essential Climate Variables (ECVs).
- Chapter 5 covers data management and data policies.
- Chapter 6 provides the actions grouped into 6 major themes:
    - Ensuring the sustainability of key existing observation programs;
    - Filling data gaps in current observing capabilities;
    - Improving data quality, availability and utility, including reprocessing;
    - Improving data management;
    - Engaging with countries and stakeholders;
    - Addressing other emerging needs.

[4] Climate observations in this context refer to measurements of physical, chemical or biological variables that critically contribute to the characterization of the Earth's climate.
[5] GCOS (2021). The Status of the Global Climate Observing 2021: The GCOS Status Report (GCOS-240).
[6] AOPC – Atmospheric Observations Panel for Climate; TOPC: Terrestrial Observations Panel for Climate; OOPC: Ocean Observations Physics and Climate Panel.
[7] GCOS (2016). The Global Observing System for Climate: Implementation Needs (GCOS-200).
[8] A full consideration of the impact of COVID19 pandemic on the global climate observing system remains to be done. However, it has already shown the importance of resilience in the observing system and the need to develop this, through network planning and a balanced development of the observing systems across different system components.

2. EVOLVING USER NEEDS FOR CLIMATE OBSERVATION

There is an ongoing need to understand the changing climate system. At a fundamental level what we do not observe we cannot understand, and what we cannot understand we cannot predict, adapt to and mitigate. It is necessary to observe, on a sustained basis, key facets of the climate system, in order to monitor and understand the changing climate for numerous sectors and applications at a sufficient level of comprehensiveness. These user needs are constantly evolving. This chapter provides a summary of these evolving needs and the benefits and costs of addressing them.

2.1 Climate assessments

Scientific assessments, such as those of the Intergovernmental Panel on Climate Change (IPCC), are critically dependent upon the global availability of high-quality observational data products for a broad range of ECVs. Observationally-based products from across the atmosphere, ocean, cryosphere, biosphere and land, underpin the findings of unequivocal changes and their attribution to human activities. Evidence from proxies spanning longer periods, informs assessments as to the unusualness of these changes in a much longer-term context than can be afforded by the instrumental record. As such, improved access to and analyses of proxy records (e.g. tree rings, ice cores) are also important.

Observations of the climate system are also essential to support the assessment of key processes, including the carbon and hydrological cycles and the energy budget (Section 2.4), each of which was the focus of a key chapter in the most recent IPCC AR6 WGI assessment report. It is only because of high quality observations of key components of these cycles that the earth system models can be assessed and hence projections be made with confidence.

Observations at regional scale, with enhanced spatial and temporal resolutions, are necessary to underpin assessments of regional climate change, and associated assessments of impacts and adaptation undertaken in the IPCC WGII assessment. These are key to understanding impacts already felt from warming experienced to date and to assess the efficacy of already deployed adaptation measures.

Observations of greenhouse gases across the atmospheric, oceanic and terrestrial domains are needed for multiple aspects of the mitigation assessment performed by IPCC WGIII. The availability of observations allows the understanding of important biogeochemical cycles assessed in IPCC WGI which underpins the climate system emulators that are necessary to project the impacts of possible future emission scenarios.

Each successive IPCC assessment cycle has been able to draw firmer conclusions thanks, in no small part, to the improved availability of new and historical observations, and improved knowledge that comes from continuous reprocessing and re-evaluation of the data records. All types of observations, in situ and remotely sensed, have utility in informing the assessments as, increasingly, do reanalyses products. It is important to make, curate, reprocess and reanalyse these observations in a cycle of continuous improvement, as new knowledge is gained, and new opportunities arise. For example, in IPCC WGI AR6 the assessment was able to, for the first time, draw upon Global Navigation Satellite System (GNSS) radio occultation measurements leading to a greatly improved assessment of temperature changes in the upper troposphere and the lower stratosphere. The assessment also benefited from greatly improved reanalysis products from the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA5) and the Japan Meteorological Agency (JMA) (JRA-55).

Observations are also essential to assess the quality of climate model simulations such as those of CMIP which underpin some of the conclusions of the IPCC reports. In this context initiatives such as Obs4MIPs have ensured that climate observation could be easily compared to model output and therefore served to speed up and improve the model development cycle.

Observations are key to underpinning the World Meteorological Organization (WMO) State of the Climate Report (which informs the UNFCCC process) and the Bulletin of the American Meteorological Society (BAMS) State of the climate series of reports as well as regional and national climate monitoring and reporting activities. These assessments are becoming increasingly comprehensive, requiring access to an ever-increasing array of observationally-based products to perform the assessment activities. The assessments have high value in communicating the changing status of the climate to numerous stakeholders. There also exist bespoke monitoring activities, such as the global carbon project, which require observations to underpin their annual assessments.

2.2 Supporting the Paris Agreement

The Paris Agreement provides the international climate policy framework which is going to evolve significantly in the coming years. Observations play a fundamental role in the policy framework and they will need to continue to keep pace with needs as the policy evolves. The needs in terms of climate observations can be summarised as follows:

- All countries will have to provide national greenhouse gases (GHGs) inventory reports and these have to follow the IPCC Guidelines for National Greenhouse Gas Inventories. Under certain conditions (spatial and temporal resolution, field data) and depending on the variables to be estimated, Earth observations can be useful for supporting verification and transparency. Connecting and merging relevant data from different sources of information, including the private sector, will be a challenge, as there could be substantial differences in how processes and variables are measured, curated and even named and acquired.
- The Global Stocktake (GST[9]) facilitates the assessment of progress in three areas: mitigation, adaptation and finance flows, and means of implementation and support. The GST is in its first phase (Information, collection and preparation) where aggregated information is needed to support the assessment of all three areas. The GST takes place every five years and the first iteration is expected to conclude in 2023.
- Countries need information that can be used at a national and sub-national levels to support decision making. This includes provision of standardised datasets and the long-term records of ECVs that are fundamental for national adaptation and mitigation planning and allow countries to build their sectoral needs and priorities. For example, observationally-based adaptation indicators, as being develop by the GCOS Adaptation Task Team, are becoming increasingly important as the impacts of climate change and associated extremes become more apparent. Observations can be used as a benchmark to assess the efficacy of adaptation measures. Observations also inform assessments of losses and damages.
- Climate change has traditionally been related to physical variables. Yet variables related to biodiversity will prove increasingly essential as we move forward in the implementation of the Paris Agreement. Biodiversity both impacts and is impacted by climate change, and observations make possible the evaluation of the effect of climate change on terrestrial and marine ecosystems and aid the discovery and understanding of important

[9] https://unfccc.int/topics/global-stocktake/global-stocktake

biophysical feedback mechanisms in the climate system[10]. Moreover, to support attainment of the goals of the Paris Agreement, the observation community needs to address knowledge gaps through those ECVs that track physical, chemical and biological cycles. Attention needs to be paid to regions particularly vulnerable to the impacts of climate change where observational capabilities are generally weakest.

2.3 Climate services and adaptation

In order to meet the ever-growing demand for tailored climate information by decision makers, stakeholders and the general public, climate services play a crucial role as co-producers of climate information systems and products. Effective climate services are essential for adaptation to climate variability and change[11]. Climate services co-produce usable information in support of climate-sensitive sectors. This is achieved through incorporation of science-based climate information and predictions into planning, policy and practical decision-making. Effective climate services facilitate climate-smart decisions that will, for example, mitigate the impacts of climate-related disasters, improve food security and health outcomes, enhance water resources management, and bring better outcomes in disaster risk reduction. As climate services continue to rise in prominence on national, regional and global agendas for climate change, it is important to re-examine regularly, as the science progresses, their needs in terms of observations.

Initiatives such as the Global Framework for Climate Services (GFCS), have been designed and implemented to support and organise the international effort to operationalise the provision of climate services. Such support could be particularly important for the Global South which face a disproportionate amount of the climate impacts whilst having a limited capacity to develop and deliver services. Maintaining and upgrading the observational networks and ensuring that the observations can be used to inform policy and decision-making is key to the development of effective and robust local services.

Perspectives for risk management and adaptation have received ample attention in the recent IPCC reports and in support of UNFCCC. Several knowledge and observational gaps on the impacts of extreme climatic and meteorological events, abrupt changes, cascading effects and compound extremes have been identified, and need supporting information. Moreover, while there is ample robust climate information at the global and regional scales, this is often lacking at the local scales required for effective decision-making and response. Nevertheless, there is generally a willingness to act even if climate information is not fully conclusive. Several of the priority actions in Chapter 6 address this and ensure that climate science and services would be effective in enabling policies and decisions to manage local-scale climate risks and reduce its impacts on vulnerable communities and regions around the world. Some of the required improvements identified in the observing systems are:

- Addressing the gap between the top-down, global, production of climate information and the "bottom-up", local-scale decision making by improving regional to local climate change information through better understanding of the local decision-making context to enable more targeted observations of relevant processes and time scales.
- Enhancing integrated and co-located observations of the physical, chemical and biological components of the climate system to better understand, and predict, the effects of climate change. This is also crucial to understanding the local pressures on ecosystems and, for instance, their ability to store carbon.

[10] This will lead to stronger links with CBD and UNCCD.
[11] With the understanding that adaptation measures increase the resilience of ecosystems to the risks of impacts of climate change.

2.4 The Earth Climate Cycles

Key features of the earth system for understanding and predicting climate change are the energy, water (or hydrological) and carbon cycles. Ideally, these should be completely monitored by ECVs. In 2018 GCOS started assessments for these cycles, identifying possible gaps and inconsistencies in existing observation systems (von Schuckmann et al., 2020; Dorigo et al., 2021; Crisp et al., 2022). By assessing how well these are observed, GCOS is able to identify gaps and inconsistencies in the global climate observing system in a more integrated way than separately considering the three domains, atmosphere, ocean and land. The global sea level budget can be used as a check on the joint closure of the energy and hydrological cycle components as articulated in Box 9.1[12] of IPCC AR6 WGI.

2.4.1 Monitoring the Earth Energy Budget

Von Schuckmann et al. (2020)[13] and (2022)[14] updated the Earth heat inventory and presented an updated assessment of ocean warming estimates as well as new and updated estimates of heat gain in the atmosphere, cryosphere and land over 1960–2018. Some key requirements for improving future assessments have been identified in this paper:

- To assure continuity of continental heat gain estimates, a more consistent global monitoring program is urgently needed for the systematic measurement of land temperatures (estimated from soil temperature measured at various depths). In addition, long term measurements at the same sites should be sustained whenever possible to reduce uncertainties in the estimates. Today, there is no internationally organised effort in place that assures the acquisition and curation of subsurface land temperature profiles, which is needed to avoid data loss and inhomogeneities, as well as to guarantee global accessibility to those data.
- Sustained remote sensing, and the acquisition of further in situ measurements for validation for all the cryosphere components are key to quantifying future changes. The continuation of satellite altimeter missions with high inclination, polar focused orbits is critical in our ability to monitor sea ice thickness in particular (see Action F2). Observations of snow thickness with multi-frequency altimeters are essential for further constraining sea ice thickness estimates. For ice sheets and glaciers, reliable gravimetric, geodetic, and ice velocity measurements, knowledge of ice thickness and extent, snow/firm thickness and density, and the continuation of the now 3-decade long satellite altimeter record are essential to quantify changes in mass balance of grounded and floating ice. The estimate of glacier heat uptake is particularly affected by lack of knowledge of ice melt below sea level and to a lesser degree, lacking knowledge of firn and ice temperatures. This gap introduces a systematic bias in the estimate of cryospheric energy uptake.
- For the global ocean observing system, the core Argo sampling needs to be sustained as well as expanded along the continental slopes up to the shelf with the implementation of different platforms (moorings, repeated ship cruises, gliders and other autonomous

[12] Fox-Kemper, B., et al. (2021), Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter09.pdf#page=10

[13] von Schuckmann, K., et al., 2020: Heat stored in the Earth system: where does the energy go?, *Earth Systems and Science Data*, 12, 2013–2041, https://doi.org/10.5194/essd-12-2013-2020.

[14] von Schuckmann K. et al., 2022. Heat stored in the Earth system 1960-2020: Where does the energy go? submitted to *Earth Systems and Science Data*

platforms), and complemented by remote sensing data. Extensions such as into the deep ocean layer need to be further fostered, and technical developments for the measurements under ice and in shallower areas need to be sustained.

- For the permafrost estimates, the primary sources of uncertainty arise from lacking information about the amount and distribution of ground ice in permafrost regions, as well as measurements of liquid water content.

2.4.2 Monitoring the Water Cycle

Dorigo et al. (2021)[15] reviewed the capability of ground-based and remotely sensed observations of water cycle ECVs to consistently observe the hydrological cycle. They evaluated the relevant land, atmosphere, and ocean water storages and the fluxes between them, including anthropogenic water use. Particularly, they assessed how well the observations close the water cycle at multiple temporal and spatial scales. The authors concluded that, while long-term water cycle monitoring has greatly advanced in the recent past, many observational gaps still exist in terms of closing the water budget and enabling a comprehensive and consistent assessment across spatial and temporal scales. The following improvements to the present observation systems have been identified:

- Expand the existing observation systems to enable the identification of trends in water cycle components.
- Ensure consistency between climate data records of different ECVs to close the water cycle.
- Develop capabilities to include so-far missing data (e.g. on infiltration, glaciers, ice sheet fluxes and snow cover runoff).
- Further consider the closure of the hydrological cycle at shorter timescales (e.g., seasonal, monthly, or shorter) and over a range of spatial domains.

2.4.3 Monitoring the Carbon Cycle

The Global Carbon Project (Friedlingstein et al (2022)[16]) provides annual updates on the key contributors to the global carbon budget and its trends. Crisp et al. (2022)[17] reviewed the atmospheric carbon cycle, including the anthropogenic drivers controlling the current fluxes of CO_2. Large uncertainties exist in the fluxes between the atmosphere and reservoirs over land and in the ocean. The authors provided an update on the mean state and emerging trends in carbon stocks and fluxes revealed by various approaches, including new observing capabilities and analysis. The assessment produced the following key recommendations:

- Continued ship-based observations combined with expanded deployments of autonomous platforms are needed to quantify ocean-atmosphere fluxes on policy relevant spatial and temporal scales.
- There is also an urgent need for more comprehensive measurements of stocks, fluxes and atmospheric CO_2 in humid tropical forests and across the Arctic and boreal regions, which appear to be experiencing rapid change.
- Although ship-based observations remain a central resource for the carbon observing system, these are expensive and tend to be seasonally biased. Driven by these demands,

[15] Dorigo W., et al., 2021: Closing the water cycle from observations across scales: Where do we stand? *Bulletin of the American Meteorological Society*, *102*(10), E1897-E1935. https://doi.org/10.1175/BAMS-D-19-0316.1
[16] Friedlingstein, P., et al., 2022: Global carbon budget 2021. Earth System Science Data, 14(4), 1917-2005. https://doi.org/10.5194/essd-14-1917-2022.
[17] Crisp, D., et al., 2022: How Well Do We Understand the Land-Ocean-Atmosphere Carbon Cycle? *Reviews of Geophysics*, 60(2), e2021RG000736.

there is a continuous development of sensors for inorganic carbon system measurements with at least some of the following attributes: increased precision and accuracy, lower power consumption and lower instrument drift. Ocean carbon data should be ingested into publicly released databases (SOCAT, GLODAP) in a timely manner that supports at least annual diagnoses of the ocean carbon sink.

- Until recently, high resolution imaging observations and moderate resolution estimates of vegetation indices provided the primary tools for scaling up plot-based observations to national and continental scales. Recently, these capabilities have been augmented by space-based observations of SIF (Solar Induced chlorophyll Fluorescence). Future SIF observations promise substantial improvements in resolution. GCOS will consider if SIF can be included as an ECV product and its potential requirements.
- The spatial resolution and coverage of in situ measurements are still far too limited to identify and quantify the natural and anthropogenic emission sources emitting CO_2 into the atmosphere and the natural "sinks" absorbing it at the surface on spatial scales ranging from large urban areas to nations. The coverage is particularly sparse in polar boreal and tropical land regions and over most ocean basins. While recent advances in space based remote sensing capabilities are providing new insights into the current state of the atmospheric carbon cycle it remains important to develop an integrated carbon observing system comprising both in situ and satellite capabilities.

2.5 Cost and Benefits of Climate Observations

There is broad consensus that the benefits to society of the global climate observing system far outweigh the costs of implementing and maintaining the system. Economic studies have consistently shown the value that accurate climate observations and corresponding climate change projections can bring to societies. The benefits arise largely because accurate and timely information improves the planning and decision making that makes societies more resilient to climate variability and change.

It is easier to estimate the overall costs[18] of the observational infrastructure (of the order of 100B US$/year) than it is to provide an assessment of its benefits to society.

A full bottom-up and comprehensive assessment of the long-term benefits of climate observations to societies is difficult because there is a large diversity among users of climate information. Furthermore, the chain linking users to information is often complex and indirect. There are also non-climatic societal benefits which are difficult to value monetarily such as livelihoods, human health and well-being. This implies also that benefit estimates are likely conservative because the full dimensions of benefits to society are hard to assess and include.

However, there are many examples where some of the benefits are costed[19].

For Numerical Weather Predictions (NWP) there are well structured frameworks for cost-benefit analyses. Data denial experiments, where specific data sources are removed from the assimilation schemes, provide us with a good understanding of the value each observation type has for the overall forecast skill. Given that a reasonable estimate of the economic value of the forecasts exists, the marginal improvement in skill associated with each observation source can then be translated into the economic value of that observation. In such a way D. Kull at al. in

[18] Elements of costs include: data collection (in situ platforms, satellites), data processing, data management and dissemination.
[19] https://www.munichre.com/en/risks/climate-change-a-challenge-for-humanity.html

2021[20] estimated that the overall benefit/cost ratio of the additional investment required to bring the international data exchange of observational data up to WMO required standards in all countries of the world is on the order of 25 (or at least 14 under even more conservative assumptions). The authors also showed that investment in surface-based meteorological observing systems measuring critical variables and intended for international exchange of data has proven to be crucial. This is particularly true in those regions where the current availability of observations fails to meet internationally agreed requirements for input into global NWP and climate models.

Thanks to a systematic collection of user requirements and an operational monitoring of the use of the data it makes available, the EU-Funded Copernicus programme could provide valuable inputs into a cost benefit analysis. An initial assessment conducted by PwC in 2019[21] indicated an overall return on investment between 2 and 3 when the whole value chain is taken into account. More recent estimates from the European Union Agency for the Space Programme (EUSPA)[22] in 2022 suggested that some sectors such as agriculture, urban development, energy and climate service consultancy to other sectors, on their own, account for over half of the value generated by the programme. The same study suggests a rapid increase in the fraction of value generated by the insurance and financial sectors.

Attempts to evaluate costs and benefits of ocean observations have been made by the Organisation for Economic Co-operation and Development (OECD), showing that it is difficult to identify and quantify them comprehensively (Jolly et al., 2021[23]). However, previous studies suggest that the benefit-to-cost ratio for investing in ocean observations is high. For instance, JERICO-NEXT project estimated a benefit-to-cost ratio of 5 when analysing the European coastal component of the observing system (Gaughan et al., 2019[24]), while another study undertaken by the Marine Environmental Data and Information Network (MEDIN) estimated that the benefit of their data services was eight times the cost invested[25].

There are also obvious cross benefits of climate observation that should be taken into account e.g., tide gauges provide sea level data that are important for climate studies but are also essential for storm surge forecasting and harbour operations. Given the above-mentioned complexities, it is not straightforward to define a unique value of the Cost Benefit Ratio for global climate observations. Completing such a task remains a high priority for the global climate community. We list here a few pathways linking the benefits of climate observations to sectoral use:

- Global climate observations are critical in providing consistent information for model initialisation and forcing for historical climate simulations. These are also essential for global climate change assessments and attribution, as well as for the validation of historical simulations, and in improving the Earth System realism in numerical models.
- Ocean and land observations provide an essential input for the initialisation of sub-seasonal, seasonal and decadal predictions as well as NWP. Whilst limited literature exists

[20] Kull, D., Riishojgaard, L.P., Eyre, J. and Varley, R.A., (2021), The Value of Surface-based Meteorological Observation Data. https://openknowledge.worldbank.org/bitstream/handle/10986/35178/The-Value-of-Surface-based-Meteorological-Observation-Data.pdf?sequence=1&isAllowed=y

[21] European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, (2019) Copernicus market report, Issue 2. Publications Office. https://data.europa.eu/doi/10.2873/011961

[22] https://www.euspa.europa.eu/sites/default/files/uploads/euspa_market_report_2022.pdf

[23] Jolly, C., et al., 2021:, "Value chains in public marine data: A UK case study", OECD Science, Technology and Industry Working Papers, No. 2021/11, OECD Publishing, Paris, https://doi.org/10.1787/d8bbdcfa-en

[24] Gaughan, P., D. Hallinan, K.Reilly, 2019: Using Economic Cost Benefit Analysis Methodologies to underpin the sustainability and strategic planning of Coastal Ocean Research Infrastructures in Europe. OCEANS 2019 - Marseille, 2019, pp.1-8, doi: 10.1109/OCEANSE.2019.8867276

[25] Marine Environmental Data and Information Network (MEDIN) (2019), Cost Benefit Analysis Final Report. https://www.medin.org.uk/sites/medin/files/documents/MEDIN%20Cost%20Benefit%20Analysis_Final%20Report.pdf

on the assessment of the value the observations have in these predictions, the methods developed for NWP could be applied to this context well.

- A significant part of the value of systematic observations for society is likely to occur through the use of observations within reanalysis systems. The data provided by Copernicus Climate Change Service suggest that there is one order of magnitude more users of the reanalysis than direct users of observations for climate applications. Reanalysis is used in a variety of contexts including the assessment of baseline risks and as an input to initialise impact models for sectoral applications such as agriculture or hydrology.
- Regional scale observations provide value to users by describing the evolution of local conditions. These are important to improve regional knowledge on the evolving climate conditions across domains (including trends on the unfolding of regional/local extreme events). They also have been shown to be essential for improving the skill of predictions across timescales (from NWP to decadal predictions). Indeed, regional observations have a demonstrated impact in regional (or downscaled) predictions/projections[26]. They are therefore meaningful to guide national adaptation policies and actions (such as revised plans of flooding and inundation risk areas, coastal management, land and ocean farming potential, etc.).
- Finally, Climate Data Records (CDR) constitute a valuable asset for insurance and reinsurance companies willing to assess their level of exposure to climate hazards in different areas of the globe. Such a requirement is also shared by international development agencies to assess the climate proofing of specific investments.

[26] According to the Glossary of IPCC AR6 WG1: A climate prediction or climate forecast is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual or decadal time scales. Because the future evolution of the climate system may be highly sensitive to initial conditions, has chaotic elements and is subject to natural variability, such predictions are usually probabilistic in nature. A climate projection is the simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases (GHGs) and aerosols and changes in land use, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/ radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized.

3. GCOS: VISION, MISSION, BENEFITS, EVOLUTION AND FUTURE PRIORITIES

GCOS is the authoritative source of information and advice on global climate observational system requirements to inform processes and stakeholders such as UNFCCC, WMO, IPCC, and the global mitigation and adaptation communities. Its activities over the past 30 years, including prior IP reports, have led to demonstrable improvements in the global observing system and the improved availability of observations to underpin climate science and climate applications in support of society.

3.1 Vision Statement

GCOS works towards a world where climate observations are high-quality and sustained, and access to climate data is comprehensive, free and open.

3.2 GCOS Mission

GCOS is the authoritative global source of information and advice for the planning and development of the Global Climate Observing System, its networks and data management. It is the authoritative source reference for formulating requirements for space and in situ climate observations. GCOS relies on contributions from a wide range of observing systems including meteorological, hydrological, terrestrial and ocean observing networks, satellites and many others and in return provides advice on how they can be used to meet climate needs.

