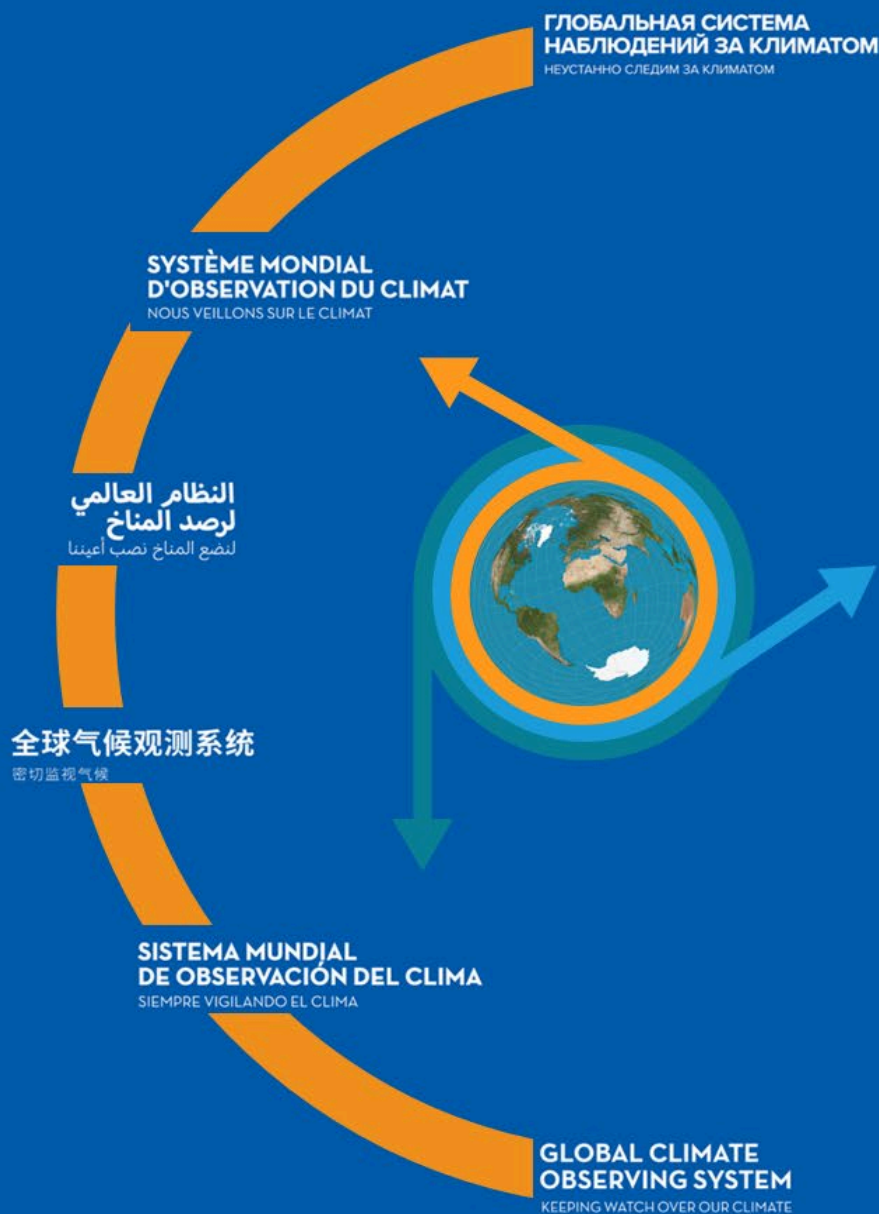


The 2022 GCOS Implementation Plan



GCOS – 244
GOOS – 272

The 2022 GCOS Implementation Plan

**GCOS-244
GOOS-272**

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

© **World Meteorological Organization, 2022**

The right of publication in print, electronic and any other form and in any language is reserved by WMO. Short extracts from WMO publications may be reproduced without authorization, provided that the complete source is clearly indicated. Editorial correspondence and requests to publish, reproduce or translate this publication in part or in whole should be addressed to:

Chair, Publications Board

World Meteorological Organization (WMO)

7 bis, avenue de la Paix

P.O. Box 2300

CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03

Fax: +41 (0) 22 730 80 40

E-mail: Publications@wmo.int

NOTE

The designations employed in WMO publications and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of WMO concerning the legal status of any country, territory, city or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The mention of specific companies or products does not imply that they are endorsed or recommended by WMO in preference to others of a similar nature which are not mentioned or advertised.

The findings, interpretations and conclusions expressed in WMO publications with named authors are those of the authors alone and do not necessarily reflect those of WMO or its Members.

This publication has been issued without formal editing.

Table of Contents

PREFACE	v
FOREWORD	vi
EXECUTIVE SUMMARY	vii
1. Introduction	1
2. Evolving user needs for Climate Observation	2
2.1 Climate assessments.....	2
2.2 Supporting the Paris Agreement	3
2.3 Climate services and adaptation	3
2.4 The Earth Climate Cycles	4
2.4.1 Monitoring the Earth Energy Budget.....	4
2.4.2 Monitoring the Water Cycle	5
2.4.3 Monitoring the Carbon Cycle	5
2.5 Cost and Benefits of Climate Observations	6
3. GCOS: vision, mission, benefits, evolution and future priorities	9
3.1 Vision Statement	9
3.2 GCOS Mission.....	9
3.3 Benefits of GCOS	9
3.3.1 In situ measurements	9
3.3.2 Satellite Observations	10
3.3.3 WMO.....	10
3.3.4 UNFCCC.....	10
3.3.5 Research and academia	11
3.3.6 International programmes on climate.....	11
3.4 The evolution of GCOS from past to present.....	11
3.5 GCOS priorities.....	12
4. Essential Climate Variables	13
5. Data management and policies	16
5.1 Free and Open Data.....	16
5.2 FAIR (Findable, Accessible, Interoperable, Reusable) Principles	17
5.3 TRUST (Transparency, Responsibility, User focus, Sustainability and Technology) Principles.....	17
6. Actions to improve the Global Climate Observing System	18
6.1 Theme A: Ensuring Sustainability	18
6.2 Theme B: Filling Data Gaps.....	22
6.3 Theme C: Improving Data Utility	37
6.4 Theme D: Managing Data	44
6.5 Theme E: Engaging with Countries	50
6.6 Theme F: Emerging Needs.....	53
APPENDIX 1: Acronyms	61
APPENDIX 2: References	62
APPENDIX 3: Acknowledgements AND List of Contributors	63
ANNEX A: ECV Requirements	64
ANNEX B: STATUS OF THE GLOBAL CLIMATE OBSERVING SYSTEM 2021.....	65

PREFACE

To be added.

FOREWORD

To be added.

EXECUTIVE SUMMARY

To be added.

1. INTRODUCTION

Climate observations are critical for understanding and responding to climate change. This report was produced in response to an invitation from the UNFCCC to update the 2016 GCOS Implementation Plan in light of the 2021 GCOS Status Report¹.

The 2021 GCOS Status Report was informed by experts from the three GCOS panels² who provided the technical information and assessments. Each Panel appointed "ECV Stewards" to monitor the performance of the observing system for specific 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 whole report undergoing a public review. Finally, the report was approved by the GCOS Steering Committee. The Executive Summary of the 2021 GCOS Status Report is provided in Annex B.

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. However, the 2021 GCOS Status Report identified a number of outstanding issues that are addressed in this report.

This 2022 GCOS Implementation Plan has a different form to earlier plans³: 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.

An Editorial Board agreed 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 whole process and 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). The updated ECV requirements are presented in Annex A
- Chapter 5 covers data 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 utility;
 - Improving data management;
 - Engaging with countries and stakeholders;
 - Addressing emerging needs.

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

² AOPC – Atmospheric Observations Panel for Climate; TOPC: Terrestrial Observations Panel for Climate; OOPC: Ocean Observations Physics and Climate Panel

³ GCOS (2016). The Global Observing System for Climate: Implementation Needs ([GCOS-200](#))

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, respond to, ameliorate or 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 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 IPCC, are critically dependent upon the global availability of high-quality observational data products for a broad range of Essential Climate Variables (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) is 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 5.4), 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 resolution, 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 trace greenhouse gases 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 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 ECMWF (ERA5) and JMA (JRA-55).

Observations are key to underpinning the WMO annual climate assessment report and the BAMS State of the climate series of reports as well as regional (e.g. Copernicus Climate Change Service) 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

1 value in communicating the changing status of the climate to numerous stakeholders. There also
2 exist bespoke monitoring activities, such as the global carbon project, which require observations
3 to underpin their annual assessments.

4 **2.2 Supporting the Paris Agreement**

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

9 All countries will have to provide national GHG emission reports. Observations support these
10 reports: they can be used as a means of their verification, and to improve transparency.
11 Connecting and merging relevant data from different sources of information, including the
12 private sector, will be a challenge.

13 The Global Stocktake (GST) facilitates the assessment of progress in three areas: mitigation,
14 adaptation and finance flows, and means of implementation and support. The GST is in its first
15 phase (Information collection and preparation) where aggregated information is needed to
16 support the assessment of all three areas.

17 In terms of supporting response measures, such as adaptation, countries need information that
18 can be used at a national level to support decision making. This includes provision of
19 standardised datasets and the long-term records of ECVs that are fundamental for national
20 adaptation planning and allow countries to build their sectoral needs and priorities. Adaptation
21 indicators are becoming increasingly important as the impacts of climate change and associated
22 extremes become more and more apparent. Observations are needed to determine the
23 benchmarks which will be used later as a reference to assess the efficacy of adaptation
24 measures. Observations also inform assessments of losses and damages.

25 Variables related to biodiversity will become more relevant as we move forward in the
26 implementation of the Paris Agreement. Observations assist the evaluation of the effect of
27 climate change on terrestrial and marine ecosystems and aid the discovery and understanding
28 of important physical feedback mechanisms in the climate system.

29 Moreover, to support attainment of the goals of the Paris Agreement the observation community
30 needs to address knowledge gaps through those ECVs that track physical, chemical and biological
31 cycles. Attention needs to be paid to regions particularly vulnerable to the impacts of climate
32 change where observational capabilities are generally weakest.

33 **2.3 Climate services and adaptation**

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

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

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

20 **2.4 The Earth Climate Cycles**

21 The most important features of the earth system for understanding and predicting climate
22 change are the energy, water (or hydrological) and carbon cycles. Ideally, these should be
23 completely monitored by ECVs. In 2018 GCOS started assessments for these cycles, identifying
24 possible gaps and inconsistencies in existing observation systems (von Schuckmann et al., 2020;
25 Dorigo et al., 2021; Crisp et al., 2022). By assessing how well these are observed, GCOS is able
26 to identify gaps and inconsistencies in the global climate observing system in a more integrated
27 way than separately considering the three domains, atmosphere, ocean and land.

28 **2.4.1 Monitoring the Earth Energy Budget**

29 Von Schuckmann et al., (2020)⁴ updated the Earth heat inventory and presented an updated
30 assessment of ocean warming estimates as well as new and updated estimates of heat gain in
31 the atmosphere, cryosphere and land over 1960–2018. Some key requirements for improving
32 future assessments have been identified:

- 33 • A more consistent global monitoring program is urgently needed for the systematic
34 measurement of land temperatures and ensuring a continuity of continental heat gain
35 estimates. In addition, long term measurements at the same sites should be sustained
36 whenever possible, as data taken after a decade or more at the same location would help
37 to reduce uncertainties in the estimates.
- 38 • Sustained remote sensing for all the cryosphere components is key to quantifying future
39 changes. For sea-ice, both area and thickness are essential, as well as albedo. For ice
40 sheets and glaciers, reliable measurements of ice thickness and extent, gravity, snow/firn
41 thickness and density are essential to quantify changes in mass balance of grounded and
42 floating ice.

⁴ von Schuckmann, K., et al., 2020: Heat stored in the Earth system: where does the energy go?, Earth Syst. Sci. Data, 12, 2013–2041, <https://doi.org/10.5194/essd-12-2013-2020>.

- 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 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.

2.4.2 Monitoring the Water Cycle

Dorigo et al. (2021)⁵ 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 new capabilities to fill observational gaps that are currently obtained from modelling (e.g., infiltration, glacier and ice sheet fluxes).
- Further consider the closure of the hydrological cycle at shorter timescales (e.g., seasonal, monthly, or shorter).

