Introduction

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

As part of this work the study team is generating a set of "Candidate Science Questions" (CSQs), that can be used by ESA and the ACEO to underpin the development of the new strategy. The CSQs are intended to encapsulate a series of pressing Earth system science issues that can be addressed using Earth observation data – either from existing and soon to be launched missions, or from future missions that need to be developed.

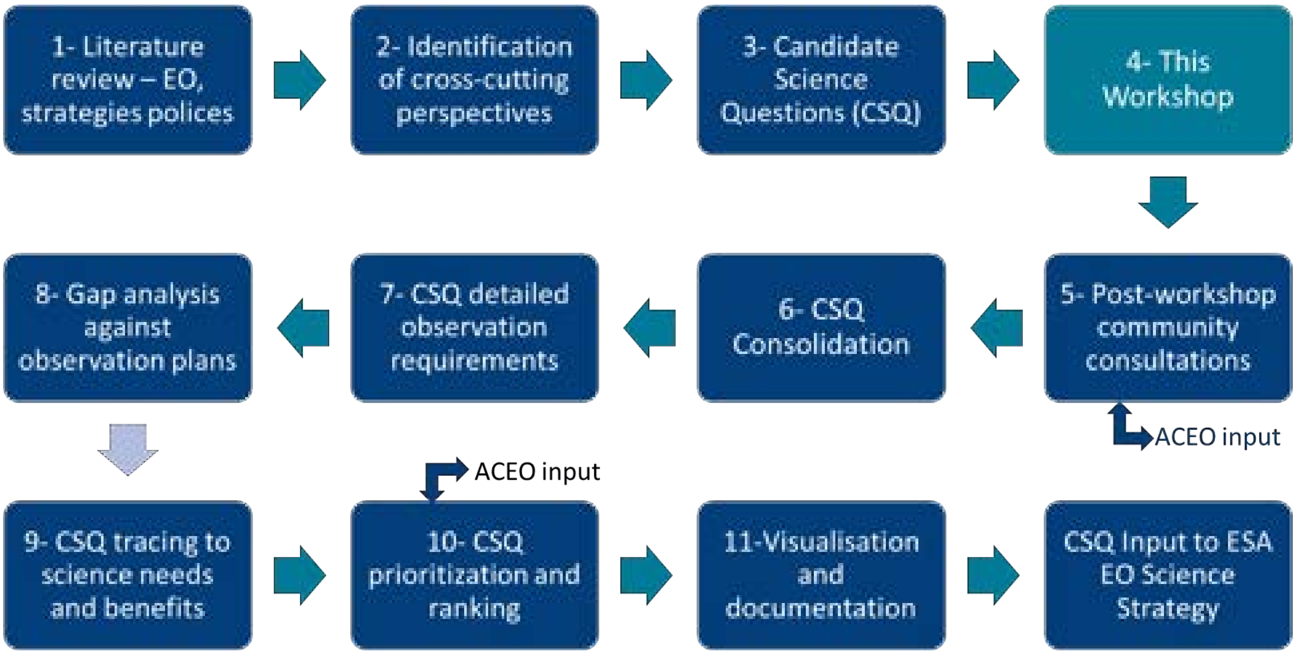
A working version of the CSQs is being published in advance of the ESA workshop in order to stimulate discussion, to help identify community priorities, and to guide future work of the study.

Context and Process

The current activity departs from previous ESA EO strategies formulation in two important ways:

1. There is consultation with the community early in the process, involving a dedicated study with a science team, and a community workshop
2. The approach is determinedly cross-disciplinary, seeking challenges that transcend traditional earth system science domain boundaries

The overall process used for the study is shown below.



In the early stages of the study the project science team split into a number of groups to review and discuss Earth system science priorities from a number of viewpoints. These views are *not* intended to be a thematic division of science domain but rather a set of perspectives from which to view the earth system science priorities. As such there are some overlaps, and some of the views are orthogonal – our intention is to consider a wide range of viewpoints and tease out cross-disciplinary issues. The list of 12 viewpoints used to initiate the CSQs is shown below:

Carbon cycle	Planetary boundaries
Water cycle	Biodiversity and ecosystems
Energy cycle	Coastal zone
Solid Earth, including mass changes/large scale hydrology and geomagnetism	Earthquakes/vulcanism and deformations, mineralogy
Climate tipping points	Polar science
Extreme events	Non topic-specific issues

At this stage we have identified a series of CSQs which are being used to support community consultation at the ESA Science Strategy workshop. After the workshop, a process of refinement and consolidation will be undertaken. At present we have 57 CSQs and it is expected to reduce this number significantly to help focus the future strategy. Subsequently the objectives for each CSQ will be refined and further details of the geophysical observables and measurement specifications added. Interactions with ACEO will occur at key stages in the process to ensure the utility of the final outputs for ACEO and ESA's subsequent production of the EO Science Strategy.

Format of the CSQs

Each of the CSQs are expressed as a summary table, with a supporting narrative. The summary table includes the following elements:

1. A high-level summary of the question
2. A set of "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 *main* geophysical variables needed to advance the science, noting that there will often be several other supporting datasets needed
4. Measurement Specifications: Initial view of the science requirements for datasets providing the geophysical observables. Note as above that many CSQs will need other subsidiary datasets.
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.

An index is provided that lists the CSQs, and each CSQ is contained in a separate PDF file, which is named with the CSQ number and the first few words of the question.

Some comments on the nature of the CSQs

The CSQs cover a wide range of disciplines and question types. There are varying levels of specificity and maturity. Some questions lend themselves quite well to specification in the format of the table – others are much more difficult, especially in the higher level cross cutting views like Tipping Points and Extreme Events. There are also ranges in the level of specificity. Some are "big" science questions, others more focussed on specific topics. In addition to discussion of individual CSQs the workshop should also help the study team and ESA gauge within this range what *kind* of questions are most helpful in defining future strategy.

Question	FileName
What anthropogenic and natural processes are driving the global carbon cycle?	CSQ-001-What anthropogenic and natural processes
How has the land biosphere responded to human activity and climate change?	CSQ-002-How has the land biosphere responded
How has the ocean carbon cycle responded to anthropogenic CO2 and climate change?	CSQ-003-How has the ocean carbon cycle responded
How do interactions between climate change and local human activities impact coastal vulnerability and resilience?	CSQ-004-How do interactions between climate change and local human activities
What processes drive changes sea level in the coastal ocean?	CSQ-005-What processes drive changes in sea level in the coastal ocean
How do extreme marine weather events impact coastal areas and how is coastal vulnerability changing in response to climate change?	CSQ-006-How do extreme marine weather events impact coastal areas
How do coastal processes mediate exchanges between land, atmosphere and the open ocean ?	CSQ-007-How do coastal processes mediate exchanges
How are coastal areas contributing to the global carbon cycle, and how are they responding to climate change and human pressures?	CSQ-008-How are coastal areas contributing to the global carbon cycle
What are the characteristics of the processes related to climate extremes and the hazards related to them?	CSQ-009-What are the characteristics of the processes related to climate extremes
How can we improve the characterization and preparedness for risks related to compound climate extremes?	CSQ-010-How can we improve the characterization and preparedness
How can we improve early warning of extreme events and climate hazards?	CSQ-011-How can we improve early warning
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)?	CSQ-013-Would it be of value to develop a system of systems
What are the main issues with calibration-validation, absolute calibration, long-term monitoring?	CSQ-014-What are the main issues with calibration-validation
Which specific observations are needed: polar / tropical regions, new measurement techniques vs long-term series of observation, large-scale field experiments?	CSQ-015-Which specific observations are needed
How to develop the link with other communities	CSQ-016-How to develop the link with other communities
How is the resilience of key Earth System components changing under multiple anthropogenic pressures?	CSQ-017-How is the resilience of key Earth System components changing
How can we attribute recent trends in Earth System components to anthropogenic activity	CSQ-018-How can we attribute recent trends in Earth System components
What is the mass balance of the cryosphere and how is it changing over time?	CSQ-020-What is the mass balance of the cryosphere
What physical processes drive ice dynamic variability, and how does the dominance of these processes differ between the different Polar regions?	CSQ-021-What physical processes drive ice dynamic variability
What are the cycles of variability for cryosphere essential variables, and how large are they?	CSQ-022-What are the cycles of variability for cryosphere essential variables
What is the impact of extreme weather events on the Polar regions?	CSQ-023-What is the impact of extreme weather events on the Polar regions
What is the impact of the Polar regions on global climate variability?	CSQ-024-What is the impact of the Polar regions on global climate variability
How does the cryosphere impact on Polar ecosystems, and how is the changing climate altering these feedbacks?	CSQ-025-How does the cryosphere impact on Polar ecosystems
What are the next generation of satellite data products for the Polar regions that will be generated through AI and ML?	CSQ-026-What are the next generation of satellite data products for the Polar regions
What is the size of anthropogenic impact on change in the Polar regions?	CSQ-027-What is the size of anthropogenic impact on change in the Polar regions
Are there tipping points/elements in the climate system not yet identified?	CSQ-028-Are there tipping points-elements in the climate system
Can we better quantify the temperature thresholds, time scales, and impacts of identified tipping points?	CSQ-029-Can we better quantify the temperature thresholds
Are the limitations in predicting climate tipping points driven by lack of process understanding or limited data availability?	CSQ-030-Are the limitations in predicting climate tipping points
What are the physical / mathematical mechanisms that generate the behaviour of tipping points in climate models? Can models be improved using more precise observations?	CSQ-031-What are the physical - mathematical mechanisms
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?	CSQ-032-Where are the alerts (pointed out by predictive models)
How does the solid Earth deform under present and past ice loads and what does it tell us about its rheology ?	CSQ-033-How does the solid Earth deform
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 ?	CSQ-034-How do active faults respond to stress
Can we quantify erosional processes of drainage basins and the resulting sediments discharge to the oceans	CSQ-035-Can we quantify erosional processes of drainage basins
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?	CSQ-036-Can we observe, model and forecast the deformation processes
Can we estimate the tsunami potential of an earthquake in real-time ?	CSQ-037-Can we estimate the tsunami potential
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 ?	CSQ-038-How does Earth's crust evolve in interaction with internal geodynamic
What is the nature of the mantle heterogeneity and the character of its convection at all depths ?	CSQ-039-What is the nature of the mantle heterogeneity
What is the dynamics of the fluid outer core at short timescales, and how is it coupled with the mantle ?	CSQ-040-What is the dynamics of the fluid outer core
How does soil status control Earth system cycles and influence surface-air exchange processes?	CSQ-041-How does soil status control Earth system cycles
To what extent can we predict the Earth's water cycle closure in space and time?	CSQ-042-To what extent can we predict the Earth's water cycle
What are the main coupling determinants between Earth's energy, water and carbon cycles and how accurately can we predict the forcings and feedbacks between the different components of the Earth system?	CSQ-043-What are the main coupling determinants between Earth's energy
How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?	CSQ-044-How important are the anthropogenic influences on the water cycle
How can we improve estimates of the internal flow of energy within the climate system with respect to major uncertainties for equilibrium climate sensitivity evaluations?	CSQ-045-How can we improve estimates of the internal flow
How does the Earth energy imbalance and Earth heat inventory changes 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?	CSQ-046-How does the Earth energy imbalance
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	CSQ-047-How can we improve the detection
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?	CSQ-048-How can we improve the monitoring
Could we improve the observations of active boundary areas dynamics?	CSQ-049-Could we improve the observations of active boundary
How we could Improve The large-scale bathymetry of the deep oceans?	CSQ-050-How we could Improve The large-scale bathymetry
How we can improve the understanding of lithosphere-atmosphere-ionosphere coupling mechanisms?	CSQ-051-How we can improve the understanding of
How can we help predict a volcanic event through the detection of thermal transient phenomena, gas emissionis and surface deformation evidence	CSQ-052-How can we help predict a volcanic event
Can we map topography, surface mineralogic composition and distribution, thermal properties, soil properties/water content?	CSQ-053-Can we map topography, surface mineralogic composition
How different drivers and threats effect the integrity of ecosystem?	CSQ-054-How different drivers and threats effect the integrity of ecosystem
What are local patterns of ecosystem structure and composition worldwide?	CSQ-055-What are local patterns of ecosystem structure
Where and how are ecosystems undergoing critical transitions?	CSQ-056-Where and how are ecosystems undergoing critical transitions
How vegetation and climate interactions vary across scales?	CSQ-057-How vegetation and climate interactions vary across scales
Are nature-based solutions delivering on multiple benefits?	CSQ-058-Are nature-based solutions delivering
How can we leverage EO data from tracking animal counts and behavior?	CSQ-059-How can we leverage EO data from tracking animal

CSQ-1 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	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.	• Column-averaged atmospheric CO_2 and CH_4 dry air mole fractions (XCO_2, XCH_4) and their gradients.	• High-spectral-resolution imaging spectroscopy of CO_2, CH_4 and O_2 bands at 1-10 km spatial resolution with 0.1 to 0.5% accuracies.	• 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
	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 CO_2 and CH_4 emission plumes • Observations of co-emitted species (NO_2, CO) to discriminate combustion sources • Fire radiative power	• High-spectral-resolution imaging spectroscopy of NO_2 and CO at 1-10 km spatial resolution • High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging	• Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • Discrete plume models	
	C) Quantify emissions and removals (fluxes) of CO_2 by the land biosphere on sub-seasonal time scales with the accuracy needed to quantify and distinguish long-term (decadal) changes from climate perturbations and disturbances (e.g., drought, floods, wildfire) and human activities (e.g., deforestation, intense agriculture).	• XCO_2 and XCH_4 and their gradients at 0.1 to 10 km resolution • Solar induced chlorophyll fluorescence (SIF) • Land use and land use change (LULUC)	• High-spectral-resolution imaging spectroscopy of CO_2 and Sif at 1-10 km spatial resolution • high spatial resolution NDVI, NIRv, Fire radiative power	• SIF retrievals • Empirical light Use Efficiency and Machine learning models	

CSQ-1 Narrative

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 atmosphere 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).

While anthropogenic CO_2 emissions from fossil fuel combustion are well constrained in well-designed bottom-up inventories, those from land-use change and management and natural sources and sinks of CO_2 and CH_4 are not well understood. In addition, there is growing evidence that natural carbon sources and sinks are beginning to evolve in response 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., 2019).

At global scales, the ocean, land, and atmospheric carbon reservoirs are expected to continue changing in response to continuing human activity (deforestation, forest degradation, intense agriculture), disturbance (drought, flooding, wildfire, infestation, tree mortality) and GHG-induced warming. Sustained and expanded global, space-based remote sensing observations are becoming more essential for monitoring these changes.

Observations needed to constrain anthropogenic emissions of CO_2 and CH_4

Our understanding of the carbon cycle and its response to natural and anthropogenic forcing has grown steadily over the past two decades as more advanced carbon cycle measurements have been made from land, ocean, airborne and satellite sensors. These data have been analyzed by carbon cycle models to constrain net CO_2 and CH_4 emissions and removals on global scales over decadal time scales. However, these measurements and models are not yet adequate to fully constrain the relative roles of land and ocean carbon sinks or to provide the time-critical, policy relevant information needed to implement and assess the effectiveness of emissions reduction policies at national scales.

To meet these emerging needs, both the observations and models of CO_2 and CH_4 require much greater precision, accuracy, and spatial and temporal resolution and coverage. High precision and accuracy are needed to detect and quantify CO_2 and CH_4 sources and sinks because the background concentrations of these gases are large enough that even the most intense anthropogenic and natural sources and sinks produce changes larger than a fraction of 1% on scales ranging from large urban areas to nations. Improved resolution and coverage are needed because both CO_2 and CH_4 have a diverse range of sources and CO_2 has a wide range of natural sinks that span a wide range of spatial and temporal scales.

While measurements of CO_2, CH_4, and other GHGs from ground-based, ship-borne and airborne in situ networks will continue to provide the most precise and accurate estimates of atmospheric concentrations and their growth rates on global scales, these networks are too sparse to identify and characterize CO_2 and CH_4 sources and sinks on scales ranging from large urban areas to nations. Recent advances in space-based remote sensing methods are providing new opportunities to augment the spatial and temporal resolution and coverage of the ground-based and airborne GHG networks. For example, Japan's Greenhouse Gases Observing Satellite (GOSAT) and GOSAT-2 and NASA's Orbiting Carbon Observatory-2 (OCO-2) and OCO3 are now returning over a hundred thousand estimates of the column average CO_2 dry air mole fraction (XCO_2) over the sunlit hemisphere of the globe each day with accuracies near 1 ppm (O'Dell et al., 2018; Kiel et_ al., 2019; Müller et al., 2021). Japan's GOSAT, GOSAT-2 and the Copernicus Sentinel 5 TROPOMI instrument are providing near global estimates of the column-averaged CH_4 dry air mole fractions (XCH_4) each day.

Ground-based, airborne, and space-based CO_2 and CH_4 estimates are being assimilated into models, along with estimates of atmospheric transport to derive estimates of CO_2 and CH_4 fluxes on spatial scales that range from individual facilities or field plots to large urban areas, to regional or national scales and to the globe. These modeling tools have evolved substantially over the past decade, and are now providing new insights into CO_2 and CH_4 emissions and CO_2 sinks on both local scales (e.g., individual power plants or pipeline leaks; e.g., Nasar et al., 2022; Cusworth et al., 2020) and regional-to-global scales (c.f., Chevallier, 2021; Peiro et al., 2021; Worden et al., 2022; Byrne et al. 2023). For example, Worden et al. (2022) find that their analysis of GOSAT data can quantify net CH_4 fluxes from up to 57 of largest countries. Similarly, Byrne et al. (2023) found that OCO-2 data could be analyzed to yield estimates of net carbon fluxes from the largest ~100 countries.

These top-down atmospheric CO_2 and CH_4 flux estimates complement the inventories of GHG emissions compiled by nations by providing an integrated constraint on the emissions and removals of CO_2 and CH_4 by all processes. They can also provide insights into processes omitted from national inventories, including transient fluxes of CO_2 and CH_4 associated with disturbances (e.g., severe weather, wildfire) and carbon flux changes on unmanaged lands that are associated with human activities or climate change. Because of this, these top-down atmospheric flux estimates are beginning to provide new insights into many aspects of the global carbon cycle.

While these space-based atmospheric CO_2 and CH_4 sensors provide much greater resolution and coverage than ground-based, ship-based and airborne sensors, they still do not yet have the spatial or temporal resolution needed to provide reliable estimates of net emissions from smaller countries or to discriminate anthropogenic from natural sources. They also do not yet have the precision or accuracy needed to quantify the weak, but spatially extensive CO_2 fluxes over the ocean. These shortcomings will be addressed to some extent over the next few years with the launch of new satellites, such as the Copernicus CO2M constellation. These sensors will extend the pioneering OCO, GOSAT and TROPOMI datasets with sub-monthly sampling of CO_2 and CH_4 over most of the globe at a spatial resolution of 2 km by 2 km. Simultaneous, co-bore-sighted observations of nitrogen dioxide (NO_2) will help to distinguish CO_2 plumes associated with high temperature combustion from land use sources or natural sources and sinks. These measurements will be augmented by data from public and private sector sensors such as GHGSat, PRISMA, Sentinel 2, EMIT, Carbon Mapper. These sensors provide much less coverage, but much higher spatial resolution to identify the locations of intense plumes of CO_2 and CH_4. These data should improve our ability to distinguish natural from anthropogenic emissions and to identify the specific sectors (i.e., energy, industry, agriculture, forestry) responsible for anthropogenic emissions. There are currently no plans for deploying space-based sensors with the precision and accuracy needed to measure ocean CO_2 fluxes.

These new sensors will offer new opportunities for monitoring natural and anthropogenic sources and sinks, but also pose several challenges. For example, they will gather orders of magnitude more measurements than existing space-based sensors and these data will have a wide range of precisions, accuracies, resolutions and coverage. Their measurements will have to be cross-calibrated against recognized standards before they can be combined to enhance coverage or provide data continuity. Remote sensing retrieval algorithms with much greater computational speed and accuracy are needed to analyze these large space-based datasets. Expanded ground-based and airborne validation systems, such as the Total Carbon Column Observing Network (TCCON; Wunch et al., 2017), COllaborative Carbon Column Observing Network (COCCON; Frey et al. 2019) and AirCore (Karion et al., 2010) will then be needed to identify and correct biases and relate these space-based data to the World Meteorological Organization (WMO) *in situ* atmospheric standards so that these data can be combined in flux inversion studies. Once these data are validated, atmospheric inverse models with much greater resolution and accuracy will be needed to retrieve reliable estimates of CO_2 and CH_4 fluxes on scales spanning large urban areas to nations or continents. Models that combine CO_2 and CH_4 flux estimates with other measurements or models of the land biosphere are needed to better diagnose or predict changes in land carbon stocks associated with human activities or climate change.

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CSQ-2 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Specifications	Tools & Models	Policies / Benefits
How has the land biosphere responded to human activity and climate change?	A) Quantify enhancements in the extra-tropical carbon sink over North America and Eurasia and identify human activities and climate variations driving these changes	• LULUC from NDVi, NIRv and SIF • Atmospheric CO_2 concentration gradients • Soil & air temperature and water content	• High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging • High-spectral-resolution imaging spectroscopy	• DGVMS • Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • Geostatistical models	CC mitigation and adaptation policy Climate finance Monitor the efficacy of natural decarbonization policies and CO_2 removal strategies.
	B) Distinguish the relative roles of climate change and disturbances (wildfire and land use change) on the tropical carbon sink across equatorial Africa, the Amazon basin and Oceania	• LULUC from NDVI, NIRv and SIF • Atmospheric CO_2 concentration gradients • Soil & air temperature and water content • Fire Radiative Power	• High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging • High-spectral-resolution imaging spectroscopy	• DGVMS • Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • Geostatistical inverse models	
	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	• microwave vegetation optical depth (VOD) • Canopy structure from Synthetic aperture Radar (SAR) and Biomass LiDAR	• Measure forest biomass at 1 km resolution with errors < 20% or ±10 tons/hectare between 70N and 56S	In situ reference systems Enhanced techniques for integrating data sources	
	D) Catalogue the impacts of climate change on crop health and forest mortality across the North American Great Plains, Central Europe and South and East Asia	• Forest/Cropland Cover • GPP via NDVI/NIRv/SIF • Impacts of disturbance (wildfire, drought, pests and disease)	• High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging • Soil and air temperature and water content • Fire Radiative Power	• DGVMS • Empirical light Use Efficiency and Machine learning models	

CSQ-2 Narrative

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 sink is intensifying in response to continued human activities and climate change.

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. 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 it's response to continuing human activities and climate change. To achieve these goals, we need high-resolution (30 m to 1 km), global, space-based measurements of above-ground carbon stocks, land use and land use change, as well as climate variations and disturbances that impact forest mortality and crop health to enhance 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.