3.3 Contributions of GCOS

3.3.1 In situ measurements

GCOS has long-standing two-way relationships with in situ data providers, providing requirements to guide the planning and development of observational networks.

There are several observational networks that have varying degrees of direct oversight and reporting to GCOS. The GCOS Upper Air Network (GUAN) and the GCOS Surface Network (GSN) represent baseline networks to enable global monitoring activities of atmospheric ECVs. The GCOS Cooperation Mechanism (GCM) has supported the GCOS network managers in addressing issues in these networks, maintaining key sites in their operations. GCOS has developed the GCOS Reference Upper Air Network (GRUAN) which has created reference-quality measurement series for key ECVs. Improved instrumental understanding has trickled down to other observational networks. A new GCOS Surface Reference Network (GSRN) is being instigated to address a gap in current capabilities.

GCOS has also worked with a broad variety of organizations concerned with the provision of additional ECVs, many taken by GCOS recognized networks such as the Global Terrestrial Networks for hydrology, glaciers and permafrost, as well as by CryoNet of the Global Cryosphere Watch (GCW) and by the Global Atmosphere Watch (GAW) programme and connected networks.

When the Global Ocean Observing System programme (GOOS) develops new observational capabilities, it considers the GCOS ECVs requirements.

GCOS works with data centres such as WGMS, HYDROLARE, ISMN, NCEI, and Copernicus (CDS), amongst many others, to ensure that data are accessible and freely available to users.

GCOS provides visibility and voice for observing system operators in the UNFCCC processes and IPCC assessments.

3.3.2 Satellite Observations

The satellite agencies have continuously worked with GCOS to inform their decision making. For the past two IP cycles the Joint CEOS/CGMS Working Group on Climate has taken the IP and issued a response document informing how they intend to respond to the actions identified. This has led to demonstrable actions by CGMS and CEOS members in terms of mission continuity and activities to curate, reprocess, rescue and create climate data records from a variety of satellite observing techniques.

3.3.3 WMO

Through activities of the Infrastructure Commission of WMO (and its predecessors), GCOS has contributed to key developments including inter-alia:

- The Global Basic Observing Network (GBON[27]).
- The Systematic Observations Financing Facility (SOFF[28]).
- The new WMO Unified Data Policy[29].
- The Regional Basic Observing Networks.
- Vision for the future of the observing system.
- Regulatory materials.
- Data formats for exchange of daily and monthly summaries.

GBON and SOFF should provide a global network of observations with adequate, sustainable funding that will provide the minimum data needs of climate reanalyses and NWP models.

For all observational types GCOS contributes climate requirements to the Rolling Review of Requirements process which is a technology-agnostic set of requirements for measuring a broad range of ECVs. GCOS has actively contributed to this process, ensuring that long-term continuity and stability are included. These requirements directly influence planning decisions by both satellite agencies and in situ operators. The latest version of these requirements is provided in the document GCOS-245 – The 2022 GCOS ECVs Requirements.

3.3.4 UNFCCC

The agreement reached in Paris in 2015 by the UNFCCC exemplifies the renewed global interest "to respond to the urgent threat of climate change on the basis of the best available scientific knowledge". This requires an unprecedented amount of data and information about the past, present and future climate, the availability of which is only made possible by a global coordinated effort towards the systematic observation and collection of key climate variables, including observations of their extremes that are increasingly important for adaptation and to understand potential impacts. From the analysis of current climate hazards and vulnerabilities to the evaluations of the realism of climate model projections through the initialisation of decadal predictions, our society requires now, more than ever before, the coordinated global effort on climate observation that GCOS has worked so hard to develop. The effort of GCOS is also essential to ensure a sufficient visibility is maintained of the value that the systematic observations of the climate provide to our ability to write informed policy.

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[27] Resolution 2 (Cg-Ext(2021) - Amendments to the Technical Regulations related to establishment of the Global Basic Observing Network (GBON) (2021)
[28] Resolution 3 (Cg-Ext(2021) - Systematic Observations Financing Facility: Supporting Members in the implementation of the Global Basic Observing Network (SOFF) (2021)
[29] WMO Unified Policy for the International Exchange of Earth System Data (2021): https://library.wmo.int/doc_num.php?explnum_id=11113#page=9.

3.3.5 Research and academia

Observations promoted by GCOS provide the basis for scientific developments and improved understanding on the climate and how it is changing. Working with the World Climate Research Programme (WCRP), GCOS can identify emerging needs arising from climate research. In addition:

- GCOS looks at how well observations support the understanding of the main climate cycles (e.g., energy, water, and carbon). GCOS is the only programme within the UN framework that encompasses all the components of these cycles.
- Observations are key to identifying climate extremes and how they are changing.
- Observations are essential to support reanalysis, modelling and other research activities.
- The IPCC assessments of climate science are underpinned by climate observations sponsored by GCOS.

3.3.6 International programmes on climate

GCOS provides the framework around which a systematic monitoring of the climate system has been developed. Reports on the state of the climate rely on GCOS ECVs (e.g. the WMO state of the climate report, and BAMS State of the Climate, and regional reports such as the European State of the climate report produced by Copernicus).

Ultimately, to be useful, all this information must be presented to the public and policy makers in an understandable form. For society to fully benefit from the currently available observations it is essential to consider the full value chain, involving scientists, experts and the long tail of intertwined actors that transform raw climate observations into monitoring tools, early warning systems or value-added climate applications.

Climate observations now serve a community that extends far beyond the academic circles and reaches all sectors of society. GCOS provides global standards and guidance these sectors require when using climate data. These standards are essential for allowing the development of credible and robust climate applications and tools.

3.4 The evolution of GCOS from past to present

GCOS has needed to evolve to identify and advocate for data to meet the established and emerging needs of users, to address gaps in global climate observations for different climate user communities and to provide guidance for their improvement. Over the 30 years of GCOS operations, the observing system has changed and improved considerably with the advent of major new in situ and satellite capabilities and the emergence of various types of reanalysis products.

Since the last IP, there have been many improvements in climate observations, including the provision of more in situ, remote and space-based data for atmospheric observations, enhanced temporal and spatial satellite observations of the Earth's surface and biosphere, and technological innovations that have contributed to the expansion of the ocean observing system. Further details on these advances can be found in the latest 2021 GCOS Status Report. These examples show the responsive nature of GCOS and its role as a catalyst to improve climate observing systems and stimulate global and regional networks. This 2022 GCOS IP makes clear to all interested communities the vision of GCOS for the free and open provision of sustainable and high-quality climate observations to meet existing and new demands. In particular, GCOS is engaged in the development of observing systems that allow the quantification of climate impacts (e.g. health, energy, water and food sectors) and associated information for national economic development, which will contribute to adaptation and mitigation measures in the implementation of the Paris Agreement. A GCOS Adaptation Task Team (GATT) has been established to assess the adequacy of the observing system to meet the information needs of adaptation.

GCOS will continue to lead the development of systematic climate observations to tackle these challenges.

3.5 Priorities identified by GCOS

This plan is based on needs and gaps identified in the latest GCOS Status Report (2021); in the sixth assessment reports of the IPCC; by Parties to the UNFCCC; studies on how well observations monitor the climate cycles of carbon, water and energy; by the Joint CEOS/CGMS Working Group on Climate (WGClimate) and feedback from the observation communities to the GCOS Expert Panels. GCOS will continue its role of monitoring the performance of the global climate observing system and encouraging its improvement. GCOS has identified a number of priority areas for activities in the next 5-10 years, and these form the thematic basis for the actions which are further outlined in Chapter 6. They represent focus areas that are necessary to advance the ability to make, curate, process and exploit observations in service to society i.e. to ensure an unbroken value chain. The themes are as follows:

A. Ensuring the sustainability of key existing observation programs. To be useful for monitoring the changing climate system, key observations across all Earth System domains from both in situ and satellite programs must be acquired on a sustained basis. Particular attention is required on programs deemed at risk.

B. Filling data gaps in current observing capabilities. For some ECVs or observing platform types there exist data gaps that require addressing. For other ECVs substantial new observation programs are required to improve monitoring and process understanding.

C. Improving data quality, availability and utility, including reprocessing. Many observations are underexploited as the data are not in a form that is easy to use. This theme looks at how the raw observational data is transformed into data useful for users. This includes reprocessing, data fusion and reanalysis.

D. Improving data management. Data should be stored in well-curated, open, sustainable archives with clear guidance to data centres and users. This is not always the case and work is required to organise more efficiently data rescue, data sharing, data curation and data provision to users to maximise the exploitation potential of Earth Observation data.

E. Engaging with countries and stakeholders. GCOS needs to engage with countries and stakeholders on a sustained basis to meet its strategic goals more effectively. Regional and national activities should encourage the incorporation of national systems into the global observing systems. GCOS can also help coordinate capacity building leading to sustainable improvements in observational infrastructure.

F. Addressing other emerging needs. The needs of end users are constantly evolving. GCOS has identified areas where observations can be exploited specifically to support developing response measures such as adaptation and mitigation. These areas include climate extremes, urban areas and carbon fluxes.

4. ESSENTIAL CLIMATE VARIABLES

To clearly present climate observational needs, GCOS has developed the concept of Essential Climate Variables. The ECVs emerged in the context of the needs of the UNFCCC in the Second GCOS Adequacy Report[30].

An ECV[31] is a physical, chemical or biological variable (or group of linked variables) that critically contributes to the characterization of Earth's climate. ECV datasets provide the empirical evidence needed to understand and predict the evolution of the climate, to guide mitigation and adaptation measures, to assess risks and enable the attribution of climatic events to underlying causes, and to underpin climate services. They are required to support the work of the UNFCCC and IPCC.

The ECVs must not be understood as a select group of stand-alone variables; they are part of a wider concept.

ECVs are identified according to the following criteria (Figure 1):

1) **Relevance:** The variable is critical for characterising the climate system and its changes.
2) **Feasibility:** Observing or deriving the variable on a global scale is technically feasible, using proven, scientifically understood methods.
3) **Cost-effectiveness:** Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

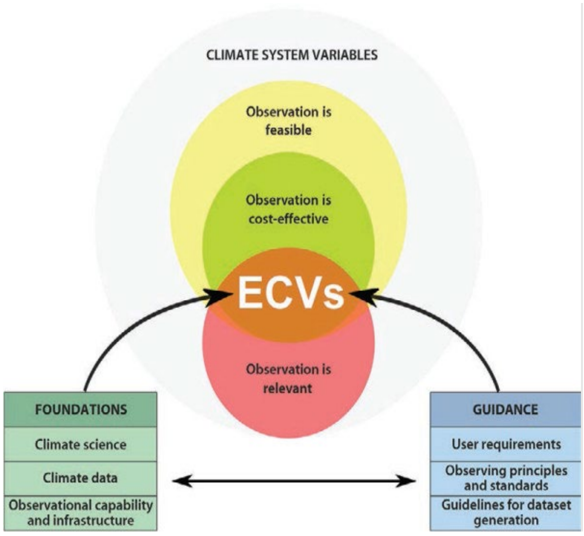

Figure 1. Schematic of the ECV concept

(*Source:* Bojinski, et al., BAMS, 2014)

Knowing existing climate-relevant observing capabilities, climate datasets, and the scientific understanding of the climate system are the foundations necessary for selecting the ECVs from the pool of climate system variables. GCOS provides guidance on ECVs covering:

- User requirements to capture the needs of science, services and policy.
- Climate-specific principles to guide the operation of observing systems and infrastructure.
- Guidelines to facilitate the transparent generation of ECV data records. This also addresses the availability of metadata, provisions for data curation, free and open distribution, and the need for quality assessment and peer review.

GCOS has asked its expert panels, informed by the wider community, to define requirements of these ECVs. The document GCOS-245 – The 2022 GCOS ECVs Requirements lists the requirements for all ECVs.

[30] GCOS (2003) Second report on the adequacy of the global observing systems for climate in support of the UNFCCC. GCOS-82, 85 pp.
[31] Bojinski, S., et al., 2014: The Concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy. *Bulletin of the American Meteorological Society*. 95. 1431. 10.1175/BAMS-D-13-00047.1. doi:10.1175/BAMS-D-13-00047.1

These requirements are specified in terms of:

- ECV – the name and definition of the ECV.
- ECV Product – name, definition and units of measurable parameters needed to characterise the ECV. Some ECVs have one product – others several.
- Temporal resolution (or frequency) – the frequency of observations e.g. hourly, daily or annual. This depends on the ECV. Some need to be measured frequently to capture short-term events and extremes, others only apply at longer intervals e.g. to measure long-term changes in glacier mass.
- Spatial Resolution - horizontal and vertical (if needed).
- Required Measurement Uncertainty and Stability - Uncertainty is "associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" (Guide to the expression of uncertainty in measurement, GUM[32]). Knowledge of the uncertainty ensures a greater confidence in the assessment of climate change and variability. Changes in the long-time series needed for climate monitoring are often gradual and usually smaller than the annual variability. Thus, measurements over long time periods are needed with reliable, sustainable systems with minimal instrumental error and drift (stability).
- Timeliness. This is a new requirement in this 2022 GCOS Implementation Plan. Timeliness defines how soon after the observation is taken, the data is needed i.e. the latency. While for general climate applications a minimum data delivery delay is not crucial, this may be important to support short-term modelling and warning systems, adaptation and inform policy. Hence, when possible, data should be delivered within the timeliness requirement.

In this Implementation Plan, for each value, a threshold, breakthrough and goal value is presented. These are defined as:

- **Threshold:** the minimum requirement to be met to ensure that data are useful.
- **Breakthrough:** an intermediate level between *threshold* and *goal* which, if achieved, would result in a significant improvement for the targeted application. The *breakthrough* value may also indicate the level at which specified uses within climate monitoring become possible. It may be appropriate to have different breakthrough values for different uses.
- **Goal:** an ideal requirement above which further improvements are not necessary.

The ECV framework has evolved since the publication of the previous list of ECVs requirements in the GCOS IP 2016. Annex A illustrates the changes between the list of ECVs and ECV products published in 2016 and the current list.

The updated ECV requirements will be part, when applicable, of the OSCAR (WMO Observing Systems Capability Analysis and Review Tool) requirements[33] for the application area "Climate Monitoring". Within climate monitoring there are multiple uses for each ECV from global monitoring to local adaptation planning (e.g. global average temperature and local heatwaves; global sea level rise and local coastal sea level changes; and global precipitation changes and local extreme precipitation events). Each of these applications may have different observational needs in terms of resolution and accuracy. However, presently it is not practical to provide

[32] Evaluation of measurement data — Guide to the expression of uncertainty in measurement, JCGM (2008) https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6

[33] https://space.oscar.wmo.int/observingrequirements

completely separate requirements of all applications as this would greatly increase the number and variety of requirements and the workload for the expert panels. GCOS needs to consider how to approach articulating requirements specifications for multiple uses of data over the next few years.

Traditionally the three GCOS Expert Panels, each covering a specific domain, have tended to work independently on relevant ECVs. More recently, GCOS has started looking at how well the climate cycles are observed, and this has allowed consideration of the ECVs across the atmospheric, oceanic and terrestrial domains, identifying inconsistencies, gaps and major uncertainties. Figure 2 illustrates the main contributing ECVs to each cycle, recognizing that many ECVs contribute to several cycles.

Over the period covered by this Implementation Plan further improvements, led by the GCOS programme, are foreseen as follows:

- Firstly, GCOS will need to ensure the observing system meets the requirements of users for climate monitoring. Satellite operators wish to know which uses are met by specific levels of resolution and accuracy. In addition to observations by the Global Climate Observing System, adaptation requires local observations and observations of extremes: observations should cover the locations of impacted populations and infrastructure. Some impacts will only occur in certain areas e.g. sea-level rise is mainly an issue for coastal areas. GCOS will work to develop a system to meet this need for multiple uses of an ECV.
- Secondly, as the complexity and maturity of the observing systems has grown, so has the list of ECVs. However, many of these are closely related and could be grouped and, more simply, be presented as a single ECV. This rationalisation of the ECVs would make it easier to explain why they are needed and to demonstrate how they work together.

  For example, temperature is measured in many different places in the Earth system, from the upper air to the deep ocean. Presently it is covered by 5 different ECVs which is hard to justify. A single ECV Temperature with different ECV products accounting for measurements taken in different locations and domains would simplify and enhance clarity. This would also encourage consistency between these different temperature measurements.
- The work that started after the previous 2016 GCOS IP on the observation of the Earth's climate cycles has indicated the importance of this holistic assessment of ECVs across the various domains. Over the next few years GCOS will work to rationalise the list of ECVs. This work will represent an evolution and improvement and will not invalidate existing efforts to observe and use ECV observations. Input from users into the discussion will be encouraged.

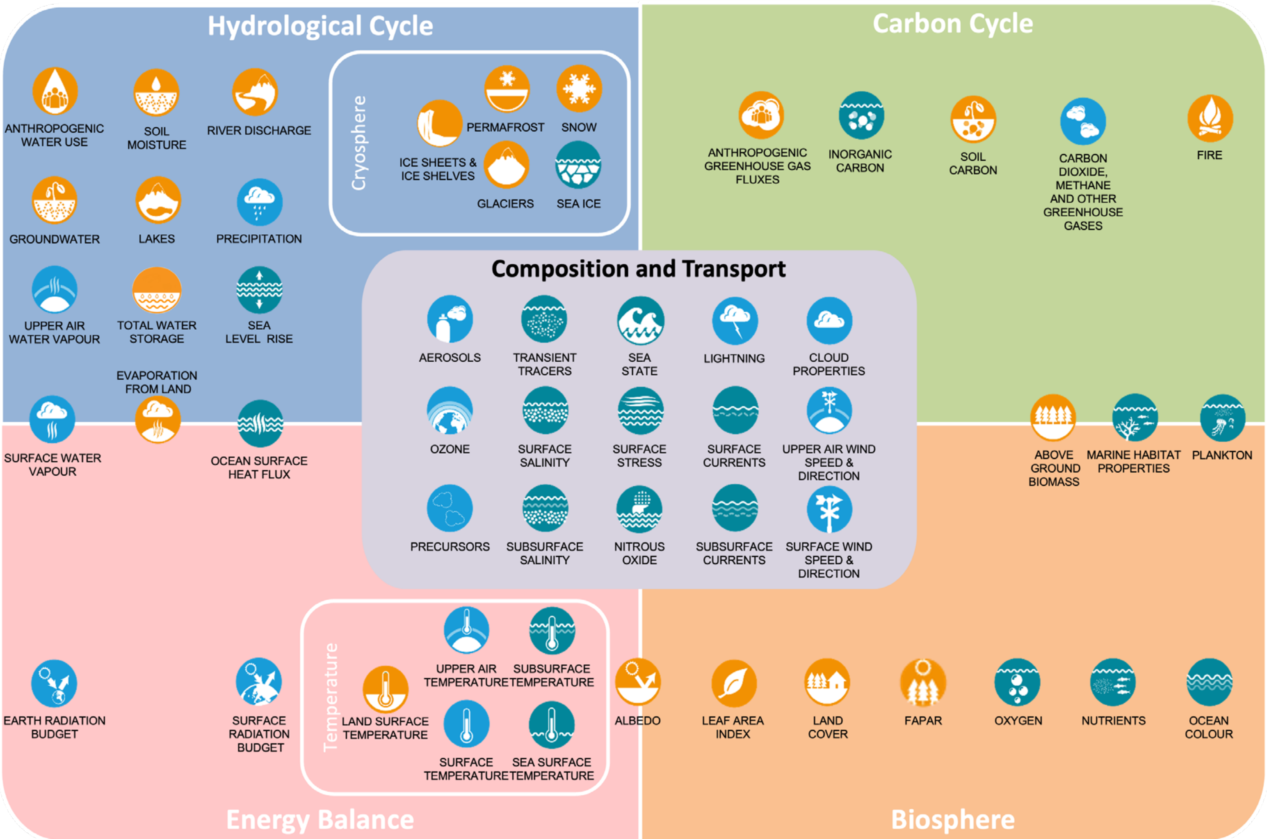

Figure 2. Essential Climate Variables and the climate cycles (See section 2.4). Many ECV contribute to understanding several different cycles – this only indicates the main links.

ECVs belong to three panel domains: ● Atmosphere ECVs (AOPC); ● Ocean ECVs (OOPC); ● Terrestrial ECVs (TOPC)

5. DATA MANAGEMENT AND POLICIES

Observations underpin all weather, climate, and water services and products. Without the collection and sharing of these observations, the ability to predict, understand, mitigate, and adapt to changes in the climate system is limited. One purpose of GCOS is to promote the collection and unrestricted distribution of accurate and sustained observations of the atmospheric, oceanic, and terrestrial components of the climate system.

Traditionally, the work of GCOS has focused on producing guidance for the improvement of the system of global climate observations. Given the ever-increasing need for historical climate observations that are reliable and easy to locate, retrieve, and use, GCOS is placing increased emphasis on activities aimed at improving the management and usefulness of these data in this Implementation Plan. This is driven by two major developments.

The first one is the ever-increasing need for timely access to accurate, easy-to-use climate data as weather and climate extremes become more frequent. More observations are being collected or digitised, and the technology enabling the processing and distribution of large amounts of data has become more readily available.

The second is the evolution, and increasingly widespread acceptance, of several sets of data sharing policies, principles, and best practices that facilitate such access. Historically, various methodological, legal, and structural challenges have hampered full compliance with data access guidelines. In addition, the multitude of data formats, processing methods, and documentation practices that are used by data distributors around the world, and the multitude of such distributors itself, hinders the utility of these data. In its 2021 Status Report, GCOS has identified several ways in which the access to and usefulness of climate observations can be improved. These fall into four broad areas:

1. Improved use of standardized metadata to check data quality.
2. Increased reliability and consistency of data processing and reanalysis methods, particularly with respect to ECVs.
3. Increased access to historical observations.
4. Identification or establishment of specific GCOS-endorsed global and regional data centres for ECVs.

The actions outlined in Chapter 6 of this plan address each of these areas.

The actions are founded not only on the new WMO Unified Data Policy, but also on three sets of data sharing principles that have emerged in the scientific data community over the past several years: the concept of free and open access, the FAIR Principles, and the TRUST Principles. Each of these sets of principles is briefly reviewed below.

5.1 Free and Open Data

In preparation for the International Geophysical Year of 1957–1958, the concept of open access to scientific data in general was institutionally established at an international level with the formation of the World Data Centre system (now called the World Data System (WDS)), by the International Council of Science (now the International Science Council (ISC)). The WDS is a federation of data centres that archive and provide access to data from across all scientific disciplines according to a set of Open Data Sharing Principles (e.g., Mauthner and Parry, 2013[34]).

[34] Mauthner, N.S., and O. Parry, 2013: Open Access Digital Data Sharing: Principles, Policies and Practices. Social Epistemology, 27:1, 47-67, DOI:10.1080/02691728.2012.760663

The rapid exchange of data and related information has also been a major purpose of the WMO since its founding in 1950 and is codified in Article 2(b) of the WMO Convention. Recently, expectations for Members in this regard were reiterated and expanded by way of the WMO Unified Data Policy which was approved by the WMO Congress in October 2021[35]. The new policy stipulates that "Members shall provide on a free and unrestricted basis the core data that are necessary for the provision of services in support of the protection of life and property and for the well-being of all nations …" and "Members should also provide the recommended data that are required to support Earth system monitoring and prediction activities at the global, regional and national levels…" and "provide without charge access to all recommended data exchanged under the auspices of WMO to public research and education communities, for their non-commercial activities…". The new policy also, for the first time, extends these obligations to exchange and share data to archives of historic data. The data defined as 'core' for each of the Earth system domains, including climate, are specified in an annex and inscribed in WMO technical regulations. A periodic, consultative review process will ensure that the specification of core and recommended data keeps pace with evolving requirements.