2.4.3 Monitoring the Carbon Cycle

The Global Carbon Project (Friedlingstein et al (2021)⁶) provides annual updates on the key contributors of the global carbon budget and its trends. Crisp et al. (2022) reviewed the atmospheric carbon cycle, including the anthropogenic drivers controlling the current fluxes of CO₂. 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 CO₂ 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,

⁵ Dorigo W., et al., 2021: Closing the water cycle from observations across scales: Where do we stand? Bulletin of the American Meteorological Society. <https://doi.org/10.1175/BAMS-D-19-0316.1>

⁶ Friedlingstein, P., et al., 2021: Global Carbon Budget 2021, Earth Syst. Sci. Data Discuss. [preprint], <https://doi.org/10.5194/essd-2021-386>, in review, 2021.

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

- 6 • Until recently, high resolution imaging observations and moderate resolution estimates
7 of vegetation indices provided the primary tools for scaling up plot-based observations to
8 national and continental scales. Recently, these capabilities have been augmented by
9 space-based observations of SIF (Solar Induced chlorophyll Fluorescence). Future SIF
10 observations promise substantial improvements in resolution.
- 11 • The spatial resolution and coverage of in situ measurements are still far too limited to
12 identify and quantify the natural and anthropogenic emission sources emitting CO₂ into
13 the atmosphere and the natural "sinks" absorbing it at the surface on spatial scales
14 ranging from large urban areas to nations. The coverage is particularly sparse in polar
15 boreal and tropical land regions and over most ocean basins. While recent advances in
16 space based remote sensing capabilities are providing new insights into the current state
17 of the atmospheric carbon cycle it remains important to develop an integrated carbon
18 observing system comprising both in situ and satellite capabilities.

19 **2.5 Cost and Benefits of Climate Observations**

20 The costs of maintaining and upgrading the global climate observing system far outweighs the
21 benefit it brings to society. Economic studies have consistently shown the value that accurate
22 climate observations and corresponding climate change projections can bring to societies. The
23 benefits arise largely because accurate and timely information improves the planning and
24 decision making that makes societies more resilient to climate variability and change.

25 It is easier to estimate the overall costs⁷ of the observational infrastructure (of the order of
26 100B€/year) than it is to provide an assessment of its benefits to society.

27 A full bottom-up and comprehensive assessment of the long-term benefits of climate
28 observations to societies is difficult because there is a large diversity among users of climate
29 information. Furthermore, the chain linking users to information is often complex and indirect.
30 There are also societal benefits which are hard to place a monetary value on such as livelihoods,
31 human health and well-being. As a consequence of the difficulties one can expect benefit
32 estimates to be conservative, i.e. the true benefit- to-costs-ratio is likely to be much higher than
33 many of the published estimates.

34 However, there are many examples where some of the benefits are costed⁸.

35 One can look at Numerical Weather Predictions (NWP) to see how earth-system observations
36 provide an unequivocal benefit to societies. For NWP there are well structured frameworks for
37 such an evaluation. Data denial experiments, where specific data sources are removed from the
38 assimilation schemes, provide us with a good understanding of the value each observation type
39 has for the overall forecast skill. Given that a reasonable estimate of the economic value of the
40 forecasts exists, the marginal improvement in skill associated with each observation source can
41 then be translated into the economic value of that observation. In such a way D. Kull et al. in

⁷ Elements of costs include: data collection (in situ platforms, satellites), data processing, data management and dissemination.

⁸ <https://www.munichre.com/en/risks/extreme-weather.html>

1 2021⁹ estimated that the overall benefit/cost ratio of the additional investment required to bring
2 the international data exchange of observational data up to WMO required standards in all
3 countries of the world is on the order of 25 (or at least 14 under even more conservative
4 assumptions). The authors also showed that investment in surface-based meteorological
5 observing systems measuring critical variables and intended for international exchange of data
6 has proven to be crucial. This is particularly true in those regions where the current availability
7 of observations fails to meet internationally agreed requirements for input into global NWP and
8 climate models.

9 Thanks to a systematic collection of user requirements and an operational monitoring of the use
10 of the data it makes available, the EU-Funded Copernicus programme could provide valuable
11 inputs into a cost benefit analysis. An initial assessment conducted by PwC in 2019¹⁰ indicated
12 an overall return on investment between 2 and 3 when the whole value chain is taken into
13 account. More recent estimates from EUSPA¹¹ in 2022 suggested that some sectors such as
14 agriculture, urban development, energy and climate service consultancy to other sectors, on
15 their own, account for over half of the value generated by the programme. The same study
16 suggests a rapid increase in the fraction of value generated by the insurance and financial
17 sectors.

18 Attempts to evaluate costs and benefits of ocean observations have been made by OECD,
19 showing that it is difficult to identify and quantify them comprehensively (Jolly et al., 2021¹²).
20 However, previous studies suggest that the benefit-to-cost ratio for investing in ocean
21 observations is high. For instance, JERICO-NEXT project estimated a benefit-to-cost ratio of 5
22 when analysing the European coastal component of the observing system (Gaughan et al.,
23 2019¹³), while another study undertaken by the Marine Environmental Data and Information
24 Network (MEDIN) estimated that the benefit of their data services was eight times the cost
25 invested¹⁴.

26 There are also obvious cross benefits of climate observation that should be taken into account
27 e.g., tide gauges provide sea level data that are important for climate studies but are also
28 essential for harbour operations.

29 Given the above-mentioned complexities, it is not straightforward to define a unique value to
30 the Cost Benefit Ratio for global climate observations. Completing such a task remains a high
31 priority for the global climate community. We list here a few pathways linking the benefits of
32 climate observations to sectoral use:

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

⁹ <https://openknowledge.worldbank.org/bitstream/handle/10986/35178/The-Value-of-Surface-based-Meteorological-Observation-Data.pdf?sequence=1&isAllowed=y>

¹⁰ https://www.copernicus.eu/sites/default/files/PwC_Copernicus_Market_Report_2019.pdf

¹¹ https://www.euspa.europa.eu/sites/default/files/uploads/euspa_market_report_2022.pdf

¹² 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>

¹³ Gaughan, P., Hallinan, D. & Reilly, K. 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](https://doi.org/10.1109/OCEANSE.2019.8867276)

¹⁴ https://www.medin.org.uk/sites/medin/files/documents/MEDIN%20Cost%20Benefit%20Analysis_Final%20Report.pdf

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

3 • A significant part of the value of systematic observations for society is likely to occur
4 through the use of observations within reanalysis systems. The data provided by
5 Copernicus Climate Change Service suggest that there is one order of magnitude more
6 users of the reanalysis than direct users of observations for climate applications.
7 Reanalysis is used in a variety of contexts including the assessment of baseline risks and
8 as an input to initialise impact models for sectoral applications such as agriculture or
9 hydrology.

10 • Regional scale observations provide value to users by describing the evolution of local
11 conditions. These are important to improve regional knowledge on the evolving climate
12 conditions across domains (including trends on the unfolding of regional/local extreme
13 events). They also have been shown to be essential for improving the skill of predictions
14 across timescales (from NWP to decadal projections). Indeed, regional observations have
15 a demonstrated impact in regional (or downscaled) predictions/projections. They are
16 therefore meaningful to guide national adaptation policies and actions (such as revised
17 plans of flooding and inundation risk areas, coastal management, land and ocean farming
18 potential, etc.).

19 • Finally, Climate Data Records constitute a valuable asset for insurance and reinsurance
20 companies willing to assess their level of exposure to climate hazards in different areas
21 of the globe. Such a requirement is also shared by international development agencies
22 to assess the climate proofing of specific investments.

23
24

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 globally accepted reference for formulating requirements for space and in situ climate observations. GCOS relies on contributions from a wide range of observing systems including meteorological and hydrological networks, the Global Ocean Observing System (GOOS), satellites and many others and in return provides advice on how they can be used to meet climate needs.

3.3 Benefits 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 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 recognised networks such as the Global Terrestrial Networks for hydrology, glaciers and permafrost.

When 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), to ensure that data is accessible and freely available to users.

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

1 **3.3.2 Satellite Observations**

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

8 **3.3.3 WMO**

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

- 11 • The Global Basic Observing Network (GBON¹⁵)
- 12 • The Systematic Observations Financing Facility (SOFF¹⁶)
- 13 • The new WMO Unified Data Policy
- 14 • The Regional Basic Observing Networks
- 15 • Vision for the future of the observing system
- 16 • Regulatory materials
- 17 • Data formats for exchange of daily and monthly summaries

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

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

26 **3.3.4 UNFCCC**

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

¹⁵ [Resolution 2 \(Cg-Ext\(2021\)\)](#) - Amendments to the Technical Regulations related to establishment of the Global Basic Observing Network (GBON) (2021)

¹⁶ [Resolution 3 \(Cg-Ext\(2021\)\)](#) - Systematic Observations Financing Facility: Supporting Members in the implementation of the Global Basic Observing Network (SOFF) (2021)

1 **3.3.5 Research and academia**

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

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

13 **3.3.6 International programmes on climate**

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

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

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

27 **3.4 The evolution of GCOS from past to present**

28 GCOS has continuously evolved to identify and advocate for data to meet the established and
29 emerging needs of users, to address gaps in global climate observations for different climate
30 user communities and to provide guidance for their improvement. Over the 30 years of GCOS
31 operations, the observing system has evolved considerably with advent of major new in situ and
32 satellite capabilities and the appearance of various types of reanalysis products. GCOS has
33 constantly evolved to meet these evolving needs.

34 Since the last IP, there have been many improvements in climate observations, including the
35 provision of more in situ, remote and space-based data for atmospheric observations, enhanced
36 temporal and spatial satellite observations of the Earth's surface and biosphere, and
37 technological innovations that have contributed to the expansion of the ocean observing system.
38 Further details on these advances can be found in the latest GCOS Status Report¹⁷. These
39 examples show the responsive nature of GCOS and its role as a catalyst to improve climate
40 observing systems and stimulate global and regional networks. This 2022 GCOS IP makes clear
41 to all interested communities the vision of GCOS for the free and open provision of sustainable

¹⁷ GCOS (2021). The Status of the Global Climate Observing System 2021: The GCOS Status Report ([GCOS-240](#)), WMO, Geneva

1 and high-quality climate observations to meet existing and new demands. In particular, GCOS
2 is engaged in the development of observing systems that allow the quantification of climate
3 impacts (e.g. health, energy, water and food sectors) and associated information for national
4 economic development, which will contribute to adaptation and mitigation measures in the
5 implementation of the Paris Agreement.

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

8 **3.5 GCOS priorities**

9 GCOS has identified a number of priority areas for activities in the next 5-10 years, and these
10 form the thematic basis for the actions which are further outlined in chapter 6. They represent
11 focus areas that are necessary to advance the ability to make, curate, process and exploit
12 observations in service to society i.e. to ensure an unbroken value chain. The themes are as
13 follows:

- 14 1. Ensuring the sustainability of key existing observation programs. To be useful for
15 monitoring the changing climate system, key observations across all Earth System
16 domains from both in situ and satellite programs must be acquired on a sustained basis.
17 Particular attention is required on programs deemed at risk.
- 18 2. Filling data gaps in current observing capabilities. For some ECVs or observing platform
19 types there exist data gaps that require addressing. For other ECVs substantial new
20 observation programs are required to improve monitoring and process understanding.
- 21 3. Improving data utility. Many observations are underexploited as the data are not in a
22 form that is easy to use. This theme looks at how the raw observational data is
23 transformed into data useful for users. This includes reprocessing and reanalysis.
- 24 4. Improving data management. Data should be stored in well-curated, open, sustainable
25 archives with clear guidance to data centres and users. This is not always the case and
26 work is required to organise more efficiently data sharing, data curation and data
27 provision to users to maximise the exploitation potential of Earth Observation data.
- 28 5. Engaging with countries and stakeholders. GCOS needs to engage with countries and
29 stakeholders on a sustained basis to meet its strategic goals more effectively. Regional
30 and national activities should encourage the incorporation of national systems into the
31 global observing systems. GCOS can also help coordinate capacity building leading to
32 sustainable improvements in observational infrastructure.
- 33 6. Addressing emerging needs. The needs of end users are constantly evolving. GCOS has
34 identified areas where observations can be exploited specifically to support developing
35 response measures such as adaptation and mitigation.

