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ESA Earth Observation Science Strategy Foundation Study, D2 v3

Updated version of Candidate Science Questions (CSQs), including description of the evolution of the CSQs and evaluation of the CSQs against a set of assessment criteria. Includes a summary of all the CSQs and a appendix detailing a subset of the CSQs, including Geophysical Observables required to progress the CSQs.

May 2024

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ACRONYMS AND ABBREVIATIONS

Acronym	**Meaning**
ABL	Atmospheric Boundary Layer
ACE	Atmospheric Chemistry Explore
ACEO	Advisory Committee on Earth Observation
AI	Artificial Intelligence
AQUAWATCH	AquaWatch
BON	GEO Biodiversity Observation Network
BSRN	Baseline Surface Radiation Network
CBD	(UN) Convention on Biological Diversity
CCI	Climate Change Initiative
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth's Radiant Energy System
CITES	Convention on International Trade in Endangered Species
CLAP	Community Land Active Passive (Microwave Radiative Transfer Modelling Platform)
CLIC	Climate and Cryosphere
CLIVAR	Climate and Ocean Variability, Predictability and Change
CMIP	Climate Modelling Intercomparison Project
CO2	Carbon Dioxide
GEO-CRADLE	H2020 project
GEO-DARMA	Data Access for Risk Management
DC	District of Columbia
DESA	(UN) Department of Economic and Social Affairs
DFKI	German Research Center for Artificial Intelligence
DIAS	Data Integration and Analysis System
DOI	Digital Object Identifier
DRM	Drought Risk Management
DRR	Disaster Risk Reduction
EA	Ecosystem Accounts
EBAF	Energy Balanced and Filled
EBV	Essential Biodiversity Variable
ECMWF	European Centre for Medium Range Weather Forecasts
ECV	Essential Climate Variable

ECWMF	European Centre for Medium Range Weather Forecasts
EEI	Earth Energy Imbalance
EO	Earth Observation
EOAC	Earth Observation Advisory Committee
EOEP	Earth Observation Envelope Programme
EOP	Earth Observation Programmes
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESAC	Earth Science Advisory Committee
ESAS	Earth Science Advisory Committee
ESS	Earth System Science
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FLEX	FLuorescence Explorer
GCOS	Global Climate Observing System
GDIS	Global Drought Information System
GDP	Gross Domestic Product
GEO	Group on Earth Observation
GEO-LDN	GEO Land Degradation Neutrality
GEOGLAM	GEO Global Agricultural Monitoring
GEOGLOWS	GEO Global Water Sustainability
GEWEX	Global Energy and Water Exchanges
GFOI	Global Forest Observation Initiative
GHG	Green House Gas
GIS	Geographical Information System
GOCE	Gravity and Ocean circulation
GOSAT	Greenhouse gases Observing SATellite
GOS4M	Global Observation System for Mercury
GPP	Gross Primary Productivity
GRACE	Gravity Recovery and Climate Experiment
GRAF	Global Risk Assessment Framework
GRAS	Global Navigation Satellite System Receiver for Atmospheric Sounding
GRUAN	GCOS Reference Upper Air Network
GSNL	Geohazard Supersites and Natural Laboratories

GSO	Geomagnetic Smallsat Observatory
GUOI	Global Urban Observation and Information
GWIS	Global Wildfire Information System
HAPS	High Altitude Platforms
HUMAN-PLANET	initiative in the GEO 2017-2019 work programme
IASI	Infrared Atmospheric Sounding Interferometer
ICES	International Council for the Exploration of the Sea
ICSU	International Council for Science
IEEE	Institute of Electrical and Electronic Engineers
IESWG	International Earth Surface Working Group
IGACGP	International Commission on Atmospheric Chemistry and Global Pollution
IOC	Intergovernmental Oceanographic Commission
IP	Implementation Plan
IPCC	Intergovernmental Panel on Climate Change
ISR	Intelligence, Surveillance, and Reconnaissance
JSC	Joint Scientific Committee
LDN	Land Degradation Neutrality
LP	Living Planet
LPS	Living Planet Symposium
LULUCF	Land Use, Land Use Change and Forestry
MEA	Multilateral Environmental Agreements
MI	Most Important
MOUNTAINS	GEO-MOUNTAINS Observations and Information in Mountain Environments
MS	Member States
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NCA	Natural Capital Accounting
NDC	Nationally Determined Contribution
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NOX	Nitrogen Oxides
NY	New York
OASIS	Observing Air–Sea Interactions Strategy
OECD	Organisation for Economic Co-operation and Development

OSCAR	Observing Systems Capability Analysis and Review tool
PB	Planetary Boundary
PBL	Planetary Boundary Layer
PLANET	GEO BLUE-PLANET
PNAS	Proceedings of National Academy of Sciences
POR	Programme of Record
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
PSI	Preliminary Site Investigation
RAMSAR	Convention on Wetlands signed in Ramsar, Iran
RECCAP	REgional Carbon Cycle Assessment and Processes Project
REDD	Reducing Emissions from Deforestation and Forest Degradation
REF	Reference
RFI	Request For Information
RFO	Request For Offer
RIO+20	UN Conference on Sustainable Development, June 2012
SAR	Synthetic Aperture Radar
SATM	Science and Applications Traceability Matrix
SCOPE	Soil Canopy Observation, Photochemistry, and Energy
SCOR	Scientific Committee on Oceanic Research
SDG	Sustainable Development Goals
SEEA	System of Environmental-Economic Accounting
SIF	Sun-Induced Fluorescence
SOLAS	Surface Ocean-Lower Atmosphere Study
SP	Special Publication
SPARC	Stratosphere-troposphere Processes And their Role in Climate
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRL	Science Readiness Level
SSFS	Science Strategy Foundation Study
STEMMUS	Simultaneous Transfer of Energy, Mass and Momentum in Unsaturated Soil
SWARM	Three satellite constellation to study the Earth's magnetic field
TABLES	Not relevant
TCFD	Taskforce on Climate-related Financial Disclosure
TGRS	Transactions on Geoscience and Remote Sensing
TROPOMI	TROPOspheric Monitoring Instrument

UK	United Kingdom
UN	United Nations
UNCBD	United Nations Convention on Biological Diversity
UNDRR	United Nations Office for Disaster Risk Reduction
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
USGS	United States Geological Survey
VENER	Vision for Energy
WCRP	World Climate Research Programme
WEF	World Economic Forum
WG	Working Group
WMO	World Meteorological Organisation

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1 INTRODUCTION

The ESA EO Science Strategy Foundation Study (SSFS) is generating evidence to support ESA in developing the next EO Science Strategy due to be released in 2024.

The primary output of the study is a series of "Candidate Science Questions" (CSQs) that will be used as input to the formulation of ESA's next EO Science strategy covering the period 2024-2030. The science questions represent high priorities in addressing gaps in our understanding of the earth system, either in terms of providing new information, or significantly reducing the uncertainties in existing information. The Science Questions should also be demonstrably relevant in addressing policy issues of high societal priority. The Science Questions must be relevant to ESA's core mandate and must therefore also be explicitly linked to requirements for geophysical observations that could be made from EO satellites. In elucidating the Science Questions, the adequacy of existing and planned observations has to be considered, and gaps in the current observation plan identified. Bearing in mind that ESA's FutureEO programme includes significant investments in R&D for data analysis, algorithm development and modelling, the elaboration of the Science Questions should also point to gaps in knowledge and capacity that could be filled by actions in these domains. They should therefore be capable of leading to actions on a variety of timescales, from short term research actions through to decadal projects leading to major new satellite missions.

The CSQs developed during the study cover a wide range of topics. They are intentionally cross-disciplinary in nature and have differing scale and breadth. They cover major questions in Earth system science that require different tools to address them, where progress can be made on a range of timescales. They tackle innovative discovery science as well as topics with clear societal impacts.

1.1 Context and Process

The overall process used for the study is shown below.

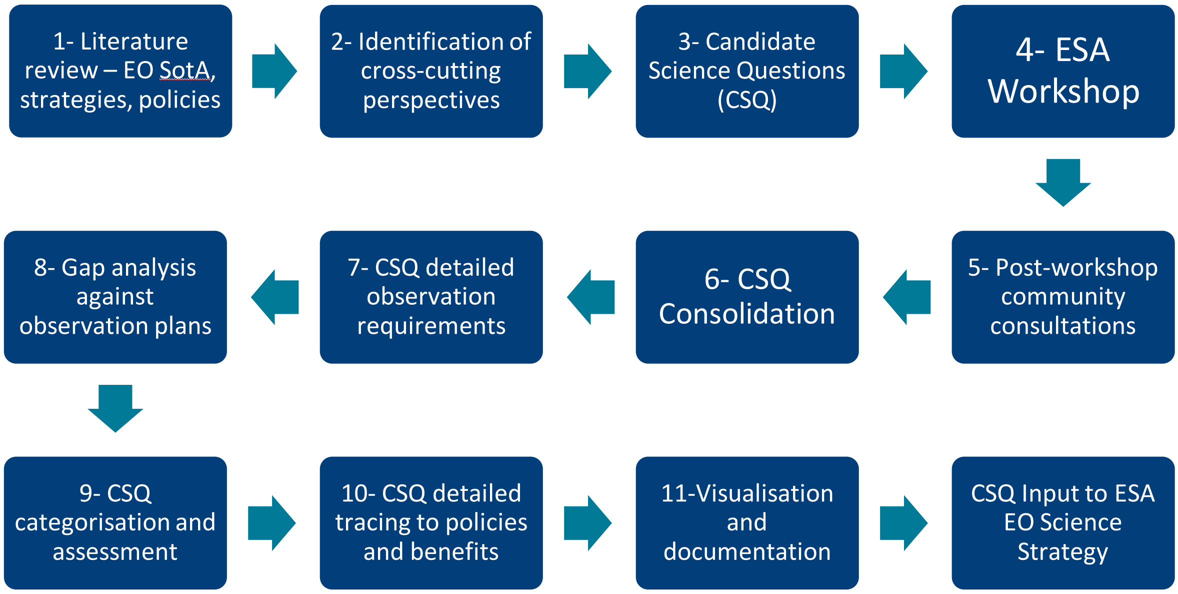

Figure 1: Overall Project Process

At the beginning of the project, the team identified a series of CSQs that were published and discussed at the ESA Science Strategy workshop in Bruges in May 2023. After the workshop, a process of refinement and consolidation was undertaken, which is described in Chapter 2 of this document.

At that stage a subset of 22 CSQs, was selected for detailed analysis, and for the identification of specific geophysical observables that were required to help answer the CSQ (step 7 in the figure above). An analysis of these observation requirements against the current and planned provision of observations from EO satellites was then undertaken (step 8). The results of that analysis are described in a separate deliverable [R-1].

Subsequently the CSQs were assessed against a set of criteria in order to support ESA's selection of priorities (step 9) and in particular for their relevance to a range of national and international policy and societal benefit categories (step 10).

Finally, a range of different visualisations were developed to describe and explain the CSQs, their relationship to geophysical observables and the their links to policy and benefits categories.

1.2 Reference Documents

[R-1] EO Science Strategy Foundation Study deliverable D5: *Links between Candidate Science Questions, Geophysical Observables and EO mission capabilities.*

2 CSQ GENERATION, SELECTION AND REFINEMENT

2.1 Initial generation of CSQs

The initial generation of the CSQs was guided by the overall requirement for a cross-disciplinary view and the desire to move away from previous strategies where challenges were organised along the lines of Earth system science domains (in the previous ESA strategies, these were: Land, Ocean, Atmosphere, Cryosphere and Solid Earth).

In the early stages of the study the project science team was split into groups to review and discuss Earth system science priorities from a number of perspectives. These perspectives were *not* intended to be a thematic division of science domain but rather a set of views from which to consider the Earth system science priorities. As such there are some overlaps, and some of the views are orthogonal – our intention was to consider a wide range of viewpoints and tease out cross-disciplinary issues. The project science team was split into three groups which conducted a series of meetings, where the consideration of each perspective was led by one member, as shown in Table 1.

Team member	**Perspective**
Han Dolman	*Group Chair*
Christine Gommenginger	Coastal
Ana Bastos	Planetary boundaries
David Crisp	Carbon cycle
Martin Herold	Biodiversity/ecosystems
Alain Hauchecorne	Cross cutting/technical issues
Jose Moreno	Climate tipping points
Peter Thorne	*Group Chair*
Karina von Schuckmann	Energy cycle
Bob Su	Water cycle
Anna Hogg	Polar
Isabelle Panet	Solid Earth/mass changes/geomagnetism
Jonny Johannesen	*Group Chair*
Maria Fabrizia Buongiorno	Earthquakes/vulcanism and minerals
Johanna Tamminen	Extreme events

Table 1: Project Science Team

Each of the topics was discussed by two of the science team sub-groups. The first of these meetings on each topic results in analysis of the current state of the art from the perspective of that topic and a preliminary list of Science Questions related to the topic. The topics were then discussed a second time by one of the other science team groups, where the Science Questions were be refined.

2.2 CSQ refinement, consolidation and detailing

The process for refinement of the CSQs after their initial generation in the science team groups is shown Figure 2, with the main steps described below.

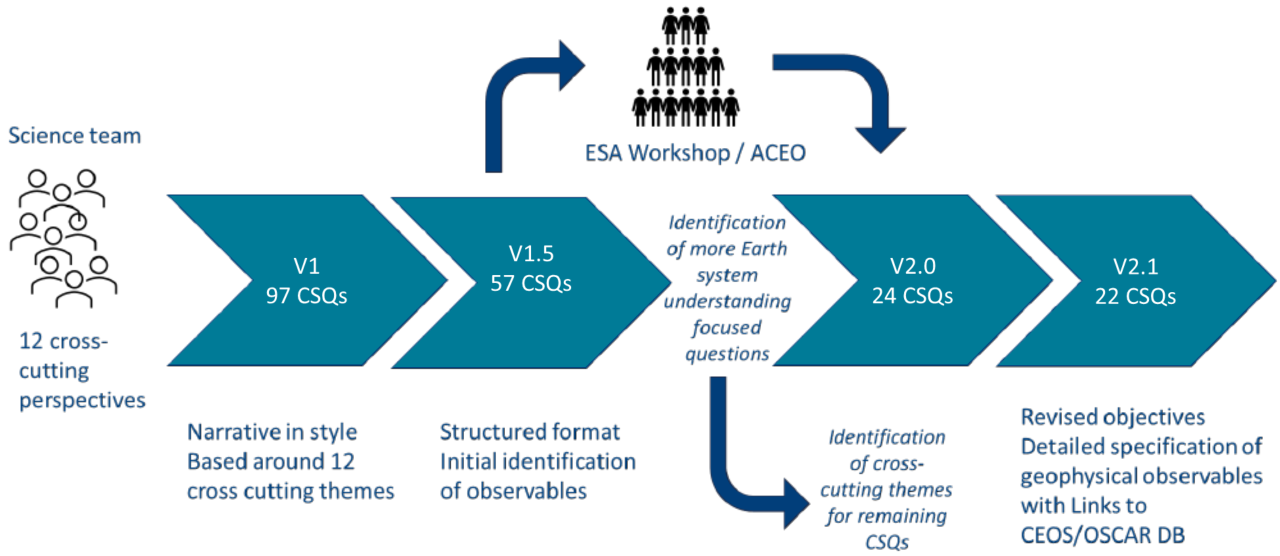

Figure 2: Process for CSQ consolidation, refinement and detailing

2.3 Community Feedback

The two rounds of science group meetings resulted in 57 CSQs which were narrative in style and organised around the initial 12 perspectives. These CSQs were presented to the European EO community at a workshop organised by ESA in Bruges, May 2023. Feedback on these CSQs came in three forms:

- Discussion at the workshop both in plenary and in splinter groups that considered specific CSQs
- Feedback after the workshop through a web form where comments could be made against individual CSQs
- Discussion with ACEO members at a meeting following the public workshop.

The comments on individual CSQs were assessed and categorised, after removing non-substantive comments (for example, sometimes there was just a single word in a comment field such as “yes” or “OK”) the remaining comments were categorised into those which were:

- Positive endorsements of the CSQs, typically noting its importance, but not seeking a change to the CSQ
- Largely commentary, without a specific question or request for a change or addition to the CSQ
- Requests for an addition to a CSQ, most often for a particular observation to be. added, but occasionally requests for additional KOs

- Points of detail, that may need to be considered in refining the CSQ
- Negative comments (of which there were few) suggesting things missing from the CSQ but not necessarily suggesting a modification.

The distribution of comments into those categories is shown in Figure 3. These comments were used in the update and of the CSQs and detailing of the geophysical observables required to satisfy each CSQ.

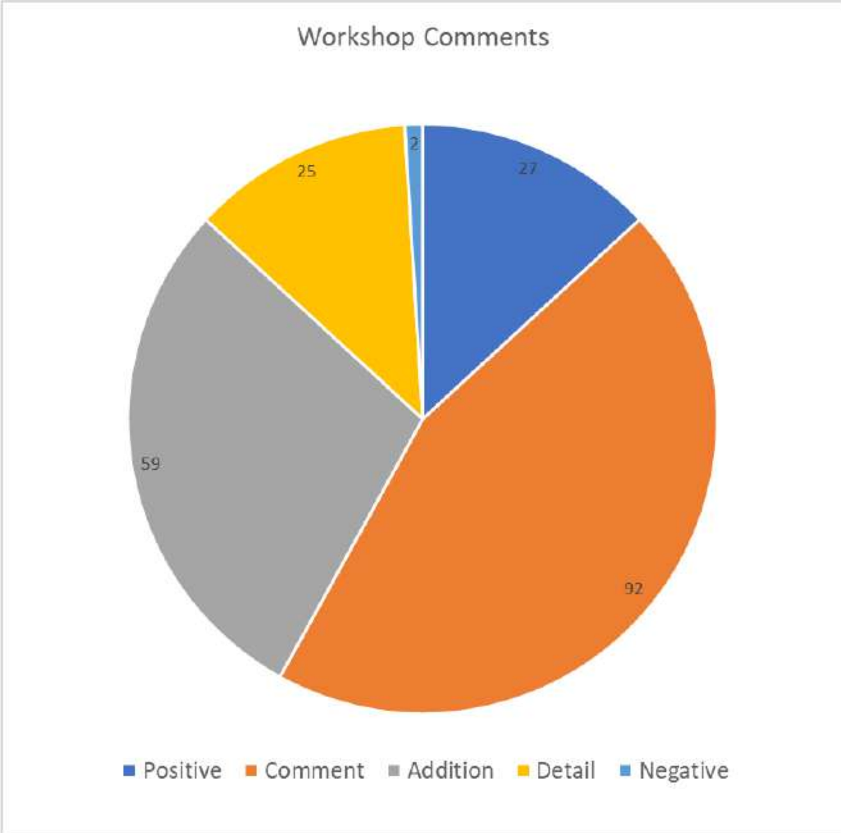

Figure 3: Summary of community workshop feedback

2.4 Selection of CSQs for linking to geophysical observables, and high-level gap analysis

At the point of the community consultation workshop, 57 CSQs were under consideration. It was recognised that this needed to be reduced to a smaller number to meet the requirements set by ESA for the study, to provide more focus for the inputs to the strategy and to make next steps of the work more manageable by reducing the large number of CSQs and associated observations to deal with. The consolidation of the CSQs to a smaller number was driven by the following:

1. Overall feedback from the workshop discussion that cross cutting issues related to methods, EO sampling, cal/val etc were important and worthy of consideration in the policy, but not necessarily the basis for the CSQ which should be more science process oriented.
2. Specific feedback from the briefing meeting held with ACEO following the community workshop where there was agreement that the focus for the CSQs should be based on the following questions:

   a. Where are benefits to society inhibited by lack of scientific understanding of Earth system processes?
   b. Where is understanding/discovery of Earth system processes inhibited by lack of appropriate Earth observation data and related innovation?
3. Insight from the project team, including detailed consideration of possible overlaps between CSQs where CSQs or KAOs could be merged, and giving consideration to the overall portfolio of the CSQs.
4. Practicality: considering the need in the next step in the process to assign specific geophysical observables to the CSQ.

As a result of this assessment 22 CSQs were selected for detailed analysis of geophysical observation requirements. The coverage of the selected science questions was checked against the ESA EO science community domains of interest to ensure a balanced portfolio. *Prior* to the consolidation each CSQ had been tagged with a flag to indicate relevance to each of the Earth system science domains that had been used as a basis for the previous two ESA EO science strategies (Cryosphere, Solid Earth, Ocean, Land Surface, Atmosphere). The occurrence of the classic domains within the CSQs before and after consolidation is shown below. Note that many of the CSQs are linked to more than one classic domain, so the totals add up to more than 22.

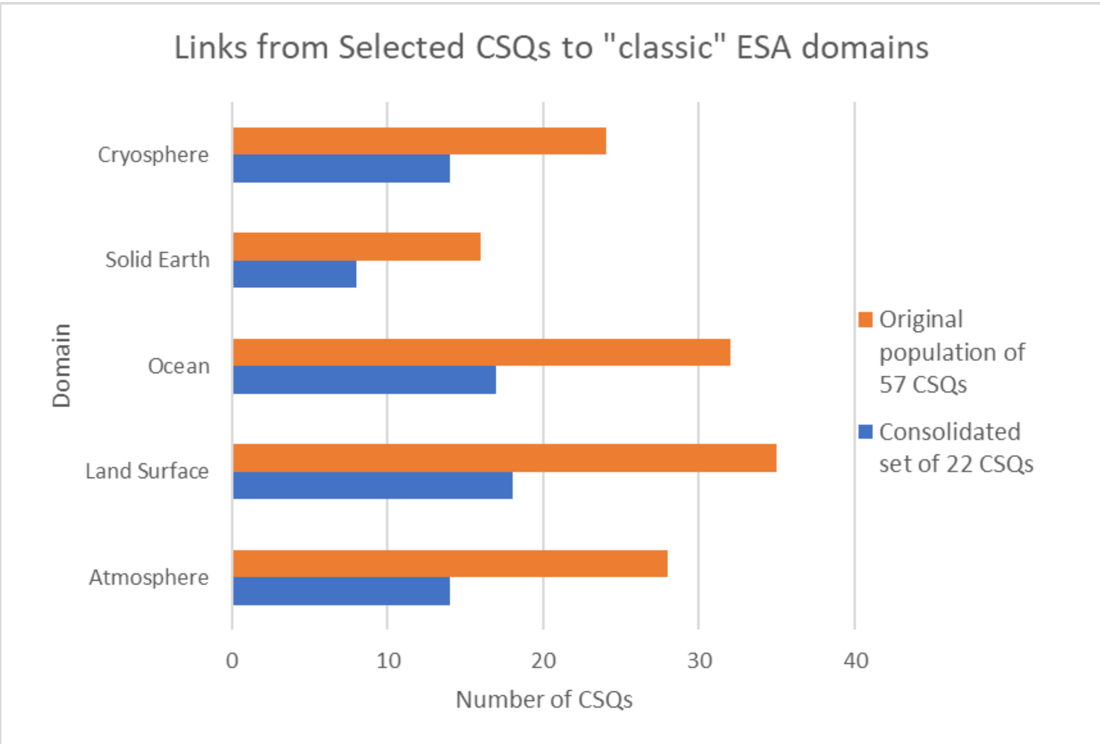

Figure 4: Distribution of CSQs across classic domains

2.5 Tracing from CSQs to geophysical observables, instruments and missions

For each of the 22 CSQs selected, summary specification sheets were completed, including identification of the most important geophysical observables required to make progress on the Science Question. Geophysical observables were identified as:

Critical: A Geophysical Observable that is uniquely enabling to address the CSQ above and beyond current capabilities.

Supporting: Other Geophysical Observables which are ancillary to those above which are assumed to be routinely available.

These required observables were mapped onto the capabilities of existing and planned EO satellites to provide an indication of where gaps in provision may exist.

Full details of this process, and the results are contained in a separate deliverable (R-1).

3 SUMMARY OF CSQS AND OBJECTIVES

3.1 Format of the CSQs

Each of the CSQs is expressed as a brief narrative, and a summary table of the main characteristics and observable requirements. The summary table includes the following elements:

1. The concise CSQ text.
2. One or more "Knowledge Advancement Objectives": Specific objectives, for example for process understanding or reducing uncertainties, through which progress towards resolving the question could be measured.
3. Geophysical Observables: identification of the geophysical variables needed to advance the science. These are divided into priority observations and supporting observations. Where possible, the Geophysical Observables are linked via reference numbers to CEOS database.
4. Measurement Specifications: specification of the science requirements for datasets providing the geophysical observables.
5. Tools and Models: beyond EO derived observations, what else is needed. These could be new retrieval algorithms, new data-model assimilation techniques, calibration/validation facilities etc..
6. Policies & Benefits: a brief link to the key societal benefit and policy areas that the CSQ's service. This aspect will be elaborated on in more detail later in the study.

3.2 CSQ and Objective index

This section contains an index of the Candidate Science Questions and their associated Knowledge Advancement Objectives. All 57 CSQs are included in the table, with the subset of 22 selected for detailed analysis flagged in the final column. The detailed text of the 22 CSQs is contained in Appendix A, in numerical order. Please note that the CSQs have retained their original numbering throughout the project, so the CSQ numbers in this document are not contiguous.

CSQ Number	CSQ Text	KAO	Knowledge Advancement Objectives	Selected for specification of observables
1	What anthropogenic and natural processes are driving the global carbon cycle?	1A	Quantify CO_2 and CH_4 emissions from both anthropogenic and natural sources and CO_2 removals from natural sinks on spatial scales from individual facilities or field plots to regional and global scales on seasonal time scales.	YES
1		1B	Distinguish intense anthropogenic CO_2 and CH_4 point source emissions associated with fossil fuel extraction, transport and use and land use change from wildfires and weak, spatially-extensive sources (wetlands, permafrost melting, agriculture).	YES
1		1C	Quantify emissions and removals (fluxes) of CO2 and CH4 from managed lands on sub-seasonal time scales with the accuracy needed to quantify and distinguish long-term (decadal) changes from human activities (e.g., deforestation, intense agriculture) from those driven by disturbances (e.g., drought, floods, wildfire) or climate perturbations	YES
2	How has the land biosphere responded to human activity and climate change?	2A	Quantify changes and uncertainties in the distribution of land sources and sinks over different biomes and latitudinal bands, and identify human activities and climate variations driving these changes	YES
2		2B	Quantify the roles of climate change and natural (wildfire, droughts, wind, pests) and human disturbances (land use change, wood harvest, illegal logging) on the land carbon sink	YES
2		2C	Quantify above ground biomass (AGB) in tropical and extratropical forests to the accuracy needed to resolve changes in stocks on sub-decadal time scales	YES
2		2D	Catalogue the impacts of climate change on crop health and forest mortality across different biomes and hotspots of change	YES

3	How has the ocean carbon cycle responded to anthropogenic CO2 and climate change?	3A	Track changes in ocean uptake and removal of CO2 associated with changes in atmospheric CO2 concentration, sea surface temperature, ocean transport and biological productivity at 1°x1° resolution over the globe.	YES
3		3B	How is the Southern Ocean CO2 sink responding to climate perturbations and long-term climate change.	YES
3		3C	What is the impact of human activities and climate change on coastal processes that regulate the carbon sink, including river runoff, upwelling and biological productivity?	YES
4	How do interactions between climate change and local human activities impact coastal vulnerability and resilience?	4A	Quantify the vulnerability and resilience of coastal environments to climate change	NO
4		4B	Quantify the vulnerability and resilience of coastal environments to local human activities	NO
4		4C	Understand interactions between climate change and local human activities and their combined impacts on increasing or reducing coastal vulnerability and resilience	NO
5	What processes drive changes sea level in the coastal ocean?	5A	Reduce uncertainties in observing, modelling and forecasting of water levels in coastal, estuarine and inland water bodies	YES
5		5B	Characterise the relative contributions to coastal sea level changes by steric and other physical processes including freshwater runoffs, vertical land motion (e.g. tectonics, post-glacial rebound), ice mass changes and associated gravitational effects	YES
6	How do extreme marine weather events impact coastal areas and how is coastal vulnerability changing in response to climate change?	6A	Characterise the magnitude, spatial distribution and occurrence of extreme marine weather events in the global coastal zone	NO
6		6B	Evaluate the vulnerability of coastal environments to extreme marine weather events in the global coastal zone	NO
6		6C	Quantify changes in extremes and associated impacts on coastal regions	NO
7	How do coastal processes mediate exchanges	7A	Determine the physical processes that control land-air-sea exchanges in coastal regions.	YES

7	between land, atmosphere and the open ocean ?	7B	Determine the interactions between physical and biogeochemistry processes and marine productivity in the global coastal ocean.	YES
7		7C	Reduce uncertainties in the global coastal ocean contributions to global land-air-sea fluxes of heat, nutrients, carbon, gases, and freshwater.	YES
8	How are coastal areas contributing to the global carbon cycle, and how are they responding to climate change and human pressures?	8A	Global inventory of Blue carbon ecosystems, including mangroves, tidal marshes and seagrass beds	YES
8		8B	Determine the extent of permafrost degradation and organic carbon releases in the polar coastal ocean	YES
8		8C	Determine contribution and drivers of change in “Blue carbon” ecosystems, and their resilience to human and climate change pressures in different coastal regions	YES
8		8D	Determine contribution and drivers of change in permafrost in the polar coastal ocean, and its resilience to human and climate change pressures in different coastal regions	YES
9	What are the characteristics of the processes related to climate extremes and the hazards related to them?	9A	Quantify how climate change is affecting large scale circulation patterns and extreme events linked to them, including magnitude, frequency and spatial distribution	NO
9		9B	Improve understanding of feedback mechanisms of extreme events in local and regional scale, including aerosol effects, albedo effects, land-atmosphere and land-ocean feedbacks.	NO
9		9C	Quantify the effects of extreme climate events on agriculture and food production in short and long term	NO
9	What are the characteristics of the processes related to climate extremes and the hazards related to them?	9D	Quantify the effects of extreme marine heat waves on marine ecosystems	NO
10	How can we improve the characterization and	10A	Characterize and quantify risks related to heat waves and linked compound effects including droughts and fires	NO

10	preparedness for risks related to compound climate extremes?	10B	Characterize and quantify risks related to flooding and heavy precipitation in specifically vulnerable areas like coastal area	NO
10		10C	Characterize processes, environmental conditions related to extreme air quality events, like haze formation and serious air pollution events during heat waves	NO
10	How can we improve the characterization and preparedness for risks related to compound climate extremes?	10D	Quantify environmental, social and economic hazards and impacts linked to climate extremes in local and regional scales.	NO
11	How can we improve early warning of extreme events and climate hazards?	11A	Characterize the vulnerability of societies on climate extremes in different spatial and temporal scales, considering also compound effects	NO
11		11B	Improve long-range (e.g. seasonal) weather forecasting systems to identify potential high risk extreme events and develop automatic early warning systems	NO
11		11C	Improve understanding of weather and climate phenomena that lead to extreme events. Utilize this information for early warnings of high risk for climate extremes	NO
13	Would it be of value to develop a system of systems while combining different types of satellites under different orbit constellations to advance monitoring capacities (e.g., diurnal cycle, higher resolution)?	13A	Diurnal cycle of essential climate variables	NO
13		13B	Increase the horizontal resolution and the revisit time	NO
14	What are the main issues with calibration-validation, absolute calibration, long-term monitoring?	14A	To obtain calibrated data in absolute values	NO
14		14B	To monitor the long-term evolution of ECVs	NO

15	Which specific observations are needed: polar / tropical regions, new measurement techniques vs long-term series of observation, large-scale field experiments?	15A	To follow the evolution of ECVs in regions more sensitive to climate changes: e.g., polar regions, upper-troposphere-lower stratosphere (UT-LS)	NO
15		15B	Monitoring of specific events: e.g., earth quakes, volcanic eruptions, flooding	NO
15		15C	Focus of specific areas: e.g,. cities, regions of high anthropic emissions	NO
15	Which specific observations are needed: polar / tropical regions, new measurement techniques vs long-term series of observation, large-scale field experiments?	15D	To organize a large-scale field experiment to study a specific region for understanding the physical processes taking place	NO
16	How to develop the link with other communities	16A	How EO observations can help to improve the models	NO
16		16B	What Artificial intelligence can bring to EO science?	NO
16		16C	How socio-economic aspects are considered taken in the EO strategy?	NO
17	How is the resilience of key Earth System components changing under multiple anthropogenic pressures?	17A	Quantify changes in resilience of the Amazon and other key biomes that might signal approaching or crossing of tipping points	NO
17		17B	Quantify changes in ecosystem function and vitality due to climate change and more extreme events	NO
17		17C	Quantify trajectories in seasonal sea-ice cover in the polar regions towards approaching a tipping point	NO
18	How can we attribute recent trends in Earth System components to anthropogenic activity	18A	Quantify the effects of deforestation and management in modulating the resilience of global ecosystems to weather extremes and climate change	NO
18		18B	Identify the role of natural climate variability in recent trends in forest disturbances and mortality	NO

20	What are the key drivers for the mass balance change of the ice sheet, the ice shelves and the glaciers?	20A	Improve the quantitative estimation of change and variability in the key components of the cryosphere, including: • Ice sheet mass balance • Ice shelf mass balance • Glacier area and volume and mass balance	YES
20		20B	Strengthen the quantitative understanding of the regional pattern of change and variability in ice mass loss.	YES
21	What are the dominant physical processes that drive the sea ice thermo-dynamic state and variability	21A	Quantify the impacts of a declining sea ice field on the interaction between the atmospheric boundary layer and the upper ocean.	YES
21		21B	Determine how dominant processes differs between the two Polar regions. Is the strength and extent of the sea ice cover imposing blocking effects on ice shelve surge?	YES
22	What are the cycles of variability for cryosphere essential variables, and how large are they?	22A	Determine what the cycles of variability are for cryosphere essential variables.	NO
22		22B	Quantify the magnitude of variability, e.g. diurnal, weekly, monthly, seasonal, annual and decadal	NO
23	What is the impact of extreme weather events on the Polar regions?	23A	Measure the impact of extreme weather events on the Polar regions, both in the short term (seasonal to annual), and over the long term (impact on long-term decadal trends).	NO
24	Determine the relationship between changes in Polar regions and global climate variability	24A	Determine what impact the polar regions have on global climate variability.	YES
25	How does the cryosphere impact on Polar	25A	Determine the impact of the cryosphere on Polar ecosystems, such as through freshwater input to the ocean	YES

25	ecosystems, and how is the changing climate altering these feedbacks?	25B	Measure how change in the polar regions is impacting these feedbacks, e.g. through nutrient cycling and primary productivity.	YES
26	What are the next generation of satellite data products for the Polar regions that will be generated through AI and ML?	26A	Develop new methods and datasets using deep learning techniques to deliver the next generation of Earth observation information.	NO
27	What is the size of anthropogenic impact on change in the Polar regions?	27A	Quantify the size of anthropogenic impact on the Polar regions.	NO
28	Are there tipping points/elements in the climate system not yet identified?	28A	Identification of all potential tipping elements in the climate system, including those currently assumed as potential or even unlikely	NO
28		28B	Association of potential tipping elements that can be activated together (cascade effects)	NO
28		28C	Identification of Extreme Events and Planetary Boundaries that can be indicative of potential tipping points	NO
28	Are there tipping points/elements in the climate system not yet identified?	28D	Discard phenomena that can lead to false positives towards the identification of tipping points	NO
29	Can we better quantify the temperature thresholds, time scales, and impacts of identified tipping points?	29A	Characterization of temperature thresholds for currently established tipping points	NO
29		29B	Characterization of time scales for currently established tipping points	NO
29		29C	Characterization of geographical extend of the impacts for currently established tipping points	NO

29	Can we better quantify the temperature thresholds, time scales, and impacts of identified tipping points?	29D	Identification of potential cascade effects in the coupling of multiple tipping points	NO
30	Are the limitations in predicting climate tipping points driven by lack of process understanding or limited data availability?	30A	Identify those tipping points where predictive capabilities are limited by lack of process understanding	NO
30		30B	Determination of experiments and activities needed to advance the understanding for such tipping points limited by lack/incomplete process understanding	NO
30		30C	Identify those tipping points where predictive capabilities are limited by lack of appropriate data	NO
30		30D	Determination of datasets and observations needed to advance the understanding of such tipping points	NO
31	What are the physical / mathematical mechanisms that generate the behaviour of tipping points in climate models? Can models be improved using more precise observations?	31A	More detailed modelization of the physical / mathematical mechanisms leading to tipping point behaviour	NO
31		31B	Sensitivity analysis of model input variables to predict tipping point behaviour	NO
31		31C	Identification of variables used by models not yet provided in spatial maps but only from punctual ground measurements	NO
31		31D	Identification of specific aspects in the climate models that can be improved by using more precise, focused or dedicated observations	NO
32	Where are the alerts (pointed out by predictive models) where observations can be focused, and how can observations be guided to verify the trends to tipping points indicated by the models?	32A	Identification of the alerts pointed out by predictive models, and the associated geographical extension and temporal scales of each alert	NO
32		32B	Identification of observations explicitly oriented to verify specific trends suggested by the models	NO
32		32C	Exploitation of current available time series and datasets to validate model behaviour at the associated spatial scales	NO
32		32D	Usage of guided observations to reduce uncertainties in model predictions	NO