5.2 FAIR (Findable, Accessible, Interoperable, Reusable) Principles

The FAIR (Findable, Accessible, Interoperable, Reusable) Principles are a set of guiding principles for scientific data management proposed by an international consortium of scientists and organizations (Wilkinson et al., 2016[36]). These guidelines now form the basis of many data archiving and distribution policies and are endorsed by nearly 300 repositories, publishers, research organizations, societies, and individuals from around the world. The FAIR Principles advance and extend key open data concepts for data users by making data easy to find, combine, and integrate.

5.3 TRUST (Transparency, Responsibility, User focus, Sustainability and Technology) Principles

The TRUST (Transparency, Responsibility, User focus, Sustainability and Technology) Principles are founded in the premise that the preservation of data over time, whether it is free and open or not, requires trustworthy digital repositories with sustainable governance and organizational frameworks, reliable infrastructure, and comprehensive policies supporting community-agreed practices (Lin et al., 2020[37]). As of 2021, through a Research Data Alliance community effort, the TRUST Principles have already been endorsed by 39 international organizations that are committed to the stewardship of digital resources. They also form the basis for CoreTRUSTSeal certification of data repositories which is now a prerequisite for membership in the WDS.

[35] Similarly, the UNESCO Recommendation on Open Science was adopted by the General Conference of UNESCO, in November 2021, and identifies concrete measures on Open Access and Open Data.

[36] Wilkinson, M.D., et al., 2016: The FAIR guiding principles for scientific data management and stewardship. *Scientific Data,* 3, DOI:10.1038/sdata.2016.18

[37] Lin, D., J. Crabtree, I. Dillo, et al., 2020: The TRUST Principles for digital repositories. *Scientific Data,* 7, 144, DOI:10.1038/s41597-020-0486-7

6. ACTIONS TO IMPROVE THE GLOBAL CLIMATE OBSERVING SYSTEM

This chapter describes the priority actions that should be undertaken over the next 5-10 years to improve the global climate observing system.

GCOS continues to advocate for the sustained, systematic observation of the climate. To that end, this chapter addresses both sustainability issues that may arise in the near future and those improvements that should be implemented. Importantly, this plan assumes that, unless discussed in theme A, observations of ECVs, as listed in Annex A, will be maintained into the future.

The GCOS expert panels have noted that greater use can be made of the totality of observations of ECVs in modelling and research applications and this is being addressed by the broader scientific community.

As mentioned in section 3.5, the priority actions are divided into 6 themes. Within each action, one or more activities are specified to achieve the overall goal of the action, with specific, measurable and relevant means of assessing progress. Whilst it is expected that the actions will be extensively assessed in the next GCOS Status Report[38], the GCOS panels will be expected to regularly review and report on progress to the GCOS Steering Committee.

In the tables below, the implementers in bold are considered to take the lead in addressing and monitoring the activities. Table 2 lists the implementers as used in this report. Table 3 presents the themes, actions and implementers responsible for each of the actions.

Table 2. List of implementers used in this report. Some bodies roles may cover more than one of these, e.g. national governments may support academia, manage their own observing systems and/or provide funding.

Implementing Body	Notes
WMO	National Meteorological and Hydrological Services (NMHS), make national observations. In some cases Meteorological and Hydrological Services are separate bodies, in other cases they are combined. Their work is supported nationally, but coordinated and supported internationally by the WMO, which provides regulations and guidance on what and how to observe.
NMHS	
Space agencies	Space agencies typically support satellite observations and are national bodies (or regional in the case of ESA). Their climate observations are coordinated through the Joint GEOS/CGMS Working Group on Climate (WGClimate). The WGClimate also maintains the ECV Inventory of satellite based ECV Climate Data Records.
GOOS	The Global Ocean Observing System (GOOS) coordinates ocean observations under the auspices of the IOC of UNESCO. Their observations meet a range of needs from navigation and meteorology to climate.
Reanalysis centres	There are several centres providing global and regional reanalysis products. These are usually linked to weather prediction and use similar input data. Reanalysis products are often used for climate services (e.g. adaptation and mitigation) rather than the raw observation data due to their completeness and consistency.
Global Data Centres	There are a range of data centres collecting and making accessible ECV datasets. These may be supported nationally, regionally or

[38] The GCOS Assessment Cycle runs over a period of 5-6 years, roughly in line with the IPCC Assessment Report series. The next Status Report is due in 2026.

Implementing Body	Notes
	internationally. Data centres should provide long-term, sustainable data storage and provide free and open access to climate data. Satellite agencies typically make available their data with the ECV inventory providing the locations of datasets.
Research organizations	A wide range of organizations making and supporting research into climate change, its impacts and how to respond. Research agencies may look at new observing techniques. Research Infrastructures are facilities that provide resources and services for research communities to conduct research and foster innovation. Includes WCRP.
National agencies	Other national agencies that are responsible for some observations. Responsibilities vary from country to country but may include agriculture and aviation.
National governments, Parties to UNFCCC	National governments and the EU are parties to the UNFCCC. Often national governments manage or direct some observations and are responsible for reporting on climate observations to the UNFCCC
Academia	Academic studies make many observations and may be part of global networks. These are often not funded for long-term observations. New techniques and approaches are often pioneered by academia.
Funding agencies	There is a wide range of funding agencies that could support global climate observations. These range from global institutions such and the World Bank and GEF, through national bodies and funds to independent non-profit organizations.
GCOS	GCOS itself is a small secretariat supported by independent experts through its standing panels, AOPC, OOPC and TOPC and task teams assembled for specific tasks. The GCOS secretariat will coordinate appropriate experts to support individual activities in this Implementation Plan. The GCOS Secretariat will also coordinate ongoing tasks as part of its workplan to monitor the observation of ECVS and implementation of activities in this Implementation Plan, to review and develop the ECVs and their requirements and to identify observations to meet emerging needs such as adaptation and mitigation.

Table 3. List of Themes, Actions, and Implementers in GCOS Implementation Plan

Theme	Actions	Implementing Bodies											
		WMO	NMHS	Space agencies	GOOS	Reanalysis Centers	Global Data Centers	Research organizations	National Agencies	Parties to UNFCCC	Academia	Funding Agencies	GCOS
A: ENSURING SUSTAINABILITY	A1. Ensure necessary levels of long-term funding support for in situ networks, from observations to data delivery	x	x					x			x	x	x
	A2. Address gaps in satellite observations likely to occur in the near future			x									
	A3. Prepare follow-on plans for critical satellite missions			x									
B: FILLING DATA GAPS	B1. Development of reference networks (in situ and satellite Fiducial Reference Measurement (FRM) programs)	x	x	x				x				x	x
	B2. Development and implementation of the Global Basic Observing Network (GBON)	x	x		x								x
	B3. New Earth observing satellite missions to fill gaps in the observing systems			x									
	B4. Expand surface and in situ monitoring of trace gas composition and aerosol properties		x					x	x			x	
	B5. Implementing global hydrological networks	x	x	x			x						
	B6. Expand and build a fully integrated global ocean observing system		x	x	x			x	x		x		
	B7. Augmenting ship-based hydrography and fixed-point observations with biological and biogeochemical parameters				x			x					
	B8. Coordinate observations and data product development for ocean CO_2 and N_2O	x			x			x	x				
	B9. Improve estimates of latent and sensible heat fluxes and wind stress		x	x	x			x			x		
	B10. Identify gaps in the climate observing system to monitor the global energy, water and carbon cycles							x				x	x
C: IMPROVING DATA QUALITY, AVAILABILITY AND UTILITY, INCLUDING REPROCESSING	C1. Develop monitoring standards, guidance and best practices for each ECV	x		x	x								x
	C2. General improvements to satellite data processing methods			x				x			x		
	C3. General improvements to in situ data products for all ECVs		x					x			x		
	C4. New and improved reanalysis products			x		x					x		
	C5. ECV-specific satellite data processing method improvements			x		x							
D: MANAGING DATA	D1. Define governance and requirements for Global Climate Data Centres	x					x						x
	D2. Ensure Global Data Centres exist for all in situ observations of ECVs	x	x		x				x			x	x
	D3. Improving discovery and access to data and metadata in Global Data Centres						x					x	x
	D4. Create a facility to access co-located in situ cal/val observations and satellite data for quality assurance of satellite products	x	x	x				x					
	D5. Undertake additional in situ data rescue activities	x	x							x		x	x
E: ENGAGING WITH COUNTRIES	E1. Foster regional engagement in GCOS	x			x					x			x
	E2. Promote national engagement in GCOS		x							x	x		x
	E3. Enhance support to national climate observations									x		x	x
F: OTHER EMERGING NEEDS	F1. Responding to user needs for higher resolution, real time data	x	x	x				x			x		x
	F2. Improved ECV satellite observations in polar regions			x				x			x		
	F3. Improve monitoring of coastal and Exclusive Economic Zones		x	x	x			x			x		
	F4. Improve climate monitoring of urban areas	x	x					x	x		x		x
	F5. Develop an Integrated Operational Global GHG Monitoring System	x		x				x	x		x		x

6.1 Theme A: Ensuring Sustainability

Long-term, continuous, in situ[39] and satellite observations of the climate are necessary to understand and respond to the changing climate.

Sustained funding is essential to ensure the continuity and the expansion needed for many in situ observations of ECVs. While many atmospheric observations have sustained long-term funding, most ocean and terrestrial observations are supported through short-term funding, with a typical lifetime of a few years, leaving the development of long-term records extremely vulnerable. This is particularly true for parameters that are not traditionally monitored for weather predictions and will not be supported by WMO's GBON and SOFF, in its present design.

Since these observations are executed by a large range of actors, an effective observing system may benefit from an improved international coordination across networks and programs. Here the potential of "economy of scales" could make procurements of instruments less expensive. Sustainable networks need sustained funding and support that covers training, capacity building, equipment maintenance and replacement. Partnerships between experienced and less experienced actors provide this support.

While satellite observations have been a major success in monitoring many ECVs, long-term continuity of some satellite observations is not assured. While new satellites incorporate innovations and improvements, it is essential that consistent time-series are available across many missions. While making best efforts to ensure continuity and/or cross-referencing of key climate data sets, satellite agencies are encouraged to proceed with the exploration and demonstration of new technologies to observe the Earth system from space (e.g. Stephens et al., 2020[40]).

Future climate observing capabilities that are at risk are identified in the 2021 GCOS Status Report. This theme focuses on those in situ and satellite observations that are particularly at risk, while acknowledging that all observations of ECVs need to be sustained.

Action A1: Ensure necessary levels of long-term funding support for in situ networks, from observations to data delivery	
Activities	1. Undertake an assessment of current levels of funding support for global in situ networks delivering relevant in situ ECV data, including cal/val measurements, and identify those in situ networks with immediate or short-term problems around adequacy and sustainability of funding - by end of 2023. 2. Identify entities that can provide support for the networks identified as at risk in Activity 1. 3. Advocate with funding agencies to support identified networks.
Issue/Benefits	Not all in situ networks have the assurance of the long-term support needed to ensure the continuity and development of long-term time-series needed for climate monitoring. Although progress has been made, some networks are still supported by short- and fixed-term funding or have inadequate funding support. This action aims to make progress in addressing this issue by improving the sustainability of in situ measurement programs. Improved funding support for networks performing measurements of ECVs would improve our ability to undertake long-term monitoring of the changing climate

[39] In this document we refer to all non-satellite observations as "in situ" including ground-based and aircraft-based remote sensing.
[40] Stephens, G., et al., 2020: Revolution in Earth Observations. *Bulletin of the American Meteorological Society* 101, 3, E274-E285, doi.org/10.1175/BAMS-D-19-0146.1

	system. This informs climate assessments such as IPCC and WMO annual reports. Furthermore, it is essential for climate services, adaptation activities and mitigation efforts. Sustained in situ observations provide critical input to reanalyses and aid satellite cal/val activities, especially as new missions/instruments are launched.
Implementers	From 1 to 3: **GCOS**, WMO, NMHSs, Research organizations, Academia, Funding agencies.
Means of Assessing Progress	1. Initial inventory of the funding profile for identified in situ networks that provide ECVs, considering adequacy and sustainability of funding support. Findings are to be prepared by all GCOS panels and consolidated in the form of a GCOS report by the end of 2023. The report should provide a current health snapshot of financial support for the networks. 2. Regularly reassess and report in future GCOS Status Reports progress towards sustainable funding for those networks designated in the initial report as inadequate or at risk. 3. Number of in situ networks for which funding support as a whole has been improved.
Additional Details	GCOS panels should inventory key current in situ networks and ascertain their levels of support, and barriers to their full implementation, and highlight examples of existing sustainable solutions. NMHSs, research performing organizations and other public and private funders should then take the outcomes of these assessments and attempt to remedy issues raised. A final assessment will then be made at the end of the IP / Status report cycle.
Links with other IP Actions	All ECV need sustained support, but this GCOS IP has identified the following actions: B4: in situ observations of atmospheric composition ECVs. B6 and B7: expansion and integration of the global ocean observing system, including observations of biogeochemical/biological parameters.

Action A2: Address gaps in satellite observations likely to occur in the near future	
Activities	Urgent actions are needed to ensure continuity of the following satellite observations: 1. Altimetry in the polar regions. 2. Gravimetry missions. 3. Biomass measurements. 4. Limb-sounding missions capable of measuring several ECV species in the Upper Troposphere/Lower Stratosphere (UTLS) and stratosphere. 5. Sea Surface Salinity (SSS) measurements. 6. Wind lidar. 7. Global scale ice surface elevation.
Issue/Benefits	Monitoring of many ECVs which are critically important to climate science are now dependent on satellite observations. There is a real danger that some observations will stop in the next 5-10 years, or even sooner for missions that have already exceeded their expected lifetime. The continuity of these measurements is essential to develop and extend the long time series needed for climate monitoring.
Implementers	From 1 to 7: **Space agencies.**

Means of Assessing Progress	From 1 to 7: Established plans of Space agencies that ensure the continuation of satellite missions for altimetry, gravimetry, biomass, limb-sounding, sea surface salinity, wind lidar, global scale ice surface elevation.
Additional Details	These address some of the gaps identified in the GCOS Status Report. 1. Sea surface height has been measured with satellite altimeters since 1992 usually with a 2-satellite configuration as a baseline. Several missions are currently in operation or designed for the near future including Jason-3, Sentinel-3 SRAL, Sentinel-6 series and the Copernicus expansion missions (CRISTAL and SNG-topography). In order to address the potential future gap in polar satellite altimetry, alternative approaches should be explored, including the lifetime extension of CryoSat-e or ICESat-2; an alternative satellite manoeuvred into a high-inclination orbit; the acceleration of CRISTAL and/or S3NG-T launches; or a systematic airborne measurement programme as a bridging capacity. Without successful mitigation, there will be a gap of between 2 and 5 years in our polar satellite altimetry capability. This would jeopardise long-term records of ice sheet and sea ice thickness change and polar oceanography. 2. Satellite gravimetry missions provide critical ECVs data, including for sea level, terrestrial water storage (TWS) and ice sheet monitoring. There is also potential for data from this source to supersede or complement the assessment of existing low (time and space) resolution anthropogenic water use and groundwater monitoring, or to serve early warning systems for large-scale flood events or drought monitoring and forecasts. Current and past measurements originate from Gravity Recovery and Climate Experiment (GRACE) during 2002-2017, GOCE (2009-2013) and the GRACE-FO (2018 – until now). Feasibility studies for next-generation gravity missions with potentially higher spatial and/or temporal resolution are underway at Space agencies, but the realisation of such missions for ensuring the long-term climate records is not assured. 3. Biomass: Space-based estimates of aboveground biomass and associated carbon stocks and changes are essential to monitor this ECV globally. Several dedicated satellite missions (such as NASA-GEDI/ICESAT/NISAR, ESA-BIOMASS, JAXA-MOLI) have been developed and are operating but none of them are part of a dedicated programme for regular, high-quality biomass monitoring in the long-term. Agencies and the EU Copernicus programme are encouraged to explore synergy and harmonise among available mission data and put in place a coordinated, continuous and consistent space-based biomass observation programme for global and national monitoring of aboveground biomass and associated carbon stock changes. 4. Only the Aura Microwave Limb Sounder (MLS) currently produces daily, near-global coverage for vertical profiles of water vapour from the upper troposphere through the stratosphere and into the mesosphere. In 2021, MLS had exceeded its "expected 5-year lifetime" by 11 years. Presently there is only one plan in progress to deploy another limb sounder (ESA's Altius) with similar capabilities as the Aura MLS and continuity is far from assured. 5. Sea Surface Salinity measurements are available from satellites since 2010 from SMOS, during 2011-2015 from Aquarius, and since 2015 from SMAP. These measurements resolve scales not afforded by in situ networks (e.g., down to tens of km) and cover regions inadequately sampled by in situ measurements (e.g., coastal oceans, marginal seas, polar oceans). Follow-on missions are needed to ensure a continuous global SSS record. Copernicus expansion mission CIMR A/B scheduled to be launched in 2028 aims to continue the satellite SSS record and, in particular, improve the sampling and accuracy of satellite SSS measurements for polar oceans.

	6. The ESA Aeolus wind lidar mission demonstrates successfully that global wind fields can be obtained from lidar in space. Assimilation of the data into NWP systems shows a positive impact, and thus will have a positive impact on future reanalysis quality. It is expected that long-term measurements would provide accurate observations in large scale wind regimes associated with climate states. No follow-on mission is presently assured although plans are actively being considered by EUMETSAT/ESA. 7. The freely available optical stereo data, such as those from Terra ASTER, are coming to an end of its lifetime and there are no plans for a replacement, that would be urgently required for the continuation of the dataset on global ice surface elevation.
Links with other IP Actions	Satellite observations are related to many other actions. In particular: C5 (Activity 2): enhancement biomass estimation at global and subnational levels. F1 (Activity 2): higher-resolution biomass data. F2 (Activity 1): sea surface salinity in polar regions.

Action A3: Prepare follow-on plans for critical satellite missions	
Activities	Develop follow-on plans to ensure medium and long-term continuity of the following satellite observations: 1. Earth Radiation Budget (ERB) measurements. 2. Cloud profiling. 3. Cloud lidar. 4. Global Precipitation Measurement (GPM) consisting of a dual-frequency precipitation radar and passive microwave measurements to provide sufficient temporal and spatial sampling of rain areas. 5. Sea ice and icebergs (or floating ice).
Issue/Benefits	Monitoring of many ECVs which are critically important to climate science are now dependent on satellite observations. The lack of confirmed plans for follow-on missions for some of these observations leaves the climate data records for some ECVs at risk. The continuity of these measurements is essential to develop and extend the long time series needed for climate monitoring.
Implementers	From 1 to 5: **Space agencies.**
Means of Assessing Progress	From 1 to 5: Established (long-term) plans of Space agencies demonstrating the continuation of satellite missions for earth radiation budget, cloud profiling radar, cloud lidar, GPM and floating ice.
Additional Details	These address some of the potential gaps identified in the GCOS Status Report. 1. Continuous Global Earth outgoing shortwave and longwave fluxes have been measured through CERES since March 2000. The latest CERES instrument was launched in 2017 on NOAA 20 and will be succeeded by the recently selected NASA instrument Libera, projected to be launched in 2027 on JPSS-3. The instrument specifics are such that seamless continuation of the ERB measurements is facilitated. Mission overlap of at least one year is anticipated but not guaranteed. Gap probability is estimated at 40% by 2028, provided that NOAA-20 remains operational. The ESA/JAXA EarthCare mission, expected to be launched in 2023, will fly a broad band radiation budget instrument.

	2. The ESA/JAXA Earth Cloud Aerosol and Radiation Explorer (EarthCARE) satellite mission will advance our understanding of the role that clouds and aerosols play in reflecting incident solar radiation back out to space and trapping infrared radiation emitted from Earth's surface. Inter alia it will fly a cloud profiling radar (CPR, 94 GHz) which provides vertical profiles of cloud structure along the subsatellite track to obtain micro- and macroscopic properties of clouds. It continues the successful NASA CloudSat mission. NASA's current plans for the Atmospheric Observation System (AOS). https://aos.gsfc.nasa.gov/spaceborne.htm) include employment of doppler radar and lidar measurements in polar and inclined orbits. 3. EarthCare will also fly an Atmospheric Lidar (ATLID). It measures the backscatter from aerosol and clouds and detects vertical profiles of radiatively significant clouds/aerosols. It continues the successful NASA/CNES CALIPSO mission. NASA's current plans for AOS include employment of Lidar measurements in polar and inclined orbits. 4. Various activities are on the way to improve precipitation observation capabilities. For example, the TROPICS mission will deploy six cubsats with passive microwave sensors in three orbital planes providing observations of tropical cyclones. Dual-frequency rain radars in space should be established as a core operational activity. However, the issue of lacking polar coverage should be addressed (e.g. through a concept of combining committed and existing missions). Current plans for NASA's AOS mission include a platform in polar orbit, combining Doppler Radar and microwave measurements (https://aos.gsfc.nasa.gov/spaceborne.htm). 5. Sea ice and icebergs can be detected, classified, and followed in their drift through satellite sensors (including microwave radiometers, altimeters and Synthetic Aperture Radar (SAR)). SAR sensors are the most valuable for these tasks because the monitoring of floating ice can be done in all weather conditions, despite the limitations of visible and infrared sensors. Current SAR missions are Sentinel-1, RADARSAT, SAOCOM-1, TerraSAR-X, COSMO-SkyMed, ALOS-2, among others. It is important to ensure that future SAR missions include in their objectives the acquisition of data for operational detection of floating ice which is also very important for safety of navigation as well as to monitor climate change.
Links with other IP Actions	Satellite observations are related to many other actions. In particular: B9: improve estimates of latent and sensible heat fluxes. B10: closure of energy budget. F2: improve ECV observations in Polar regions.

6.2 Theme B: Filling Data Gaps

This theme addresses gaps in the existing observing system identified in the 2021 GCOS Status Report.

By and large the observations fulfil many requirements and provide the basis for the very useful sets of ECVs. However, in situ observations for almost all the ECVs are consistently deficient over certain regions, most notably parts of Africa, South America, Southeast Asia, in the deep ocean and polar regions, a situation that has not improved since the 2015 GCOS Status Report (GCOS-195).

Despite their successes, gaps do exist in satellite observations. For instance, the existing Global Space-based Intercalibration System (GSICS) needs to be complemented and upgraded by satellite missions with stable reference instruments in the infrared (and other) parts of the spectrum (e.g. the CLARREO and TRUTHS missions). Another, important aspect hampering geographical coverage (notably with geostationary satellites) is the fact that not all satellite agencies have made observations available to the ECV inventory. All satellite agencies should strive to reprocess their data and make them available as climate data records.

Reference quality observations respond to the need for monitoring the changes that are occurring in the climate system and ensure greater confidence in the assessment of future climate change and variability. They support also timely political decisions for adaptation and can help to monitor and quantify the effectiveness of internationally agreed mitigation steps. Reference quality measurement programs have already been established for different domains, however there are still gaps that need to be addressed. For surface meteorological and terrestrial networks there is currently no global and coordinated reference observing tier. Existing national reference observations are not coordinated internationally, and do not provide coordinated data access.

WMO has adopted the concept for a Global Basic Observing Network (GBON) and for the Systematic Observations Financing Facility (SOFF). If their implementation is successful, GBON will provide essential observations for NWP and reanalyses, covering some ECVs, and SOFF will provide targeted financial and technical support for the implementation and operation of GBON and will address some of the gaps identified in the 2021 GCOS Status Report.