Observations needed to understand processes driving change in the land biosphere

Space-based multi-spectral imaging of the land biosphere has long been the primary tool for characterizing land use and land use change (LULUC) and to track disturbances such as deforestation and wildfires. These data yield vegetation indices (e.g., enhanced vegetation index, EVI, normalized difference vegetation index, NDVI, leaf area index, LAI, near-infrared reflectance of vegetation, NIRv) that quantify "greenness". Vegetation indices are used to estimate the absorbed photosynthetically active radiation (fAPAR) and to parameterize other processes in semi-empirical gross primary production (GPP) models. They are also incorporated with other measurements in dynamic global vegetation models (DGVMs) to estimate the net ecosystem exchange (NEE) of carbon.

These measurement capabilities have recently been augmented with high-spatial resolution hyperspectral imagers, which better exploit spectroscopic information throughout the reflected solar spectrum. In addition, moderate-spatial-resolution observations of solar induced chlorophyll fluorescence (SIF) are providing more reliable constraints on light use efficiency, and thus the relative efficiency of the land carbon sink. These new tools are being used to provide more insight into plant species types (biodiversity), GPP and to track forest mortality and crop health on regional scales.

Existing space-based multi-spectral imaging sensors, such as Landsat, MODIS, VIIRS, and Sentinel 2 are expected to continue providing data and extending their time series. Public sector hyperspectral imaging sensors such as PRISMA, EnMAP, HISUI and EMIT will soon be joined by private sector sensors such as Carbon Mapper and Orbital Sidekick GHOSt constellations and lager public sector systems such as NASA Surface Biology and Geology (SBG) mission. These hyperspectral sensors can detect intense plumes of CO_2 and CH_4 as well as well as land surface properties, providing additional insight into carbon cycle processes. Moderate-spatial-resolution (2-10 km) observations of SIF from GOME-2, GOSAT/GOSAT-2, OCO-2/OCO-3 and TROPOMI will be augmented with higher-spatial resolution (300 m x 300 m) observations from FLEX in 2025.

These multi-spectral and hyperspectral observations are expected to continue playing major roles in tracking land use and land use change and disturbances that govern the exchange of CO_2 and CH_4 between the land biosphere and the oceanic and atmospheric carbon reservoirs. Insights into the land biospheric processes from these measurements are also expected to drive the development of more sophisticated DGVMs and Earth System Models (ESMs) for diagnosing the and predicting the impacts of human activities and climate change on the land carbon cycle.

Recent advances in space-based remote sensing measurements of above-ground biomass (AGB) are providing more direct ways to track long-term changes in carbon stocks at increasingly high resolution across the globe. Remote sensing cannot directly measure above ground woody biomass, but this quantity can be estimated from optical, passive and active microwave and Light Detection and Ranging (LiDAR) observations. Optical data from sensors such as Landsat and MODIS have been combined with empirical and statistical models to estimate above-ground biomass (e.g., Powell et al. 2010). These data provide the longest records of biomass change, but have large uncertainties.

Passive microwave observations of vegetation optical depth (VOD) have been collected since the early 1990s and provide the second longest space-based record of land carbon stock changes (e.g., Liu et al., 2015). Their main disadvantage is their relatively low spatial resolution (> 10 km). This limitation is mitigated in some investigations, which combine biomass estimates derived from VOD with high-spatial-resolution maps of forest cover and disturbances derived from optical measurements to model carbon losses (e.g., Fawcett et al., 2022). Existing passive VOD sensors such as AMSR-E, AMSR-2, SMOS and SMAP will soon be joined by AMSR-3 on GOSAT-GW, the Copernicus Imaging Microwave Radiometer, CIMR, extending the VOD record.

These passive VOD measurements are now being augmented by higher spatial resolution (0.1 to 1 km) above ground biomass measurements from synthetic aperture radars (SARs) and lidars. Data from existing SARs, such as the ALOS and ALOS-2 PALSARs, Sentinel-1 C-band and TanDEM-X PollInSAR have been used to create above ground biomass maps with spatial resolutions as find a 100 m (e.g., Berninger et al., 2018). In addition to their high resolution, SAR penetrates both clouds and vegetation better than optical remote sensing. The principal limitation of SAR data is signal saturation in regions of high biomass, such as tropical forests and strong dependence to environmental conditions (e.g., rainfall, humidity, freeze/thaw). SAR measurements also require costly, high-power satellites with large antennas. In spite of these challenges, existing SAR missions will soon be joined by the ESA BIOMASS, NASA NISAR and DLR Tandem-L missions, which will extend the data record with increased spatial resolution and sensitivity.

LiDAR missions, such as ICESat-2 and GEDI provide a third method for characterizing canopy height and above-ground biomass. LiDAR, like SAR, penetrates vegetation, providing some insight into its 3-d structure, but is less affected by signal saturation in regions with high biomass (Duncanson et al., 2022). LiDAR measurements may therefore provide both high accuracy and high spatial resolution (~25 m). The primary limitation of this method is its spatial coverage, since LiDARs only sample a narrow (~100 m) track along the satellite ground track. The coverage from GEDI is further restricted by the orbit of the International Space Station (ISS), which is constrained between $\pm 51^\circ$ latitude.

Because high-resolution, global measurements of above ground biomass are critical parameter for monitoring carbon stocks and because all existing space-based remote sensing methods face challenges, there have been numerous effort to combine the data types to extend coverage and reduce uncertainties (e.g., Saatchi et al., 2011; Urbazaev et al., 2018). There have also been broad community-wide efforts to establish a forest biomass reference system for validating remote sensing estimates of biomass (Labrière et al., 2022).

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CSQ-3 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirement	Tools & Models	Policies / Benefits
How has the ocean carbon cycle responded to anthropogenic CO2 and climate change?	A) Can space-based measurements 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° resolution over the globe.	• Precise/accurate estimates of near-surface atmospheric CO_2 and its spatial and temporal gradients • Sea surface temperature (SST) and salinity • Surface vector winds • Ocean colour	• Precise/accurate (0.1 ppm) CO_2 and O_2 from high-spectral-resolution spectroscopy and LiDAR • Ocean colour • SST, salinity and wind speed at 1°x1°	• Atmospheric GHG retrieval algorithms • Atmospheric flux inverse models • Global ocean biogeochemical models (GOBMs) • Enhanced Cal/val	CC mitigation and adaptation policy
	B) How is the Southern Ocean CO_2 sink responding to climate perturbations and long-term climate change.	• Precise/accurate estimates of near-surface atmospheric CO_2 and its spatial changes throughout the seasonal cycle • SST • Surface vector winds	• Precise/accurate (0.5 ppm) CO_2 and O_2 from high-spectral-resolution spectroscopy and LiDAR • SST, salinity & wind at 1°x1°	• Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • GOBMs • Coordination with surface in situ data	
	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?	• XCO_2 and its spatial and temporal gradients near coastlines • SST and salinity • Surface vector winds • Ocean colour	• Precise/accurate (< 0.1 ppm) imaging spectroscopy of XCO_2 at < 1km resolution • High spatial resolution SST, salinity and ocean colour	In situ reference systems Enhanced techniques for integrating data sources	

CSQ-3 Narrative

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). However, ocean dynamics continually transports anthropogenic carbon away from the surface into the interior and refreshes the surface with lower pCO_2 water. 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. 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. 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 sparce. Existing ship-based *in situ* measurements are accurate, but cover less than 1% of the 1°x1° 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. 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.

Ocean carbon observations with much greater coverage, resolution and repeat frequency are needed to monitor changes in the ocean sink 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. If not carefully monitored and understood, the changes in the ocean sink could partially mask the effectiveness of the emissions reductions efforts and potentially undermining their continuity and expansion.

In principal, 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.

Observations needed to track changes in the ocean carbon sink

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.

Fortunately, to monitor these processes over the open ocean, these observations do not need high spatial resolution. Space-based measurements could revolutionize our understanding of the ocean CO_2 sink if they could yield precisions and accuracies of 0.1 to 0.2 ppm on spatial scales of 1°x1° at monthly time scales. The largest challenge will be to deliver observations with this resolution and coverage over the polar oceans during the winter, when there is little sunlight and the regions are persistently cloudy. Active CO_2/O_2 lidars might be needed to address this need. These advances are achievable, but are not currently being targeted by any space agency.

Monitoring changes in the ocean sink associated with coastal processes (e.g., river runoff, upwelling, biological productivity) poses different challenges. Here, much higher high spatial and temporal resolution are needed to resolve the underlying biogeochemical and transport processes associated with the coastline. However, somewhat less precision and accuracy may be needed to resolve the atmospheric CO_2 signals associated with the coastal processes. Space-based CO_2 monitoring systems currently being developed to monitor anthropogenic and land biospheric processes may therefore provide the precision, accuracy, resolution and coverage needed for this application.

Sustained and improved space-based observations of weather and climate variables (ocean surface winds, ocean topography, and sea surface temperatures, salinity, ocean color and ice cover) are also needed to better constrain the relative roles of surface winds and ocean dynamics on CO_2 fluxes as these critical ocean processes continue to evolve in response to anthropogenic emissions and climate change.

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CSQ-4 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How do interactions between climate change and local human activities impact coastal vulnerability and resilience?	A) Quantify the vulnerability and resilience of coastal environments to climate change	New and improved EO measurements of all ocean parameters, including: - sea level (sea surface height) - 2D total surface current vectors - 2D surface winds vectors - directional wave spectra including integral wave parameters (wave height, period, direction) - sea surface temperature - hyperspectral ocean colour - salinity - coastal bathymetry	Fine spatial resolution: - sea level, currents, winds, waves, salinity: 1km or finer - SST, ocean colour, bathymetry: 10-50 metres Fast revisit (daily, sub-daily, hourly) 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	Coastal circulation models at 1km or finer grid spacing Numerical wave models Coupled atmosphere-wave-ocean prediction/assimilation systems	UN Decade of the Ocean Actions (Increase community resilience to ocean hazards; Unlock ocean-based solutions to climate change) UN Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas and marine resources GCOS, GOOS, and WCRP (ECVs)
	B) Quantify the vulnerability and resilience of coastal environments to local human activities	All EO observables of human activities, e.g land use, transport, agriculture, mining, water extraction, energy production, etc.		Digital Twins use 1km or finer grid spacing to evaluate benefits and impacts	
	C) Understand interactions between climate change and local human activities and their combined impacts on	Long term EO datasets Combine multiple EO datasets across domains, and with socio-economic data			

	coastal vulnerability and resilience				

CSQ-4 Narrative

The coastal zone is subject to intense stress linked to climate change (e.g. sea level rise, storm surges, high winds, extreme waves, heat waves, ocean acidification, deoxygenation, water cycle intensification, habitat and biodiversity losses) and anthropogenic pressures due to rapid coastal population growth, urban migration, land use change, freshwater extraction, subsidence, nutrient loading, pollution, overfishing, etc… (Singh et al., 2019). He and Silliman (2019) suggest that the interactions between climate change and local human actions can determine the vulnerability and resilience of coastal ecosystems. Better understanding of the interactions between climate-driven and human pressures on the coastal environment could help to identify where those pressures combine, to determine what mitigation strategies are most appropriate in which regions. Earth Observation can provide evidence about both climate change and socio-economic impacts and has an important role to play in assessing the vulnerability and resilience of the global coastal zone. Synergistic exploitation of EO datasets across the multiple Earth System domains (ocean, land, cryosphere, atmosphere) and the development of new and improved observations are needed to observe these complex coastal environments. EO can contribute to delivering comprehensive assessments of global coastal vulnerability and resilience to support the objectives of the UN Sustainable Development Goals and the UN Ocean Decade.

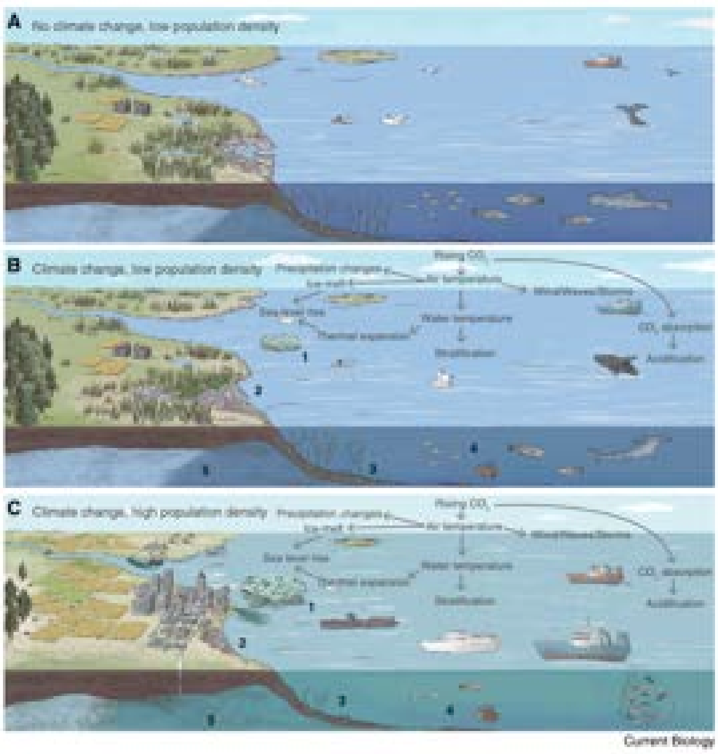

Figure 1. Impacts of climate change and local human activities on coastal ecosystems.
Shown is a temperate estuary adjoining land and ocean. (A) Scenario when the system is not affected by climate change. (B) Scenario when the system is pressured primarily by climate change. (C) Scenario when the system is pressured by both climate change and intense local human impacts. In (B), 1, climate warming promotes algal blooms [129]; 2, seaward loss and landward movement of coastal wetland as a result of sea level rise [102], and mangrove replacement of salt marsh grasses as a result of climate warming [105]; 3, warming-driven replacement of temperate seagrasses by subtropical seagrasses [130], and loss of bivalves due to ocean acidification [131]; 4, invasion of tropical fishes into temperate coastal waters and changes in fish species abundance and composition with warming [132]; 5, saltwater intrusion due to sea level rise [28]. In (C), 1, impacts of warming on algal blooms and hypoxia are exacerbated by eutrophication [12]; 2, loss of coastal wetlands due to the compounding effects of sea level rise and sea reclamations for urban, industrial and agricultural expansion [133]; 3, seagrass/bivalve loss is exacerbated due to synergistic/additive interactions between warming/ocean acidification and eutrophication [33,75]; 4, collapse of fisheries due to synergistic interactions between overfishing and warming [134]; 5, intense groundwater withdrawal exacerbates saltwater intrusion driven by sea level rise [28].

From He & Silliman, 2019

Observations and Geophysical parameters required: By definition, the coastal zone represents the interface between ocean, land, atmosphere and (in polar regions) the cryosphere. Understanding pressures and impacts at the coast call for multi-disciplinary cross-domain partnerships that bridge the traditional barriers between the land, ocean, atmosphere and cryosphere domains and communities. Efforts are needed also to develop new EO missions to sample the short temporal scales that dominate coastal regions (e.g. tides, diurnal warming), deliver high-resolution imaging of key parameters (e.g. directional wave spectra, wind vectors, total current vectors) and address data quality issues close to the land/water edge (e.g. sea level, salinity).

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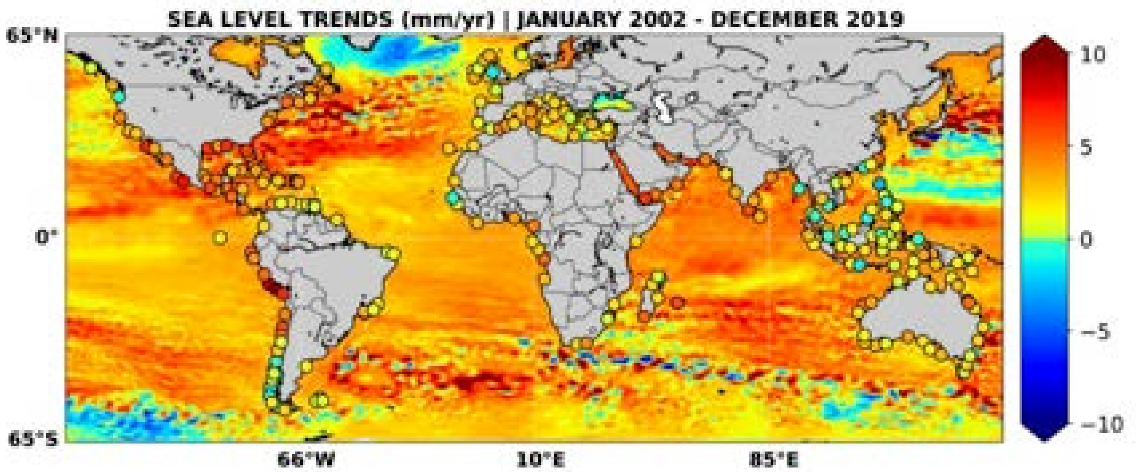
CSQ-5 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	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	- sea surface height - directional wave spectra including integral wave parameters (wave height, period, direction) - 2D total surface current vectors - 2D surface winds vectors - salinity - inland water levels - river flow, river discharge - soil moisture - precipitation - coastal bathymetry - surface air pressure - vertical land movement	Fine-resolution (1 km) Frequent revisit (daily, sub-daily) to observe fast-changing ocean processes (e.g. tides) and extreme events (storm surges, extreme waves, rainfall) 2D mapping High-resolution coastal wind data (1km or finer) Improved coastal bathymetry for water depths > 30m (not optical) New surface air pressure measurements	Coastal circulation models Hydrological models Storm surge and flood forecasting systems Coastal morpho-dynamics and coastal erosion models	Operational coastal and inland flood forecasting systems Climate projections of coastal sea level change
	B) Characterise the relative contributions to coastal sea level changes by steric and other physical processes				
	C) Understand the processes that drive land-ocean water exchanges and their associated impacts on marine and land-side coastal environments (e.g. salt intrusion)				

CSQ-5 Narrative

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 EO 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 reduce 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.

Fig. 5: Coastal and regional sea level trends (mm/yr) over the 18-yr time span.



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 would 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.

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CSQ-6 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How do extreme marine weather events impact coastal areas and how is coastal vulnerability changing in response to climate change?	A) Characterise the magnitude, spatial distribution and occurrence of extreme marine weather events in the global coastal zone	- sea surface height - surface winds vectors - directional wave spectra including integral wave parameters (wave height, period, direction) - total surface current vectors - coastal bathymetry	Sub-daily to hourly High spatial resolution (1km or finer) 2D imaging Similar uncertainty levels as offshore	Coupled atmosphere-waves-ocean models Coastal morpho-dynamic models	National policies and strategies for flood and coastal risk Coastal planning and management policies EU strategy on adaptation to climate change (EC, 2013)
	B) Evaluate the vulnerability of coastal environments to extreme marine weather events in the global coastal zone	- land use - coastal morphology, coastline	Land surface imagery 5-10m		
	C) Quantify changes in extremes and associated impacts on coastal regions	- long-term time series - multi-sensor, cross-disciplinary synergy			

CSQ-6 Narrative

Extreme marine weather events like storm surges, high winds and extreme waves are dominant causes of damage and flooding in coastal areas. Their contributions to increasing water levels come in addition to underlying coastal sea level rise and are particularly destructive when they coincide with high tides or large river discharge (e.g. due to extreme precipitation). Projections of future extreme sea level indicate significantly greater vulnerability to coastal flooding in most regions when contributions by surges and waves are included (Vousdoukas et al., 2017; EEA, 2022). Analyses of tide gauge data indicate that trends in surge extremes and sea-level rise both made comparable contributions to the overall change in extreme sea levels in Europe since 1960 (Calafat et al., 2022). Climate projections indicate that episodic events of storm surge and wave setup will, between them, contribute approximately 68% of projected coastal flooding by 2100 (Kirezci et al., 2020). Thus, as coastal sea level rise and severe weather events become more frequent, how well can EO quantify the exposure of coastal areas to these different contributions, and establish the spatial distribution of coastal risks in the global coastal ocean, and how these are changing? Can EO determine how different land properties (e.g. coastal morphology, land use) influence the response of the coastal environment to extreme weather events, and provide evidence where human actions exacerbate or mitigate the impact of extremes on the coast ?

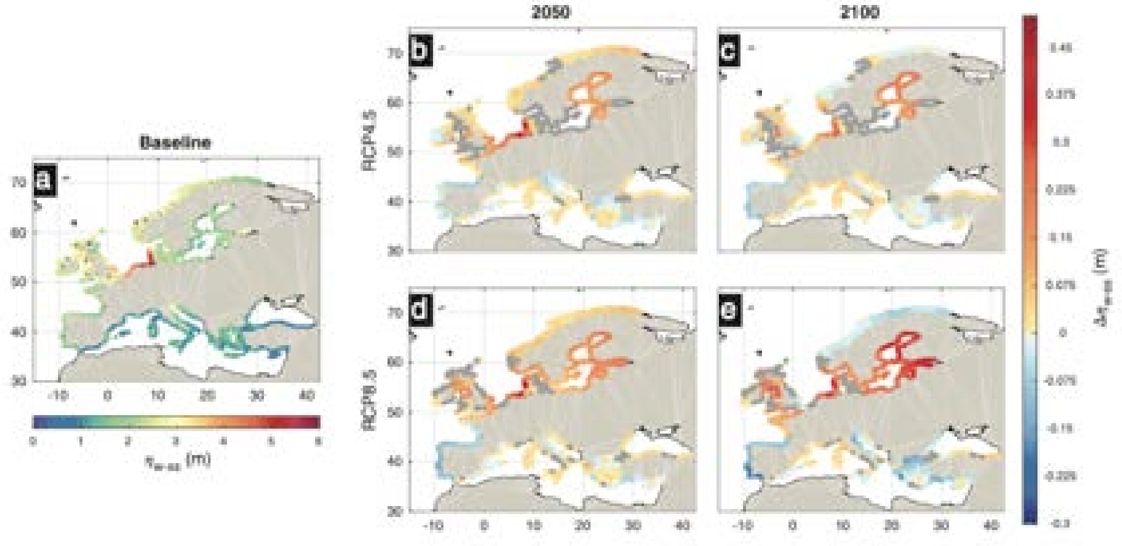

Figure 5. Contribution of climate extremes to extreme sea levels (ESL) along the European coastline and projected changes. Ensemble mean of episodic ESL contributions due to the combined effect of waves and storm surges (η_{w-ss}), expressed as the present-day 100-year η_{w-ss} (a) and projected changes under Representative Concentration Pathway (RCP)4.5 by 2050 (b) and 2100 (c), and under RCP8.5 by 2050 (d) and 2100 (e). Warm/cold colors express an increase/decrease, respectively, while points with high model disagreement are shown in gray (|CV| > 1).

From Vousdoukas et al. (2017)

Observations and Geophysical parameters required: Satellites have been shown to provide useful measurements of extreme marine weather events (e.g. altimetry for storm surges and extreme waves; SAR for extreme winds) but the typical 5-20 days temporal revisit of present-day missions makes them unsuited for extremes analyses. Scatterometers daily quasi-global data Efforts are needed to develop products and missions that deliver sub-daily high-resolution coastal 2D imaging of water levels, waves, winds and currents, to use in combination with existing and improved high-resolution land data.