33	How does the solid Earth deform under present and past ice loads and what does it tell us about its rheology ?	33A	Quantify the long-term GIA signal of the Pleistocene deglaciation in ice sheet elevation and gravity field in regions of present-day ice caps melting, and separate it from contributions reflecting ice sheet imbalance and from GIA responses to the Little Ice Age	YES
33		33B	Quantify the solid Earth visco-elastic response to recent or contemporary ice mass change in glaciated regions associated with low mantle viscosity, such as active plate boundaries	YES
33		33C	Constrain the radial and lateral viscosity structure of the mantle (including in particular low viscosity layers and lateral variations between cratonic and oceanic areas or along hotspot tracks), from data-driven GIA models integrating a broad range of data types. In these models, describe the trade-offs between mantle structure and spatio-temporal evolution of the past ice load	YES
34	How do active faults respond to stress perturbations associated with the water cycle, and what are the relative contributions of climate extremes and human activities ?	34A	Quantify and locate changes in groundwater storage at daily to weekly timescales and high spatial resolution, as well as the associated spatial variations of aquifer storage parameters. Discriminate these deep water mass changes from those of the shallow hydrological components	NO
34		34B	Estimate crustal deformations and stress field perturbations due to groundwater and shallow water mass changes, and assess the impact on the seismicity. Compare results in contexts of extreme climatic events, or in areas subject to human pumping	NO
35	Can we quantify erosional processes of drainage basins and the resulting sediments discharge to the oceans	35A	Quantify the long-term present-day sediment discharge to the oceans, and locate modern sedimentation zones, at the mouth of major rivers. An objective could be to resolve accumulations of ~0.5 cm year -1 of sediment at 200-km spatial resolution, close to the highest river discharges (Amazon, Ganges-Brahmaputra, Yangtze, ...).	YES

35		35B	Resolve large variations in sediment discharge following typhoons and El Nino events. So far only accumulated sediment over long time periods could be considered, in order to build up enough mass to be detected by GRACE. With a higher sensitivity, the detection of temporal variations in sediment discharge might be considered.	YES
35		35C	Quantify sediments loss in mountainous areas	YES
36	Can we observe, model and forecast the deformation processes during the seismic cycle at plate boundaries, from pre- to post-seismic phases and during the inter-seismic phase ?	36A	Identify and delineate the locked versus the creeping segments of plate boundaries, and monitor inter-seismic strain accumulation, by accurately measuring the surface deformations of the plates around major boundaries.	YES
36		36B	Document the spatio-temporal characteristics of transient aseismic events in subduction systems.	YES
36		36C	Document the possible existence of a short-term preparatory phase for earthquakes.	YES
36		36D	Quantify the co-seismic slip distribution and discriminate between early rupture models.	YES
36		36E	Assess the relative contributions of localised vs distributed deformations at depth along the plates interface and in the surrounding mantle during the post-seismic phase, in order to quantify the stress redistribution along plate boundaries after an earthquake.	YES
37	Can we estimate the tsunami potential of an earthquake in real-time ?	37A	Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events. Assess the tsunami potential of an earthquake in real time.	NO
37		37B	Monitor trans-oceanic propagation of tsunamis, estimation of the wave height and propagation speed from the ionosphere	NO

38	How does Earth's crust evolve in interaction with internal geodynamic processes, and how does this reshape the Earth's surface over the long-term?	38A	Quantify the long-term, present-day changes in Earth's surface and Moho topography due to processes of creation, evolution and destruction of Earth's crust : mountain building, long-term plate subduction, oceanic spreading, extensional tectonics.	YES
39	What is the nature of the mantle heterogeneity and the character of its convection at all depths ?	39A	Map the 3D variations in the physical properties of the Earth's interior, with a high spatial resolution globally : seismic velocities, densities, viscosity, electrical conductivity	NO
39		39B	Quantify the present-day 3D structure of the Earth's mantle, in terms of temperature, composition and melting	NO
39		39C	Interpret this present-day structure in terms of dynamical processes, that govern the circulation of heat, materials and volatiles between the surface and the top of the core.	NO
40	What is the dynamics of the fluid outer core at short timescales, and how is it coupled with the mantle ?	40A	Improve the separation of the internal and external sources of the magnetic field measured by satellites. In particular, separate core signals from those generated by electrical currents in the ionosphere, and from induced secondary fields in the conducting mantle, at high spatial and temporal resolutions	NO
40		40B	Quantify the screening effect of the conducting mantle on core field signals measured by satellites, from the mapping of the 3D variations of the electrical conductivity of the mantle.	NO
40		40C	Resolve the geomagnetic signatures of periodic motions at sub-decadal timescales in the core flows, and constrain the corresponding rapid core dynamics.	NO
40		40D	Assess whether and where the regions near the core-mantle boundary are stably stratified or not, and the impact on the core flows.	NO
40		40E	Assess the impact on core flows due to mantle heterogeneity and spatial or spatio-temporal variations in core-mantle boundary topography	NO
41	How does soil status control Earth system	41A	Quantify surface soil hydraulic and thermal properties	NO
41		41B	Soil moisture profile as control of photosynthesis rates in vegetation canopies	NO

41	cycles and influence surface-air exchange processes?	41C	Quantify impacts of surface soil moisture and that of rooting depth soil moisture on surface-air exchanges	NO
41		41D	Quantify the contribution of latent heat flux from bare soil and canopy to total surface-air exchanges, as well as that of groundwater level	NO
42	To what extent can we predict the Earth's water cycle closure in space and time?	42A	Reservoirs: Quantify the rate of expansion of the fast and slow reservoirs (atmospheric water vapor in the troposphere and stratosphere; storage on the land surfaces and in the oceans), its spatial character, its determinant factors and the extent of its predictability	NO
42		42B	Flux exchanges: Quantify fluxes of water between Earth's main reservoirs in space and time and their predictability (precipitation, evaporation, water vapor convergence and surface and groundwater discharges)	NO
42		42C	Extremes in precipitation and floods: Quantify the changes in local rainfall and its extremes under climate change across the regions of the world and the associated flood extremes (frequency, extent and severity)	NO
43	What are the main coupling determinants between Earth's energy, water and carbon cycles? How accurately can we predict the forcings and feedbacks between the different components of the Earth system?	43A	Quantify the relationships between Earth's energy, water and carbon cycles: a. Identify the main climate forcings and feedbacks formed by energy, water and carbon exchanges; b. Quantify response of terrestrial photosynthesis to changes in temperature, CO_2 concentration and water stress; c. Reduce uncertainty estimates of fluxes (sensible, latent heat, and carbon fluxes – Gross Primary Productivity and Net Ecosystem Exchange) to < 10% uncertainty (currently 20%)	YES
43		43B	Quantify the role of surface and upper troposphere - lower stratosphere (UTLS) forcings in atmospheric boundary layer (ABL) processes: Quantify the role of sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere (i.e., horizontal advection and UTLS exchanges).	YES

43		43C	Quantify circulation controls: Quantify the influence of large-scale atmospheric and oceanic circulations on exchanges between water, energy and carbon.	YES
43		43D	Quantify land-atmosphere interactions: Identify the roles of atmosphere-land surface interactions in the water, energy and carbon budgets across multiple spatiotemporal scales.	YES
44	How important are anthropogenic influences on the water cycle, and how accurately can we predict them?	44A	Quantify anthropogenic forcing of continental scale water availability: Quantify extent to which the changing greenhouse effect modified the water cycle over different regions and continents.	YES
44		44B	Detect water management influences: Determine extent to which water management practices and land use changes (e.g., deforestation) modified the water cycle on regional to global scales.	YES
44		44C	Quantify variability and trends of water availability: Quantify effects of water and land use and climate changes on the variability (including extremes) of the regional and continental water cycle	YES
45	How can we reduce the uncertainties in the surface energy budget while improving the estimate of the internal flow within the climate system?	45A	Reduce uncertainties of regional energy fluxes: Quantify and reduce regional uncertainties of surface observations, retrievals of energy fluxes, and their parametrisations	YES
45		45B	Study of cumulative regional cloud feedbacks, weighted by the global ratio of fractional coverage to evaluate the global cloud feedback	YES
45		45C	Study the causality in aerosol–cloud relationships, particularly for anthropogenic perturbations	YES
46	How does the Earth energy imbalance and Earth heat inventory change over time and why? And what can we	46A	Earth heat inventory evaluation: Quantify how much surplus anthropogenic heat is going into warming the ocean, the land, the atmosphere and melting the cryosphere	YES

46	learn from this for the interplay between effective radiative climate forcing, Earth's surface temperature response and climate sensitivity, as well as its implication on Earth system change?	46B	Global energy budget closure studies: Investigate links between the global energy budget, planetary heating, effective radiative forcing, surface temperature response and climate sensitivity. Take stock of the long-term change in the Earth energy imbalance, and further tackle underlying uncertainties.	YES
46		46C	How does the Earth energy imbalance changes over time and why? Which are the implications of a changing Earth energy imbalance on changes in atmospheric warming, land warming and ice melt?	YES
47	How can we improve the detection of natural variations of the energy cycle and the attribution to anthropogenic long-term change, as well as our understanding on the interlinkage between major Earth	47A	Understand sources and drivers of temporal variations for components of the global energy budget relation linking planetary heating, effective radiative forcing, surface temperature response and climate sensitivity to understand the global interplay of natural variability versus anthropogenic change	NO
47		47B	Detection and attribution studies for the global energy budget relation, allowing also for systematic observing system recommendations for the monitoring of planetary warming to support decisions on climate change action and sustainable development	NO
47		47C	Identify and study feedbacks between climate change and the energy cycle, and between major Earth's system cycles	NO
48	How can we improve the monitoring and understanding of planetary heat exchange at regional scale? And which essential	48A	Identify, and improve understanding of, small-scale thermal air-surface feedback mechanisms Analyse critical surface-atmosphere thermal feedback mechanisms, particularly for small-scale processes (and variations), using high resolution observation-driven coupled atmosphere-ocean models, to improve weather and climate predictability.	YES

48	advancements can we achieve for research and monitoring on weather and climate patterns?	48B	Further advance knowledge on dynamics of extreme events such as heat waves, extreme precipitation, storms to improve prediction skills for early warning systems	YES
48		48C	Improved understanding of momentum and kinetic energy transfer between components of the Earth's system (ocean, atmosphere, cryosphere, land.	YES
49	Could we improve the observations of active boundary areas dynamics?	49A	Knowing better seismic cycles, both in spatial and time scale	NO
49		49B	improve systematic measurements of changes in topography associated to active tectonics	NO
49		49C	Improve the study soil gas change and isotopic signatures during seismic sequences	NO
50	How we could Improve The large-scale bathymetry of the deep oceans?	50A	Map Sea floor morphology at high spatial resolution <1km deep ocean <100 m coastal At global scale only the 17-18% is covered 1 km resolution	NO
50		50B	improve modeling of tsunami run-up and its impact on coastal populations.	NO
50		50C	Improve the systematic measurements of sea floor seismicity along marine active faults	NO
51	What are the mechanisms that couple the lithosphere, atmosphere and ionosphere, and can they be modelled and monitored with adequate	51A	Measure at high resolution the total electron content of the ionosphere	YES
51		51B	Improve the measurements of Atmospheric anomalies (short term)	YES

51	to support hazard risk management ?	51C	Measure short term atmospheric pressure waves triggered by earthquakes, explosions, volcanic eruptions, tsunamis	YES
52	How can we help predict a volcanic event through the detection of thermal transient phenomena, gas emissionis and surface deformation evidence	52A	Ability to estimate the changing magma supply volume and depth beneath volcanos via the changing in shape of the volcano and Expansion or contraction of the summit region	NO
52		52B	Assessment of surface vertical deformation extent and atmospheric contamination, and composition and temperature of volcanic products following volcanic eruption	NO
52		52C	Measurement of the composition and quantity of the gas emitted prior to and during an eruption as well as the composition of any ash.	NO
52		52D	Inference of changes at shallow depths as magma reaches the uppermost plumbing system prior to an eruption	NO
52		52E	Capturing transient behaviour in an ongoing eruption to model the vent-scale processes	NO
52		52F	Routinely monitor the of Earth's entire active land volcano inventory (pre-, syn-, and post eruption) surface deformation and products of Earth's entire active land volcano inventory.	NO
53	Can we map topography, surface mineralogic composition and distribution, thermal properties, soil properties/water content?	53A	Improve the detection of minerals species and which compose surface materials both in natural and urban environments (including waste deposits) Measure better resolution bare-earth topography at high spatial and vertical resolution (1 m) and measure surface deformations in areas of active mineral extraction	NO
53		53B	Improve the measurement of quality of soils which are very important ingredients for agriculture and ecology	NO
53		53C	Measure the composition of dust sources in atmosphere and AOD and particle size parameters analysis to sand/dust storms	NO
54		54A	Long-term, global land use and land use change monitoring	NO

54	How different drivers and threats effect the integrity of ecosystem?	54B	Monitoring direct exploitation patterns worldwide	NO
54		54C	Explore different approaches for monitoring environmental pollution and invasive alien species	NO
54		54D	Monitoring ecosystem integrity	NO
55	What are local patterns of ecosystem structure, composition and functions worldwide?	55A	Improve the characterization of ecosystems based on their structure	YES
55		55B	Improve the understanding of atmospheric anomalies and linkages between lower atmosphere through the middle and upper atmosphere	YES
55		55C	What is the current state of land ecosystems and their functions?	YES
56	Where and how are ecosystems undergoing critical transitions?	56A	Comprehensive assessment of ecosystem dynamics including the identification of critical changes in ecosystem resilience directly through monitoring disturbance frequency, impacts and recovery rates over time	YES
56		56B	Understanding links between vegetation characteristics and climate at relevant scales.	YES
57	How vegetation and climate interactions vary across scales?	57A	Linking vegetation characteristics to climatic conditions at detailed/plot level often monitored by ecologists	NO
57		57B	Scale from plot level (monitored by ecologists) to more macro-Earth System models to improve the monitoring the impacts of changing climates at the level of species and individual	NO
58	Are nature-based solutions delivering on multiple benefits?	58A	Monitoring the implementation and progress of different type of nature-based solutions including various activities of restoration (i.e. forests, peatlands), sustainable supply chains (for different commodities) and certification schemes	NO
58		58B	Monitor and assess the local and regional impacts considering different nature-based solution and different areas of “benefits” (i.e. climate, biodiversity, livelihoods)	NO
59		59A	Demonstrate the use of EO date for animal counting in different ecozones and types of fauna (i.e. large mammals, penguins, cows)	NO

59	How can we leverage EO data from tracking animal counts and behavior?	59B	New approaches for tracking animal behavior to understand species–environment interactions and for generating and analyzing animal movement data	NO

Table 2: Index of CSQs

A summary of the 22 CSQs selected for detailed assessment is shown in Table 3, which highlights the relevance of these CSQs to the Earth system domains used in previous ESA EO Strategies.

CSQ	Short Title	Atmosphere	Land	Ocean	Solid Earth	Cryosphere
CSQ-1	Anthropogenic influences on the carbon cycle	x	x			
CSQ-2	Land biosphere response to CC	x	x			
CSQ-3	Ocean carbon cycle responses to climate	x		x		
CSQ-5	Sea level change in the coastal ocean		x	x		
CSQ-7	Coastal interfaces with land atmosphere and	x	x	x		
CSQ-8	Coastal climate change feedbacks		x	x		
CSQ-20	Ice mass balance			x	x	x
CSQ-21	Sea Ice thermodynamics					x
CSQ-24	Polar change and climate variability	x		x		x
CSQ-25	Cryosphere and Polar ecosystems		x	x		x
CSQ-33	Ice sheets and rheology				x	x
CSQ-35	Erosion and sedimentation		x	x	x	
CSQ-36	Plate boundary deformation dynamics				x	
CSQ-39	Crust and internal dynamics interactions				x	
CSQ-43	Coupling between energy water and carbon	x	x	x		
CSQ-44	Anthropogenic influences on the water cycle	x	x			
CSQ-45	internal energy flux estimates	x	x	x		x
CSQ-46	Earth energy imbalance	x	x	x		x
CSQ-48	Regional planetary heat exchange	x	x	x		
CSQ-51	Lithosphere-atmosphere-ionosphere coupling	x			x	
CSQ-55	State of Land ecosystems		x			
CSQ-56	Land ecosystem critical transitions		x			

Table 3: Summary of 22 CSQs selected for detailed analysis

4 CSQ CATEGORISATION AND ASSESSMENT

4.1 Considerations for Strategy relevance

The criteria for assessment of the CSQs need to be selected in the light of ESA's requirements for the new EO Science strategy, bearing in mind the desired evolution of the strategy from previous iterations. In developing the criteria , the team considered the following factors.

Timescales for the future strategy
The lifetime for the next ESA EO Science strategy will be shorter than for previous strategies, recognising the accelerating pace of science, discovery and applications. This has implications for the implementation of the programme, and for the rates of progress of different programme elements. While major missions may take many years between idea and launch, smaller missions can be completed within a shorter timeframe. In addition, technology development for future missions must also be guided by strategic science priorities of a decade ahead, when missions to address these priorities may be feasible. On an even shorter timescale, exploitation of ongoing missions and available data require in some cases novel approaches to addressing questions of raised priority.

Scope of activities the strategy has to address
The identification, refinement, selection and implementation of new (Earth Explorer) missions represents an important key focus of ESA's science strategy, and the envelope programme has delivered significant success , scientific progress and impact through this mechanism. But the science strategy has to support a range of other actions including R&D on new techniques to extract information from existing data, early phase mission concept science, and international collaboration to name a few. The CSQs should therefore include objectives that require a range of different programmatic actions to progress them, including new mission concepts, specific R&D on TRL advancement; research on algorithms, retrievals and data assimilation.

Science Excellence
The recent independent review of ESA's EO science programme has confirmed the need to ensure that excellent, innovative and challenging science is the main driver for ESA´s future EO activities. A key priority for the portfolio of CSQs is therefore identify the most critical areas where EO can contribute in the coming decades, and make a significant impact. This factor has been further emphasised in the discussions during the community workshop, and with ACEO, that the focus of the CSQs should be on critical areas of Earth system process understanding.

Significance of societal benefits and policy frameworks
EO science does not exist in isolation. There is a continuing and increasing need to demonstrate the benefits of investment in EO science to society. These benefits come through a range of means, including the increasing need and ability to manage and protect our environment through a better understanding of the dominant multidisciplinary interactive processes within the Earth system; and through the spin-off benefits where data designed for science can be employed in operational environmental monitoring to support policy implementation or management. The CSQs must therefore include elements where clear policy and societal benefits can be delivered

The role of ESA
ESA plays a leading role internationally in promoting and delivering EO science capacity in terms of observations, data, information products and R&D outputs and tools. However, it does not act in

isolation and other international agencies, individual countries and indeed commercial organisations are continuing to develop innovative new missions, data and information products that meet scientific, operational and commercial needs. CSQs must therefore help identify areas where ESA can contribute most effectively.

4.2 Assessment criteria

With these requirements in mind, a set of criteria has been established against which to assess the CSQs. These criteria, and associated guidance on their application, are described in the following table.

Category	**Justification**	**Scoring Criteria**
1. Novel / discovery science	Innovative / blue-skies science that is groundbreaking / technologically challenging. can best be addressed via multilateral cooperation through ESA.	**High Score:** Answering the question would deliver fundamentally new knowledge or help to quantify processes, fluxes or stores that are unmeasured, or have large or poorly understood uncertainties. **Low Score:** The science is derivative – delivers incremental gains in already well understood processes.
2. Policy relevance and benefits, and risk reduction	Clear benefits to society are an increasingly important driver to the ESA strategy. Need to support greater confidence in actions by governments the private sector and individuals	**High Score:** Makes a unique or leading contribution to an area of societal benefit that is significant in scope, economic impact, or risk. EO data plays a unique or very significant role in delivering **Low Score:** The societal or policy relevance of the CSQ is minimal or marginal. EO data makes a minor contribution alongside several other actions by other parties.
3. Scope to reduce critical knowledge gaps in the next 5-6 years	The updated EO science strategy will have a horizon of 5-10 years, with the associated need to demonstrate significant progress within the first 5-6 years.	**High Score:** Demonstrable progress can be made on specific and scientifically / societally important objectives through R&D and technology development (including with AI/ML) that exploits existing or planned data, particularly from the ESA science programme. **Low Score:** Progress can only be achieved in the long term, possibly because entirely new missions would be needed that are not currently planned
4. Potential to fill critical observation gaps through innovation in space technology	Filling critical observation gaps through technology development is fundamental to the ESA EO programme.	**High Score:** Represents a critical knowledge gap and advancement is critically / uniquely dependent on new EO technologies. Technology development needed for CSQ progress could result in new operational observations in the long term. **Low Score:** Criticality of knowledge gap is low and / or existing data and instrument types are adequate to make progress. Or, conversely, required measurements cannot feasibly be made from space.

Table 4: CSQ Assessment categories

4.3 Assessment of policy Relevance

The assessment of policy relevance was a specific requirement of the study and hence has been given particular emphasis. This section describes the process of scoring CSQs according to their relevance to international and national policy making. The scoring is used to rank the CSQs accordingly to policy relevance in order to feed into the overall assessment of CSQ importance to the future ESA EO Science Strategy.

Policy domains were divided into (i) International treaties and agreements and (ii) National policy domains (see Table 5 and Table 6). This allows for connection to be made at the various level of policy decision making and to include important areas of national policy not covered by international treaty.

4.3.1 International agreements and treaties

Table 5 shows the Agreements/Treaties assessed. Each policy domain is broken down by key policy goals or objectives that act as the link to CSQs. For the Paris Agreement and CBD, we use the Articles of each Convention following Heggelin et al. The UN Sustainable Development Goals are well known as are the priorities for the Sendai Framework on Disaster Risk Reduction. The EU Green Deal is defined here as an international treaty due to its multinational applicability. It is a wide-ranging policy framework encompassing climate change action, biodiversity/ecosystems, agriculture, air quality and other domains linked to sustainability and human wellbeing.

Treaty/Agreement	**Policy goals/objectives**
Paris Agreement (following Heggelin et al)	Article 4. Mitigation (incl Climate state and Climate sensitivity) Article 5 Maintaining sinks and reservoirs (incl land/biosphere and ocean) Article 7 Adaptation Article 8 Minimizing loss and damage Article 12 Public engagement Article 13 Enhanced Transparency Framework Article 14 Global Stocktake
Convention on Biodiversity (CBD)	Article 6. General Measures for Conservation and Sustainable Use Article 7. Identification and Monitoring Article 8. In-situ Conservation Article 9. Ex-situ Conservation Article 11. Incentive Measures Article 13. Public Education and Awareness
UN Sustainable Development Goals (SDGs)	SDG1 No poverty SDG2 Zero hunger SDG3 Good health & wellbeing SDG4 Quality education

	SDG5 Gender equality SDG6 Clean water, sanitation SDG7 Affordable, clean energy SDG8 Work & economic growth SDG9 Industry, innovation SDG10 Reduced inequalities SDG11 Sustainable cities SDG12 Climate action SDG13 Life below water SDG14 Life on land
Sendai Framework on Disaster Risk Reduction	Priority 1: Understanding disaster risk Priority 2: Strengthening disaster risk governance to manage disaster risk Priority 3: Investing in disaster risk reduction for resilience Priority 4: Enhancing disaster preparedness for effective response
EU Green Deal	Net Zero by 2050 (incl Climate Law) Clean, affordable, secure energy Circular economy Energy efficiency Zero pollution Ecosystems and biodiversity (incl EU Taxonomy) Farm to fork' sustainable food system Sustainable mobility

Table 5. International treaties/agreement and related policy goals/objectives

4.3.2 National policy domains

National policy domains shown in Table 6 have been chosen to reflect a range of relevant policy areas common to modern democratic nation states. While the international treaties/agreements often form the backdrop to policy making in these areas, national policy making is sovereign and often markedly different from one nation to another. For instance, nations that are party to the Paris Agreement are free to determine how their own national GHG inventories are defined and reported. Similarly, while some areas of the EU Green Deal are binding, others are not. This list of policy domains is not meant to be exhaustive but representative of the major areas of policy with relevance to EO science.

In each policy area, an attempt has been made to identify the key sub-domains, targets and objectives. describes these areas.

Policy domain	Policy goals/objectives/sub-domain
Energy	Net Zero Transition Reducing emissions Energy security Managing energy demand Transition risk
Environment	Air quality Nature and biodiversity Marine and coastal environment Urban environment Water Soil and land
Agriculture, fisheries and food security	Farm to fork emissions Food security Sustainable Fisheries Increased production
Transport and infrastructure	Land transport Maritime transport Air transport Infrastructure
Civil protection and humanitarian assistance	Understanding disaster risk Enhanced preparedness Increasing disaster risk resilience
Public health & wellbeing	Vector borne disease risk Temperature and humidity related Respiratory disease

Table 6: National policy domains and related policy goals/objectives

4.3.3 Linking CSQ to policy areas

We use a modified version of the Onoda and Young model for describing the EO-policy interface as summarised in Table 7. In addition to the existing role of Inform-Assist-Comply, we add a role called 'Evaluate' wherein scientific evidence can be used to evaluate impact of policy responses.

For our purpose, this model is used to identify 'relevance' to the policy domain. The output of a CSQ can be deemed relevant if it provides knowledge, data or tools to 'inform' policy and policy options, 'assist' policy delivery, ensure 'compliance' with regulations and 'evaluation' of the impact of any enacted policy response.

Evaluation of policy relevance is based on published evidence or professional opinion of the study team.

Policy role	Description	Example contribution
Inform	EO science to inform policy debate through provision of knowledge, understanding and evidence. Includes *identifying*, *monitoring* and *assessing* global environmental issues.	Further understanding regarding drivers and constraints affecting global terrestrial and ocean GHG sinks and reservoirs required for Art 4/5 of the Paris Agreement (SQ1); Increased understanding of processes driving climate sensitivity will be a direct contribution to Art.4 of the Paris Agreement (SQ45); Art.6/7 of the CBD concerning conservation options and means to monitor global biodiversity require improved knowledge of ecosystem function and responses to climate change (CSQ2,5,25,55,56).
Assist	Supporting society address environmental issues, reduce loss of life, etc	Combination of improved understanding of hydrometeorological processes and understanding of coastal flood risk will assist reduction of loss to life and property (CSQ5,44); Advancing understanding of geophysical processes will aid our ability to model and assess risk of loss from hazardous events (CSQ33,35,38).
Comply	Enforcement of policy outcomes/legislation	Improved ability to model and monitor sources and sinks of GHGs will support verification of commitments to meeting Net Zero (CSQ1,2); Compliance with aims of CBD will be aided by better understanding of the extent, condition and dynamics of critical ecosystems (CSQ2,25, 55,56).
Evaluate	Assessment of the outcomes of specific policy decisions	A variety of policy commitments at national and international scale will require global monitoring and interpretation; Example include Net Zero policies (CSQ1,2,3,8,20,45,48,56), voluntary carbon markets (CSQ1,2,55,56), zero deforestation (CSQ55,56) and efforts to reduce risk exposure and loss (CSQ5,33,35,38,44).

Table 7: Framework for defining relevance of EO science to policy needs (modified version of Onoda and Young model[1])

4.3.4 Assessment

A basic scoring regime was applied to the relevance of each CSQ to a policy domain. If a CSQ is deemed relevant, it gains a score of 1 immediately. That score could be increased to 2 or 3 depending on the quality of the contribution made. The quality of the contribution depends on two factors, (i) the directness of the contribution and (ii) uniqueness of the contribution where:

Directness

- Direct = Clear and direct link between observation/science output and policy application
- Indirect = Observation/science only indirectly linked to policy application eg via modelling or integration with other datasets.

Uniqueness

- Complementary = CSQ contribution one of many inputs to policy process
- Unique = CSQ contribution is the sole or dominant input to policy process

The scoring chart is as follows:

[1] Onoda, M. and Young, Oran R., Satellite Earth Observations and Their Impact on Society and Policy, 2017, p14.

Scoring	Direct	2	3
	Indirect	1	2
		Complementary	Unique
		Uniqueness	

A matrix of the 22 CSQs was created against each policy domain/sub-domain. A score was given for each cell in the matrix. These score were then accumulated for each CSQ. The scores were then ranked and given a relevance score inversely related to rank (i.e. highest scores were given to the highest ranked CSQs).

International Treaty heatmap

This figure shows the results of the policy relevance mapping between CSQs and the international agreements/treaties assessed.

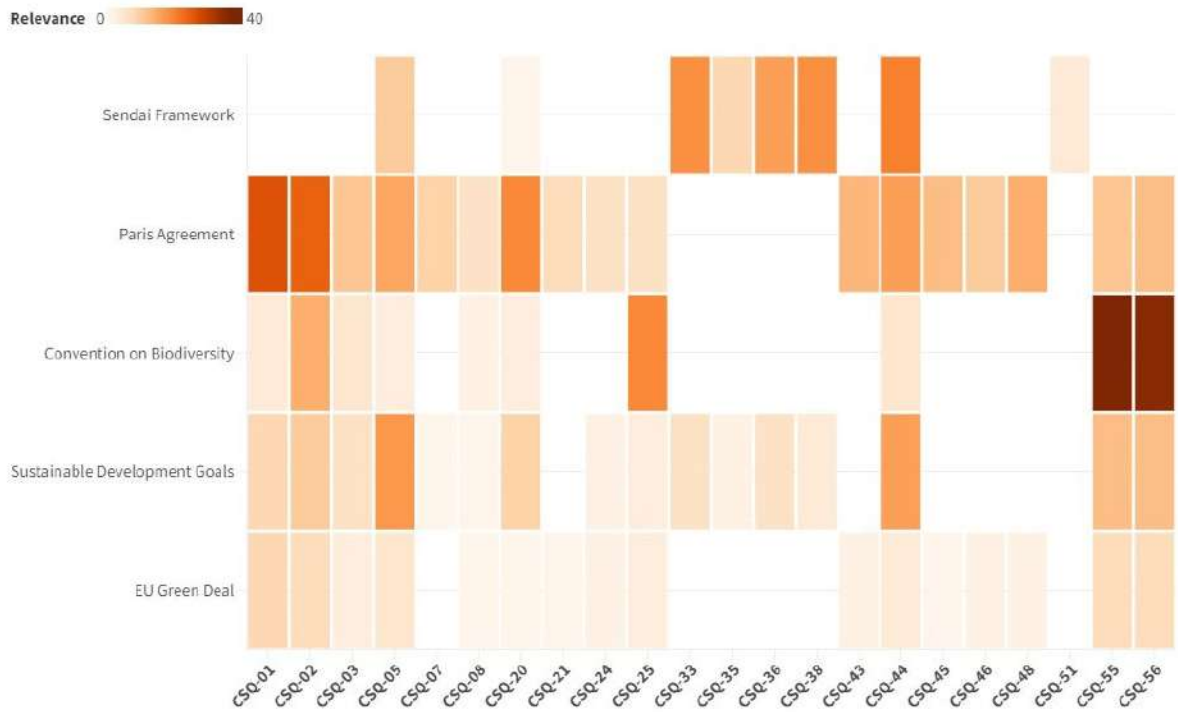

Figure 5: Heatmap showing relationship between CSQs and international treaties and agreements

National Policy Heatmap

This figure shows the results of the policy relevance mapping between CSQs and the national policy domains assessed.

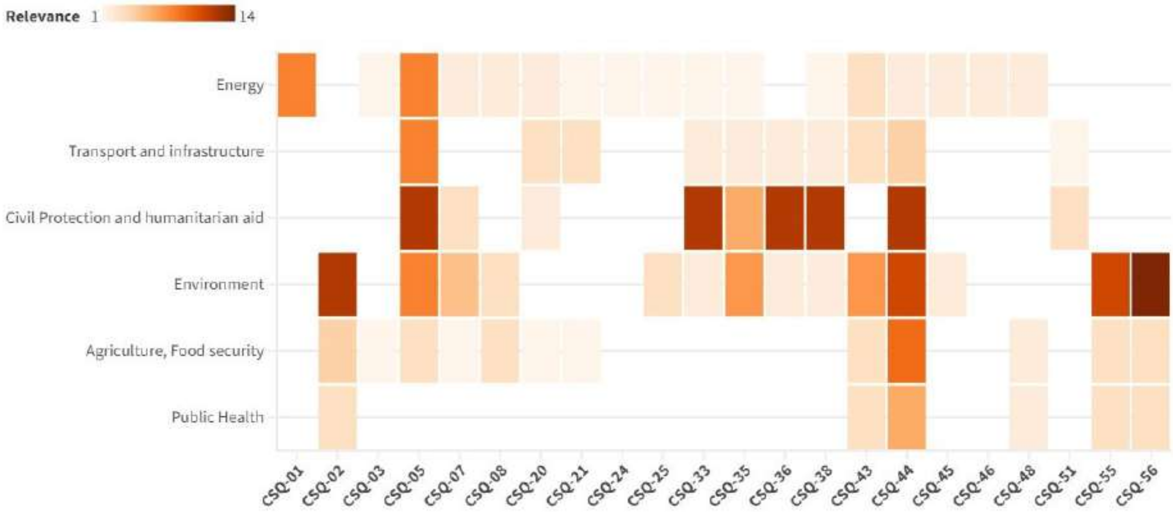

Figure 6: Heatmap showing relationship between CSQs and national policy domains

Further commentary on the basis for policy relevance scoping is shown in Appendix B (International agreement/treaties) and Appendix C (National policy domains).

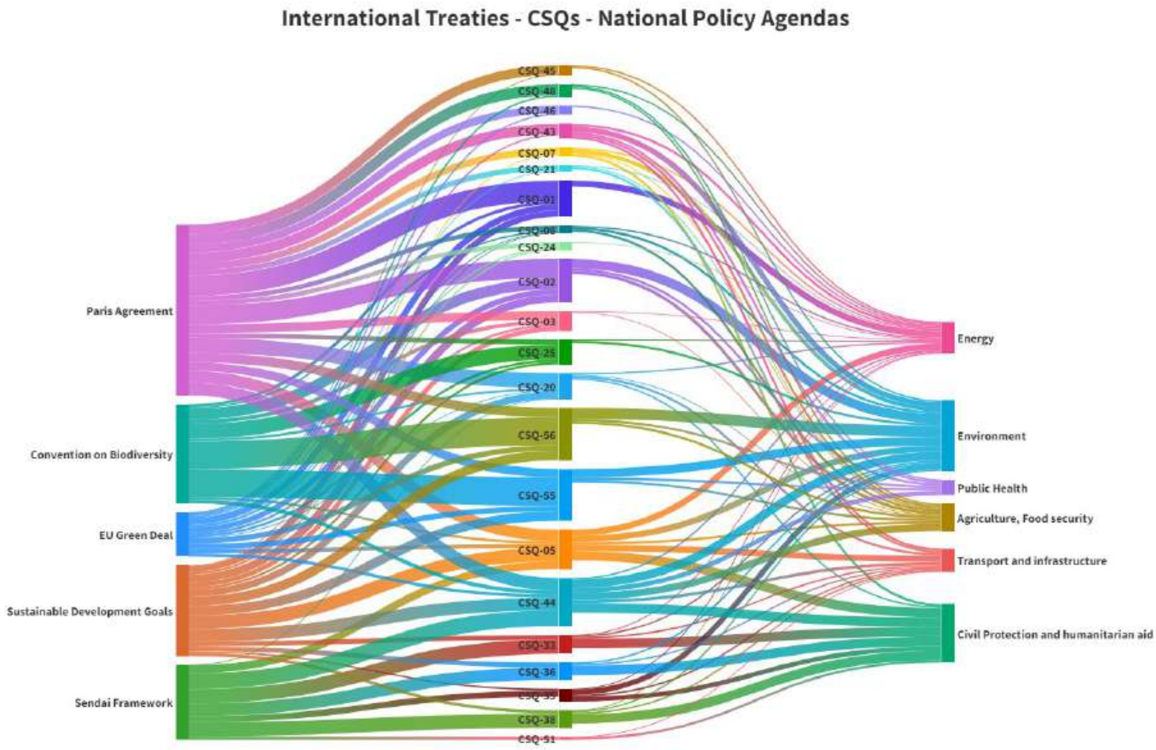

Figure 7: Summary of links between CSQs, International Treaties and National Policy Domains

An overall summary of the assessment is shown in Figure 7, which illustrates the links between CSQs in the centre, with international treaties on the left, and national policies on the right. The strength of the link is reflected in the thickness of the lines.

4.4 Overall assessment

The remaining assessment categories were assessed by members of the project team, and the Science team group chairs. For each of these categories, the criteria in Table 4 were used to give each CSQ a score of for each category. Bearing in mind the CSQs had already been through a process of selection and refinement, the overall scoring was very high. In order provide some normalisation between the different assessors, and to differentiate between the CSQs, a ranking based scoring was adopted. For each assessor, the 22 CSQs were ranked in score order, then the top scored was given 22 points, the next 21 points etc.. The ranks were averaged to give the final scores.

The result of this is an assessment of the CSQs *relative to each other*, showing in comparative terms which CSQs rank most highly in the four categories. The results of this assessment are shown in Figure 8. It should be stressed that this assessment is intended to give an indicative guide to the ratings of each CSQ by the assessment process but should but not be used to provide an absolute ranking of CSQs.