Action B1: Development of reference networks (in situ and satellite Fiducial Reference Measurement (FRM) programs)	
Activities	1. Continue development of GRUAN. 2. Implement the GSRN. 3. Better align the satellite FRM program to the reference tier of tiered networks and enhance / expand FRM to fill gaps in satellite cal/val. 4. Develop further the concept of a reference network tier across all earth observation domains. 5. Establish a long-term space-based reference calibration system to enhance the quality and traceability of earth observations. The following measurables are to be considered: high-resolution spectral radiances in the reflected solar (RS) and infrared (IR) wave bands, as well as GNSS radio occultations.
Issue/Benefits	The principal benefits of reference quality networks / measurements are: • Well characterised measurement series that are traceable to SI and/or community standards with robustly quantified uncertainties that can be used with confidence. • Improved instrument performance that transfers down to other broader global regional and national networks. • Characterisation of wider networks, especially of measurement quality. • Robust calibration/validation of satellite data. • Improved process understanding and model validation. However: • Although GRUAN has been successfully implemented since 2005, it remains far from being globally well distributed. • There is no Global Surface Reference Network, as yet. • The FRM programs of satellite agencies have been carried out independent of broader concerns around tiered network design, yet these measurements

	should be sustained as part of reference networks and not be funded or considered separately from broader observational strategies. There is also a need to undertake additional FRM measurements to fill critical cal/val capability gaps for some ECVs. • Whilst several in situ networks are considered to be of reference quality, as yet, apart from GRUAN, there are no additional GCOS recognized global reference networks. • Enabling traceable Earth observations from satellites will improve the accuracy and quality of many ECV data sets. In addition to meeting crucial inter-calibration needs, this effort will aid in better understanding climate relevant processes and their spectral signatures.
Implementers	1. **Lead Centre (DWD),** GCOS, WMO, NMHS. 2. **GCOS**, Lead Centre (CMA), WMO, NMHS. 3. **Space agencies**, WMO, GCOS, Funding agencies. 4. **GCOS**, WMO, NMHS, Research organizations. 5. **Space agencies.**
Means of Assessing Progress	1. Number of certified GRUAN stations and geographical distribution of stations; number of data products; data usage measured through citations. 2. Operational GSRN (for an initial set of stations focussing on temperature and precipitation). 3. a) Alignment of FRM programs into the tiered network of networks concept; b) Additional FRM measurements to fill gaps to support satellite cal/val of ECVs such as Above Ground Biomass, albedo, FAPAR, LAI and burned area. 4. Inventory of (potential for) global reference networks across atmosphere, ocean and terrestrial. 5. Implementation of CLARREO pathfinder, TRUTHS and Prefire. Plans for long-term follow-on missions to the short-term (~1 year) pathfinder missions (CLARREO and Prefire) and long-term continuous measurements.
Additional Details	Reference-quality measurements must be traceable to SI or community recognized standards and have their uncertainties fully quantified following the guidance laid out by BIPM. Measurements across a reference network must be metrologically comparable. 1. GRUAN is envisaged as a global network of eventually 30-40 measurement sites. As of August 2021, GRUAN comprises 30 sites, 12 of which have been officially certified. However, few GRUAN stations exist in several geographical regions (e.g. Africa, South America). There is also substantial work required to expand the number of GRUAN Data Products including from a range of ground-based remote sensing and in situ balloon-borne techniques. The WG-GRUAN is supported by, and reports to, AOPC who should continue to oversee progress. Regular Implementation and Coordination Meetings should continue. Efforts should be made to better integrate GRUAN into WIGOS operations. 2. A task team has been created under GCOS and SC-ON / SC-MINT to work towards the implementation of the GSRN. The GSRN should measure both near-surface atmospheric ECVs and site-relevant terrestrial ECVs and therefore the network will be overseen jointly by AOPC and TOPC from GCOS. CMA has agreed to host the Lead Centre for the GSRN. The GSRN TT, together with CMA, is

	expected to develop a proposal for the initial composition of the GSRN and start operations for the selected pilot stations by 2024. 3. Integration of FRM program measurements and associated support into long-term reference quality observing programs and networks assuring long-term cal/val operations. Including the provision of new FRM measurement programs and supporting infrastructure to fill critical current gaps in ECV satellite cal/val such as: • Networks in high and low above-ground biomass regions; • Ground-based in situ measurements of above-ground biomass and vegetation dynamics following FRM protocols (Dunanson et al., 2021); • Ground-based time-series in situ measurements of surface albedo, FAPAR and LAI with their uncertainties; • An open-access network of sites for burned area products. 4. There are known networks and activities that produce reference quality measurements, i.e. BSRN, GAW networks. Efforts should be made to better recognize these as global reference networks. The panels will plan how to implement other reference networks across all domains. 5. Spearheading spectral RS and IR measurements are the following space missions: CLARREO pathfinder will measure spectral (350 – 2300 nm) radiances and reflectances in the visible and near-IR (NASA; launch in 2023); Prefire will measure spectral (5-45 µm) far-IR emissivity (NASA; launch in 2022); Forum will measure spectral far-IR outgoing radiation (ESA; launch in 2026); and TRUTHS will measure spectral RS (ESA; launch in 2029). It is essential that Space agencies consider long-term follow-on missions to the short-term pathfinder missions (CLARREO and Prefire). This should draw upon GSICS.
Links with other IP Actions	C2: Improvements to satellite data processing depends on the availability of reference observations. D4: Improve access to co-located satellite and reference quality in situ observations.

Action B2: Development and implementation of the Global Basic Observing Network (GBON)	
Activities	1. Implementation of initial GBON and the associated SOFF mechanism to fill long-standing gaps to globally monitor climate over land and oceans. 2. Consideration of alignment of GSN and GUAN with GBON. 3. Planning the development of GBON and SOFF to cover more marine, hydrological, and atmospheric composition observations.
Issue/Benefits	To date the GBON has been scoped by and adopted by WMO members along with the associated SOFF mechanism. However, the network has yet to be formally implemented and monitoring and enforcement mechanisms put in place. The use of the SOFF to fill persistent gaps has yet to start. If successful, given potential overlaps with GSN and GUAN, the implications for the future of those GCOS networks has yet to be fully evaluated. Furthermore, the initial implementation of GBON is focussed on requirements for NWP and reanalyses and an extension is required in future to ensure that GBON also meets the broader needs for climate monitoring and adaptation. This needs an expansion of the observational variables supported by GBON and can be supported through, for example, inclusion of daily and monthly summary reports. The GBON effort and associated SOFF, if fully implemented, would represent a step-change in the ability to monitor surface and upper-air atmospheric ECVs on a

	sustained basis. Benefits will include more complete sampling of many GCOS ECVs over land, ocean and the cryosphere, and filling gaps that exist over several geographical regions. The GBON network, if fully implemented, would meet the stated requirements for ECV monitoring for those ECVs it measures.
Implementers	1. **WMO**, GCOS, GOOS, NMHS. 2. **GCOS**, WMO, NMHS. 3. **WMO**, GCOS, GOOS, NMHS.
Means of Assessing Progress	1. Number of GBON stations (including marine platforms in Exclusive Economic Zones (EEZs)), their geographical completeness and their continuity of data provision to data centres as well as over the WIS. 2. Assessment by GCOS of the continued relevance and role of GSN and GUAN at such time as GBON is considered to be fully implemented in its first phase with recommendations to GCOS Steering Committee. 3. GBON scope expanded to incorporate additional ECVs which are then observed on a sustained basis as part of GBON expanded operations.
Additional Details	1. In collaboration with WMO, ensure the full implementation of GBON and the associated SOFF mechanism to fill long-standing gaps to monitor climate over land and oceans. In particular, ensure that: • The initial GBON as adopted at WMO Extraordinary Congress in 2021 is implemented in full, including both surface and upper-air components; • GBON surface stations are encouraged to submit monthly and daily summaries in addition to synoptic reports; • The SOFF is used to target areas of data sparsity over land and EEZs and ensure continuity of capability. 2. After 2-3 years of operation, consider the relationship of GBON to GSN and GUAN. Does GBON fulfil all aims of GSN and GUAN or is there value in retaining GSN and GUAN as independent network designations? If they are retained: are any changes required to GSN and GUAN aims and governance accordingly? AOPC to report to GCOS Steering Committee in 2024/2025. 3. WMO envisages that GBON will expand to cover other domains. GCOS to take an active role in the continued evolution of the GBON network to ensure that climate needs are adequately accounted for. Progress to this end is to be assessed in the next GCOS status report.
Links with other IP Actions	B4: The extension of GBON (Activity 3) will benefit expansion of in situ monitoring of atmospheric composition ECVs. B8: The extension of GBON (Activity 3) will benefit the coordination of N_2O observations. C4: The implementation of GBON will benefit reanalysis.

Action B3: New Earth observing satellite missions to fill gaps in the observing systems	
Activities	1. Improve diurnal sampling of observations and coverage of GHGs, precursor aerosols, and solar-induced fluorescence (SIF) to improve estimation of emissions and vegetation carbon uptake. 2. Explore new ways to improve estimates of Earth's Energy Imbalance (EEI) with novel remote sensing techniques and with very well calibrated hyperspectral measurements over the full spectrum of the outgoing longwave and shortwave radiation.

	3. Provide direct measurements of ocean surface currents from space. 4. Explore and demonstrate the feasibility of satellite missions based on new satellite technologies for climate monitoring. 5. Develop operational techniques to estimate permafrost extent.
Issue/Benefits	1. Improving the coverage and spatio-temporal resolution of GHG, precursor aerosols and SIF measurements can be facilitated by constellations of low-earth-orbiting (LEO) satellite with varying overpass times, or observations from geostationary (low and mid-latitudes) and highly elliptical (high latitudes) orbits. High temporal frequency measurements are required for better diurnal characterization of GHG lifecycles, carbon cycle components and improved emission estimation in synergy with expanded in situ systems. 2. Direct measurements of the EEI need to be improved to the extent possible. However, the EEI cannot currently be determined from space-borne broad-band radiometers with sufficient accuracy. Direct measurements indicative of EEI from space would allow us to quantify and track Earth's energy uptake responsible for global climate change. On the one hand, new approaches based on hyperspectral longwave and shortwave radiances could provide the insight sought to understand the temporal change of the EEI. On the other hand, novel techniques that measure radiation pressure accelerations in orbit are expected to exceed accuracy limitations of broadband radiometry, but are currently at the concept stage of development[41]. 3. Ocean surface currents play an important role in redistributing heat, salt, passive tracers, and ocean pollutants in the surface layer of the ocean. These currents have significant implications to climate, weather, sea state, marine biology, ecosystems, and biogeochemistry. Currently, space-based estimates of near-surface currents are produced by combining surface geostrophic currents derived from altimetry and Ekman Current derived from ocean-surface wind stress (e.g., from scatterometers). They are more representative of mixed-layer currents than surface currents. Moreover, the geostrophic and Ekman theories break down near the equator, preventing reliable estimates of the currents from altimetry and scatterometry measurements. Direct measurements of surface currents from space are thus needed. 4. It is important to take climate related requirements directly into account during the development and implementation of new satellite missions. Therefore, it is necessary to proceed with exploration and demonstration of new satellite missions to be compatible with climate monitoring needs (Stephens et al., 2020)[42]. 5. Knowledge of changes in permafrost extent are important to adapt infrastructure and minimize losses due to melting permafrost.
Implementers	From 1 to 5: **Space agencies.**
Means of Assessing Progress	From 1 to 3 and 5: Feasibility studies addressing mission concepts relevant to observation and mission gaps. Solicitations by Space agencies for satellite mission development relevant to the above points. 4. Number of publications on new potential satellite climate observations.
Additional details	1. GeoCarb, to be launched in 2024, will be the first GEO-satellite to measure GHGs and SIF, covering latitudes between 50S - 50N over the Americas.

[41] M. Z. Hakuba et al., 2019: Earth's Energy Imbalance Measured from Space, in IEEE Transactions on Geoscience and Remote Sensing, vol. 57, no. 1, pp. 32-45, doi: 10.1109/TGRS.2018.2851976
[42] Stephens, G., et al., 2020: Revolution in Earth Observations. Bulletin of the American Meteorological Society 101, 3, E274-E285, doi.org/10.1175/BAMS-D-19-0146.1

	Complementary LEO (CO2M, OCO2, GOSAT-GW, TANSAT, as well as MicroCarb, to be lunched in 2023) and HEO satellite missions would provide high spatio-temporal resolution across the globe including the poles to improve monitoring of GHG emissions, which feature substantial diurnal variations, and changes to them. 2. Explorative studies to infer EEI directly from radiation pressure accelerations or alternative remote sensing techniques, and indirectly, through assessment of well-calibrated hyperspectral shortwave and longwave radiances. 3. Technologies for direct measurements of ocean surface currents already exist (e.g., using Doppler Scatterometry, Synthetic Aperture Radar, or Along-track Synthetic Aperture Radar Interferometry). But no such satellite mission has been committed by space agencies, although concepts are being studied by space agencies. The technologies have also been demonstrated from airborne campaigns. These technologies provide surface current measurements with much finer spatial resolutions (down to sub-mesoscales) than those of near-surface currents estimated from altimetry plus scatterometry data. The emerging new technological capabilities of satellite missions should be pursued with a view to obtain climate quality data with well-characterised and well-calibrated instruments.
Links with other IP Actions	Satellite observations are related to many other actions. In particular: B10: Develop plans to address gaps in the climate system for the energy cycle. F2: Improve ECV satellite observations in polar regions. F5 (activity 2): Design a constellation of operational satellites to provide near-real time global coverage of CO_2 and CH_4 column observations.

Action B4: Expand surface and in situ monitoring of trace gas composition and aerosol properties	
Activities	1. Expand surface-based and in situ observations of a range of atmospheric and oceanic composition ECVs, including GHGs, ozone, aerosol, clouds and water vapour, and other gaseous precursors, in the atmosphere. 2. Promote cooperation of the existing networks for establishing new composition observing capabilities in areas where they are lacking over land (in large areas of Africa, South America, Southeast Asia), over oceans, and over ice-covered regions.
Issue/Benefits	Well-functioning networks monitoring atmospheric composition of ECVs are beneficial for: i) evaluating the effectiveness of policies on agreed emission reductions; ii) monitoring trends and variability of atmospheric composition; iii) detecting early warning signals for climate system feedbacks on natural emissions; iv) providing real-time information in case of atmospheric hazards (e.g.biomass burning, dust events, volcanic eruptions); v) providing information for radiative forcing evaluation in global/regional climate-chemistry models; vi) evaluating global forecasting systems and atmospheric composition reanalysis using independent observations. While observations of atmospheric composition variables have further improved in the past decade thanks to new in situ observations from the ground and from commercial aircraft, surface-based and in situ networks for monitoring composition ECVs still suffers from important weaknesses: • Long-term continuity of some observations is not assured due to lack of sustained funding.

	• There are still important gaps in the global coverage of in situ composition observations.
Implementers	From 1 to 2: **NMHS,** Research organizations, Funding agencies, National agencies.
Means of Assessing Progress	1. Number of traceable composition observation data available from areas where they are current gaps, including remote locations. 2. Expansion of current composition networks (number of sampling stations) in areas not covered by observations.
Additional Details	Sustained composition observation capabilities both at the surface and of column characteristics of a range of trace gases, including well mixed GHGs, ozone, ozone precursors and water vapour, and aerosol with global coverage are needed. Existing capabilities need to be maintained, coordinated, and expanded to meet GCOS requirements. These include observations performed in situ (near-surface and onboard drones, aircrafts, ships, balloons and other vectors) and using remote sensing (e.g. lidar, FTIR, Brewer-Dobson). Integration needs to be sought with novel approaches to satellite measurements. In order to achieve activities 1) and 2), the following needs to be addressed: • Ensure the benefits of in situ composition observations in terms of future climate services are clearly understood by relevant national and regional authorities. • Design an implementation plan including network design and commence implementation. • Staff training.
Links with other IP Actions	A1: Expansion of atmospheric composition observations requires sustained funding. B2: Expansion of GBON could lead to more atmospheric composition observations. F4: Improve climate monitoring of urban areas will include atmospheric composition ECVs. F5: Activity 1: Design and start to implement a comprehensive global set of surface-based observations of CO_2, CH_4 and N_2O concentrations.

Action B5: Implementing global hydrological networks	
Activities	1. Improve the collection of hydrological observations, in particular: a) Improve global reporting of river discharge (e.g. to Global Runoff Data Center – GRDC) and water level data (e.g. to WMO Hydrological Observing System - WHOS), from a selected set of stations; b) Increase the number of in situ river level observations that are exchanged internationally and can be used to calibrate satellite observations of water levels; c) Increase global exchange of in situ water level observations of lakes and reservoirs to the International Data Centre on Hydrology of Lakes and Reservoirs (HYDROLARE); d) Increase the number of in situ observations of soil moisture in the International Soil Moisture Network (ISMN), including below-ground measurements. 2. Include in situ observations of Groundwater Level from national authorities (or other sources) that are minimally impacted by human influence into the Global Groundwater Monitoring Network (GGMN) to establish a global system.

	3. Report anthropogenic water use to Food and Agriculture Organization of United Nations (FAO) AQUASTAT in areas where data are missing.
Issue/Benefits	Hydrological observations contribute to model and satellite calibration and validation, climate studies, regional and local water resources assessments, improvement of prediction tools, impact assessments, freshwater inputs into the ocean and regional and local water resources studies. Currently there are no effective global networks for river discharge or groundwater. Many river discharge data have not been exchanged internationally for decades. Databases of groundwater, soil moisture, terrestrial evaporation, lake levels–and anthropogenic water use are incomplete. In some cases, this is due to restrictive data policies and political considerations, in others it may reflect observational problems. Although global data centres exist for most water-related ECVs, data exchange from the individual data providers to the data centres is often limited. To rectify this situation, this action aims to: • Establish a network of a limited set of river discharge measurement sites that are most important for international use, and that exchange data. • Support the use of satellite observations of river level to supplement in situ observations. This requires measurements of river levels at points useful for calibration and validation of satellite observations as well as being useful locally. • Establish a network that emphasizes below-ground measured soil moisture. This is a gap that consistently comes up for many applications and cannot be derived by remote sensing. Provide easy, open access to the network data to benefit all countries. A discovery service and the interoperability of hydrological observations should be introduced. So far, information on existing data is only available in a distributed form in the global data centres. This makes access difficult. • Identify where additional resources and support are needed for river discharge and groundwater observations to support future development of GBON and SOFF. The implementation of the three new WMO initiatives (i.e. the Unified Data Policy, the Global Basic Observing Network, and the Systematic Observations Financing Facility) should assist these activities. Anthropogenic water use data is collected in the AQUASTAT database managed by FAO. Despite recent improvements, the AQUASTAT database which is based on national reporting, has gaps, is not up to date and the spatial and temporal resolutions are too low. The satellite-based Total Water Storage ECV gives timely and complete regional coverage but does require the continuation of satellite gravity observations and will not replace the spatial resolution of AQUASTAT.
Implementers	From 1 to 3: **WMO (WHOS), NMHS, Space agencies, Global Data centres (GTN-H).**
Means of Assessing Progress	1. a) Identification of a set of river discharge stations to exchange data; b) Increased availability of calibrated satellite estimates of water levels in rivers; c) Increased reporting of river discharge and level data to GRDC using unrestrictive data policies; d) Improved reporting of groundwater data to the International Groundwater Resources Assessment Centre (IGRAC) using unrestricted data policies. 2. Identification a set of groundwater stations that are minimally impacted by human influence for reporting to IGRAC.

	3. Increased number of countries reporting to AQUASTAT and improve resolution: More countries reporting and increased resolution.
Additional Details	Many activities, developed in cooperation with GTN-H, provide hydrological products, including the groundwater level data collected at IGRAC, the river discharge at GRDC, the lake levels at HYDROLARE, the soil moisture data at ISMN, and the anthropogenic water use at AQUASTAT. However, large data gaps still exist and there is an insufficient exchange and delivery of the collected hydrological data to data centres. In line with WMO Resolution 1 (Cg-Ext(2021), these activities are all aimed at improving the global exchange of hydrological data and delivery to data centres of networks encompassed by GTN-H, in particular the GCOS baseline networks, and to facilitate the development of integrated hydrological products to demonstrate the value of these coordinated and sustained global hydrological networks. 1. To encourage more countries to freely provide quality-controlled river discharge data, there should be clear criteria for reporting only the selected data that are most important for the regional and global assessment of the water cycle. Data from selected hydrological gauging stations meeting the following criteria should be exchanged: • The most downstream stations on major rivers not impacted by tidal influences to better capture freshwater fluxes to oceans; • Hydrological monitoring stations representative of regional hydrology; • Minimally impacted stations suitable as reference or baseline stations for climate studies; • These selected sites will form a new global network exchanging and reporting data for use in global and regional assessments; • Potentially, satellite data of river levels can be used as a surrogate to fill in gaps in coverage. In situ data are needed to calibrate and validate satellite observations so they become an important source of water levels and ultimately discharge data e.g. the SWOT mission and follow-ups. 2. Despite the existence of a data centre (at IGRAC) there is no global reporting of data. To provide the information needed at a global level, data from selected groundwater monitoring stations that are minimally impacted by human influence should be collected and exchanged. While this new network of groundwater monitoring stations is a subset of all monitoring stations it defines the information that is needed for global assessments. 3. The collection of data for AQUASTAT needs to be improved to increase both coverage and temporal resolution with countries encouraged to improve reporting and greater understanding of the benefits of the global dataset.
Links with other IP Actions	B2: The development of GBON will contribute to implement Action B5. B10: Closure of water cycle.

Action B6: Expand and build a fully integrated global ocean observing system	
Activities	Increase the measurements of ocean ECVs into the deep ocean, under the ice and marginal seas by improving: 1. The Core Argo (ensuring that the target density is met), biogeochemical (BGC) and Deep Argo to achieve the OneArgo design. 2. The ship-based hydrography, fixed-point observations, autonomous and uncrewed observations. 3. The integration of observing networks to respond adequately to ECVs requirements.

Issue/Benefits	There are critical sampling gaps that limit the monitoring of the ocean state (for example, heat storage, carbon cycle and impacts on the biosphere). The transformation of the current Argo array to the integrated "OneArgo" array, the deployment of repeated hydrography, the deployment of fixed-point and other autonomous observing platforms and their integration aims to address these gaps by providing observations of surface and subsurface ocean properties, physical, biogeochemical, and optical properties aiming to collect ocean ECVs with an improved and very much needed global coverage. The extended in situ network will be key in closing budgets for climate cycles assessments, monitoring the state of the ocean, evaluating climate risks and impacts and guiding adaptation policies. It will be essential for calibration and validation of satellite measurements. An enhanced coverage for the ocean in situ surface and subsurface ECVs is also key for improving seamless forecasts as well as contributing to meeting the goals of the Paris Agreement.
Implementers	From 1 to 3: **GOOS**, Research Agencies, Academia, National agencies (oceanographic Institutes), Space agencies, NMHS (*see also key programmes and networks in* "Additional details").
Means of Assessing Progress	1. Number of core floats deployed to maintain the target density in the global ocean including marginal seas and polar regions; and number of Deep and BGC Argo floats operating after 5 years. 2. Increase of coverage in the global ocean of ship-based hydrography and fixed-point observations, including polar areas and marginal seas after 5 years. 3. Availability of integrated products.
Additional Details	In 2020, the Argo Steering Team endorsed a new Argo array design (called "OneArgo") that is truly global (including marginal seas and under ice), full depth, and multi-disciplinary, including Core, Deep, and biogeochemical BGC Argo floats. The estimated budget of OneArgo represents a three-fold increase in cost. OneArgo will include a novel data management system with real-time data freely shared through the GTS/WIS and high-quality datasets delivered within 12 months, supporting climate-relevant assessments, inventories, and metrics. Since 2021, OneArgo is a project endorsed by the UN Ocean Decade. Ship-based hydrography and fixed-point observations, autonomous and uncrewed are essential and complementary to Argo and further efforts must be undertaken to realise the vision of a fully integrated Ocean Observing System[43]. Some of the key programs and networks contributing to this Action are GO-SHIP, OceanSITES, Ocean Color satellites, Deep Argo, Biogeochemical Argo and Global Alliance of Continuous Plankton Recorder Surveys (GACS) (see OceanOPS Report Card[44] for more details).
Links with other IP Actions	B7 and B8: Improve components of the global ocean observing system. B9: Improve estimates of latent and sensible heat fluxes and wind stress. F3: Expand global ocean climate in situ observations into EEZ and coastal zones.