4. ESSENTIAL CLIMATE VARIABLES

To clearly present climate observational needs, GCOS has developed the concept of Essential Climate Variables (ECVs). The ECVs emerged in the context of the needs of the UNFCCC in the Second GCOS Adequacy Report¹⁸.

An ECV¹⁹ 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.

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:

- 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.

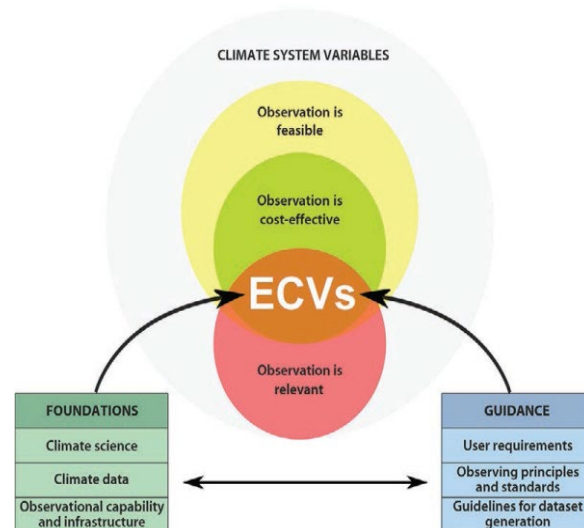


Figure 1. Schematic of the ECV concept (Source: Bojinski, et al, BAMS, 2014)

¹⁸ Second report on the adequacy of the global observing systems for climate in support of the UNFCCC. GCOS-82, 85 pp. [Available online at WMO Library here.]

¹⁹ Based on Bojinski, et al., (BAMS, 2014). DOI:10.1175/BAMS-D-13-00047.1

1 GCOS has asked its expert panels, informed by the wider community, to define requirements of
2 these ECVs and Annex A lists the requirements for all ECVs. These requirements are specified in
3 terms of:

- 4 • ECV – the name and definition and units of the ECV.
- 5 • ECV Product – Measurable parameter needed to characterise the ECV. Some ECVs have
6 one product – others several.
- 7 • Temporal resolution (or frequency) – the frequency of observations e.g. hourly, daily or
8 annual. This depends on the ECV. Some need to be measured frequently to capture short
9 events and extremes, others only apply at longer intervals e.g. to measure long-term
10 changes in glacier mass.
- 11 • Spatial Resolution - horizontal and vertical (if needed).
- 12 • Required Measurement Uncertainty and Stability. It is essential to develop long-time
13 series for climate monitoring. Often changes are gradual: gradual change is usually
14 smaller than the annual variability. Thus, measurements over long time periods are
15 needed with reliable, sustainable systems with minimal instrumental error and drift
16 (stability).
- 17 • Timeliness. This is a new requirement in this 2022 GCOS Implementation Plan. *Timeliness*
18 defines how soon after the observation is taken, the data is needed i.e. the latency. There
19 is an increasing need for data to be available with a minimum delay from observations
20 e.g. to support short-term modelling and warning systems, adaptation and inform policy.

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

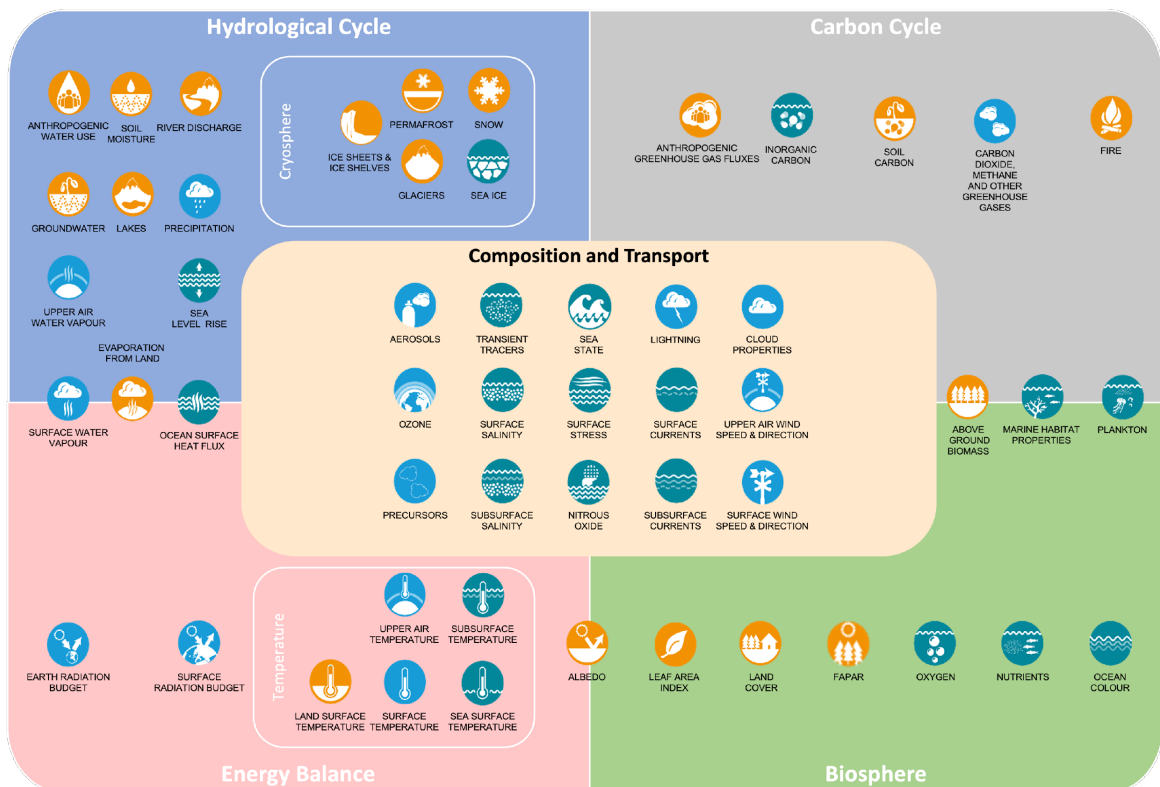
- 23 • **Threshold:** the minimum requirement to be met to ensure that data are useful
- 24 • **Breakthrough:** an intermediate level between *threshold* and *goal* which, if achieved,
25 would result in a significant improvement for the targeted application. The *breakthrough*
26 value may also indicate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

30 Within climate monitoring there are multiple uses for each ECV from global monitoring to local
31 adaptation planning (e.g. global average temperature and local heatwaves; global sea level rise
32 and local coastal sea level changes; and global precipitation changes and local extreme
33 precipitation events). Each of these applications may have different observational needs in terms
34 of resolution and accuracy. However, presently it is not practical to provide completely separate
35 requirements of all applications as this would greatly increase the number and variety of
36 requirements and the workload for the expert panels. GCOS needs to consider how to approach
37 articulating requirements specifications for multiple uses of data over the next few years.

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

44 Over the period covered by this Implementation Plan further improvements are foreseen as
45 follows:

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20
- 21
- 22
- 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, more simply, be presented as a single ECV. 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. This rationalisation of the ECVs would make it easier to explain why they are needed and to demonstrate how they work together. The work that started after the previous 2017 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. Traceability to existing ECV definitions and products will be provided and input from users into the discussion will be encouraged.



23 **Figure 2. Essential Climate Variables and the climate cycles. Many ECV contribute to**
 24 **understanding several different cycles – this only indicates the main links.**
 25

26 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 three broad areas:

1. Increased reliability and consistency of data processing and reanalysis methods, particularly with respect to ECVs;
2. Increased access to historical observations;
3. 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, 2013²⁰).

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,

²⁰Mauthner, 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

1 expectations for Members in this regard were reiterated and expanded by way of the WMO
2 Unified Data Policy²¹ which was approved by the WMO Congress in October 2021. The new policy
3 stipulates that “Members shall provide on a free and unrestricted basis the core data that are
4 necessary for the provision of services in support of the protection of life and property and for
5 the well-being of all nations ...” and “Members should also provide the recommended data that
6 are required to support Earth system monitoring and prediction activities at the global, regional
7 and national levels...” and “provide without charge access to all recommended data exchanged
8 under the auspices of WMO to public research and education communities, for their non-
9 commercial activities...”. The new policy also, for the first time, extends these obligations to
10 exchange and share data to archives of historic data. The data defined as ‘core’ for each of the
11 Earth system domains, including climate, are specified in an annex and inscribed in WMO
12 technical regulations. A periodic, consultative review process will ensure that the specification of
13 core and recommended data keeps pace with evolving requirements.

14 **5.2 FAIR (Findable, Accessible, Interoperable, Reusable) Principles**

15 The FAIR (Findable, Accessible, Interoperable, Reusable) Principles are a set of guiding principles
16 for scientific data management proposed by an international consortium of scientists and
17 organizations (Wilkinson et al., 2016²²). These guidelines now form the basis of many data
18 archiving and distribution policies and are endorsed by nearly 300 repositories, publishers,
19 research organizations, societies, and individuals from around the world. The FAIR Principles
20 advance and extend key open data concepts for data users by making data easy to find, combine,
21 and integrate.

22 **5.3 TRUST (Transparency, Responsibility, User focus, Sustainability and 23 Technology) Principles**

24 The TRUST (Transparency, Responsibility, User focus, Sustainability and Technology) Principles
25 are founded in the premise that the preservation of data over time, whether it is free and open
26 or not, requires trustworthy digital repositories with sustainable governance and organizational
27 frameworks, reliable infrastructure, and comprehensive policies supporting community-agreed
28 practices (Lin et al., 2020²³). As of 2021, through a Research Data Alliance community effort,
29 the TRUST Principles have already been endorsed by 39 international organizations that are
30 committed to the stewardship of digital resources. They also form the basis for CoreTRUSTSeal
31 certification of data repositories which is now a prerequisite for membership in the WDS.
32

²¹ WMO Unified Policy for the International Exchange of Earth System Data (2021):
https://library.wmo.int/doc_num.php?explnum_id=11028#page=10

²² 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

²³ Lin, D., J. Crabtree, I. Dillo, et al., 2020: The TRUST Principles for digital repositories. *Sci 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 defined 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 5.3, 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 Report²⁴, 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.

6.1 Theme A: Ensuring Sustainability

Long-term, continuous, in situ²⁵ 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 prediction and will not be supported by WMO's GBON and SOFF.

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.

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)²⁶.

²⁴ 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

²⁵ In this document we refer to all non-satellite observations as "in situ" including ground-based and aircraft-based remote sensing.

²⁶ Stephens, G., Freeman, A., Richard, E., Pilewskie, P., Larkin, P., Chew, C., Tanelli, S., Brown, S., Posselt, D., and Peral, E. (2020). The Emerging Technological Revolution in Earth Observations. Bulletin of the American Meteorological Society 101, 3, E274-E285, available from: <https://doi.org/10.1175/BAMS-D-19-0146.1> [Accessed 20 March 2022]

1 Future climate observing capabilities that are at risk are identified in the 2021 GCOS Status
 2 Report. This theme focuses on those in situ and satellite observations that are particularly at
 3 risk, while acknowledging that all observations of ECVs need to be sustained.
 4

Action A1: Ensure necessary levels of long-term funding support for in situ networks, from observations to data delivery	
Activities	<ol style="list-style-type: none"> 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. GCOS to advocate with funding agencies to support identified networks.
Issue/Benefits	<p>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.</p> <p>Improved funding support for networks performing measurements of ECVs would improve our ability to undertake long-term monitoring of the changing climate 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.</p>
Implementers	From 1 to 3: GCOS , NMHSs, Research organizations, Academia, Funding agencies
Means of Assessing Progress	<ol style="list-style-type: none"> 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	<p>All ECV need sustained support, but this GCOS IP has identified the following actions:</p> <p>B4: in situ observations of atmospheric composition ECVs.</p> <p>B6 and B7: expansion and integration of the global ocean observing system, including observations of biogeochemical/biological parameters.</p>

5
6

Action A2: Address gaps in satellite observations likely to occur in the near future	
Activities	<p>Ensure continuity of the following satellite observations:</p> <ol style="list-style-type: none"> 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 measurements. 6. Wind lidar.
Issue/Benefits	<p>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.</p>
Implementers	<p>From 1 to 6: Space agencies.</p>
Means of Assessing Progress	<p>From 1 to 6: Established (long-term) plans of Space Agencies demonstrating the continuation of satellite missions for altimetry, gravimetry, biomass, limb-sounding, sea surface salinity, wind lidar.</p>
Additional Details	<p>These address some of the gaps identified in the GCOS Status Report.</p> <ol style="list-style-type: none"> 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 Sentinel-6 and CRISTAL. However, 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 launch; or a systematic airborne measurement program 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 ECV data, including for sea level, groundwater 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. 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 program for regular, high-quality biomass monitoring in the long-term. Agencies and the EU Copernicus program are encouraged to explore synergy and harmonise among available mission data and put in place a coordinated, continuous and consistent space-based biomass observation program for global and national monitoring of aboveground biomass and associated carbon stock changes.