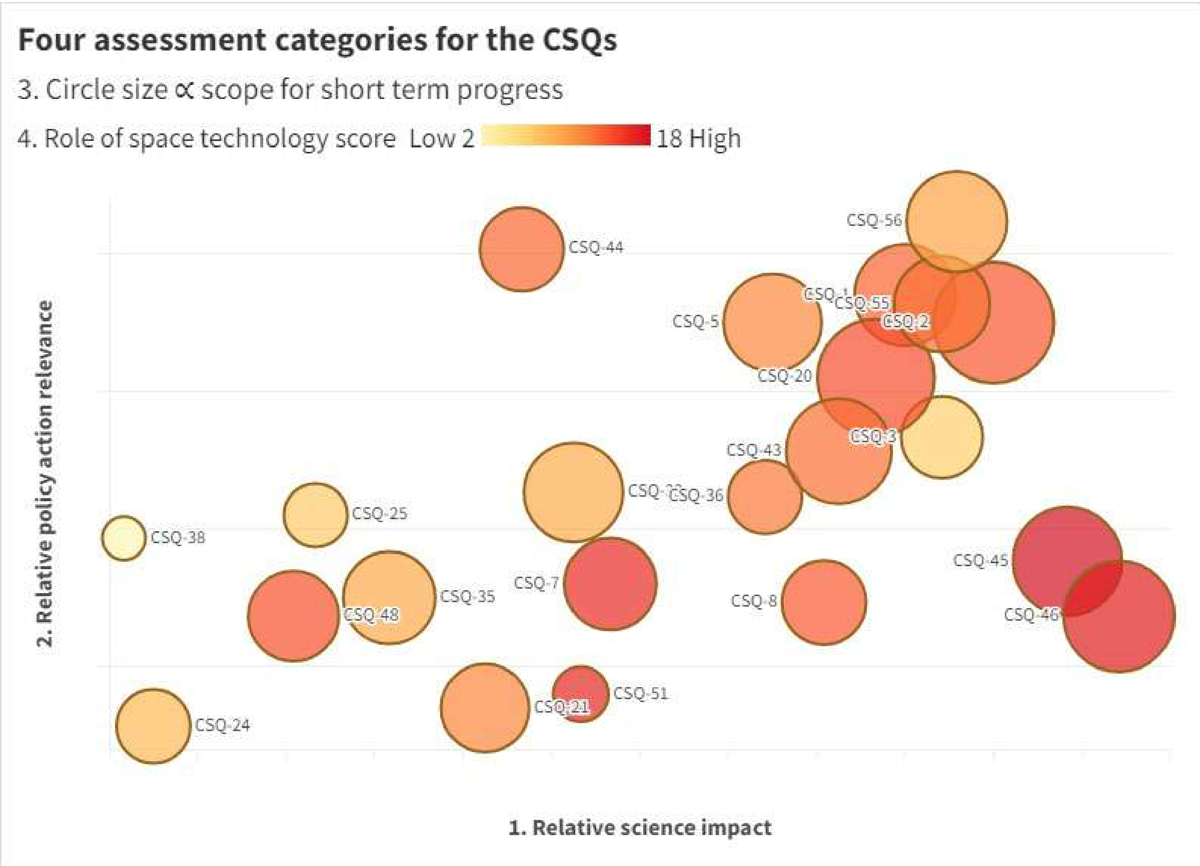

Figure 8: Relative assessment of CSQs

All four assessment criteria are shown in this figure, the science impact and policy relevance scores are shown on the x and Y axes respectively. The size of the circle is relative to the score for the scope for short term progress, and the colour of the circle is relative to the role of space technology in addressing the science question.

In previous strategy documents (2006, 2015) some 25 challenges were selected as being of highest priority with no ranking among them. It was the intention of ESA in this exercise to provide a smaller number of highest priority questions – maybe 6-8 – to enable a more focused approach in program actions. This runs into the problem discussed elsewhere of the incompatibility of three factors: a small number of CSQs v comprehensiveness of science v specificity of question. These are mutually incompatible. But the four-dimensional structure of assessment implemented in the study allows ESA to select a smaller number of CSQs from among the 22, depending on which of the four criteria are deemed to be most important in any given phase of the program.

This brings back the notion of being more focused, but for specific reasons. These reasons may also be different at different points in the programme implementation e.g. a particular phase may want to concentrate on actions that are most relevant to answering policy drivers, and this gives a particular perspective on the 22 CSQs. We are hence able to define a smaller number of questions of interest, but in a flexible way.

To summarise this section, the top five ranked CSQs in each category are shown in Table 8. Again, it should be stressed that the scoring between the CSQs was in many cases very close, so not too much weight should be put on the relative positions.

Novel / discovery science		**Potential for short term progress**	
CSQ-02	Land biosphere response to CC	CSQ-02	Land biosphere response to CC
CSQ-03	Ocean carbon cycle responses to climate change	CSQ-20	Ice mass balance
CSQ-45	Internal energy flux estimates	CSQ-46	Earth energy imbalance
CSQ-46	Earth energy imbalance	CSQ-45	Internal energy flux estimates
CSQ-55	State of Land ecosystems	CSQ-43	Coupling between energy water and carbon cycles
Policy relevance and benefits		**Potential to fill critical observation gaps through innovation in space technology**	
CSQ-01	Anthropogenic influences on the carbon cycle	CSQ-07	Coastal interfaces with land atmosphere and ocean
CSQ-56	Land ecosystem critical transitions	CSQ-20	Ice mass balance
CSQ-44	Anthropogenic influences on the water cycle	CSQ-45	Internal energy flux estimates
CSQ-55	State of Land ecosystems	CSQ-46	Earth energy imbalance
CSQ-05	Sea level change in the coastal ocean	CSQ-51	Lithosphere-atmosphere-ionosphere coupling

Atmosphere   Land   Ocean   Solid earth   Cryosphere

Table 8: Highest ranked CSQs in each category

The links to Earth system domains originally shown in Table 3 have been transferred to this table to illustrate the range of Earth system domains that are represented in the CSQs ranked most highly in each category.

5 EXAMPLE CSQ TRACING AND LINKING VISUALISATIONS

The information generated during the project allows for a range of different visualisations to illustrate the links between different aspects of the science questions and the policy / benefit domains they serve, the observations they require and themes which they represent. The overall structure of the information model is shown in Figure 9.

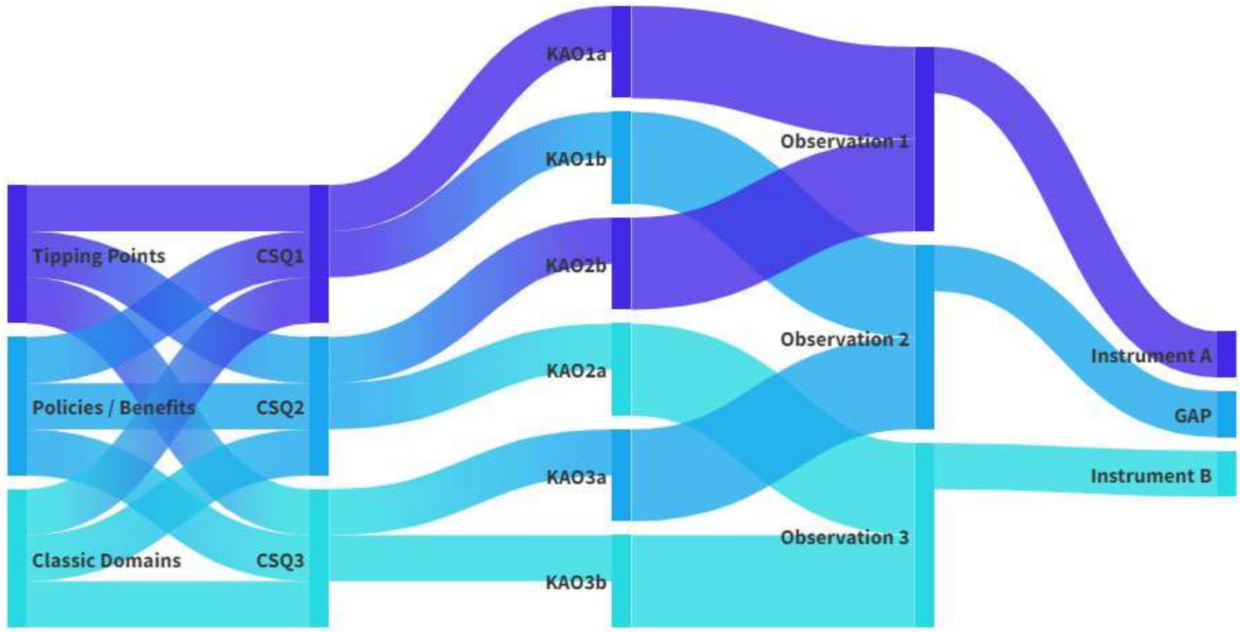

Figure 9: Overall information model

The previous sections provide some examples of the use of this information model in describing and characterising the CSQs (for example, Figure 5, Figure 6, Figure 7, and Figure 8) In the remainder of this section, a few more examples of different styles of visualisation are provided to illustrate how the approach to CSQ elaboration can be used to view the CSQs in different ways.

5.1 Linkages between CSQs, policy objectives, and observables

The information chain between policies and observables is illustrated in Figure 10 for one example (CSQ-44). On the left hand side of the figure, the international treaties and agreements, and national policy domains described in section 4.3 are shown in Yellow and Blue respectively. The CSQ and its KAOs are shown in the middle with links to geophysical observables requirements on the right. Here the thinner lines represent supporting observations, with the thicker links representing critical observations. A “traffic light” colour coding scheme is used to illustrate the availability of EO missions to deliver these observations over the next 5-15 years. Green represents abundant sources of data, amber limited sources, and red a gap (or potential gap). It should be stressed that these assessments are driven by the database that lists the number of missions and instruments available. More detailed analysis would be required to assess the scientific suitability of specific instrument data for a particular application.

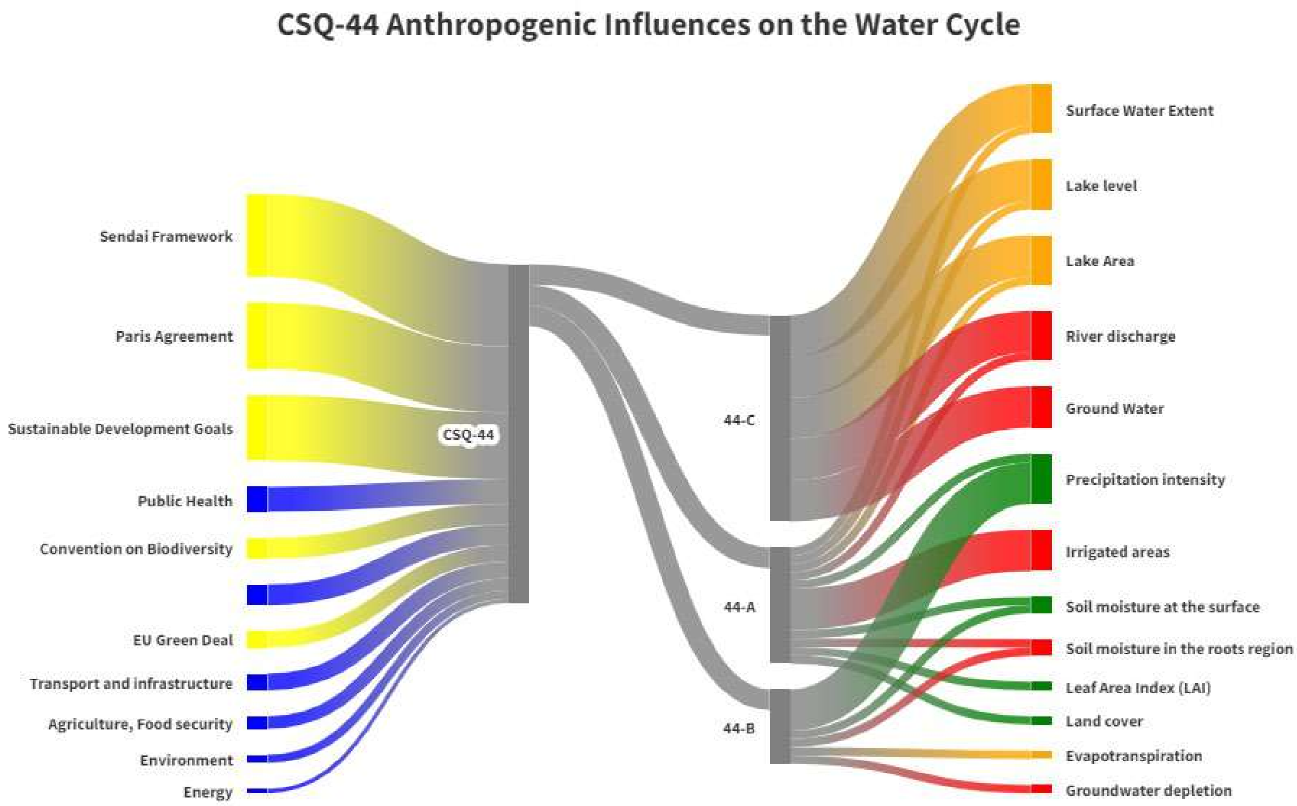

Figure 10: Links between Policies, CSQ, KAO and observations for one example (CSQ-44)

5.2 Cross cutting technology themes

During the initial assessment of all 57 science questions immediately after the ESA community workshop, each science question was tagged with link to a number of cross cutting technology themes that were mentioned in discussion of the CSQs. The themes were as follows:

Cal/Val: All CSQs are likely to benefit from higher quality or better characterised data, but certain CSQs specifically refer to the need for improved calibration or validation in order to make progress.

Sampling/ Orbits: This category refers to a wide range of requirements for better provision of data in terms of improved spatial resolution, improved temporal resolution, or improved timing of acquisitions.

Field experiments / in situ observations: Certain CSQs refer specifically to the need for more campaigns or field experiments, or for sustained improved in situ observations.

AI/Modelling: Several CSQs refer to the scope for progress with more advanced models, or the use of AI, as opposed to the acquisition of new types or improved quality of data.

Long term continuity: This category reflects the requirement for long term continuity, as opposed to improved data resolution . quality – typically in CSQs where small trends have to be identified over a long term against a background of large natural fluctuations.

Reprocessing: This category refers to specific requests for reprocessing existing long term datasets based on improved algorithms.

The significance of these themes is that in many cases (with the exception of the sampling / orbits category), action can be taken on relatively short timescales and hence actions could be designed in the next ESA science strategy that would deliver impact within the lifetime of the strategy.

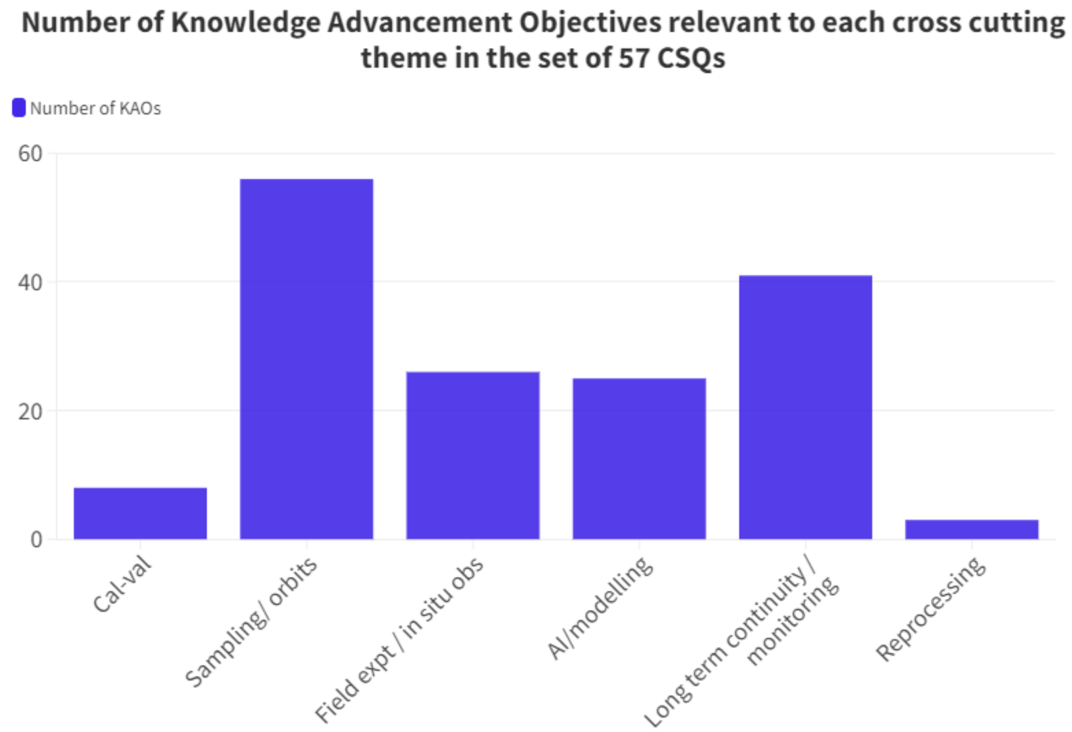

Figure 11: Frequency of occurrence of each cross-cutting technology themes amongst the 57 CSQs. Note that the occurrence is counted for each CSQ Knowledge Advancement Objective within the CSQs

5.3 Relationship between CSQs and Global Tipping Points

In one final example, we have examined the relationships between the CSQs and the Global Tipping Points (GTP) identified in the recent GTP report[2]. The GTP report identifies 18 harmful Tipping Points as summarised in Table 9.

[2] T. M. Lenton et al (Eds), 2023, The Global Tipping Points Report 2023.] University of Exeter, Exeter, UK.

TP Number	Domain	Tipping Point name
TP-1	Cryosphere	Ice Sheets (collapse)
TP-2	Cryosphere	Sea Ice (loss)
TP-3	Cryosphere	Glaciers (retreat)
TP-4	Cryosphere	Permafrost (thaw)
TP-5	Biosphere	Tropical Forests (dieback)
TP-6	Biosphere	Boreal Forests (dieback / expansion)
TP-7	Biosphere	Temperate Forests (dieback)
TP-8	Biosphere	Savannas and Grasslands (regime shifts)
TP-9	Biosphere	Drylands (regime shifts)
TP-10	Biosphere	Freshwater / Lakes (regime shifts)
TP-11	Biosphere	Coastal - warm-water coral reefs (die-off)
TP-12	Biosphere	Coastal - mangroves and seagrass meadows (die-off)
TP-13	Biosphere	Marine ecosystems and environment (regime shifts)
TP-14	Ocean & Atmosphere	Ocean overturning (collapse)
TP-15	Ocean & Atmosphere	Monsoons (collapse / abrupt strengthening)
TP-16	Ocean & Atmosphere	Tropical clouds and circulation (reorganisation)
TP-17	Ocean & Atmosphere	ENSO (more extreme or permanent)

Table 9: Summary of harmful Tipping Points

For each Tipping Point, the report identifies the current strength of evidence available for the dynamics on a scale of 0 to 4. This information has been used, alongside an analysis of each of the 22 CSQs to assemble a summary of the relevance of the CSQs to the 18 Tipping points. This analysis was based on an assessment of the contribution that progress on each of the CSQs could make to better understanding of Tipping Point dynamics.

The results are shown in Figure 12, where the size of the circle relates to the strength of the relevance of each CSQ to the tipping points, and the colour of the circle relates to the strength of Tipping point dynamics evidence as stated in the GTP report.

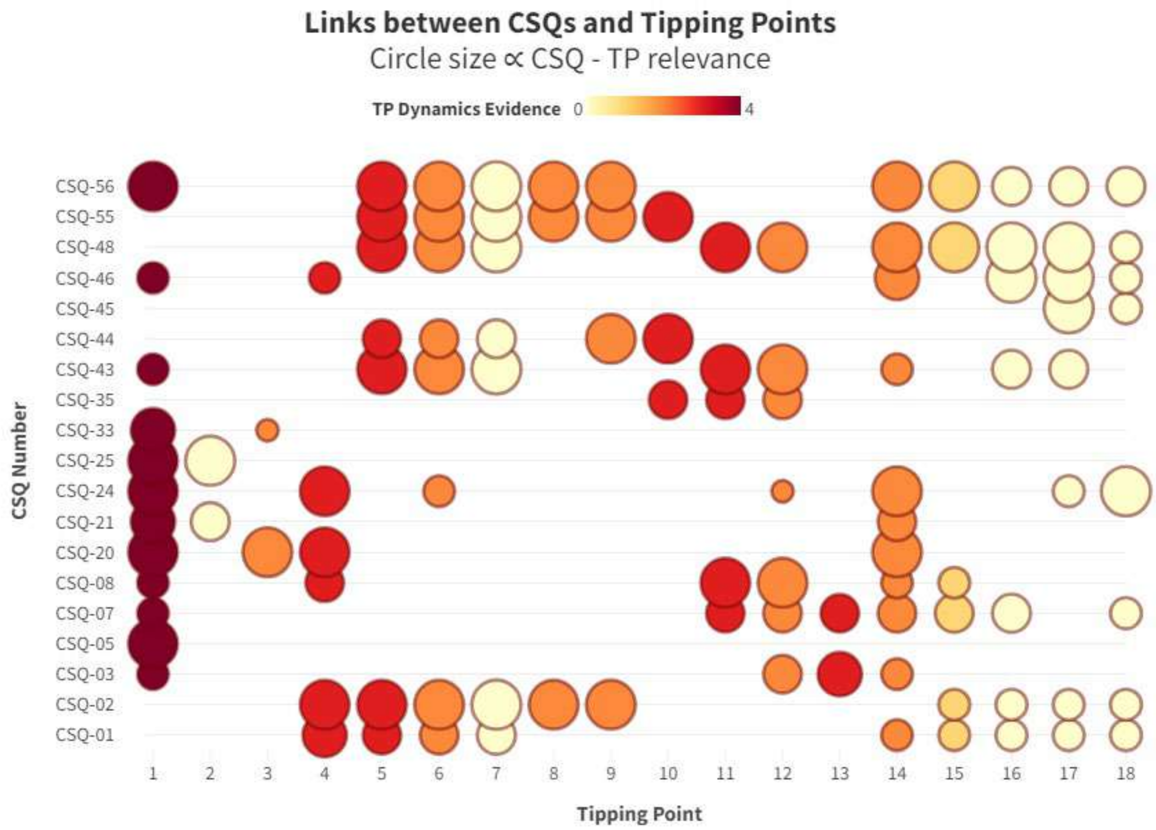

Figure 12: Relevance of CSQs to Global Tipping Points

5.4 Concluding remarks

The ESA Science Strategy Foundation Study has developed a new methodology and approach for supporting the development of the ESA EO science Strategy. The project has delivered:

1. A set of Candidate Science Questions characterised by the geophysical observables needed to progress them.
2. A comprehensive database of capabilities of current and planned EO satellites, along with an analysis of the gaps between the CSQ requirements and current and planned capabilities (see separate deliverable, D5: Links between Candidate Science Questions, Geophysical Observables and EO mission capabilities).
3. An assessment of the relevance of CSQs to a range of international treaties and national policy objectives which provides traceability and justification.
4. A linked information model and visualisation tools that allow the CSQs to be described and evaluated from a range of different perspectives.

The information and tools developed in the project will allow the CSQs to be further developed and augmented, and for progress against them to be tracked throughout the implementation phase of the next EO science strategy.

Appendix A Candidate Science Questions Narratives and Summaries

A.1 CSQ-01: What anthropogenic and natural processes are driving the global carbon cycle?

Since the beginning of the industrial age, anthropogenic CO_2 emissions from fossil fuel combustion, land use change and other activities have increased and are now adding more than 40 billion tonnes of CO_2 to the atmosphere each year. These emissions have increased the atmospheric CO_2 concentration by about 50% from values near 277 parts per million by volume (ppm) prior to 1750 to values near 420 ppm in 2023 (see https://gml.noaa.gov/ccgg/trends/). Over this same period, methane (CH_4) emissions from fossil fuel extraction, transport and use, changes in agriculture and wetlands and waste management practices have increased the atmospheric CH_4 concentrations by more than 160%, from values near 0.72 ppm to more than 1.90 ppm. These large changes in the atmospheric carbon reservoir affect the Earth's energy balance because CO_2 and CH_4 are efficient atmospheric greenhouse gases (GHGs). Anthropogenic CO_2 and CH_4, alone, contribute more than 90% of the present-day 1.1 °C global warming (IPCC 2021).

Anthropogenic emissions of CO_2 and CH_4 would have produced much larger changes in the atmospheric composition and climate if these carbon-bearing gases were not regulated by natural processes. For example, on multi-year time scales, natural sinks in the land biosphere and ocean remove over half of the CO_2 emitted into the atmosphere by anthropogenic activities, consistently maintaining the airborne fraction near 0.45 over the past 60 years (e.g., Ballantyne et al., 2012; Bennedsen et al., 2019; Friedlingstein et al. 2021). For CH_4, the primary sink is oxidation by the hydroxyl radical (OH^-), which limits its atmospheric lifetime to about a decade (Saunois et al., 2020).

Anthropogenic CO_2 emissions from fossil fuel combustion can be accurately estimated in well-designed bottom-up inventories. However, those from land-use management and change and those from natural sources and sinks on unmanaged lands are much more difficult to quantify and thus have much larger uncertainties. In addition, there is growing evidence that natural carbon sources and sinks are beginning to respond to continuing anthropogenic forcing and climate change. For example, while the efficiency of the ocean sink has increased in proportion to the atmospheric CO_2 abundance, the response of the land biospheric carbon sink has been more complicated, becoming less efficient in the tropics and somewhat more efficient across the northern extratropics (Crisp et al., 2021). Modelling studies suggest that the overall efficiency of the land sink will decrease with increasing emissions (IPCC 2021).

Recent changes in the atmospheric CH_4 reservoir are even less well understood. CH_4 has a diverse range of natural sources, led by emissions from wetlands (~33%), inland waters, termites and wildfire (~7%). Its primary anthropogenic sources are agriculture (~25%), fossil fuel extraction, transport and use (~18%), waste management (~12%) and biomass burning (Saunois et al., 2020; IEA, 2020). While atmospheric oxidation is the primary CH_4 sink, soils are responsible for removing ~6% of the atmospheric CH_4 each year. The global atmospheric CH_4 growth rate was 8-12 parts per billion per year (ppb/yr) between 1983 and 1991, but then fell to -5 to 5 ppb/yr from 1992 to 2014, and then began rising rapidly to > 15 ppb/yr by 2020 and continues to grow. The causes for these changes are not well understood, but there is growing isotopic evidence that the recent increased growth rate is driven primarily by increased emissions from biogenic sources (wetlands, agriculture and waste) rather than fossil fuel sources (e.g., Nisbet et al., 2023).

The 6th IPCC (IPCC 2021) assessment identifies the Agriculture, Forestry and Other Land Use (AFOLU) sector as the second largest source of anthropogenic carbon emissions. They note that this sector contributed between 13 and 21% of total emissions (5.9 ± 4.1 $GtCO_2eq/yr$) between 2010 and 2019. Bookkeeping models (e.g., Houghton and Nassikas, 2017) indicate that deforestation and forest degradation are the largest contributors to carbon emissions from AFOLU. Other land management activities, such as reforestation, afforestation, and intense agriculture, are credited with increasing the intensity of the extratropical land sink (e.g., Bastin, et al., 2019; Cunningham et al., 2015; Zeng et al., 2014). Unfortunately, the uncertainties on CO_2 and CH_4 emissions from the AFOLU sector are still quite large in bottom-up inventories because the activity data are difficult to quantify and the emission factors vary substantially with location and time. These uncertainties complicate efforts to assess the effectiveness of policies supporting nature-based offsets for carbon emissions, assess food security or predict the response of managed land to severe weather (droughts, floods), disturbance (wildfire) or climate extremes (heat stress).

Space-based observations of land cover and land use change are widely used for monitoring activity across the AFOLU sector. For example, high-resolution space-based imagery often provides the best-available time-resolved estimates of the spatial extent of deforestation, reforestation or afforestation and croplands. However, these data provide much less direct information about the CO_2 and CH_4 emissions or removals associated with AFOLU. If these observations could be combined with space-based estimates of CO_2 and CH_4 fluxes, the results could yield an integrated constraint on regional scale carbon emission and removals by managed lands. In addition, time-resolved observations of CO_2 and CH_4 fluxes at finer spatial scales could be combined with space-based observations of SIF and vegetation indices to yield improved estimates of emission factors, further reducing uncertainties in bottom-up AFOLU inventories. They could also foster the development of more comprehensive models of the impacts of severe weather, disturbance or climate extremes on carbon sources and sinks in highly-managed ecosystems, and their recovery from these events.

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CSQ-01	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
What anthropogenic and natural processes are driving the global carbon cycle?	**A) Quantify CO_2 and CH_4 emissions from both anthropogenic and natural sources and CO_2 removals from natural sinks on spatial scales from individual facilities or field plots to regional and global scales on seasonal time scales.**	**Critical Parameters** *Column-averaged atmospheric CO2 and CH4 dry air mole fractions (XCO2, XCH4) and their gradients.*			Atmospheric CO_2 and CH_4 retrieval algorithms Atmospheric flux inverse models	Integrated constraint on net emissions and removals of CO_2 and CH_4 for climate change (CC) mitigation and adaptation policy Climate finance. Monitor the efficacy of decarbonization policies and CO_2 removal strategies
		CO_2 Mole Fraction	CEOS 44	High resolution CO_2, CH_4 and O_2 measurements at 1-10 km spatial resolution with 0.1 to 0.5% accuracy. High spatial resolution CO_2, CH_4 observations with accuracies of 1-2% on spatial scales 0.01 to 1 km.		
		CO_2 Total Column	CEOS 274			
		CH_4 Mole Fraction	CEOS 39			
		CH_4 Total Column	CEOS 272			
		Supporting Parameters				
		Aerosols optical depth	CEOS 33	Co-bore-sighted aerosol and cloud measurements to mitigate biases. Co-bore-sighted NO2 and CO to identify plumes and discriminate wildfire from high-temperature combustion.		
		Cloud imagery	CEOS 109			
		Cloud cover	CEOS 111			
		NO_2 Mole Fraction	CEOS 74			
		CO Mole Fraction	CEOS 49			
		1. Critical Parameters				

CSQ-01	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
	B) Distinguish intense anthropogenic CO_2 and CH_4 point source emissions associated with fossil fuel extraction, transport and use and land use change from wildfires and weak, spatially-extensive sources (wetlands, permafrost melting, agriculture).	*High spatial and temporal resolution measurements to detect CO2 and CH4 emission plumes*			Atmospheric GHG retrieval algorithms Atmospheric assimilation systems Discrete plume models	
		CO_2 Mole Fraction	CEOS 44	CO_2, CH_4 and O_2 at 1-10 km spatial resolution with 0.1 to 0.5% accuracy.		
		CH_4 Mole Fraction	CEOS 39			
		Observations of co-emitted species (NO_2, CO) to discriminate combustion sources				
		NO_2 Mole Fraction	CEOS 74	NO_2 and CO at 1-10 km spatial resolution		
		CO Mole Fraction	CEOS 49			
		2. Supporting Parameters *Fire radiative power*				
		Fire radiative power	CEOS 288	High-spatial resolution (< 30m) imaging and shortwave IR and thermal IR imaging (< 100m).		
		Fire fractional cover	CEOS 177			
	C) Quantify emissions and removals (fluxes) of CO_2 and CH_4 from managed lands on sub-seasonal time scales with the accuracy needed to quantify and distinguish long-term (decadal) changes from human activities (e.g., deforestation, intense	**1. Critical Parameters** *XCO_2 and XCH_4 and their gradients at 0.1 to 10 km resolution*				
		CO_2 Mole Fraction	CEOS 44	CO_2 at 1-10 km spatial resolution with 0.1 to 0.5% accuracy.	Atmospheric GHG retrieval algorithms	
		CH_4 Mole Fraction	CEOS 39			
		Vegetation dynamics and functioning				

CSQ-01	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
	agriculture) from those driven by disturbances (e.g., drought, floods, wildfire) or climate perturbations	Hyperspectral surface reflectance	CEOS 133	High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging	SIF retrieval algorithms Empirical light Use Efficiency and Machine learning models for flux upscaling and change detection	
		Chlorophyll Fluorescence (SIF) from Vegetation on Land	CEOS 250	SIF at 1-10 km spatial resolution		
		Above Ground Biomass	CEOS 268	Observations of forest biomass at 1 km resolution with errors < 20% or ±10 tons/hectare between 70N and 56S		
		Land use and land use change (LULUC)				
		Land cover	CEOS 179	Very high spatial resolution (metre scale) visible and NIR reflectance measurements for estimating vegetation indices (NDVI, NIRv) Fire radiative power, and CO at 1-10 km spatial resolution		
		Land surface imagery	CEOS 181			
		Normalized Differential Vegetation Index (NDVI) and near-infrared reflectance of vegetation (NIRv)	CEOS 172			
		Fire radiative power	CEOS 288			

CSQ-01	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
		2. Supporting Parameters				
		Soil temperature	CEOS 170	Routine meteorological measurements, soil moisture as available from current systems.		
		Near-surface air temperature	CEOS 138			
		Soil water content	CEOS 171			
		Near-surface air water content	CEOS 139			

A.2 CSQ-02: How has the land biosphere responded to human activity and climate change?

As atmospheric CO_2 concentrations have increased, the land biosphere has become a more efficient sink, and is now absorbing almost 30% of all anthropogenic emissions (Friedlingstein et al., 2022). However, land use change continues to be the second largest source of CO_2 emissions, after fossil fuel use. Over the industrial age, CO_2 uptake by intact forests and other natural parts of the land biosphere has roughly balanced anthropogenic emissions from land use change. While the efficiency of the land biospheric sink has been roughly constant over the past 60 years, its uptake varies substantially from year to year in response to climate fluctuations (e.g., ENSO), volcanic eruptions, disturbances (wildfire, floods, droughts) and other processes less well understood. In addition, observations of carbon stocks and fluxes acquired since the 1990s indicate that the tropical land sink is now weakening while the northern hemisphere extratropical land sink is changing in more complicated ways. These changes have been attributed to a broad range of human activities (deforestation, increased harvest, pollution, intense agriculture), as well as the increased frequency of disturbance (storm damage, floods, droughts, fire) driven by climate change (Crisp et al., 2022; Friedlingstein et al., 2022).

Atmospheric CO_2 and CH_4 observations reinforce these conclusions about the land carbon sink by providing an integrated constraint on net fluxes by all processes (Byrne et al., 2023; Chevallier, 2021). However, these data provide much less insight into the physical and biological processes driving these changes. A much greater understanding of these processes is needed to diagnose the current state of the land biosphere and to predict its response to continuing human activities and climate change. To achieve these goals, we need a coordinated architecture for space-based carbon cycle observations that can be combined with process-based models for attribution of observed changes. This architecture includes high-resolution (30 m to 1 km), global, space-based measurements of above-ground carbon stocks, land use and land use change, land management type and intensity, as well as the detection and characterization of disturbances that impact forest and crop health and productivity to develop the scientific basis for carbon management. Even higher spatial resolution (1-10 m) is needed to assess forest degradation, tree mortality, or to map individual species and monitor changes in biodiversity.

Looking to the future, these carbon cycle observations must be combined with precise global observations of atmospheric CO_2 and CH_4, to directly relate the observed changes in land carbon stocks with GHG fluxes and - ultimately - their growth rates in the atmosphere. Other ancillary measurements will be needed to interpret these carbon cycle observations and improve our ability to predict its evolution in response to continuing human activities and climate change. For example, measurements of carbon monoxide (CO) could be combined with observations of CO_2, CH_4 and fire radiative power to improve models of the GHG fluxes from wildfire. Measurements of near surface temperature, water vapour and surface wetness could be combined with observations of XCO_2 and XCH_4, SIF, and vegetation indices to develop more realistic models of disturbances such as drought and temperature stress on the carbon cycle. Furthermore, efforts are needed to improve the compatibility of these - and future new - observations with different types of carbon cycle models in order to better constrain variables that cannot be directly observed globally, attribute observed changes to natural vs. anthropogenic processes and, more generally, improve our predictive capacity of the future land carbon cycle.

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CSQ-02	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
How has the land biosphere responded to human activity and climate change?	**A) Quantify changes and uncertainties in the distribution of land sources and sinks over different biomes and latitudinal bands, and identify human activities and climate variations driving these changes**	**1. Critical Parameters** *LULUC from optical / NIR imagery, and SIF*				CC mitigation and adaptation policy Climate finance Monitor the efficacy of natural decarbonization policies and CO_2 removal strategies. Independent space-based estimates of biomass carbon changes, land-use and land management fluxes, fire carbon
		Land cover and land cover change	CEOS 179	High-spatial resolution (~1-10 m) (<30 m) imaging from visible NIR andradar	DGVMS Atmospheric GHG retrieval algorithms Atmospheric assimilation systems Geostatistical models	
		Land surface imagery	CEOS 181			
		Chlorophyll Fluorescence from Vegetation on Land	CEOS 250			
		Above Ground Biomass	CEOS 268	Observations of forest biomass at 1 km resolution with errors < 20% or ±10 tons/hectare between 70N and 56S		
		Vegetation water content				
		Burned area	CEOS 177	High-spatial resolution (< 30m) optical and thermal imaging (< 100m).		
		Fire radiative power	CEOS 288	High-spatial resolution (< 30m) optical and thermal imaging (< 100m).		