[43] Révelard et al., 2022: Ocean Integration: The Needs and Challenges of Effective Coordination Within the Ocean Observing System. *Frontiers in Marine Science.* https://doi.org/10.3389/fmars.2021.737671

[44] OceanOPS Report Card 2021 (ocean-ops.org)

Action B7: Augmenting ship-based hydrography and fixed-point observations with biological and biogeochemical parameters	
Activities	Add biological and enhanced biogeochemical sensors and field/laboratory measurements to the already existing ship-based hydrography and fixed-point observations to establish a baseline of plankton distributions and phenology (seasonal timing in phenotype and abundance).
Issue/Benefits	Some of the greatest uncertainties in the projections of future climate are associated with the response of the biosphere to present and future environmental change, and the subsequent biotic interactions, responses and feedback mechanisms. Both established and novel technologies provide the capacity to include measurements of plankton on existing coordinated observing platforms across a wide range of scale that can contribute to both the GOOS Biology and Ecosystem Essential Ocean Variables (EOVs) and the GCOS ECVs to deliver global observations. Broadening current hydrography and oceanography programs to include measurements of plankton EOVs/ECVs that can then contribute to global observing systems will assist in filling gaps in understanding of primary and secondary productivity dynamics and their role in ocean-climate interactions. It will also strengthen efforts in incorporating primary and secondary productivity and their dynamics in Earth System Models, thereby improving current capacity to forecast the response of the system under climate scenarios that are informative for policy-making and management of coastal and marine systems. Comprehensive in situ multidisciplinary measurements at scale will also support many other efforts in quantifying ocean productivity, including ocean colour radiometry, and will be complementary to other global ocean observing networks (e.g., Biogeochemical Argo, GACS) in contributing to the plankton ECVs.
Implementers	**GOOS**, Research organizations, (*see also key programmes and networks in* “Additional details”).
Means of Assessing Progress	Increased number of ocean biological and biochemical datasets available and shared via global repositories.
Additional Details	In 2019, at the conclusion of the OceanObs’19 decadal conference, recommendations of the scientific community were to maintain and expand spatial extension of co-located physical and biological / biogeochemical observations. This development will require sustained coordinated campaigns, standardisation of some methods including data QC, data management approaches and establishment of best practices around the world. The key programs and networks are ship-based time series, local/regional/national surveys, national reference stations, GO-SHIP, OceanSITES, Ocean Color satellites, Biogeochemical Argo, GACS.
Links with other IP Actions	B8: Improve components of the global ocean observing system. F3: Expand global ocean climate in situ observations into EEZ and coastal zones.

Action B8: Coordinate observations and data product development for ocean CO_2 and N_2O	
Activities	1. Develop a strategy and implementation plan to operationalize the data production and delivery of surface ocean CO_2 information. 2. Coordinate the existing nitrous oxide (N_2O) ocean observations into a harmonised network.
Issue/Benefits	Parties to the UNFCCC, in its Paris Agreement, have committed to conserving and enhancing sinks and reservoirs of greenhouse gases, such as CO_2 and N_2O, including oceans and coastal and marine ecosystems. As part of the Global Stocktake exercise, it will be necessary to quantify and assess both carbon emissions and natural sinks. There are already considerable national and regional efforts contributing to monitor CO_2 and N_2O in the ocean, but most of them rely on short-term research projects. A more sustained funding and better coordination will result in a better estimation of the oceanic CO_2 and N_2O emissions, an optimisation of resources of Member States and better compliance with UN agreements.
Implementers	From 1 to 2: **GOOS**, WMO, Research organizations, National agencies (*see also key programmes and networks in* "Additional details").
Means of Assessing Progress	1. Internationally agreed strategy and implementation plan that can be used by governments for funding decisions that enable integration of individual pilot elements to achieve the required global system. 2. a) Annually published sets of harmonised global N_2O concentration and emission fields data products; b) Initiated coordinated observing network of N_2O observations.
Additional Details	1. While all of the required elements of a surface ocean CO_2 monitoring system exist (observations, data quality control and synthesis, gap-filling protocols, and projection capability) individually, there is currently no internationally-agreed strategy that coordinates national and regional efforts and expands the global network to better quantify carbon sources and sinks. In recent years, serious gaps have developed in surface CO_2 data coverage owing to funding cuts in some key underway CO_2 programmes that had been operating for decades supported by 3-4-year funding horizons based on research proposals. These programmes, and the international ocean and climate science communities they serve, suffer from the lack of an internationally agreed strategy that recognizes individual programmes as essential elements in a coordinated global network. In fact, all the elements of this monitoring system rely on individual research proposals and voluntary contributions and as such lack any long-term perspective. The development of an internationally agreed strategy for a global surface CO_2 monitoring network, with a focus on the open ocean and marginal seas, will allow Member States to identify priority observing system investments to meet data needs, further develop the foundations of a sustainable surface ocean carbon monitoring system, and respond to international and intergovernmental policy drivers and commitments to UN agreements. The key programs and networks are: WMO Global Atmospheric Watch (GAW), International Ocean Carbon Coordination Project (IOCCP), Surface Ocean CO_2 reference Observing NETwork (SOCONET), Integrated Carbon Observation System-Ocean Thematic Centre (ICOS-OTC), Surface Ocean CO_2 Atlas (SOCAT), Surface Ocean CO_2 Mapping intercomparison initiative (SOCOM), Global Carbon Project (GCP), Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), Global Data Analysis Project (GLODAP), Biogeochemical Argo.

	2. To reduce uncertainties in oceanic N_2O emission estimates and to characterise the spatial and temporal variability in N_2O distributions in a changing ocean, the establishment of a harmonised N_2O Observation Network (N_2O-ON) combining discrete and continuous data from various platforms is needed. The network will integrate observations obtained by calibrated techniques, using time-series measurements at fixed stations and repeated hydrographic sections on voluntary observing ships and research vessels. As a greenhouse gas, N_2O is involved in tropospheric warming and stratospheric ozone depletion, with estimates of the global ocean contribution to N_2O emissions ranging from 10-53%. It is important to monitor how oceanic N_2O cycling and emissions to the atmosphere are affected by observed changes in the marine environment due to warming, deoxygenation and acidification. Therefore, new N_2O data products issued annually will include a harmonised global N_2O concentration and emission fields to inform the global research community and policy makers on the status and projections of future oceanic N_2O emissions. The key programs and networks are: N_2O GO-SHIP, Ship-Of-Opportunity Programme (SOOP), MarinE MethanE and NiTrous Oxide (MEMENTO).
Links with other IP Actions	Together with B8, B6 and B7 target different aspects and components of global and integrated ocean observing system recognizing its essential role in the climate system.

Action B9: Improve estimates of latent and sensible heat fluxes and wind stress	
Activities	This action focuses on ice-free oceans and the terrestrial land surface 1. Improve and extend in situ measurements needed to estimate surface fluxes, with the objectives of improving accuracy and better defining the uncertainties of those measurements and calculated fluxes. 2. Extend sites with co-located measurements of direct turbulent and radiative fluxes and variables required to estimate turbulent surface fluxes targeted at improving parameterisations of air-sea exchange and air-land exchange. 3. Develop new approaches over land, focusing on improved estimation of transpiration, interception and soil evaporation separately. 4. Develop new approaches and improved methods to better exploit relevant ECV measurements to estimate ocean surface heat, moisture and momentum flux including: a) Better integration of in situ and satellite measurements, data assimilation, fusion techniques, ensuring consistency between different types of measurements and their harmonisation; b) Development and deployment of new satellite missions that are tuned to maximise the sensitivity to the state variables needed to estimate heat flux over the ocean and land; c) Increase and improvements in satellite observations that target both the surface parameters and the near-surface air-parameters; d) Simultaneously use of an approach based on high resolution numerical models (Large Eddy Simulation (LES)) to augment satellite product validations; e) Include in future intercomparison campaigns of latent and sensible heat fluxes measurements inferred from simultaneous observations with a water vapour differential absorption lidar (WVDIAL), a Doppler wind lidar and temperature from rotational Raman lidar.

Issue/Benefits	Understanding and estimating surface fluxes is essential for improving projections of climate change and planning adaptation and response measures. The need for surface, near surface, and boundary layer information, across different temporal and spatial scales for multiple disciplines, has outstripped the capabilities of existing observing networks. Direct observation of surface turbulent (sensible, latent and momentum) fluxes is difficult and costly and globally impractical. For global coverage it is therefore necessary to estimate the surface heat and momentum fluxes using empirical parameterisations based on other ECVs (including surface temperature, near surface air temperature and humidity, near surface wind speed and direction). To improve the parameterizations, and quantify uncertainty, high quality in situ measurements of both direct fluxes and collocated ECVs used to calculate the fluxes are needed at key representative locations. Improvement of estimates of ocean surface heat, moisture and momentum flux requires integrating in situ and satellite observations, use of data assimilation and fusion techniques. New and improved methods need to be developed to better achieve this integration.
Implementers	From 1 to 2: **NMHS,** GOOS, Research organizations. 3. **Academia,** Research organizations, NMHS. 4. **Space agencies**, NMHS, Academia.
Means of Assessing Progress	1. a) A catalogue of the in situ observations providing good quality observations of ECVs relevant for surface fluxes; b) Number of observations in 1(a) (above) available in data centres; c) Demonstration reference stations for ECVs needed to calculate surface heat, moisture and momentum fluxes; d) A plan for the establishment/maintenance/extension of a global network of reference stations for ECVs needed to calculate surface heat, moisture and momentum fluxes. 2. a) Increased availability of co-located direct flux measurements and flux-relevant ECVs in data centres; b) Published paper(s) demonstrating the reduction in the uncertainty in empirical parameterizations used to calculate turbulent fluxes. 3. Published paper(s) on new approaches for separate estimation of transpiration, interception and soil evaporation. 4. a) Reduced uncertainty in both air-sea and land-atmosphere flux products; b) Scoping and development of satellite missions to better optimise measurements in the Planetary Boundary Layer.
Additional Details	1. To improve the understanding of partitioning of energy fluxes between the surface and lower atmosphere over all surfaces and the understanding of uncertainty, it is necessary to improve and extend in situ measurements of variables needed to calculate surface fluxes. This requires a tiered approach including: (i) a network of multi-variate high quality reference stations covering representative climates; (ii) a network of stations or mobile marine platforms to provide good quality globally-representative coverage and enable comparison with reference stations; (iii) widespread regional and global measurements only

	some of which will meet specified quality standards but will extend coverage and provide information on variability. 2. Uncertainty in empirical parameterizations used to provide estimates of surface heat and momentum fluxes with global coverage from more easily-measured ECVs remains significant. Improved parameterisations, and improved quantification of uncertainty in those parameterizations requires co-located measurements of direct turbulent fluxes and variables required to calculate turbulent surface fluxes along with direct measurements of shortwave and longwave radiation to provide net heat fluxes. Given the advanced capabilities to infer the shortwave net radiative fluxes at the surface (from satellites) and the longwave net radiative fluxes (from satellite and ancillary data), the use of empirical formulae for the radiative fluxes should be abandoned. 3. Develop novel algorithms able to partition terrestrial evaporation into its various components (transpiration, soil evaporation, interception) with a stronger reliance on observational data and lower dependency on model assumptions. 4. Satellite measurements provide global, but indirect measurements of the surface and atmospheric state variables required to compute heat flux, while in situ measurements provide a local direct measure. The best flux estimates will be achieved by optimally combining these complementary global and local measurements constrained by physical models using data assimilation, that include both in situ and remote sensing data, and fusion techniques. New assimilation algorithms to cope with observations at higher spatiotemporal resolution need to be developed. It is necessary to develop new satellite missions or constellations of satellites optimised, to the extent physically achievable, for the derivation of accurate estimates of air-sea heat, moisture and momentum flux, such as the Butterfly mission concept[45]. Spatio-temporal mismatches in sampling of ECVs required for flux estimation should be minimised to reduce errors in the heat flux estimation resulting from the combination of observations sampled at different times, or with different spatial footprints. Further advances in the field of global terrestrial evaporation monitoring should include developments in microwave remote sensing and high-resolution optical platforms (Fisher et al., 2017)[46]. Moreover, the potential of novel thermal missions such as ECOSTRESS (Fisher et al., 2020)47 and TRISHNA (Lagouarde et al., 2018)[48] is yet to be exploited. The use of simultaneous Lidar's measurements to infer latent and sensible heat fluxes is exemplified and demonstrated by Behrendt et al., (2019), https://amt.copernicus.org/preprints/amt-2019-305/amt-2019-305.pdf. There are high resolution models that are capable of resolving turbulence, which could help to resolve horizontally the fluctuations that are not being resolved with current satellite technology. The following approach can be used to augment satellite product validations using numerical modelling with high-resolution models (LES): • Have only few well-equipped validation sites for the products; • Compute fluxes with the models and validate models with measurements;

[45] Butterfly: a satellite mission to reveal the oceans' impact on our weather and climate https://doi.org/10.5281/zenodo.5120586
[46] Fisher, J. B., et al., 2017: The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources. *Water Resources Research* 53, 2618–2626, doi:10.1002/2016WR020175
[47] Fisher, J. B., and Coauthors, 2020: ECOSTRESS: NASA's Next Generation Mission to Measure Evapotranspiration from the International Space Station. *Water Resources Research* 56, doi:10.1029/2019WR026058
[48] Lagouarde, J.P., 2018: The Indian-French Trishna Mission: Earth Observation in the Thermal Infrared with High Spatio-Temporal Resolution. In Proceedings of the IGARSS 2018—2018 IEEE International Geoscience and Remote Sensing Symposium, Valencia, Spain, 22–27 July 2018; pp. 4078–408

	• Use models to 'check' satellite products elsewhere.
Links with other IP Actions	This action links to other actions: B1: Reference networks are needed to improve flux estimates. B10: Closure of energy cycles will benefit from a better understanding of heat fluxes. C2 and C3: Improvements to data processing methods will benefit this action. D3 (Activity 3). Access to field campaign data useful for testing of parameterization. D4: Easy access to co-located satellite and reference quality in situ observations.

Action B10: Identify gaps in the climate observing system to monitor the global energy, water and carbon cycles	
Activities	1. Continue to periodically review observations of the Earth's energy, water, carbon cycles to identify gaps and areas of high uncertainty. 2. Review consistency of the underlying observations. 3. Develop plans to address the gaps identified in (1), if feasible.
Issue/Benefits	This action will implement an objective approach to identifying gaps and major uncertainties in the global climate monitoring system. The energy, water and carbon cycles and their closure/imbalance are fundamental to understanding current climate state and change, and improved observations of the cycles will lead to improved climate projections and reduced model biases.
Implementers	From 1 to 3: **GCOS,** Research organizations, Funding agencies, WCRP.
Means of Assessing Progress	1. a) Periodic assessments of each cycle and its components at least as part of the Status Report (about every five years); b) Periodic reviews of suitability of existing ECV structure to monitor energy, water and carbon cycles at least as part of the Status Report. 2. Periodic assessment of consistency of the underlying ECVs. 3. Include plan to address the main issues for the next GCOS Implementation Plan.
Additional Details	GCOS has reviewed how well the existing structure of ECVs monitors these cycles and their components. This has revealed significant gaps in observations and highlighted areas of highest uncertainty – this information will be used to guide developments and improvements to the observing system. Expert teams reviewing observations of the cycles will report on gaps and major uncertainties for inclusion in the next GCOS Status Report. They will develop plans to address these issues in subsequent Implementation Plans. See also Section 2.4 in this GCOS IP for more details and references.
Links with other IP Actions	This action indirectly links with many others but in particular with: B3: Better EEI measurements. B4: In situ GHG observations. B8: Coordinate observations and data product development for ocean CO_2. C5: Activity 2 (estimation of aboveground biomass).

6.3 Theme C: Improving data quality, availability and utility, including reprocessing

Information about the climate system has never been as important as it is now for our society. This is underpinned by climate observations, but many are currently underexploited because of the lack of consistency in their processing and usability. This theme looks at how the original observational data is transformed into user-relevant information. Starting from climate monitoring, adopted standards are required to facilitate inter-comparisons, "mash-up-ability" and ensure the overall quality of the final information. Standards are also required through the other phases of the processing chain that transform observations into user-relevant products. These should address a comprehensive characterisation of uncertainty, the use of uniform metadata and quality attributes and also support the effort towards the generation of sensor-agnostic gridded datasets to facilitate intercomparison. Acknowledging the fact that the use of observational data is often mediated by other systems, a dedicated effort should also go toward ensuring the fitness for purpose of the data provided for its use in reanalysis. This includes a dedicated effort towards data reprocessing, bias characterisation and more generally a comprehensive characterisation of the uncertainty associated with both observations and modelling.

Action C1: Develop monitoring standards, guidance and best practices for each ECV	
Activities	1. Review existing monitoring standards, guidance and best practices for each ECV, ensuring these reflect current state-of-the-art. Maintain a repository of this guidance for ECVs. 2. Ensure the development of monitoring standards, guidance and best practices, including intercomparison procedures, for those ECVs where such guidance does not exist. 3. Review and revise the climate monitoring guidance in the WIGOS manual to bring it in line with the updated guidance developed in this Action. 4. Review the GCOS climate monitoring principles.
Issue/Benefits	Many ECVs have standards, guidance and best practices that, when followed, ensure consistency between the observations which is necessary to ensure that the global datasets meet user requirements. However, monitoring standards for some ECVs are missing and need to be established, and for others they are either substantively dated or not fit-for-purpose. Improvements in observations and their consistency across countries and regions would lead to more accurate observations, predictions/projections, and warnings and would thus improve adaptation planning.
Implementers	From 1 to 4: **GCOS,** GOOS, WMO, Copernicus, Space agencies.
Means of Assessing Progress	1. Unified repository of standards, guidance, and best practices for all observations of atmospheric, oceanic and terrestrial ECVs by time of next status report. 2. New monitoring standards, guidance, and best practices for ECVs where this is identified as absent or requiring updates. 3. WMO adopts revisions to WIGOS regulatory materials to ensure they meet climate needs as articulated in the unified repository. 4. Review and undertake revisions to GCOS Monitoring Principles to align with outcomes of activities 1-3 by time of next status report.
Additional Details	For 1 and 2:

	Guidance for collecting observations of ECVs is incomplete, particularly in the terrestrial domain. Therefore, the first step is to identify gaps in the guidance, or where guidance is outdated, and provide up-to-date guidance that covers siting, observations, data collection, processing, and QA/QC. Any new guidance should be based on existing guidance where this exists and is appropriate: Where possible, this can include ballpark costs and manpower requirements for implementation, operation and maintenance of ECV observations. The WIGOS manual guides NMHS in making observations. However, the current guidance on climate observations is inadequate and unclear. It should therefore be revised to be consistent with ECV requirements. 3. The GCOS Climate monitoring principles were adopted in the 1990s. They need to be reviewed and updated as appropriate in light of new methods, insights and best practices.
Links with other IP Actions	Best practices, guidance and standards are relevant for most of the Actions in themes A, B, C, D and F.

Action C2: General improvements to satellite data processing methods	
Activities	1. Improve radiance measurement records and Radiative Transfer (RT) models for simulating them. 2. Improve uncertainty quantification of satellite retrievals. 3. Periodically reprocess full satellite data records whenever an update of underlying methods occurs, especially when those risks introducing discontinuities into the time series. 4. Consolidate satellite observations into instrument-independent space-time grids for easy intercomparisons and fusion. 5. Ensure harmonisation and quality of ancillary data used to generate satellite products such as solar irradiance and meteorological data.
Issue/Benefits	Many data products depend on extended processing streams from observations to data products. Improving data processing methods facilitates ease of use, regular reprocessing and robust uncertainty quantification of available observations. This action identifies key areas for improvements. Ensuring the availability of relevant, high-quality estimates with long-term continuity across multiple instruments and satellites results in better quality of the satellite climate data records.
Implementers	From 1 to 5: **Space agencies,** Academia, Research organizations.
Means of Assessing Progress	For 1 and 2: New publications showing improvements in radiative transfer and uncertainty characterisation. 3. Increased number of available reprocessed Fundamental Climate Data Records (FCDRs). 4. Increased number of available consolidated gridded satellite datasets. 5. Products with consistent traceability to ancillary data and associated quality assessment.
Additional Details	1. Radiance measurement records need to be carefully assessed, characterised, and calibrated. Radiative Transfer (RT) schemes for simulating them also need to be improved, as this is a key component of processing radiance measurements and quality evaluation/assessment. Line-by-line radiative transfer models are critical and need to be available as reference for faster RT schemes.

	2. Improve uncertainty quantification of satellite retrievals on all processing levels. Specifically (i) consider more carefully non-linearities and non-Gaussian uncertainties in the retrievals and (ii) consider and report spatially correlated uncertainties. Presently these are not properly considered in the satellite retrievals. Proper characterization of the uncertainties is key when data are further used e.g., in assimilation (e.g., in inverse modelling for emission estimation). 3. The quality of retrieved quantities also depends critically on the methods, ancillary, and auxiliary data used in the retrieval algorithm. As all these dependencies improve or ECV requirements changes, the satellite observations can (and should) regularly be reprocessed to ensure that the satellite data record is as useful as it can be (i.e., information content is fully exploited). 4. The typical lifetime of individual satellite instruments is shorter than the time scale required for climate applications. Therefore, satellite observations need to be consolidated across multiple instruments and satellites into high-quality estimates with long-term continuity in order to maximise their value for the climate community. This consolidation must be done in an optimal and standardised way, ensuring consistency across multiple instruments and satellites.
Links with other IP Actions	The following Actions are relevant to improve satellite data processing methods: B1: Reference observations (Uncertainty characterizations and improved uncertainty quantification of satellite retrievals). D4: Access to co-located data.

Action C3: General improvements to in situ data products for all ECVs	
Activities	1. Periodically reprocess in situ data products to account for new knowledge, new techniques and improved access to historical data holdings. 2. Improve uncertainty quantification of in situ-based products. 3. Undertake efforts to account for spatio-temporal sparsity of in situ measurements via interpolation. 4. Ensure adequate sampling of the structural uncertainty inherent in in situ product development via supporting the development of multiple methodologically distinct products and their intercomparison.
Issue/Benefits	It is necessary to periodically reassess in situ-based estimates of climate change and to have multiple independently produced estimates for each ECV. Ensuring that datasets produced from in situ holdings reflect the latest availability of access, the latest knowledge, and the latest processing techniques assures the best possible estimates of long-term climate change are available to users. The availability of multiple independent estimates per ECV identifies those ECVs for which the true evolution is well known and thus informs directly assessments undertaken by e.g. IPCC.
Implementers	From 1 to 4: **Research organizations**, Academia, NMHSs.
Means of Assessing Progress	1. New publications of updated in situ datasets and availability of those datasets following FAIR data principles. 2. Increased number of available in situ-based datasets for which a documented and quantified uncertainty assessment is available. 3. Increased spatio-temporal completeness of in situ-based products based upon use of additional data and application of interpolation techniques. 4. Increased number of ECVs for which two or more global in situ datasets exist.