	<p>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.</p> <p>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 cover the late 2020ies and 2030ies to ensure a continuous global SSS record.</p> <p>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. 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.</p>
<p>Links with other IP Actions</p>	<p>Satellite observations are related to many other actions. In particular:</p> <p>C5 (Activity 2): enhancement biomass estimation at global and subnational levels.</p> <p>F1 (Activity 2): higher-resolution biomass data.</p> <p>F2 (Activity 1): sea surface salinity in polar regions.</p>

1
2

<p>Action A3: Prepare follow-on plans for critical satellite missions</p>	
<p>Activities</p>	<p>Ensure continuity of the following satellite observations:</p> <ol style="list-style-type: none"> 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 sampling of rain areas.
<p>Issue/Benefits</p>	<p>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.</p>
<p>Implementers</p>	<p>From 1 to 4: Space agencies.</p>
<p>Means of Assessing Progress</p>	<p>From 1 to 4: Established (long-term) plans of Space Agencies demonstrating the continuation of satellite missions for earth radiation budget, cloud profiling radar, cloud lidar and GPM.</p>
<p>Additional Details</p>	<p>These address some of the potential gaps identified in the GCOS Status Report.</p> <ol style="list-style-type: none"> 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 and will be succeeded by the recently selected NASA instrument Libera, projected to launch in 2027 on JPSS-3. The instrument specifics are such that seamless continuation of the ERB measurements is

	<p>facilitated; mission overlap of at least one year is anticipated but not guaranteed beyond Libera which has a projected mission lifetime 2027-2032. The ESA/JAXA EarthCare mission will fly a broad band radiation budget instrument.</p> <ol style="list-style-type: none"> 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. 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. 4. Various activities are on the way to improve precipitation observation capabilities. 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.
<p>Links with other IP Actions</p>	<p>Satellite observations are related to many other actions. In particular:</p> <p>B9: improvement of estimates of latent and sensible heat fluxes.</p> <p>B10: closure of energy budget.</p>

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

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, as well as the ocean and in particular 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/TRUTHS mission). 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.

WMO has adopted the concept for a Global Basic Observing Network (GBON), which will provide essential observations for global Numerical Weather Prediction (NWP) and reanalyses, covering some ECVs. The Systematic Observations Financing Facility (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.

<p>Action B1: Development of reference networks (in situ and satellite Fiducial Reference Measurement (FRM) programs)</p>	
<p>Activities</p>	<ol style="list-style-type: none"> 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.

	<ol style="list-style-type: none"> 4. Develop further the concept of a reference network tier across all earth observation domains. 5. Establish a 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	<p>The principal benefits of reference quality networks / measurements are:</p> <ul style="list-style-type: none"> • Well characterised measurement series that are traceable to SI 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. • Support and characterisation of wider networks, especially of measurement quality. • Robust calibration/validation of satellite data. • Improved process understanding and model validation. <p>However:</p> <ul style="list-style-type: none"> • Although GRUAN has been successfully implemented since 2005, it remains far from 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	<ol style="list-style-type: none"> 1. Lead Centres (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	<ol style="list-style-type: none"> 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). 3. <ol style="list-style-type: none"> 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, surface albedo, FAPAR, LAI and burned area. 4. Inventory of (potential for) global reference networks across atmosphere, ocean and terrestrial.

	<p>5. Implementation of CLARREO pathfinder and Prefire. Plans for long-term follow-on missions to the short-term (~1 year) pathfinder missions (CLARREO and Prefire).</p>
<p>Additional Details</p>	<p>Reference-quality measurements must be traceable to SI or community recognised standards and have their uncertainties fully quantified following the guidance laid out by BIPM. Measurements across a reference network must be metrologically comparable.</p> <ol style="list-style-type: none"> 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 Center 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: <ul style="list-style-type: none"> o Networks in high and low above-ground biomass regions; o Ground-based in situ measurements of above-ground biomass and vegetation dynamics following FRM protocols (Dunanson et al., 2021); o Ground-based time-series in situ measurements of surface albedo, FAPAR and LAI with their uncertainties; o 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.
<p>Links with other IP Actions</p>	<p>C2: Improvements to satellite data processing depends on the availability of reference observations.</p> <p>D4: Improve access to co-located satellite and reference quality in situ observations.</p>

1

Action B2: Development and Implementation of the Global Basic Observing Network (GBON)	
Activities	<ol style="list-style-type: none"> 1. Implementation of initial GBON and the associated Systematic Observations Financing Facility (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	<p>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.</p> <p>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 through, for example, inclusion of daily and monthly summary reports.</p> <p>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.</p>
Implementers	<ol style="list-style-type: none"> 1. WMO, GCOS, GOOS, NMHS. 2. GCOS, WMO, NMHS. 3. WMO, GCOS, GOOS, NMHS.
Means of Assessing Progress	<ol style="list-style-type: none"> 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 SC. 3. GBON scope expanded to incorporate additional ECVs and the open ocean beyond EEZs which are then observed on a sustained basis as part of GBON expanded operations.
Additional Details	<ol style="list-style-type: none"> 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: <ul style="list-style-type: none"> ○ 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

	<p>any changes required to GSN and GUAN aims and governance accordingly? AOPC to report to GCOS SC in 2024/2025.</p> <p>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.</p>
Links with other IP Actions	<p>B4: The extension of GBON (Activity 3) will benefit expansion of in situ monitoring of atmospheric composition ECVs.</p> <p>B8: The extension of GBON (Activity 3) will benefit the coordination of N2O observations.</p> <p>C4: The implementation of GBON will benefit reanalysis.</p>

1
2

Action B3: New Earth observing satellite missions to fill gaps in the observing systems	
Activities	<ol style="list-style-type: none"> 1. Improve diurnal sampling of observations and coverage of greenhouse gases (GHG), 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.
Issue/Benefits	<ol style="list-style-type: none"> 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 Earth’s energy imbalance (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 development²⁷. 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

²⁷ M. Z. Hakuba et al., "Earth’s Energy Imbalance Measured From Space," in IEEE Transactions on Geoscience and Remote Sensing, vol. 57, no. 1, pp. 32-45, Jan. 2019, doi: 10.1109/TGRS.2018.2851976

	<p>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 is thus needed.</p> <p>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 needs²⁸.</p>
Implementers	From 1 to 4: Space agencies.
Means of Assessing Progress	<p>From 1 to 3: Feasibility studies addressing mission concepts relevant to observation and mission gaps. Solicitations by Space Agencies for satellite mission development relevant to the above points.</p> <p>4. Number of publications on new potential satellite climate observations.</p>
Additional details	<p>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. Complementary GEO (CO2M, OCO2, GOSAT-GW, TANSAT) 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.</p> <p>2. Explorative studies to infer Earth’s energy imbalance (EEI) directly from radiation pressure accelerations or alternative remote sensing techniques, and indirectly, through assessment of well-calibrated hyperspectral shortwave and longwave radiances.</p> <p>3. Technologies for direct measurements of ocean surface currents already exist (e.g., using Doppler Scatterometry or Synthetic Aperture Radar). But no such satellite mission has been committed 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 utility of reflected GPS signals should be explored and demonstrated.</p> <p>4. 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.</p>
Links with other IP Actions	<p>Satellite observations are related to many other actions. In particular:</p> <p>B10: Develop plans to address gaps in the climate system for the energy cycle.</p> <p>F2: improved ECV satellite observations in polar regions.</p> <p>F5 (activity 2): design a constellation of operational satellites to provide near-real time global coverage of CO₂ and CH₄ column observations.</p>

1
2
3
4
5
6

²⁸ Stephens et al., Bulletin of the American Met. Society, 2020: The emerging technological revolution in Earth observations
<https://doi.org/10.1175/BAMS-D-19-0146.1>

Action B4: Expand surface and in situ monitoring of trace gas composition and aerosol properties	
Activities	<ol style="list-style-type: none"> 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	<p>Well-functioning networks monitoring atmospheric composition of ECVs are beneficial for: i) evaluation of 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 (biomass burning, dust events); v) providing information for radiative forcing evaluation in global/regional climate-chemistry models; vi) evaluations of global forecasting systems using independent observations.</p> <p>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:</p> <ul style="list-style-type: none"> • 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	<p>Number of traceable composition observation data available from areas where they are current gaps.</p> <p>Expansion of current composition networks (number of sampling stations) in areas not covered by observations.</p>
Additional Details	<p>Sustained composition observation capabilities both at the surface and of column characteristics of a range of trace gases, including WMGHGs, 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.</p> <p>In order to achieve activities 1) and 2), the following needs to be addressed:</p> <ul style="list-style-type: none"> • 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	<p>A1: expansion of atmospheric composition observations requires sustained funding.</p> <p>B2: Expansion of GBON will lead to more atmospheric composition observations.</p>

1
2

	<p>F4: Improve climate monitoring of urban areas will include atmospheric composition ECVs.</p> <p>F5: Activity 1: Design and start to implement a comprehensive global set of surface-based observations of CO₂, CH₄ and N₂O concentrations.</p>
--	--

Action B5: Implementing global hydrological networks

Activities	<ol style="list-style-type: none"> 1. Improve the collection of hydrological observations, in particular: <ol style="list-style-type: none"> a) Establish a global network reporting river discharge and water level data from a selected set of stations; b) Increase the number of in situ observations of water levels in rivers that are exchanged internationally and can be used to calibrate satellite observations of water levels. 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 FAO AQUASTAT in areas where data are missing.
-------------------	---

Issue/Benefits	<p>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</p> <p>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.</p> <p>To rectify this situation, this action aims to</p> <ul style="list-style-type: none"> • 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. • 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. <p>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.</p> <p>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</p>
-----------------------	--

	complete regional coverage but does require the continuation of satellite gravity observations and will not replace provide the spatial resolution of AQUASTAT.
Implementers	From 1 to 3: WMO (WHOS), NMHS, Satellite agencies, Global Data centres (GTN-H).
Means of Assessing Progress	<ol style="list-style-type: none"> 1. <ol style="list-style-type: none"> a) Identify a set of river discharge stations to exchange data; b) Increased availability of calibrated satellite estimates of water levels in rivers; c) Increase reporting of river discharge and level data to GRDC and groundwater data to IGRAC using unrestrictive data policies. 2. Identify a set of groundwater stations that are minimally impacted by human influence for reporting to IGRAC. 3. Increase number of countries reporting to AQUASTAT and improve resolution: More countries reporting and increased resolution.
Additional Details	<p>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.</p> <ol style="list-style-type: none"> 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: <ul style="list-style-type: none"> ○ 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	<p>B2: The development of GBON will contribute to implement Action B5.</p> <p>B10: Closure of water cycle.</p>

1

Action B6: Expand and build a fully integrated global ocean observing system	
Activities	<p>Increase the measurements of ocean ECVs into the deep ocean, under the ice and marginal seas by improving:</p> <ol style="list-style-type: none"> 1. The current Argo array of profiling floats ("OneArgo"). 2. The ship-based hydrography and fixed-point observations. 3. The integration of observing networks to respond adequately to ECVs requirements.
Issue/Benefits	<p>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 development and deployment of the OneArgo system, repeated hydrography, 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.</p> <p>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.</p>
Implementers	From 1 to 3: GOOS , Research Agencies, Academia, National agencies (oceanographic Institutes), Space Agencies, NMHS (<i>see also key programmes and networks in "Additional details"</i>).
Means of Assessing Progress	<ol style="list-style-type: none"> 1. Number of new Argo floats deployed 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	<p>In 2020, the Argo Steering Team endorsed a new Argo array design (called "OneArgo") that is truly global, full depth, and multi-disciplinary, including Core, Deep, and biogeochemical BCG 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 programme endorsed by the UN Ocean Decade.</p> <p>Ship-based hydrography and fixed-point observations are essential and complementary to Argo and further efforts must be undertaken to realise the vision of a fully integrated Ocean Observing System²⁹. The key programs and networks contributing to this Action are GO-SHIP, OceanSITES, Ocean Color satellites, Deep Argo, Biogeochemical Argo and GACS.</p>
Links with other IP Actions	<p>B7 and B8: improve components of the global ocean observing system.</p> <p>B9: ocean observations to Improve estimates of latent and sensible heat fluxes and wind stress.</p>