CSQ-02	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
		2. Supporting Parameters *Atmospheric CO2 and CH4 concentration gradients*				emissions, crop yields, etc.
		CO_2 Mole Fraction	CEOS 44	XCO_2 and XCH_4 – specifications as for CSQ-1		
		CH_4 Mole Fraction	CEOS 39			
		Soil & air temperature and water content				
		Near-surface air temperature	CEOS 138	Air temperature and water vapour measurements at < 10 km resolution throughout the day and near-infrared water vapour measurements.		
		Near-surface air water content	CEOS 139			
		Soil wetness	CEOS 171	Observations of soil moisture at a spatial resolution of < 10 km.		
		Land surface temperature	CEOS 170	Thermal observations footprint size < 10 km.		
	B) Quantify the roles of climate change and natural (wildfire, droughts, wind,	**1. Critical Parameters** *LULUC, biomass loss and disturbance detection*			DGVMS	

CSQ-02	**Knowledge Advancement Objectives**	**Geophysical Observables [Links to MIM databases]**	**MIM Number**	**Measurement Specifications**	**Data sets, Methods, Tools & Models**	**Policies / Benefits**
	pests) and human disturbances (land use change, wood harvest, illegal logging) on the land carbon sink	Burned area	CEOS 177	High-spatial resolution (< 30m) optical and thermal imaging (< 100m).	Atmospheric GHG retrieval algorithms	
		Fire radiative power	CEOS 288	High-spatial resolution (< 30m) optical and thermal imaging (< 100m).	Atmospheric assimilation systems	
		Above Ground Biomass	CEOS 268	Observations of forest biomass at 1 km resolution with errors < 20% or ±10 tons/hectare between 70N and 56S	Geostatistical inverse models	
		Vegetation water content	None			
		Land cover	CEOS 179	High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging		
		Land surface imagery	CEOS 181			
		Chlorophyll Fluorescence (SIF) from Vegetation on Land	CEOS 250	< 4 sq. km resolution.		
		2. Supporting Parameters *Atmospheric CO2 concentration gradients*				
		CO_2 Mole Fraction	CEOS 44	XCO_2 – specifications as for CSQ-1		
		Soil & air temperature and water content				

CSQ-02	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
		Near-surface air temperature	CEOS 138	Air temperature and water vapour measurements at < 10 km resolution throughout the day		
		Near-surface air water content	CEOS 139			
		Soil moisture at the surface	CEOS 171	Observations of soil moisture at a spatial resolution of < 10 km.		
		Land surface temperature	CEOS 170	Thermal observations footprint size < 10 km.		
		Fire Radiative Power				
		Fire radiative power	CEOS 288	High-spatial-resolution (< 100m) shortwave IR and thermal IR imaging.		
		Fire fractional cover	CEOS 177			
	C) Quantify above ground biomass (AGB) in tropical and extratropical forests to the accuracy needed to resolve changes in stocks on sub-decadal time scales	**1. Critical Parameters** *Microwave vegetation optical depth (VOD)* *Canopy structure from Synthetic aperture Radar (SAR) and Biomass LiDAR*			In situ reference systems Enhanced techniques for integrating data sources	
		Above Ground Biomass (AGB)	CEOS 268	Observations of forest biomass at 1 km resolution with errors < 20%		

CSQ-02	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
				or ±10 tons/hectare between 70N and 56S		
		2. Supporting Parameters				
		Very high resolution tree cover change	CEOS 240	Surface reflectance at metre scale spatial resolution, at least in the visible and NIR bands		
	D) Catalogue the impacts of climate change on crop health and forest mortality across different biomes and hotspots of change	**1. Critical Parameters** *Forest/Cropland Cover*			DGVMS Empirical light Use Efficiency and Machine learning models	
		Land cover	CEOS 179	High-spatial resolution (< 30m) imaging		
		Land surface imagery	CEOS 181			
		NPP and GPP via optical/NIR imagery /SIF				
		Vegetation status	CEOS 172	High spatial resolution (<30 m) multispectral or hyperspectral imaging at visible and near-IR wavelengths.		
		Solar induced chlorophyll fluorescence (SIF)	CEOS 250	SIF in solar Fraunhofer lines at a spatial resolution of < 4 sq. km.		

CSQ-02	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
		Impacts of disturbance (wildfire, drought, pests and disease)				
		Vegetation water content	None	Moderate to high resolution (1km - 10m) and high temporal resolution (sub-daily to daily)		
		Plant stress	None			
		Above Ground Biomass (AGB)	CEOS 268	Observations of forest biomass at 1 km resolution with errors < 20% or ±10 tons/hectare between 70N and 56S		
		Very high resolution tree cover change	CEOS 240	Surface reflectance at metre scale spatial resolution		
		2. Supporting Parameters				
		Fire radiative power	CEOS 288	High-spatial-resolution (< 100m) imaging.		
		Near-surface air temperature	CEOS 138	Air temperature and water vapour measurements at < 10 km resolution throughout the day		
		Near-surface air water content	CEOS 139			

CSQ-02	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
		Soil moisture at the surface	CEOS 171	1-km scale resolution		
		Land surface temperature	CEOS 170	Thermal observations footprint size < 10 km.		

A.3 CSQ-03: How has the ocean carbon cycle responded to anthropogenic CO2 and climate change?

The ocean carbon cycle is driven by interactions with CO_2 in the atmosphere, ocean dynamics and ocean biology. At the surface, CO_2 absorption is governed by Henry's Law (i.e., the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid, pCO_2; e.g., McKinley et al., 2020). However, ocean dynamics continually transports anthropogenic carbon away from the surface into the interior and refreshes the surface with lower pCO_2 water (e.g., Bronselaer and Zanna, 2020). Some of the carbon transported to depth is remineralized and precipitates out of solution into a long-term sink. Biological processes within the ocean act to increase natural carbon with depth (Sarmiento and Gruber, 2006). All of these processes are now being affected by rapidly-increasing atmosphere CO_2 concentrations and the resulting changes in climate.

Over the industrial age, the amount of CO_2 absorbed by the ocean has increased in proportion to the increasing atmospheric CO_2 partial pressure, such that the ocean sink has continued to absorb about 25% of all anthropogenic emissions (Hauck et al., 2020; Friedlingstein et al., 2022). While this has substantially reduced the atmospheric CO_2 growth rate and resulting climate change, this carbon absorption has contributed directly to ocean acidification. Other impacts are more difficult to assess because the spatial sampling of the ocean carbon measurement system is very sparse. Existing ship-based *in situ* measurements are accurate, but cover less than 1% of the 1° x 1° grid boxes across the ocean on decadal time scales, providing far too little resolution or coverage to track transient events or the effects of climate change (e.g., Landschützer et al., 2020). These ship-based measurements are now being augmented by *in situ* carbon measurements collected by autonomous platforms, but these data have much lower accuracy than the ship-based measurements (e.g., Sabine et al., 2020).

Ocean carbon observations with much greater coverage, resolution and repeat frequency are critically needed to monitor the changes in the ocean sink that are expected in response to human activities and climate change. The ocean sink is expected to respond quickly to reductions in anthropogenic emission intensity. The Southern Ocean, a major component of the ocean carbon sink, is currently poorly constrained by observations and is expected to evolve in response to climate change (Hauck et al., 2015; Ridge and McKinley, 2020). If not carefully monitored and understood, the changes in the ocean sink could partially mask the effectiveness of the emissions reductions efforts and potentially undermine their continuity and expansion.

In principle, global, space-based measurements of atmospheric CO_2 could dramatically improve the spatial resolution and coverage provided by the *in situ* data. Unfortunately, existing space-based measurements do not have the precision and accuracy needed to resolve the subtle (< 0.1 ppm) CO_2 concentration gradients associated with the weak, spatially-extensive ocean sources and sinks (c.f., Byrne et al., 2023). There are currently no plans for developing and deploying space-based sensors with the precision and accuracy needed to measure ocean CO_2 fluxes.

Improved and sustained, global, space-based observations and models of the ocean carbon cycle are critically needed to enhance the scientific utility of these data and to support carbon management strategies. Space-based estimates of XCO_2 could provide the data needed to upscale carbon fluxes inferred from the sparse *in situ* measurements collected by surface ships and autonomous platforms, but substantial (factor of 5) improvements in their precision and accuracy are needed for this application.

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CSQ-03	**Knowledge Advancement Objectives**	**Geophysical Observables [Links to MIM databases]**	**MIM Number**	**Measurement Specifications**	**Data sets, Methods, Tools & Models**	**Policies / Benefits**
How has the ocean carbon cycle responded to anthropogenic CO2 and climate change?	**A) Track changes in ocean uptake and removal of CO_2 associated with changes in atmospheric CO_2 concentration, sea surface temperature, ocean transport and biological productivity at 1°x1° or higher resolution over the globe?**	**1. Critical Parameters** *Precise/accurate estimates of near-surface atmospheric CO2 and its spatial and temporal gradients*			Atmospheric GHG retrieval algorithms Atmospheric flux inverse models Global ocean biogeochemical models (GOBMs) Enhanced Cal/val	CC mitigation and adaptation policy
		Atmospheric CO_2 dry air mole fraction	CEOS 44	Precise/accurate (0.1 ppm) XCO_2 and XO_2 with resolution of 1°x1° or higher at monthly intervals		
		Sea surface temperature (SST) and salinity				
		Sea Surface salinity	CEOS 152	SST, salinity at a spatial resolution of 1°x1° or higher at daily intervals		
		Sea surface temperature	CEOS 144			
		Surface vector winds				
		Wind speed over sea surface (horizontal)	CEOS 141	Ocean wind speed at a spatial resolution of 1°x1° or higher at daily intervals		
		Wind vector over sea surface (horizontal)	CEOS 143			
		Ocean colour				
		Ocean chlorophyll concentration	CEOS 149			

CSQ-03	**Knowledge Advancement Objectives**	**Geophysical Observables [Links to MIM databases]**	**MIM Number**	**Measurement Specifications**	**Data sets, Methods, Tools & Models**	**Policies / Benefits**
		Ocean suspended sediment concentration	CEOS 150	Ocean colour at a spatial resolution of 1°x1° or higher at daily intervals		
		Colour dissolved organic matter (CDOM)	CEOS 151			
		2. Supporting Parameters				
		Precipitation	CEOS 116	Observations of precipitation at a spatial resolution of 1°x1° or higher daily		
	B) How is the Southern Ocean CO_2 sink responding to climate perturbations and long-term climate change?	**1. Critical Parameters** *Precise/accurate estimates of near-surface atmospheric CO2 and its spatial changes throughout the seasonal cycle*			Atmospheric GHG retrieval algorithms Atmospheric assimilation systems GOBMs Coordination with surface in situ data	
		CO_2 Mole Fraction	CEOS 44	Precise/accurate (0.1 ppm) CO_2 and O_2 at a spatial resolution of 1°x1° or higher at monthly intervals		
		2. Supporting Parameters *Sea Surface Temperature*				
		Sea surface temperature	CEOS 144	SST, salinity & wind at 1°x1°		
		Surface vector winds				

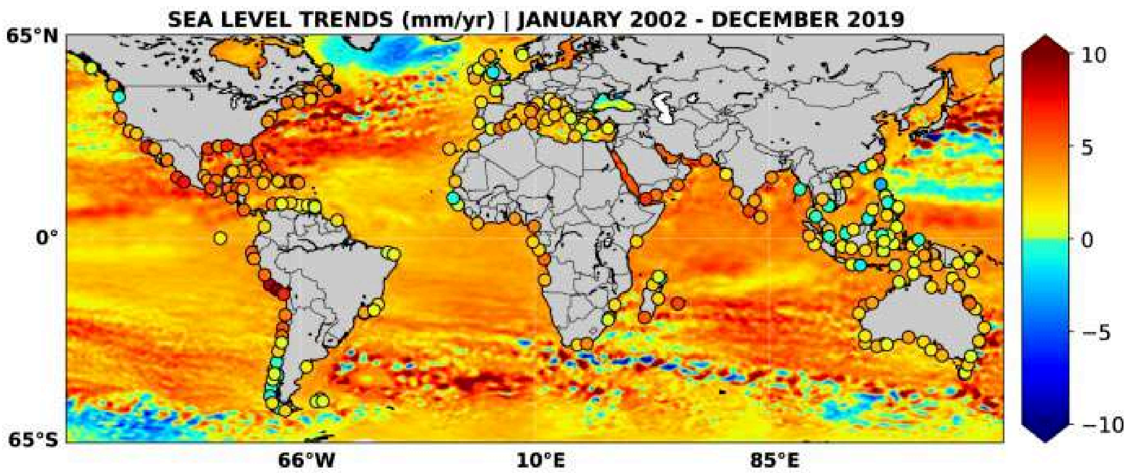
CSQ-03	**Knowledge Advancement Objectives**	**Geophysical Observables [Links to MIM databases]**	**MIM Number**	**Measurement Specifications**	**Data sets, Methods, Tools & Models**	**Policies / Benefits**
		Wind speed over sea surface (horizontal)	CEOS 141	SST, salinity & wind at a spatial resolution of 1°x1° at daily intervals		
		Wind vector over sea surface (horizontal)	CEOS 143			
	C) What is the impact of human activities and climate change on coastal processes that regulate the carbon sink, including river runoff, upwelling and biological productivity?	**1. Critical Parameters** *XCO_2 and its spatial and temporal gradients near coastlines*			In situ reference systems Enhanced techniques for integrating data sources	
		CO_2 Total Column	CEOS 274	Precise/accurate (< 0.5 ppm) XCO_2 at < 1 km resolution		
		SST and salinity				
		Sea surface temperature	CEOS 144	High spatial resolution (< 1km) SST, salinity at daily intervals		
		Sea Surface salinity	CEOS 152			
		Ocean colour				
		Ocean chlorophyll concentration	CEOS 149	High spatial resolution (< 1km) observations of ocean colour at daily intervals		
		Ocean suspended sediment concentration	CEOS 150			

CSQ-03	**Knowledge Advancement Objectives**	**Geophysical Observables [Links to MIM databases]**	**MIM Number**	**Measurement Specifications**	**Data sets, Methods, Tools & Models**	**Policies / Benefits**
		Color dissolved organic matter (CDOM)	CEOS 151			
		2. Supporting Parameters *Surface vector winds*				
		Wind speed over sea surface (horizontal)	CEOS 141	Observations of ocean vector winds and precipitation at a spatial resolution of 1°x1° at daily intervals		
		Precipitation	CEOS 116			

A.4 CSQ-05: What processes drive changes in sea level in the coastal ocean?

Sea Level Rise (SLR) is a critical manifestation of climate change with severe impacts on coastal environments, human activities and infrastructure. Coastal threats associated with SLR include coastline changes, coastal erosion, sediment transport and bathymetry shifts, subsidence, coastal flooding, salt intrusion (aquifers) and loss of coastal habitats and biodiversity. Woodworth et al. (2019) point out the many physical phenomena that can contribute to SLR in coastal regions, including ocean surface waves (Melet et al., 2018), river discharge (Durand et al., 2019) and ocean dynamics (Hughes et al., 2019). International tide gauge networks provide long-term high-quality coastal sea level records at a small number of globally distributed coastal locations. Satellite altimeters measure sea level continuously since early 1990s and provide estimates of SLR on global and regional scales. Recent progress with new sensor technology (Cryosat-2) and coastal processing have led to improved altimeter data quality within 10km of land, bringing the prospect of global EO-based sea level records close to land. Cazenave et al. (2022) report that coastal SL trends within 3.5 km of land are broadly consistent with observed trends further offshore, but that significant – sometimes large - discrepancies remain in many coastal sites worldwide.

Comprehensive observations of the 2D dynamics of the coastal zone are needed to understand the driving processes of coastal SLR in different regions, their relative contributions and space-time composition. The goal is to properly estimate the uncertainty in spaceborne coastal SLR estimates to improve the representation of these processes in models and forecasts, and - combined with improved water level estimates over estuaries, rivers, lakes and reservoirs – to evaluate their interactions and impacts on land-side hydrology. The preliminary findings obtained with the interferometric SWOT altimeter mission signal promising capabilities to improve the uncertainty estimate. As such the planned ESA Copernicus expansion mission (Sentinel-3 Next Generation Altimetry) secures SWOT mission concept continuation.



Coastal trends at virtual stations closer than 3.5 km from the coast are indicated by the black circles. The background map shows regional sea level trends from the C3S data set.

From Cazenave et al. (2022)

Observations and Geophysical parameters required: Key data needs are coastal observations of water level, surface winds, ocean waves (height, period, direction), ocean currents and river flow and discharge. High-resolution 2D imaging as provided by the SWOT mission (and to be continued with ESA Sentinel-3 Next Generation Altimeter mission) is expected to deliver greater understanding of coastal processes by revealing spatial structure in the across- and along-shore directions, and facilitate interpretation with land-side hydrological data. Mass change observations from NGGM and MAGIC should determine the contributions of ice and mountain glaciers to regional patterns of sea-level change to within 0.05 mm/yr over the course of a decade. River runoff and freshwater availability will be estimated in finer temporal and spatial scales with reduced uncertainty compared to GRACE-FO (Daras, I. (Ed), 2023)

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CSQ-05	Specific Objectives (Knowledge Advancement Objectives)	Geophysical Observables [Variable, Source]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
What processes drive changes in sea level in the coastal ocean?	**A) Reduce uncertainties in observing, modelling and forecasting of water levels in coastal, estuarine and inland water bodies**	**Critical Parameters:** For most of the geophysical observable the resolution and revisit times are challenging, compared to the state of the art technologies and observations.			Tide gauges Coastal circulation models Hydrological models Storm surge and flood forecasting systems Coastal morpho-dynamics and coastal erosion models Glacial Isostatic Adjustment (slow process at annual time scale)	Operational coastal and inland flood forecasting systems Climate projections of coastal sea level change
		Sea Level	CEOS 148	Fine resolution (100 m – 1 km) Frequent revisit (6 – 24 h) 2D mapping 0 – 50 km from land Change due to thermosteric effect and mass change (from melting ice sheet and glaciers), atmospheric pressure,		
		Coastal sea level (tide)	CEOS 279	Fine resolution (100 m – 1 km) Frequent revisit (6 – 24 h) 2D mapping 0 – 50 km from land		
		Ocean surface currents (vector)	CEOS-153	Fine resolution (100 m – 1 km) Frequent revisit (6 – 24 h) 2D mapping (along- and across-shore currents) 0 – 50 km from land		
		Run-up waves	NONE	1 km scale		

		Freshwater runoff	OSCAR-132	For estuaries and rivers 100 m or wider		
		Wave directional energy frequency spectrum	CEOS-236	Fine resolution (1 – 5 km) 6 h sampling or finer 0 – 50 km from land		
		Wind speed over sea surface (horizontal)	CEOS 141	Fine resolution (1 km or finer) 6 h sampling or finer 2D mapping 0 – 50 km from land		
		Wind vector over sea surface (horizontal)	CEOS 143.	Fine resolution (1 km or finer) 6 h sampling or finer 2D mapping 0 – 50 km from land		
		Supporting Parameters				
		Sea Surface Temperature	CEOS 144	Existing capabilities adequate		
		Ocean imagery and water leaving spectral radiance	CEOS-154	Existing capabilities adequate		
		Gravity Field	CEOS 185	time-varying gravity at 100km spatial resolution		

		Bathymetry	CEOS-155	need finer spatial and temporal resolution for coastal and estuarine applications		
		Salinity	CEOS 152	altimetry estimation of bathymetry is limited to water depths greater than 100 m, whilst spaceborne optical methods give reliable estimates only for shallow waters less than 30 m deep		
		Ice mass balance (GIA)	NONE	Existing capabilities adequate		
	B) Characterise the relative contributions to coastal sea level changes by steric and other physical processes including freshwater runoffs, vertical land motion (e.g. tectonics, post-glacial rebound), ice mass changes and associated gravitational effects	• As above				

A.5 CSQ-07: How do coastal processes mediate exchanges between land, atmosphere and the open ocean?

The coastal ocean, defined as the area between the continental slope and estuaries, links the terrestrial, marine and atmospheric environments through a multitude of physical and biogeochemical processes. Exchanges between the coastal ocean and the deep ocean control the transport of heat, nutrients, carbon, gases, and freshwater, as well as the export of pollutants such as waste water and plastic. Although the coastal zone is proportionally small, it is the most biologically productive part of the ocean, responsible for the majority of the world's fish catch (Siefert & Plattner, 2004). By absorbing anthropogenic CO2 and contributing to long-term burial of organic matter and calcium carbonate, it plays an important role in the global carbon cycle. Updated compilation of air-sea CO2 fluxes based on observations in the literature show that the global coastal ocean represents an integrated CO2 sink of −0.25 ± 0.05 Pg C year−1, confirming its role as an efficient sink for CO2, particularly at high latitudes (Dai et al., 2022). Coastal regions dominated by rivers show marked differences in exchanges, transport and intrinsic biogeochemical reactions. However, it remains unclear to what extent coastal areas around the globe are taking up or releasing carbon, how much of the carbon exported from the coastal areas enters the deep ocean and how these fluxes are changing. Constraining uncertainties and developing predictive modelling capability remains hindered by the need to resolve fine scale fast-evolving processes and the paucity of observations to validate and improve models (Mathis et al., 2022; Roobaert et al., 2019). Satellite EO has the means to provide improved and new observations of land, coastal, open ocean and atmospheric conditions to determine physical and biogeochemical processes and their interactions, improve their representation in model predictions and climate projections and reduce uncertainties in estimated contributions by the coastal ocean to global carbon, energy and water budgets.

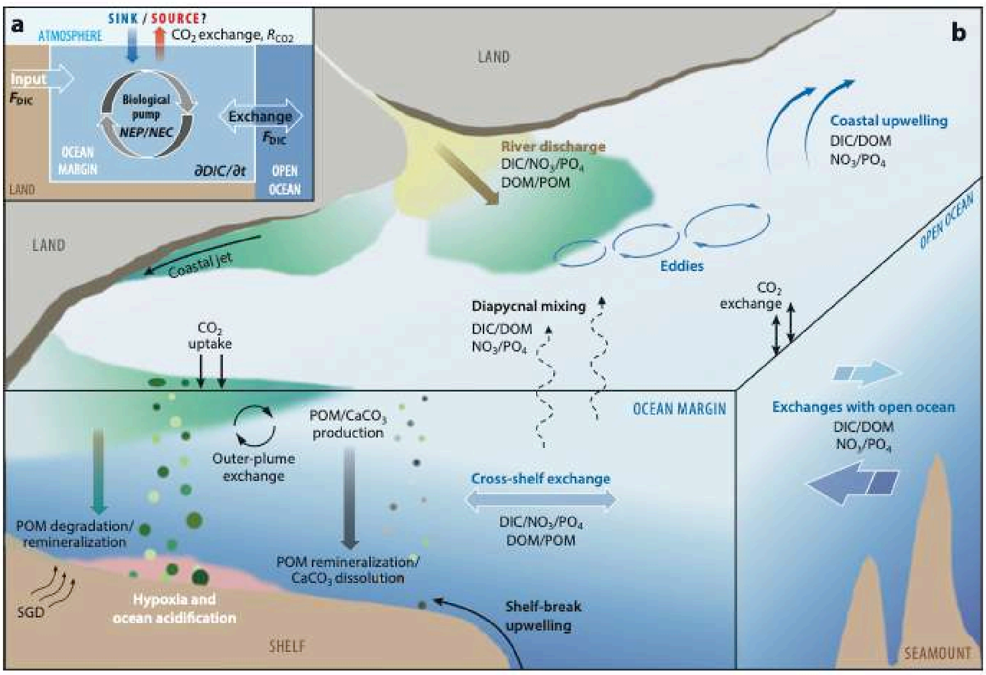

Figure 1

Conceptual schematics of air-sea CO_2 exchanges (*a*) and major physical and biogeochemical processes in the coastal ocean (*b*), highlighting the transport of matter between land, ocean margin, and open ocean. (*a*) The sea-air CO_2 flux (R_{CO_2}) is balanced by the sum of DIC inputs and outputs (F_{DIC}) across the boundaries, the NEP and NEC, and the change in the amount of DIC over time ($\partial DIC/\partial t$) within the coastal system (Equation 1 in the text). (*b*) The ocean margin is bordered by the coastline on the land side and by the open ocean on the outer side. Rivers discharge DIC, NO_3, PO_4, DOM, and POM onto the continental shelf via a buoyant plume,

From Dai et al. (2022)

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CSQ-05	**Specific Objectives (Knowledge Advancement Objectives)**	**Geophysical Observables [Variable, Source]**	**MIM Number**	**Measurement Specifications**	**Data sets, Methods, Tools & Models**	**Policies / Benefits**
How do coastal processes mediate exchanges between land, atmosphere and the open ocean?	**A) Determine the physical processes that control land-air-sea exchanges in coastal regions.**	**Critical Parameters:** For most of the geophysical observable the resolution and revisit times are challenging, compared to the state of the art technologies and observations.			Tide gauges Storm surge models Coastal circulation models at 1km or finer grid spacing Numerical wave models Coupled atmosphere-wave-ocean prediction/assimilation systems Coastal, regional and climate biogeochemical models – CMIP Coastal buoys (wind, waves, ..) Lagrangian models for tracking surface drift and spreading	UN Decade of the Ocean (CoastPredict) UN Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas and marine resources GCOS, GOOS, and WCRP (ECVs) IPCC, Climate mitigation policy Food security UN SDG Goal 2: Zero Hunger UN SDG Goal 13: Climate action Marine Protected Areas (MPA)
		Sea Level	CEOS 148	1km or finer. Fast revisit (daily, sub-daily, hourly)		
		Coastal sea level (tide, storm surge)	CEOS 279	1km or finer Fast revisit (daily, sub-daily, hourly)		
		Wave directional energy frequency spectrum	CEOS-236	Fine resolution (1 – 5 km) 6 h sampling or finer 0 – 50 km from land		
		River runoff/Freshwater fluxes	OSCAR-132	TBD		
		Sea surface salinity	CEOS 152	Fast revisit (daily, sub-daily, hourly)		

		Ocean surface currents (vectors)	CEOS 153	1km or finer Fast revisit (daily, sub-daily, hourly)		Marine Spatial Planning (MSP) Water Framework Directive
		Chromophoric dissolved organic matter (CDOM)	CEOS-151	10-50 metres		
		Dom (or FDOM)	NONE	10-50 metres		
		Supporting Parameters				
		Ocean Salinity	CEOS-281	1km or finer Fast revisit (daily, sub-daily, hourly)		
		Ocean imagery and water leaving spectral radiance	CEOS 154	10-50 metres Fast revisit (daily, sub-daily, hourly)		
		Wind speed over sea surface (horizontal)	CEOS 141	1km or finer Fast revisit (daily, sub-daily, hourly)		
		Wind vector over sea surface (horizontal)	CEOS 143	1km or finer Fast revisit (daily, sub-daily, hourly)		

		Wind stress	CEOS-206	1km or finer Fast revisit (daily, sub-daily, hourly)		
		Evaporation (ocean)	NONE	1-10 km Fast revisit (daily, sub-daily, hourly)		
		Precipitation	CEOS-116	1-10 km Fast revisit (daily, sub-daily, hourly)		
		Sea surface temperature	CEOS 144	Fast revisit (daily, sub-daily, hourly)		
		Ocean Temperature (include Marine Heatwaves)	CEOS 284			
		Bathymetry	CEOS 155	10-50 metres Fast revisit (daily, sub-daily, hourly)		
		Land Surface Imagery	CEOS-181	Mapping of Mangroves, river deltas, sediment transport, Coastal erosion .		

				2D mapping to observe space-time variability in complex coastal setup, with swath sensors or constellations. Measurements up to the land/water edge with uncertainty levels similar or better than offshore		
	B) Determine the interactions between physical and biogeochemistry processes and marine productivity in the global coastal ocean.	*As above, plus*				
		CO2 Mole Fraction	*CEOS-44*	*pCO2measurement*		
		Nutrient discharge	*NONE*	For estuaries and rivers 100 m or wider		
	C) Reduce uncertainties in the global coastal ocean contributions to global land-air-sea fluxes of heat, nutrients, carbon, gases, and freshwater.	*As A)*				

A.6 CSQ-08: How are coastal areas contributing to the global carbon cycle, and how are they responding to climate change and human pressures?

"Blue carbon" ecosystems such as mangroves, seagrass beds, tidal marshes and other marine and coastal vegetated ecosystems are among the most intense carbon sinks on the planet. Coastal habitats cover less than 2% of the total ocean area but account for approximately half of the total carbon sequestered in ocean sediments (https://www.thebluecarboninitiative.org). Together with delivering valuable climate services, coastal ecosystems also offer effective nature-based solutions for coastal and estuarine protection (de **Moraes** et al., 2022). But there is growing evidence that these ecosystems are under theat. Amongst the top 10 science questions to set the direction for Blue Carbon research, McCreadie et al. (2019) lists the need for more accurate estimates of the global extent and temporal distribution of Blue Carbon ecosystems, notably tidal marshes and seagrass area which are poorly quantified outside industrialised countries. Estimating the net flux of greenhouse gases between Blue Carbon ecosystems and the atmosphere, accounting for fluxes of GHGs like CH4 and N2O as well as CO2, highlights the need for more comprehensive assessments of the contribution of these coastal ecosystems to the global carbon cycle.

In polar regions though, the contribution of coastal environments to the global carbon cycle could be quite different in response to climate change. Sediment cores in the Arctic indicate that degrading permafrost under the action of sea-level rise and coastal erosion led to the mobilization of terrestrial carbon, and likely contributed significantly to changes in atmospheric CO2 around 14.6 and 11.5 kyrs BP (Winterfeld et al., 2018). Projections confirm that increased coastal erosion in the Arctic under the influence of global warming, retreating sea ice and greater scouring by wind, waves and currents (Nielsen et al., 2022) could lead to significant organic carbon releases from melting permafrost.

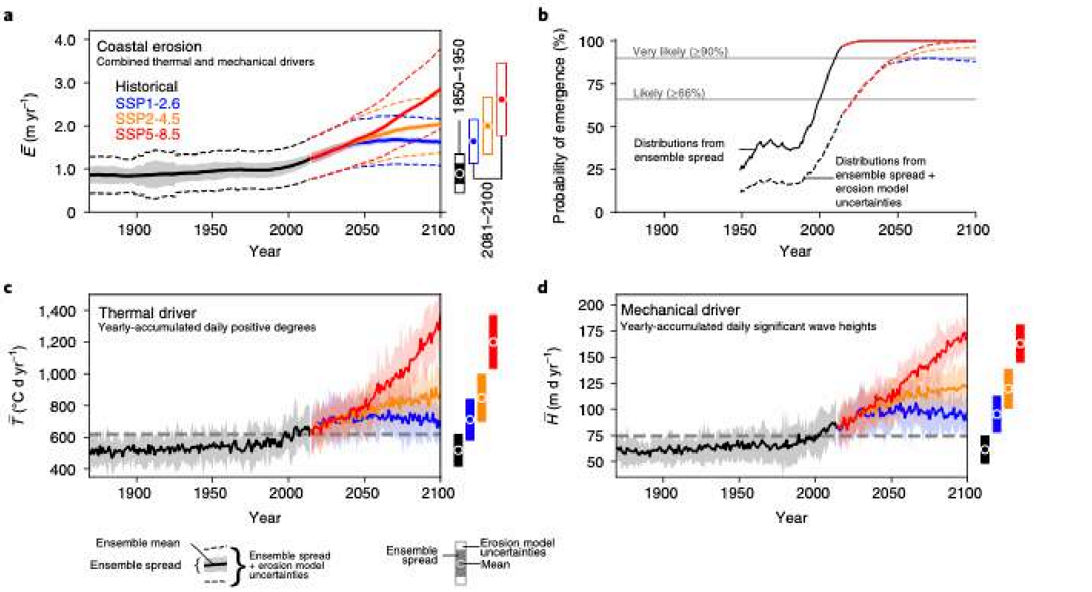

Fig. 1 | Arctic coastal erosion projections. a, Time evolution of the Arctic-mean coastal erosion rate, expressed as the combined effect of its thermal and mechanical drivers. **b**, Yearly probabilities that the Arctic-mean coastal erosion rate leaves the historical range of variability, calculated from distributions of ensemble spread and erosion model uncertainties (see Methods). In all scenarios, it is very likely (>90% probability) that the Arctic-mean erosion emerges from its historical range by mid-twenty-first century, although the exact time of emergence is sensitive to our erosion model uncertainties. **c**,**d**, The thermal (**c**) and mechanical (**d**) drivers of erosion, expressed as yearly-accumulated daily positive degrees and significant wave heights, respectively. The erosion time series depict long-term means and therefore show little interannual variability in comparison with its drivers. Dashed horizontal grey lines in **c** and **d** mark the upper bound of the historical range of variability for the erosion drivers, defined as 2σ from the ensemble mean.

From Nielsen et al. (2022)

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CSQ-08	Knowledge Advancement Objectives	Geophysical Observables	MIM Number	Measurement Requirements	Tools & Models	Policies / Benefits
How are coastal areas contributing to the global carbon cycle, and how are they responding to climate change and human pressures?	**A) Global inventory of Blue carbon ecosystems, including mangroves, tidal marshes and seagrass beds** **B) Determine the extent of permafrost degradation and organic carbon releases in the polar coastal ocean**	**Critical Parameters:** For most of the geophysical observable the resolution and revisit times are challenging, compared to the state of the art technologies and observations.			Coastal to regional models Earth System models Climate forecasts CMIP	Nature-based solutions Restoration efforts Improve projects Climate change adaptation and mitigation policy. Polar region treaties IPCC monitoring and Paris agreement Marine Protected Area Marine Spatial Planning Water Framework Directive
		Chlorophyll concentration	CEOS-149	High spatial resolution (10-50m) for SST, bathymetry, canopy height, biomass Sentinel-1/Sentinel-2 type imaging with daily or better revisit Multi-frequency SAR/InSAR for multiple penetration depths of dense vegetation and snow		
		Ocean subsurface dissolved oxygen concentration	CEOS-282			
		pH	OSCAR-125			
		River discharge (include nutrients)	OSCAR-132			
		Ocean suspended sediment concentration	CEOS-150			
		SST	CEOS-144			
		Permafrost	OSCAR-124			
		Sea Level	CEOS-148			
		Waves	CEOS – 145/146/147			
		Supporting Parameters				
		Sea surface temperature	CEOS144			

		Air temperature (2 m)				
		Sea ice surface temperature	CEOS-158			
		Land Surface temperature	CEOS170			
		Snow surface temperature	CEOS246			
		Ocean Temperature	CEOS284			
		salinity	CEOS152			
			CEOS281			
		soil moisture	CEOS171			
		soil moisture	CEOS239			
		freeze thaw	CEOS297			
		surface inundation	CEOS298			
		Ocean surface currents (vector)	CEOS-153			

		Coastal zone features (mangroves, tidal flats, kelps) [land surface imagery]	CEOS-181			
	C) Determine contribution and drivers of change in "Blue carbon" ecosystems, and their resilience to human and climate change pressures in different coastal regions **D) Determine contribution and drivers of change in permafrost in the polar coastal ocean, and its resilience to human and climate change pressures in different coastal regions**	**Supporting Parameters**				
		2D surface winds vectors	CEOS140			
			CEOS141			
			CEOS142			
			CEOS143			
		Wind stress	CEOS-206			
		directional wave spectra including integral wave parameters (wave height, period, direction)	CEOS-236,			
			CEOS-258,			
			CEOS-145,			
			CEOS-146,			
			CEOS-147			
		2D total surface current vectors	CEOS-153			

A.7 CSQ-20: What are the key drivers for the mass balance change of the ice sheet, the ice shelves and the glaciers?

Fluctuations in Earths ice mass have occurred in almost all regions of the cryosphere, in response to change in environmental forcing mechanisms and as a longer-term response to climate change. Satellite observations have shown that the mass balance of the Antarctic and Greenland Ice Sheets (see Figure 1) has changed dramatically over the last 40-years, with ice loss increasing by six times over this period, increasing global sea levels by 17.8 mm (The IMBIE team, 2018). While in Greenland surface melt driven lubrication drives the majority of ice mass loss, in Antarctica the dominant process is warm ocean water driven melt, demonstrating that the dominant physical process is different in the North and South Hemispheres. While the ice sheets contribute one third of the total sea level rise budget, ice loss is also occurring on mountain glaciers and ice caps. Observations have shown that glacier mass loss has increased from -120 Gt per year in the 1970 to -327 Gt per year between 2010 and 2019. In mountain glacier regions the dominant cause of ice loss is increasing air temperatures (Slater et al., 2021).