Additional Details	In situ data products are not some frozen set of estimates which should remain unchanged. Over time new data, new insights and new and improved computational techniques appear. A high-profile example of this is the recent IPCC WGI report wherein the surface temperature datasets changed their estimates on a like-for-like basis by circa 0.1C. This change in the estimate of warming to date of the order 10-15% of the estimate before arose from a combination of improved understanding of data biases, improved access to historical data, improved interpolation techniques, and the emergence of new estimates.
Links with other IP Actions	B1: Reference observations. B9: Estimation of heat fluxes and wind stress. D5: Data rescue.

Action C4: New and improved reanalysis products	
Activities	1. Implement new production streams using improved data assimilation systems and better collections of observations, particularly aiming at: a) Further increasing resolution; b) Improving handling of systematic observational and model biases; c) Providing (improved) estimates for the uncertainty in the mean state; d) Improving quality control in data sparse areas. 2. Develop coupled reanalysis (ocean, land, sea-ice). 3. Improve the capability of sparse-input reanalysis that covers the entire 20th century and beyond. 4. Develop and implement regional reanalysis and other approaches to regionalisation. 5. Reduce data latency.
Issue/Benefits	Reanalysis systems that employ data assimilation techniques are highly effective at combining disparate observations with physical principles to represent complex Earth systems, although there is a need for further improvement for reanalysis. Reducing the uncertainty in the estimation of trends and in the description of low-frequency variability from reanalyses leads to better understanding of climate change from these products compared to precursor generations. Improved representation of Earth system components and consistency among them is still, however, needed. Increasing their spatial resolution and reducing the latency will increase the range of potential applications of reanalyses.
Implementers	From 1 to 5: **Reanalysis centres**, Academia, Space agencies.
Means of Assessing Progress	1. Publications describing new reanalysis production streams and their validation with improved estimation of uncertainty of reanalysis data products. 2. Demonstrated benefits of coupled reanalysis. 3. New versions of sparse-input reanalysis products. 4. Number of in-depth performance assessments of regional reanalyses and other regionalised datasets. 5. Reduced latency of data product updates.
Additional Details	1. Reanalysis centres should regularly upgrade their products by introducing improved data assimilation techniques and better collections of observations (including reprocessed and data rescued data). Use of ensemble approaches will help to provide users with information on the uncertainty of products. Increased computational capacity will enable production at a higher spatial resolution and

	greater complexity (e.g., coupled systems, interactive chemistry). Use of homogenised, recalibrated or reprocessed observations is important in order to mitigate the impact of disruptions in instrument technology or processing algorithms. Use of advanced methods for dealing with data discontinuities will help improve the reliability of historical reanalyses. 2. A coupled data assimilation technique has a potential advantage over separate data assimilation in terms of consistency across the Earth system components. A proven benefit so far is that it can improve the SST field in a sparse observing system setting such as in the mid-20th century and earlier, but clear benefits in the current dense observing system setting have yet to be demonstrated. 3. Another type of reanalysis is a sparse-input reanalysis that only assimilates surface observations and covers a significant portion of the instrumental record, extending back into the 19th century. For this type of reanalysis, further improvement can be expected through data rescue for early instrumental meteorological observations and refinement of data assimilation systems. 4. There is a growing demand for datasets with higher resolution and accuracy, particularly for surface variables, for local and regional applications such as adaptation and monitoring of climate extremes. This demand should be met through regional reanalysis and other approaches for regionalising global data products. 5. Reduced latency of reanalysis data products should be aimed for, since it increases reanalyses' potential for applications. It also helps to reduce latency of other climate products that rely on reanalysis as input data, e.g. satellite retrievals.
Links with other IP Actions	B2: Implementing GBON will be of benefit for this action. C2: Improving reprocessing of satellite data. F1: Higher resolution observations.

Action C5: ECV-specific satellite data processing method improvements	
Activities	1. Generate timely permafrost, land cover change, burnt area, and fire severity/burning efficiency products from high resolution data satellite observations (e.g. Sentinel1/-2 and Landsat). 2. Produce harmonised and validated Above Ground Biomass (AGB) and change datasets from different satellite data streams, for enhancing aboveground biomass estimation at global and (sub-national) levels. 3. Ensure that the Bidirectional Reflectance Distribution Function (BRDF) parameters are provided together with surface albedo. 4. Reprocess the LEO NASA 25+ year Lightning Imaging Sensor (LIS) data set from the Optical Transient Detector (OTD, 1995-2000), LIS on the Tropical Rainfall Measuring Mission (TRMM-LIS, 1997-2015) and International Space Station (ISS-LIS, 2017-Present). 5. Reprocess the GEO Geostationary Lightning Mapper (GLM) on GOES-16/17/18 (2017-Present). 6. Improve consistency of the inter-dependent land products.
Issue/Benefits	Many data products depend on extended processing streams from observations to data products. This action identifies key areas for improvements. 1. Generate improved permafrost, land cover and burnt area products that can be used for adaptation and mitigation. Rapid updating and delivery of data is important to serve such applications. Consistency between existing/historical

	and new products should be considered, and existing products might be updated based on new methods where possible. 2. Reduced uncertainty levels of datasets/approaches of AGB monitoring and less confusion among users (in particular countries) about which datasets and biomass estimates to use and integrate in their reporting. 3. Allow the complete understanding of surface albedo uncertainties budget. 4. Reprocess the data to remove known artefacts and provide continuity between similar instruments in different orbits. 5. Reprocess the data to remove known artefacts and allow for new and improved products using ML/AI (e.g., megaflashes, flash type, continuing current). An Enterprise science algorithm is planned that would be applied to all space-based instruments similar to GLM (e.g., forthcoming MTG-Lightning Imager). 6. Currently some satellite-based products are developed separately with different data sets and processing streams despite several ECVs being closely inter-related (e.g. surface albedo, Fire, FAPAR and LAI). Consistency between these products needs to be ensured so that data from multiple sources can be used together. This will improve the interoperability and the stability of long-term satellite data and has an impact in the reanalysis when they are assimilated together.
Implementers	From 1 to 6: **Space agencies**, Reanalysis centres.
Means of Assessing Progress	1. Improved and validated permafrost, land cover and change products and updated, and higher resolution, burnt area and fire severity products. 2. Global harmonised biomass and change datasets, with validated estimates at sub-national levels. 3. Provision of the isotropic BRDF spectral parameters used in surface albedo retrieval at the same spatial and temporal scale of the products and the uncertainties error budget associated to the surface albedo products. 4. Validated and updated 0.1 x 0.1 deg product for satellites and ground-based lightning RF data sets (GLD360, WWLLN); and ThunderHour grids (derived from the satellite lightning detection) for GLD360, ENGLN, WWLLN, GLM. 5. Validated and updated space and RF ground-based lightning data at 0.1 x 0.1 deg grids. 6. Maps of all biospheric ECVs using a common geographic definition, at the same temporal/spatial scale as climate models with plant functional types.
Additional Details	For 1 and 2: Monitoring programs (i.e. from Copernicus, NASA, ESA etc.), respective expert communities and reference networks should focus on generating timely, high-resolution and validated land cover change, permafrost, burnt area, and fire severity/burning efficiency products from medium resolution data satellite observations (e.g. Sentinel1/-2 and Landsat). These products should be developed in close partnership with user communities in climate change mitigation and adaptation; incl. for national GHG inventories, estimating activity data and to support global Agriculture, Forestry and Other Land Use (AFOLU) modelling and assessments. Although global in scope, these products with increasing detail and quality should be suitable for national and local uptake. 2. Monitoring aboveground biomass has been a priority for several new and upcoming space agency missions, including GEDI, ICESat-2, BIOMASS, ALOS-4 and NISAR. The availability of multiple satellite products confuses policy users (such as country experts) and a lack of consistent and transparent product inter-comparison and validation jeopardises the successful uptake of any biomass

	product by the policy community. This is a pressing issue as the world prepares for the UNFCCC's first 'Global Stocktake' which will take place in 2023 with planned repeat every five years (2023, 2028, 2032 and onwards). Building upon new satellite missions and increasing reference databases (i.e. GEOTREES, country National Forest Inventories (NFIs), a single recommended biomass estimation product is encouraged rather than several products that may not agree and may lead to confusion and reduced uptake. This requires a partnership among different CEOS agencies and their related experts to jointly work on providing such estimates in coordinated manner towards the UNFCCC global stocktake and for the integration of space-based biomass data in national monitoring and reporting (GFOI). 3. The provision of surface albedo products shall be provided their respective bidirectional reflectance distribution function (BRDF) parameters as they are part of the ECV definition. They allow a better assessment of uncertainty budget. For 4 and 5: Space-based and very low frequency ground-based lightning network data are complementary in the information they provide (flash energy, size, duration, extent). Regional ground-based lightning networks would be a useful addition as they also provide more definitive information on flash type to compare or add to the Lightning ECV database. Although most lightning occurs in the continental tropics and mid-latitudes, recent observations are indicating an increase in lightning at high latitudes associated with a warming arctic. Monthly, daily and even hourly data are available. There is some evidence that this quantity has also been increasing at high latitudes. Lightning has long been associated with severe and high impact mesoscale weather phenomena, precipitation, NOx, aerosols, tropospheric temperature and moisture. Lightning-initiated wildfires and the threat to public safety are increasing concerns.
Links with other IP Actions	B10: this action will benefit addressing gaps for the carbon cycle.

6.4 Theme D: Managing Data

To address and understand climate change, the longest possible time series need to be preserved in perpetuity. Every ECV needs to have a recognized global data repository and where there is one, it should be complete, adequately supported and funded. Satellite Agencies maintain and update the ECV inventory and use it to conduct regular gap analysis. The ECV inventory lists available satellite-based climate data records and details of their access[49]. Data should be stored in well-curated, open and freely available, sustainable archives with clear guidance for data centres and users. Clearly defined principles such as the TRUST and FAIR Principles (see sections 5.2 and 5.3) as well as clear and enforced data management plans and data citation are required (Chapter 5). Data rescue from hard copy or archaic digital formats allows data series to be extended in the past and needs to be adequately planned and funded with the results openly and freely available. This may include old satellite data if discovered (Poli et a., 2017[50]). Sustained support to these activities is required. This theme aims to organise more efficiently data rescue, data sharing, data curation and data provision.

[49] https://climatemonitoring.info/ecvinventory/
[50] Poli, P., et al. (2017), Recent Advances in Satellite Data Rescue. Bulletin of the American Meteorological Society 98, 7, 1471-1484. https://doi.org/10.1175/BAMS-D-15-00194.1

Action D1: Define governance and requirements for Global Climate Data Centres	
Activities	1. Draft requirements for the activities of Global Climate Data Centres and identify the relevant internationally agreed standards. 2. Develop any new standards as required. 3. Implement the agreed-upon requirements at all global data centres. 4. Advocate for implementation of the WMO Unified Data Policy to foster a free and unrestricted exchange of available data.
Issue/Benefits	It is vital that all users have unrestricted access to well-documented, historical and near-real-time climate data and associated metadata, including relevant documentation. However, despite various efforts to implement appropriate data stewardship and sharing standards, such "free and open" access to well-maintained data archives is not available consistently across all data centres and data types. This action aims to improve the situation by encouraging global climate data centres with global-scale data holdings to agree on and implement relevant standards. Open exchange of easily accessible and findable data, particularly well-maintained long-term time series, will improve the completeness and accuracy of the data and metadata necessary for climate science, climate adaptation activities, and climate change mitigation planning.
Implementers	From 1 to 4: **GCOS,** WMO, Global Data Centres.
Means of Assessing Progress	For 1 and 2: Published GCOS document defining requirements and standards for data and metadata. 3. GCOS to periodically audit climate data centres for compliance with the requirements and availability of all applicable mandatory metadata as defined in the WIGOS Metadata Standard. GCOS to develop implementation plans as required. 4. Increased number and volume of ECVs for which data is exchanged according to the WMO Unified Data Policy.
Additional Details	1. Working with existing data centres, GCOS should coordinate the development of an agreed set of requirements with respect to data centre activities such as processing, quality controlling, archiving, and distribution of climate-related observations of the atmosphere, land, and ocean. These should be general enough to be widely used but also specific enough to be directly applicable to climate data. They should emphasize the FAIR principles; comply with existing standards of the WMO, World Data System, and other international bodies; ensure interoperability between data and metadata stored at different centres; ensure consistency with WMO systems (e.g., OSCAR), especially for ECVs; contribute to the implementation of the new WMO Unified Data Policy; and call for free and open data policies. This activity involves the development of standards in areas where adequate standards currently do not exist. One such area is the development of standards for compiling and managing collection-level metadata, i.e., metadata that provides the data user information about the data that is needed for assessing the data's utility for a particular purpose as well as for acquiring and processing the data. Such metadata standards are particularly lacking for the terrestrial domain. GCOS, alongside other relevant bodies, should develop such standards and coordinate their implementation. 2. Once all necessary requirements and standards have been developed, an implementation plan needs to be developed that outlines how GCOS will

	facilitate and encourage the implementation of these standards. Implementation activities may include (1) coordination with funding agencies to ensure that funding is available to data centres that need to upgrade their infrastructure or undertake significant amounts of work in order to meet the requirements; (2) the development and distribution of relevant training materials for data centre personnel; and (3) the establishment of a mechanism for determining and tracking progress towards implementation of the requirements globally. 3. The stewardship of GCOS related data sources should be assessed on a regular basis according to the requirements and standards identified in Activities 1 and 2. Internationally agreed-upon standards for the assessment of the maturity of data repositories exist with the CoreTrustSeal of the International Science Council's World Data System or the WMO Stewardship Maturity Matrix for Climate Data (SMM-CD) and could be utilized for this purpose if the working groups developing the data centre requirements decide to include them. 4. At the most recent Congress WMO adopted its Unified Data Policy which places a requirement on Members to share historical data holdings. Activity is now required to enable the sharing of these historical data via documented routes to recognized global and regional repositories. GCOS, working with WMO must develop guidance and support and integrate requirements into relevant technical regulations.
Links with other IP Actions	Action D1, D2 and D3 are interconnected and pursue a common goal of preserving and providing access to ECV data in Global Data Centres, including interoperability. D5: data rescue is connected to data sharing of historical data.

Action D2: Ensure Global Climate Data Centres exist for all in situ observations of ECVs	
Activities	1. Identify ECVs for which adequate global centres do not exist or are insufficiently supported and facilitate and support the creation or improvement of global data centres for these ECVs. 2. Promote regional data centres, their interoperability, where possible, synchronisation of their data holdings, and the provision of data in their archives to global data centres.
Issue/Benefits	The aim of this action is to ensure that all available observations for each ECV/ observation type are distributed from integrative data centres that meet the requirements established in Action D1. Data centres do not exist for every ECV and the continued existence of some of those that do exist is not assured due to the lack of long-term funding. This action addresses this issue and targets specifically in situ data.
Implementers	From 1 to 2: **GCOS**, WMO, GOOS, NMHS, National agencies, Funding agencies.
Means of Assessing Progress	1. a) List of climate data centres, identifying those in need of additional support followed by annual reports by GCOS panels on data centres at risk; b) List of ECVs for which no data centre exists, followed by annual updates on progress towards filling the identified gaps. 2. Establishment of a functional network of regional data centres for all ECVs of relevance in the region and their synchronisation with global data centres.
Additional Details	1. Global Climate Data Centres need to maintain and construct long-term time series of ECV data and to archive and disseminate these time series for the long term, at least several decades following the requirements established as part of

	Action D1. The maintenance of these data centres requires long-term assured funding. The first step is to identify all existing data centres and the status of their funding. ECVs for which data centres are missing need to be identified, and the relevant GCOS panels should advocate for the establishment of the missing centres. GCOS should also make a clear case for adequate funding of data centres and the benefits that will accrue. For example, sustained funding is urgently needed for the Global Ocean Data Analysis Project (GLODAP), where ocean biogeochemistry data is collected and stored. Despite a recent increase in the quantity of these observations GLODAP is a largely unfunded community effort. Such a situation is unsustainable, and there is a significant risk that the effort will diminish or disappear in the next few years. Following an initial assessment of adequacy, it is necessary to continuously review the health of the network of global data centres. GCOS panels should annually review the status of global data centres within their domain and highlight any issues so that these can be remedied. 2. The Global data centres are part of a network of data centres that include regional data centres and in some cases the observation networks. These need to be integrated into a global system to improve data exchange and data availability. They should also follow the requirements developed in Action D1. Sustainable funding of regional data centres and observation networks is key. Working with Regional Associations and Regional WIGOS Centres, GCOS should advocate for regional level data collection and curation which may then be passed on to the extent possible for inclusion in global data centre collections. This action focuses on in situ data. Information about satellite-based climate data records can be found in the ECV inventory.
Links with other IP Actions	Action D1, D2 and D3 are interconnected and pursue a common goal of preserving and providing access to ECV data in Global Data Centres.

Action D3: Improving discovery and access to data and metadata in Global Climate Data Centres	
Activities	1. Support the creation of improved systems for accessing global archives of ECVs and facilitating their interoperability. 2. Support the development and maintenance of software tools that assist users in discovering and accessing publicly available data sets. 3. Facilitate access to field campaign data, where available and relevant, to improve understanding of fundamental processes.
Issue/Benefits	Presently data are often held in ECV-specific or time-aggregation specific repositories, often without regional or global coordination and in a broad variety of formats and access protocols. This makes accessing data laborious. Sometimes, related data needs to be integrated into global collections with multiple ECVs collated together to enable data fusion. Global climate databases must be able to provide easy discovery and access of data to all potential users, maximising the utility of the data.
Implementers	From 1 to 3: **Global Data Centres**, GCOS, Funding agencies.

Means of Assessing Progress	1. Increased number of users of integrated data holdings. 2. Increased availability of open-source software tools for accessing data in common data formats. 3. Increased number of traceable field campaign data available in global archives.
Additional Details	1. GCOS should support this action by identifying organizations, data centres, and other groups interested in participating in the creation of relevant software and databases and by advocating for relevant funding opportunities to be created by funding agencies. GCOS should also communicate appropriate standards on data management, such as those developed and/or referenced in Action D1, to funding agencies and funded organizations. 2. Governments, non-governmental organizations, and funding agencies should support the development and maintenance of software tools that assist users in utilising publicly available data sets. GCOS should support this activity by communicating standards for such software, e.g., data formats to be supported, functions to be included. 3. Access to campaign field data, in particular those used for instrument intercalibration and validation, is very important to improve the traceability and thus the quality of many ECV datasets.
Links with other IP Actions	Action D1, D2 and D3 are interconnected and pursue a common goal of preserving and providing access to ECV data in Global Data Centres.

Action D4: Create a facility to access co-located in situ cal/val observations and satellite data for quality assurance of satellite products	
Activities	1. Improve access to co-located satellite and reference quality in situ observations, as well as tools for evaluation purposes. This facility will use data from reference networks and FRM programs for a broad range of ECVs for calibration/validation of satellite programs. 2. Develop tools to use the co-located data collection developed under Activity 1 to undertake various analyses of satellite-based measurements.
Issue/Benefits	The uncertainty for satellite measurements of ECVs are determined and/or verified through intercomparison against in situ measurements. These intercomparison field experiments also provide test bed opportunities for assessing measurement capabilities of new technologies, for testing and developing best practices, and to assess uncertainties in Numerical Weather Prediction and Climate Models. The current limited availability of co-located in situ and satellite data for calibration and validation data restricts the ability of users to assess the quality of satellite products. This action will improve the ability to exploit high quality reference measurement sites/networks including, but not limited to, FRM programs (see Action B1) to provide such calibration and validation data for a broad range of satellite products. What is required is a database of reference measurements and co-located satellite measurements to enable cal/val activities along with provision of a suite of tools. The provision of a centralised facility would minimise overall cost while maximising overall exploitation potential and is therefore preferable to such efforts at the satellite mission-level. It also enables applications which may wish to consider multiple ECVs from multiple satellites and their data fusion. A centralised well-supported facility would enable the long-term satellite cal/val capability necessary to extract the value from considerable investments in satellites and reference networks including FRM programs on a sustained basis.

Implementers	From 1 to 2**: Space agencies**, WMO, NMHS, Research organizations.
Means of Assessing Progress	1. Establishment of a unified database of and access to co-located, reference quality, ground-based measurements suitable for satellite cal/val. 2. Increased number of available compatible satellite and in situ datasets.
Additional Details	This activity addresses the need to improve the exploitation of the high-quality data needed to calibrate and validate satellite observations by making these data easily available: access is currently a major barrier to their use. A more coordinated, centralised approach to the storage and provision of data for satellite cal/val, with greater involvement of and partnership with reference networks (Action B1), along with the development of associated tools would yield cost efficiencies as well as scientific benefits. Users could come to centralised repositories which serve data for multiple satellite missions, enabling their usage in a more seamless manner. Tools could be shared between similar missions and made available to users. The centralised repository would serve to highlight the presence of critical gaps in provision of high-quality in situ data to inform the quality of ECVs measured from space. This, in turn, would help inform the strategic further investment in new reference networks and FRM programs to fill these gaps. Further details are given in Sterckx et al. (2020)[51].
Links with other IP Actions	This activity has strong links to other actions: A1: Sustained support for the source in—situ observations that underpin this action. B1: Provision of reference quality in situ measurements including from FRM; and several other actions that underpin the in situ observations (B4, B6, B7, C4, F4).

Action D5: Undertake additional in situ data rescue activities	
Activities	1. Augment existing archives as inventoried by the WMO DARE initiative (https://community.wmo.int/data-rescue-projects-and-initiatives-dare) and the ACRE project (http://met-acre.net/) with newly discovered or as yet un-inventoried holdings available for potential rescue. 2. Continue efforts to advance the rescue of key historical data records from hard copy or image form via an appropriate combination of professional, citizen science and class-based activities. 3. Maintain and update data rescue best practice guidelines as detailed at e.g. https://datarescue.climate.copernicus.eu/tools-community-support.
Issue/Benefits	The coverage of historical observations is uneven across space, time, and for different parameters. While some of these differences are due to differences in the volume of observations taken, others are a function of the amount of historical data that have been rescued and made available to the global community. The degree to which national archives have been digitised differs substantially. Furthermore, many digitization efforts have focused on the most widely-used parameters, e.g., temperature, often leaving out other parameters that are nevertheless of increasing interest. One such parameter is the occurrence of thunder, which can be used to extend lightning records back in time.

[51] Sterckx, S., et al., 2020: Towards a European Cal/Val service for earth observation, *International Journal of Remote Sensing*, 41:12, 4496-4511, doi: 10.1080/01431161.2020.1718240

	Given the need for as much historical climate data as possible for the purposes of climate assessment, adaptation and mitigation planning, and reanalyses, this action aims to encourage a renewed concerted effort to locate and rescue observations of particular interest that are available but have not yet been digitised and incorporated into existing archives.
Implementers	From 1 to 3: **Existing data rescue organizations**, WMO, GCOS, Funding agencies, NMHSs, National governments.
Means of Assessing Progress	1. Updates by NMHSs and others of data rescue inventories maintained by WMO DARE with newly discovered and as yet unregistered holdings. 2. New funded data rescue efforts leading to the provision of additional data rescued to recognized global repositories for relevant ECVs via a variety of approaches (professional keying, citizen science, participatory learning). 3. Updated best guidance documentation for data rescue activities readily available to support funded data rescue activities.
Additional Details	WMO Unified Data Policy includes sharing of historical data and should inform the planning and execution of the activities within this Action. It is important to rescue the raw data as well as the processed ECVs.
Links with other IP Actions	A successful D5 will provide datasets with historical observations feeding into global climate data centres considered in Actions D1-D3.