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CSQ-7 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	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. B) Determine the interactions between physical and biogeochemistry processes and marine productivity in the global coastal ocean.	New and improved EO measurements of all ocean parameters in coastal regions, including: - sea level (sea surface height) - 2D total surface current vectors - 2D surface winds vectors - directional wave spectra including integral wave parameters (wave height, period, direction) - sea surface temperature - hyperspectral ocean colour - salinity - coastal bathymetry	Fine spatial resolution: - sea level, currents, winds, waves, salinity: 1km or finer - SST, ocean colour, bathymetry: 10-50 metres Fast revisit (daily, sub-daily, hourly) 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	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	UN Decade of the Ocean 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
	C) Reduce uncertainties in the global coastal ocean contributions to global land-air-sea fluxes of heat, nutrients, carbon, gases, and freshwater.	Global assessments			

CSQ-7 Narrative

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.

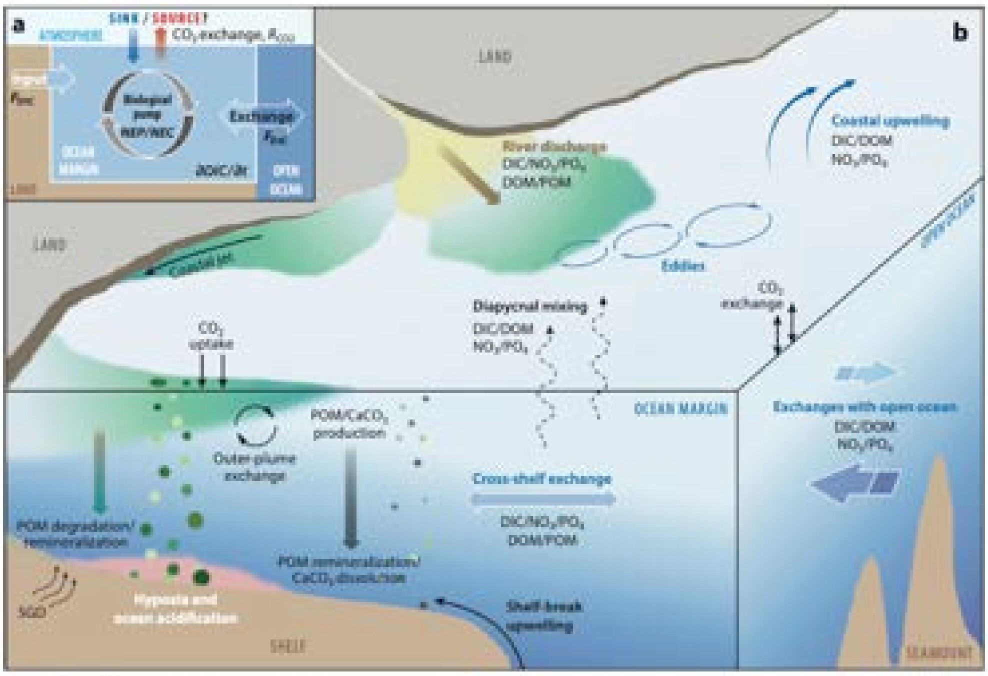

Figure 1

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_{CO2}) 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-8 Summary

<table>
<tr><th>Question</th><th>Knowledge Advancement Objectives</th><th>Observables</th><th>Measurement Requirements</th><th>Tools & Models</th><th>Policies / Benefits</th></tr>
<tr><td rowspan="4">How are coastal areas contributing to the global carbon cycle, and how are they responding to climate change and human pressures?</td><td>A) Global inventory of Blue carbon ecosystems, including mangroves, tidal marshes and seagrass beds</td><td rowspan="2">- biomass
- land cover
- canopy height
- surface temperature
- coastal bathymetry
- water level/DEM
- salinity
- soil moisture
- snow depth
- Atmospheric CO2, CH4</td><td rowspan="4">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</td><td rowspan="4">Coastal to regional models
Earth System models
Climate forecasts</td><td rowspan="4">Nature-based solutions
Restoration efforts
Improve projects
Climate change adaptation and mitigation policy.
Polar region treaties
IPCC monitoring and Paris agreement</td></tr>
<tr><td>B) Determine the extent of permafrost degradation and organic carbon releases in the polar coastal ocean</td></tr>
<tr><td>C) Determine contribution and drivers of change in “Blue carbon” ecosystems, and their resilience to human and climate change pressures in different coastal regions</td><td rowspan="2">Long term datasets for comprehensive assessments, including:
- 2D surface winds vectors
- directional wave spectra including integral wave parameters (wave height, period, direction)
- 2D total surface current vectors
- sea ice (extent, fraction, thickness)</td></tr>
<tr><td>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</td></tr>
</table>

CSQ-8 Narrative

"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.

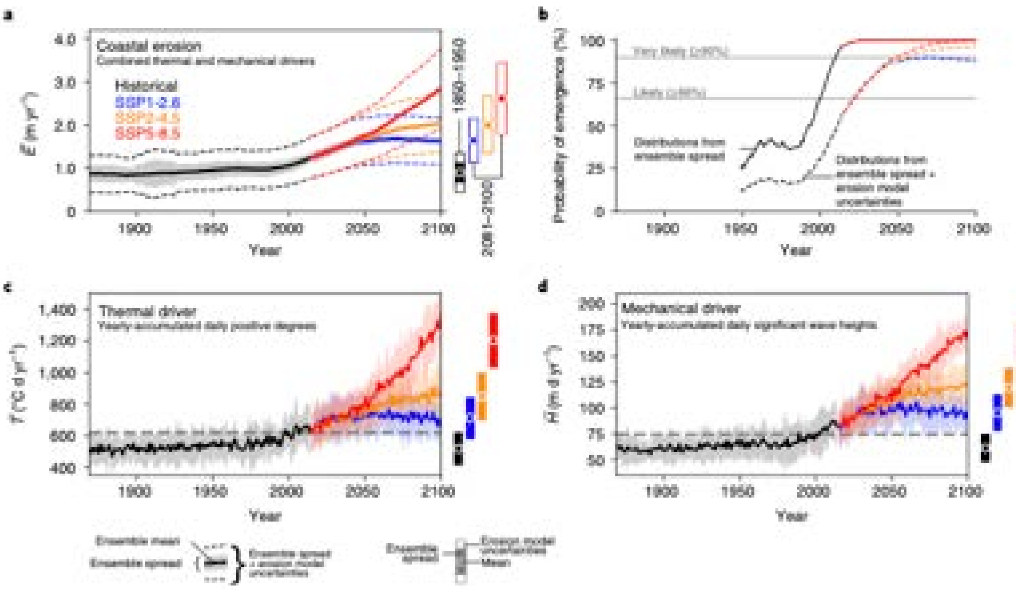

Fig. 1 | Arctic coastal erosion projections. a, Time evolution of the Arctic-mean coastal erosion rate, expressed as the combined effect of its thermal and mechanical drivers. **b**, Yearly probabilities that the Arctic-mean coastal erosion rate leaves the historical range of variability, calculated 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-9 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What are the characteristics of the processes related to climate extremes and the hazards related to them?	A) Quantify how climate change is affecting large scale circulation patterns and extreme events linked to them, including changes in their magnitude, frequency and spatial distribution.	• High spatial resolution and temporally continuous observations of many basic weather and climate related atmospheric and surface parameters • Oceans, currents, ocean-atmosphere processes • Vertical profiles of temperature, humidity, and wind. • Cloud observations	High frequency measurements of key geophysical parameters, ideally co-located in space and time	ESMs, RCMs	Improved understanding of various types of extremes and their changes in a changing climate
	B) Improve understanding of feedback mechanisms of extreme events at local and regional scales, including aerosol effects, albedo effects, land-atmosphere and land-ocean feedbacks.	• High horizontal and vertical resolution and temporally continuous observations of many basic weather and climate related atmospheric and surface parameters • Aerosols, clouds, atmospheric chemistry (aerosol formation), radiation, albedo • Land-ocean feedbacks, land-atmosphere feedbacks (soil moisture).	Earth system models need to be refined in resolution. Measurements commensurate with time and scale length with local downscaled models needed.	ESMs, RCMs	
	C) Quantify the effects of extreme climate events on agriculture and food	• Temperature, soil moisture, precipitation, wind • SIF?	VHR optical/NIR, soil moisture (passive/active microwave, 50m-	DGVMs, agricrop models,	

	production in the short and long term.	• Land use, vegetation parameters	25km), biospheric measures (LAI, SIF, …)		
	D) Quantify the effects of extreme marine heat waves on marine ecosystems.	• Ocean parameters, currents, temperature, marine ecosystems	Hi resolution (<= 1km) SST, Ocean Colour,	Ocean bio-models	

CSQ-9 Narrative

Climate change has already increased the frequency and intensity of several extreme weather phenomena as documented in the latest IPCC AR6 cycle reports. To minimize risks of potential disasters related to extreme events we need to understand the processes causing the events and their effects. Managing risks and hazards related to climate extremes has become an increasingly important part of climate change adaptation planning.

Large-scale atmospheric circulation patterns and modes of internal climate system variability (such as. the El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Atlantic Multi-decadal Variability (AMV), and the Pacific Decadal Variability (PDV)) are important to understand the changes in timing, duration, extent, and intensity of extreme events such as droughts, heavy rains, flooding, and snow cover (Chen et al, 2018). Some changes to circulation patterns are clearly linked to human-induced climate change, like the poleward shift of extratropical jets and cyclone tracks. But there are critical gaps in understanding how climate change affects other key circulation patterns such as changes in monsoonal circulations which may cause extreme precipitation (IPCC 2021). This uncertainty in how some large-scale circulation patters are affected by climate change, means there is also uncertainty in how altered circulation patterns may affect related climate extremes, and the sectoral impacts of those extreme events (e.g. on agriculture).

While understanding large-scale patterns is a key factor, climate extremes are often further modulated by local and regional forcings and feedback processes, including aerosols, albedo, and land-atmosphere and ocean-atmosphere feedbacks. Understanding hazards related to climate extremes requires an improved understanding of these regional feedback mechanisms. This understanding needs to be underpinned by observations of these phenomena at the scale at which they are to be modelled.

Finally, quantifying the social and economic impacts of the climate extremes is crucial for developing effective adaptation strategies. A significant consequence of climate change is extreme weather events that affect food security, both on land and in the ocean. Changes in rainfall patterns, droughts, and flooding are expected to hamper agriculture through reduced crop productivity. Whilst in the oceans, marine heat waves cause dramatic effects on marine ecosystems, including mass mortality of species and habitats, caused by heat stress.

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CSQ-10 Summary

Question	**Knowledge Advancement Objectives**	**Geophysical Observables**	**Measurement Requirements**	**Tools & Models**	**Policies / Benefits**
How can we improve the characterization and preparedness for risks related to compound climate extremes?	• Characterize and quantify risks related to heat waves and linked compound effects including droughts and fires.	• Temperature, soil moisture, humidity, clouds, winds, FRP, vegetation, land use,	In general specifications are commensurate with local climate models	ESMs, RCMs, statistical downscaling, event attribution	Improved climate adaptation (UNFCCC Loss and damage, IPCC WG), disaster response (Sendai), general sustainability and SDGs.
	• Characterize and quantify risks related to flooding and heavy precipitation in specifically vulnerable areas like coastal areas.	• Precipitation, humidity, sea level, river discharge, wind,	Sufficient repeat measurements at requisite scales to adequately capture short duration pluvial extremes	ESMs, RCMs, statistical downscaling, event attribution	
	• Characterize processes, environmental conditions related to extreme air quality events, like haze formation and serious air pollution events during heat waves.	• Aerosols (AOD, size distribution, type), air quality, UV-radiation, • Meteorological conditions	Synoptic and mesoscale measurements to understand pollution event scale, duration and evolution	Development of aerosol proxies or improved observations for aerosol size distribution. ESMs, RCMs	
	• Quantify environmental, social and economic hazards and impacts linked to climate extremes in local and regional scales.			Utilize also AI techniques, especially in socio-economic responses of systems to extreme events	

CSQ-10 Narrative

Simultaneous (in space and / or time) or sequential extreme events, which may or may not be extreme individually, can in combination lead to a compound extreme event that can cause severe environmental, economic, and societal impacts. Examples include coincident heatwave and drought, or pluvial river flooding combined with storm surge in the estuarine zone (amongst many others). Risk assessment of these *compound* hazards is particularly challenging and often underestimated (IPCC-21). An improved understanding of environmental vulnerability and risks related to compound events is therefore needed. Furthermore, quantification of the economic and societal hazards and impacts are also needed to understand climate adaptation needs arising from compound extreme events.

Climate change is affecting flooding by altering the intensity, frequency, and timing (e.g., earlier snowmelt) of floods. Rising sea levels also affect human activities and infrastructures in coastal areas in multiple ways, whilst simultaneously making coastal areas more vulnerable to damages due to storms, cyclones, and flooding.

Drought (low soil moisture and low humidity) and heatwaves are associated with increased wildfire risks. Dramatically large wildfires have recently taken place e.g. in Australia, Europe, Siberia, California, and very recently in Canada. In Australia, observations already show a long-term trend of weather conditions that may support bushfires (IPCC 2021). Whilst in 2012 – 2018 a catastrophic sequence of extreme weather events took place in southern California (Figure 1) resulting in 23 deaths. This was caused by extreme precipitation induced mudslides and debris flows on areas that had just been seriously burnt after a dry and hot season.

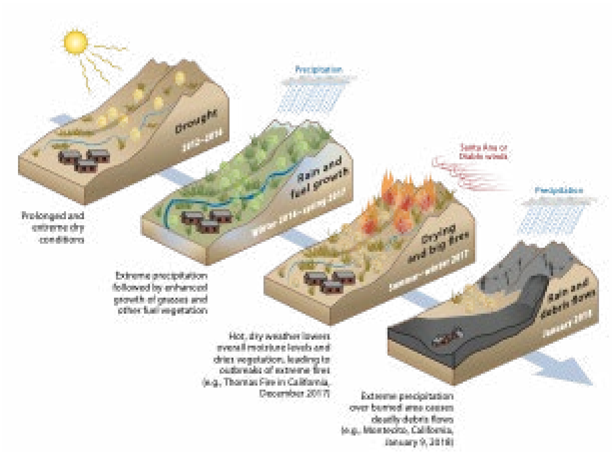

Figure 1: Example of Southern Californian compound extreme event which consisted of four events that occurred In a sequence. Figure from AghaKoucha et al., 2020.

Serious air pollution episodes are also climate related extreme events. They are often linked to suitable meteorological conditions, e.g. heat waves, but uncertainties in the details of these processes remain. For example, our understanding of haze (and new aerosol particle) formation is still limited. Furthermore, several studies indicate that the mortality risks related to air-pollution (PM2.5, PM10, ozone, NO_2) increase during heat waves. Fires and urbanisation also further amplify the compound risk of heat and air pollution.

Finally, vulnerability is a key concept in risk assessment of extreme events. In addition to environmental factors, it is known to depend on various socioeconomic, demographic, biophysical, cultural, and institutional factors. Quantifying environmental, social and economic hazards and impacts linked to climate extremes at local and regional scales can help identify the communities and regions that are most vulnerable to extreme events, and thus direct funding and planning to the areas and populations most at risk from this aspect of climate change.

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CSQ-11 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How can we improve early warning of extreme events and climate hazards?	• Characterize the vulnerability of societies to various types of climate extremes s.	• N/A		AI methods could be considered.	Disaster risk reduction, climate adaptation, loss and damage, insurance and socioeconomic risk reduction.
	• Improve long-range (e.g. seasonal) weather forecasting systems to identify potential high risk extreme events and develop automatic early warning systems.	• temperature, pressure, humidity and wind observations. • Extend the vertical coverage to stratosphere to enable better long-term predictability.	High spatial, vertical and horizontal resolution	AI techniques could be considered.	
	• Improve understanding of weather and climate phenomena that lead to extreme events. Utilize this information for early warnings of high risk for climate extremes.	• Long time series of weather and climate related parameters. • Continuous monitoring of weather and climate anomalies/patterns. • Temperature, precipitation, circulation	High spatial, vertical and horizontal resolution	Data mining and time series analysis of historical data. Application of AI techniques.	

CSQ-11 Narrative

Timely and reliable early warnings are acknowledged as efficient ways for minimizing risks related to disasters by saving lives and economic losses. This is recognised by the new WMO flagship early warnings for all initiative endorsed at the recent WMO Congress (https://beta.wmo.int/site/early-warnings-all-initiative) which recognises a key role for EO science. Such, early warnings can be seen as concrete solutions for climate adaptation, emphasized, e.g. by IPCC 2021. Observations together with forecasting form the heart of early warning systems (see Figure 1 as an example). Therefore it is important to ensure that the observational data supporting early warning systems is of the highest possible quality (https://beta.wmo.int/site/early-warnings-all-initiative/observation-and-forecasting-early-warnings).

Figure 1: Key pillars and budget overview of the Early Warnings for All initiative – an initiative with the goal to improve early warning systems especially in the developing countries. Figure taken from Early Warnings for All Initiative Executive Action Plan 2023-2027, WMO 2022.

Vulnerability is also a key concept in risk assessment of extreme events. It depends, in addition to environmental factors, on various socioeconomic, demographic, biophysical, cultural, and institutional factors. Various spatial and temporal scales are also important to consider when characterizing vulnerability and risks.

To develop early warning alerts for extreme events, accurate forecasting of extreme events (or increased probability for such events) is important. In this respect, improved long-range (e.g. seasonal) weather forecasts could allow identification of dangerous weather conditions in advance and allow improved preparedness for climate extremes. Alternative data-driven approaches for early warning systems could be developed by extensively analysing historical data to identify conditions that lead to extreme events. In all cases such activities are underpinned by high quality observations both the initialise forecasts and verify model performance.

References

AR6, IPCC 2021 (WG-I: Climate Change 2021, The Physical Science Basis)

WMO, 2022 (Early Warnings for All Initiative Executive Action Plan 2023-2027)

CSQ-13 Summary

<table>
<tr><th>Question</th><th>Knowledge Advancement Objectives</th><th>Geophysical Observables</th><th>Measurement Requirements</th><th>Tools & Models</th><th>Policies / Benefits</th></tr>
<tr><td rowspan="2">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)?</td><td>Diurnal cycle of essential climate variables</td><td>Essential climate variables (ECVs) presenting a strong diurnal cycle</td><td>Measurements at different local time at ascending node (LTAN)</td><td>Instruments on board satellites with precessing orbits or on board several sun-synchronous orbits with different LTAN</td><td rowspan="2">Better survey of diurnal and seasonal cycle of ECVs
Observations with higher spatial and temporal resolutions in key areas</td></tr>
<tr><td>Increase the horizontal resolution and the revisit time</td><td>ECVs that need to be followed frequently and at high resolution to follow the seasonal evolution and/or to observe fast changes: e.g. energy cycle, water cycle.</td><td>Measurements at higher spatial and temporal resolution</td><td>Constellation of satellites with different LTAN
Combination of one large satellites for the accuracy and small satellites for the spatial and local time coverage
Combination of geostationary for the continuous observations and LEO satellites for the resolution</td></tr>
</table>

CSQ-13 Narrative

Many geophysical variables present a diurnal cycle, for instance the cloud cover is very dependent on local time. The deep convection develops during the day. Low-level clouds are affected by the diurnal warming and cooling of the surface temperature. Most Earth observation LEO satellites have sun-synchronous orbits (SSO), observing only at two local times, one during the day and one during the night. Orbits of LEO satellites are characterised by the local time of their ascending node (LTAN). Geostationary satellites provide the information on the diurnal cycle but, due to their distance to the Earth, with a lower resolution than LEO satellites. Some LEO satellites are able to observe the diurnal cycle due to the drifting LTAN of their orbit, which is depending on the orbit inclination. For instance, the ISS orbit with a 51.6° inclination precesses 360° in roughly 60 days, allowing observation at all local times in 30 days. But it may be difficult to separate the diurnal cycle to the evolution during the month and the geographical coverage is limited to latitudes smaller than the inclination, excluding the polar regions.

Different strategies can be defined to monitor the diurnal cycle, for instance:

- Combination of GEO and LEO orbits
- Constellation of satellites with different LTAN.

The observation of the diurnal cycle is not required for all geophysical variables and, due to the cost of these strategies, it is important to determine what are the observations for which the diurnal cycle needs to be observed.

The constellation of satellites, by multiplying the number of observations, would also increase spatial resolution and reduce the revisit time of observations at the same location. This would be beneficial for several scientific subjects, e.g. the energy cycle at high resolution.

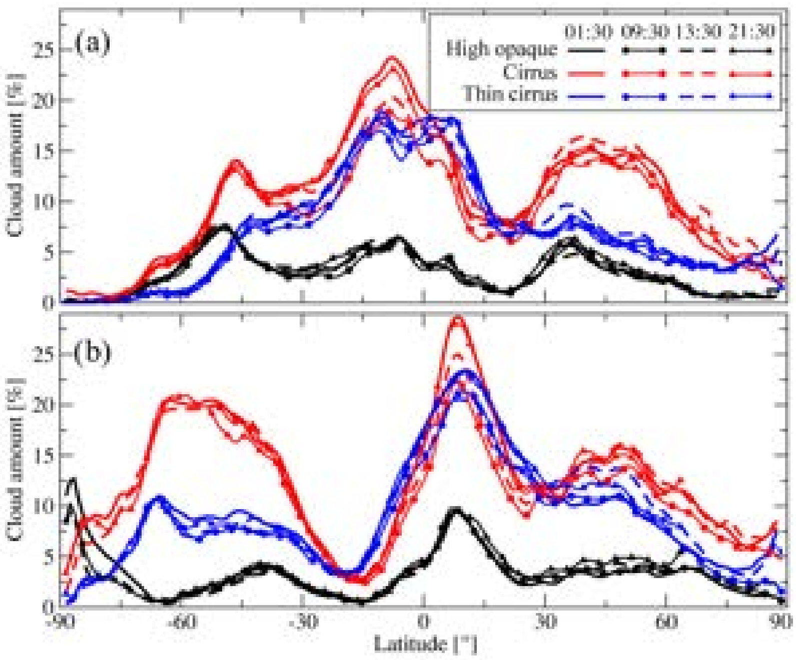

Figure 1: top, cloud cover as a function of local time and latitude, Feofilov and Stubenrauch, diurnal cycle cloud coverage, ACP 2019.