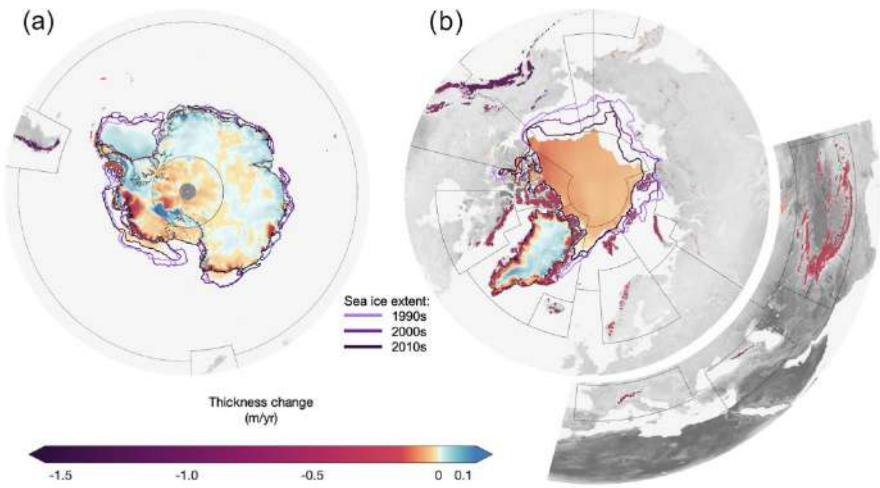

Fig. 1: Average rate of ice thickness change in the (a) Southern Hemisphere and (b) Northern Hemisphere. Changes in Antarctic (1992– 2017) and Greenland ice sheet (1992–2018) thickness were estimated using repeat satellite altimetry following the methods of Shepherd et al. (2019). Sea ice thickness trends between 1990 and 2019 are determined from numerical sea ice and ocean modelling (Zhang and Rothrock, 2003), as well as the average minimum of sea ice extent in February (Antarctic) and September (Arctic) (purple lines) for each decade during the same period. Glacier thickness change between 1992 and 2018 for glacier regions defined in the Randolph Glacier Inventory (RGI Consortium, 2017) (black boundaries) are from mass change estimates (Braun et al., 2019; Foresta et al., 2016; Jakob et al., 2020; Tepes et al., 2021; Wouters et al., 2019; Zemp et al., 2019b) which have been converted to a thickness change assuming an ice density of 850 kg m−3. From Slater et al., 2021.

Ice (sheet, shelves, glaciers) dynamics, which relates to the change in the rate of ice flow (see Figure 2), are responsible for approximately one third of all ice mass loss on the Greenland Ice Sheet, and almost all (98%) ice mass loss on the Antarctic Ice Sheet (Slater et al., 2021). The IPCC reports that the largest remaining uncertainty in the ice sheet contribution to sea level rise is linked to ice dynamics, where the speedup of glaciers can lead to imbalance and then instability, through the Marine Ice Sheet Instability (MISI) and

Marine Ice Cliff Instability (MICI) mechanisms. In Antarctica ice dynamics are thought to be largely driven by incursions of warm, deep circumpolar water onto the continental shelf, which causes enhanced melt (Dutrieux et al., 2014). More recently, the very high temporal resolution (weekly) satellite observations from operational ESA-EC missions such as Sentinel-1a and -1b, have enabled short-term, seasonal changes in ice speed the be better characterized on the Greenland Ice sheet, and observed for the first time in Antarctica (Wallis et al., 2023). This enables short-term ice dynamics to be studied in more depth, providing further insight with which changes in ice speed can occur, and enabling us to better understand the physical processes driving this change in different regions of the world. In future, the capabilities of SAR missions for monitoring surface change will be augmented by gravity missions such as NGGM and MAGIC to Improve knowledge of the dynamic response of ice flow to changing oceanic and atmospheric boundary conditions, including interactions with intra- and sub-glacial hydrology (Daras et al 2023).

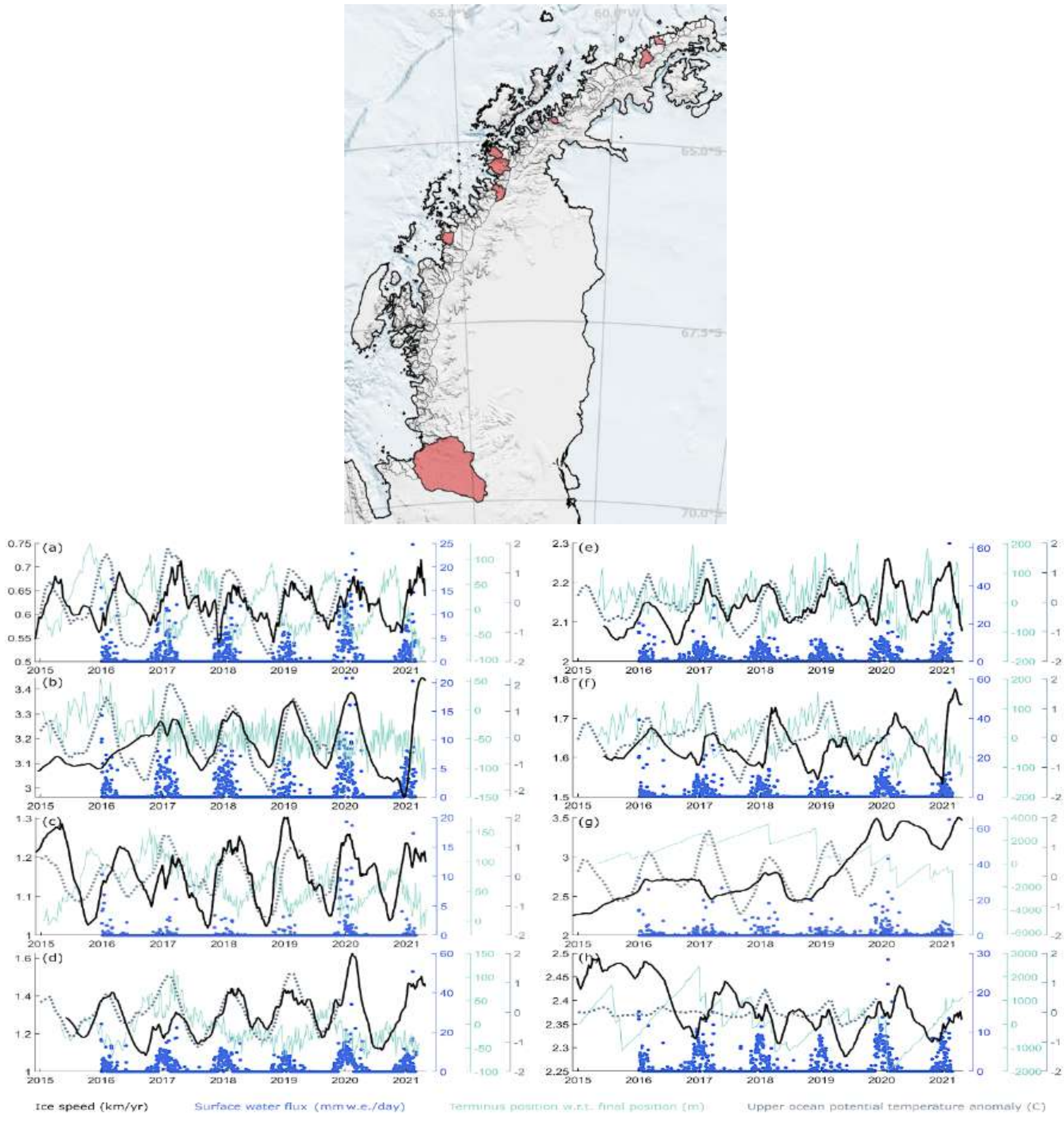

Fig. 2: Highlight glaciers' time series of ice speed, surface water flux, terminus position and upper ocean potential temperature anomaly at the Antarctic Peninsula for unnamed north Bone Bay (a), Gavin Ice Piedmont (b), Leonardo (c), Hotine (d), Trooz (e), Keith (f), Cadman (g) and Fleming (h) Glaciers. Time series of Kalman-smoothed ice speed (black solid line), Highlight glaciers in a–f were selected based on their large seasonal ice speed variability (autocorrelation values of 0.648, 0.314, 0.586, 0.703, 0.575 and 0.575, respectively), From Wallis et al., 2023.

Overall, the rate of ice loss on Earth has increased by 57 % since the 1990's, increasing the cryosphere's contribution to global sea level rise. However, there is a need to better quantify the regional variability in the change in ice mass of different elements of the cryosphere (also accounting for permafrost, snow and sea ice decline), and to understand the physical mechanisms driving this change

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CSQ-20	Specific Objectives	Geophysical Observables	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
What are the key drivers for the mass balance change of the ice sheet, the ice shelves and the glaciers?	A) Improve the quantitative estimation of change and variability in the key components of the cryosphere, including: • Ice sheet mass balance • Ice shelf mass balance • Glacier area and volume and mass balance Improve the projections of future ice mass loss and its impact on sea level rise. Advance the understanding of ice shelves – ocean interaction and its	**Critical Parameters**			CEOS DB measurements Sensor synergy Bedrock topography data. Regional climate model estimation of surface mass balance components. Reprocessing. Use of AI/ML for simulation of ice flow speed and calving rates.	Delivering on Paris agreement. Reduced uncertainties in IPCC AR. Improved reliability of CMIP simulations. Climate change adaptation and mitigation (e.g. indigenous people).
		Ice sheet topography	CEOS-243	Sustain global record of mass loss at best possible temporal and spatial resolution for all variables. Minimum monthly to weekly at medium (1-5 km) resolution. Bedrock topography (1-5 km) Ice flow speed (1 km) Calving front location (~ 10s of m to 100 m) Calving rate (weekly) Grounding line location (~ 10s of m to 100 m) Gravity field variations at 100km resolution		
		Snow Cover	CEOS-163			
		Snow depth	OSCAR-206			
		Snow water equivalent	CEOS-165			
		Calving front location	NONE			
		Calving rate	NONE			
		Grounding line location	NONE			
		Ice surface melt and freshwater runoff	NONE			
		Bedrock topography	NONE			
		Permafrost Extent	OSCAR-124			
		Gravity field	CEOS-185			

	impact on deep water formation and the global Meridional Overturning Circulation.	Glacier motion	CEOS-167	High (~100 m) spatial resolution measurements required for glaciers and drainage basins.	What/if simulation of future changes in ice flow and calving rates.	
		Supporting parameters			Ocean temperature and salinity change, through the full water column.	
		Air temperature (2 m above surface)	CEOS-138	(1-5 km)		
		Ice surface temperature	CEOS-170, CEOS-246	(1-5 km)	Modelling of underwater ice shelf melting	
		Ocean temperature (bottom of ice shelves)	NONE	1km horizontal, 10-50M vertical		
		Ocean currents (bottom of ice shelves)	NONE	1km horizontal, 10-50M vertical		
		Snow accumulation Rate	CEOS-116	(1-5 km)		
		Snow melting	NONE	(1-5 km)		
		Permafrost Thawing	NONE			

	B) Strengthen the quantitative understanding of the regional pattern of change and variability in ice mass loss.	As above.		As above Target the 3-poles (Greenland, Antarctica, Tibetan plateau) Other mountain glaciers in Europe, North- and South America	As above. NRT raw satellite data access and automated processing chains for online portal services.	

A.8 CSQ-21: What are the dominant physical processes that drive the sea ice thermo-dynamic state and variability?

As the sea ice cover breaks up it exposes the underlying warmer ocean to the atmosphere within narrow elongated openings in the sea ice cover known as leads. This has important consequences for air-sea momentum, heat and gas exchanges, mesoscale eddy generation and dynamics and sea ice production. In particular, during winter months when the heat fluxes over sea ice are generally low, the oceanic heat loss within leads may cause air surface temperature rise of more than 20°C. In turn, this enhances turbulent convection in the atmospheric boundary layer, possibly driving further breakup and sea ice production. The sea ice breakup in winter due to storm events combined with long-distance wave propagation also weaken the sea ice cover, potentially preconditioning the minimum sea ice extent in the subsequent summer (Babb et al., 2019), thus creating a positive feedback to Arctic amplification (Esau et al, 2023). Extreme sea ice breakup events, expected to increase due to global warming, are therefore of crucial importance for understanding the seasonal to long-term evolution and change of sea ice extent and volume, which, in turn, affects weather, ecosystems, and local communities in polar regions and beyond (Forbes et al., 2016).

In a recent neXtSIM-based sea ice simulation experiment Rheinlænder et al., (2022) successfully captured the main features of the sea ice breakup in the Beaufort Sea observed in the MODIS satellite images during a 2-week period in February 2013 (see Figure 1). They also documented significant impact of the storm induced breakup event on the evolution of sea ice volume over the remaining winter in 2013.

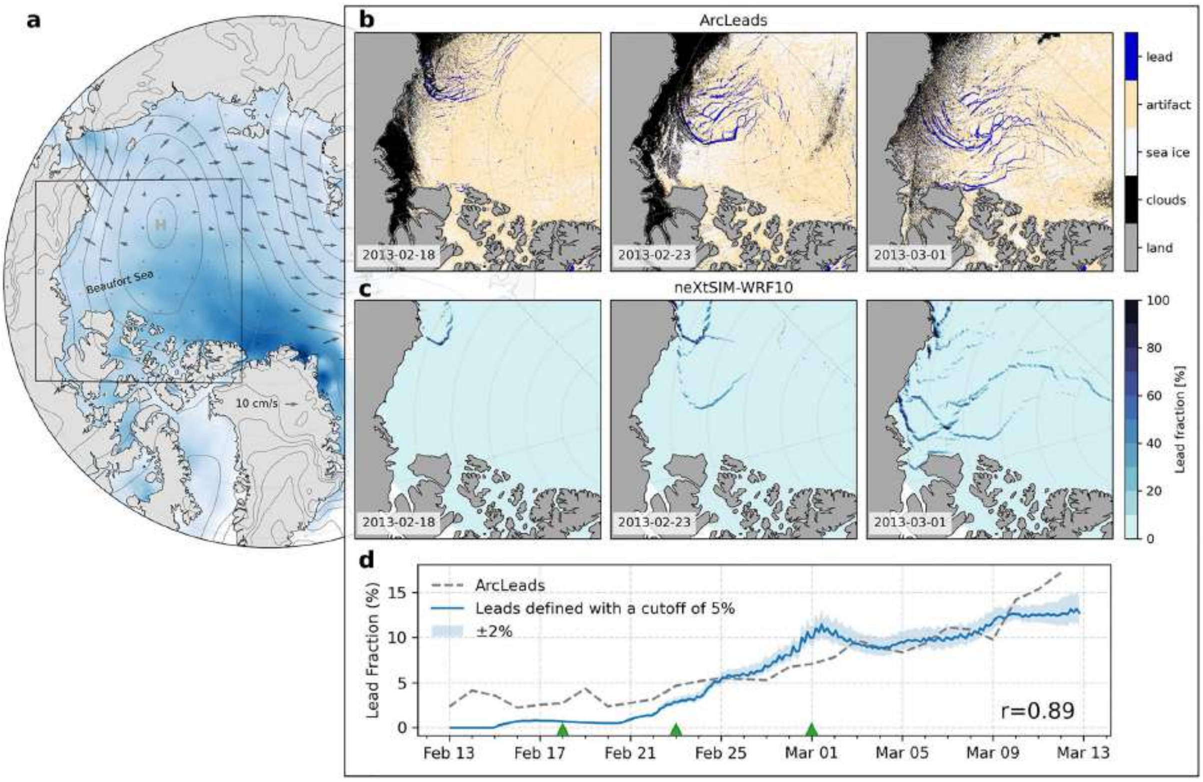

Figure 1. (a) Map of observed winter sea ice thickness from CS2/SMOS (shaded), ice flow from neXtSIM (arrows), and mean sea-level pressure from ERA5 (solid and gray lines) on 23 February 2013. (b) Daily maps of sea ice breakup derived from MODIS. (c) neXtSIM-based lead fraction simulation

using WRF10 as the atmospheric forcing. (d) Time series of lead area fraction in the Beaufort Sea for the neXtSIM model (blue) and Arcleads (gray-dashed line).

The opening of leads trigger increased heat and buoyancy fluxes that in turn affect large-scale sea ice dynamics and drift (Cohanim et al., 2021) as well as enhanced sea ice transport out of the Arctic Ocean. The latter will result in a thinner and weaker sea ice cover by the start of the melting season, which could promote an earlier breakup of sea ice in spring. In turn, the albedo feedback would strengthen and stimulate further melting of sea ice (Dai et al.,2019). The increase in sea ice drift will also promote enhanced ocean mixing, strengthen mesoscale eddy generation mechanisms and more under sea ice melting as warmer water are upwelled from below (Graham et al.,2019). Most of these processes and feedbacks occur at fine to intermediate spatial and temporal scales, and they are not properly simulated in CMIP-type climate models (Hutter et al., 2022). All in all, the short term to long term variations in the sea ice thermodynamics are dominated by multiple drivers that are acting in a highly complex and interactive manner both in space and time. Our quantitative understanding of the thermodynamic state and variability of sea ice is therefore fragmented and restricts the development of sub-grid-scale parameterizations in climate model simulations. As such, we are faced with a significant demand for advances in the observing system combined with the need for innovative development and implementation of data driven physical constrained analytics, LES simulations, AI/ML methods and novel modelling and forecasts.

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CSQ-21	**Knowledge Advancement Objectives**	**Geophysical Observables [Links to MIM databases]**	**MIM Number**	**Measurement Specifications**	**Data sets, Methods, Tools & Models**	**Policies / Benefits**
What are the dominant physical processes that drive the sea ice thermo-dynamic state and variability	Quantify the impacts of a declining sea ice field on the interaction between the atmospheric boundary layer and the upper ocean. Reduce uncertainties in estimates of snow depth, freeboard height and sea ice thickness. Improve the quantitative understanding of the role of sea ice for the marine ecosystem. Identify teleconnections and the influence of a changing polar region at mid-latitude. Quantify the impact of reducing sea ice extent and thickness	**Critical Parameters**			CEOS DB measurements Reprocessing Sensor synergy, colocation and co-variability analyses based on data driven physical constrained approach. Large Eddy Simulation (LES) experiments for studies of coupled atmosphere boundary layer - sea ice-upper ocean interaction in the presence of a declining sea ice field. Use of AI/ML and sensor synergy for simulation of sea ice damage, lead fraction and new sea ice production.	Climate change adaptation and mitigation policy (e.g. indigenous people). Reduced uncertainties in IPCC AR. Improved reliability of CMIP simulations. Impact of warmer Polar region atmospheres for mid-latitude weather and climate. Impact of fresher Polar regions on deep water formation and hence MOC.
		Sea ice surface roughness (partially covered)	OSCAR-200	<10km		
		Sea ice age (type)	CEOS 157	<5km		
		Ice Surface stress (challenging) CEOS-206 is for ocean	CEOS-206	<10km		
		Under ice stress (highly challenging)	None	<10km		
		Sea ice motion	CEOS 255	<5km		
		Sea ice thickness/Freeboard height	CEOS 193	<5km horizontal <5cm accuracy vertical		
		Snow depth on ice	None	<5km horizontal <5cm accuracy vertical		
		Sea ice volume (thickness + cover)	CEOS 193 + CEOS 156	<5km		

	on the Arctic Amplification	Waves in sea ice (challenging)	None	100m	neXtSIM (sea ice model) what/if simulations and predictions. Marine ecosystem model simulations.	Safe navigation - ship routing across the Arctic Ocean.
		Lead fraction/damage (in sea ice characteristics ?)	None	100m		
		Melt ponds (in sea ice characteristics ?)	None	100m		
		Supporting Parameters				
		Sea surface salinity	CEOS 152	TBD		
		Surface temperature (sea ice/ocean)	CEOS 144 / CEOS 158	TBD		
		Air temperature (2 meter)	CEOS 138	TBD		
		Ocean surface currents (vectors)	CEOS 153	1km or finer		
		Wind speed over sea surface (horizontal)	CEOS 141	1km or finer		
		Wind vector over sea surface (horizontal)	CEOS 143	1km or finer		
		Directional wave spectra: Significant wave height	CEOS 145	1km or finer		
		Directional wave spectra: Dominant wave period	CEOS 146	1km or finer		
		Fast ice extent	None			

	Determine how dominant processes differs between the two Polar regions. Is the strength and extent of the sea ice cover imposing blocking effects on ice shelve surge?	As above. (No multiyear sea ice present around Antarctica)		As above Flooding of sea ice due to heavy snow load at 1-5 km resolution.	As above	

A.9 CSQ-24: Determine the relationship between changes in Polar regions and global climate variability

The remote Polar regions are geographically far away from other environments on Earth, however changes in the Poles can have dramatic impacts on the global climate system. The cold high elevation ice masses, reflect a large proportion of the suns incoming radiation, and affect atmospheric circulation and weather patterns in the mid latitudes. When cold freshwater is input to the ocean through ice melt, this can lead to ocean freshening and change in the strength of ocean circulation. Similarly, we now know that major climate cycles, such as La Nina and ENSO, are directly responsible for driving the decadal cycle of ice shelf melt in West Antarctica (Jenkins et al.), demonstrating the long-range tele-connections between the polar regions and the equator. The impact of global climate variability on the Polar regions, and vice versa, should be studied to better understand the complexity of Earths systems.

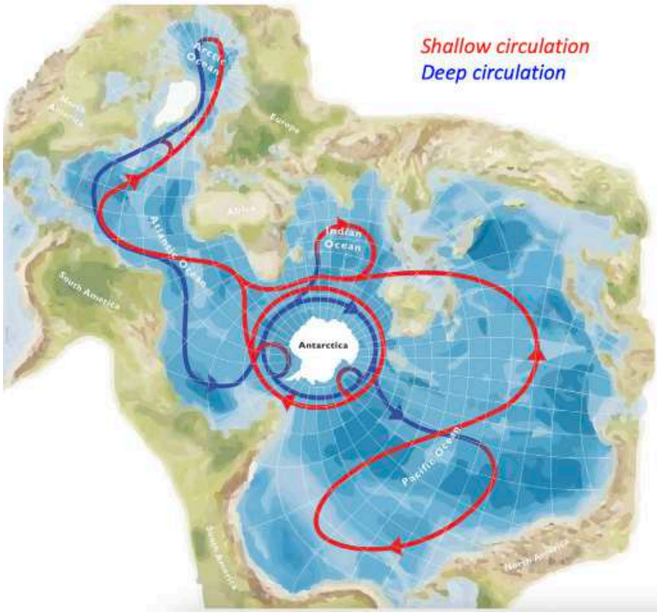

Fig. 1: Shallow and deep ocean circulation pathways between the Arctic and Southern oceans.

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CSQ-24	Specific Objectives (Knowledge Advancement Objectives)	Geophysical Observables [Variable, Source]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
Determine the relationship between changes in Polar regions and global climate variability?	Determine what impact the polar regions have on global climate variability. Changes in albedo, mass, geoid, freshwater flux, sea level, sea ice extent, thickness, air temperature, atmospheric boundary layer height, upper ocean stratification, deep water formation, ocean circulation, mean sea level pressure, atmospheric circulation.	**Critical Parameters**				
		Earth Surface Albedo	CEOS-218	Weekly At least 1km Multi-decadal (30-40 year) records	EO satellite datasets. Reprocessing Climatology data including global temperature, ocean temperature and salinity, atmospheric winds CMIP Reanalyses Large Eddy Simulation (LES) experiments for studies of coupled atmosphere boundary layer - sea	Climate change adaptation and mitigation policy. IPCC monitoring.
		Ice sheet mass balance Ice sheet topography Gravity field	CEOS-243 CEOS-185	Weekly At least 1km Multi-decadal (30-40 year) records		
		Ice shelf mass balance Ice sheet topography	CEOS-159	Weekly At least 1km Multi-decadal (30-40 year) records		
		Deep water formation/ocean circulation (AMOC)	NONE	Seasonal Multi-decadal		

		Ocean temperature and salinity	CEOS-284 CEOS-281	Weekly 10km, all weather Multi-decadal (30-40 year) records	ice-upper ocean interaction. Use of AI/ML and sensor synergy for simulation of sea ice damage, lead fraction and new sea ice production. Improved measurements of SST and SSSunder clouds (using MW)	
		Sea ice thickness and extent	CEOS-193 CEOS-255	Weekly At least 1km Multi-decadal (30-40 year) records		
		Atmospheric pressure field (AO, NAO, PDO, PO)	CEOS-136 CEOS-137	Seasonal Multi-decadal	Atmospheric pressure field (AO, NAO, PDO, PO)	

		Permafrost extent Permafrost depth	OSCAR-124 NONE	Weekly At least 1km Multi-decadal (30-40 year) records		
		Atmospheric winds	CEOS-140 CEOS-142	Weekly At least 1km Multi-decadal (30-40 year) records		

A.10 CSQ-25: How does the cryosphere impact on Polar ecosystems, and how is the changing climate altering these feedbacks?

Ice mass loss from the cryosphere delivers large volumes of cold freshwater input, and nutrients into the ocean. These freshwater inputs are visible as meltwater plumes around the ice sheets and marine terminating glaciers and ice caps, and may also cause change in the nutrient content of proglacial lakes on land terminating ice regions. In the ocean, these meltwater plumes serve as an important source of nutrients, driving the formation of algal blooms which are observable themselves from multi-spectral optical images, which in-turn are a source of food for krill. As the food chain goes up, krill are a vital source of protein for many larger mammals including whales, seals, fish and penguins, supporting the whole of the Polar ecosystem. As ice mass loss increases over time, the freshwater input to the oceans is changing, which may also alter the primary productivity of our oceans. Other polar datasets such as sea ice, provide an important habitat that breeding populations of penguins live on in the Antarctic, and polar bears hunt on in the Arctic. As sea ice extent and thickness change over time, this will impact these populations, and these changes must be monitored by satellite measurements (Fretwell et al., 2021).

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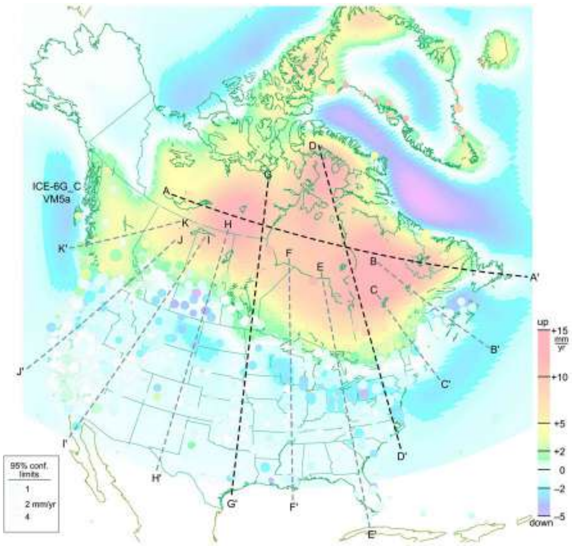
CSQ-25	Specific Objectives (Knowledge Advancement Objectives)	Geophysical Observables [Variable, Source]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
How does the cryosphere impact on Polar ecosystems, and how is the changing climate altering these feedbacks?	**A) Determine the impact of the cryosphere on Polar ecosystems, such as through freshwater input to the ocean.**	**Critical Parameters**			EO satellite datasets. Auxiliary data including global temperature, ocean temperature and salinity, atmospheric winds	Climate change adaptation and mitigation policy. IPCC monitoring.
		Freshwater input to the ocean from the cryosphere • Ice sheet discharge: Ice sheet topography	CEOS-243	Weekly 100m Multi-decadal (30-40 year) records		
		Sea Ice sheet topography	CEOS-243	Weekly 100m Multi-decadal (30-40 year) records		
		• River discharge	OSCAR-132	Weekly- monthly Multi-decadal (30-40 year) records		
		Sea ice cover	CEOS-159	Weekly- monthly ~1 km Multi-decadal (30-40 year) records		
		Ocean colour in the Polar-ocean and sea ice marginal zone • Ocean chlorophyll concentration ()	CEOS 149	Weekly- monthly ~1 km Multi-decadal (30-40 year) records		
		Sediment plume location and frequency • Ocean suspended sediment concentration (CEOS 150)	CEOS-150	Weekly 100m Multi-decadal (30-40 year) records		
		• Dissolved inorganic carbon (CEOS 280)	CEOS-280	Weekly		

				100m Multi-decadal (30-40 year) records		
		• Euphotic depth	NONE	Weekly 100m Multi-decadal (30-40 year) records		
		• Mixed layer depth	NONE	Weekly 100m Multi-decadal (30-40 year) records		
		Primary productivity measurements (land) • Leaf Area Index (LAI) • Fraction of Absorbed PAR (FAPAR)	CEOS-173 CEOS-175	Weekly 100m Multi-decadal (30-40 year) records		
		Earth surface Albedo	CEOS-218	Weekly 100m Multi-decadal (30-40 year) records		
		Supporting Parameters				
		Sea Surface Salinity	CEOS-152	Monthly 1-10 km Multi-decadal (30-40 year) records		
		SST	CEOS-144	Monthly 1-10 km Multi-decadal (30-40 year) records		
		Wind speed over sea surface (horizontal)	CEOS 141	1km or finer Fast revisit (daily, sub-daily, hourly)		

		Wind vector over sea surface (horizontal)	CEOS 143	1km or finer Fast revisit (daily, sub-daily, hourly)		
		Directional wave spectra: Significant wave height	CEOS 145	1km or finer Fast revisit (daily, sub-daily, hourly)		
		Directional wave spectra: Dominant wave period	CEOS 146	1km or finer Fast revisit (daily, sub-daily, hourly)		
		Directional wave spectra: Dominant wave direction	CEOS 147	1km or finer Fast revisit (daily, sub-daily, hourly)		
	B) Measure how change in the polar regions is impacting these feedbacks, e.g. through nutrient cycling and primary productivity	As above		As above		

A.11 CSQ-33: How does the solid Earth deform under present and past ice loads and what does it tell us about its rheology ?

The solid Earth deforms both elastically and visco-elastically under the water/ice loads applied at its surface. It is still deforming today in response to past ice mass changes at different timescales, where the thickness of the lithosphere and the mantle viscosity influence the wavelength and the rate of the deformation. The main Glacial Isostatic Adjustment (GIA) signal reflects the upper and lower mantle viscous responses to the Pleistocene deglaciation. Smaller GIA signals result from relaxation processes at much shorter timescales due to the presence of low-viscosity regions in the mantle, and induced by more recent ice mass changes, over the last centuries (Little Ice Age). Because they change the topography of ocean basins and extend over the ice caps, these signals constitute a major source of uncertainty in order to understand the origin of the sea level variations and accurately estimate the mass balance of the ice caps. Global mass balance estimates based on satellite gravity are actually an important tool to understand present climate variations, which are reflected in present-day ice melting, a major contributor to sea level variations (IPCC, 2021). Assessing the contribution of glaciers and ice caps to these global mass budgets requires a precise GIA model. In addition, GIA signals bring one of the few observational constraints on the Earth's rheology and the mantle viscosity, a key parameter, yet not well understood, to model Earth's dynamics as well as the redistribution of stress at plate boundaries and in their interior. Building an accurate GIA model remains a challenge today (Whitehouse, 2018), because it requires knowledge on both the spatio-temporal evolution of the ice load, and the solid Earth rheology in 3D, taking into account low-viscosity layers and lateral viscosity variations between cratonic and oceanic areas, or along hotspot tracks. Future avenues consist in constraining GIA models from observations in regions, where the GIA signals are large but not well determined due to the superimposition with present-day ice melting (e.g. over the polar ice caps). Thus, the challenge is to co-estimate GIA and present-day ice mass balance using multi-technic approaches.



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CSQ-33	Knowledge Advancement Objectives	Geophysical Observables	MIM Number	Measurement Requirements	Tools & Models	Policies / Benefits
How does the solid Earth deform under present and past ice loads and what does it tell us about its rheology ?	A) Quantify the long-term GIA signal of the Pleistocene deglaciation in ice sheet elevation and gravity field in regions of present-day ice caps melting, and separate it from contributions reflecting ice sheet imbalance and from GIA responses to the Little Ice Age.	**Critical parameters**		• High accuracy over medium to high spatial resolutions to enhance ice vs GIA signals separation and combination of different types of observations • Gravity: 10 cm EWH* /yr, spatial scale < 100 km (wish). • Continuity over time to separate inter-annual variations from long-term trends. • Coverage of polar areas • Multi-satellite missions with orbit inclination choice can help to improve gravity recovery.	Models of visco-elastic mantle relaxation under a surface load. Need for models able to account for 3D variations in physical properties of the Earth (not only radial). Algorithms for source separation in geodetic data Cosmogenic exposure dating and local sampling (past ice mass thickness)	Assess the contributions of glaciers and ice caps to global mass balance estimates, which constitute an important tool to understand present climate variations Understand the causes of sea level variations and assess the contributions of glaciers and ice caps.
		Gravity field	CEOS-185			
		Gravity gradient	CEOS-186			
		Ice sheet topography	CEOS-243			
		Glacier Topography	CEOS-168			
		Surface topography	CEOS-183			
		Supporting parameters				
		Seismology (lithospheric thickness)	NONE			
		Geomorphological data (past ice mass extent) from Land Surface Imagery	CEOS-181			
	B) Quantify the solid Earth visco-elastic	• Same as above		• Same as above, with an emphasis towards higher spatial resolutions.	Models of visco-elastic mantle	

	response to recent or contemporary ice mass change in glaciated regions associated with low mantle viscosity, such as active plate boundaries.				relaxation under a surface load. Need for models able to account for 3D variations in physical properties of the Earth (not only radial). Methods for data assimilation in GIA models.	
	C) Constrain the radial and lateral viscosity structure of the mantle (including in particular low viscosity layers and lateral variations between cratonic and oceanic areas or along hotspot tracks), from data-driven GIA models integrating a broad range of data types. In these models, describe the trade-offs between mantle structure and spatio-temporal evolution of the past ice load.	• Same as above		• Same as above, with an emphasis towards higher spatial resolutions.		

A.12 CSQ-35: Can we quantify erosional processes of drainage basins and the resulting sediments discharge to the oceans?

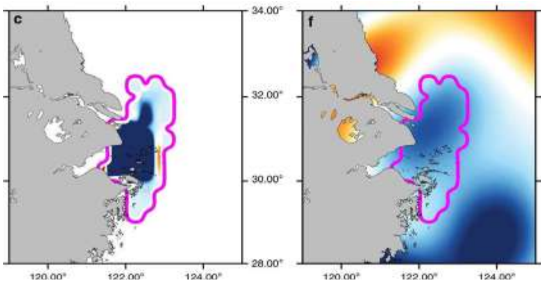
Contemporary erosion of drainage basins is controlled by natural processes (frost and precipitation related to climate versus topography changes related to tectonics) and also by human activities (agriculture, deforestation, sand extraction). Monitoring and modelling the on-going erosional processes is needed in order to constrain landscape dynamics including coastal subsidence, how it responds to natural and human forcings, and to quantify the sediments discharge from sources to sinks (oceans). The latter is difficult to quantify with terrestrial observations and modelling, because *in situ* measurements of sediment transport in the rivers and at rivers mouths are difficult and expensive. Therefore a remote sensing method is very welcome and would have multidisciplinary benefits.

Redistribution of mass at the Earth's surface associated with erosional and depositional processes could provide a new proxy to quantify erosional fluxes: eroded mass loss in mountainous areas, accumulation in deltas after the transport by river networks, and discharge into the oceans, bringing organic matter and nutrients. Such observations would be useful to quantify the Earth's subsidence due to surface sediment loading and compaction, as well as marine and offshore sediments deposition. For the first time, observations of gravity and mass changes associated with sedimentation offshore the Amazon, the Changyiang, the Indus and the Magdalena rivers have been obtained from the GRACE mission (Mouyen et al., 2018), complementing *in situ* data over a broader range of spatial and temporal scales. These results suggest that future satellite missions could provide new insights on the processes of sediment transport.

Table 2.6. *Highest and lowest average annual sediment loads, in descending order (in bold). 13 of the 15 highest loads are in rivers whose headwaters exceed 3000 m in elevation; 7 drain the Himalayas. Rivers with the lowest sediment loads are located in Scandinavia and the British Isles, most with headwaters <1000 m (upland rivers), many <500 m (lowland rivers).*

River	Country	Area ($\times 10^3$ km^2)	Elevation	Runoff (mm/yr)	Sed. load (Mt/yr)	Sed. yield (t/km^2/yr)	*Qsc* (g/l)
Amazon	Brazil	6300	High Mt	6300	**1200**	190	0.19
Huanghe	China	750	High Mt	15	**1100**	1500	19
Brahmaputra	Bangladesh	670	High Mt	630	**540**	810	0.86
Ganges	Bangladesh	980	High Mt	490	**520**	530	1.1
Changjiang	China	1800	High Mt	900	**470**	260	0.52
Mississippi	USA	3300	High Mt	490	**400**	120	0.82
Irrawaddy	Burma	430	High Mt	430	**260**	600	0.6
Indus	Pakistan	980	High Mt	<10	**250**	250	2.8
Orinoco	Venezuela	1100	High Mt	1100	**210**	140	0.14
Godavari	India	310	Mountain	92	**170**	550	1.8
Mekong	Vietnam	800	High Mt	690	**150**	190	0.27
Magdalena	Colombia	260	High Mt	230	**140**	540	0.61
Fly	Papua New Guinea	76	High Mt	180	**110**	1100	0.44
Song Hong	Vietnam	160	High Mt	120	**110**	690	0.92
Skellefte	Sweden	12	Lowland	410	**0.009**	1	2
Welland	England	0.53	Lowland	210	**0.007**	13	63
Conon	Scotland	0.96	Mountain	1600	**0.006**	6	4
Slaney	Ireland	1.8	Upland	610	**0.006**	3	5
Teith	Scotland	0.52	Mountain	1400	**0.005**	10	7
Liffey	Ireland	1.4	Lowland	335	**0.004**	3	8
Karjaanjoki	Finland	2	Lowland	320	**0.002**	1	3
Rane	Sweden	4.1	Upland	320	**0.002**	0.5	1
Siikajoki	Finland	4.4	Lowland	320	**0.002**	0.4	1
Mandalselva	Norway	1.7	Upland	880	**0.001**	1	1

Table: River discharge to the coastal ocean, a global synthesis, by J.D. Milliman and K. L. Farnsworth, Cambridge University Press, ISBN 9780511781247, 2011.