6.5 Theme E: Engaging with Countries

Many climate observations are made by national bodies, however these efforts need support and coordination. Some countries have national programmes that need to be connected regionally and globally to share and communicate issues and solutions. GCOS can help by linking these national efforts into the global system, providing information on observing needs, promoting needs for support and access to global information.

GCOS has started to engage at regional and national levels through a series of regional workshops. These have been paused due to COVID but need to be restarted and strengthened. Links to national observing systems should be put into place. Ultimately the benefits of climate observations need to be widely understood and the contributions of national observations to global datasets enhanced.

Some national GCOS systems can also fill gaps in the global system, for example by providing support for regional and global data centres.

Action E1: Foster regional engagement in GCOS	
Activities	1. Undertake at least one regional GCOS Workshop each year. a) Promote the benefits of coordination of climate observations (in situ and satellite) and GCOS programs. b) Explore regional issues, gaps and needs and develop plans to address them. 2. Report regional needs and issues to the UNFCCC, WMO and other relevant stakeholders.
Issue/Benefits	Lack of regional and national input into global observing decisions can make GCOS seem remote from implementers "on the ground" and leaves GCOS unable to fully understand and respond to the issues facing observing systems at a local level. There

	is a need to better integrate GCOS needs into national and regional decision making to ensure sustainable observations for climate. These activities will better inform the global system of local needs and link local observing systems with international support and capacity development. They can also provide some capacity development, explain the needs and uses of climate data and help ensure that countries have access to all the data. For example, GBON and SOFF were developed from needs identified in a GCOS regional workshop on climate observations systems in the Pacific Island states[52].
Implementers	From 1 to 2: **GCOS**, Parties to the UNFCCC, WMO (Regional Organizations), GOOS (Regional Alliances).
Means of Assessing Progress	1. Number of regional workshops held annually in collaboration with WMO and other stakeholders. 2. Reports to UNFCCC and WMO.
Additional Details	This work can be done with WMO Regional Organizations and GOOS Regional Alliances, as appropriate. Other stakeholders should be considered: in the past Copernicus has supported regional workshops. 1. Regional workshops engage countries directly. Engagement of countries needing support and more experienced countries will be beneficial. Involving both those making observations and those from the climate policy sphere will allow the workshops to identify issues and potential solutions and will also inform the countries about how observations support services and policy development. An important part of obtaining support, financial and political, for climate observations is providing a rationale for the observations and a clear description of the benefits. International coordination and data exchange enhance these benefits. Regional workshops should agree to regional needs, gaps and develop plans to address these needs. 2. A key component will be reports to appropriate stakeholders, especially the UNFCCC and WMO on needs and issues. The discussions of these reports, and decisions based upon them, will enhance the implementation of observation systems.
Links with other IP Actions	Actions E2 and E3.

Action E2: Promote national engagement in GCOS	
Activities	1. Encourage the development of national coordination of climate observations (e.g. national GCOS programs). a) Collect annual reports of these programmes; b) Promote the benefits of national coordination; c) Support the development of new national climate observing programmes, including bi-lateral programmes to develop and support national GCOS activities; 2. Engagement of National GCOS Focal Points a) Revise terms of reference (ToR) for National GCOS Focal Points; b) Increased nomination of National GCOS Focal Points.

[52] Full workshop report available online: https://ane4bf-datap1.s3.eu-west-1.amazonaws.com/wmod8_gcos/s3fs-public/fijiworkshopoct2017_final1.pdf?E8vbQOTXp3.VJII2p6utJLP.I8xM7huA.

Issue/Benefits	National programmes provide the information needed to support adaptation and mitigation and can be focussed on specific issues of national importance. Some countries have established national GCOS programmes or national climate observing programmes in their territories to monitor climate and climate change. These programmes are important to focus effort within a country, identify national priorities and, where appropriate, report issues and needs internationally to potential donors. Where national resources for climate observations are very limited, national climate observing programmes can aid in requesting support, resources and capacity development. National GCOS programmes can also provide the reporting on observations to the UNFCCC required for national communications. These actions will better inform the global system of local needs and link local observing systems with international support and capacity development. They can also provide some capacity development, explain the needs and uses of climate data and help ensure that countries have access to all the data. GCOS National Focal Points should be the point of contact between GCOS and all national climate observations, especially those observations made outside of the NMHS. However, many countries do not have a focal point, current lists of focal points are out of date and their ToR need updating.
Implementers	From 1 to 2: **GCOS**, Parties to the UNFCCC, NMHS, Academia.
Means of Assessing Progress	1. a) Number of national climate coordination programs 2. a) Revised ToR for National Focal Points; b) Number of active National GCOS Focal Points.
Additional Details	1. A few countries have national GCOS programmes. Others have similar climate monitoring programmes. GCOS should support the development of these programmes and encourage the spread of best practices to other countries. GCOS needs to inventory those national programmes that exist, collect recent reports, and identify contacts. Support and guidance to the development of new programmes can be given. If there is sufficient interest, workshops to exchange best practices and experiences can be held. 2. GCOS needs to revitalise the national GCOS focal points, starting by developing a revised ToR. The GCOS focal points should coordinate with all bodies producing climate data, and not just NMHS. New ToR for the National GCOS Focal Points should emphasise this role outside of the NMHS and other state bodies. Currently most of the existing focal points are within NMHS and the need to link to all climate observations is not recognized. If there is a national climate observing system the Focal Point should be a link to that programme as well. Once the ToR are revised and agreed, nominations for the role should be requested from all countries. The GCOS Secretariat will need to support Focal Points, exchanging information and ideas to develop national observation systems and increase communication.
Links with other IP Actions	Actions E1 and E3.

Action E3: Enhance support for national climate observations	
Activities	1. Identify additional sources of support for climate observations. 2. Identify national needs for network support that will not be addressed by WMO's GBON and SOFF. 3. Publicise these to potential donors and try to mobilise the resources needed.
Issue/Benefits	In countries with limited resources, it is often difficult to maintain long-term systematic climate observations, due to competing priorities. The WMO GBON and SOFF have been established to address this need for climate and meteorological observations: however, there are many ECVs that will not be addressed via these mechanisms, for many years to come, if ever. The GCOS Cooperation Mechanism was established to assist countries in developing their climate observation capacity. In recent years donations to the GCM have been limited and it has focussed on supporting radiosondes – this will now be covered by GBON and the SOFF. While the GCM should try to address other ECVs it should also return to its original concept: identifying national needs and international assistance available.
Implementers	From 1 to 3: **GCOS**, National governments, Funding Agencies.
Means of Assessing Progress	1. List of additional donors. 2. List of national network support needs. 3. a) Increase in national network support; b) Funds raised by the GCM.
Additional Details	1. An inventory of potential donors should be established and maintained. Pro-actively engage with the potential donors to explore additional funding models/streams. 2. There are many needs for support to observations. Based on the regional workshops (E1) and national engagement (E2) as well as an understanding of the major gaps identified in the GCOS Status Report, a list of specific proposals to improve observing networks can be established. 3. Fundraising for the GCM should recommence. This will require clarity on how it will supplement the SOFF for climate observations, the benefits of the observations and how they provide global goods. In parallel, matching of countries to donors can also provide the required resources.
Links with other IP Actions	Actions E1 and E2.

6.6 Theme F: Other Emerging Needs

As countries respond to the impacts of climate change, they need data related to the specific areas impacting their countries. Many impacts are directly related to extremes, for example heatwaves, flooding and droughts. While work continues to identify how the global system can support these national and local needs, some requirements are already evident. Many users will not use the observed data directly, but rather use reanalysis products. Observing in areas of interest, at relevant resolutions will greatly improve reanalysis. This theme addresses some of these needs ranging from higher resolution data, (both spatial and temporal) to monitor extremes, to monitoring of areas of specific concern where impacts on humans are at their greatest: coastal and urban areas. Finally, there is a widespread interest in improving monitoring of GHGs fluxes to support national GHGs inventories and mitigation and to detect changes in the overall cycles of these gases. GCOS will continue to identify the needs of adaptation and supporting the Paris Agreement: this theme just addresses actions that have already been identified and can be started in the lifetime of this plan, 5-10 years.

Action F1: Responding to user needs for higher resolution, near real time data	
Activities	1. Identify the higher resolution observations of ECVs to support the Climatic Impact-Drivers (CIDs) identified in the IPCC AR6 and develop plans to address the priority needs. (see IPCC WGI AR6 Figure SPM.9). 2. Improve biomass, land cover, land surface temperature, and fire data with sub-annual observations and improved local detail and quality. 3. Increase temporal resolution of surface air temperature, soil moisture and precipitation to capture both climate and human-induced changes and extremes. 4. Include daily averages with the monthly CLIMAT reports for land surface stations (GSN/RBON).
Issue/Benefits	High-resolution and near-real time information of ECV-based climate information at global, regional and local scales allows planning to consider the full range of possible impacts. High-resolution data (in space and time), which, for many ECVs are currently not available, will allow rapid monitoring of changes in the climate system. This will allow the tracking of sustainable mitigation and adaptation measures. Improved high-resolution and near-real-time ECV data will allow improved understanding of CIDs. Whilst monthly CLIMAT reports have been available for many decades, the option to include daily averages has not been implemented operationally across the GSN/RBCN networks although it was approved by WMO in 2015. Daily averages would allow users to monitor the Regional/National impact of climate change, including an assessment of extremes.
Implementers	1. **GCOS,** Research organizations, Academia, WMO. 2. **Space agencies.** 3. **NMHS,** WMO. 4. **WMO**, NMHS.
Means of Assessing Progress	1. Inventory of improvements to ECVs needed to inform CIDs (e.g. spatial and temporal resolution, latency, uncertainty and data stewardship) and plans for priority actions. 2. a) Availability of key terrestrial ECVs at resolutions of 10-30 m stored in long term archives; b) Availability of Near Real Time (NRT) sub-annual data for critical land changes and to identify extremes stored in long term archives. 3. Availability of temperature, precipitation and soil moisture at higher temporal resolution stored in long term archives. 4. Increased availability of CLIMAT reports with daily averages.
Additional Details	1. CIDs are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems and are thus a priority for climate information provision. Sustainable adaptation and mitigation planning and management need high-resolution data and in near real time to monitor critical changes in CIDs as they occur and so allow adaptation responses to be implemented. This includes the need for systematic data for land changes (land

	cover/use, fire, biomass), hydrological conditions (runoff, soil moisture), cryosphere data (e.g. sea ice, ice sheets, permafrost, snow, glaciers), atmospheric data (e.g. temperature and precipitation and related extremes such as droughts, floods, heavy storms and cyclones, heat waves etc.), and oceanic data (e.g. marine extremes, ocean warming, ocean acidification, and oxygen depletion) to be available in timely and easy-accessible manner. Often, consistency across spatial and temporal scales is needed, as well as consistency among multi-variable sources. Existing data streams for ECVs informing CIDs need to evolve to increase regional (e.g. national) and local detail and quality and aim for much faster data delivery than available today. The various data streams should be provided in integrated, consistent ways so the various user and expert communities can use and combine them for their purposes. GCOS should make sure that the ECV requirements are updated accordingly. 2. and 3. The GCOS expert panels have already identified some specific high-resolution, near real time datasets that have been requested by users and that the existing monitoring systems are able to support within the next 5 years. 3. When implemented GBON will deliver higher resolution spatial and temporal data record for most land surface stations and some marine platforms. Where stations report on an hourly basis it will be possible to construct both monthly and daily CLIMAT reports for those stations which do not compute/report the CLIMAT operationally.
Links with other IP Actions	B2: GBON. C4: Develop regional reanalysis; reduce data latency. Reanalysis is important for responding to user needs for higher-resolution data. Observations in this action will benefit reanalysis. D2: Availability of data in archives. D3: Easy accessibility of data.

Action F2: Improved ECV satellite observations in polar regions	
Activities	Improve satellite observations of: 1. Sea Surface Salinity of polar oceans. 2. Greenhouse gases at high latitudes with a focus on the permafrost regions in wintertime. 3. Sea-ice thickness. 4. Surface temperatures of all surfaces (sea, ice, land). 5. Atmospheric ECVs at the very highest latitudes. 6. Albedo for all surfaces (land and sea-ice).
Issue/Benefits	Satellite missions in polar regions present particular challenges and this action highlights some of them affecting the measurement of certain ECVs. 1. SSS retrievals from the current generation of single-frequency, narrow L-band radiometry for salinity-measuring satellites (SMOS, Aquarius, SMAP) have much larger uncertainties in the polar oceans than for lower-latitude oceans, even though signal-to-noise ratio in certain regions of the Arctic Ocean is found to be relatively large. Future satellite salinity missions need to learn from the experience gained from the current generation of salinity-measuring satellites to improve precision and spatial resolution in polar oceans. Technology advance is thus needed to improve satellite-based polar ocean SSS which is important

	for the water cycle, freshwater inputs into the ocean and marine biogeochemistry. 2. Current SWIR-based satellite observations cannot measure GHG in polar winter. These GHG emissions are important. Active missions to monitor high latitude areas are important for measuring changes in the carbon cycle in the warming polar/permafrost regions. 3. There is a need to improve sea-ice thickness sensing. Sea-ice thickness is, together with the sea-ice area derived from the sea-ice concentration, the key ingredient to compute the sea-ice volume and mass. Long-term sea-ice volume and mass changes are considered as the integral response of climate change exerted on the polar regions. 4. There is a need to improve sensing of temperatures of the surface for all surface types across the polar regions. This can inform assessments of warming of the polar regions for which in situ measures of near-surface air temperature are sparse and hard to maintain. 5. Knowledge gaps exists at highest latitudes for atmospheric ECVs describing climate change including forcing and feedback effects and there is a need for further analyses to address these gaps with satellite observations (e.g. monitoring solid precipitation). True polar orbiters would improve coverage at the highest latitudes. 6. There is a need to improve the accuracy and consistency of observations of albedo for ice and snowy surfaces across domains (terrestrial snow, land ice, sea-ice and its snow cover) to improve the characterization of the Earth Energy cycle.
Implementers	From 1 to 6: **Research organizations**, Academia, Space agencies.
Means of Assessing Progress	From 1 to 3: Proof of concept for new technologies and new methodologies to measure SSS, sea-ice thickness and GHGs at high latitudes, particularly in wintertime. For 4 and 6: Feasibility study for true pole-to-pole orbital mission to measure changes at the very high latitudes for a set of targets ECVs. For 5: Feasibility studies on current and potential future satellite constellations or instrument combinations to improve satellite observations at the very highest latitudes for atmospheric ECVs.
Additional Details	1. Empirical algorithms using satellite observed salinity from SMOS and Aquarius, as well as CCI SST, have been demonstrated to be suitable to calculate total alkalinity and total dissolved inorganic carbon, and reproduce the wider spatial patterns of these two variables. Using multiple frequencies and increasing bandwidth near L-band can improve the retrieval accuracy of polar-ocean salinity from satellites. 2. The measurements of GHG emission, CO_2 and CH_4 in polar regions require active LIDAR missions such as the French-German research satellite MERLIN (expected to be launched in 2024). These use LIDAR technology to quantify the CH_4 and CO_2 mixing rations and emissions rather than rely on passive light (SWIR). Continuity and further development of this mission concept and its applications are important to track carbon-climate feedbacks. 3. Sea-ice thickness is a highly spatially variable parameter. Its derivation at hemispheric scale requires composition and averaging of multiple satellite overpasses when using currently employed altimetry. For thin ice (< 0.5 m thickness) alternative satellite sensors must be used. These are imaging sensors supporting finer temporal sampling at hemispheric scale. Combination of both

	types of sensors can add value. Currently, sea-ice thickness retrieval is considerably more mature for the Arctic than the Antarctic. This fact is due to, on the one hand, a larger amount of data used for evaluation in the Arctic than Antarctic. On the other hand, sea-ice thickness retrieval in the Antarctic is complicated by ice and snow conditions being different from the Arctic. Improving sea-ice thickness retrieval also requires improving observing snow-depth and sea-ice age (proxy for sea-ice thickness and density), among others. 4. Skin temperature to all surfaces in polar regions is needed in order to infer estimates of near surface temperature changes; the poles are one of the regions where fast changes occur. 5. True polar orbiters like TRUTHS enable simultaneous Nadir Overpass (SNO) type observations at all latitudes with sun-synchronous polar orbiter-payloads thus improving and supporting atmospheric ECV observations from current and future satellite constellations and/or instrument combinations. 6. The albedo of iced and snowy surfaces varies rapidly and drastically in the event of melting. This requires frequent observations and the attribution of albedo changes to the melt processes (e.g. linking albedo and melt-pond fraction over land and sea-ice).
Links with other IP Actions	A2: Continuity of space-based Sea Surface Salinity measurements. A3: Continuity of GCM measurements. B3: New satellite missions (GHGs).

Action F3: Improve monitoring of coastal and Exclusive Economic Zones	
Activities	1. Expand global ocean climate in situ observations and satellite products into Exclusive Economic Zones (EEZs) and coastal zones. 2. Develop new satellite-based products for coastal biogeochemistry. 3. Produce land cover datasets in coastal areas without land surface masks and in near real time, including uncertainties. 4. Improve national coastal and EEZ data collection, data processing, uncertainty evaluation and data curation by improving access to equipment and ensuring local practices are consistent with the global guidelines and best practices.
Issue/Benefits	Monitoring of coastal zones and EEZs is necessary to allow policies and measures to be developed to protect the significant vulnerable populations, infrastructure and ecosystems in these areas. Coastal zones are subject to rapid change and are the home to a substantial part of the Earth's population and to sensitive ecosystems. Changes near the coast directly impact ecosystems, people's health and livelihoods. Impacts such as storms, sea level rise, coastal erosion and inundation, flooding and saltwater intrusion are increasing. Currently these areas are poorly observed. Most of the purposely designed arrays of instrumentation and high resolution hydrographic transects (such as GO-SHIP) or the Argo program provide ocean observations at the open ocean, and the coastal and national waters are poorly monitored in many regions. From the land side, observations are directed at land properties and cover and so do not capture all the changes that are occurring. This action aims to address these issues. Developing products for variables such as temperature, turbidity, chlorophyll, and CDOM within 1 km of coasts, within estuaries and at EEZs will improve modelling of organic dissolved and particulate carbon distribution and dynamic, including land-

	ocean interaction. Turbidity/suspended particulate matter products, for example, can document the enhanced erosion in Arctic regions associated with permafrost loss.
Implementers	1. **GOOS**, Space agencies, NMHS. 2. **Space agencies,** Research organizations, Academia. 3. **Space agencies.** 4. **GOOS,** NMHS, Research organizations.
Means of Assessing Progress	1. Increased density of observations and reprocessed products in EEZ and coastal waters, and related uncertainties. 2. Number of global operational biogeochemical products in coastal areas. 3. Number of land-cover data sets produced without masks. 4. Published national and regional guidelines.
Additional Details	1. Coastal regions are where boundary currents and upwelling regimes modulate fluxes of heat, carbon and other properties, with small-scale phenomena highly impacting the climate globally and locally, and also ecosystems. Not all observing systems used elsewhere, such as Argo, can provide high-resolution full-depth monitoring in coastal areas. Argo measurements do not sample at shelf-shelf break regions (< 2000 m depth). Consolidation and development of in situ observing networks could be done through national and regional engagements, including local actors from certain sectors such as fisheries or maritime transport. Activity 1 should consider the on-going discussions and efforts to facilitate access to the EEZs to carry out systematic ocean observations, as reflected on a recent multi-agency workshop lead by UNESCO/IOC[53]. A successful implementation of GBON can increase the number of surface marine meteorological observations collected by member states in their respective EEZs. At the coast, "climate quality" tide gauge observations that include co-located vertical land motion measurements are needed for our understanding of contemporary and future coastal flood hazard. Finally, reprocessing of existing satellite records in coastal regions and generation of global products which include the coastal regions (e.g. altimetry and wind data records) is needed to increase coverage near the coast, which may require some software development. Products should include clear information on their limitations in coastal areas and EEZs, and their related uncertainties. 2. There are currently no biogeochemical operational products from high resolution satellites (e.g., Sentinel 2AB, Landsat 8) in coastal areas. Satellite observations need to be reprocessed to provide products for variables such as the temperature, turbidity, chlorophyll, and chromophoric dissolved organic matter (CDOM). 3. Land cover datasets should be reprocessed without masking to allow the detection of changes at the coastline. This activity will allow extremes and long-term trends such as sea-level rise to be captured (e.g. changes in the coastline and neighbouring land areas). Currently, impacts of changes in the sea level at the coast are not monitored because the way satellite observations are processed obscures these details.

[53] GOOS-246 (2021), Report of Ocean Observations in Areas under National Jurisdiction Workshop. https://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=26607

	4. Many coastal states lack access to equipment and expertise to monitor their coastal water and areas within their EEZs. Resources for equipment and capacity building are needed. In 2022 a task team has been set up under the IOC Ocean Best Practices framework[54], to identify common and accepted best practices used within the community for observations of physical, chemical and biological parameters and produce a package of easy-to-use operating procedures to monitor the coastal ocean. This guidance will need to be implemented at a national level.
Links with other IP Actions	B2: Implementing GBON will be of benefit for this action. B6 and B7: Expansion and integration of the global ocean observing system, including observations of biogeochemical/biological parameters. B8: Augmenting ship-based hydrography and fixed-point observations with biogeochemical and biological parameters. C1: Develop Monitoring standards, guidance and best practice for each ECV. C2: Activity 2 -reprocessing of satellite observations.

Action F4: Improve climate monitoring in urban areas	
Activities	1. Audit existing GCOS ECVs to identify those that are urban-relevant and produce updated requirements where needed. 2. Identify new urban-relevant products and define their requirements. 3. Develop plans to address the urban monitoring requirements identified in Activities 1 and 2.
Issue/Benefits	The majority of the human population lives in cities and urban areas, including informal settlements, are primary locations for economic and social activity, and hence these are critical locations for emissions mitigation and climate adaptation. Effective monitoring of climate relevant parameters will therefore yield substantial benefits. Such climate relevant parameters include the normal meteorological observations, but also extend to observations of other relevant variables such as pollution emissions and land use and land cover (LULC). Traditional measurements of standard meteorological parameters have sought to eliminate urban influences, wherever possible, but the reality is that temperatures that are elevated by urban influence do actually represent the climatic conditions experienced by a large proportion of the global population and are especially important when considering adaptation to climate change. Sufficient standardised observations of these complex environments are required to understand the heterogeneity of urban climates, and this in turn is key to making informed adaptation decisions.
Implementers	From 1 to3: **GCOS**, WMO, Academia, National agencies, Research organizations, NMHS.
Means of Assessing Progress	1. GCOS Adaptation Task Team progress and final reports to GCOS Steering Committee. 2. Upgraded GCOS documentation (especially for TOPC and AOPC) to clearly identify existing, upgraded and new ECVs relevant to urban climate and adaptation. 3. Plans to address urban monitoring needs and updating the user requirements.

[54] https://www.oceanbestpractices.org/about/task-teams/task-team-22-01-coastal-observing-in-under-resourced-countries

Additional Details	Processes and procedures are identified in the working documents produced by the GCOS Adaptation Task Team (GATT). Better monitoring in the urban area is also clearly needed to measure exposure to black-carbon, ozone and aerosol precursor emissions, NO_2. The enhancement of GCOS capability in these areas will additionally broaden GCOS engagement with stakeholders in both provision and use of the relevant observations. For example, enhancement of LULC capability for urban areas might require engagement with urban climate community and the World Urban Database and Planning Tool (WUDAPT).
Links with other IP Actions	B4: expansion of atmospheric composition observations. F5: Activity 4 – improve measurements of relevant ECVs om large cities.