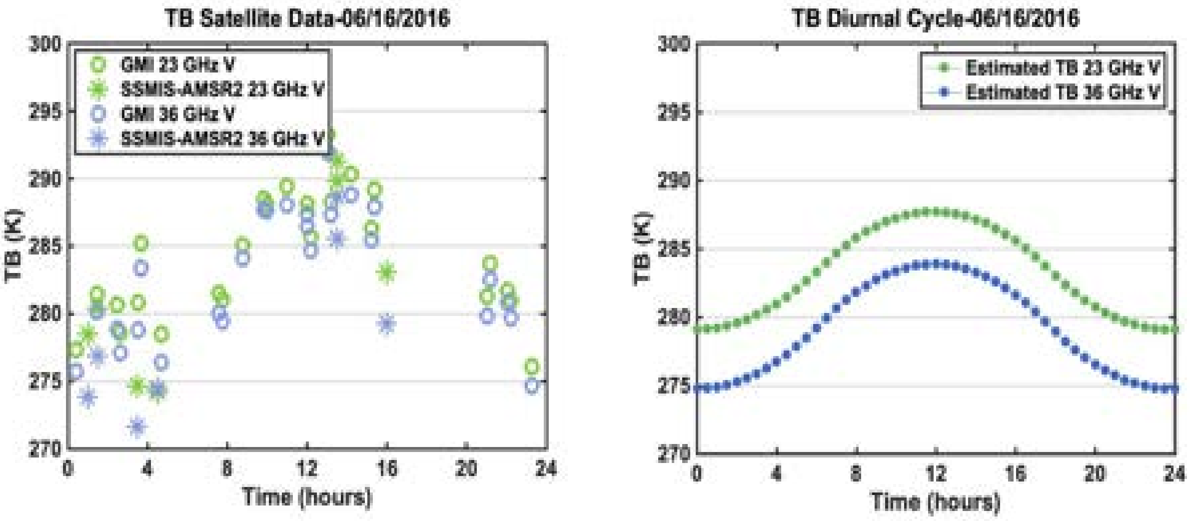

Figure 2: diurnal cycle microwave brightness temperature over land. From Sharifnezhad et al., Remote Sensing, 2021.

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CSQ-14 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What are the main issues with calibration/validation, absolute calibration, long-term monitoring?	To obtain calibrated data in absolute values	• all ECVs for which quality is crucial for inputting models and understanding ongoing processes	• Calibration before flight and validation on-flight of space instruments • Cross-calibration between instruments on board different satellites	• Ground-truth observation networks • CalVal facilities • Coordinated airborne observations	• Better absolute calibration of space sensors to provide high quality observations needed for the climate models • Determination of long-term trends and variability of ECVs
	To monitor the long-term evolution of ECVs	• ECVs that need to be followed on the long term to follow global and regional changes	• Validation of space observations during the full life of satellite missions	• Ground-truth observation networks • Gap filling in space observations using ground-based data • Homogenisation of past data for reanalysis	

CSQ-14 Narrative

High quality space data of geophysical variables are needed to perform process studies, build climatologies, evaluate long-term trends and constrain and validate models. Space instruments are calibrated before launch but the measurement configuration is often not representative of observations in orbit. Furthermore, the instruments may suffer from in-flight degradation and changes in their calibration characteristics. In-flight calibration is then needed during the Calibration/Validation (CalVal) and the operational periods of each space mission This can be done in different ways:

- Validation with ground-based and airborne observations. These observations may be performed during specific validation campaigns or using the data from monitoring network, for instance Total Carbon Column Observing Network (TCCON) for greenhouse gases and Network for the Detection of Atmospheric Composition Changes (NDACC) for ozone and chemical species. There is considerable room to improve the long-term relationships between space agencies and such networks with many potential win-wins. Access to sustained European Cal/Val facility for all satellite / in-situ comparisons as requested in the Global Climate Observing System Implementation Plan (GCOS-IP, Sterckx et al.,2020) would be strongly beneficial for the exploitation of EO missions.
- Cross-calibration between satellites measuring the same variables. In order to observe the same scene at the same time with the two satellites, it is needed to have cross-cutting orbits, for instance SSO and tropical orbits.

The long-term observation of Essential Climate Variables (ECVs) is required to monitor the evolution of the climate at global and regional scales and to evaluate the impact of human activities (see GCOS-IP 2022)[2]. Space data provide the main contribution to the survey of ECVs. Among the 54 ECVs identified by the GCOS, 60% can be only observed from space[3]. To perform this monitoring several conditions are required:

- High quality data of the same variables during several decades
- Each satellite has a limited lifetime. Long-term series are build using several different satellites. An intercalibration between satellite sensors during overlapping periods is needed.
- Long-term stability of the instruments.
- Gaps in data series need to be filled by ground observations.
- Reanalysis of past data to homogenise the series as it is made in Climate Change Initiative.

Reference

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CSQ-15 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
Which specific observations are needed: polar / tropical regions, new measurement techniques vs long-term series of observation, large-scale field experiments?	A) To follow the evolution of ECVs in regions more sensitive to climate changes: e.g., polar regions, upper-troposphere-lower stratosphere (UT-LS)	Key observables to follow the evolution of these specific regions	• To concentrate observations in the target regions	Orbits and modes of observation adapted to the target regions: • Molniya orbits to favour observations over the polar regions • Limb observations to observe strong vertical gradients in the UT-LS	• Better understanding of the physical processes involved in the regions more sensitive to climate change. • Better survey of geophysical and environmental hazards
	B) Monitoring of specific events: e.g., earth quakes, volcanic eruptions, flooding	Observables characterizing these specific events	• To adapt the observation schedule on alert	Link with model communities studying these events	
	C) Focus of specific areas: e.g,. cities, regions of high anthropic emissions	Observables characterizing these specific areas	• Operation modes to increase the spatial and temporal coverage of observations in the target areas	Link with the relevant model communities	
	D) To organize a large-scale field experiment to study a specific region for understanding the physical processes taking place	Coordination between satellite, ground-based, airborne observations and models during the field experiment	• Denser observations and measurement of more variables over a period of time	Organisational structure of the field campaign	

CSQ-15 Narrative

Climate changes are amplified in polar regions. They are warming faster than any other area on Earth and they are affected by the ice melting. These regions are less covered by satellite observations. Geostationary satellites can only observe at latitudes smaller than 60° and SSO generally only reach 82.5 degrees leaving a hole over the true poles. It is possible to define orbit configurations allowing to observe more frequently the polar regions. Molniya-type orbits are highly elliptical orbits with a 63.4° inclination and a 12-h period with an apogee above northern latitude. The satellite is above northern latitudes most of the time with a very good coverage of polar regions. Alternatively precessing orbits can be true pole to pole as proposed for e.g. TRUTHS and would have benefits for diurnal cycle characterisation and cal/val. More generally novel orbital configurations may better sample the poles amongst other undersampled or target regions.

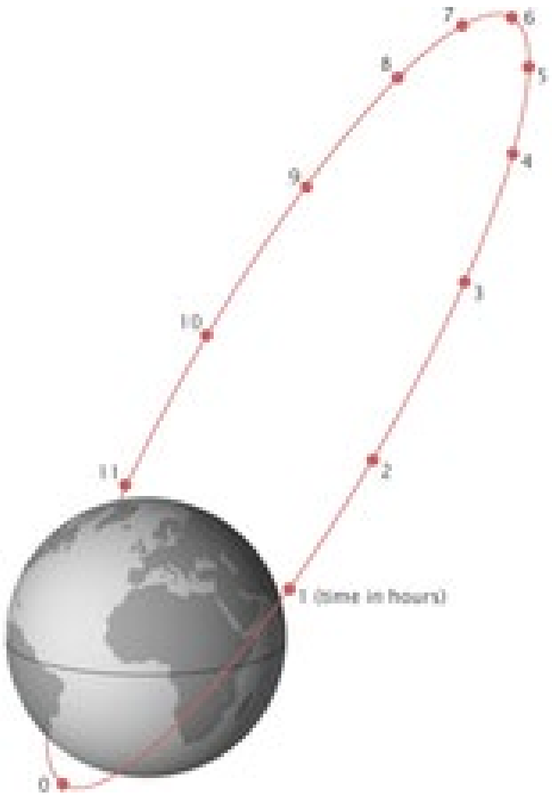

Figure 3: The Molniya orbit. Usually the period from perigee +2 hours to perigee +10 hours is used to transmit to the northern hemisphere. From https://en.wikipedia.org/wiki/Molniya_orbit

It may be interesting to program targeted observations with greater density for a period of time, after a specific geophysical event (earthquake, volcanic eruption, flooding, …) or/and in a particular area, i.e. above cities and region of anthropic emissions. These operation modes should be defined before the launch in order to be able to activate them in flight.

The combination of different modes of observation can bring new information on the vertical and horizontal variability of the atmosphere. For instance, to monitor the vertical gradients in the upper troposphere-lower stratosphere (UT-LS), a critical region in the climate system, it may be useful to combine limb and nadir observations. This was the case for SCIAMACHY instrument on Envisat. If these observations are made in the orbit plane, this would also allow tomography.

In addition to long-term monitoring of certain ECVs, it may be interesting to make denser observations with more variables measured over a period of time and over a targeted area. This is necessary to improve our understanding of physical processes taken place. An efficient way is to organise large-scale field experiments with satellite, ground-based and airborne observations. A good candidate for this is a field experiment in the Amazon rainforest, a key region for the climate and the biodiversity, strongly affected by deforestation.

Long-term series of observations are essential to monitor the evolution of the Earth system but in the same time it is important to develop new measurement techniques to improve the quality and the observations and to measure new variables. Financial resources are limited and an equilibrium should be found between the continuation of well-established and new measurement techniques.

CSQ-16 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How to develop the link with other communities	A) How EO observations can help to improve the models?	• Observations directly comparable with model variables • Observations characterizing sub-grid phenomena	Observables not resolved by the global models	• Specific high-resolution models resolving the sub-grid processes • Parameterization of sub-grid processes in global models	• To improve the link between satellite and model communities • To optimize the use of the huge quantity of space data • To benefit from the development of commercial space observations for scientific studies. • To promote the development of space observation-based services
	B) What Artificial intelligence can bring to EO science?	• Development of algorithms to fully exploit the huge quantity of space data • Combination of space and ground-based observations	Building data bases to train artificial intelligence	Artificial intelligence algorithms	
	C) How socio-economic aspects are considered taken in the EO strategy?	• How commercial satellites can provide data that complement the data from space agencies satellites • EO observations for climate risk assessments • Space observation-based services for transport logistics optimisation	To promote the use of public and private EO data	• Cooperation with private companies to exploit their data for science objectives • Development of tools to support the use of spatial data by private companies and public institutions	

CSQ-16 Narrative

1. **How EO observations can help to improve the models?**

Space observations and models are two essential components of the Earth climate system monitoring. Space observations provide the global view of geophysical variables but it is not possible to measure everywhere at any time. Models provide an estimate of these variables at any grid point and any time but they may be affected by biases due to an imperfect representation of physical processes taking place. The quality of space data assimilated in the models is also critical for the accuracy of model outputs. Space observations are highly needed to:

- Constrain and validate the models
- Improve the parametrization of sub-grid phenomena.

A reinforcement of the link between the satellite and the model communities is highly desirable at any stage of a space mission. During the definition of the mission the needs of the model community should be considered. During the phase of exploitation of the mission, regular exchanges between the two communities should be ensured to guarantee an optimised use of the space data to constrain and validate the models.

2. **What Artificial intelligence can bring to EO science?**

Earth observations provide a huge amount of data, increasing with time due to the progress in the resolution of the instruments and in the rate of data transmission. These data are very often not properly used due to a lack of knowledge of the users on the performances and limitations of the instruments. It is very important to guide users in order to correctly interpret the data.

The retrieval of geophysical variables from raw satellite data, for instance radiances at some spectral and spatial resolution, may be very difficult using classical methods if the physical forward model is too complex to be explicated. Artificial intelligence (AI) methods may be used to bypass the difficulty. Neural networks are often used to do that. A base of training is given to the neural network. These methods work well as long as observations stay within the limits of the training base but may fail when they are outside the limits. Furthermore, one has to be conscient that the neural network is used as a black box and does not help to provide physical information for the observed phenomena.

AI methods are widely used in satellite imagery. They combine space and ground data[6]. Machine learning-based detection and mapping systems are developed to extract the useful information from multi-spectral imagery with the help of ground-truth data.

Space-based EO makes an essential contribution to supporting the achievement of the Sustainable Development Goals (Anderson et al., 2017). They provide geospatial information needed for early warning, disaster risk management, loss and damage, climate risk assessment, ... AI will optimise the use of space-based EO in conjunction with other information sources such as ground-based EO and socio-economic data to construct disaster risk reduction indicators to inform decision makers.

3. **How socio-economic aspects are considered taken in the EO strategy?**

Several private companies are building EO satellites. These satellites are not driven by the science but by commercial interests and it does not exempt the space agencies from continuing to program scientifically driven EO satellites. However, these commercial satellites can provide data that complement the data from space agencies satellites and a good link with them then should be maintained. For instance, the commercial company Spire provides GNSS Radio occultation data useful for the meteorology and the space weather that complement the data from classical satellites (Bowler, 2020). Spire is now considered as an ESA's third-party mission.

With the cost increase of environmental disasters, the climate risk assessment becomes a high priority in the finance community. Satellite observations are essential to anticipate the risks, model the exposure to climate risks and find solutions to mitigate these risks.

Satellite observations can help to develop services to optimise transport and logistics processing, for instance to optimise the marine and aviation transport routes to reduce the CO_2 emissions.

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CSQ-17 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How is the resilience of key Earth System components changing under multiple anthropogenic pressures?	Quantify changes in resilience of the Amazon and other key biomes that might signal approaching or crossing of tipping points	• Microwave vegetation optical depth (VOD) • LAI • Biomass (e.g. from inventories for ground-truthing)	• High spatial resolution VNIR imagery (< 30m) • Synthetic aperture Radar (SAR) imagery • Low-frequency microwave for better time resolution of changes in the canopy depth • LiDAR	• Statistical approaches to derive resilience metrics • DGVMs • Machine Learning models (upscaling) • ESMs for future projections	• Identify regional hotspots of change in response to human activities → priorities for conservation / adaptation • Guide policy towards avoidance of crossing planetary boundaries / tipping points
	Quantify changes in ecosystem function and vitality due to climate change and more extreme events	• Vegetation water content • Indicators of gross primary productivity (NIRv, SIF, …) • LAI • Evapotranspiration (LST) • Net CO_2 fluxes (from in-situ or XCO_2) • Burned area	• High spatial resolution VNIR imagery (< 30m) • High temporal resolution imagery (<10 days) • Multi-spectral and hyperspectral imaging	• Atmospheric inversion modelling • Data-model integration systems (e.g. CARDAMOM) • Machine Learning models (upscaling and unobservable variables) • DGVMs (unobservable variables) • ESMs + impact models for future projections	
	Quantify trajectories in seasonal sea-ice cover in the polar regions towards approaching a tipping point	• Sea ice cover • …	TBD	TBD	

CSQ-17 Narrative

The definition of Planetary Boundaries (PBs) is highly uncertain and, to some extent, subjective but it is a powerful concept in that it facilitates communication with policy makers and societies by providing an easy-to-understand and multivariate assessment of the "state of the planet" (Rockstrom et al., 2009; Steffen et al., 2015). The definition of PBs requires the identification of processes/systems that might exhibit threshold behavior, or non-linear dynamics without a fixed threshold. This is analogous to the way the potential for tipping points is evaluated, but PBs are placed upstream of the estimated tipping/acceleration point (Figure 1).

The definition of PB, relies on a broad definition of reference states to control variables, some of which are not easily measurable in the Holocene (Running, 2012). Such reference states are, in most cases, not directly quantifiable – at least at global scales – given the limitations of global observational records, so they might be derived from a mix of modeling and expert knowledge, as done for example for the quantification of “biosphere integrity” (Alkemade et al., 2009). Even if an exact PB might be difficult to quantify, arguably it is possible to estimate how far and how fast systems are approaching a given PB by continuously observing the trajectories of the processes associated with each PB.

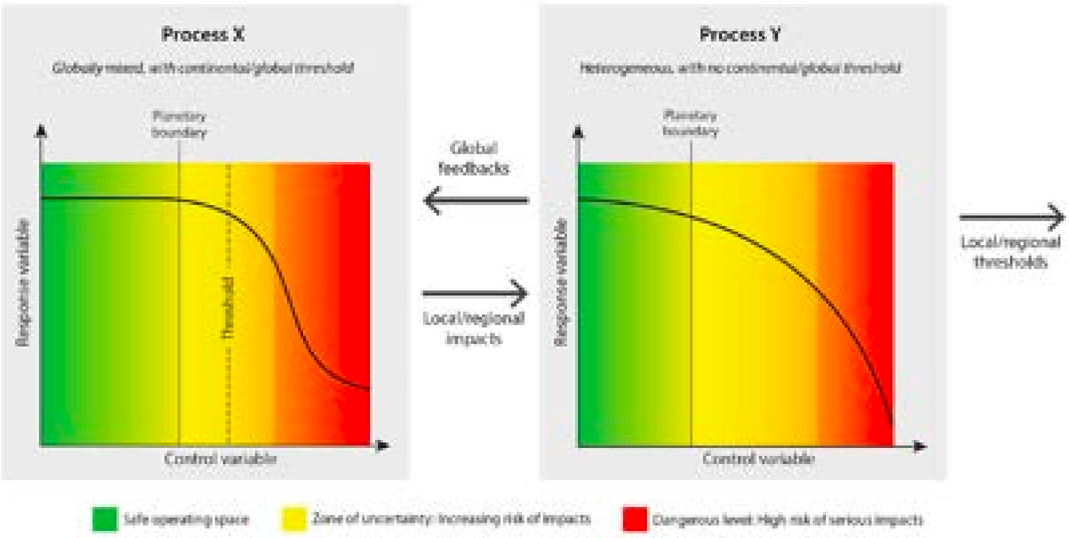

Figure 1: The conceptual framework for the planetary boundary approach, showing the safe operating space, the zone of uncertainty, the position of the threshold (where one is likely to exist), and the area of high risk. From Steffen et al. (2015).

PBs are, per definition, global, but the processes and the policy decisions influencing trajectories towards/away from PB happen mostly at local scale (e.g., tree mortality, biodiversity loss, ice-shelf collapse, coral reef mortality, …). Therefore, in order to guide policy making towards sustainable development, one needs to be able to quantify the local contributions to global-scale processes.

Earth Observation (EO) and particularly global space-based EO can play a key role in supporting the monitoring of planetary stability/destabilization from local to global scales, at least for some of the defined PBs. Furthermore, the range of defined PBs is far from exhaustive, with different communities calling for dedicated PBs in other systems (e.g. aquatic systems, (Nash et al., 2017)). Therefore, EO can also play a key role in identifying processes showing threshold behavior that are not yet considered in the PB framework, e.g., in marine biomes (Nash et al., 2017). Additionally, for processes that are not directly observable, data-driven and process-based models constrained by EO can be used to derive global estimates of relevant variables, as exemplified for ocean pH (Gregor and Gruber, 2021) or for nutrient flows (De Sisto et al., 2022).

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CSQ-18 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How can we attribute recent trends in Earth System components to anthropogenic activity	Quantify the effects of deforestation and management in modulating the resilience of global ecosystems to weather extremes and climate change	• Microwave vegetation optical depth (VOD) • Vegetation and soil water content • Indicators of gross primary productivity (NIRv, SIF, …) • LAI • Evapotranspiration (LST) • Net CO_2 fluxes (from in-situ or XCO_2) • Land-cover and Land-cover change	• Long temporal coverage • High spatial resolution imagery (< 30m) • Multi-spectral and hyperspectral imaging • Synthetic aperture Radar (SAR) • Low-frequency microwave for better time resolution of changes in the canopy depth • LiDAR	• Atmospheric inversion modelling • Data-model integration systems (e.g. CARDAMOM) • Explainable Machine Learning methods for observation-based inference • DGVMs (storylines)	• Identify potential for offsetting / amplifying interactions between multiple anthropogenic pressures on key Earth Systems • Develop more realistic future risk assessments by incorporating uncertainties from natural climate variability
	Identify the role of natural climate variability in recent trends in forest disturbances and mortality	• Burned area / FRP • Vegetation and soil water content • Evapotranspiration (LST) • NBR and other disturbance indicators •	• Long temporal coverage • Moderate spatial resolution (1km) • Multi-spectral and hyperspectral imaging • Low-frequency microwave for better time	• Atmospheric inversion modelling • Data-model integration systems (e.g. CARDAMOM) • Explainable Machine Learning methods for observation-based inference • Machine Learning for disturbance classification • DGVMs (storylines)	

			resolution of changes in the canopy depth • LiDAR	• Landscape models (storylines)	

CSQ-18 Narrative

The definition of PBs requires the assessment of states prior to human influence in order to define thresholds for “safe” human activities (Rockstrom et al., 2009). However, humans have been influencing key Earth System processes for millennia, e.g., the water, carbon and nutrient cycles through agriculture, land cover and land-use change and biodiversity. Furthermore, many of the processes associated with PB are not only influenced by human activities, but are also driven by natural variability in environmental conditions and can further interact through biophysical or biogeochemical feedbacks (Deser et al., 2012; Li et al., 2022; Nemani et al., 2003; Bonan, 2008). Therefore, PBs are expected to be to some extent dynamic, making the human contribution (D) to trajectories difficult to detect due to low signal to noise ratios especially in short global EO records.

This challenge is not exclusive to the PBs problem but is a common challenge in climate change and extreme weather event attribution (Masson-Delmotte et al., 2021; Seneviratne et al., 2012). Indeed, internal climate variability is an irreducible source of uncertainty in future climate projections, that needs to be taking into account for more robust risk assessment. Moreover, because it is superimposed on the climate change signal, it can act to mask or amplify climate-change driven trends in the relatively short observational records of many variables and processes.

The field of climate change and extreme weather attribution has evolved rapidly in the climate community and been applied mostly to physical systems. The attribution of human fingerprints on changes in other systems, e.g., ecosystem functioning or biodiversity is complicated by multiple human pressures on those systems beyond climate change (Bastos et al., 2023) and potential feedbacks with climate (Mahecha et al., 2022). However, attribution should be possible through a combination of EO and impact models as a base for storylines and/or statistical attribution approaches to quantify human D on those systems.

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CSQ-20 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What is the mass balance of the cryosphere and how is it changing over time?	Measure the change in the mass balance of all components of the cryosphere system, including ice sheets and ice shelves, glaciers and ice caps, sea ice, permafrost and snow cover.	• Glacier area change and volume change • Ice sheet mass balance • Ice shelf mass balance • Sea ice thickness and extent • Permafrost volume change • Snow mass on land	Global record of mass loss across all parts of the cryosphere. Continuous record of change required throughout the full 30-40-year satellite record. Monthly or finer temporal resolution measurement frequency for all observational components. Medium (1 km) spatial resolution for all components. Multi measurement type observational capability.	EO satellite datasets. Auxiliary data including bed topography under all land ice, and regional climate model data estimating surface mass balance component.	Climate change adaptation and mitigation policy. Delivering on Paris agreement and IPCC monitoring. Improve future projections of ice mass loss, which remain the greatest uncertainty in future sea level rise projections.
	Measure the regional pattern of variability in ice mass loss.	As above.	High (100 m) spatial resolution measurements required, at the	As above.	

			glacier or basin scale.		
	Provide near real time monitoring of ice mass change	As above.	NRT raw satellite data access and automated processing chains. Online portal to deliver service through. Weekly measurements of all components.	As above.	