Modelled annual sedimentation at the mouth of the Yangtze river ; right : equivalent sedimentation observed by GRACE (Mouyen et al., 2018). Dark blue : 3mm/yr.

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CSQ-35	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
Can we quantify erosional processes of drainage basins and the resulting sediments discharge to the oceans	**A) Quantify the long-term present-day sediment discharge to the oceans, and locate modern sedimentation zones, at the mouth of major rivers. An objective could be to resolve accumulations of ~0.5 cm year $^{-1}$ of sediment at 200-km spatial resolution, close to the highest river discharges (Amazon, Ganges-Brahmaputra, Yangtze, ...).**	**Critical Parameters** *Gravity to constrain mass changes*			A proper correction of hydrological leakage effects in coastal areas is needed. This aims to properly distinguish mass (gravity) changes due to water vs those due to sediment. Knowledge on the location of the sedimentation zones : previous marine studies + use Lagrangian circulation models (such as [Parcels](https://doi.org/10.5194/gmd-10-4175-2017) https://doi.org/10.5194/gmd-10-4175-2017) to evaluate the deposition areas Decipher the elastic and visco-elastic response of the crust and mantle to the accumulated sediment load from the sediment Newtonian effect alone.	Global quantification of erosion Identify areas suffering from severe erosion rates Promote sustainable land management by quantifying erosion processes Relates to UN SDG 15 https://sdgs.un.org/goals/goal15
		Gravity field	CEOS 185	Multi-satellite missions with orbit inclination choice can help to improve the gravity recovery		
		Gravity gradients	CEOS 186			
		Supporting Parameters				
		River discharge and surface water levels (as from SWOT), to correct for hydrological leakage effects in coastal areas				
		Lake level	CEOS 247	Satellite altimetry + gauges stations. Mostly for removing leakage from lakes that are within a few 100 km from the oceanic sedimentation zone. Nevertheless, lakes can also accumulate sediments, though the amount of sediment mass might be too low to be unravelled by satellite gravity		
		River sediment discharge	OSCAR 132	The fundamental idea is to observe the sediment mass accumulation hence the need to have a long time series (decadal at least). Ideally, the system should be designed to be easily renewed when ageing. Accumulation of 0.5 cm/year of sediment replacing water over a 200-km radius region: ~1 Gt/year net mass increase. Highest river sediment discharges: ~1 Gt/year,		

CSQ-35	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
				as in the case of the Amazon and the Yellow River delta (see Table in the Narrative). For comparison, threshold MAGIC: 1 cm EWH/year @ 200km, long-term. Coverage of the land-sea transition High spatial resolution (1 degree or less) in coastal areas and at the mouth of large rivers		
		Surface Water Extent	CEOS 295	Use hydrological products. Challenge: most of these do not account for groundwater storage variations. Recent GLDAS2 products assimilate GRACE observations to complement their products with such groundwater info. However, as for now, the GRACE signal is processed without accounting for a possible influence from sediments. Ideally, avoid using such a model in coastal areas, where leakage might increase uncertainty of the hydrological model		
	B) Resolve large variations in sediment discharge following typhoons and El Nino events. So far only accumulated sediment over	**Critical Parameters** *Gravity to constrain mass changes*			Compile available information on the time variability of the sediment discharge to better evaluate its signature in the gravity time series.	
		Gravity field	CEOS 185	Time resolution of one month at least to properly decipher sedimentation at interannual		
		Gravity gradients	CEOS 186			

CSQ-35	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
	long time periods could be considered, in order to build up enough mass to be detected by GRACE. With a higher sensitivity, the detection of temporal variations in sediment discharge might be considered.			(climate change, El Nino), seasonal (seasonal variations of river, hence sediment, discharge) and “rapid” (sedimentation due to landslides following eg. typhoon or heavy rain events) time scales	Model the dynamics of sediment transport in rivers, to relate water discharge to sediment discharge.	
		Supporting Parameters				
		River discharge and surface water levels (as from SWOT), to correct for hydrological leakage effects in coastal areas				
		Lake level	CEOS 247	Same as for long term: satellite altimetry and gauges stations, also ideally at the same time scale as the gravity measurements		
		River discharge	OSCAR 132	Accumulation of 0.5 cm/year of sediment replacing water over a 200-km radius region: ~1 Gt/year net mass increase. Highest river sediment discharges: ~1 Gt/year, as in the case of the Amazon and the Yellow River delta (see Table in the Narrative). For comparison, threshold MAGIC: 1 cm EWH/year @ 200km, long-term. Coverage of the land-sea transition		
		Surface Water Extent	CEOS 295	Hydrological models: already available at subdaily time scales. Same challenge as above regarding missing groundwater effects.		

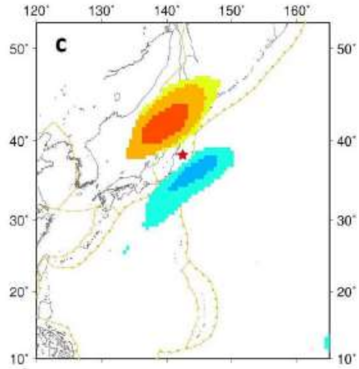
CSQ-35	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
	C) Quantify sediments loss in mountainous areas	**Critical Parameters** *Gravity to constrain mass changes*			Requires accurate hydrological corrections. Need for data on ice thickness variations (to account for ice mass variations and induced solid Earth deformations, on gravity data). Use CryoSat products. Ability to improve the spatial resolution of the results in post-processing (for instance using mascons modelling of the gravity field) Try to make a sediment budget within the watershed. Evaluate how much time is needed to evacuate a given amount of eroded sediment from the watershed. Needs coupled landslide vs sediment transport simulation.	
		Gravity field	CEOS 185	Focus on lakes and valleys. Ideally must distinguish the slopes (loss) and the valleys (mass gain) within a watershed. Lakes are also sediment traps Note that mass is much lower than in final deposition areas.		
		Gravity gradients	CEOS 186			
		Data on ice thickness variations				
		Ice sheet topography	CEOS 243	TBA - further simulations/understanding is required		
		Supporting Parameters				
		N/A				

A.13 CSQ-36: Can we observe, model and forecast the deformation processes during the seismic cycle at plate boundaries, from pre- to post-seismic phases and during the inter-seismic phase?

Constraining the mechanisms of stress accumulation and stress release at plate boundaries during the seismic cycle remains a major challenge of Earth's sciences. We need to identify the processes leading up to the initiation of a rupture, to accurately quantify the spatio-temporal distribution of the co-seismic slip and decipher the post-seismic deformation mechanisms, which contribute to the stress redistribution near the faults, thus the assessment of the seismic hazard. The seismic cycle includes preparatory and post-seismic phases, which are slow and only partially emit seismic waves. Therefore satellite-derived observations of all possible parameters affected by the earthquake cycle are extremely valuable. These include space geodetic deformation and gravity observations, integrated together with seismic networks sensitive to the seismic waves.

At subduction zones, space geodetic observations of crustal displacements have shown that the plate boundaries include freely slipping sections and locked zones, where the interface between the plates cannot slip and the continental plate progressively deforms, until the stresses applied to the faults become too large and the rupture occurs. Finely monitoring this progressive strain accumulation in the continental plate remains essential in order to map the areas prone to a seismic rupture. Until now, it has however not been sufficient to anticipate a rupture over the short term. Geodetic and seismic data have also revealed a variety of transient motions at different time scales at the shallower depths of the plate interface, from tenths of second for tremors, to years during slow slip events (Schwartz & Rokosky, 2007). Their interactions with seismic ruptures is still not well understood. At greater depths, these transient motions are less well documented because they have not produced measurable crustal displacements, but they are reflected in observations of deep seismic activity, and more recently, in anomalous gravity signals observed 1-2 months before two great ruptures from GRACE (Panet et al., 2022). Retrospective analyses have evidenced a variety of such transient signals before large ruptures, suggesting the existence of interactions between deep and shallow deformation processes at different time scales prior to large subduction earthquakes (see references in Panet et al., 2022).

Today, our understanding of rupture initiation is still based on a partial image of the movements near the plate boundaries, missing a large part of the motions at depth. The oceanic domain is also not well covered, yet subduction boundaries are located in coastal oceanic areas. To progress in the modelling, and possibly forecasting, of seismic cycle processes, it is essential to monitor deformation at all depths, over a broad range of spatial and temporal scales, on both sides of the plate boundaries. At subduction zones, this could allow us to understand the role of deeper slab dynamics in the initiation of a rupture. Combined with ground deformation and seismological data, a homogeneous coverage of mass changes all over oceanic epicentral areas as obtained by satellite gravity would provide a better description of the spatial extent of the co-seismic slip and enable us to assess the relative role of different post-seismic deformation processes, such as localised slip or mantle visco-elastic relaxation. Note that corrections for hydrological and oceanic signals in the gravity data are needed, which relates to other CSQs.



Anomalous gravity gradient signal in February 2011, before the March 2011 Tohoku earthquake, attributed to slab extension (Panet et al., 2022). Colours : -0.075 to 0.075 mEötvös.

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CSQ-36	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
Can we observe, model and forecast the deformation processes during the seismic cycle at plate boundaries, from pre- to post-seismic phases and during the inter-seismic phase ?	**A) Identify and delineate the locked versus the creeping segments of plate boundaries, and monitor inter-seismic strain accumulation, by accurately measuring the surface deformations of the plates around major boundaries.**	**Critical Parameters** *Surface displacements on land by GNSS and satellite imagery*			Models of surface deformations and gravity changes associated with slip at the plates interface (back-slip models)	Seismic hazard assessment and risk mitigation Emergency planning and response
		Land surface imagery	CEOS 181	Long-term trends High accuracy over all spatial scales Observed area: few 100's of kms (around plate boundaries) Spatial resolution: 100-10 m Accuracy : <10 mm Deformation on all 3 directions (N-S, E-W, Vertical)		
		Land surface topography	CEOS 183			
		Seafloor displacements				
		N/A for satellites - Sea bottom pressure measurements, GNSS-acoustic observation systems with high frequency of observation		N/A for satellites		
		Supporting Parameters *Gravity to constrain mass changes*				
		Gravity field	CEOS 185	Multi-satellite missions with orbit inclination		
		Gravity gradients	CEOS 186			

CSQ-36	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
				choice can help to improve the gravity recovery (this point is valid for all the Objectives here) Long-term trends The spatial resolution and accuracy depend on the size of the locked patches and the rate of strain accumulation (simulations would be needed).		
	B) Document the spatio-temporal characteristics of transient aseismic events in subduction systems.	**Critical Parameters** *Surface displacements on land by GNSS and satellite imagery*			Models of surface deformations and gravity changes associated with slip on faults (see below).	
		Land surface imagery	CEOS 181	Timescales from ~1 day to 2 years High accuracy over all spatial scales. Mw 6 event: ~10x10km fault plane. Mw 7: ~30x30km plane. Mw 8: 100’s km.		
		Land surface topography	CEOS 183			

CSQ-36	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
		Seafloor displacements				
		N/A for satellites - Sea bottom pressure measurements, GNSS-acoustic observation systems with high frequency of observation				
		Gravity to constrain mass changes				
		Gravity field	CEOS 185	Multi-satellite missions with orbit inclination choice can help to improve the gravity recovery (this point is valid for all the Objectives here) Timescales : 1 day to ~2 years High accuracy over all spatial scales, including medium scales (100's of km) to monitor deep deformations Gravity: 1cm EWH@200km (resp. 100km) resolution, monthly =		
		Gravity gradients	CEOS 186			

CSQ-36	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
				detection of motions equivalent to Mw > 7.4 (resp. 7.0) ruptures (not too deep).		
		Ground geophysical dataset: seismicity				
		N/A for satellites - Support the development of arrays of seafloor seismometers.				
	C) Document the possible existence of a short-term preparatory phase for earthquakes.	**Critical Parameters** *Surface displacements on land by GNSS and satellite imagery*			Models of surface deformations and gravity changes associated with slip on faults and slab deformation. Calculation of stress redistribution	
		Land surface imagery	CEOS 181	Timescales from ~1 day to decadal High accuracy over all spatial scales, including medium scales (100's of km) to monitor deep deformations		
		Land surface topography	CEOS 183			
		Gravity to constrain mass changes				
		Gravity field	CEOS 185	Multi-satellite missions with orbit inclination choice can help to improve the gravity recovery (this point is valid for all the		
		Gravity gradients	CEOS 186			

CSQ-36	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
				Objectives here) High accuracy over all spatial scales, including medium scales (100's of km) to monitor deep deformations		
		Ground geophysical dataset: seismicity				
		N/A for satellites – Support the development of arrays of seafloor seismometers.				
		Seafloor displacements				
		N/A for satellites – Sea bottom pressure measurements, GNSS-acoustic observation systems with high frequency of observation				
	D) Quantify the co-seismic slip distribution and discriminate between early rupture models.	**Critical Parameters** *Surface displacements on land by GNSS and satellite imagery*			Models of surface deformations and gravity changes associated with slip on faults. Need to develop models able to account for the 3D structure of plate boundary zones (not only a radial stratification, also a lateral structuration of the Earth's physical	
		Land surface imagery	CEOS 181	High accuracy over all spatial scales. M_w 5 event: ~3x3km fault plane. M_w 6: ~10x10km fault plane. M_w 7: ~30x30km plane. M_w 8: 100's km. Coverage on both sides of the plate boundaries and		
		Land surface topography	CEOS 183			

CSQ-36	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
				over epicentral areas.	parameters). Calculation of stress redistribution	
		Gravity to constrain mass changes				
		Gravity field	CEOS 185	Gravity: 1cm EWH@200km (resp. 100km) resolution, monthly = detection of Mw > 7.4 (resp. 7.0) earthquakes.		
		Gravity gradients	CEOS 186			
		Seafloor displacements				
		N/A for satellites - Sea bottom pressure measurements, GNSS-acoustic observation systems with high frequency of observation				
		Ground geophysical dataset: seismology, tsunami records from near-coastal pressure gauges and sea bottom pressure measurements				
		N/A for satellites - Support the development of arrays of seafloor seismometers.				
	E) Assess the relative contributions of localised vs distributed deformations at depth along the plates interface and in the surrounding mantle during the post-seismic phase, in order to quantify the stress redistribution along plate	**Critical Parameters** *Surface displacements on land by GNSS and satellite imagery*			Models: same challenge as above to take into account the 3D structure of the Earth, also including models of visco-elastic relaxation of the	
		Land surface imagery	CEOS 181	Time scales from weeks to decades Coverage on both sides of the plate boundaries and over epicentral areas		

CSQ-36	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
	boundaries after an earthquake.			High accuracy over a range of spatial scales to separate different spatio-temporal signatures of deep aseismic slip (more local) and mantle relaxation (involves larger scales)	mantle after a co-seismic rupture, and coupled models combining slow slip and visco-elastic relaxation. Calculation of stress redistribution	
		Land surface topography	CEOS 183			
		Gravity to constrain mass changes				
		Gravity field	CEOS 185	Gravity: 1cm EWH@200km (resp. 100km) resolution, monthly = detection of Mw > 7.4 (resp. 7.0) earthquakes.		
		Gravity gradients	CEOS 186			
		Seafloor displacements				
		N/A for satellites - Sea bottom pressure measurements, GNSS-acoustic observation systems with high frequency of observation				

A.14 CSQ-38: How does Earth's crust evolve in interaction with internal geodynamic processes, and how does this reshape the Earth's surface over the long-term?

Deeper geodynamical processes contribute to the evolution of the Earth's crust and long-term reshaping of the surface through processes connected to relative lithospheric plate movements and to the presence of a hot mantle underlying the lithosphere. These include processes of mountain building at convergent plate boundaries (Pivetta et al., 2021), the long-term subduction of tectonic plates at major plate boundaries, which also contributes to long-term inter-seismic stress build-up on active faults, the creation of crust at oceanic spreading ridges or active extensional tectonics in different areas of the world (Sabadini et al., 2019). They can be coupled with the climatic system, as in the case of mountain building coupled with erosional processes, or in the case of the subduction of oceanic plates which brings water into the Earth's mantle, strongly impacting rock rheology. Observing the long-term surface manifestations of these geodynamical processes is key to advance the modelling of the Earth's interior dynamics and the knowledge of its physical properties, which remains a challenge today (Daras 2023). This is also needed, in order to understand how the global Earth dynamics impacts the long-term evolution of our near-surface environment (the crustal layer) and the slow inter-seismic deformations at plate boundaries, which benefits the study of the seismic cycle and the deformation in volcanic areas. For this purpose, a relevant topic is to distinguish geodynamically-driven vertical movements, from the response of the crust to loading and unloading.

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CSQ-38	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
How does Earth's crust evolve in interaction with internal geodynamic processes, and how does this reshape the Earth's surface over the long-term?	**A) Quantify the long-term, present-day changes in Earth's surface and Moho topography due to processes of creation, evolution and destruction of Earth's crust : mountain building, long-term plate subduction, oceanic spreading, extensional tectonics.**	**Critical Parameters** *Gravity to constrain mass changes*			Complementary datasets on surface water loads to separate long-term tectonic signals from Solid Earth deformations associated with these loads. Models for the elastic and visco-elastic response of the crust and mantle to the water loads. Geodynamic models and ability to calculate accurately the corresponding geophysical observables (gravity, topography).	Understand the controls exerted by deep geodynamic processes on long-term changes of our near-surface environment.
		Gravity field	CEOS 185	Long-term trends High accuracy at medium spatial scales Subduction: Gravity: 0.04 microGal in 10 years, per each cm/yr of convergence velocity, (i.e. 1 mm EWH* in 10 years) Gravity Gradients: 50 microEötvös in 10 years @ 230-330 km resolution Oceanic spreading: Gravity 1 microGal in 10 years (i.e. 2.5 cm EWH* in 10 years), for 2 cm/yr of opening rate. @ 230-330 km resolution Tectonic crustal uplift in mountains: ~1 microGal in 10 years @ 400 km resolution (ex. Tibet). Multi-satellite missions with orbit inclination choice helps to improve the gravity recovery.		
		Gravity gradients	CEOS 186			
		Ground displacements by GNSS				

CSQ-38	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
		N/A for satellite EO				
		Supporting Parameters				
		Bathymetry	CEOS 155	The time dependent variations due to slow tectonic processes (e.g. subduction and oceanic spreading) are under study.		
		Glacier topography	CEOS 168	TBA - further simulations/understanding is required		
		Land surface topography	CEOS 183	The time dependent variations due to slow tectonic processes (e.g. subduction and oceanic spreading) are under study.		
		Geoid	CEOS 184	The time dependent variations due to slow tectonic processes (e.g. subduction and oceanic spreading) are under study.		
		Ocean dynamic topography	CEOS 194	TBA - further simulations/understanding is required		
		Ice sheet topography	CEOS 243	TBA - further simulations/understanding is required		

A.15 CSQ-43: What are the main coupling determinants between Earth's energy, water and carbon cycles? How accurately can we predict the forcings and feedbacks between the different components of the Earth system?

We need to be able to quantify the inter-relationships between Earth's energy, water and carbon cycles in order to advance our understanding of the Earth system and our ability to predict it across scales, in particular:

- Forcing-feedback understanding: How can we improve the understanding of climate forcings and feedbacks formed by energy, water and carbon exchanges?
- ABL process representation: To what extent are the properties of the atmospheric boundary layer (ABL) defined by sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere ? UTLS exchanges of water vapor, heat and chemicals influence the ABL processes (growth and dynamics in profiles of temperature, water vapour, pressure, aerosols, ozone and clouds). Together with surface ABL interactions - through radiation, latent and sensible heat fluxes, they determine the dynamics, chemistry and cloud (micro)physics of ABL.
- Understanding circulation controls: To what extent are exchanges between water, energy and carbon determined by the large-scale circulations of the atmosphere and oceans?
- Land-atmosphere interactions: How can we improve the understanding of the role of land surface-atmospheric interactions in the water, energy and carbon budgets across spatiotemporal scales?

The coupling of the energy and water cycles with the carbon cycle needs to be pursued by including the observation and description of photosynthesis as a major component of the whole system, such that we can better close the water budget over land, provide improved information for water availability and quality for decision making for water, energy and food security and for initializing and assessing climate predictions across multiple time scales and at the relevant adaptation scales (e.g. political and administrative regions). Detecting and attributing past changes in the water cycle due to either changing greenhouse gasses or land and water use changes will be essential to advance our prediction capability and tools.

The importance of describing photosynthesis in a coupled dynamic water-energy-carbon system is illustrated in Figure 1 and Figure 2.

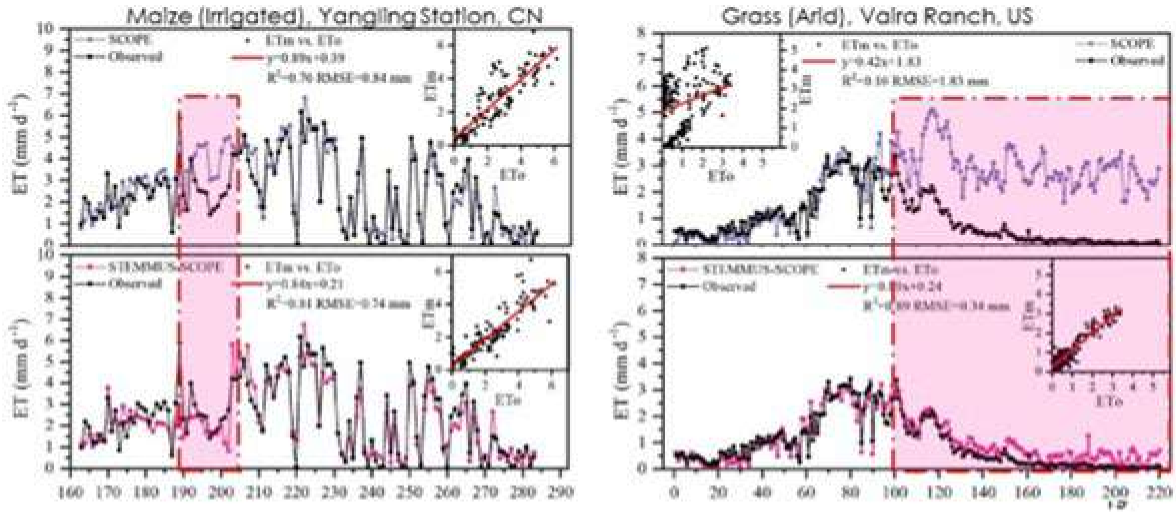

Figure 2: Drought Responses: Evapotranspiration

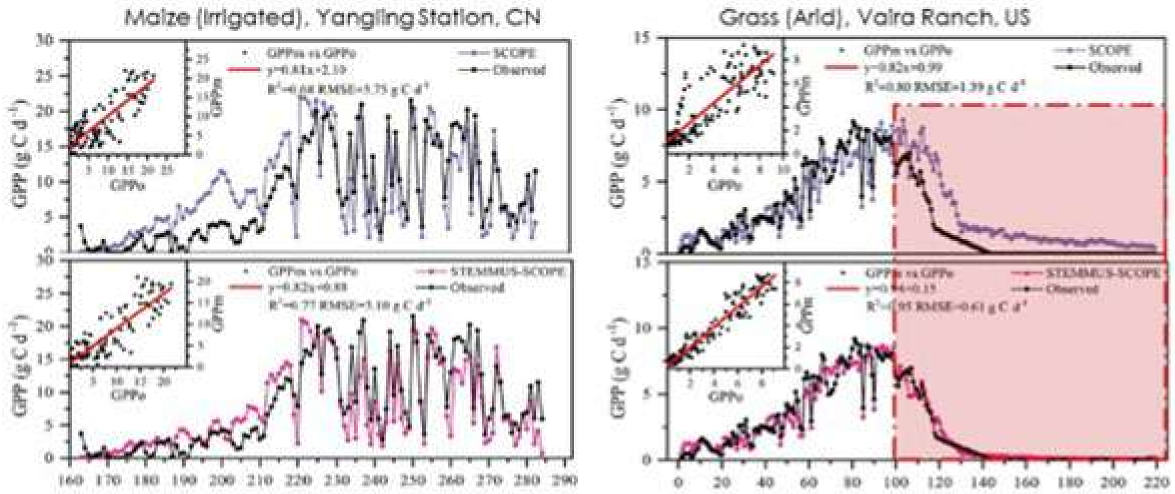

Figure 1: Drought responses: primary productivity

Figure 1 and Figure 2 describe the simulations of evaporation and transpiration (evapotranspiration, ET) and carbon dioxide fluxes (primary productivity, GPP) of two sites: one irrigated maize and another grassland in arid climate by two modelling systems (Wang et al., 2021). The modelling system SCOPE describes the canopy radiative transfer (including sun-induced fluorescence), energy balance and photosynthesis but ignores the water and heat transport in the soil and roots system (instead an average soil moisture is prescribed), while the STEMMUS-SCOPE system describes the coupled processes both in the canopy and rooting systems. Under non-water stressed conditions, both modelling systems can reasonably simulate the exchanges of energy, water and carbon between land and the atmosphere. However, when the plants suffer drought stress (highlighted areas in both figures), SCOPE grossly overestimated the water fluxes and the carbon fluxes, while STEMMUS-SCOPE achieves a much better fidelity compared to the observed fluxes.The major improvements have been achieved by describing the transfer of water through the soil, roots, stem and leaves through the concept of water potential and link the change of water potential to external forcings of radiation, precipitation and meteorology on the one hand and the growth of above and below ground plant biomass (shoots and roots) and the extraction of water by the growing roots on the other. Further progress is required to continue integrating new observations in integrated models.

CSQ-43	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
What are the main coupling determinants between Earth's energy, water and carbon cycles? How accurately can we predict the forcings and feedbacks between the different components of the Earth system?	**A) Quantify the relationships between Earth's energy, water and carbon cycles** *a. Identify the main climate forcings and feedbacks formed by energy, water and carbon exchanges.* *b. Quantify response of terrestrial photosynthesis to changes in temperature, CO2 concentration and water stress* *c. Reduce uncertainty estimates of fluxes (sensible, latent heat, and carbon fluxes – Gross Primary Productivity and Net Ecosystem Exchange) to < 10% uncertainty (currently 20%)*	**Critical parameters**			Retrieval algorithms for reflectance (albedo), vegetation parameters, LST, fluorescence, and SM, Vegetation Water Content, WV (profile of relative air humidity); Coupled model of energy, water and carbon process in Earth System Model (ESM) and Digital Twin Earth (coupled surface and atmospheric models); Validation by in-situ flux observations (e.g. Fluxnet)	Advance our understanding of the Earth system, which improves our ability to predict it across scales. Climate change adaptation and mitigation policy. Reduced uncertainties in IPCC AR. Improved reliability of CMIP simulations.
		• Soil moisture in the roots region [CEOS 239] • Atmospheric specific humidity (column/profile) [CEOS 13] • Vegetation water content **[None]** • Vegetation canopy (height) [CEOS 241] • Above ground biomass [CEOS 268] • Chlorophyll fluorescence from vegetation on land [CEOS 250]	CEOS 239 CEOS 13 CEOS 241 CEOS 268 CEOS 250	Spatial resolution Ideal: 1 hm Minimum: 1 km *(field scale)* Temporal resolution: Ideal: Half hour Minimum: 3 hour		
		Supporting parameters				
		• Earth surface albedo [CEOS 218] • Land surface temperature [CEOS 170] • Soil moisture at the surface [CEOS 171] • Water vapour imagery [CEOS 231] • Fraction of absorbed photosynthetically active radiation [CEOS 175] • Leaf area index [CEOS 173]	CEOS 218 CEOS 170 CEOS 171 CEOS 231 CEOS 175 CEOS 173	*Same as above*		
	B) Quantify the role of surface and upper troposphere - lower	**Critical parameters**			Validation by radiosoundings;	
		• **Surface observables:** same as above;	CEOS 1	Spatial resolution Ideal: 1 km		

	stratosphere (UTLS) forcings in atmospheric boundary layer (ABL) processes *Quantify the role of sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere (i.e., horizontal advection and UTLS exchanges).*	• Atmospheric temperature (column/profile) [CEOS 1] • Atmospheric specific humidity (column/profile) *(listed above - CEOS 13)*		Minimum: 10 km Temporal resolution Ideal: Half hourly Minimum: 3 hour Spatial position - Upper troposphere lower stratosphere - Atmospheric profiles up to the tropopause, with emphasis on near surface and troposphere	Reanalysis based on data assimilation	
		Supporting parameters				
		-	-	-		
	C) Quantify circulation controls *Quantify the influence of large-scale atmospheric and oceanic circulations on exchanges between water, energy and carbon.*	**Critical parameters**			Comparison to reanalysis; CDR (climate data records)	
		• Cloud liquid water (column/profile) [CEOS 18] • Precipitation Profile (liquid or solid) [CEOS 21] • Cloud ice (column/profile) [CEOS 24] • Cloud cover [CEOS 111] • Cloud top height [CEOS 113] • Cloud top temperature [CEOS 114] • Cloud drop effective radius [CEOS 127] • Cloud optical depth [CEOS 128]	CEOS 18 CEOS 21 CEOS 24 CEOS 111 CEOS 113 CEOS 114 CEOS 127 CEOS 128	Spatial resolution Ideal: 10 km Minimum: 100 km Temporal resolution Ideal: Half hourly Minimum: 3 hour Spatiotemporal requirement: Simultaneous observation of surface and atmospheric variables		
		Supporting parameters				

		• Land surface temperature [CEOS 170] • Soil moisture at the surface [CEOS 171] • Precipitation intensity at the surface (liquid or solid) [CEOS 116] • Downward short-wave irradiance at Earth surface [CEOS 131] • Downward long-wave irradiance at Earth surface [CEOS 132] • Upwelling (Outgoing) long-wave radiation at Earth surface [CEOS 134] • Upwelling (Outgoing) Short-wave Radiation at the Earth Surface [CEOS 260]	CEOS 170 CEOS 171 CEOS 116 CEOS 131 CEOS 132 CEOS 134 CEOS 260	*Same as above*		
	D) Quantify land-atmosphere interactions *Identify the roles of atmosphere-land surface interactions in the water, energy and carbon budgets across multiple spatiotemporal scales.*	**Critical parameters**			Comparison to 3D lidar observation at super observation sites; LES (large eddy simulation); ML algorithms Derivation of heat fluxes	
		• Sensible heat flux (derived) • Latent heat flux (derived)		Spatial resolution Ideal: 1 hm Minimum: 10km Temporal resolution Ideal: Half hourly Minimum: TBD		
		Supporting parameters				
		• Earth surface albedo [CEOS 218] • Land surface temperature [CEOS 170] • Soil moisture at the surface [CEOS 171]	CEOS 218 CEOS 170 CEOS 171	*Same as above*		

A.16 CSQ-44: How important are anthropogenic influences on the water cycle, and how accurately can we predict them?

We need to develop observation and simulation technologies to quantify anthropogenic influences on the water cycle and to understand and predict the changes to Earth's water cycle due to anthropogenic influences.

The observation aspects for answering these questions can be achieved by observing the land cover changes (at seasonal to annual scale), changes in water levels in lakes and man-made reservoirs (at daily to weekly and seasonal scale), as well as irrigated areas. It is possible to estimate the water used for irrigation by estimating the cumulative difference between evaporation and precipitation of an area. If the region is irrigated by extracting groundwater, it has been demonstrated that GRACE observations can be linked to the depletion of groundwater levels for large regions (Rodell and Reager, 2023). Availability of management data and coupled modeling are other necessary means to fully resolve the above questions and progress in closure f the water budget is being supported by the GCOS ECV Terrestrial Water Storage (TWS), primarily measured by satellite gravity missions (Pail et al 2015)

Progress towards solving these science questions of water cycle requires the generation and exploitation of improved data sets of precipitation, evaporation and transpiration, river discharge, soil moisture, snowpack, surface water bodies, groundwater, vegetation, land use change data, among other information. This can be synchronized with advances in Earth system modeling across scales to advance the development of an integrated analysis of the water and energy exchanges within and between the atmospheric and continental reservoirs. Advances in these aspects directly contribute to our ability in devising adaption strategies and to strengthen the resilience of our society to adverse impacts due to anthropogenic changes.

In summary, despite the many advances in the satellite observation of many water cycle related variables and parameters, major efforts are still needed to be able to close the water, energy and carbon cycles at different scales in space and time. In awaiting the availability of fluorescence as an observable from the ESA FLEX satellite, another geophysical variable (or loosely observable), water potential in soils, plants and atmosphere, appear to be extremely promising in closing the water, energy and carbon processes on land. (The same process may also prove important in sequestration of CO_2 in oceans, though the description must be via algae mediated radiation-water-carbon photosynthesis processes). On such basis of state-of-the-art in describing, analyzing and modeling energy-water-carbon fluxes on land, the following can be summarized:

- Interpretation of SIF (sun-induced fluorescence) requires (and will advance) full spectrum understanding of water-energy-carbon (Soil-Water-Plant-Energy) interactions.
- Describing water potential gradients is one key step for explaining SIF-GPP (gross primary productivity) dynamics. *(This is identified as a gap/hole in geophysical information)*
- SIF and microwave observation (of plant water content) (radiometry, scatterometry, SAR tomography) can potentially access water potential in soil and plants (Zhao, et al. 2023).
- Observation of the profile of water vapor concentration in the atmosphere from troposphere to stratosphere are highly desirable and may be achieved by means of combined vertical profiling (or via IASI type of sensing) and limb sounding.

- Gravity measurements from MAGIC and NGGM will help closure of the water cycle budget and identification of changes in the cycle through better quantification of anthropogenic uses of water and changes in water storage (Daars (2023)).

Diurnal observations appear necessary to observe water potential at scales of half-hourly to hourly in time and kilometre to hectometre in space. *(This is seen as an Observation gap that needs to be bridged to adequately characterize and describe the diurnal processes at the relevant scale where the processes take place).*

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CSQ-44	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies/Benefits
How important are anthropogenic influences on the water cycle, and how accurately can we predict them?	**A) Quantify anthropogenic forcing of continental scale water availability** *Quantify extent to which the changing greenhouse effect modified the water cycle over different regions and continents.*	**Critical parameters**			Retrieval of globally consistent irrigated areas Time series analysis of observations; Scenario simulations with coupled ESM models; Use of DTE for decision support Drive and constrain predictive hydrological models with Data Assimilation (DA) techniques	Provide evidence for climate change adaptation plans and fund eligibility. Contribute to regional water management strategies. Climate change adaptation and mitigation policy. Reduced uncertainties in IPCC AR. Improved reliability of CMIP simulations.
		Irrigated areas [derived]	*None*	Spatial resolution Ideal: 10 km Minimum: 100 km Temporal resolution Ideal: Annual Minimum: 5 year		
		Supporting parameters				
		• Precipitation [CEOS 116] • LAI [CEOS 173] • *Soil moisture at the surface [CEOS 171]* • *Soil moisture in the roots region [CEOS 239]*	CEOS 116 CEOS 173 CEOS 171 CEOS 239	TBD		
		• Land Cover [CEOS 179] • *Surface Water Extent [CEOS 295]* • *River discharge [OSCAR 132]* • *Lake level [CEOS 247]* • *Lake Area [CEOS 254]*	CEOS 179 CEOS 295 OSCAR 132 CEOS 247 CEOS 254	Spatial resolution Ideal: 10 km Minimum: 100 km Temporal resolution Ideal: Seasonal Minimum: Annual		
		Critical parameters				

	B) Detect water management influences *Determine extent to which water management practices and land use changes (e.g., deforestation) modified the water cycle on regional to global scales.*	• Precipitation intensity at the surface (liquid or solid) [CEOS 116]	CEOS 116	Spatial resolution Ideal: ≤1km Minimum: 10 km Temporal resolution Ideal: Daily Minimum: Weekly	Estimate amount of water used for irrigation by estimating the cumulative difference between evaporation and precipitation of an area. Time series analysis of precipitation and evaporation products. Time series analysis of Terrestrial Water Storage (TWS) and Groundwater Storage (GWS) products. Comparison of observation products to reanalysis Data assimilation of mass change data with hydrological models	
		Supporting parameters				
		• Evapotranspiration [CEOS 294] • Soil moisture at the surface *(listed above - CEOS 171)* • Soil moisture in the roots region *(listed above - CEOS 239)* • Groundwater depletion **[None]**	CEOS 294	Spatial resolution Ideal: ≤1km Minimum: 10 km (regional) Minimum 300km (global) Temporal resolution Ideal: Daily Minimum: Weekly		
	C) Quantify variability and trends of water availability	**Critical parameters**			Estimate use of groundwater for irrigation.	
		• Ground water [OSCAR 74] • Surface water (variables listed above – CEOS	OSCAR 74	Spatial resolution Ideal: ≤10km		

	Quantify effects of water and land use and climate changes on the variability (including extremes) of the regional and continental water cycle	295, 247, 254 and OSCAR 132)		Minimum: 50 km Temporal resolution Ideal: Weekly Minimum: Monthly	Availability of management data and coupled water cycle modelling (incl. groundwater, SM, discharge and evaporation and precipitation) Drive and constrain predictive hydrological models with Data Assimilation (DA) techniques	

A.17 CSQ-45: How can we reduce the uncertainties in the surface energy budget while improving the estimate of the internal flow within the climate system?