Action F5: Develop an Integrated Operational Global GHG Monitoring System	
Activities	The overall aim here is to develop an integrated operational global greenhouse gas monitoring infrastructure. The first steps are: 1. Design and start to implement a comprehensive global set of surface-based observations of CO_2, CH_4 and N_2O concentrations routinely exchanged in near-real time suitable for monitoring GHG fluxes. 2. Design a constellation of operational satellites to provide near-real time global coverage of CO_2 and CH_4 column observations (and profiles to the extent possible). 3. Identify a set of global modelling centres that could assimilate surface and satellite-based observations to generate flux estimates. 4. Improve and coordinate measurements of relevant ECVs at anthropogenic emissions hotspots (large cities, powerplants) to support emission monitoring and the validation of tropospheric measurements by satellites.
Issue/Benefits	The Paris Agreement requests Parties to regularly provide estimates of anthropogenic emissions by sources and removals by sinks of greenhouse gases, and information necessary to track progress made in implementing and achieving their nationally determined contribution under Article 4. The proposed global greenhouse gas monitoring infrastructure would support the development of these estimates (i.e. emission inventories); validate national and regional achievement of Parties' commitments in their National Adaptation Plans (NAPs); and monitor changes to the cycles of GHG that may impact the achievement of the temperature goal of the Paris Agreement. Monitoring of hot-spots via dedicated observations to validate specific point-source emissions and identify missing sources form emission inventories. Remote monitoring of atmospheric composition can quantify and identify major emission sources. Anthropogenic emission hotspots like cities and industrial facilities and power plants contribute strongly to the global GHG emissions and to emission of key ozone and aerosol precursors (SO_2, VOCs). Reliable remote observations of these emission hotspots in synergy with source detection models can contribute to verifying emission estimates and monitor and guide mitigation efforts (link to Flux ECV).
Implementers	1. **WMO (INFCOM, GAW and IG3IS).** 2. **Space agencies**, National agencies, Research organizations, Academia. 3. **WMO (INFCOM, GAW and IG3IS)**, National agencies. 4. **GCOS,** Space agencies, National agencies.

Means of Assessing Progress	1. Expanded observations of GHGs, ozone and aerosol precursors, aerosols and aerosol profiles near hotspots. 2. Designs and plans for in situ and satellite observations. 3. Identification of global monitoring centres that run global Chemistry Transport Models. 4. a) Improved satellite retrievals in the presence of varying aerosol loadings in urban and hotspot conditions. Improved uncertainty quantification of GHG retrievals in the presence of aerosols; b) Number of emission detection studies using in situ and satellite data near hot spots.
Additional Details	From 1 to 3: Based on an initial concept paper prepared by the WMO Secretariat entitled "A WMO-coordinated Global Greenhouse Gas Monitoring Infrastructure" and the Report from the WMO-hosted Greenhouse Gas Monitoring Workshop in May 2022, the 75th Session of the WMO Executive Council decided to proceed with the further development of the concept for a WMO-coordinated Global Greenhouse Gas Monitoring Infrastructure, building on existing WMO programmes and other regional or global infrastructure and initiatives. This infrastructure will consist of the following main elements: a) A comprehensive global set of surface-based observations of CO_2, CH_4 and N_2O concentrations routinely exchanged in near-real time; b) A constellation of satellites to provide near-real time global coverage of CO_2 and CH_4 column observations (and profiles to the extent possible); c) A global Chemistry Transport Model (CTM) driven by output from a high-resolution global NWP model; d) Operational near-real time assimilation of the GHG observations a) and b) into CTM and routine dissemination of the output. 4. Hot spots include urban areas, industrial zones and individual large plants. 4.1 Enhance observations in urban areas: a) Expand the network of GHG observations that measure around urban areas, in particular column and profile observations. These observations will support integration of satellite missions that detect and quantify sources; b) Ensure co-located observations of co-emitted gases (typically ozone and aerosol precursors) CO, NO_2, SO_2, VOCs. 4.2 Ensure co-located observations of aerosols loadings and aerosol profiles in urban areas: a) Improve satellite retrievals in emission hotspots; b) Evaluate GHG retrievals in urban areas by considering varying aerosol loadings using reference observations; c) Focus on improving GHG retrievals and their uncertainty quantification in urban and other local hotspot cites (Action B3). Present challenges in monitoring emission hotspots include: • Missing reference data sets of GHGs and other co-emitted gases and aerosols in urban areas. • Challenges in estimating GHG concentrations in the presence of varying aerosol loads. Underestimated (or overestimated) uncertainties can mislead the emission estimation.

	• Integration of in situ and satellite measurements. In the future, measuring stable isotopes of carbon will allow separation of natural and fossil sources of GHG.
Links with other IP Actions	B3: New satellite missions. B4: In situ monitoring of aerosols and greenhouse gases. F4: Climate monitoring in urban areas.

APPENDIX 1: ACRONYMS

AFOLU	Agriculture, Forestry and Other Land Use
AGB	Above Ground Biomass
AOPC	Atmospheric Observations Panel for Climate
AOS	Atmospheric Observation System (NASA)
AQUASTAT	FAO Global Information System on Water Resources and Agricultural Water Management
ATLID	Atmospheric Lidar
BAMS	Bulletin of American Meteorological Society
BGC	BioGeoChemical
BIPM	International Bureau of Weights and Measure (Bureau International de Poids et Mesures)
BRDF	Bidirectional Reflectance Distribution Function
BSRN	Baseline Surface Radiation Network
CDR	Climate Data Records
CDS	Climate Data Store (Copernicus)
CDOM	Chromophoric Dissolved Organic Matter
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
CIMR	Copernicus Imaging Microwave Radiometer
CMA	China Meteorological Agency
CSIS	Climate Services Information System
CTM	Chemistry Transport Model
DWD	Deutsche Wetterdienst
EarthCARE	Earth Cloud Aerosol and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecast
ECV	Essential Climate Variable
EEI	Earth Energy Imbalance
EEZ	Exclusive Economic Zone
EOV	Essential Ocean Variables
ERB	Earth Radiation Budget
ESA	European Space Agency
EU	European Union
EUSPA	European Union Agency for the Space Programm
FAIR	Findable, Accessible, Interoperable, Reusable
FAO	Food and Agriculture Organization
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCDR	Fundamental Climate Data Records
FRM	Fiducial Reference Measurement
FTIR	Fourier Transformed Infrared Spectroscopy
GACS	Global Alliance of Continuous Plankton Recorder Surveys
GATT	GCOS Adaptation Task Team
GAW	Global Atmospheric Watch
GBON	Global Basic Observation Network
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GCM	GCOS Cooperation Mechanism
GCW	Global Cryosphere Watch
GDP	Gross Domestic Product
GFCS	Global Framework for Climate Services
GFOI	Global Forest Observations Initiative (FAO)
GGMN	Global Groundwater Monitoring Network
GHG	Greenhouse gases
GLM	Geostationary Lightning Mapper
GLODAP	Global Data Analysis Project
GNSS	Global Navigation Satellite System
GOOS	Global Ocean Observing System
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations
GPM	Global Precipitation Measurement

GRACE	Gravity Recovery and Climate Experiment
GRUAN	Global Reference Upper Air Network
GSICS	Global Space-based Intercalibration System
GSN	Global Surface Network
GSRN	Global Surface Reference Network
GST	Global Stocktake
GUAN	Global Upper Air Network
GUM	Guide to the expression of uncertainty in measurement
HYDROLARE	International Data Centre on Hydrology of Lakes and Reservoirs
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
ICOS-OTC	Integrated Carbon Observation System-Ocean Thematic Centre
IG3IS	Integrated Global Greenhouse Gas Information System
IGRAC	International Groundwater Resources Assessment Centre
INFCOM	WMO Commission for Observation, Infrastructure and Information Systems
IOC	Intergovernmental Oceanographic Commission
IOCCP	International Ocean Carbon Coordination Project
IP	Implementation Plan
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISC	International Scientific Council
ISMN	International Soil Moisture Network
JMA	Japan Meteorological Agency
LAI	Leaf Area Index
LEO	Low-Earth Orbiting
LES	Large Eddy Simulations
LIDAR	Light Detection And Ranging
LIS	Lightning Imaging Sensor
LULC	Land Use and Land Cover
MEDIN	Marine Environmental Data and Information Network
MEMENTO	MarinE MethanE and NiTrous Oxide
MLS	Microwave Limb Sounder
NAP	National Adaptation Plan
NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NFI	National Forest Inventory
NMHS	National Meteorological and Hydrological Services
NOAA	National Oceanographic and Atmospheric Administration
NRT	Near Real Time
NSIDC	National Snow and Ice Data Center
NWP	Numerical Weather Prediction
OECD	Organisation for Economic Co-operation and Development
OOPC	Ocean Observations Physics and Climate Panel
OTD	Optical Transient Detector
RS	Reflected Solar
RT	Radiative Transfer
SC-MINT	Standing Committee on Measurements, Instrumentation and Traceability
SC-ON	Standing Committee on Earth Observing Systems and Monitoring Networks
SI	International System of Units
SIF	Solar Induced Fluorescence
SMM-CD	Stewardship Maturity Matrix for Climate Data
SNO	Simultaneous Nadir Overpass
SOCAT	Surface Ocean CO2 Atlas
SOCOM	Surface Ocean CO2 Mapping intercomparison initiative
SOCONET	Surface Ocean CO2 reference Observing NETwork
SOFF	Systematic Observations Financing Facility
SOOP	Ship-Of-Opportunity Programme
SSS	Sea Surface Salinity
TOPC	Terrestrial Observations Panel for Climate
TRUST	Transparency, Responsibility, User focus, Sustainability and Technology
TWS	Terrestrial water storage
UNEP	United Nations Environment Programme

UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UTLS	Upper Troposphere/Lower Stratosphere
WCRP	World Climate Research Programme
WDS	World Data System
WGClimate	Working Group on Climate
WGMS	World Glacier Monitoring System
WHYCOS	World Hydrological Cycle Observing System
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
WUDAPT	World Urban Database and Planning Tool
WVDIAL	Water Vapour Differential Absorption Lidar

APPENDIX 2: REFERENCES

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ANNEX A: LIST OF ECVS AND ECVS PRODUCTS

The ECV framework has evolved since the publication of the previous list of ECVs requirements in the GCOS IP 2016. The list of ECVs and ECVs products has changed as well, and the following table illustrates those changes.

Atmosphere			
ECV	**ECV Product 2016**		**ECV Product 2022**
Surface Pressure	Pressure (surface)		Air Pressure (near surface)
Surface Temperature	Temperature (surface)		Air Temperature (near surface)
Surface wind Speed and Direction	Surface wind Speed and Direction		Wind Speed (near surface)
			Wind Direction (near surface)
			Wind Vector (near surface)
Surface Water Vapour	Water Vapour (surface)		Dew Point Temperature (near surface)
			Relative Humidity (near surface)
			Air Specific Humidity (near surface)
Precipitation	Estimates of Liquid and Solid Precipitation		Accumulated precipitation
Surface Radiation Budget	Surface ERB Short-Wave		Downward Short-Wave Irradiance at Earth Surface
	Surface ERB long-Wave		Downward Long-Wave Irradiance at Earth Surface
			Upward Long-Wave Irradiance at Earth Surface
Upper-air Temperature	Tropospheric Temperature Profile		Atmospheric Temperature in the Boundary Layer
	Stratospheric Temperature Profile		Atmospheric Temperature in the Free Troposphere
			Atmospheric Temperature in the Upper Troposphere and Lower Stratosphere
	Temperature of the Deep Atmospheric Layers		Atmospheric Temperature in the Middle and Upper Stratosphere
			Atmospheric Temperature in the Mesosphere
Upper-air Wind Speed and Direction	Upper-Air Wind Retrievals		Wind (horizontal) in the Boundary Layer
			Wind (horizontal) in the Free Troposphere
			Wind (horizontal) in the Upper Troposphere and Lower Stratosphere
			Wind (horizontal) in the Middle and Upper Stratosphere
			Wind (horizontal) in the Mesosphere
			Wind (vertical) in the Boundary Layer
			Wind (vertical) in the Free Troposphere
			Wind (vertical) in the Upper Troposphere and Lower Stratosphere
			Wind (vertical) In the Middle and Upper Stratosphere

			Wind (vertical) in the Mesosphere
Upper-air Water Vapour	Tropospheric and Lower-Stratospheric profile of Water Vapour		Water Vapour Mixing Ratio in the Upper Troposphere and Lower Stratosphere
			Water Vapour Mixing Ratio in the Middle and Upper Stratosphere
			Water Vapour Mixing Ratio in the Mesosphere
			Relative Humidity in the Boundary Layer
	Upper Tropospheric Humidity		Relative Humidity in the Free Troposphere
			Relative Humidity in the Upper Troposphere and Lower Stratosphere
			Specific Humidity in the Boundary Layer
			Specific Humidity in the Free Troposphere
	Total Column Water Vapour		Integrated Water Vapour
Earth Radiation Budget	Solar Spectral Irradiance		Solar Spectral Irradiance
	Total Solar Irradiance		Downward Short-Wave Irradiance at Top of the Atmosphere
	Top of the Atmosphere ERB Long-Wave		Upward Long-Wave Irradiance at Top of the Atmosphere
	Top of the Atmosphere ERB Short-Wave		Upward Short-Wave Irradiance at Top of the Atmosphere
			Radiation Profile
Cloud Properties	Cloud Amount		Cloud Cover
	Cloud Water Path (liquid and ice)		Cloud Liquid Water Path
			Cloud Ice Water Path
	Cloud Effective particle radius (liquid and ice)		Cloud Drop Effective Radius
	Cloud Optical Depth		Cloud Optical Depth
	Cloud Top Temperature		Cloud Top Temperature
	Cloud Top Pressure		Cloud Top Height
Lightning	Lightning		Total Lightning Stroke Density
			Schumann Resonances
Carbon Dioxide, Methane and Other Greenhouse Gases	Tropospheric CO_2		CO_2 Mole Fraction
	Tropospheric CO_2 Column		CO_2 Column Average Dry Air Mixing Ratio
	Tropospheric CH_4		CH_4 Mole Fraction
	Stratospheric CH_4		
	Tropospheric CH_4 Column		CH_4 Column Average Dry Air Mixing Ratio
			N_2O Mole Fraction
Ozone	Troposphere Ozone		Ozone Mole Fraction in the Troposphere
	Ozone Profile in Upper and Lower Stratosphere		Ozone Mole Fraction in the Upper Troposphere/ Lower Stratosphere
	Ozone Profile in Upper Stratosphere and Mesosphere		Ozone Mole Fraction in the Middle and Upper Stratosphere
	Total Column Ozone		Ozone Total Column
			Ozone Tropospheric Column
			Ozone Stratospheric Column
Precursors (Supporting	CO Tropospheric Column		CO Tropospheric Column
	CO Tropospheric Profile		CO Mole Fraction

the aerosol and ozone ECVs)	SO_2, HCHO Tropospheric Columns		HCHO Tropospheric Column
			SO_2 Tropospheric Column
			SO_2 Stratospheric Column
	NO_2 Tropospheric Column		NO_2 Tropospheric Column
			NO_2 Mole Fraction
Aerosols Properties	Aerosol Extinction Coefficient Profile		Aerosol Light Extinction Vertical Profile (Troposphere)
			Aerosol Light Extinction Vertical Profile (Stratosphere)
	Aerosol Optical Depth		Multi-wavelength Aerosol Optical Depth
	Single Scattering Albedo		Aerosol Single Scattering Albedo
	Aerosol Layer Height		
			Chemical Composition of Aerosol Particles
			Number of Cloud Condensation Nuclei
			Aerosol Number Size Distribution

Ocean			
ECV	**ECV Product 2016**		**ECV Product 2022**
Sea-Surface temperature	Sea-Surface temperature		Sea-Surface temperature
Subsurface Temperature	Interior Temperature		Interior Temperature
Sea-Surface Salinity	Sea-Surface Salinity		Sea-Surface Salinity
Subsurface Salinity	Interior Salinity		Interior Salinity
Surface Currents	Surface Geostrophic Current		Surface Geostrophic Current
			Ekman Currents
Subsurface Currents	Interior Currents		Vertical Mixing
Sea Level	Regional Sea Level		Regional Mean Sea Level
	Global Mean Sea Level		Global Mean Sea Level
Sea State	Wave Height		Wave Height
Surface Stress	Surface Stress		Surface Stress
Ocean Surface Heat Flux	Radiative Heat Flux		Radiative Heat Flux
	Sensible Heat Flux		Sensible Heat Flux
	Latent Heat Flux		Latent Heat Flux
Sea Ice	Sea Ice Concentration		Sea Ice Concentration
	Sea Ice Thickness		Sea Ice Thickness
	Sea Ice Drift		Sea Ice Drift
	Sea Ice Extent/Edge		Sea Ice Age
			Sea Ice Surface Temperature (IST)
			Sea ice Surface Albedo
			Snow Depth on Sea Ice
Oxygen	Interior Ocean Oxygen Concentration		Dissolved Oxygen Concentration
Nutrients	Interior Ocean Concentrations of Silicate, Phosphate, nitrate		Silicate
			Phosphate
			Nitrate

Ocean Inorganic Carbon	Interior Ocean Carbon Storage. (At least 2 of DIC, TA or pH)		Total Alkalinity (TA)
			Dissolved Inorganic Carbon (DIC)
			pCO_2
Transient Tracers	Interior Ocean CFC-11, CFC-12, SF_6, ^{14}C, tritium, ^{3}He, ^{39}Ar		^{14}C
			SF_6
			CFC-11
			CFC-12
Ocean nitrous oxide N_2O	Interior Ocean Nitrous Oxide N_2O		Interior Ocean Nitrous Oxide N_2O
	N_2O Air-Sea Flux		N_2O Air-Sea Flux
Ocean Colour	Water Leaving Radiance		Water Leaving Radiance
	Chlorophyll-a concentration		Chlorophyll-a concentration
Plankton	Zooplankton		Zooplankton Diversity
			Zooplankton Biomass
	Phytoplankton		Phytoplankton Diversity
			Phytoplankton Biomass
Marine Habitat Properties	Coral Reefs, mangrove forests, seagrass beds, Macroalgal Communities		Mangrove Cover and Composition
			Seagrass Cover (areal extent)
			Macroalgal Canopy Cover and Composition
			Hard coral cover and composition

Terrestrial			
ECV	**ECV Product 2016**		**ECV Product 2022**
Groundwater	Groundwater Volume Change		Groundwater Storage Change
	Groundwater Level		Groundwater Level
	Groundwater Recharge		
	Groundwater Discharge		
	Wellhead Level		
	Water Quality		
Lakes	Lake Water Level		Lake Water Level (LWL)
	Water Extent		Lake Water Extent (LWE)
	Lake Surface-Water Temperature		Lake Surface Water Temperature (LSWT)
	Lake Ice Cover		Lake Ice Cover (LIC)
	Lake Ice Thickness		Lake Ice Thickness (LIT)
	Lake Colour (Lake Water-Leaving Reflectance)		Lake Water-Leaving Reflectance
River Discharge	River Discharge		River Discharge
	Water Level		Water Level
	Flow Velocity		
	Cross-Section		
Soil Moisture	Surface Soil Moisture		Surface Soil Moisture
	Freeze/Thaw		Freeze/Thaw
	Surface Inundation		Surface Inundation
	Root-Zone Soil Moisture		Root Zone Soil Moisture
Terrestrial Water Storage[55]			Terrestrial Water Storage Anomaly

[55] This is the only new ECV approved by GCOS Steering Committee in 2020.

Snow	Area Covered by Snow		Area Covered by Snow
	Snow Depth		Snow Depth
	Snow-Water Equivalent		Snow-Water Equivalent
Glaciers	Glacier Area		Glacier Area
	Glacier Elevation Change		Glacier Elevation Change
	Glacier Mass Change		Glacier Mass Change
Ice Sheets and Ice Shelves	Surface Elevation Change		Surface Elevation Change
	Ice Velocity		Ice Velocity
	Ice Mass Change		Ice Volume Change
	Grounding Line Location and Thickness		Grounding Line Location and Thickness
Permafrost	Thermal State of Permafrost		Permafrost Temperature (PT)
	Active Layer Thickness		Active Layer Thickness (ALT)
			Rock Glacier Velocity (RGV)
Fraction of FAPAR	Maps of FAPAR for Modelling		Fraction of Absorbed Photosynthetically Active Radiation
	Maps of FAPAR for Adaptation		
Leaf Area Index	Maps of LAI for Modelling		Leaf Area Index (LAI)
	Maps of LAI for Adaptation		
Albedo	Maps of DHR Albedo for Adaptation		Spectral and Broadband (Visible, Near Infrared and Shortwave) DHR & BHR with Associated Spectral Bidirectional Reflectance Distribution Function (BRDF) Parameters
	Maps of BHR Albedo for Adaptation		
	Maps of DHR Albedo for Modelling		
	Maps of BHR Albedo for Modelling		
Land-Surface Temperature	Maps of Land-Surface Temperature		Land Surface Temperature (LST)
			Soil Temperature[56]
Above-Ground Biomass	Maps of AGB		Above-Ground Biomass (AGB)
Land Cover	Maps of Land Cover		Land Cover
	Maps of High-Resolution Land Cover		Maps of High-Resolution Land Cover
	Maps of Key IPCC Land Use, Related Changes and Land-Management Types		Maps of Key IPCC Land Classes, Related Changes and Land Management Types
Soil Carbon	% Carbon in Soil		Carbon in Soil
	Mineral Soil Bulk Density to 30 Cm and 1 M		Mineral Soil Bulk Density
	Peatlands Total Depth of Profile, Area and Location		Peatlands
Fire	Burnt Areas		Burned Area
	Active Fire Maps		Active Fires
	Fire Radiative Power		Fire Radiative Power (FRP)
Anthropogenic Greenhouse-Gas Fluxes	Emissions from Fossil Fuel Use, Industry, Agriculture and Waste Sectors		Anthropogenic CO_2 Emissions from Fossil Fuel Use, Industry, Agriculture, Waste and Products Use
			Anthropogenic CH_4 Emissions from Fossil Fuel, Waste, Agriculture, Industrial Processes and Fuel Use

[56] Soil Temperature is a new ECV product temporarily included under the ECV Land-Surface Temperature. Its positioning will be subject to evaluation by the TOPC Panel and the GCOS Steering Committee.

			Anthropogenic N_2O Emissions from Fossil Fuel Use, Industry, Agriculture, Waste and Products Use, Indirect from N-Related Emissions/Depositions
			Anthropogenic F-Gas Emissions from Industrial Processes and Product Use
	Estimated Fluxes by Inversions of Observed Atmospheric Composition – National		Total Estimated Fluxes by Coupled Data Assimilation/Models with Observed Atmospheric Composition – National
	Estimated Fluxes by Inversions of Observed Atmospheric Composition – Continental		Total Estimated Fluxes by Coupled Data Assimilation/Models with Observed Atmospheric Composition - Continental
	Emissions/ Removals by IPCC Land Categories		Anthropogenic CO_2 Emissions/Removals by Land Categories
	High-Resolution CO_2 Column Concentrations to Monitor Point Sources		High-Resolution Footprint Around Point Sources
Evaporation from Land	TOPC was considering the practicality of this being an ECV (Latent and Sensible Heat Fluxes) and, if so, what the requirements might be.		Sensible Heat Flux
			Latent Heat Flux
			Bare Soil Evaporation
			Interception Loss
			Transpiration
Anthropogenic Water Use	Anthropogenic Water Use		Anthropogenic Water Use

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