CSQ-20 Narrative

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 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). While Arctic sea ice cover has been decreasing for the last 40-years, Antarctic sea ice extent remained stable through to the 2020's. In recent years we have seen a dramatic reduction in Antarctic sea ice extent, impacting the energy balance of the region and causing devastating impacts on emperor penguin breeding cycles who are reliant on sea ice floes. 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. As yet, snow on land and permafrost volume are not included in global cryosphere mass budget assessments, however this will be possible in the future. Studies should quantify the regional variability in the change in ice mass of different elements of the cryosphere, and understand the physical mechanisms driving this change.

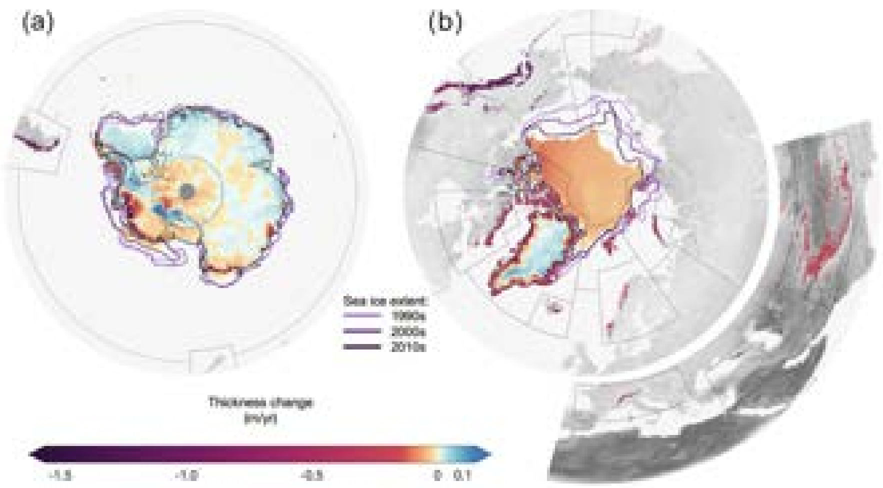

Fig. 1: Average rate of ice thickness change in the (a) Southern Hemisphere and (b) Northern Hemisphere. Changes in Antarctic (1992– 2017) and Greenland ice sheet (1992–2018) thickness were estimated using repeat satellite altimetry following the methods of Shepherd et al. (2019). Sea ice thickness trends 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.

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CSQ-21 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What physical processes drive ice dynamic variability, and how does the dominance of these processes differ between the different Polar regions?	Determine what physical processes drive ice dynamic variability.	• Ice speed measurements on all glaciers and ice streams globally • Ocean temperature change • Ice surface melt and runoff • Calving front location • Grounding line location • Surface elevation change	Ice speed measurements at as fine temporal resolution as possible (weekly), with enough sensitivity to measure change in speed Multi-decadal record of change required over last 30-40-years, updating continuously in NRT High (100 m) spatial resolution for all components.	EO satellite datasets. Auxiliary data including bed topography under all land ice, and regional climate model data estimating surface mass balance, surface melt and runoff. Ocean temperature change, throughout full water column	Climate change adaptation and mitigation policy. IPCC monitoring. Improve future projections of ice mass loss, which remain the greatest uncertainty in future sea level rise projections.
	Determine how the dominance of these processes differs between the different Polar regions, including Northern hemisphere vs South, glaciers vs ice sheets.	As above.	As above.	As above.	

CSQ-21 Narrative

Ice dynamics, which relates to the change in the rate of ice flow, 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., 2020). Ice dynamic change is primarily concentrated in the marine terminating regions of the ice sheets, which are often also be grounded below present-day sea level. The IPCC reports consistently state 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 on the speed 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.

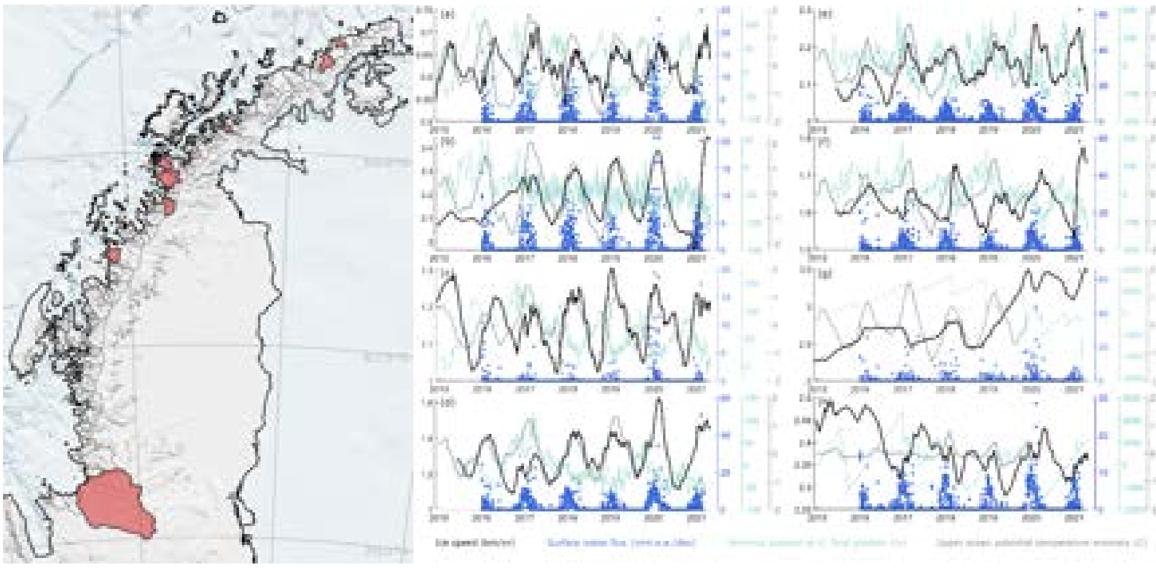

Fig. 3: Highlight glaciers' time series of ice speed, surface water flux, terminus position and ocean temperature anomaly. a–h, Time series of Kalman-smoothed ice speed (black solid line), RACMO2.3p2 surface water flux (snowmelt plus rain; blue dots)43,52, terminus position with respect to the final position (green solid line) and upper-ocean (110 m) potential temperature anomaly (grey dashed line)56. Time series are shown for unnamed north Bone Bay (a), Gavin Ice Piedmont (b), Leonardo (c), Hotine (d), Trooz (e), Keith (f), Cadman (g) and Fleming (h) Glaciers. 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), to give a spread of locations along the west AP, and to show a range of faster and slower mean ice speeds. w.r.t., with respect to; w.e., water equivalent. From Wallis et al., 2023.

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CSQ-22 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What are the cycles of variability for cryosphere essential variables, and how large are they?	Determine what the cycles of variability are for cryosphere essential variables.	• Measurements of all Polar climate data records, including sea ice extent and thickness, ice speed, ice surface elevation change, ice shelf basal melt, surface mass balance, calving front location, permafrost area, etc.	Fine temporal resolution (weekly), with enough sensitivity to measure change Multi-decadal record of change required over last 30-40-years, updating continuously in NRT High (100 m) spatial resolution for all components.	EO satellite datasets. Auxiliary data including bed topography.	Improve future projections of ice mass loss, which remain the greatest uncertainty in future sea level rise projections.
	Quantify the magnitude of variability, e.g. diurnal, weekly, monthly, seasonal, annual and decadal	As above.	As above.	As above.	

CSQ-22 Narrative

Historically, the remote location of the Polar regions and the constraints on downlinking high volumes of satellite data, has meant that image acquisitions over the global cryosphere have been limited to annual (or even less frequent) sampling, since the 1990's. The revolution in high temporal frequency and high spatial resolution satellite observations acquired by the EC-ESA Copernicus missions, enables the cycles of variability for all essential cryosphere variables to be studies in depth for the first time. The development of new data analysis techniques, such as deep learning and AI, enables the full exploitation of these satellite datasets to generate measurements of new climate variables in an automated way. Furthermore, these new methods combined with the use of High-Performance Computer facilities, allows the full archive of satellite data to be processed routinely. Now that our capacity to acquire and process the full archive of satellite observations has been realized, this enables essential cryosphere measurements to be made at the finest spatial and temporal resolution. This is already delivering new high impact science results, such as measurements of summer sea ice thickness in the Arctic by using AI to distinguish between altimetry waveform returns over leads and melt ponds in the sea ice (Landy et al., 2021). On the Antarctic Peninsula, previously undocumented seasonal ice speed variations have been observed, where glaciers are flowing 22 % faster in the summer vs the winter time (Wallis et al., 2023). These methods and approaches can be extended and applied to other cryosphere parameters, improving our knowledge about the cycles of variability in these important variables.

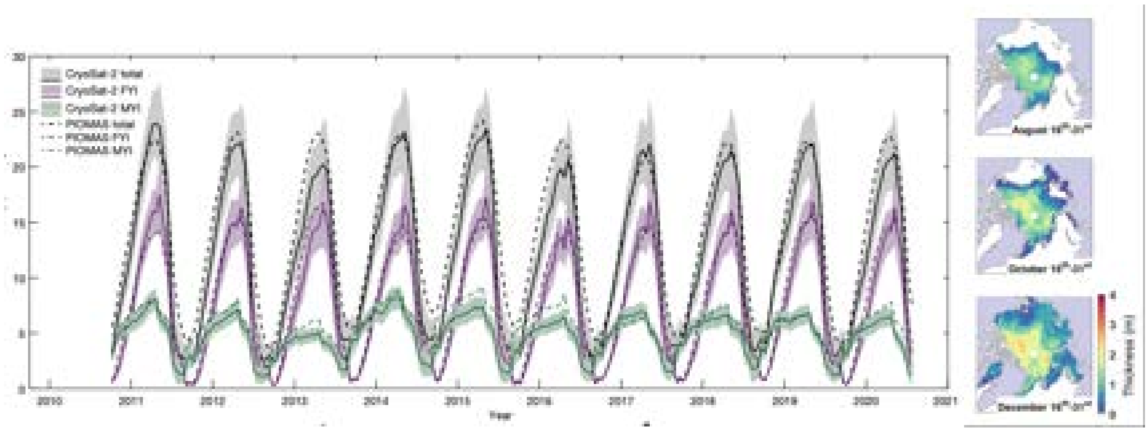

Fig. 3: Time series of SIV derived from CryoSat-2 compared with reanalysed predictions of ice volume from PIOMAS. Sea ice volume from CryoSat-2 is presented with uncertainty envelopes for the entire Arctic and separated into zones of predominantly FYI and MYI (using the NSIDC sea-ice-age dataset43). The CryoSat-2 sea ice volume uncertainties are derived from the total ice thickness uncertainty (Methods) multiplied by the ice area. Maps of sea ice thickness shown alongside. From Landy et al., 2022.

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CSQ-23 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What is the impact of extreme weather events on the Polar regions?	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).	● Surface melt ● Ice speed change ● Surface elevation change ● Sea ice extent and thickness ● Freshwater input to the oceans	Fine temporal resolution (weekly), with enough sensitivity to measure change Multi-decadal record of change required over last 30-40-years, updating continuously in NRT High (100 m) spatial resolution for all components.	EO satellite datasets. Auxiliary data including bed topography and regional climate model data estimating surface mass balance, surface melt and runoff.	Climate change adaptation and mitigation policy. IPCC monitoring. Improve future projections of ice mass loss, which remain the greatest uncertainty in future sea level rise projections.

CSQ-23 Narrative

Climate change has led to more frequent occurrences of extreme weather. In the Polar regions prominent examples of this include the 2012 extreme surface melt event which covered the whole surface of the Greenland Ice Sheet (Nilsson et al., 2015); extreme lows in sea ice cover; and extreme snowfall events such as atmospheric rivers which can deposit double the amount of snowfall in a short period of time (Mottram et al., 2021), offsetting ice mass loss from dynamic processes (Davison et al., 2023). As the occurrence of extreme weather events evolves over time, we mush characterize this new variability, and understand its long-term impact on all elements of the Polar domain.

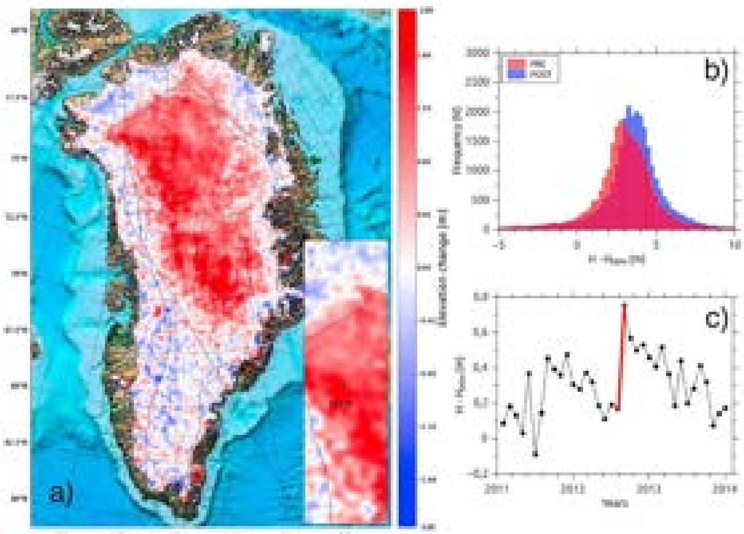

Fig. 4: (a) Surface elevation differences between the May–June and August–September 2012 CryoSat-2 L2i data. The differences in surface elevation shows a clear positive increase in the dry-snow zone and ablation in the coastal regions. Black lines indicate the 2000 and 3000 m elevation contours. Found in the supporting information are 2011 and 2012 reference figures. (b, c) Histograms (regional analysis) and time series (local analysis) of the changes in surface elevation around NEEM estimated from the reanalysed CryoSat-2 L1b data presented in this study. The 2012 elevation change is indicated in red. From Nilsson et al., 2015.

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CSQ-24 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What is the impact of the Polar regions on global climate variability?	Determine what impact the polar regions have on global climate variability.	• Glacier area change and volume change • Ice sheet mass balance • Ice shelf mass balance • Sea ice thickness and extent • Permafrost volume change • Global temperature • Ocean temperature and salinity • Atmospheric winds	Fine temporal (weekly) resolution, with enough sensitivity to measure change Multi-decadal record of change required over last 30-40-years, updating continuously Medium (1 km) spatial resolution for all components.	EO satellite datasets. Auxiliary data including global temperature, ocean temperature and salinity, atmospheric winds	Climate change adaptation and mitigation policy. IPCC monitoring.
	Determine what impact global climate variability has on the polar regions.	As above.	As above.	As above.	

CSQ-24 Narrative

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.

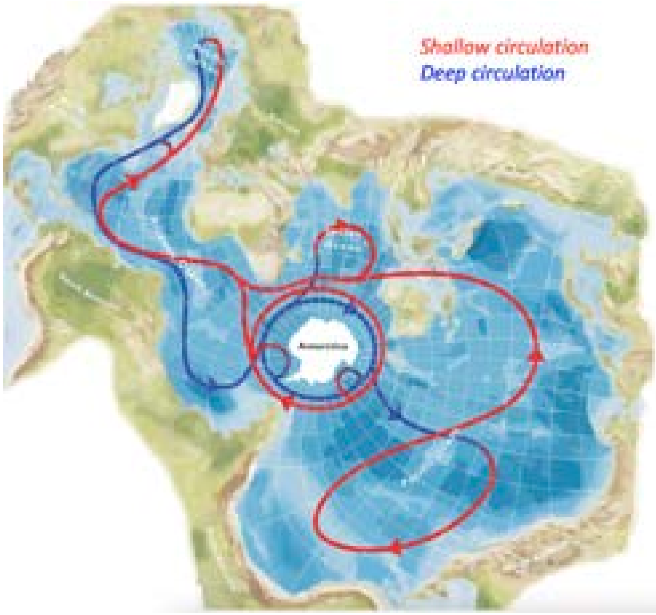

Fig. 5: Shallow and deep ocean circulation pathways between the Arctic and Southern oceans.

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CSQ-25 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How does the cryosphere impact on Polar ecosystems, and how is the changing climate altering these feedbacks?	Determine the impact of the cryosphere on Polar ecosystems, such as through freshwater input to the ocean.	• Freshwater input to the ocean from the cryosphere • Ocean colour in the Polar-ocean and sea ice marginal zone • Sediment plume location and frequency • Primary productivity measurements • Sea ice extent	Fine temporal (weekly) resolution, with enough sensitivity to measure change Multi-decadal record of change required over last 30-40-years, updating continuously high (100 m) spatial resolution for all components.	EO satellite datasets. Auxiliary data including ocean bathymetry in the polar regions. Polar ecosystem counts (e.g. number of seals and penguins)	Climate change adaptation and mitigation policy. IPCC monitoring. Foreign commonwealth fisheries and ecological monitoring. Polar region treaties (e.g. Antarctic treaty)
	Measure how change in the polar regions is impacting these feedbacks, e.g. through nutrient cycling and primary productivity.	As above.	As above.	As above.	

CSQ-25 Narrative:

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-26 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What are the next generation of satellite data products for the Polar regions that will be generated through AI and ML?	Develop new methods and datasets using deep learning techniques to deliver the next generation of Earth observation information.	● Raw satellite input data of all types, SAR, multispectral optical, and altimetry waveforms ● Training datasets ● Validation data	Fine temporal (weekly) resolution, and high (meters) spatial resolution.	EO satellite datasets. Training and validation data	Advance knowledge of the Polar regions. Improve future projections

CSQ-26 Narrative

Deep learning and AI are methodological advances that enable the production of a new generation of satellite data products. In the polar regions, prominent examples of this include using machine learning to delineate glacier and ice shelf calving front locations (Baumhoer et al., 2019), mapping crevasses or damage on the ice sheet and ice shelves (Surawy-Stepney et al., 2023), and measuring summer sea ice thickness in the Arctic for the first time (Landy et al., 2022). In many cases, these products were previously only measurable using the time-consuming method of manual delineation, which has a low accuracy in itself, and is also logistically unfeasible for processing the large volumes of satellite data acquired today. While generating high spatial-resolution static maps of these Polar parameters is a key milestone, in the future, methods must evolve and be sensitive enough to detect change in these variables.

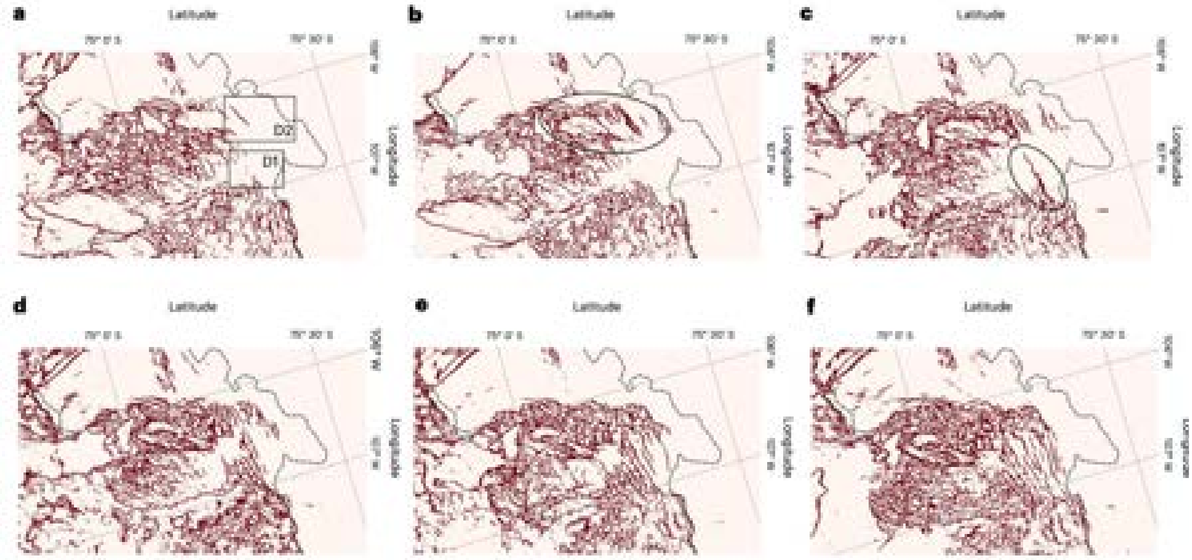

Fig. 7: Observed fractures on the TGIT. Annual fracture maps generated by applying a trained neural network to Sentinel-1 SAR images acquired in March of each year during 2016 to 2021. a–f, Snapshots of mapped fractures on 29 March 2016 (a), 12 March 2017 (b), 25 March 2018 (c), 26 March 2019 (d), 8 March 2020 (e) and 27 March 2021 (f). Time series of relative fracture density shown in Fig. 3c,d are extracted from bounding boxes D1 and D2 in a. We highlight the location of a large section of ice that detached from the upstream shear margin in 2017 (black oval, b) and an approximately 14 km-long transverse crack (black oval, c), with the MEaSUREs grounding line location also shown on all maps (dashed black line)31. From Surawy-Stepney et al., 2023.

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CSQ-28

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Specifications	Tools & Models	Policies / Benefits
What is the size of anthropogenic impact on change in the Polar regions?	Quantify the size of anthropogenic impact on the Polar regions.	• Glacier area change and volume change • Ice sheet mass balance • Sea ice thickness and extent • Permafrost volume change	Medium temporal (monthly to annual) resolution, and medium (kilometres) spatial resolution.	EO satellite datasets. Climate models	Climate change adaptation and mitigation policy. IPCC monitoring. Improve future projections

Narrative:

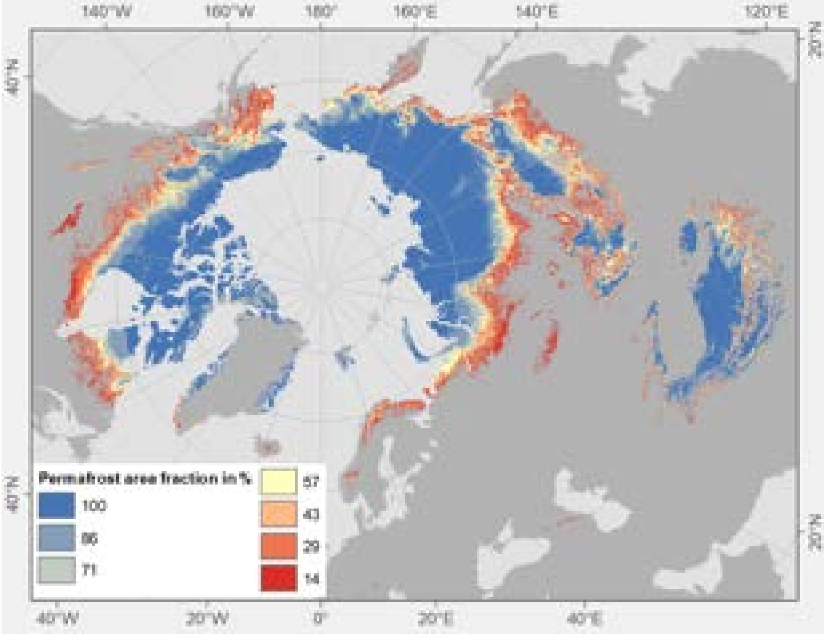

Fig. 9: Change in Permafrost area Fraction. From ESA CCI Permafrost.