The surface energy budget is a key driver of the global water cycle, atmosphere and ocean dynamics, as well as a variety of surface processes (Forster et al., 2021). These internal flows of energy within the climate system are another critical part of the Earth's energy budget, and consist of the net solar and thermal radiation as well as the non-radiative components such as sensible, latent and ground heat fluxes (Wild, 2020) (Fig. 1). The radiation components of the surface energy budget are associated with large uncertainties since they are less directly measured by passive satellite sensors and require retrieval algorithms and ancillary data for their estimate (Kato et al., 2018). The use of complementary approaches that make use of satellite products from active and passive sensors (L'Ecuyer et al., 2015; Kato et al., 2018) and information from surface observations and Earth system models (ESMs) has resulted into recent converge of independent estimates within a few Wm^{-2}.

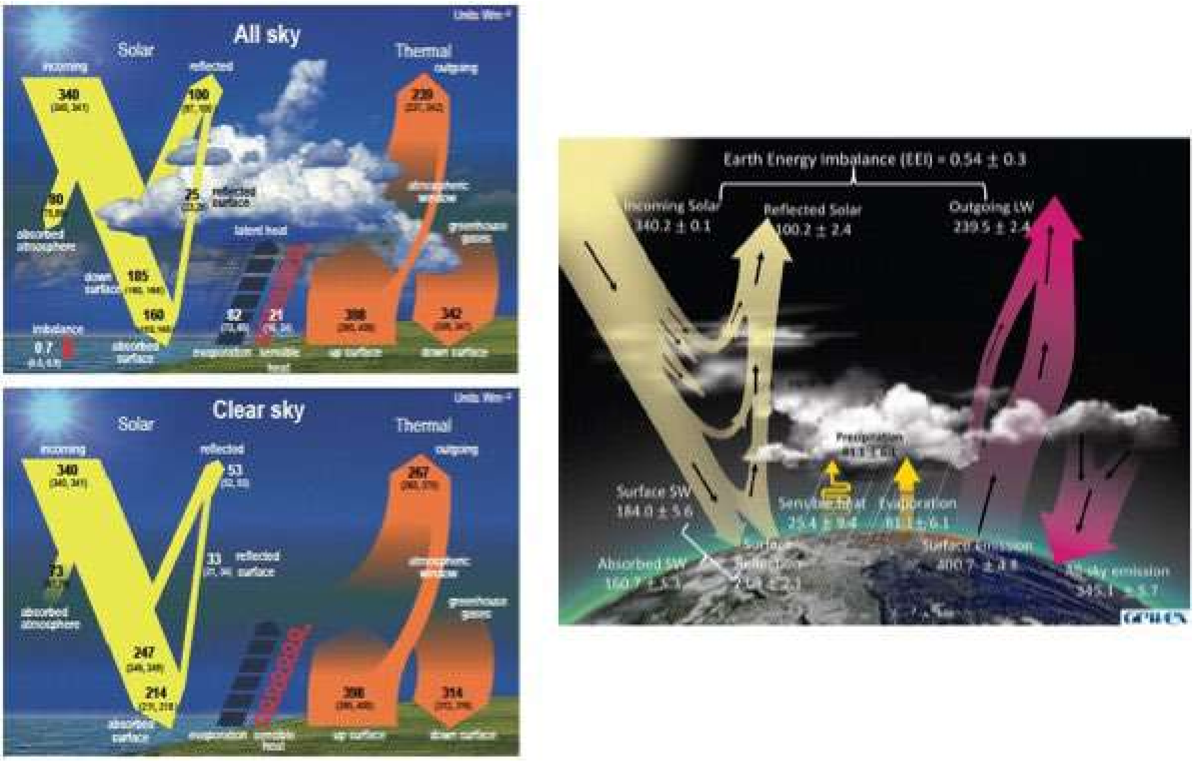

Fig. 1: *Schematic representation of internal flow of energy within the climate system for all sky (upper) and clear sky (lower) conditions (left panels) after Wild et al., 2020. Their difference is used to obtain the cloud radiative effect on Earth's energy budget. Right panel: mean annual fluxes of the global energy budget after Stephens et al. (2023). All values are given in W m^{-2}.*

However, on regional scales, the closure of the surface energy budgets remains a challenge with satellite-derived datasets (L'Ecuyer et al., 2015), and associated uncertainties being area dependent with respect to the number of surface sites, regional uncertainty of surface observations (Kato et al., 2018), the retrieval of flux-relevant meteorological variables, as well as from differences in the flux parametrizations. For example, uncertainties can reach up to 25 Wm^{-2} for latent heat and 5 Wm^{-2} for sensible heat over the ocean, and 10-20% over land (L'Ecuyer et al., 2015).

Albeit the magnitude of the energy budget components of the CMIP6 climate models generally show better agreement with reference estimates than previous model generations, considerable uncertainties remain in the representation of the internal flows of energy in climate models.

Particularly, climate models show larger discrepancies in their surface energy fluxes than at the Top Of the Atmosphere (TOA) due to weaker observational constraints, with a spread of typically 10–20 W m^{-2} in the global average, and an even greater spread at regional scales (Wild et al., 2013; Wild, 2020), often related to their representation of clouds.

Clouds are important modulators of energy fluxes, and the cloud radiative effect on Earth's energy budget is measured by through the difference between clear and all skies radiation budgets (Fig. 1). Clouds affect shortwave (SW) radiation by reflecting sunlight due to their high albedo (cooling the climate system), and depends on the cloud optical properties. They also affect longwave (LW) radiation by absorbing the energy from the surface and emitting at a lower temperature to space, and this greenhouse effect of clouds strengthens with height.

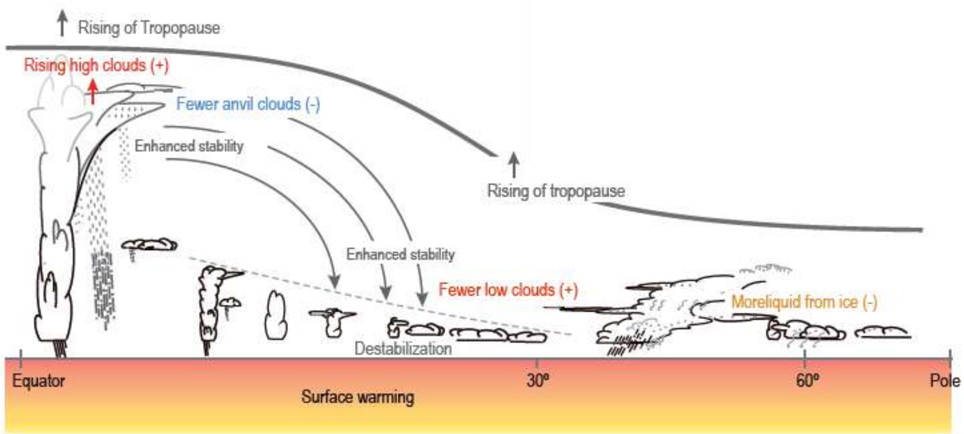

***Fig. 2:** Schematic representation of cloud feedsbacks in different regimes from diverse cloud responses to surface warming. Adopted from Foster et al., 2021.*

Clouds consist of liquid water droplets and/or ice crystals, and these droplets and crystals can grow into larger particles of rain, snow or drizzle. These microphysical processes interact with aerosols, radiation and atmospheric circulation, resulting in a highly complex set of processes governing cloud formation and life cycles that operate across a wide range of spatial and temporal scales. Any perturbations of the cloud fields can hence have a strong influence on the energy distribution in the climate system, such as the positive net cloud feedback in different cloud regimes (Foster et al., 2021, Fig. 2), which is a dominant source of uncertainty to evaluate equilibrium climate sensitivity in climate models, and hence remains the largest contributor to uncertainty of net climate feedback evaluations (Forster et al., 2021).

Another perturbator of cloud fields includes forcing by aerosol–cloud interactions (or also called 'indirect aerosol effect') affecting cloud micro- and macro-physics and thus cloud radiative properties. Different cloud regimes show different sensitivities to aerosols. Multiple studies have found a positive relationship between cloud fraction and/or cloud liquid water pathway and aerosols. There is high confidence that anthropogenic aerosols lead to an increase in cloud droplet concentrations (Foster et al., 2021). However, albeit considerable advances have been made to infer causality in aerosol–cloud relationships, a major challenge remains the identification of the anthropogenic perturbation of the aerosol to assess (Foster et al., 2021).

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CSQ-45	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Datasets, Methods, Tools & Models	Policies / Benefits
How can we reduce the uncertainties in the surface energy budget while improving the estimate of the internal flow within the climate system?	**A) Reduce uncertainties of regional energy fluxes** *Quantify and reduce regional uncertainties of surface observations, retrievals of energy fluxes, and their parametrisations*	**Critical Parameters** • Latent heat flux at Earth surface [None] • Sensible heat flux at Earth surface [None] • Evapotranspiration [CEOS 294] • Precipitation intensity at the surface (liquid or solid) [CEOS 116]	CEOS 294 CEOS 116	Spatial resolution Ideal: 0.25° Temporal resolution Ideal: Daily Minimum: Monthly	Atmospheric & oceanic assimilation systems; Earth system models Use regional budget closure studies to improve observational constraints for climate models.	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of CC prediction / climate models (due to improved observational constraints (A))
		Supporting Parameters • Downward short-wave irradiance at Earth surface [CEOS 131] • Upwelling (Outgoing) Short-wave Radiation at the Earth Surface [CEOS 260] • Upwelling (Outgoing) long-wave radiation at Earth surface [CEOS 134] *Radiative fluxes* • Downwelling (Incoming) solar radiation at TOA [CEOS 123] • Upward short-wave irradiance at TOA [CEOS 124] • Upward long-wave irradiance at TOA [CEOS 125] • Downward long-wave irradiance at Earth surface [CEOS 132] • *Parameters listed above (CEOS 131, 260 & 134)* *Surface temperature* • Land surface temperature [CEOS 170] • Sea surface temperature [CEOS 144] • Lake surface temperature [CEOS 293] • Sea-ice surface temperature [CEOS 158] • Snow surface temperature [CEOS 246]	CEOS 131 CEOS 260 CEOS 134 CEOS 123 CEOS 124 CEOS 125 CEOS 132 CEOS 170 CEOS 144 CEOS 293 CEOS 158 CEOS 246 CEOS 1 CEOS 284 CEOS 287	Spatial resolution Ideal: 0.25° Temporal resolution Ideal: Daily Minimum: Monthly		

		Atmospheric and oceanic planetary heat content and transport • Atmospheric temperature (column/profile) [CEOS 1] • Ocean temperature [CEOS 284] • Sea surface heat flux [CEOS 287]				
	B) Study of cumulative regional cloud feedbacks, weighted by the global ratio of fractional coverage to evaluate the global cloud feedback	**Critical Parameters** • Cloud type [CEOS 110] • Cloud drop effective radius [CEOS 127]	CEOS 110 CEOS 127	Spatial resolution Ideal: 0.25° Temporal resolution Ideal: Daily Minimum: Monthly	Atmospheric assimilation systems Earths system models High-resolution cloud resolving models (CRMs) Large eddy simulations (LES) Aerosol reanalysis; multi-model ensembles (e.g., AEROCOM)	
		Supporting Parameters • Cloud ice (column/profile) [CEOS 24] • Cloud imagery [CEOS 109] • Cloud cover [CEOS 111] • Cloud ice content (at cloud top) [CEOS 112] • Cloud top height [CEOS 113] • Cloud top temperature [CEOS 114] • Cloud optical depth [CEOS 128] • Cloud ice effective radius (column/profile) [CEOS 232] • Freezing level height [CEOS 234] • Melting layer depth in clouds [CEOS 235] • Cloud top pressure [CEOS 269] • Cloud liquid water (column/profile) [CEOS 18] • Water vapour imagery [CEOS 231] • Atmospheric specific humidity (column/profile) [CEOS 13] • Atmospheric temperature (column/profile) *(listed above - CEOS 1)*	CEOS 24 CEOS 109 CEOS 111 CEOS 112 CEOS 113 CEOS 114 CEOS 128 CEOS 232 CEOS 234 CEOS 235 CEOS 269 CEOS 18 CEOS 231 CEOS 13	Spatial resolution Ideal: 0.25° Temporal resolution Ideal: Daily Minimum: Monthly		

	C) Study the causality in aerosol–cloud relationships, particularly for anthropogenic perturbations	**Critical Parameters**				
		• Aerosol Extinction / Backscatter (column/profile) [CEOS 29] • Aerosol effective radius (column/profile) [CEOS 126]	CEOS 29 CEOS 126	Spatial resolution Ideal: 0.25° Temporal resolution Ideal: Daily Minimum: Monthly		
		Supporting Parameters				
		• Aerosol optical depth (column/profile) [CEOS 33] • Visibility [CEOS 207] • Volcanic ash [CEOS 209] • Aerosol absorption optical depth (column/profile) [CEOS 220] • Aerosol Single Scattering Albedo [CEOS 256] • Aerosol Layer Height [CEOS 257] • *Parameters listed under objective (B) (cloud feedbacks)*	CEOS 33 CEOS 207 CEOS 209 CEOS 220 CEOS 256 CEOS 257	Spatial resolution Ideal: 0.25° Temporal resolution Ideal: Daily Minimum: Monthly		

A.18 CSQ-46: How does the Earth energy imbalance and Earth heat inventory change over time and why? And what can we learn from this for the interplay between effective radiative climate forcing, Earth's surface temperature response and climate sensitivity, as well as its implication on Earth system change?

The Earth climate system is out of energy balance manifested as a positive Earth energy imbalance (EEI) at the top of the atmosphere (IPCC, 2021; von Schuckmann et al., 2020). As a consequence, heat has accumulated continuously over the past decades, warming the ocean, the land, the cryosphere and the atmosphere. As the ocean, the land, the cryosphere and the atmosphere warms from this surplus heat, unprecedented and committed changes in the Earth system have evolved, with adverse impacts for ecosystems and human systems (IPCC, 2021, 2022). This Earth heat inventory (Fig. 1a) plays a central role for climate change monitoring as it provides information on the absolute value of the Earth energy imbalance, the total Earth system heat gain, and how much and where heat is stored in the different Earth system components. Quantifying the heat stored in the different Earth system components is then essential to further unravel impacts of increase in heat content across the entire Earth system (Fig. 1b). Moreover, a quantification of the Earth heat inventory is also relevant for climate model constraint approaches, validations, and unravelling sources of uncertainties in the calculations such as for example on effective climate sensitivity (Gregory et al., 2002). The Earth heat inventory is estimated via the heat content of each Earth system component, using a combination of in situ measurements, satellite data, reanalysis and model outputs. Given the large gaps in the observing system for these quantifications, estimates still suffer large uncertainties, and partly rely on a hybrid data approach, which is particularly the case for the cryosphere and the land components (von Schuckmann et al., 2023).

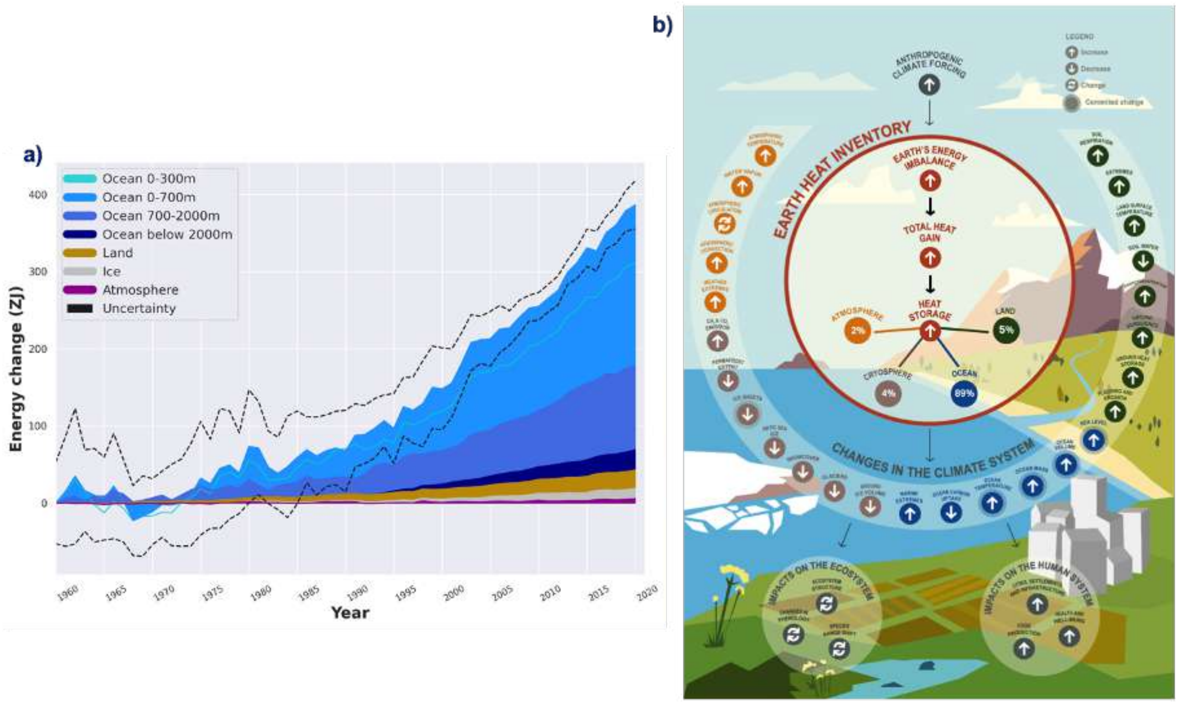

Figure 1: a) *Total Earth system heat gain in ZJ (1 ZJ =10^{21} J) relative to 1960 and from 1960 to 2020, with a total heat gain of 381±61 ZJ over the period 1971–2020, which is equivalent to a heating rate (i.e., the EEI) of 0.48±0.1 W m^{-2} applied continuously over the surface area of the Earth (5.10×10^{14} m^2).* ***b)*** *Schematic overview on the central role of the Earth heat inventory and its linkage to anthropogenic*

emissions, the Earth energy imbalance, change in the Earth system and implications for ecosystems and human systems. Examples of associated global-scale changes in the Earth system as assessed in Gulev et al. (2021) are drawn, together with major implications for the ecosystem and human systems (IPCC, 2022). Upward arrows indicate increasing change, downward arrows indicate decreasing change, and turning arrows indicate change in both directions. After von Schuckmann et al. (2023).

Most recent studies have shown that the EEI has increased during the most recent era as compared to the long-term (e.g., past century) estimate of EEI increase (Forster et al., 2022; Hakuba et al., 2021; Kramer et al., 2021; Loeb et al., 2021; Raghuraman et al., 2021; von Schuckmann et al., 2020). The drivers of a larger EEI in the 2000s than in the long-term period since 1971 are still unclear, and several mechanisms are discussed in literature. For example, Loeb et al. (2021) argue for a decreased reflection of energy back into space by clouds and sea-ice, and increases in well-mixed greenhouse gases (GHG) and water vapor to account for this increase in EEI. Kramer et al. (2021) refers to a combination of rising concentrations of well-mixed GHG and recent reductions in aerosol emissions accounting for the increase, and Liu et al. (2020) addresses changes in surface heat flux together with planetary heat re-distribution and changes in ocean heat storage. Raghuraman et al. (2021) attribute the observed increase to anthropogenic forcing, manifesting the observed evidence of climate change from remote sensing. Sustained and continued measurements are needed to monitor the temporal evolution of the EEI (Cheng et al., 2022; Dewitte et al., 2019; Hakuba et al., 2019), and to further study drivers of EEI change, together with implications for changes in the Earth system. Current uncertainties and requirements for EEA are described in Meyssignac et al, (2023).

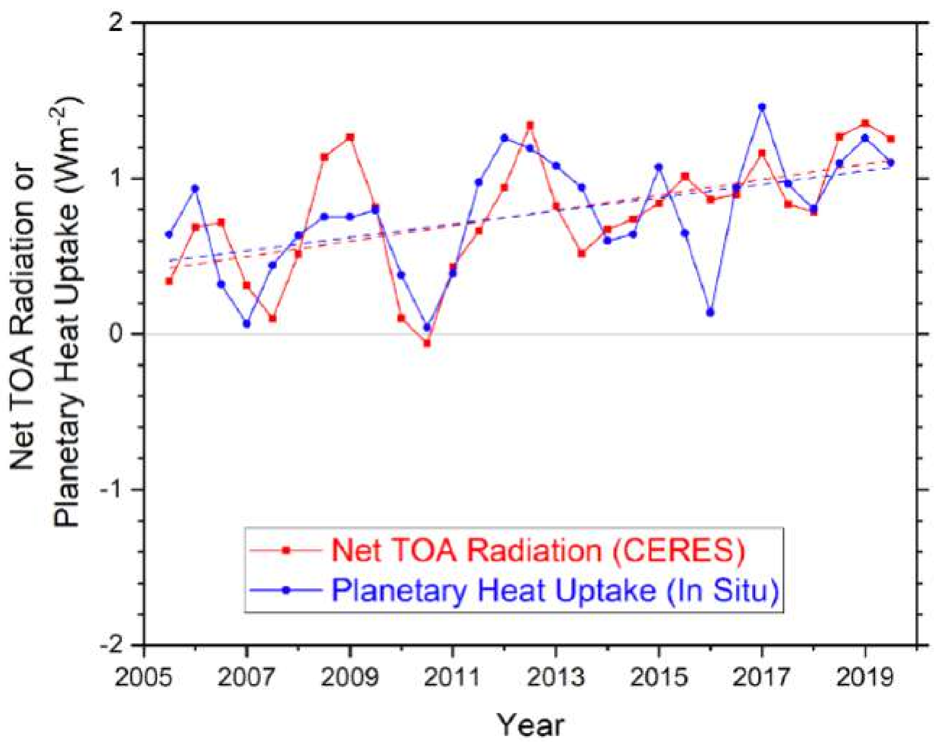

Figure 2: Comparison of overlapping one-year estimates at 6-month intervals of net top-of-the-atmosphere annual energy flux from CERES (red) and the uptake of energy by the Earth climate system. From Loeb et al., 2021.

Estimates for continental heat storage suffer from lacking international data acquisition and curating efforts for subsurface temperature profile data (Cuesta-Valero et al., 2021). Both, heat storage estimates for permafrost and inland freshwater bodies suffer from a lack of relevant observations, and are hence dependent on model evaluations. However, data from the SWOT mission are promising for this purpose (Cuesta-Valero et al., 2022). For the estimate of atmospheric heat content, a sustained and enhanced operational long-term monitoring system for the provision of climate data records of relevant ECVs is recommended, including associated reference data (e.g., upper air network GRUAN, radio occultation). Moreover, there is an urgent need for satellite missions in high inclination orbits to provide full global and local time coverage. For the cryosphere, sustained remote-sensing with polar-focused orbits and multi-frequency altimeters (e.g., albedo, sea ice area & thickness) are recommended, together with an earlier launch of Sentinel-1c for monitoring ice-speed change at higher frequency. Moreover, reliable gravimetric, geodetic, ice velocity, ice thickness and extent, snow and firn thickness and density measurements are recommended. For the ocean, sustained in-situ measurements are recommended together with extensions into the deep, polar and shallow ocean areas. Recent efforts for full-depth ocean heat content estimates from remote sensing are under the way (Hakuba et al., 2021; Marti et al., 2022).

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CSQ-46	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Data sets, Methods, Tools & Models	Policies / Benefits
How does the Earth energy imbalance and Earth heat inventory change over time and why? **And what can we learn from this for the interplay between effective radiative climate forcing, Earth's surface temperature response and climate sensitivity, as well as its implication on Earth system change?**	**A) Earth heat inventory evaluation** *Quantify how much surplus anthropogenic heat is going into warming the ocean, the land, the atmosphere and melting the cryosphere*	**Critical Parameters**		Spatial resolution Ideal: 0.25° Minimum: 1° Temporal resolution Ideal: Daily Minimum: TBD *Multi-satellite approach*	Earth system models Atmospheric & oceanic & coupled assimilation systems Multi-product approach (in situ, satellite, model)	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of CC prediction / climate models (validation, parametrization, detection & attribution) High-temporal resolution captures everything from extremes to long-term change
		Atmospheric heat content (derived) • Atmospheric temperature (column/profile) [CEOS 1] • Atmospheric specific humidity (column/profile) [CEOS 13] *Ocean heat content (derived)* • Ocean temperature [CEOS 284] *Land heat content (derived)* • Land surface temperature [CEOS 170] • Lake surface temperature [CEOS 293] *Heat available to melt ice (derived)* • Ice-sheet topography [CEOS 243]	CEOS 1 CEOS 13 CEOS 284 CEOS 170 CEOS 293 CEOS 243			
		Supporting parameters				
		Ocean heat content (derived) • Sea level [CEOS 148] • Ocean mass **[None]** *Land heat content (derived)* • Permafrost [CEOS 169] • Surface water extent [CEOS 295] • Lake area [CEOS 254] • Leaf area index [CEOS 173] • Land cover [CEOS 179] *Heat available to melt ice (derived)* • Sea-ice cover [CEOS 156]	CEOS 148 CEOS 169 CEOS 295 CEOS 254 CEOS 173 CEOS 179 CEOS 156 CEOS 193 CEOS 159 CEOS 161 CEOS 162 CEOS 166			

		• Sea-ice thickness [CEOS 193] • Sea-ice sheet topography [CEOS 159] • Iceberg fractional cover [CEOS 161] • Iceberg height [CEOS 162] • Glacier cover [CEOS 166]				
	B) Global energy budget closure studies *Investigate links between the global energy budget, planetary heating, effective radiative forcing, surface temperature response and climate sensitivity.* *Take stock of the long-term change in the Earth energy imbalance, and further tackle underlying uncertainties.*	**Critical Parameters**				
		Net flux at the top of the atmosphere (incoming & outgoing radiation) (derived) • Downwelling (Incoming) solar radiation at TOA [CEOS 123] • Upward short-wave irradiance at TOA [CEOS 124] • Upward long-wave irradiance at TOA [CEOS 125] • Downward short-wave irradiance at Earth surface [CEOS 131] • Downward long-wave irradiance at Earth surface [CEOS 132] • Upwelling (Outgoing) long-wave radiation at Earth surface [CEOS 134] • Upwelling (Outgoing) Short-wave Radiation at the Earth Surface [CEOS 260] *Effective radiative forcing (derived)* • CO_2 Total Column [CEOS 274] • Water vapour imagery [CEOS 231] • *Aerosols that contribute to effective radiative forcing (TBD)*	CEOS 123 CEOS 124 CEOS 125 CEOS 131 CEOS 132 CEOS 134 CEOS 260 CEOS 274 CEOS 231			
		Supporting Parameters				

		Effective radiative forcing (derived)
		• *Forcing due to changes in albedo*
		    ○ Earth surface albedo [CEOS 218]
		    ○ Black and white sky albedo [CEOS 259]
			CEOS 218
			CEOS 259
			CEOS 231			

		• *Trace gases that contribute to effective radiative forcing (excluding CO2 – TBD)* *Earth heat inventory (see above)*				
	C) How does the Earth energy imbalance changes over time and why? Which are the implications of a changing Earth energy imbalance on changes in atmospheric warming, land warming and ice melt?	**1. Critical Parameters**				
		Both lists above (inventory & constraint approach)				
		2. Supporting Parameters				
		Both lists above (inventory & constraint approach)				

A.19 CSQ-48: How can we improve the monitoring and understanding of planetary heat exchange at regional scale? And which essential advancements can we achieve for research and monitoring on weather and climate patterns?

Regional scale exchanges at the interface between the Earth's surface and the atmosphere are a critical part of the global energy cycle, while fuelling weather and climate variability and controlling important feedbacks such as for example through heat and moisture exchange. Observations at low spatial scale allowing to unlock small-scale processes and variations of the thermodynamic coupling are then key (Gentemann et al., 2021) (Fig. 1a) to allow for predictability from mere days to weeks as these small-scale features can affect large-scale weather and climate. For example, better weather prediction on time scales of 2–12 weeks provides advance warning of events such as heat waves and extreme precipitation, which are known to enhance and occur more frequently under global warming (IPCC, 2021), with severe impacts on human systems (IPCC, 2022). Moreover, small-scale air–sea interactions induce deep atmospheric circulation responses that affect mid-latitude storms and long-term weather (Gentemann et al., 2021). Also, the dynamic coupling of the atmosphere and the Earth surface plays an important role for understanding how momentum and kinetic energy are transferred between components of the Earth's system, such as between the ocean and atmosphere (Zippel et al., 2022) (Fig. 1b). Measurements of wind interactions and surface total currents (vectorial) are then key, which either do not meet WMO sampling requirements (esp. in resolving diurnal scale), or are faced to an observational gap. Beside the need for improved measurement techniques, consistency studies of flux estimates at regional scale have been used for developing reference data sets and uncertainty evaluations, and remain a promising tool for regional energy budget closure approaches, process understanding and uncertainty evaluations.

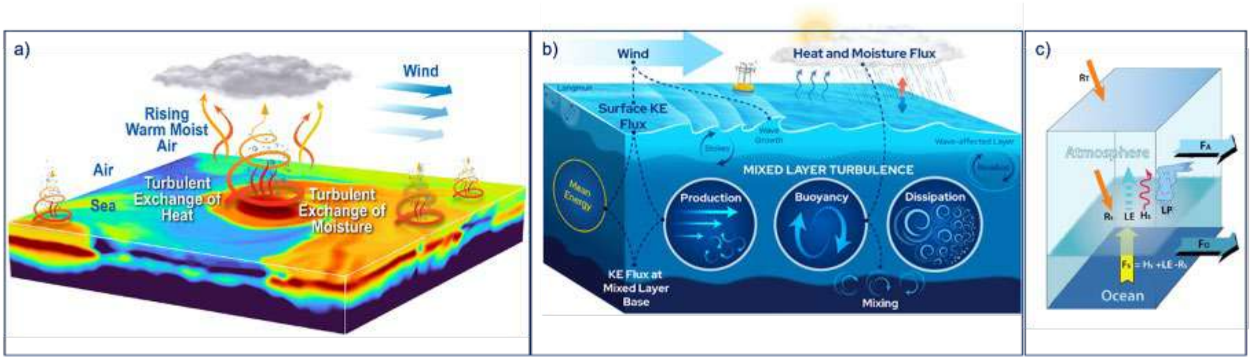

Figure 1: *a) Schematic representation of thermodynamic coupling and the role of turbulent fluxes at the air-sea interface. Figure from Genteman et al., 2021. b) Schematic representation of dynamic coupling highlighting surface processes and pathways for kinetic energy (KE) transfer between the atmosphere and the ocean. Dashed lines and solid dots indicate how terms in the vertically integrated mixed-layer turbulent kinetic energy (TKE) equation connect to the atmosphere, the wave-affected layer, the deeper ocean, and the mean kinetic energy (KE) equation. KE fluxes from the wind are split between viscous and wave-driven terms at the interface. The majority of wave-supported energy fluxes balance with terms in the wave-affected layer. Here, the focus is on the balance in the mixed-layer, where surface-driven production and buoyancy are primarily balanced by TKE dissipation rates. From Zippel et al., 2022. c) Schematic of the regional budget constraint approach tackling the consistency of energy flows through the atmosphere (top) and ocean (below), include radiation at the top and surface RT and Rs, surface sensible heat flux Hs, and surface latent heat flux LE. Latent heat is realized here in*

the atmosphere as precipitation LP. The vector transports of total vertically integrated energy in the atmosphere FA and ocean FO are indicated. Figure from Trenberth et al., 2019.

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CSQ-48	Knowledge Advancement Objectives	Geophysical Observables [Links to MIM databases]	MIM Number	Measurement Specifications	Dataset, Methods, Tools & Models	Policies / Benefits
How can we improve the monitoring and understanding of planetary heat exchange at regional scale? **And which essential advancements can we achieve for research and monitoring on weather and climate patterns?**	**A) Identify, and improve understanding of, small-scale thermal air-surface feedback mechanisms** *Analyse critical surface-atmosphere thermal feedback mechanisms, particularly for small-scale processes (and variations), using high resolution observation-driven coupled atmosphere-ocean models, to improve weather and climate predictability.* B) Further advance knowledge on dynamics of extreme events such as heat waves, extreme precipitation, storms to improve prediction skills for early warning systems C) Improved understanding of momentum and kinetic energy transfer between components of the Earth's system (ocean, atmosphere, cryosphere, land.	**Critical Parameters** *Latent heat flux (derived)* • Wind profile (horizontal) [CEOS 5] • Wind profile (vertical) [CEOS 9] • Atmospheric specific humidity (column/profile) [CEOS 13] *Sensible heat flux (derived)* • Air temperature (near surface) [CEOS 138] • Sea surface temperature [CEOS 144] • Wind speed parameters listed above (CEOS 5 and 9) *Planetary ocean and atmospheric heat transport / advection (derived)* • Atmospheric temperature (column/profile) [CEOS 1] • Sea surface heat flux [CEOS 287] • Ocean velocity [CEOS 285] • Ocean surface currents (vector) [CEOS 153] • Ocean temperature [CEOS 284] • *Wind profiles listed above – CEOS 5 and 9* *Earth surface temperature (derived)*	CEOS 5 CEOS 9 CEOS 13 CEOS 138 CEOS 144 CEOS 1 CEOS 287 CEOS 285	*Spatial resolution (latent and sensible heat flux input parameters)* Ideal: 25km *Gentemann et al. (2021)* *Spatial resolution (ocean surface currents)* Ideal: 5km *Spatial resolution (other parameters)* Ideal: TBD *Temporal resolution* Ideal: Daily	High-resolution models Atmospheric & oceanic & coupled assimilation systems (high-resolution, regional/nested)	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of weather and climate forecast, CC prediction / climate models (validation, parametrization, detection & attribution) Disaster risk management Early warning systems Climate and national services

		• Land surface temperature [CEOS 170] • Lake surface temperature [CEOS 293] • Sea-ice surface temperature [CEOS 158] • Snow surface temperature [CEOS 246] • Sea surface temperature (listed above - CEOS 144) • Land ice surface temperature [None]	CEOS 153 CEOS 284 CEOS 170 CEOS 293 CEOS 158 CEOS 246			
		Supporting Parameters				

		Net radiation (derived) • Downwelling (Incoming) solar radiation at TOA [CEOS 123] • Upward short-wave irradiance at TOA [CEOS 124] • Upward long-wave irradiance at TOA [CEOS 125] • Downward short-wave irradiance at Earth surface [CEOS 131] • Downward long-wave irradiance at Earth surface [CEOS 132] • Upwelling (Outgoing) long-wave radiation at Earth surface [CEOS 134] • Upwelling (Outgoing) Short-wave Radiation at the Earth Surface [CEOS 260]	CEOS 123 CEOS 124 CEOS 125 CEOS 131 CEOS 132 CEOS 134 CEOS 260			

A.20 CSQ-51: What are the mechanisms that couple the lithosphere, atmosphere and ionosphere, and can they be modelled and monitored with adequate to support hazard risk management ?

The structure and dynamics of Planet Earth is unique in our solar system because of Plate Tectonics, a process coupled with deep mantle convection whereby continents drift and collide, and oceanic lithosphere is continuously created at mid- oceanic ridges and consumed at subduction zones. The Earth´s internal dynamics generate and shape the evolution of the continental and oceanic masses, and these process have made the Earth habitable thanks to planetary-scale mass transfers that have regulated Earth's atmosphere volatiles cycling and temperature, and the generation of a protective magnetic field. Forces acting deep within the Earth's interior are manifested in deformation at the surface, predominantly adjacent to tectonic plate boundaries.. Geodetic and seismological measurements have provided the principal data for understanding mantle dynamics, lithospheric processes and crustal response, and for improving numerical modelling for forecasting catastrophic events such as earthquakes, volcanic eruptions and Tsunami. Major advances have been made in research and risk mitigation, but much more still needs to be done to understand the processes at work within the Earth, and the interactions between these processes their manifestation at the surface, in the oceans, and in the atmosphere.

Tsunamis are one of the most destructive hazards on Earth, yet satellite data have previously been peripheral in monitoring their generation and propagation. However, mapping ionospheric waves has recently provided some limited information on tsunami propagation. Tsunami Early Warning Systems for the Indian Ocean, for example (https://www. gitews.org/; Falck et al., 2010), largely rely on "classic" geophysical data sets. However, despite numerous efforts, the classic methods still fail to correctly estimate the magnitude of large earthquakes (Mw > 8) in real time, and therefore, they also fail to correctly estimate the tsunami potential. In response to this need, it has recently been suggested that the ionosphere-based technique could, in future, present a novel approach for Natural Hazard-detection in near-real time (e.g., Savastano et al., 2017).