²⁹ 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>

	F3: expand global ocean climate in situ observations into EEZ and coastal zones.
--	--

1
2

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	<p>Some of the greatest uncertainties in the prediction 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 EOVs and the GCOS ECVs to deliver global observations.</p> <p>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, Global Alliance of Continuous Plankton Recorder Surveys (GACS)) in contributing to the plankton ECVs.</p>
Implementers	GOOS , Research organizations, Space agencies, <i>(see also key programmes and networks in "Additional details")</i> .
Means of Assessing Progress	Increased number of ocean biological and biochemical datasets available and shared via global repositories.
Additional Details	<p>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.</p> <p>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.</p>
Links with other IP Actions	<p>B8: improve components of the global ocean observing system.</p> <p>F3: expand global ocean climate in situ observations into EEZ and coastal zones.</p>

3
4

1

Action B8: Coordinate observations and data product development for ocean CO₂ and N₂O	
Activities	<ol style="list-style-type: none"> 1. Develop a strategy and implementation plan to operationalize the data production and delivery of surface ocean CO₂ information. 2. Coordinate the existing nitrous oxide (N₂O) ocean observations into a harmonised network.
Issue/Benefits	<p>Parties to the UNFCCC, in its Paris Agreement, have committed to conserving and enhancing sinks and reservoirs of greenhouse gases, such as CO₂ and N₂O, 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 CO₂ and N₂O 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 CO₂ and N₂O emissions, an optimisation of resources of Member States and better compliance with UN agreements.</p>
Implementers	<p>From 1 to 2: GOOS, WMO, Research organizations, National agencies (<i>see also key programmes and networks in "Additional details"</i>).</p>
Means of Assessing Progress	<ol style="list-style-type: none"> 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. <ol style="list-style-type: none"> a) Annually published sets of harmonised global N₂O concentration and emission fields data products; b) Initiated coordinated observing network of N₂O observations.
Additional Details	<ol style="list-style-type: none"> 1. While all of the required elements of a surface ocean CO₂ 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 CO₂ data coverage owing to funding cuts in some key underway pCO₂ 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. <p>The development of an internationally agreed strategy for a global surface CO₂ monitoring network, with a focus on the open ocean and marginal seas, will permit 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.</p> <p>The key programs and networks are: WMO Global Atmospheric Watch (GAW), International Ocean Carbon Coordination Project (IOCCP), Surface Ocean CO₂ reference Observing NETwork (SOCONET), Integrated Carbon Observation System-Ocean Thematic Centre (ICOS-OTC), Surface Ocean CO₂ Atlas (SOCAT), Surface Ocean CO₂ Mapping intercomparison initiative (SOCOM), Global Carbon Project (GCP).</p>

	<p>2. To reduce uncertainties in oceanic N₂O emission estimates and to characterise the spatial and temporal variability in N₂O distributions in a changing ocean, the establishment of a harmonised N₂O Observation Network (N₂O-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.</p> <p>As a greenhouse gas, N₂O is involved in tropospheric warming and stratospheric ozone depletion, with estimates of the global ocean contribution to N₂O emissions ranging 10-53%. It is important to monitor how oceanic N₂O cycling and emissions to the atmosphere are affected by observed changes in the marine environment due to warming, deoxygenation and acidification. Therefore, new N₂O data products issued annually will include a harmonised global N₂O concentration and emission fields to inform the global research community and policy makers on the status and projections of future oceanic N₂O emissions.</p> <p>The key programs and networks are: N₂O Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), Ship-Of-Opportunity Programme (SOOP), Marine Methane and Nitrous Oxide (MENTO).</p>
Links with other IP Actions	B6, B7 and B8 target different aspects and components of global and integrated ocean observing system recognizing its essential role in the climate system.

1
2

Action B9: Improve estimates of latent and sensible heat fluxes and wind stress	
Activities	<ol style="list-style-type: none"> 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 over the ocean to better exploit relevant ECV measurements to estimate ocean surface heat, moisture and momentum flux including: <ol style="list-style-type: none"> a) Better integration of in situ and satellite measurements, data assimilation, fusion techniques; 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 (LES) to augment satellite product validations.
Issue/Benefits	<p>Understanding and estimating surface fluxes is essential for improving projections of climate change and planning adaptation and response measures.</p> <p>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.</p> <p>Direct observation of surface turbulent (sensible, latent and momentum) fluxes is difficult and costly and globally impractical. For global coverage it is therefore</p>

	<p>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.</p> <p>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.</p>
Implementers	<p>From 1 to 2: NMHS, GOOS, Research organizations</p> <p>3. Academia, Research organizations, NMHS.</p> <p>4. Satellite agencies, NMHS, Academia.</p>
Means of Assessing Progress	<ol style="list-style-type: none"> 1. <ol style="list-style-type: none"> 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. <ol style="list-style-type: none"> 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. <ol style="list-style-type: none"> 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 PBL.
Additional Details	<ol style="list-style-type: none"> 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

	<p>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.</p> <ol style="list-style-type: none"> 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 concept³⁰. 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. <p>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)³¹. Moreover, the potential of novel thermal missions such as ECOSTRESS (Fisher et al., 2020)³² and TRISHNA (Lagouarde et al., 2018)³³ is yet to be exploited.</p> <p>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 (Large Eddy Simulation (LES)):</p> <ul style="list-style-type: none"> ○ Have only few well-equipped validation sites for the products; ○ Compute fluxes with the models and validate models with measurements; ○ Use models to 'check' satellite products elsewhere.
<p>Links with other IP Actions</p>	<p>This action links to other actions:</p> <p>B1: reference networks are needed to improve flux estimates.</p> <p>B10: closure of energy cycles will benefit from a better understanding of heat fluxes.</p> <p>C2 and C3: improvements to data processing methods will benefit this action.</p> <p>D3 (Activity 3). Access to campaign field data useful for testing of parameterization.</p> <p>D4: easy access to co-located satellite and reference quality in situ observations.</p>

³⁰ Butterfly: a satellite mission to reveal the oceans' impact on our weather and climate <https://doi.org/10.5281/zenodo.5120586>

³¹ Fisher, J. B., and Coauthors, 2017: The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources. *Water Resour. Res.* 53, 2618–2626, doi:10.1002/2016WR020175

³² Fisher, J. B., and Coauthors, 2020: ECOSTRESS: NASA's Next Generation Mission to Measure Evapotranspiration From the International Space Station. *Water Resour. Res.* 56, doi:10.1029/2019WR026058

³³ 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

1
2

Action B10: Identify gaps in the climate observing system to monitor the global energy, water and carbon cycles	
Activities	<ol style="list-style-type: none"> 1. Continue to periodically review observations of the Earth's energy, water, carbon cycles to identify gaps and areas of high uncertainty. 2. Develop plans to address the gaps identified in (1), if feasible.
Issue/Benefits	<p>This action will implement an objective approach to identifying gaps and major uncertainties in the global climate monitoring system.</p> <p>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.</p>
Implementers	From 1 to 2: GCOS , GOOS, Research organizations, Funding agencies, Space agencies, WCRP, NMHS.
Means of Assessing Progress	<ol style="list-style-type: none"> 1. <ol style="list-style-type: none"> a) Periodic assessments of each cycle and its components at least as part of the Status Report; 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. Include plan to address the main issues for the next GCOS Implementation Plan.
Additional Details	<p>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.</p> <p>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.</p> <p>See also Section 2.4 in this GCOS IP for more details and references.</p>
Links with other IP Actions	<p>This action indirectly links with many others but in particular with:</p> <ul style="list-style-type: none"> B3: Better EEI measurements. B4: In situ GHG observations. B8: Coordinate observations and data product development for ocean CO₂. C5: Activity 2 (estimation of aboveground biomass).

3
4

5 **6.3 Theme C: Improving Data Utility**

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

1 ensuring the fitness for purpose of the data provided for its use in reanalysis. This includes a
 2 dedicated effort towards data reprocessing, bias characterisation and more generally a
 3 comprehensive characterisation of the uncertainty associated with both observations and
 4 modelling.
 5
 6

Action C1: Develop monitoring standards, guidance and best practices for each ECV	
Activities	<ol style="list-style-type: none"> 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 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	<p>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.</p> <p>Improvements in observations and their consistency across countries and regions would lead to more accurate observations, predictions, and warnings and would thus improve adaptation planning.</p>
Implementers	From 1 to 4: GCOS , GOOS, WMO, Copernicus, satellite agencies.
Means of Assessing Progress	<ol style="list-style-type: none"> 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	<p>For 1 and 2:</p> <p>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.</p> <p>3. 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.</p> <p>4. 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.</p>
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.

7
8

1

Action C2: General Improvements to Satellite Data Processing Methods	
Activities	<ol style="list-style-type: none"> 1. Improve radiance measurement records and Radiative Transfer (RT) models for simulating them. 2. Improve uncertainty quantification of satellite retrievals. 3. Reprocess full satellite data records whenever an update of underlying methods introduces discontinuities in 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	<p>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.</p>
Implementers	<p>From 1 to 5: Space agencies, Academia, Research organizations.</p>
Means of Assessing Progress	<p>For 1 and 2: New publications showing improvements in radiative transfer and uncertainty characterisation.</p> <ol style="list-style-type: none"> 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	<ol style="list-style-type: none"> 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 and leading to FCDRs.
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.

1
2

Action C3: General Improvements to in situ Data Products for all ECVs	
Activities	<ol style="list-style-type: none"> 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	<p>It is necessary to periodically reassess in situ based estimates of climate change and to have multiple independently produced estimates for each ECV.</p> <p>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.</p>
Implementers	From 1 to 4: Research organizations , Academia, NMHSs.
Means of Assessing Progress	<ol style="list-style-type: none"> 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. Increase in 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.

3
4
5
6
7

Action C4: New and improved reanalysis products	
Activities	<ol style="list-style-type: none"> 1. Implement new production streams using improved data assimilation systems and better collections of observations, particularly aiming at: <ol style="list-style-type: none"> 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	<p>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.</p>
Implementers	From 1 to 3: Reanalysis centres , Academia.
Means of Assessing Progress	<ol style="list-style-type: none"> 1. Number of papers describing new reanalysis production streams 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	<ol style="list-style-type: none"> 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

	<p>improvement can be expected through data rescue for early instrumental meteorological observations and refinement of data assimilation systems.</p> <p>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.</p> <p>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.</p>
Links with other IP Actions	<p>B2: implementing GBON will be of benefit for this action.</p> <p>C2: improving reprocessing of satellite data.</p> <p>F1: higher resolution observations.</p>

1
2

Action C5: ECV-specific Satellite Data Processing Method Improvements	
Activities	<ol style="list-style-type: none"> 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	<p>Many data products depend on extended processing streams from observations to data products. This action identifies key areas for improvements.</p> <ol style="list-style-type: none"> 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).

	<p>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.</p>
Implementers	From 1 to 6: Space Agencies , NMHS, Reanalysis Centres.
Means of Assessing Progress	<ol style="list-style-type: none"> 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 for GLD360, ENGLN, WWLLN, GLM. 5. Validated and updated space and RF ground-based lightning data at 0.1x0.1 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	<p>For 1 and 2:</p> <p>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 AFOLU modelling and assessments. Although global in scope, these products with increasing detail and quality should be suitable for national and local uptake.</p> <p>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 United Nations Framework Convention on Climate Change (UNFCCC)'s first 'Global Stocktake' (GST) 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 NFI's), 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 (link to GFOI)</p>

	<p>3. The provision of surface albedo products shall be provided their respective BRDF parameters as they are part of the ECV definition. They allow a better assessment of uncertainty budget</p> <p>For 4 and 5:</p> <p>Space-based and VLF 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. The Thunder Day observation at meteorological stations is a long-term WMO database. 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, NO_x, aerosols, tropospheric temperature and moisture. Lightning-initiated wildfires and the threat to public safety are increasing concerns.</p>
<p>Links with other IP Actions</p>	<p>B10: this action will benefit addressing gaps for the carbon cycle.</p>

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

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 recognised global data repository and where there is one, it should be complete, adequately supported and funded. 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 Principles (Lin et al., 2020)³⁴ and FAIR Principles (Wilkinson et al., 2016³⁵) 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. Sustained support to these activities is required. This theme aims to organise more efficiently data rescue, data sharing, data curation and data provision.