To be completed

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CSQ-28 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
Are there tipping points/elements in the climate system not yet identified?	A) Identification of all potential tipping elements in the climate system, including those currently assumed as potential or even unlikely	• While most actual or potential tipping points are currently known, there are potential tipping elements, not yet confirmed, where observations should be focus: ✓ Southern Ocean sea-ice ✓ Tibetan Plateau Snow ✓ Indian summer monsoon ✓ Indian Ocean upwelling ✓ Equatorial stratocumulus clouds and other cloud feedbacks ✓ Ocean deoxygenation ✓ Antarctic bottom water ✓ Temperate forests, Congo forest	• Given the unknown properties of such new tipping points, it is difficult to establish precise requirements for each individual measurement, also because of the largely unknown sensitivity of the inputs variables in climate models related to such new tipping points • Focus observations on: ✓ Spatial and temporal extend of sea ice (arctic summer sea ice) ✓ Optical spectroscopy to study the chemistry of the ocean surface (ocean biological pump and ocean	Models exist, but most likely not adequate enough to deal with new tipping points not yet identified by the climate models	Knowledge of new, currently unknown, tipping points would increase the possibilities to establish corrective actions, in terms of adaptation and mitigation, with enough time in advance to react.

			carbon sink, marine methane hydrates) ✓ Ocean temperature, waves and currents (El Niño Southern Oscillation ✓ Better resolved land cover dynamics (gradual thaw of boreal permafrost) ✓ Better characterization of land carbon exchanges (land carbon sink) ✓ Continue and improved atmospheric ozone monitoring (arctic ozone hole)		
	B) Association of potential tipping elements that can be activated together (cascade effects)	• From the list above about potential tipping points, together with the list of currently assumed tipping points, associations among them in terms of cascade effects and teleconnections can	• Requires previous knowledge of specific properties of each tipping point before	Models exist, but they may not be particularly suitable when dealing with new tipping points associated to	

		be determined by combination of time series of observations and dynamical predictive models	associations can be established. • Basic underlying variables (surface temperature, sea ice extend, forest vegetation factional cover evolution, etc.) may serve to check potential couplings among tipping points	processes not yet properly described by the models.	
	C) Identification of Extreme Events and Planetary Boundaries that can be indicative of potential tipping points	• Analyse time series and geographical maps with locations of Extreme Events potentially indicative of evolution towards a tipping point • Explore Planetary Boundaries that can be indicate of where a tipping point may occur • Focus observation on processes related to potentially irreversible transformations associated to tipping point behaviour.	• Observations of extreme events and trend to planetary boundaries are already available (for instance, time series of sea ice extend, time series of forest burned areas), and can be used to check potential trends to tipping points	Data and models are available, but probably time series are not yet long enough to see trends associate to tipping point behaviour.	
	D) D) Discard phenomena that can lead to false positives towards the identification of tipping points	• Some elopement currently considered as generating tipping points may result in false alarms and some elements currently considered as unlikely to generate tipping points may become	Type of observations are very extensive to establish precise requirements for each individual measurement, also		

		tipping points as models and observations are available. • Focus observations on elements currently assumed to be unlikely, such as: ✓ Arctic ozone hole ✓ El Niño Southern Oscillation ✓ Northern polar jet stream ✓ Arctic summer sea ice ✓ Marine methane hydrates ✓ Boreal permafrost (gradual thaw) ✓ Ocean biological pump and ocean carbon sink ✓ Land carbon sink	because of the largely unknown sensitivity of the inputs variables in climate models to such processes linked to the new tipping points		

CSQ-28 Narrative

There is a growing evidence that overshooting 1.5°C may push the Earth over a number of so called "tipping points", leading to irreversible and severe changes in the climate system, with potential large effects, and challenges for rapid adaptations.

By definition (Fig. 1-1), a tipping point, for a tipping element of the climate system, is a critical threshold beyond which global or regional climate changes from one stable state to another stable state, and the climate system reorganizes, often in a non-linear manner, abruptly and irreversibly, with dangerous impacts and serious implications for humanity. There are several definitions in the literature, but the key idea is that the system arrives to an unstable point in between two stable states, so that a small change in the properties may result in the system turning to one or another state, both with very different properties. Tipping points represent a level of change in system properties beyond which changes in a part of the climate system become self-perpetuating, and the system does not return to the initial state, although the irreversible behaviour is now questioned, at least for some tipping elements.

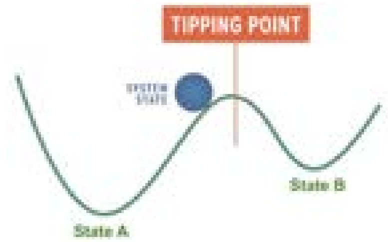

Fig. 1-1: Typical behaviour of a climate tipping point as an unstable transition point between two stable states

A consensus on what tipping points are the most critical ones is not yet available in the literature, since the determination of the tipping point (estimated range for the temperature threshold) for each tipping element (component of the Earth System subject to tipping behaviour) remains controversial, and even the identification of tipping elements is evolving in recent years according to scientific literature (see references below). For instance, gradual versus abrupt permafrost lose will have impacts in very different time scales, but still large uncertainty exists in model predictions and impact estimates. The list of potential tipping elements is open to changes as there is progress in the research.

Fig. 1-2. Identified tipping elements in the climate system

Recent work has suggested that up to 15 tipping elements are now active, in the order of 9 global "core" tipping elements, plus about 7 regional "impact" tipping elements which contribute substantially to the Earth system functioning.

Additional tipping elements have been proposed (e.g., parts of the East Antarctic ice sheet) and the status of others (e.g., Arctic summer sea ice) has been questioned. Some formerly considered tipping points are now discarded. Identification of tipping points is still an open issue.

The list of tipping elements is open to changes as there is progress in the research, but the question is if all "potential" tipping points are already identified. The link between Planetary Boundaries and Tipping Points plays also a role here. One would expect that when all Planetary Boundaries are identified, those leading to Tipping Points can be also identified, but this is not so straightforward. The identification of tipping points in the climate system through climate models, or tipping elements subject to such type of transformations, remains in discussion, and some critical tipping points may still remain unidentified.

At least it would be important to identify tipping elements, and then figure out the tipping point corresponding to each element. The focus can be on those tipping elements now considered as "potential / uncertain" tipping element candidates. Particular focus should be put on those now considered "unlikely" tipping elements, because some of them were previously considered Tipping elements in the past and this classification may evolve with time.

The way of identifying new potential tipping points is to focus on those elements that have been already considered but where evidence of tipping behavior is not yet demonstrated. Moreover, there is no consensus on the research community if some of such elements may or not develop a tipping point, so that focusing on such elements which are at the moment considered potential / unlikely tipping elements should be a research priority. The observations needed for such tipping point candidates are:

- ✓ Spatial and temporal extend of sea ice (arctic summer sea ice)
- ✓ Optical spectroscopy to study the chemistry of the ocean surface (ocean biological pump and ocean carbon sink, marine methane hydrates)
- ✓ Ocean temperature, waves and currents (El Niño Southern Oscillation
- ✓ Better resolved land cover dynamics (gradual thaw of boreal permafrost)
- ✓ Better characterization of land carbon exchanges (land carbon sink)
- ✓ Continue and improved atmospheric ozone monitoring (arctic ozone hole)

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CSQ-29 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
Can we better quantify the temperature thresholds, time scales, and impacts of identified tipping points?	A) Characterization of temperature thresholds for currently established tipping points	• For the already identified tipping points, determination of a more precise range for the temperature thresholds depends on models. Model inputs require geophysical observable depending on the articular tipping element being addressed: **Cryosphere:** ✓ Greenland ice sheet ✓ Arctic winter sea ice ✓ West Antarctic ice sheet ✓ East Antarctic ice sheet and subglacial basins ✓ Mountain glaciers ✓ Boreal permafrost ✓ Barents Sea ice **Ocean-Atmosphere circulation:** ✓ Atlantic Meridional Overturning Circulation ✓ North Atlantic subpolar gyre / Labrador-Irminger Sea Convection collapse **Biosphere:** ✓ Low-latitude Coral Reefs ✓ Sahel & the West African Monsoon	• Given the wide range of typing elements and the many geophysical variables involved in the modelling of each one of the tipping elements, and the different sensitivity of the climate models to geophysical variables used as input (current observations versus future model predictions), a precise specification for the required measurements is not possible in this case.	Climate Models, both regional and global, in particular those models that include explicit behaviour of tipping points	A more precise determination of the temperature thresholds, time scales, and associated geographical impacts, would be extremely beneficial to establish more adequate adaptations and mitigation strategies at the proper spatial and temporal scales.

		✓ Boreal forest (southern dieback and northern expansión) ✓ Amazon rainforest			
	B) Characterization of time scales for currently established tipping points	• Time scales for each tipping point depends even more on models, and observations used as inputs to the models are in this case critical when long time series are available	• Same as above, but focused on time series of observables	Climate models can be used, although they are known to have some limitations and results may depend on model assumption	
	C) Characterization of geographical extend of the impacts for currently established tipping points	• Spatial maps (global and regional) are essential tools, for multiple variables depending on the tipping point considered in each case • Earth Observation data can play a key role in this particular aspect	• Key role of EO data in this particular aspect, but EO data represents current status and can only serve to validate models with current observations to make them more accurate in future predictions	Climate models can be used, although they are known to have limitations when coming to regional effects and coupling between tipping points having a global-scale effects and those tipping points that have regional impacts.	
	D) Identification of potential cascade effects in the coupling of multiple tipping points	• Coupling of models for multiple tipping points and general climate models, supported by available observations depending on the sets of tipping points considered in each cascade/teleconnection analysis	• All the variables needed to describe each tipping element separately, plus those variables that can serve to inter-connect the multiple tipping elements. Time	Models are not yet very accurate when handling multiple tipping point effects and the connections among them. Running ensembles of several models under multiple scenarios is the only possible approach, but	

			series are needed in all cases.	it is subject to potentially controversial interpretation of the results.	

CSQ-29 Narrative

Tipping points are characterized by three key aspects:

- Temperature threshold (the increase in temperature where the activation takes place)
- Time scale for such activation after the temperature threshold is reached
- Spatial impact scale (global or regional scale)

Assuming all the (main) tipping points in the climate system are already identified, the question would be to determine the temperature thresholds and associated time scales and impacts for each one of such tipping elements. Identification of the most critical tipping elements where more focused efforts are necessary is also important, but the impacts of reaching the corresponding tipping point for each tipping element are difficult to be quantified up to the level of establishing specific mitigation actions given the uncertainties in the time scales involved in each case.

As illustrated in Fig. 2-1, for some elements we have already reached (or are about to reach) the corresponding tipping point. This argument often used to justify the need for urgent climate actions.

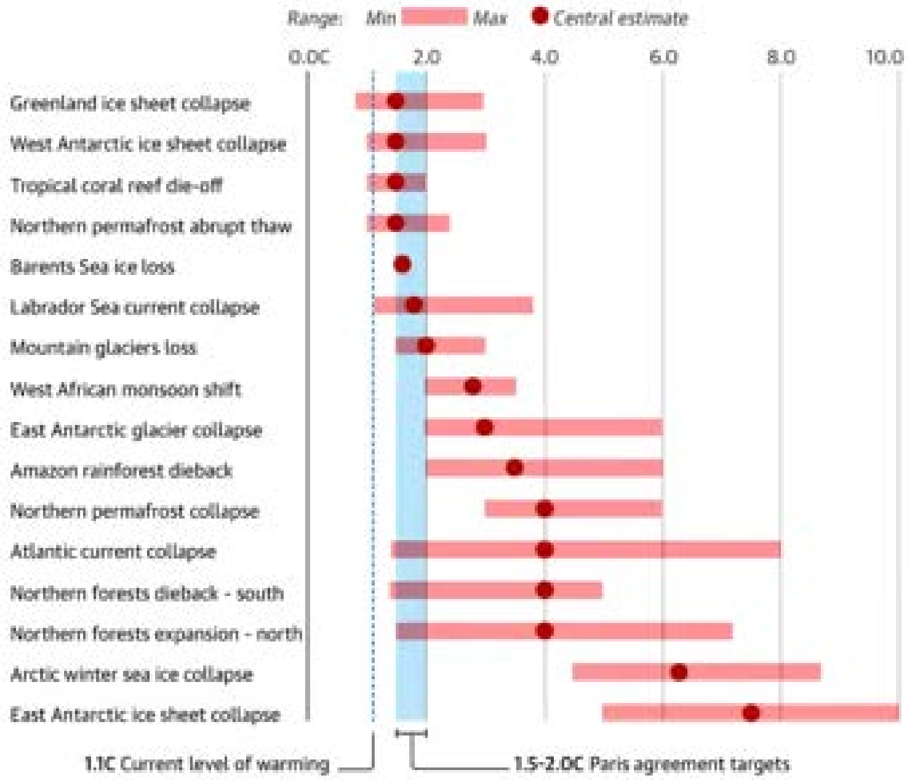

Fig. 2-1: Temperature thresholds (central estimate and min/max range) for identified tipping points in the climate system, indicating the current warming level and the targets for warming levels of the Paris agreements.

In order to identify specific mitigation actions, all tipping elements in the climate system must be identified and the tipping points well characterized. This is also important because of the interactions among tipping points (cascade effects) introduce enhancements in the effects associated to the coupling of multiple tipping points, related to the fact that triggering a tipping point may induce other cascade effects in the climate system. Particularly important is the potential coupling of multiple tipping points, the so called cascade effects, and teleconnections.

One element which makes the analysis of tipping points more complicated is the coupling of multiple tipping points, particularly through the so called "cascade effects". That means activating a single tipping point may imply the activation of multiple tipping points just a kind of domino effect. There are multiple possibilities, with different probabilities and different effects depending on which is the tipping point that initiate the cascade, and again this is subject of research and a consensus on what are the dominant tipping points and the associated cascade effects is still somehow controversial.

Apart from cascade effects, there is another aspect that can connect multiple tipping points and that have deserved attention in the last years, the so called teleconnections (Zhou D. et al., 2015; Liu T. et al., 2023). While there are connections among different tipping points through feedback loops and cascade effects, teleconnections have a special effect and they imply some kind of pathways that connect tipping elements that are located even at large distance and are in principle independent. Climate teleconnections have been also proposed to modulate global burned area (Cardil et al., 2023). Whether or not such teleconnection really exist through some physical mechanism or they are just spurious statistical effects, the teleconnection effects illustrates the complexity of tipping points research.

Figure 2-2 illustrates how multiple tipping can be triggered together through cascade effects, and some of the identified teleconnections (indicated in red in the map) according to the current scientific understanding.

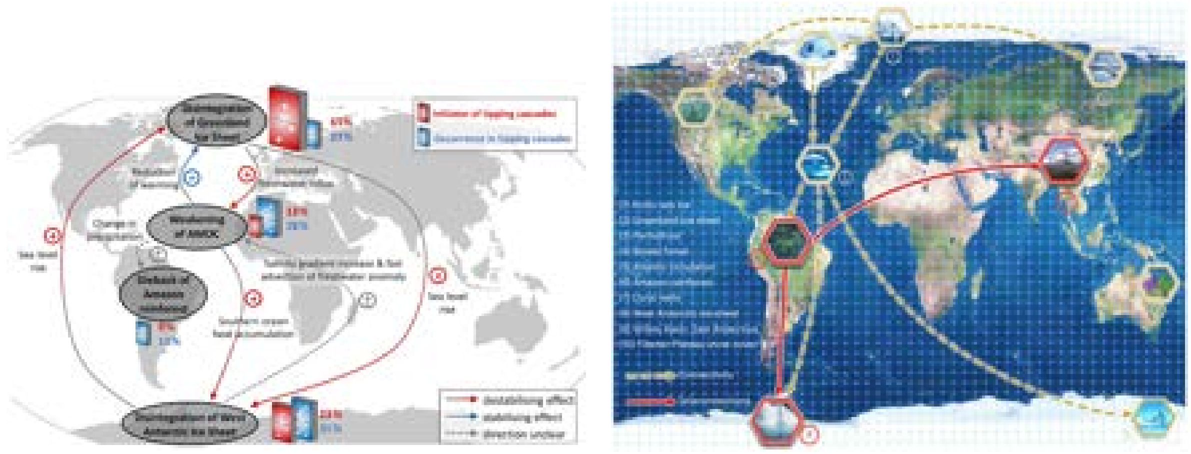

Fig. 2-2: (left) cascade effects activation of multiple tipping points, (right) teleconnections relating the potential activation of multiple tipping points

As illustrated in Fig. 2-3, while triggering a tipping point is a concern, triggering multiple tipping points at the same time, by reaching the corresponding temperature thresholds, can have unpredictable consequences. The figure illustrates how multiple tipping points can be sequentially reached over the next decades. A more quantitative characterization of the temperature thresholds and time scales is essential when multiple tipping points get activated in parallel. Up to 14 different tipping points may be activated in the next 80 years in this century, with significant couplings among them, as a function of different potential warming scenarios.

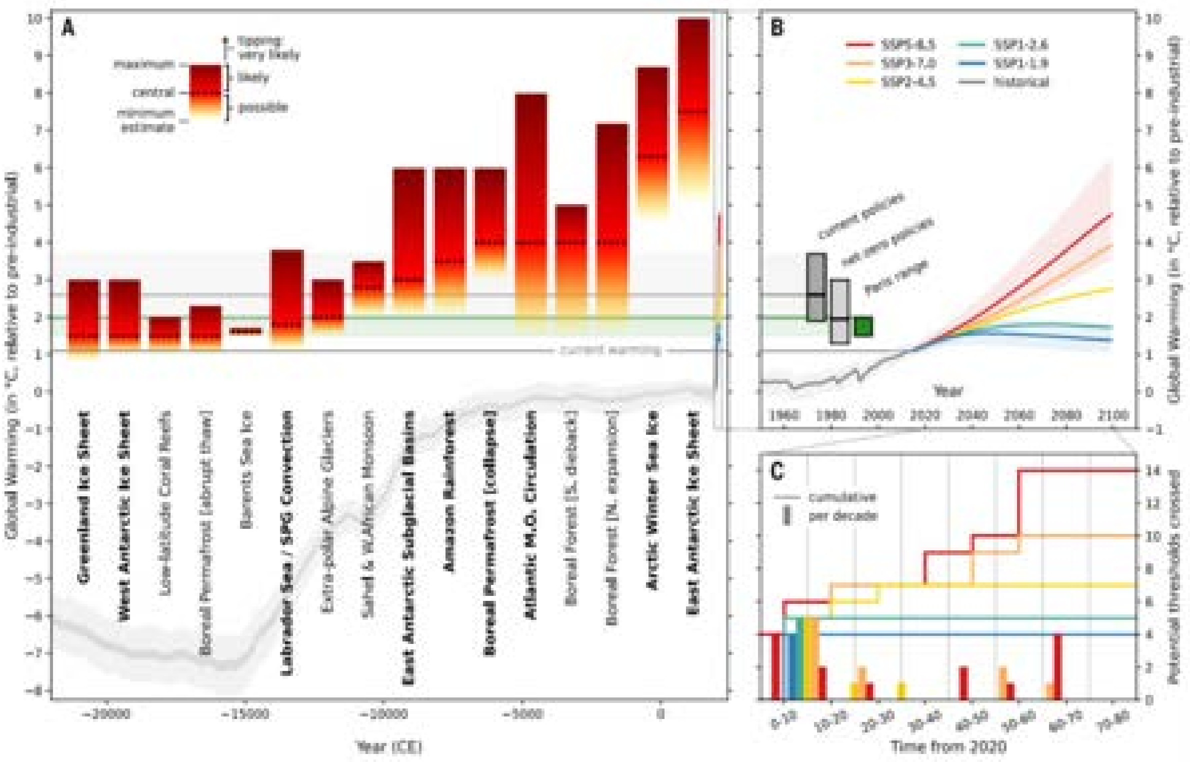

Fig. 2-3. Activation of multiple tipping points by reaching the corresponding temperature thresholds, over the next 80 years, for assumed warming scenarios (McKay, D. I. et al., 2022)

According to recent research, although tipping points are thresholds assumed to be a point of no return, they could be temporarily exceeded without prompting permanent changes, if global warming is reversed quickly enough. Clearly this is a controversial aspect that need more attention to better identify and characterize the different tipping points in the climate system.

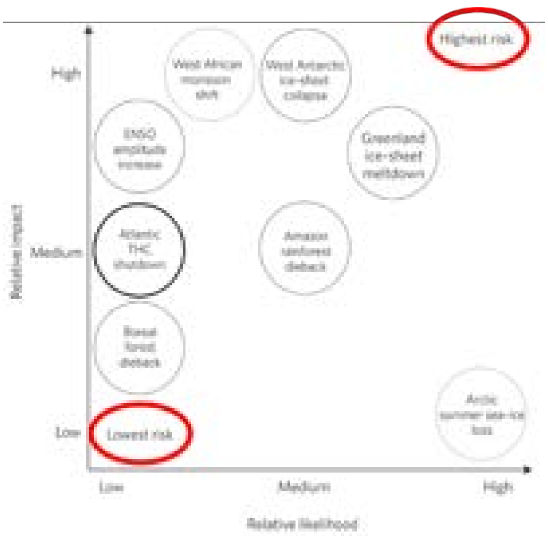

Fig. 2-4: Classification of tipping points in terms of relative likelihood and impact, and then associated risk (Risk (R) = probability (p) multiplied by damage (D)) (Lenton, 2011c.)

Tipping points also need to be modelled in terms of relative likelihood and impact, and then associated risk, defining Risk as the probability of occurrence multiplied by damage. There is another relevant concept for tipping points which is the Emergency, defined as the product of risk and urgency. Based on this we can classify the tipping points according to the risk, as illustrated in Figure 2-4. Then research can be focused on those tipping points with more risk, like melting ice-sheets or Amazon forest dieback.

But the quantification is somehow model-dependent, and different approaches may lead to classification of tipping elements into other categories.

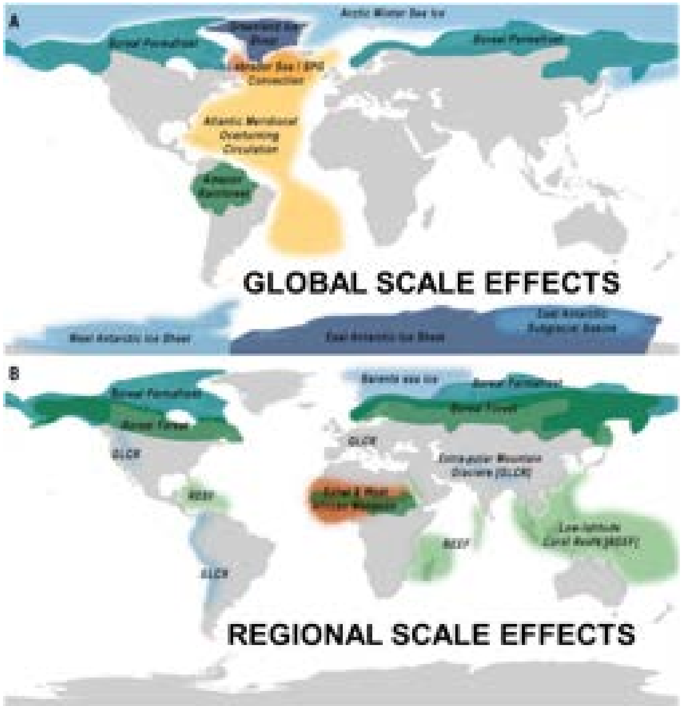

Fig. 2-5. Some tipping points have a global impact, or can be associated to a global tipping elements, while some other tipping points have regional scale affects associate to some specific tipping elements. The need to address such different geographical scenarios represents a unique opportunity for global Earth Observation, as a key source for geophysical variables in the form of spatial maps (McKay, D. I. et al., 2022)

Considering the implications in the context of the ESA Earth Observation Strategy, the spatial scales of impacts for climate tipping points deserve special attention. Some tipping points have a global impact, but many other have regional impacts that need spatial maps, with high spatial resolution to determine spatial internal variance of the phenomena under study, and accounting for spatial and temporal correlations. Time series of satellite data are essential tools for such type of characterization of tipping point effects.