The ionosphere can be strongly perturbed by disturbances in the geomagnetic field, such as geomagnetic storms and substorms. In addition, the magnetic field plays an important role in the propagation of plasma perturbations. The ionized particles are not free to move horizontally, as they are confined by the Earth's magnetic field. As a result, any movement of the neutral air in the meridional direction will blow ionization along the magnetic field.

Impulsive forcing from the Earth's surface occurring due to earthquakes, explosions, volcanic eruptions, tsunamis, and so forth triggers atmospheric pressure waves. Depending on their frequencies, these atmospheric waves can be distinguished as acoustic and gravity waves. The acoustic waves are characterized by frequencies higher than the acoustic cutoff frequency (ωa), that is, higher than ~3.3 mHz. The acoustic waves are longitudinal waves in which particle moves in the direction of the wave propagation.

During earthquakes, vertical displacements of the ground or of the ocean floor induce perturbations in the atmosphere and ionosphere (Figure). The ionospheric perturbations, called coseismic ionospheric disturbances (CSID), are usually detected ~8–9 min after an earthquake. The Rayleigh surface waves generated by earthquakes propagate along the Earth's surface and induce acoustic waves that ~8–9 min later can be registered in the ionosphere, similarly to CSID generated by the coseismic crustal piston-like motion (Figure 1).

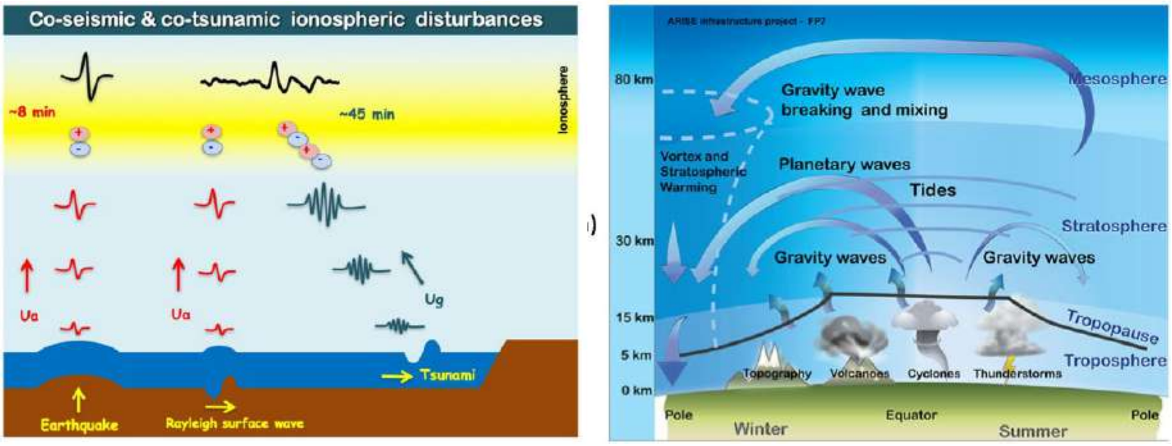

Figure 1: Coseismic ionospheric disturbances

References

Falck, C., Ramatschi, M., Subarya, C., Bartsch, M., Merx, A., Hoeberechts, J., and Schmidt, G.: Near real-time GPS applications for tsunami early warning systems, Nat. Hazards Earth Syst. Sci., 10, 181–189, https://doi.org/10.5194/nhess-10-181-2010, 2010.

Savastano, G., Komjathy, A., Verkhoglyadova, O. *et al.* Real-Time Detection of Tsunami Ionospheric Disturbances with a Stand-Alone GNSS Receiver: A Preliminary Feasibility Demonstration. *Sci Rep* **7**, 46607 (2017). https://doi.org/10.1038/srep46607

<table>
<tr><th>CSQ-51</th><th>Knowledge Advancement Objectives</th><th>Observables</th><th>MIM Number</th><th>Measurement Requirements</th><th>Tools & Models</th><th>Policies / Benefits</th></tr>
<tr><td rowspan="8">What are the mechanisms that couple the lithosphere, atmosphere and ionosphere, and can they be modelled and monitored with adequate to support hazard risk management ?</td><td rowspan="7">A) Measure at high resolution the total electron content of the ionosphere</td><td colspan="3">Critical Parameters</td><td rowspan="7">GNSS receivers,
Ionosonde networks
and airglow cameras
Gravimeters
Magnetometers
Plasma detectors
Langmuir probes</td><td rowspan="8">Support the emergency plans during large earthquake and tsunami
And major Volcanic eruption
Improve the knowledge of interactions between lithosphere-atmosphere-ionosphere.

Investigate potential inks between ionospheric anomalies and earthquake precursors

Better understand the impacts of the Ionosphere on GNSSS and communications satellite systems</td></tr>
<tr><td>Total Electron Content (TEC)</td><td>CEOS-238</td><td rowspan="6">Measurements at frequency of up to ~ 3.5MHz; measurements every 1min;
Electric field sensitivity 0.2 uV $Hz^{-1/2}$ at 500 kHz

Ionic temperature: 1000-5000K; density $5x10^2 – 5x10^8$ cm^{-3}; & composition (H^+, He^+, O^+, NO+)
Electron temperature: 500-3000K and density: $10^2 – 5x10^6$ cm^{-3}

Magnetic field, B @ 10Hz-17kHz; sensitivity $2x10^{-5}$ nT $Hz^{-1/2}$ at 1kHz;</td></tr>
<tr><td>Magnetic field (vector)</td><td>CEOS-188</td></tr>
<tr><td>Plasma density waves</td><td>OSCAR-279
OSCAR-88</td></tr>
<tr><td>Gravity waves</td><td>None</td></tr>
<tr><td>Acoustic waves</td><td>None</td></tr>
<tr><td>Ionosphere density</td><td>CEOS-264</td></tr>
<tr><td>B) improve the understanding of</td><td colspan="3">Critical Parameters</td><td></td></tr>
</table>

	atmospheric anomalies and linkages between lower atmosphere through the middle and upper atmosphere	Atmospheric temperature	CEOS-1	TBD	Atmospheric profiles from different sources	
		Clouds imagery	CEOS-109	TBD		
		Ion Density, Drift Velocity, and Temperature	CEOS-264	TBD		
		Electric Field (vector)	CEOS-262	TBD		
		Magnetic field (vector)	CEOS-187	TBD		
		Magnetic field (scalar)	CEOS-188	TBD		
		Electron temperatures, densities and composition, Neutral winds	None	TBD		
		Supporting Parameters				
		Atmospheric composition: • O3 • Water vapour • CO • CH4 • SO2	CEOS-34 CEOS-231 CEOS-33 CEOS-49 CEOS-39 CEOS-289	TBD		
	C) Measure short term atmospheric pressure waves triggered by earthquakes, explosions, volcanic eruptions, tsunamis,	**Critical Parameters**			**From ground:** Magnetic & Electric fields, Ionosonde data, TEC from GNSS	
		Atmospheric pressure	CEOS-136 CEOS-137	TBD		

A.21 CSQ-55: What are local patterns of ecosystem structure composition and functions worldwide?

While ecosystems are undergoing rapid changes worldwide, a consistent, accurate and spatially detailed characterization of ecosystem structure, composition (in terms of species diversity) and function (in terms of the role land cover plays in energy/carbon/water exchange with the atmosphere) and their changes over time is largely lacking to date. Such information is essential to understand fundamental patterns of ecosystems and biodiversity and are needed to provide integrated information for guiding and assessing actions and policies aimed at managing and sustaining its many functions and benefits. In the recent assessment of EBV vs. remote sensing priorities (Skidmore et al., 2021), the variables focusing on the monitoring of ecosystem conditions (beyond just ecosystem extent) and structure (i.e. habitat structure, fragmentation etc.) have received a high score; considering that many of the top-ranking EBV's in that prioritization study are also covered by Essential Climate Variables (ECVs).

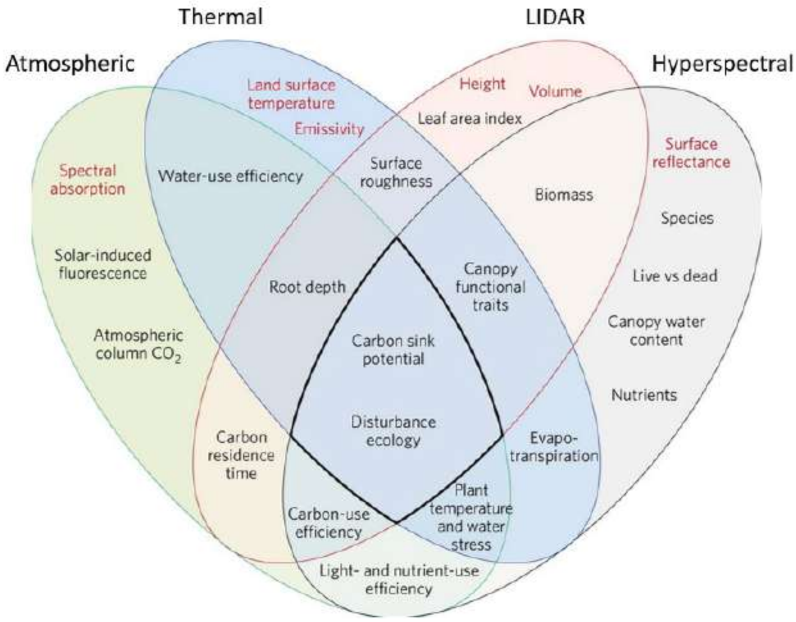

Fig 1. Synergy of different EO-based approaches for characterizing Ecosystems and Biodiversity (adapted from Stavros et al., 2017).

Advancing EO-based monitoring for such priority Essential Biodiversity Variables (EBVs) covering structure and composition can capitalize on new remote sensing opportunities. Only considering the synergy and interoperability of different novel EO-data streams allows for an increasingly comprehensive characterization of ecosystems and biodiversity (see figure above). Quantifying the structure as key feature of many terrestrial ecosystems, for example, can take advantage of various space-based mission either operation or forthcoming (GEDI/ICESAT-2, Sentinel-1, BIOMASS, ROSE-L …) that allow for much more detailed measurements of the three-dimensional structure at high resolution and at scales that also relate to existing in-situ ecological and forest monitoring networks. For characterizing ecosystem composition, the recent arrival of space-based imaging spectroscopy (ENMAP, PRISMA, EMITS, CHIME) provides new opportunities. EO-based data streams will have impact in particular when combined with innovative ground data (i.e. eDNA, sound sensors, citizen science) to provide high resolution and accurate estimates of community composition. New information on ecosystem structure and composition will underpin a novel stock take on the state of ecosystems worldwide and their functions.

These approaches should be leveraged for a new global effort for characterizing both ecosystem structures and composition and its relationships at local and regional level. From an observation perspective, most opportunities exist for forests and other vegetated ecosystems (e.g., grasslands, savannas) that should be the primary focus. But under-studied ecosystems (IPBES, 2019) such as freshwater systems, Arctic, marine/ocean, seabed, and wetlands should also be considered.

From an observation perspective, using EO-system operating now or in the coming years provide a lot of additional information that still needs to be fully explored. One key challenge is interoperability. Different sensors and observational datasets will be useful (optical, hyperspectral, SAR, LIDAR etc.) and make sure they can be analyzed in conjunction and in consistent manner is to be ensured. For example, for quantifying three-dimensional vegetation structure and species requires space-based information at scales that also relate to ongoing on the ground ecological and forest monitoring networks (Calders et al., 2023). Integrating space-based and on-the ground monitoring effectively will be key to achieve progress. There is need for streamlining workflows from data collection to estimation and modeling across the different data streams and sources. High quality LIDAR/SAR observations are only available for recent years and will result in higher quality estimations. For long-term trends, however, the use of optical and SAR-based systems with a longer time series record is required.

References:

Calders, K., B Brede, G Newnham, et al., 2023. StrucNet: a global network for automated vegetation structure monitoring, Remote Sensing in Ecology and Conservation, 9, 5, 587-598, https://doi.org/10.1002/rse2.333

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S.

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Stavros, E., Schimel, D., Pavlick, R. *et al.* ISS observations offer insights into plant function. *Nat Ecol Evol* **1**, 0194 (2017). https://doi.org/10.1038/s41559-017-0194

CSQ-55	Knowledge Advancement Objectives	Geophysical Observables (Links to MIM databases)	MIM Number	Measurement Specifications	Datasets, Methods, Tools & Models	Policies / Benefits
What are local patterns of ecosystem structure, composition and functions worldwide?	A) Improve the characterization of ecosystems based on their structure	**Critical Parameters**			• Various EO data analysis methods • Processing tools to allow for interoperability. • Statistical and AI methods for integrating EO with innovative ground data • Key to have both satellite and on-the ground monitoring at representative sites	- UNCBD - IPBES - Nature-based solutions - Restoration efforts
		Three-dimensional canopy structure, layering, plant area at different heights Canopy components, biomass distribution, geometry	NONE	Footprints less than< 30 m Resolution of vertical layers TBD		
		Vegetation Canopy (height) [CEOS 241]	CEOS-241	Soundings or gridded data with footprints < 30m		
		Supporting Parameters				
		Fraction of Absorbed PAR (FAPAR) [CEOS 175] Land cover/use and change [CEOS] 179 Earth surface albedo [CEOS 218] Vegetation Canopy (cover) [CEOS 240] Vegetation Cover [CEOS 242] Active Fire Detection and burnt area [CEOS 249] Chlorophyll Fluorescence from Vegetation on Land [CEOS 250]	CEOS 175 CEOS 179 CEOS 218 CEOS 240 CEOS 242 CEOS 249 CEOS-177 CEOS 250	• Spatial resolution: 10-20m • Temporal resolution: Monthly-annual • Spatial extent: global • Temporal extent: Long-time series wanted, at least 5-10 years history • Very-high spatial resolution optical data (< 1 m) • Coordinated ground data (i.e. terrestrial/drone LIDAR citizen science)		
	B) Improve the characterization of ecosystems based on their composition.	**Critical Parameters**			• Various EO data analysis methods • Processing tools to allow for interoperability.	
		Leaf/canopy level information on pigments (hyperspectral)	(NONE)	TBD		
		Vegetation Canopy (height)	CEOS-241	Soundings or gridded data with footprints < 30m		
		Supporting Parameters				

		• Precipitation Profile [CEOS 21] • Air temperature (near surface) [CEOS 138] • Land surface temperature [CEOS 170] • Soil Moisture at the surface [CEOS 171] • Leaf Area Index (LAI) [CEOS 173] • Fraction of Absorbed PAR (FAPAR) [CEOS 175] • Vegetation type [CEOS 176] • Fire fractional cover [CEOS 177] • Land cover/use and change [CEOS 179] • Soil type [CEOS 180] • Land surface imagery [CEOS 181] • Land surface topography [CEOS 182] • Vegetation Canopy (cover) [CEOS 240] • Vegetation Cover [CEOS 242] • Active Fire Detection [CEOS 249] • Chlorophyll Fluorescence from Vegetation on Land [CEOS 250] • Above Ground Biomass (AGB) [CEOS 268]	CEOS 21 CEOS 138 CEOS 170 CEOS 171 CEOS 173 CEOS 175 CEOS 176 CEOS 177 CEOS 179 CEOS 180 CEOS 181 CEOS 182 CEOS 240 CEOS 242 CEOS 249 CEOS 250 CEOS 268	• Spatial extent: global • Temporal extent: Long-time series wanted, at least 5-10 years history • Spatial resolution: 1-20m • Temporal resolution: Monthly-annual • High-spectral-resolution / hyperspectral (every ~5-10nm) • Vegetation LIDAR with footprints less than 30 m • Very-high resolution optical data (< 1 m) • Thermal data • SAR data at different wavelengths and polarizations • Innovative ground data (i.e. eDNA, sound sensors, citizen science)	• Statistical and AI methods for integrating EO with innovative ground data • Key to have both satellite and on-the ground monitoring	
	C) What is the current state of land ecosystems and their functions?	**Critical Parameters**			• Various hyperspectral data analysis methods • AI for integrating EO with innovative ground data (i.e. eDNA, sound sensors, citizen science) • Assimilation of global	
		Non-photosynthetic vegetation characterization (hyperspectral) (NONE)	NONE (NPV)	• Spatial extent: global • Temporal extent: Long-time series wanted, at least 5-10 years history • Spatial resolution: 1-20m • Temporal resolution: Monthly-annual		
		Supporting Parameters				
		• Precipitation Profile [CEOS 21] • Air temperature (near surface) [CEOS 138]	CEOS 21 CEOS 138	• Spatial extent: global		

		• Land surface temperature [CEOS 170] • Soil Moisture at the surface [CEOS 171] • Leaf Area Index (LAI) [CEOS 173] • Fraction of Absorbed PAR (FAPAR) [CEOS 175] • Vegetation type [CEOS 176] • Fire fractional cover [CEOS 177] • Land cover [CEOS 179] • Soil type [CEOS 180] • Land surface imagery [CEOS 181] • Land surface topography [CEOS 182] • Vegetation Canopy (cover) [CEOS 240] • Vegetation Canopy (height) [CEOS 241] • Vegetation Cover [CEOS 242] • Active Fire Detection [CEOS 249] • Chlorophyll Fluorescence from Vegetation on Land [CEOS 250] • Above Ground Biomass (AGB) [CEOS 268] • Lake Area [CEOS 254] • Fire radiative power [CEOS 288] • Lake Surface Temperature [CEOS 293]	CEOS 170 CEOS 171 CEOS 173 CEOS 175 CEOS 176 CEOS 177 CEOS 179 CEOS 180 CEOS 181 CEOS 182 CEOS 240 CEOS 242 CEOS 249 CEOS 250 CEOS 268 CEOS 254 CEOS 293	• Temporal extent: Long-time series wanted, at least 5-10 years history • Spatial resolution: 1-20m • Temporal resolution: Monthly-annual	circulation models (GCMs)/dynamic global vegetation models (DGVMs) and observations • Key to have both satellite and on-the ground monitoring	

A.22 CSQ-56: Where and how are ecosystems undergoing critical transitions?

The systematic monitoring of ecosystem dynamics has been demonstrated using remote sensing time series across a range of ecosystem and change types (IPBES, 2019, Skidmore et al., 2021). With satellite-based sensors like Landsat and Sentinels 1 and 2 and those providing 3D-structural and hyperspectral information becoming increasingly available with longer and more temporally dense time series, studying ecosystems dynamics (that is, spatial and temporal variation in ecological processes) can be substantially improved, which will lead to a better understanding of ecosystem resilience. Case study examples have shown the value of using temporal autocorrelation or mapping the rate and speed of recovery after disturbances to quantify resilience directly from remotely sensed data (Verbesselt et al., 2016, Senf, 2022). The ever-increasing length of remote sensing time series on the matter of decades underpins a new comprehensive assessment of ecosystem dynamics including the identification of critical changes in ecosystem resilience directly through monitoring disturbance frequency and recovery rates over time, and underpin rapid/near real time monitoring and development of early warning signals for critical transitions to occur (Senf 2022).

A key piece of understanding currently missing is the need for better understanding of vegetation-climate interactions. At macro-climatic levels this has been addressed by the Earth System modeling community using coarse-scale data (i.e., MODIS data). A key scientific question now is how macro-climate is linked to micro-climate, that is the climate experienced by the local flora and fauna and also humans (Senf 2022). Micro-climate is often regulated by vegetation and spatially detailed remote sensing data of land surface temperature, albedo and water vapor can help linking vegetation characteristics to local climatic conditions, allowing to scale from the plot level (often monitored by ecologists) to more macro-Earth System models and global climate reanalysis data (e.g., Copernicus ERA5). Bridging information and process understanding across spatial and also temporal scales will improving monitoring the impacts of changing climates (and thus driving critical ecosystem changes) at levels important for species and individuals as well as humans.

From EO-data perspective, the most important objective is to provide time series that are as long and as temporally dense as possible. It is essential here to make use and ensure the long-term continuity and consistency of the all observations from Landsat and Sentinels 1,2 to capture vegetation dynamics and using various sensors capturing soil and soil moisture dynamics globally (like SMOS). In addition, land surface temperature (i.e. Landsat, LSTM, TRISHNA), albedo and water vapor are critical variables. In particular LSTM with good spatial/temporal resolution and high precision and making good use of ENMAP/CHIME as way to measure albedo would be desirable.

References:

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S.

Senf C. (2022). Seeing the System from Above: The Use and Potential of Remote Sensing for Studying Ecosystem Dynamics, Ecosystems 25: 1719–1737, https://doi.org/10.1007/s10021-022-00777-2

Skidmore, A. et al., (2021). Priority list of biodiversity metrics to observe from space, Nature Eco Evo, 5, 896–906, https://doi.org/10.1038/s41559-021-01451-x

Verbesselt J. et al. (2016). Remotely sensed resilience of tropical forests. Nature Climate Change 6:1028–1031.

CSQ-56	Knowledge Advancement Objectives	Geophysical Observables (Links to MIM databases)	MIM Number	Measurement Specification	Datasets, Methods, Tools & Models	Policies / Benefits
Where and how are ecosystems undergoing critical transitions?	A) Comprehensive assessment of ecosystem dynamics including the identification of critical changes in ecosystem resilience directly through monitoring disturbance frequency, impacts and recovery rates over time	**Critical Parameters**			• Various EO data analysis methods • Processing tools to allow for interoperability. • Statistical and AI methods for integrating EO with innovative ground data • Different resilience measures, i.e. temporal autocorrelation or mapping the rate and speed of recovery after disturbances to quantify resilience directly from remotely sensed data • Coordinated ground data on ecosystem disturbances and recovery (i.e. terrestrial/drones, citizen science) • Key to have both satellite and on-the ground monitoring •	- UNCBD - IPBES - Nature-based solutions - Restoration efforts
		Vegetation Canopy (height)	CEOS-241	• Dense, long time series-based datasets from different optical, thermal and SAR sensors incl. Landsat, S1/2, SMOS etc. • Very-high resolution optical data (< 1 m) • Temporal extent: Long-time series wanted, at least 10-20 years history • Spatial resolution: 5-20m • Temporal resolution: weekly-annual, importance of near-real time data delivery		
		Vegetation Cover	CEOS-242			
		Three-dimensional canopy structure, layering, plant area at different heights Canopy components, biomass distribution, geometry	None			
		Supporting Parameters				
		• Land surface temperature [CEOS 170] • Soil Moisture at the surface [CEOS 171] • Leaf Area Index (LAI) [CEOS 173] • Fraction of Absorbed PAR (FAPAR) [CEOS 175]	CEOS 170 CEOS 171 CEOS 173 CEOS 175 CEOS 176 CEOS 177 CEOS 179 CEOS 181 CEOS 218	• Dense, long time series-based datasets from different optical, thermal and SAR sensors incl. Landsat, S1/2, SMOS etc. • Very-high resolution optical data (< 1 m)		

		• Vegetation type [CEOS 176] • Fire fractional cover [CEOS 177] • Land cover [CEOS] 179 • Land surface imagery [CEOS 181] • Earth surface albedo [CEOS 218] • Vegetation Canopy (cover) [CEOS 240] • Active Fire Detection [CEOS 249] • Chlorophyll Fluorescence from Vegetation on Land [CEOS 250] • Above Ground Biomass (AGB) [CEOS 268] • Fire radiative power [CEOS 288]	CEOS 240 CEOS 249 CEOS 250 CEOS 268 CEOS 288	• Temporal extent: Long-time series wanted, at least 10-20 years history • Spatial resolution: 5-20m • Temporal resolution: weekly-annual, importance of near-real time data delivery		
	B) Understanding links between vegetation characteristics and climate at relevant scales.	**Critical Parameters**			• Various EO data analysis methods • Processing tools to allow for interoperability • Statistical and AI methods for integrating EO with innovative ground data • Integration and comparison with	
		Land Surface Temperature	CEOS-170	• High- spatial resolution (5-20 m) information and related dynamics over time • 10-20 m time series data: Sentinel 1 / 2 time series, supported by very high-resolution data		
		Earth Surface Albedo	CEOS-218			
		Canopy water content	NONE			

		Supporting Parameters			climate/vegetation modelling at different space-time scales • **Coordinated ground data on ecosystem disturbances and recovery (i.e. terrestrial/drones, citizen science)** • Key to have both satellite and on-the ground monitoring Remote sensing data analysis to be underpin by site level local climate/vegetation experiments and campaigns (i.e. from ecosystem plots/networks), and/or near-sensing (drone, terrestrial) measurements, i.e. capitalizing on LTER or ICOS sites.	
		These new layers can be combined/enriched with information from existing products, incl.: • Precipitation Profile [CEOS 21] • Air temperature (near surface) [CEOS 138] • Soil Moisture at the surface [CEOS 171] • Leaf Area Index (LAI) [CEOS 173] • Fraction of Absorbed PAR (FAPAR) [CEOS 175] • Vegetation type [CEOS 176] • Fire fractional cover [CEOS 177] • Land cover [CEOS 179] • Land surface imagery [CEOS 181] • Land surface topography [CEOS 182] • Vegetation Canopy (cover) [CEOS 240] • Vegetation Canopy (height) [CEOS 241] • Vegetation Cover [CEOS 242] • Active Fire Detection [CEOS 249]	CEOS 21 CEOS 138 CEOS 171 CEOS 173 CEOS 175 CEOS 176 CEOS 177 CEOS 179 CEOS 181 CEOS 182 CEOS 240 CEOS 241 CEOS 242 CEOS 249 CEOS 250 CEOS 268 CEOS 288 CEOS 294	• Temporal extent: Long-time series wanted, at least 5-10 years history • Spatial resolution: 5-20m • Temporal resolution: weekly-annual, importance of near-real time data delivery		

		• Chlorophyll Fluorescence from Vegetation on Land [CEOS 250] • Above Ground Biomass (AGB) [CEOS 268] • Fire radiative power [CEOS 288] • Evapotranspiration [CEOS 294]				

Appendix B CSQ Relevance to International Treaties, Agreements and Conventions

		Paris Agreement	Convention on Biodiversity	Sustainable Development Goals	Sendai Framework	EU Green Deal
CSQ-01	Anthropogenic influences on the carbon cycle	Major contribution to informing Art. 4 Mitigation and evaluating policy responses; Major contribution to Art. 5 on maintaining sinks and reservoirs, both terrestrial and ocean; Other contribution to Enhanced Transparency Framework and Global Stocktake	Informs Arts 6/7/8/9 pm measures, monitoring, in-situ conservation and ex-situ conservation	Major contribution to SDG 12 Climate Action	N/A	Contributes to policy goals Net Zero by 2050 and Clean, Affordable Energy
CSQ-02	Land biosphere response to CC	Major contribution to informing Art 4 policy on climate state ; Major contribution to Art. 5 on maintaining land/biosphere sinks and reservoirs; Potential to assist adaptation policy and Global Stocktake	Major contribution to Art 9 Ex-situ conservation; Inform/evaluate contribution to Arts 6, 7, 8, 11 and 13; Needed to assess impact of financing measures	Major contribution to SDG154 Life on Land; Informs policy goal on SDG12 Climate action	N/A	Contributes to Net Zero by 2050 ; Strong contribution to Ecosystems and Biodiversity policy
CSQ-03	Ocean carbon cycle responses to climate change	Relevance to Art 4 Mitigation, reporting on climate state ; Informs Art 5 on ocean sink status and potential to assist policy delivery	Some relevance to Art 6 on measures for conservation; Some relevance to Art 7 on identification and monitoring ;	Relevance to SDG12 Climate action and SDG13 Life below water	N/A	Some relevance to Net Zero by 2050
CSQ-05	Sea level change in the coastal ocean	Some relevance to Art 4 on climate state and Art 5 ocean sinks; Strong contribution to Art	Some relevance to Art 6/7/13 incl. impacts on conservation measures for coastal habitats	Strong relevance to SDG11 Sustainable cities and costal population/ development; Relevance to SDG12/13/14	Informing Priorities 1/2/3/4 for coastal risk assessment and adaptation policies;	Informs urgency of Net Zero by 2050

		7 on adaptation and Art 8 Minimise loss and damage		pertaining to climate action, life on land and life under water;	Informs financing of prevention measures	
CSQ-07	Coastal interfaces with land atmosphere and ocean	Relevance to Arts 4/5/7/8	N/A	Some relevance to SDG13 Life below Water	N/A	N/A
CSQ-08	Coastal climate change feedbacks	Medium relevance to Art 4 mitigation; Some contribution to Art 5 maintaining ocean sink	Art 7/13 some relevance to Identification/ Monitoring and Public education	Some relevance to SDG13 Life below water	N/A	Indirect relevance to Net Zero policy
CSQ-20	Ice mass balance	Strong contribution to informing Art 4 Mitigation; Strong relevance to Art 7/8 on adaptation and minimising loss and damage; Strong public relevance	Art7 Identification and monitoring of Arctic habitat	Relevance to SDG12/13/15 Climate action and life on land/under the ocean	Indirect relevance to understanding disaster risk via to sea level	Informs Net Zero policy
CSQ-21	Sea Ice thermodynamics	Informs Art 4 Mitigation on climate state and sensitivity; Indirect contribution to Art 5/& on adaptation, loss and damage	N/A	N/A	N/A	Indirect relevance to Net Zero policy
CSQ-24	Polar change and climate variability	Relevance to Art 4/5 on mitigation and maintaining sinks/reservoirs	N/A	Link to SDG12 Climate action	N/A	Indirect relevance to Net Zero policy
CSQ-25	Cryosphere and Polar ecosystems	Informs Art 4 mitigation policy; Some relevance to Art 5 and 7	Strong relevance across all CBD Articles; Strong role for public education and awareness	Relevance to SDG14 Life on Land	N/A	Relevance to Ecosystems and biodiversity policy
CSQ-33	Ice sheets and rheology	N/A	N/A	Relevance to SDG11 Sustainable cities and SDG14 Life on Land	Strong relevance to all Sendai Priorities	N/A
CSQ-35	Erosion and sedimentation	N/A	N/A	Some relevance to SDG14 Life on Land	Good relevance to all Sendai Priorities	N/A

CSQ-36	Plate boundary deformation dynamics	N/A	N/A	Relevance to SDG11 Sustainable Cities and SDG14 Life on Land	Strong relevance across all Sendai priorities	N/A
CSQ-38	Crust and internal dynamics interactions	N/A	N/A	Relevance to SDG11 Sustainable Cities and SDG14 Life on Land	Strong relevance across all Sendai priorities	N/A
CSQ-43	Coupling between energy water and carbon cycles	Very strong relevance for Art 4 Mitigation	N/A	N/A	N/A	Relevance to Net Zero by 2050
CSQ-44	Anthropogenic influences on the water cycle	Strong relevance to Art 4 Mitigation; Contributes to Art 7/8 on adaptation and minimising loss and damage	Useful input to all Article of CBD	Informs SDG6 on clean water and sanitation; Strong input to SDG11/12/13 due to impact on life and society	Very strong contribution to all Sendai priorities due to the high % of hydro-met losses	Links with Net Zer policy and Ecosystems/ Biodiversity policy
CSQ-45	Internal energy flux estimates	Very strong relevance to Art4 on climate state and sensitivity	N/A	N/A	N/A	Indirect link to Net Zero policy
CSQ-46	Earth energy imbalance	Very strong relevance to Art4 on climate state and sensitivity	N/A	N/A	N/A	Indirect link to Net Zero policy
CSQ-48	Regional planetary heat exchange	Very strong relevance to Art4 on climate state and sensitivity	N/A	N/A	N/A	Indirect link to Net Zero policy
CSQ-51	Lithosphere-atmosphere-ionosphere coupling	N/A	N/A	N/A	Informs all Sendai Priorities	N/A
CSQ-55	State of Land ecosystems	Informs most Articles of the Paris Agreement	Strong relevance across all Articles of the CBD	Strong link to SDG14 Life on land; Relevance to SDG12 Climate action	N/A	Strong relevance to Ecosystems and Biodiversity policy
CSQ-56	Land ecosystem critical transitions	Informs most Articles of the Paris Agreement	Strong relevance across all Articles of the CBD	Strong link to SDG14 Life on land; Relevance to SDG12 Climate action	N/A	Strong relevance to Ecosystems and Biodiversity policy

Appendix C CSQ Relevance to National policies

		Energy	**Environment**	**Agriculture, Food security**	**Transport & infrastructure**	**Civil Protection & humanitarian aid**	**Public Health**
CSQ-01	Anthropogenic influences on the carbon cycle	Informs Net Zero transition and emission reduction policy	N/A	N/A	N/A	N/A	N/A
CSQ-02	Land biosphere response to CC	N/A	Strong relevance to Nature and Biodiversity policy; Relevance to Soil and Land policy; Some impact on urban environment	Farm to fork emissions; Increased production	N/A	N/A	Habitat change linked with vector borne disease risk;
CSQ-03	Ocean carbon cycle responses to climate change	Informs Net Zero transition	N/A	Sustainable fisheries	N/A	N/A	N/A
CSQ-05	Sea level change in the coastal ocean	Informs energy transition; ; Transition risk to renewable assets; Informs Energy security	Informs marine and costal environment policy; Impact on Urban environment policy (risk)	Informs risk to food production in coastal areas; Role of ports in food import/export	Informs risk to land transport; Informs maritime transport infrastructure and other infrastructure categories (eg ports)	Strong relevance to understanding disaster risk; Contributes to enhanced risk preparedness and increase risk resilience	N/A

CSQ-07	Coastal interfaces with land atmosphere and ocean	Informs and assists coastal renewable sources (tide, wind)	Informs marine and costal environment policy	Informs sustainable fisheries	N/A	Informs risk understanding, preparedness and resilience	N/A
CSQ-08	Coastal climate change feedbacks	Informs and assists coastal renewable sources (tide, wind)	Informs marine and costal environment policy	Informs food security, sustainable fisheries and increased production	N/A	N/A	N/A
CSQ-20	Ice mass balance	Informs and assists coastal renewable sources (tide, wind)	N/A	Informs risk to glacier-fed agriculture systems (eg N India/Himalayas)	Impacts on maritime transport ; Inform risk to supporting infrastructure	Informs risk understanding and preparedness, esp to maritime communities	N/A
CSQ-21	Sea Ice thermodynamics	Informs renewable energy transition	N/A	Informs Arctic sea routes and use for shipping and fisheries	Informs maritime shipping esp in Arctic waters	N/A	N/A
CSQ-24	Polar change and climate variability	Informs energy transition	N/A	N/A	N/A	N/A	N/A
CSQ-25	Cryosphere and Polar ecosystems	Informs energy transition	Informs Nature and Biodiversity policy	N/A	N/A	N/A	N/A
CSQ-33	Ice sheets and rheology	Informs transition risk , risk to assets	Relevance to urban environment policy	N/A	Informs risk to land transport and supporting infrastructure	Strong contribution to risk understanding, preparedness and resilience	N/A
CSQ-35	Erosion and sedimentation	Informs transition risk , risk to assets	Relevance to urban environment policy; Good link to Soil and land policy	N/A	Informs risk to land transport and supporting infrastructure	Some contribution to risk understanding, preparedness and resilience	N/A

CSQ-36	Plate boundary deformation dynamics	Informs transition risk , risk to assets	Relevance to urban environment policy	N/A	Informs risk to land transport and supporting infrastructure	Strong contribution to risk understanding, preparedness and resilience	N/A
CSQ-38	Crust and internal dynamics interactions	Informs transition risk , risk to assets	Relevance to urban environment policy	N/A	Informs risk to land transport and supporting infrastructure	Strong contribution to risk understanding, preparedness and resilience	N/A
CSQ-43	Coupling between energy water and carbon cycles	Net Zero transition ; Informs emission reduction strategy	Relevant to Marine & coastal environment; Relevance to Water policy and Soil and land policy	Informs farm to fork emissions, food security and increased production	Informs risk to land, maritime and air transport	N/A	Improved understanding of vector borne, respiratory and temperature related health risks
CSQ-44	Anthropogenic influences on the water cycle	Informs renewable energy transition; Informs transition risk , risk to assets	Relevant to Marine & coastal environment; Strong relevance to Water policy and Soil and land policy	Strong input to food security and increased production; Support to understanding farm to fork emissions	Risk of inundation to all forms of transport and supporting infrastructure	Improved weather and flood risk models improve risk understanding, preparedness and resilience	Strong contribution to improved understanding of water borne, health risks
CSQ-45	Internal energy flux estimates	Net Zero transition ; Informs emission reduction strategy	Informs water policy	N/A	N/A	N/A	N/A
CSQ-46	Earth energy imbalance	Net Zero transition ; Informs emission reduction strategy	N/A	N/A	N/A	N/A	N/A
CSQ-48	Regional planetary heat exchange	Net Zero transition ; Informs emission reduction strategy	N/A	Informs food security and sustainable fisheries policy	N/A	N/A	Links with respiratory and temperature related health risks

CSQ-51	Lithosphere-atmosphere-ionosphere coupling	N/A	N/A	N/A	Impacts on air transportation	Some contribution to risk understanding, preparedness and resilience	N/A
CSQ-55	State of Land ecosystems	N/A	Strong contribution to Nature and Biodiversity policy; Contribution to soil and land policy	Informs increased production and food security policy	N/A	N/A	Range of links ecosystem function and pest and pathogen disease risk
CSQ-56	Land ecosystem critical transitions	N/A	Strong contribution to Nature and Biodiversity policy; Contribution to soil and land policy; Informs marine and coastal policy	Informs increased production and food security policy	N/A	N/A	Range of links ecosystem function and pest and pathogen disease risk