<p>Action D1: Define governance and requirements for Global Climate Data Centres</p>	
<p>Activities</p>	<ol style="list-style-type: none"> 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.
<p>Issue/Benefits</p>	<p>It is vital that all users have unrestricted access to well-documented, historical and near-real-time climate data and associated metadata. However, despite various efforts to implement appropriate data stewardship and sharing standards, such</p>

³⁴ Lin, D., J. Crabtree, I. Dillo, et al., 2020: The TRUST Principles for digital repositories. Sci Data 7, 144, DOI:10.1038/s41597-020-0486-7

³⁵ 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

	<p>“free and open” access to well-maintained data archives is not available consistently across all data centres and data types.</p> <p>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.</p>
Implementers	From 1 to 4: GCOS , WMO, Global Data Centres.
Means of Assessing Progress	<p>For 1 and 2:</p> <p>Published GCOS document defining requirements and standards for data and metadata.</p> <p>3. GCOS to periodically audit climate data centres for compliance with the requirements and availability of all mandatory metadata as defined in the WIGOS Metadata Standard. GCOS to develop implementation plans as required.</p> <p>4. Increased number and volume of ECVs for which data is exchanged according to the WMO Unified Data Policy.</p>
Additional Details	<p>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 Findability, Accessibility, Interoperability, and Reusability (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.</p> <p>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.</p> <p>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.</p> <p>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</p>

	<p>Climate Data (SMM-CD) and could be utilized for this purpose if the working groups developing the data centre requirements decide to include them.</p> <p>4. At the most recent Congress WMO adopted its Unified Data Policy (Resolution 1 (Cq-Ext(2021))) 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 recognised global and regional repositories. GCOS, working with WMO must develop guidance and support and integrate requirements into relevant technical regulations.</p>
Links with other IP Actions	<p>Action D1, D2 and D3 are interconnected and pursue a common goal of preserving and providing access to ECV data in Global Data Centres.</p> <p>D5: data rescue is connected to data sharing of historical data.</p>

1
2

Action D2: Ensure Global Climate Data Centres exist for all ECVs	
Activities	<ol style="list-style-type: none"> 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	<p>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.</p>
Implementers	<p>From 1 to 2: GCOS, WMO, GOOS, NMHS, National agencies, Funding bodies.</p>
Means of Assessing Progress	<ol style="list-style-type: none"> 1. List of climate data centres identifying those in need of additional support as well as for those for which no data centre exists followed by annual assessments and statements on data centres at risk by GCOS panels. 2. Verify the 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	<ol style="list-style-type: none"> 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. <p>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.</p> <p>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.</p> <p>Following an initial assessment of adequacy, it is necessary to continuously review the health of the network of global data centres. GCOS panels should</p>

	<p>annually review the status of global data centres within their domain and highlight any issues so that these can be remedied.</p> <p>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.</p>
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

1
2

Action D3: Improving discovery and access to data and metadata in Global Climate Data Centres	
Activities	<ol style="list-style-type: none"> 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 utilising publicly available data sets. 3. Facilitate access to campaign field data, where available and relevant, to improve understanding of fundamental processes.
Issue/Benefits	<p>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. Data needs to be aggregated to global collections with multiple ECVs collated together to enable data fusion.</p> <p>Global climate databases must be able to provide easy discovery and access of data to all potential users, maximising the utility of the data.</p>
Implementers	From 1 to 3: Global Data Centres , GCOS, Funding Agencies.
Means of Assessing Progress	<ol style="list-style-type: none"> 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	<ol style="list-style-type: none"> 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.
------------------------------------	---

1
2

Action D4: Create a database of co-located in situ cal/val observations and satellite data for quality assurance of satellite products	
Activities	<ol style="list-style-type: none"> 1. Improve access to co-located satellite and reference quality in situ observations through the creation of a co-location database. This database 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 developed under Activity 1 to undertake various analyses of satellite-based measurements.
Issue/Benefits	<p>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.</p> <p>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.</p> <p>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.</p>
Implementers	From 1 to 2: WMO , Space agencies, NMHS, Research organizations, GOOS.
Means of Assessing Progress	<ol style="list-style-type: none"> 1. Establishment of a unified database of 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	<p>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.</p> <p>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.</p>

	Further details are given in Sterckx et al. (2020) ³⁶ .
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).

1
2

Action D5: Undertake Additional Data Rescue Activities	
Activities	<ol style="list-style-type: none"> 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 uninventoried 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	<p>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.</p> <p>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.</p>
Implementers	From 1 to3: Existing data rescue organizations , WMO, GCOS, Funding agencies, NMHSs, Governments.
Means of Assessing Progress	<ol style="list-style-type: none"> 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 recognised 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 (res 1) includes sharing of historical data and should inform the planning and execution of the activities within this Action.

³⁶ Sindy Sterckx, Ian Brown, Andreas Käab, Maarten Krol, Rosemary Morrow, Pepijn Veeffkind, K. Folkert Boersma, Martine De Mazière, Nigel Fox & Peter Thorne (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](https://doi.org/10.1080/01431161.2020.1718240)

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.
------------------------------------	--

1

2 6.5 Theme E: Engaging with Countries

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

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

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

14

15

Action E1: Foster regional engagement in GCOS	
Activities	<ol style="list-style-type: none"> 1. Undertake at least one regional GCOS Workshop each year. 2. Promote the benefits of coordination of climate observations and GCOS programs. 3. Explore regional issues, gaps and needs and develop plans to address them. 4. Report regional needs and issues to the UNFCCC, WMO and other relevant stakeholders.
Issue/Benefits	<p>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.</p> <p>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.</p> <p>For example, GBON and SOFF were developed from needs identified in a GCOS regional workshop on climate observations systems in the Pacific Island states³⁷.</p>
Implementers	From 1 to 4: GCOS , Parties to the UNFCCC, WMO (Regional Organizations). GOOS (Regional Alliances).
Means of Assessing Progress	<p>Number of regional workshops held annually in collaboration with WMO and other stakeholders</p> <p>Reports to UNFCCC and WMO</p>
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.

³⁷ Full report available online: https://ane4bf-datap1.s3.eu-west-1.amazonaws.com/wmod8_gcoss/s3fs-public/fijiworkshopoct2017_final1.pdf?E8vbQOTXp3.VJII2p6utJLP.I8xM7huA

	<p>1. Regional workshops engage countries directly. 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.</p> <p>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.</p> <p>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.</p>
Links with other IP Actions	Actions E1-E3.

1
2

Action E2: Promote national engagement in GCOS	
Activities	<p>1. Encourage the development of national coordination of climate observations (e.g. national GCOS programs).</p> <ul style="list-style-type: none"> a) Collect annual reports of these programmes; b) Promote the benefits of national coordination; c) Support the development of new national climate observing programmes; d) Inclusion of national climate observations needs in WMO technical regulations and guides. <p>2. Engagement of National GCOS Focal Points</p> <ul style="list-style-type: none"> a) Revise terms of reference (ToR) for National GCOS Focal Points; b) Increased nomination of National GCOS Focal Points.
Issue/Benefits	<p>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.</p> <p>Where national resources for climate observations are very limited, national climate observing programmes can aid in requesting support, resources and capacity development.</p> <p>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.</p> <p>Most WMO members respond positively to guidance and standards mandated in the WMO technical regulations. Updating these technical regulations to adequately capture national climate data needs will provide the means to unambiguously define Members' obligations regarding collecting/sharing climate data.</p> <p>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.</p>

Implementers	From 1 to2: GCOS , Parties to the UNFCCC, NMHS, Academia; WMO.
Means of Assessing Progress	<ol style="list-style-type: none"> 1. Number of national climate coordination programs <ol style="list-style-type: none"> a) Updated WMO technical regulations. 2. <ol style="list-style-type: none"> a) Revised ToR for National Focal Points; b) Number of active National GCOS Focal Points.
Additional Details	<ol style="list-style-type: none"> 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 recognised. 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-E3.

1
2

Action E3: Support to national climate observations	
Activities	<ol style="list-style-type: none"> 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	<p>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.</p> <p>The GCOS cooperation mechanism (GCM) 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.</p> <p>While the GCM should try to address other ECVs it should also return to its original concept: identifying national needs and international assistance available.</p>
Implementers	From 1 to3: GCOS , Parties to the UNFCCC, Funding Agencies.

Means of Assessing Progress	<ol style="list-style-type: none"> 1. List of additional donors 2. List of national network support needs. 3. <ol style="list-style-type: none"> a) Increase in national network support; b) Funds raised by the GCM.
Additional Details	<ol style="list-style-type: none"> 1. An inventory of potential donors should be established and maintained. Proactively 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-E3.

1
2
3

6.6 Theme F: Emerging Needs

Action F1: Responding to user needs for higher resolution, near real time data	
Activities	<ol style="list-style-type: none"> 1. Identify the higher resolution observations of ECVs to support the Climate 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	<p>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.</p> <p>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.</p> <p>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.</p>
Implementers	<ol style="list-style-type: none"> 1. GCOS, research organizations, Academia, WMO. 2. Space agencies. 3. NMHS, WMO.

	4. WMO, NMHS.
Means of Assessing Progress	<ol style="list-style-type: none"> 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. <ol style="list-style-type: none"> 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	<ol style="list-style-type: none"> 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. 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 it is possible for the existing monitoring systems 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	<p>B2: GBON.</p> <p>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.</p> <p>D2: availability of data in archives.</p> <p>D3: easy accessibility of data.</p>

1
2

1

Action F2: Improved ECV satellite observations in polar regions	
Activities	<p>Improve satellite observations of:</p> <ol style="list-style-type: none"> 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.
Issue/Benefits	<p>Satellite missions in polar regions present particular challenges and this action highlights some of them affecting the measurement of certain ECVs. The current single-frequency, narrow L-band radiometry for salinity-measuring satellites (SMOS, Aquarius, SMAP) is not optimal for polar ocean SSS. 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.</p> <p>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.</p> <p>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.</p> <p>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.</p> <p>Sun-synchronous polar orbiters do not sample the very highest latitudes. True pole-to-pole-orbital configurations such as e.g. the upcoming TRUTHS mission can provide coverage of the very highest latitudes for a range of ECVs.</p>
Implementers	From 1 to 5: Research organizations , Academia, Space agencies.
Means of Assessing Progress	<p>From 1 to 3:</p> <p>Proof of concept for new technologies to measure SSS, albedo over snow and ice, sea-ice thickness and greenhouse gases at high latitudes, particularly in wintertime</p> <p>For 4 and 5:</p> <p>Feasibility study for true pole-to-pole orbital mission to measure changes at the very high latitudes for a set of targets ECVs.</p>
Additional Details	<ol style="list-style-type: none"> 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, CO₂ and CH₄ in polar regions require active, LIDAR missions such as the French-German research satellite MERLIN (expected launch 2024). These use LIDAR technology to quantify the CH₄ and

	<p>CO₂ mixing ratios 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.</p> <ol style="list-style-type: none"> 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. 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. In addition to sampling the very highest latitudes a true polar orbiter like TRUTHS processes with time enabling SNO-type observations at all latitudes with SSO-payloads. It also allows direct measurement of the diurnal cycle in the measured radiances at all latitudes.
<p>Links with other IP Actions</p>	<p>A2: continuity of space-based Sea Surface Salinity measurements. B3: new satellite missions (GHG).</p>

1
2

Action F3: Improve monitoring of coastal and Exclusive Economic Zones	
<p>Activities</p>	<ol style="list-style-type: none"> 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.
<p>Issue/Benefits</p>	<p>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.</p> <p>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 programme 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.</p> <p>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,</p>

	can document the enhanced erosion in Arctic regions associated with permafrost loss.
Implementers	<ol style="list-style-type: none"> 1. GOOS, Space agencies, NMHS. 2. Space agencies, research organizations, Academia. 3. Space agencies. 4. GOOS, NMHS, research organizations.
Means of Assessing Progress	<ol style="list-style-type: none"> 1. Number of global operational biogeochemical products in coastal areas. 2. Increased density of observations and reprocessed products in EEZ and coastal waters, and related uncertainties. 3. Number of land-cover data sets produced without masks. 4. Published national and regional guidelines.
Additional Details	<ol style="list-style-type: none"> 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 <p>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.</p> <p>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.</p> <p>Products should include clear information on their limitations in coastal areas and EEZs, and their related uncertainties.</p> <p>This activity should take into account 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/IOC³⁸.</p> 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. 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 framework³⁹, 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