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CSQ-30 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
Are the limitations in predicting climate tipping points driven by lack of process understanding or limited data availability?	A) Identify those tipping points where predictive capabilities are limited by lack of process understanding	• Focus on specific tipping elements where deficient model understanding has been identified, such as ✓ Boreal permafrost: collapse, versus abrupt thaw or gradual thaw ✓ Boreal forest: southern dieback and northern expansion ✓ Land carbon sink: Amazon rainforest, temperate forests ✓ Ocean biological pump and ocean carbon sink ✓ Cloud feedbacks: equatorial stratocumulus clouds	• Running ensemble of models under prescribed conditions to set the statistical dispersion in model predictions	Current climate models available, but with identified limitations.	With the final goal of establishing mitigation and adaptation approaches, early enough to avoid major consequences, any advance in the characterization of tipping points and the evolution of processes that may lead to tipping points, is clearly important. The fact that the current limitations come from the understanding and modelling of the processes or by the availability of adequate data is important to establish appropriate actions to solve the predictive capability
	B) Determination of experiments and activities needed to advance the understanding for such tipping points limited by lack/incomplete process understanding	• Dedicated field experiments where all relevant data are collected simultaneously over a period of time long enough to see trends in observations • Focus on tipping elements identified above	• Accuracy equal or better than current model predictive performances • Long time series is a key step to identify trends	Existing climate models would have to be improved according to such new observations, with emphasis on the pieces of the models related to the tipping points where deficiencies were previously identified	

	C) Identify those tipping points where predictive capabilities are limited by lack of appropriate data	• Focus on specific tipping elements where data availability is the limitation, such as ✓ Greenland ice sheet ✓ Arctic winter sea ice ✓ West Antarctic ice sheet ✓ East Antarctic: ice sheet and subglacial basins ✓ Mountain glaciers	• Since in this case the models are well understood, uncertainty in each observation can be set to make an improvement in model performances	Current climate models are available and known to be already with a good description of key processes and adequate model parameterization	of the models to allow establishing more precise corrective actions.
	D) Determination of datasets and observations needed to advance the understanding of such tipping points	• Identification of current archived datasets, covering long time series with relevant information ready to be used • Identification of new observations not yet available but necessary for the future	• Accuracy requirements depend on each particular tipping elements and geophysical variables involved in each tipping element model	Methods to ingest the datasets into climate models already exist, particularly for existing or new datasets with information already represented in the models	

CSQ-30 Narrative

Our ability to quantify the tipping points in the climate system, and to better predict future trends and effects, is limited by two different factors. On the one hand, for some tipping points there is a lack of detailed physical understanding of the mechanisms underlying the different effects, and their interactions (feedback loops), or at least a lack of capability to transform such knowledge into numerical equations and process mechanisms that can be incorporated in climate models. This is even more obvious when not just physical processes are involved, but also chemical cycles and biological processes, like plant adaptations to environmental stresses or the role of biodiversity that improves resilience, which are even more difficult to model than the pure physical phenomena. On the other side, the limitations can come from the lack of proper data, covering the adequate spatial and temporal scales, and providing direct information about the processes and not just indirect proxies with limited correlation to the true physical observables.

Identification if the limitations come from inadequate understanding of the processes or lack of adequate data is critical to better focus the actions. In the case of lack of process understanding, dedicated experiments can be planned to focus on the unresolved processes, and to incorporate such understanding into the models. In the case limitation comes from the lack of input data to such models, dedicated observations by means of in-situ networks or global satellite systems can be put in place. In some cases, like when tipping elements involve ocean or ice, the tipping point can be reached while the behaviour is not seen yet in the observations. Developing indicator tools for tipping points where there is not enough knowledge or confidence in the predictions can also be addressed.

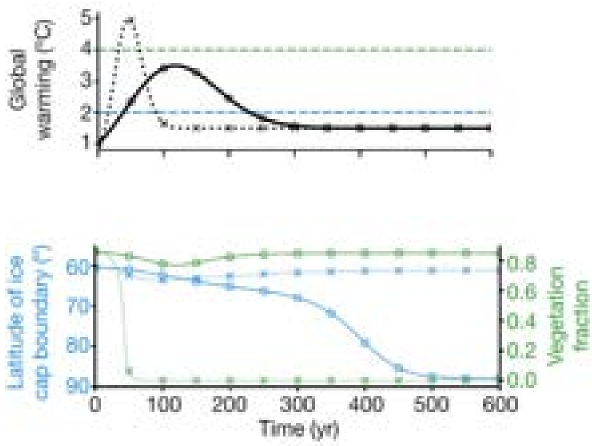

Fig. 3-1: (top) Time series of sample overshoot trajectories in global warming, and thresholds for the ice cap (blue) and forest dieback (green). (bottom) Time series of ice cap boundary (blue) and Amazon vegetation fraction (green) in response to the two overshoot trajectories presented above (Ritchie P. D. L., et al., 2021)

To illustrate these two situations, Fig. 3-1 shows an interesting example. In the top plot we have time series of sample overshoot trajectories in global warming, and thresholds for the ice cap (blue) and forest dieback (green). In the bottom plot we have the corresponding time series of ice cap boundary (blue) and Amazon vegetation fraction (green) in response to the two overshoot trajectories presented above. The tipping point behaviour is very different for both cases, and occur for different overshoot trajectories.

It looks like the behaviour of ice caps is well understood and then it would be a question of data availability to better model the process (based on physics at the end). However, for the case of Amazon forest dieback, the behaviour seems quite extreme (in one scenario they will disappear quickly) and probably there is a lack of understanding on the underlying processes and feedback looks (biology also plays a role in vegetation dynamics).

Specific actions can be established to help improving the models as needed. Moreover, the examples indicated also show the large potential and relevant possibilities to use time series of spatial maps derived from EO data as inputs to such models. Many of the inputs needed by the models are readily observable at the global scale by means of dedicated satellites, representing a unique source of data for such global climate models.

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CSQ-31 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What are the physical / mathematical mechanisms that generate the behaviour of tipping points in climate models? Can models be improved using more precise observations?	A) More detailed modelization of the physical / mathematical mechanisms leading to tipping point behaviour	• Long time series of several (preferably uncorrelated) geophysical observables, depending on the tipping points being studied, but including at least the following tipping elements: **Cryosphere:** ✓ Greenland ice sheet ✓ Arctic winter sea ice ✓ West Antarctic ice sheet ✓ East Antarctic ice sheet and subglacial basins ✓ Mountain glaciers ✓ Boreal permafrost ✓ Barents Sea ice **Ocean-Atmosphere circulation:** ✓ Atlantic Meridional Overturning Circulation ✓ North Atlantic subpolar gyre / Labrador-Irminger Sea Convection collapse **Biosphere:** ✓ Low-latitude Coral Reefs ✓ Sahel & the West African Monsoon	• Surface temperature (land and ocean) • Ice sheet extend • Forest vegetation cover extension and inter-annual variability • Temporal and spatial variability in ocean currents • Ocean salinity • Extension and dynamics of mountain glaciers	Existing climate models can take into account tipping point behaviour, at least for some tipping elements.	Better predictability in climate models would allow more precise and effective mitigation or adaptations approaches.

		✓ Boreal forest (southern dieback and northern expansion) ✓ Amazon rainforest			
	B) Sensitivity analysis of model input variables to predict tipping point behaviour	• Specific studies are needed to test model sensitivity in particular to input variables associated to tipping points, using key geophysical variables with well-known uncertainty and properly validated (Essential Climate Variables), particularly in the form of time series.	• Focus on key Essential Climate variables with well-characterised uncertainties	Filter models by using the adequacy to describe tipping point behaviour, as a particular feature of the different available models used for sensitivity studies	
	C) Identification of variables used by models not yet provided in spatial maps but only from punctual ground measurements	• Geophysical variables currently provided only by punctual field measurements but that can be potentially derived as spatial maps from EO data or using EO data to refine spatial gridding • Direct observables from EO data are already provided in the form of spatial maps and can replace (sometimes as proxys) data from ground networks • Focus on defined Essential Climate Variables, but also addressing new type of information when time series are already available	• Focus on data from surface networks with well-characterised uncertainties	Data exist, but reanalysis needed to use such time series in tipping points research	
	D) Identification of specific aspects in the climate models that can be improved by using more	• Running models under different scenarios to identify the critical elements in the models where observations (particularly in the	• Model inter-comparison exercises	Filter models by using the adequacy to describe tipping point behaviour, as a	

	precise, focused or dedicated observations	form of spatial maps) would be more beneficial.	particularly welcome	particular feature of the different available models	

CSQ-31 Narrative

The identifications of tipping elements and the corresponding tipping points are completely determined by the climate models used to forecast future trends and to identify future turning points in the climate system, by exploiting the predictive capabilities of the models.

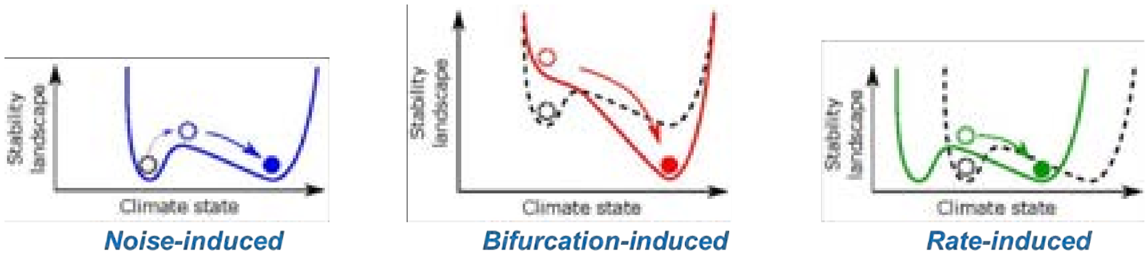

Fig. 4-1: Three main physical / mathematical mechanisms that generate the behaviour of tipping points in climate models

As illustrated in Fig. 4-1, three main different mechanisms are suggested to characterize the dynamics of tipping points:

(a) Noise-induced tipping is the transition from one state to another due to random fluctuations or internal variability of the climate system, the most common one. Noise-induced transitions are unpredictable, because the underlying potential does not change and there are no early warning signals.

(b) Bifurcation-induced tipping happens when a particular parameter in the climate system passes a critical level, where a bifurcation takes place, passing from one stable conditions to another stable condition, but quite different. This is the most typical case of tipping point behaviour.

(c) Rate-induced tipping occurs when a change in the environment is faster than the force that restores the system to its stable state. The states themselves do not change, is a change in the background potential what induces the tipping behaviour.

The reliability and accuracy of the predictions about climate tipping points depend very much on the physical understanding of the underlying processes and in the ability to represent such processes by means of mathematical models, to be more confident in the predictions.

Deficiencies in the models that describe such type of behaviours have been identified. Whether such potential deficiencies in the models can invalidate the predictive alerts for tipping points in the climate system is unlikely, but the actual magnitude of the effects may have a large uncertainty.

Can those models be improved or be better validated, by using more precise observations? Global satellite observations can help not only to identify tipping elements but also the geographical spatial extend of the identified tipping elements, and also the corresponding spatial variability (geophysical spatial patterns and associated spatial and temporal variances). The simple example shown in Fig. 4-2 is illustrative. It is based on one of the used models for forest dieback.

$$\frac{dv}{dt} = gv(1-v) - \gamma v$$

v = fractional vegetation cover

$$g = g_0\left[1 - \left(\frac{T_l - T_{opt}}{\beta}\right)^2\right]$$

$$T_l = T_f + (1-v)\alpha$$

Fig. 4-2: Simple forest dieback model (Ritchie P. D. L., et al., 2021)

The model assumes a single type of vegetation layer, and the governing equation for the driving parameter, the vegetation fraction *v*, accounts for a growth term, *g*, which is assumed to be parabolic in the local temperature, T_l, and a disturbance rate, □. There is an optimal temperature for which growth is maximal and β determines the dependence with temperature vegetation growth. Negative growth rate implies tree mortality. There is an additional feedback on the local temperature, T_l: a decline in vegetation results in an increase in temperature. The temperature T_f is used as the forcing parameter, and is modulated by the vegetation cover and the temperature difference between total forest cover and bare soil, given by □.

This elementary example illustrate two things: one is that models are many times too simple and very empirical, easy to improve, but also that global Earth Observation data can definitely help to derive much better models, particularly for the example here presented of forest dieback, because most of the key variables in the model can be effectively measured by satellites, and many of such data are even already available.

Global models necessarily must assume some simplifications when running over long time scales, but validation of the pieces of the global models by means of regional models, which can be more detailed in the representation of processes and can also be better constrained by available observations, is definitely a way to improve the global models in the way of describing the different processes.

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CSQ-32 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
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?	A) Identification of the alerts pointed out by predictive models, and the associated geographical extension and temporal scales of each alert	• As an output from model results, key geophysical variables where models are more sensitive to changes can be identified. • The conclusions can be model-dependent and probably require some reanalysis given the different sensitivity of each model to different geophysical inputs.	• Critical dependence on model capability to simulate some of the effects, particularly for regional sales	Models exist, but global models must be complemented with regional models to make possible a direct coupling to more detailed observations	New observations leading to an improved knowledge of tipping points effects, temperature threshold and spatial and temporal scales of the predicted effects, will be extremely beneficial to establish potential actions early enough to be effective.
	B) Identification of observations explicitly oriented to verify specific trends suggested by the models	• Since models need to be validated with current available datasets before they can be used in a predictive mode for the future, key current observations are: ✓ Time series of surface temperature over extended geographical areas ✓ Time series of sea area extend ✓ Time series of glacier extension and motions ✓ Time series of vegetation fraction al cover over boreal forest and Amazonian rainforest	• Time series long enough (ideally more than 30 years). This is possible for some records, even satellite data, but not for all the variables needed as inputs by the climate models • Accuracy in some key geophysical variables may be bot enough to be used for tipping points, due to the high sensitivity to small changes in input variables	Tools are available, both in terms of data (time series with associated uncertainties) and in terms of models, but the length and accuracy of the datasets may be not adequate for this type of models with high sensitivity to inputs variables (tipping behaviour).	

	C) Exploitation of current available time series and datasets to validate model behaviour at the associated spatial scales	• While time series for some geophysical variables already exist, the usage in tipping point models is not straightforward, due to the specific sensitivity of tipping point behaviour to small changes in input data.	• Accuracy in time series must be adequate to detect the small changes that are characteristic of tipping point behaviour	Model exist, but sensitivity to small changes in input parameters need to be analysed in more detail	
	D) Usage of guided observations to reduce uncertainties in model predictions	• New observations (either field, airborne, or satellite observations) can be explicitly planned to test specific model predictions and to improve model implementation	• Time series are needed in all cases, and the accuracy required to detect trends to tipping points can be quite demanding, particularly for time series with less than 30 year records.	Model exists, but uncertainty still too high to make possible the coupling to specific observations	

CSQ-32 Narrative

Tipping points are not directly measurable, but are predicted by climate models, ideally over long-term scales with enough anticipation to be still in time to establish corrective actions. What is really important is the identification of how the system changes before reaching the tipping point, or the pathways that may lead to the risk of being close to a tipping point, then introducing mitigation actions over such pathways that may lead to a tipping point well before there is too late.

Given the fact that identification of tipping elements, and the associated tipping points, must rely necessarily in climate models, the output of such models should guide the observations, focusing them on the most critical geographical areas, and spatial and temporal scales where observations are more critical, or focusing the observations on specific processes pointed out by the alerts provided by the climate models. Being able to measure how resilient the system is when approaching a tipping point is also relevant to focus the observational strategies.

Fig. 5-1: (left) Location of climate tipping elements in the cryosphere (blue), biosphere (green), and ocean/atmosphere (orange), and global warming levels at which their tipping points will likely be triggered. (right) Earth observations pointed out to better monitor the behaviour of tipping points.

In a first step, such observations can mostly serve to validate the models using current data and to help developing models with a better description of geographical extensions and spatial and temporal variances. Over time, the observations can verify the model predictions and help refining the models as needed. An important aspect in all cases is to account for uncertainties and error propagation, both the in the models and in the observations, something often not accounted for in a proper manner.

Identification of areas where changes are more likely to happen, and what changes can readily be observed, is already a major step. But dealing with tipping point effects and identification of thresholds and impacts will probably require the development of new observation capabilities. The identified deficiencies in the models, or areas in the models known to have a large uncertainty, can guide the definition of new global observing systems. In the case of tipping points, long time series to detect trends in changes is more important than short-term sophisticate new technologies to measure new type of information, but new temporal observation strategies can be explored, and also the role of data processing and model-data integration should be improved as well.

An important aspect on where to focus observations is the definition of safe boundaries for interactions of multiple tipping points. This is a topic that is deserving special attention in the last years, related to the possibility of activating several multiple tipping points at the same time and what would be the effects. The combined analysis of multiple tipping points also tries to determine which the dominant ones are or which are the ones that due to particular risk deserve the focus of the attention in order to focus observation strategies.

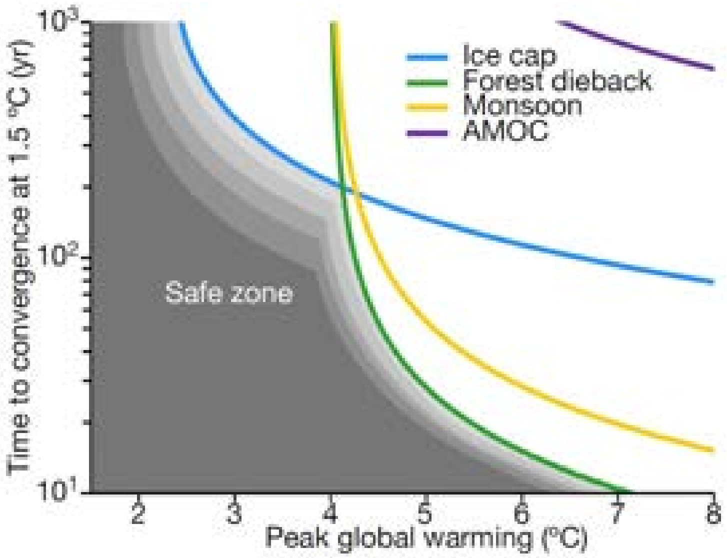

Fig. 5-2: Boundaries of safe overshoots for multiple tipping points (Ritchie P. D. L., et al., 2021)

The diagram in Fig. 5-2 shows the boundaries of safe overshoots for multiple tipping points, as a function of the peak global warming temperature and the time to convergence at 1.5 degrees warming goal. Above and right of the individual curves the tipping cannot be avoided, below and left indicate the safe zone. The grey-shaded region indicates the safe zone for all tipping points. Different grey shades indicate the boundary of the safe zone if the threshold for all tipping elements were 0.1 °C lower.

As indicated by the results plotted in the Fig. 5-2, one can conclude that ice cap and forest dieback dominate the safe zone. Then, those two would be the critical ones to be studied in more detail, and where observations can be definitely focused.

However, results are for sure model-dependent and should be interpreted with caution, more research is needed before coming to premature conclusions.

Given the limited temporal extent of time series of satellite data, covering 4-5 decades in the best cases, the direct monitoring of trends and indicators for the activation of tipping points is restricted to tipping points with fast evolution over decadal time scales (such as winter sea ice in the Arctic, forest dieback for both tropical and boreal forest, or Arctic permafrost), although some potential proxy indicators can be also used to monitor processes when direct observations are not possible. Moreover, current time series of observations can also serve to better validate models and the use the model in a more precise predictive way.

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CSQ-33 Summary

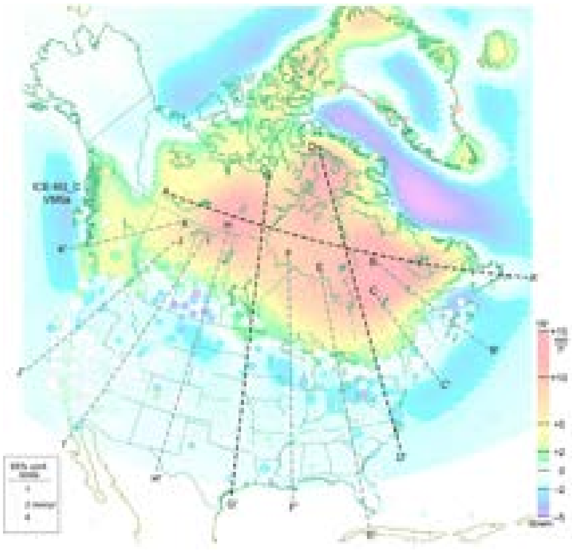
Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How does the solid Earth deform under present and past ice loads and what does it tell us about its rheology ?	A) Quantify the long-term GIA signal of the Pleistocene deglaciation 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.	• geomorphological data (past ice mass extent) • cosmogenic exposure dating and local sampling (past ice mass thickness) • GNSS and InSAR (surface deformation due to present-day ice load and mantle relaxation to past ice loads) • gravimetry (mass changes due to present-day ice load and mantle relaxation to past ice loads), altimetry (ice volume) • seismology (lithospheric thickness)	• 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	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.
	B) Quantify the solid Earth visco-elastic response to recent or contemporary ice mass change	• Same as above	• Same as above, with an emphasis	Models of visco-elastic mantle relaxation under a surface load.	

	in glaciated regions associated with low mantle viscosity, such as active plate boundaries.		towards higher spatial resolutions.	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.	
	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		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). Methods for data assimilation in GIA models.	