³⁸ Report on Ocean Observations in Areas under National Jurisdiction Workshop (GOS 246, 2020)

³⁹ <https://www.oceanbestpractices.org/about/task-teams/task-team-22-01-coastal-observing-in-under-resourced-countries>)

	monitor the coastal ocean. This guidance will need to be implemented at a national level.
Links with other IP Actions	<p>B6 and B7: Expansion and integration of the global ocean observing system, including observations of biogeochemical/biological parameters.</p> <p>B8: Augmenting ship-based hydrography and fixed-point observations with biogeochemical and biological parameters.</p> <p>C1: Develop Monitoring standards, guidance and best practice for each ECV.</p> <p>C2: Activity 2 -reprocessing of satellite observations.</p>

1
2

Action F4: Improve climate monitoring in urban areas	
Activities	<ol style="list-style-type: none"> 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	<p>The majority of the human population lives in cities and urban areas 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 change (LULC).</p> <p>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.</p>
Implementers	From 1 to3: GCOS , WMO, Academia, national agencies, research organizations, NMHS
Means of Assessing Progress	<ol style="list-style-type: none"> 1. GCOS Adaptation Task Team progress and final reports to GCOS SC. 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.
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	<p>B4: expansion of atmospheric composition observations.</p> <p>F5: Activity 4 – improve measurements of relevant ECVs om large cities.</p>

3

1

Action F5: Develop an Integrated Operational Global GHG Monitoring System	
Activities	<p>The overall aim here is to develop an integrated operational global greenhouse gas monitoring infrastructure. The first steps are:</p> <ol style="list-style-type: none"> 1. Design and start to implement a comprehensive global set of surface-based observations of CO₂, CH₄ and N₂O 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 CO₂ and CH₄ 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	<p>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 NAPs; and monitor changes to the cycles of GHG that may impact the achievement of the temperature goal of the Paris Agreement.</p> <p>Monitoring of hot-spots via dedicated observations to validate specific point-source emissions and identify missing sources from emission inventories.</p> <p>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 (SO₂, 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).</p>
Implementers	<ol style="list-style-type: none"> 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	<ol style="list-style-type: none"> 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. <ol style="list-style-type: none"> 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.

<p>Additional Details</p>	<p>From 1 to 3:</p> <p>WMO is preparing a Concept Paper “A WMO-coordinated Global Greenhouse Gas Monitoring Infrastructure” that contemplates the following four components for an integrated operational global greenhouse gas monitoring infrastructure:</p> <ol style="list-style-type: none"> a) A comprehensive global set of surface-based observations of CO₂, CH₄ and N₂O concentrations routinely exchanged in near-real time; b) A constellation of satellites to provide near-real time global coverage of CO₂ and CH₄ column observations (and profiles to the extent possible); c) A global Chemistry Transport Model (CTM) [2] driven by output from a high-resolution global NWP model; d) Assimilation of the observations a) and b) into the model c). <p>4. Hot spots include urban areas, industrial zones and individual large plants.</p> <p>4.1 Enhance observations in urban areas:</p> <ol style="list-style-type: none"> 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, NO₂, SO₂, VOCs. <p>4.2 Ensure co-located observations of aerosols loadings and aerosol profiles in urban areas:</p> <ol style="list-style-type: none"> 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 cities (B3). <p>Present challenges in monitoring emission hotspots include:</p> <ul style="list-style-type: none"> • 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.
<p>Links with other IP Actions</p>	<p>B3: New satellite missions.</p> <p>B4: In situ monitoring of aerosols and greenhouse gases.</p> <p>F4: Climate monitoring in urban areas.</p>

1
2

1 **APPENDIX 1: ACRONYMS**

2 To be added.

1 **APPENDIX 2: REFERENCES**

2 To be added.

3

4

5

6

- 1 **APPENDIX 3: ACKNOWLEDGEMENTS AND LIST OF CONTRIBUTORS**
- 2 To be added.

1 **ANNEX A: ECV REQUIREMENTS**

2

3 The Annex A is provided in a separate file for ease of reviewing.

ANNEX B: STATUS OF THE GLOBAL CLIMATE OBSERVING SYSTEM 2021

EXECUTIVE SUMMARY

This report aims to inform policy makers, and those with oversight over observing networks and satellite observations, about the status of the global climate observing system, its recent improvements and achievements, as well as its gaps and deficiencies.

The Global Climate Observing System (GCOS) was established in 1992 to aid in developing and coordinating a Global Climate Observing System that simultaneously supports scientific understanding of climate change, policy development, public information and planning for adaptation and mitigation.

GCOS prepares regular reports on the state of the global climate observing system (so-called "status" or "adequacy" reports) and submits them to the United Nations Framework Convention on Climate Change (UNFCCC). This is the fifth such report and it reviews developments in the observing system since the previous report published in 2015 (GCOS-195).

In 2014, the Intergovernmental Panel for Climate Change (IPCC) stated that evidence of climate change was unequivocal and so the 2016 GCOS Implementation Plan (2016 GCOS-IP, GCOS-200) indicated that the emphasis of GCOS needed to expand beyond the scientific observation of the climate to also supporting policy and planning. This resulted in two new areas of work for GCOS.

The first area looks at how well global climate cycles⁴⁰ are monitored. By assessing how well these are observed by the Essential Climate Variables (ECVs)⁴¹ as a whole, GCOS has identified gaps and inconsistencies in the global climate observing system. The 2016 GCOS Implementation Plan (2016 GCOS-IP) took the new approach of not only concentrating on the quality of a single ECV, but also considering that the ECVs are increasingly being used to close the global, or continental scale budgets of energy, carbon and water. Understanding changes in these budgets and how they are linked is vital. For example, changes in the amount of water in the different components of the Earth system directly affect access to water of good quality, which is a basic human requirement, while changes in the energy cycle directly drive impacts such as terrestrial and ocean heatwaves, extreme precipitation and drought. Changes in the carbon cycle directly drive changes in the energy cycle and impact emission targets. Thus, understanding and observing the Earth's cycles is important for both climate science and for determining and monitoring key policy targets set in the Paris agreement framework.

The second area of new work for GCOS looks at how the global observing system can support adaptation. Climate data supplied by a global system is an essential component in delivering the products and information needed for adaptation. Data products derived from climate monitoring, together with climate predictions generated from a global climate model and downscaled to the regional and national level, provide climate information at multiple spatial and time scales that meet the requirements of adaptation. At the global scale, observations can be used to review

⁴⁰ GCOS has looked at the water and carbon cycles and the energy balance but there are other important Earth system cycles (e.g. Nitrogen cycle) that are impacted by climate change and human activities.

⁴¹ An Essential Climate Variable (ECV) is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate.

1 the collective progress on adaptation by all countries. GCOS international
2 coordination ensures that high-quality global climate data are available and
3 accessible, providing critical support for adaptation.

4
5 Securing and extending the observing systems needed for the long-term monitoring
6 of the Earth system as a whole requires substantial efforts and collaboration at all
7 levels including

8 Meteorological Organization (WMO), the Global Ocean Observing System (GOOS),
9 the Joint Working Group on Climate (WGClimate) of the Committee on Earth
10 Observation Satellites (CEOS), the Coordination Group for Meteorological Satellites
11 (CGMS), and a broad range of other partners and relevant organizations.

12 **The approach**

13 The writing of this report has been guided by a writing team, while experts from the
14 three GCOS panels⁴² have provided the technical information and assessments. Each
15 Panel has appointed "ECV Stewards" to monitor the performance of the observing
16 system for specific ECVs. Similarly, experts were appointed to report on each of the
17 actions on the 2016 Implementation Plan (IP Actions). All assessments have been
18 internally and externally reviewed. The whole report was publicly reviewed with over
19 500 comments received. Finally, the report was approved by the writing team and
20 the GCOS Steering Committee.

21 **Benefits**

22 Sustained long-term support for a global system of climate observations, both in situ
23 and satellite, provides many benefits. All countries can benefit from the outputs of
24 global models, forecasts and predictions supported by global climate observations.
25 Emergency warning systems use local models and observations that are embedded in
26 a global modelling system, while planning often uses models downscaled from global
27 results. Climate-related policy is driven by data: the UNFCCC is a science-based
28 process that uses IPCC assessments of the state of the climate based on the climate
29 observations as well as observation-based reports on the state of the climate.

30 **Achievements**

31 Since the 2016 GCOS Implementation Plan was published there has been substantive
32 progress in many areas of the Earth's climate observation system and this effort
33 needs to be maintained and supported by sustainable, long-term, and adequate
34 finance. The major improvements include:

- 35 • Satellite observations have improved their coverage spatially,
36 temporally and in terms of observed variables. Satellite data are
37 accessible and well curated⁴³. Many ECVs, especially terrestrial ECVs
38 such as land cover, leaf area index and FAPAR (Fraction of Absorbed
39 Photosynthetically Active Radiation), are now available from satellites
40 providing a near-global coverage with good resolution.
- 41 • WMO and, through its Members, the worldwide network of National
42 Meteorological and Hydrological Services (NMHSs) ensure the required
43 long-term monitoring, with established practices and instruments, for
44 many ECVs. Many of these data are exchanged internationally and
45 support weather and climate modelling.
- 46 • Observations of atmospheric variables have further improved in the
47 past decade thanks to new in situ observations from the ground and

⁴² Atmospheric Observation Panel for Climate (AOPC), Ocean Observations Physics and Climate Panel (OOPC),
Terrestrial Observation Panel for Climate (TOPC)

⁴³ e.g. see the ECV Inventory <https://climatemonitoring.info/ecvinventory/>

1 from commercial aircrafts.

- 2 • Most ground-based networks are well managed and archives
3 appropriately stewarded in data centres such as the National Centers for
4 Environmental Information (NCEI) hosted by the National Oceanic and
5 Atmospheric Administration (NOAA) in the US; the National Snow and
6 Ice Data Center (NSIDC) in the US and the International Comprehensive
7 Ocean-Atmosphere Data Set (ICOADS). The Copernicus Climate Change
8 Service (C3S) also provides access to data and derived products as well
9 as tools to use the data.
- 10 • GCOS and WMO are now working together to establish a reference
11 network for atmospheric and land surface meteorological observations,
12 which will be the surface equivalent to the GCOS Reference Upper-Air
13 Network (GRUAN).
- 14 • The ocean observing community is working in structuring ocean
15 observations in a fit-for-purpose observing system, with agreements on
16 best practices for observations and data and metadata standards.
- 17 • The decision was made to expand the Argo program to the full water
18 column and under sea ice, including biogeochemical variables. These
19 subsurface measurements are critical to monitor and forecast the
20 climate system.
- 21 • Technological innovations have contributed to expanding the ocean
22 observing system and its capability, in particular with the development of
23 autonomous platforms and suitable sensors for a range of ECVs.

24 Sustainability

25 Long-term continuity of some satellite observations is not assured.

26 While satellite observations have been a major success, there are gaps:

- 27 • No follow up mission for Aeolus (wind profiles) is planned.
- 28 • No continuity is assured for cloud radar and lidar on research satellites.
- 29 • Only one limb sounder with similar capabilities to the Aura Microwave
30 Limb Sounder (MLS) is planned. The MLS provides near-global coverage
31 every day for water vapour vertical profiles from the upper troposphere
32 through the mesosphere but has now exceeded its expected lifetime.
- 33 • High-inclination altimetry is still problematic with only two research
34 satellites flying (CryoSat-2 and ICESat-2). In the future, European
35 missions Copernicus Polar Ice and Snow Topography Altimeter
36 (CRISTAL) and Copernicus Imaging Microwave Radiometer (CIMR)
37 would extend operational monitoring capabilities to the late 2020s (if
38 confirmed). Sentinel-3A/B altimeter data could be optimized for sea ice
39 in the future.
- 40 • High-latitude sea-ice thickness monitoring is at risk (when CryoSat-2
41 and ICESat-2 or, for thin ice <50 cm, SMOS, stop working) and a gap
42 might occur if CRISTAL is delayed.

43 **Sustained funding** is needed for in situ observations. While many atmospheric
44 observations have sustained long-term funding, most ocean and terrestrial
45 observations are supported through short-term research funding, with a typical
46 lifetime of a few years, leaving the development of long-term records vulnerable.
47 This is particularly true for parameters that are not traditionally monitored for
48 weather prediction. Since these observations are executed by a large range of
49 actors, a functional and effective observing system for climate needs appropriately
50 funded support and coordination bodies are essential.

1 **Many otherwise successful projects have not led to long-term sustained**
 2 **improvements.** One clear message from the GCOS Regional Workshops is that most
 3 of the projects in developing countries that have a component devoted to
 4 observations have not led to sustainable long-term improvements in the
 5 observational capacity of these countries due to lack of resources and planning. More
 6 sustainable solutions are needed such as the proposal for WMO's Global Basic
 7 Observing Network (GBON) and the Systematic Observations Financing Facility
 8 (SOFF) discussed below.

9 **Gaps in geographical coverage**

10 There are still gaps in the global coverage of in situ observations.

11 In situ observations for almost all the ECVs are consistently deficient over certain
 12 regions, most notably parts of **Africa, South America, Southeast Asia**, the
 13 **Southern Ocean**, and **ice-covered** regions, a situation that has not improved since
 14 the *2015 GCOS Status Report*

15 (GCOS-195).

16 The three GCOS Regional Workshops in Fiji, Uganda and Belize ⁴⁴have looked at
 17 why some regions have problems in making sufficient observations. These issues
 18 include:

- 19 • For small nations (e.g. SIDS and PSIDS) the costs of observations may
 20 far exceed the resources available nationally amounting to a substantial
 21 fraction of the Gross Domestic Product (GDP).
- 22 • Lack of planning for foreseeable expenses (e.g. maintenance,
 23 equipment replacement, consumables).
- 24 • Lack of trained staff and poor staff retention.
- 25 • Poor understanding of the national benefits of observations: their
 26 contribution to disaster preparedness, adaptation planning and other
 27 climate services.

28 Furthermore, in remote and inaccessible areas, there are technical difficulties in the
 29 maintenance of operational observations.

30 The WMO Congress in 2019 adopted the concept for a **Global Basic Observing**
 31 **Network (GBON)**, which, if fully implemented, will provide essential observations
 32 for global Numerical Weather Prediction (NWP) and reanalyses, covering a few
 33 ECVs. WMO is currently working to establish a Systematic Observations Financing
 34 Facility (SOFF) that will provide financial and technical support for the
 35 implementation and operation of GBON to those Members who would not otherwise
 36 be able to implement this network. Transforming the GBON and SOFF from
 37 concepts to an operational reality requires the efforts and support of all parties.

38 Some of the problems related to the operation of the in situ network have been
 39 addressed by the GCOS Cooperation Mechanism (GCM). While the impact of the GCM
 40 at a station or national level can be significant, the funding available to the GCM only
 41 allows a handful of countries to be assisted. The SOFF, if funded to the level
 42 envisaged on a sustained basis, would lead to global improvements but only
 43 addresses a few ECVs. **The need for support for the remaining in situ ECV**
 44 **observations remains.**

45 **Large gaps still exist in ocean observations.** Subsurface measurements are
 46 critical to monitor and forecast the climate system. The decision to expand the Argo
 47 program to the full water column and under sea ice, including biogeochemical

⁴⁴ <https://gcos.wmo.int/en/regional-workshops>

variables, addresses that challenge. More regular sampling by high-quality oceanographic cruises and an increase in the deployment of observing platforms are needed, in particular along continental boundaries, the polar oceans and marginal seas. Ocean conditions affecting the loss of ice from Greenland and the Antarctic need to be better monitored to improve projections of future rates of ice loss and sea level rise. On-ice in situ observations remain a challenge due to logistical difficulties. Improving both quality and coverage of surface flux measurements of heat, carbon, freshwater, and momentum is necessary.

Gaps in the satellite-based observations include:

- Lower tropospheric ozone (to supplement the limited coverage of surface and to determine statistically significant trends).
- An instrument that measures stratospheric CH₄ profiles globally.
- There is a regional imbalance of satellite observations. In high mountain areas satellite data acquisition of cryospheric observations is poor. For certain atmospheric ECVs in polar regions satellites have poor or no coverage.

Data Stewardship, Archiving and Access

Preservation of the fundamental climate data record is essential. Reanalysis and other added value products can always be recreated or improved from the basic data record. To address and understand climate change the longest possible time series need to be preserved in perpetuity. Not every ECV has a recognized global data repository (such as ICOADS, where almost all qualifying data has been collected). Even when there is a recognized global data repository, it can be incomplete and inadequately supported. Data should be open and freely available to all users. Adequate data stewardship, archiving and access requires sustainable, long-term, sufficient funding, as well as requirements that will ensure a consistent approach among the data centres. Clearly defined principles such as the TRUST Principles (Lin et al., 2020) and FAIR Principles (Wilkinson et al., 2016) as well as clear and enforced data management plans and data citation are required.

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. Sustained support to these activities is required. New approaches including citizen science and classroom-based approaches, if widely deployed, may help achieve digitization steps at the required scale.

New needs and requirements identified since the 2016 Implementation Plan

Supporting the Paris Agreement

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 areas particularly susceptible to the impacts of climate change and to how well ECV requirements capture the relevant temporal and spatial scales. These include:

- The feedbacks associated with changes in land use/cover, for example the timing and implications of the release of stored carbon in Arctic permafrost in different temperature and stabilization regimes (IPCC, 2018).
- Improving understanding of how response options and policies can reduce or augment the cascading impacts of land and climate, especially in relation to non-linear and tipping point changes in natural and human systems (IPCC, 2019a).

- 1 • The ocean overturning circulation is a key factor that controls heat
2 and carbon exchanges with the atmosphere, and hence global
3 climate, however there are no direct measures of this and only
4 sparse indirect indicators of how it may be changing. This is a critical
5 weakness in sustained observations of the global ocean (IPCC,
6 2019b).
- 7 • Given the carbon reduction commitments that have been proposed by
8 most countries, there is a need for quantitative assessment of
9 anthropogenic greenhouse gas fluxes through measurements of
10 atmospheric composition. It is also necessary to ensure that the global
11 climate observations support the quantitative evaluation of the effect
12 of human activities on climate change.
- 13 • Climate observations have a key role in adaptation, a major goal
14 of the Paris Agreement.

15 **The Earth System Cycles**

16 In 2018 GCOS started assessments for the energy balance, and the carbon and the
17 water cycles, identifying possible gaps and inconsistencies in existing observation
18 systems, (von Schuckmann et al., 2020; Dorigo et al., 2021; Crisp et al., in prep).

19 Major implications include:

- 20 • The uncertainty in the overall energy cycle is dominated by the oceanic
21 heat uptake where there is a need to sustain and extend an integrated
22 ocean observing system.
- 23 • The largest uncertainties in the energy fluxes are precipitation, short
24 wave heating of the atmosphere, and the ocean and land turbulent
25 fluxes of sensible and latent heat. Research is underway looking at
26 improvements to the measurement capabilities for fluxes, especially
27 over the oceans. This needs to be concluded and, if successful,
28 implemented.
- 29 • The uncertainty (interannual variability) in the total carbon budget is
30 dominated by the land use flux and ocean and land uptakes. These
31 uncertainties are cause for concern as they suggest that our current
32 observing systems do not yet have the required precision to annually
33 monitor these trends adequately enough to guide Parties in the
34 emission reductions that they need to achieve the Paris agreement
35 temperature goal. This will require observational improvements
36 particularly in the Southern Ocean and in the atmosphere over land.
37 Satellite observations need to be complimented with a significant
38 increase of in situ observations of GHGs with special attention given to
39 improving the observations around urban areas.
- 40 • The largest uncertainty in the water cycle is in the evaporative fluxes
41 over land (including polar regions) and ocean and precipitation over
42 the ocean and mountains. There is a need to measure key variables
43 to determine evaporative fluxes to improve water budget closure
44 over tropical areas. A snow measurement mission is also needed to
45 better constrain the cold land hydrology.
- 46 • A new ECV Terrestrial Water Storage (a satellite, gravimetric,
47 observation) is being introduced. It will aid in quantifying the net effect
48 of changes in the climate, human water use and other hydrological
49 effects on the continental water budget and helps closing the terrestrial
50 water balance. It will also support adaptation studies for identifying hot
51 spots of changes in the water cycle assessing the severity of droughts.

52 **Adaptation and Extremes**

1 GCOS has started considering adaptation but has not yet concluded this work. Many
2 of the major issues being addressed by adaptation, such as flooding, droughts and
3 heatwaves, relate to extremes rather than long-term means of ECVs. Monitored data
4 need to be relevant to the specific vulnerabilities (e.g. people, agriculture or
5 infrastructure) rather than broader averages. Thus, in the future, attention needs to
6 be given to monitoring extremes at appropriate spatial and temporal resolutions for
7 each specific use. Therefore, in defining ECV requirements, single values for
8 accuracy and resolution may not be sufficient.

9 It was concluded that with current capabilities in relation to its ECVs and ECV
10 products, the global climate observing system could provide indicators for adaptation
11 that could be used in the global stocktake. With modest enhancement of products or
12 new products, these could be used at national level to add value to National
13 Adaptation Plans, through assessment of climate hazards and vulnerabilities, assisting
14 in identification of adaptation options and implementation, and in management,
15 monitoring and evaluation of adaptation actions.

16 **Next Steps**

17 There have been many significant improvements in the global climate observing
18 system since 2015. These have contributed to improved understanding of climate
19 change and better policy development and adaptation and mitigation planning.

20 This report will be submitted to the UNFCCC and the GCOS co-sponsors, WMO, IOC,
21 UNEP and ISC for their consideration. It will be followed by a new GCOS
22 implementation Plan in 2022 that will identify key priority areas for improvement
23 based upon the findings discussed here.

References

- 1
2
3 Crisp D. et al: How well do we understand the land-ocean-
4 atmosphere carbon cycle? (in preparation)
5 <https://doi.org/10.1002/essoar.10506293.1>
- 6 Dorigo, W. et al., 2021: Closing the water cycle from observations
7 across scales: Where do we stand? Bulletin of the American
8 Meteorological Society (published online ahead of print 2021).
9 <https://doi.org/10.1175/BAMS-D-19-0316.1>
- 10 GCOS-195: Status of the Global Observing System for Climate,
11 World Meteorological Organization (WMO) WMO, 2015.
12 https://library.wmo.int/doc_num.php?explnum_id=7213
- 13 GCOS-200: The Global Observing System for Climate:
14 Implementation Needs, World Meteorological Organization (WMO)
15 WMO, 2016.
16 https://library.wmo.int/doc_num.php?explnum_id=3417
- 17 IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the
18 impacts of global warming of 1.5°C above pre-industrial levels and related
19 global greenhouse gas emission pathways, in the context of strengthening
20 the global response to the threat of climate change, sustainable
21 development, and efforts to eradicate poverty. In Press.
22 [https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_versio
23 n_stand_alone_LR.pdf](https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_version_stand_alone_LR.pdf)
- 24 IPCC, 2019a: Climate Change and Land: an IPCC special report on climate
25 change, desertification, land degradation, sustainable land management,
26 food security, and greenhouse gas fluxes in terrestrial ecosystems,
27 <https://www.ipcc.ch/srccl/>
- 28 IPCC, 2019b: IPCC Special Report on the Ocean and Cryosphere in a Changing
29 Climate. <https://www.ipcc.ch/srocc/>
- 30 Lin D. et al., 2020: The TRUST Principles for digital
31 repositories. Sci Data 7, 144.
32 <https://doi.org/10.1038/s41597-020-0486-7>
- 33 von Schuckmann, K. et al., 2020: Heat stored in the Earth system: where
34 does the energy go?, Earth Syst. Sci. Data, 12, 2013-2041,
35 <https://essd.copernicus.org/articles/12/2013/2020/>
- 36 Wilkinson, M. et al., 2016: The FAIR Guiding Principles for scientific data
37 management and stewardship. Sci Data 3, 160018.
38 <https://doi.org/10.1038/sdata.2016.18>
39
40
41
42
43
-

GCOS Secretariat
Global Climate Observing System
c/o World Meteorological Organization
7 bis, Avenue de la Paix
P.O. Box No. 2300
CH-1211 Geneva 2, Switzerland
Tel: +41 22 730 8067
Fax: +41 22 730 8181
Email: gcos@wmo.int