* EWH = equivalent water height

CSQ-33 Narrative

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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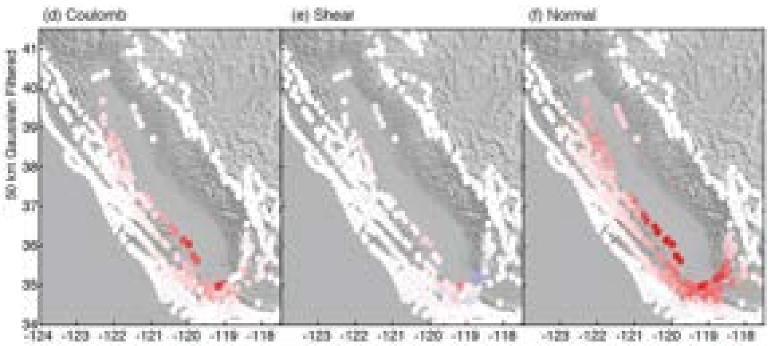
CSQ-34 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
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 ?	A) 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.	• Ground deformation derived from GNSS measurements to constrain regional-scale water loads (from the elastic deformation response) • High-resolution ground deformations from InSAR to constrain local groundwater level variations • Gravity to constrain total water mass • Data on soil moisture, surface water levels	• Daily to weekly timescales • High spatial resolution • Multi-satellite missions can help improve the gravity recovery	Models of elastic and poro-elastic deformations of the solid Earth under a water load	Improved seismic hazard assessment from improved understanding of earthquake nucleation processes
	B) 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.	• Knowledge on surface and deep water loads derived from the previous objective • Ground deformations due to water loads observed from GNSS and InSAR • Seismicity		Models of elastic and poro-elastic deformations of the solid Earth under a water load Knowledge on the distribution of faults Ability to calculate stress variations	

CSQ-34 Narrative

Changes in the water mass at the Earth's surface generate small variations in the crustal stress field from local to regional scales. Despite their small amplitude, it has been proposed that these changes could modulate seismicity, by affecting the state of stress on active faults and pore fluid pressure at depth (e.g. Craig et al. 2017). A number of studies have provided support for this hypothesis, such as those focussing on seasonal variations in the rate of seismicity (Johnson et al., 2017). Studying earthquakes modulation by water loads actually provides a natural laboratory to explore the effects of specific stress perturbations on faults and better understand earthquakes nucleation processes. Note that in active tectonic environments such as plate boundaries, changes in the stress field induced by hydrological loads are much smaller than the secular rates of stress accumulation due to tectonic processes, but the situation may be different within continental interiors, where the secular tectonic stresses are smaller. Current efforts aim at a better estimation of the groundwater contribution to the total water mass change, by combining different types of geodetic observations (e.g. Carlson et al., 2020). Indeed, this groundwater contribution may be under-estimated in GPS-based water load models, resulting in an under-estimation of the non-tectonic crustal stress. Its accurate quantification and location is crucial to better describe the forces that modulate seismicity, the contributions of human pumping activities and climate extremes, and their influence on the seismic hazard.



Stress field perturbation along faults in California from total groundwater loss during the 2007–2010 drought. Red color : 1-1.5 kPa stress change (Carlson et al., 2020).

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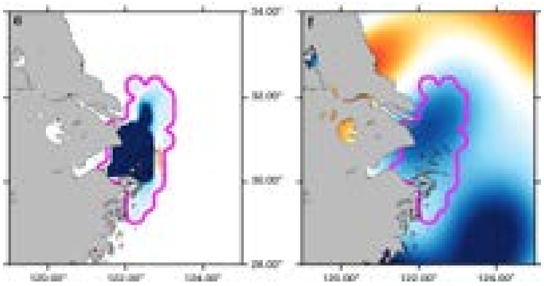
CSQ-35 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	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, ...).	● Gravity to constrain mass changes ● River discharge and surface water levels (as from SWOT), to correct for hydrological leakage effects in coastal areas.	● 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 ● Multi-satellite missions with orbit inclination choice can help to improve the gravity recovery	A proper correction of hydrological leakage effects in coastal areas is needed. Knowledge on the location of the sedimentation zones. Use Lagrangian circulation models (such as Parcels 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
	B) Resolve large variations in sediment discharge following	. Gravity to constrain mass changes		Compile available information on the	

	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.	• River discharge and surface water levels (as from SWOT), to correct for hydrological leakage effects in coastal areas.		time variability of the sediment discharge to better evaluate its signature in the gravity time series. Model the dynamics of sediment transport in rivers, to relate water discharge to sediment discharge.	
	C) Quantify sediments loss in mountaneous areas	• Gravity to constrain mass changes • Data on ice thickness variations		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) Ability to improve the spatial resolution of the results in post-processing (for instance using mascons modelling of the gravity field)	

CSQ-35 Narrative

Contemporary erosion of drainage basins is controlled by natural processes (frost and precipitations 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 landscapes 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 still not accurate enough, because in-situ measurements of sediment transport at rivers mouths are difficult and expensive. 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. 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.



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

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 (x 10³ km²)	Elevation	Runoff (mm/yr)	Sed. load (Mt/yr)	Sed. yield (t/km²/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	1900	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	1000	**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 from: River discharge to the coastal ocean, a global synthesis, by J.D. Milliman and K. L. Farnsworth, Cambridge University Press, ISBN 9780511781247, 2011.

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CSQ-36 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	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.	. Surface displacements on land by GNSS and satellite imagery • Seafloor displacements • Gravity to constrain mass changes	• Long-term trends • High accuracy over all spatial scales • Multi-satellite missions with orbit inclination choice can help to improve the gravity recovery (this point is valid for all the Objectives here).	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
	B) Document the spatio-temporal characteristics of transient aseismic events in subduction systems.	. Surface displacements on land by GNSS and satellite imagery • Seafloor displacements • Gravity to constrain mass changes • Ground geophysical dataset: seismicity	• 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.	Models of surface deformations and gravity changes associated with slip on faults (see below).	
	C) Document the possible existence of a short-term preparatory phase for earthquakes.	• Surface displacements on land by GNSS and satellite imagery • Seafloor displacements • Gravity to constrain mass changes • Ground geophysical dataset: seismicity	• Timescales from ~1 day to decadal • High accuracy over all spatial scales, including medium scales (100's of km) to	Models of surface deformations and gravity changes associated with slip on faults and slab deformation.	

			monitor deep deformations	Calculation of stress redistribution	
	D) Quantify the co-seismic slip distribution and discriminate between early rupture models.	. Surface displacements on land by GNSS and satellite imagery • Seafloor displacements • Gravity to constrain mass changes • Ground geophysical dataset: seismology, tsunami records from near-coastal pressure gauges and sea bottom pressure measurements	• 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 over epicentral areas. • Gravity: 1cm EWH@200km resolution, monthly = detection of Mw > 7.4 earthquakes.	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 parameters). Calculation of stress redistribution	
	E) Assess the relative contributions of localized 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.	• Surface displacements on land by GNSS and satellite imagery • Seafloor displacements • Gravity to constrain mass changes	• Time scales from weeks to decades • Coverage on both sides of the plate boundaries and over epicentral areas. • High accuracy over a range of spatial scales to separate different spatio-	Models: same challenge as above to take into account the 3D structure of the Earth, also including models of visco-elastic relaxation of the mantle after a co-seismic rupture, and coupled models combining slow slip	

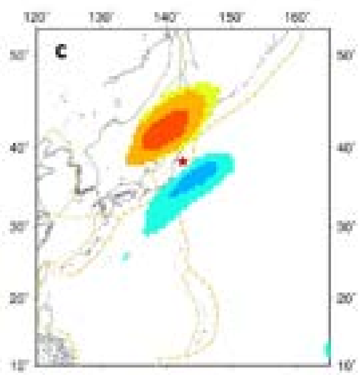
			temporal signatures of deep aseismic slip (more local) and mantle relaxation (involves larger scales)	and visco-elastic relaxation. Calculation of stress redistribution	

CSQ-36 Narrative

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.

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 ruptures 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 localized slip or mantle visco-elastic relaxation.



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

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Chen, J., Cazenave, A., Dahle, C., Llovel, W., Panet, I., Pfeffer, J., Moreira, L. (2022). Applications and Challenges of GRACE and GRACE Follow-On Satellite Gravimetry, *Surveys in Geophysics*, 43, 305-345, https://doi.org/10.1007 (Section 6: Solid Earth Mass Change from GRACE/GRACE-FO)

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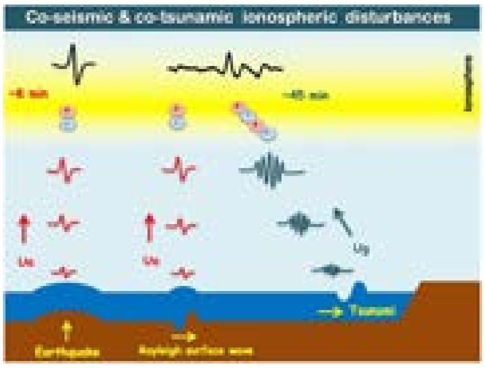
CSQ-37 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
Can we estimate the tsunami potential of an earthquake in real-time ?	A) Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events. Assess the tsunami potential of an earthquake in real time.	• GNSS receivers (total electron content, TEC, co-seismic crustal displacements) • ionosondes (maximum ionization height HmF2, virtual height h'F2, electron density Ne)	We need dual-frequency GNSS receivers, dense network, and higher data cadence (1Hz) for GNSS data (currently the "standard" resolution is 30-sec) and up to 30s in ionosonde data (currently the standard is 5 to 15 min which is insufficient).	Ground-based GNSS receivers in the vicinity of epicentres; methods of automatic detection of ionospheric disturbances; Empirical seismo-ionospheric models that will be developed soon.	Emergency planning and response
	B) Monitor trans-oceanic propagation of tsunamis, estimation of the wave height and propagation speed from the ionosphere	• GNSS receivers (TEC) ionosondes (HmF2, h'F2, Ne) ground-based airglow cameras (fluctuations in the atmospheric density, sky luminosity) future space-borne airglow cameras	Denser networks on islands, higher resolution TEC data. For space-borne observations, we need a mission, or even a constellation.	Ground-based receivers on islands. DART buoys, GNSS buoys Empirical tsunami-ionospheric relationships that will be developed soon.	

CSQ-37 Narrative

The vertical displacements of the ground and the ocean surface during earthquakes and tsunamis generate acoustic and gravity waves that propagate upward and generate significant local perturbations in the ionosphere. These perturbations can be detected by ionospheric sounding. Retrospective studies have shown that ionospheric measurements can be used to estimate earthquakes magnitude and tsunami potential minutes after the mainshock (Astafyeva, 2019 ; Manta et al., 2020). This opens important perspectives to mitigate the damages caused by natural hazards. The development of real-time-compatible methods is an on-going effort.



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CSQ-38 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	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.	. Gravity to constrain mass changes • Ground displacements by GNSS	• Long-term trends • High accuracy at medium spatial scales • 1 mm EWH* in 10 years @ 230-330 km resolution • Multi-satellite missions with orbit inclination choice can help to improve the gravity recovery.	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.

* EWH = equivalent water height

CSQ-38 Narrative

Deeper geodynamical processes contribute to the evolution of the Earth's crust and long-term reshaping of the surface, such as processes of mountain building at convergent plate boundaries, the long-term subduction of tectonic plates in-depth subduction 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 rocks 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 (see Question 7). 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.

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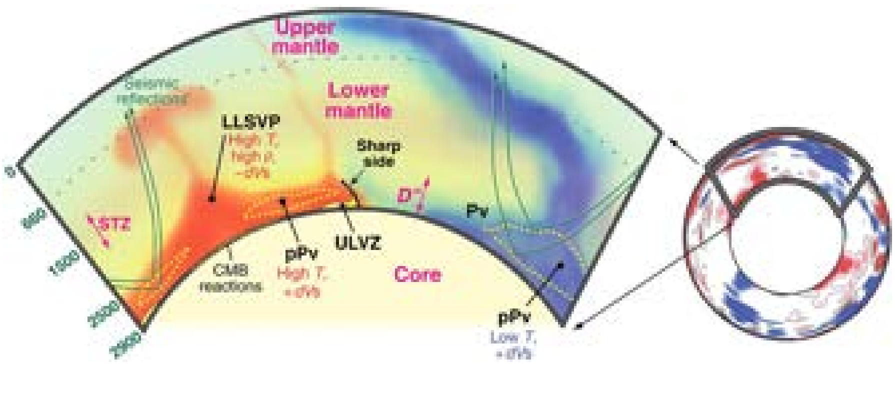
CSQ-39 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What is the nature of the mantle heterogeneity and the character of its convection at all depths ?	A) 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.	. Gravity field and gravity gradients to constrain the mantle mass distribution • Surface topography to constrain dynamical topographies • Geomagnetic field, magneto-telluric data • Surface displacements from GNSS (for tidal tomography of the mantle). • Seismology (for seismic velocity maps, data on the depths of internal interfaces, crustal thickness)	• Current challenges: aim at high spatial resolution at all depths.	Mineral physics data (to compute density, seismic velocity, electrical conductivity corresponding to different hypotheses on the thermo-chemical structure of the mantle). Models of gravito-visco-elastic deformations of the mantle caused by internal loads. Need for models able to account for 3D variations in physical properties of the Earth (not only radial). Methods to combine all geophysical observables within a unified modelling approach. Joint inversions.	Understand the deep processes governing changes in our near-surface environment. Constrain the deep water cycle and the deep carbon cycle inside the Earth.

				Methods to separate crustal vs mantle sources.	
	B) Quantify the present-day 3D structure of the Earth's mantle, in terms of temperature, composition and melting.	. Same as above	• Current challenges: aim at high spatial resolution at all depths.	Same as above.	
	C) 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.	• Same as above	• Same as above	Same as above. Mantle convection models. Ability to calculate accurately the geophysical observables predicted by a convection model.	

CSQ-39 Narrative

Obtaining a high-resolution and global image of the Earth's interior structure in 3D, and interpreting this present-day structure in terms of dynamical processes, remains an outstanding question of geophysics, in order to understand the thermal and compositional evolution of the Earth, and describe the deep geodynamical processes underlying near-surface changes. This is also a key to understand the circulation and recycling of materials and volatiles (including water) between the depths of the core and the surface, and how the internal heat is evacuated towards the surface. Examples of questions include : what is the buoyancy of the deep mantle (Romanowicz, 2017) ? What is the path of subducted slabs and how deep do they go ? Do the upper and the lower mantle convect together or separately ? An accurate image of Earth's interior temperature, melting and composition would also provide constraints on its viscosity. Around subduction boundaries, mapping the lateral variations of structure and geometry of the subducted plates in the mantle contributes to a better understanding of the segmentation of the plates interface and the existence of possible barriers to the propagation of a rupture, thus to the assessment of the seismic hazard. Current challenges consist in further advancing the joint inversions and modelling of different geophysical observables in terms of 3D thermal and compositional structure. They include seismic data (sensitive to the 3D elastic structure of the Earth at depth through maps of seismic velocities), gravity and gravity gradient data (which provide a high lateral resolution and, in the case of the gradients, an enhanced sensitivity to the morphology of the mass sources), and geomagnetic/magneto-telluric data (sensitive to the electrical conductivity, see Kuvshinov et al., 2021). All these geophysical parameters (seismic velocities, density and conductivity) are sensitive to the temperature and chemical composition in different ways, and to the presence of melt and water. Their combination remains an active area of research benefiting from the development of appropriate data analysis and modelling methods, and also from an increase in accuracy of the observations.



Right : a seismic image of Earth's interior, together with interpretative elements (right). As a first-order approximation, blue colors indicate cold material (subducted slabs) and red, hot material (upwellings).
From Garnero & McNamara (2008).

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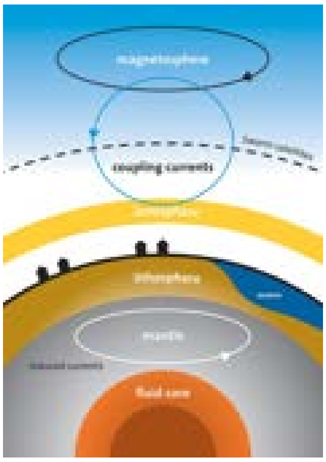
CSQ-40

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirement	Tools & Models	Policies / Benefits
What is the dynamics of the fluid outer core at short timescales, and how is it coupled with the mantle ?	A) 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.	. Magnetic field measured by satellites ● Ground Magnetic data from observatories and variation stations	● High temporal resolutions (including 1s data from ground stations) ● Global coverage ● Multi-satellite missions with orbits inclination choice to cover efficiently local times (e.g. combination of polar orbits with orbit with large inclination ~60°)	Theoretical magnetic models of ionosphere, magnetosphere, FAC contributions at low altitudes. Ground observatories are needed to separate core field from ionospheric field and separate magnetosphere contribution Models of mantle conductivity Models for induced fields Dynamo models	Forecast the evolution of the geomagnetic field Production of accurate reference field models Improved understanding of deep Earth processes (core dynamics, core-mantle coupling, deep mantle properties…), governing how energy flows from the core to the surface. Improved knowledge of spaceweather
	B) 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.	• Magnetic field measured by satellites ● Ground Magnetic data from variation stations (Magneto-telluric data to constrain the lithosphere and upper mantle) ● Combination of geophysical observables to constrain the 3D		As above Surface conductivity models Mantle composition models Methods for joint inversions of various	

		electrical conductivity of the mantle: geomagnetic data, gravity data, seismology, mineral physics.		geophysical observables (needed to improve mantle composition models)	
	C) Resolve the geomagnetic signatures of periodic motions at sub-decadal timescales in the core flows, and constrain the corresponding rapid core dynamics.	• Magnetic field measured by satellites • Ground Magnetic data from variation stations	• Multi-satellite missions with orbits inclination choice to cover efficiently local times (e.g. combination of polar orbits with orbit with large inclination ~60°) • High temporal resolution and high spatial resolution, globally	Theoretical magnetic models of ionosphere, magnetosphere, FAC contributions at low altitudes. Ground observatories are needed to separate core field from ionospheric field and separate magnetosphere contribution Mantle conductivity models to separate core and induced fields Geodynamo models able to describe rapid variations; geomagnetic data assimilation in these models	
	D) Assess whether and where the regions near the core-mantle boundary are stably stratified or not, and the impact on the core flows.	. Observations of the core field to constrain flow velocities at the top of the core • Seismic data (constraining the stratification)	• Multi-satellite missions with orbits inclination choice to cover efficiently local times (e.g. combination of polar orbits with	As above plus: Constraints on the heat flow, models of mantle flow velocity (seismological & geodynamic models of	

			orbit with large inclination ~60°)	the top of the core and the bottom of the mantle). Dynamo models able to handle stratification	
	E) Assess the impact on core flows due to mantle heterogeneity and spatial or spatio-temporal variations in core-mantle boundary topography.	• Gravity and seismology to constrain core-mantle boundary topography variations • Earth's rotation (angular momentum) • Mineral physics • Observations of the magnetic field to constrain flow velocities at the top of the core (see above)		As above plus: Models of gravito-visco-elastic deformations of the Earth's mantle able to handle 3D variations in structure (not only radial). Models of mantle conductivity (3D) Models of core-mantle coupling Continuous models of core flows based on satellite and ground data Dynamo models able to handle the considered boundary conditions	

Solid Earth 8: Narrative



Internal and external sources of the magnetic field (@ESA).

Convection in the fluid core is considered a primary source of the geodynamo, at the origin of the Earth's main magnetic field. Constraining the space-time evolution of the geodynamo and forecasting the evolution of the geomagnetic field thus requires to improve our knowledge of the fluid core motions. This is also needed in order to understand the origin of large interannual changes in the observed geomagnetic field. Great progress have been made in recent years in modelling the flow dynamics, as we are now able to build geodynamo models approaching Earth's like conditions (Aubert & Gillet 2021). However, the dynamics of the flows is not well constrained on timescales shorter than a couple of years by the current geomagnetic observations, due to unmodelled ionospheric and magnetospheric signals (Lesur et al., 2022). Periodic structures have been recently detected at timescales of a few years, but their temporal frequencies are still unperfectly resolved from satellite data covering a limited time-span (Gillet et al, 2022, Ropp & Lesur, 2023). Exploring and understanding these transient wave-like motions is a possible avenue to decipher the dynamo field inside Earth's core. This calls for long-lived satellite coverage, continuing after the Swarm mission of ESA.

Another challenge is to assess the impact of a non-spherical core-mantle boundary, which can be significant even for a small deformation of the boundary (Mandea et al., 2015 ; Vidal & Cebron, 2020, 2021). This last point raises the question of the interactions with the mantle. The core-mantle coupling involves e.g. redistributions of mass at the core-mantle boundary, a possible gravitational torque between a non-spherical inner core and mass anomalies in the mantle, or forces generated by electrical currents in the lowermost mantle (Buffett, 2015). Finally, we still struggle to understand whether the regions near the core-mantle boundary are stably stratified or not (Irving et al, 2018), and the impacts of such stratification on the flows is potentially large (Mound et al, 2019). This key issue has important consequences regarding the Earth's thermal history. To answer these questions, geomagnetic data provide a major observational constraint.

The core field is the main contributor to the observed magnetic field at the Earth's surface, which also includes contributions from the lithosphere and from external sources: the ionosphere and the magnetosphere. Thus, satellite observations of the space-time variations of the Earth's magnetic field provide an indirect sensor on the space-time patterns of the core flows, provided that they can be separated from the other sources (Lesur et al., 2022). It requires observations from ground observatories, in addition to geomagnetic satellite data at high temporal resolution. Signals from the core are also overprinted by induced secondary fields in the electrically conducting mantle, and filtered out by the conductive mantle. This screening effect is not well estimated, stressing the need for a better knowledge of the 3D mantle conductivity (see also Question 7). Conversely, mapping and understanding the transient motions in the core opens a possible way to sample the electrical properties of the deep mantle, because the core dynamics is sensitive to the electrical condition (conducting or insulating) at the top of the core (Schaeffer & Jault, 2016). Improving the separation of the internal and external sources of the magnetic field measured by satellites, at the highest possible spatial and temporal resolutions, is crucial and would benefit from improved knowledge in particular of the electrical currents in the ionosphere.

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CSQ-41 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Specifications	Tools & Models	Policies / Benefits
How does soil status control Earth system cycles and influence surface-air exchange processes?	A) Quantify surface soil hydraulic and thermal properties	Common soil attributes in soil spectral libraries (SSLs): mechanical composition (clay, silt, and sand content), organic matter, carbonate, iron oxides, hygroscopic moisture, and specific surface area); Soil dielectric properties (TIR emissivity; MW emissivity – dielectric constants) & SM from passive microwave observations (SMOS and SMAP) and follow-on high resolution mission, and SAR sensors	Soil and vegetation reflectance spectra at high resolution (10 – 100m), diurnal scale LST (100m) SM & VWC: kilometer scale (e.g. 1 - 10 km) at daily to diurnal time steps - a future higher resolution L-band space mission is highly desirable;	Spectroscopy; Multispectral/hyperspectral TIR SM & VWC: Retrievals algorithms (0th order RT models); Combination with SAR and scatterometer data; in-situ data for validation from e.g. International Soil Moisture Network (ISMN) GNSS and bistatic retrievals; use of auxiliary data by means of machine learning;	CC mitigation and adaptation policy; Climate finance; Green deal; Water and food security; Agriculture transition; EC Soil Deal mission: Farm to Fork Strategy, and EU Biodiversity Strategy for 2030; Climate Adaptation Strategy; New EU Forest Strategy; Long-term Vision for Rural Areas; Organic Action Plan; Common Agricultural Policy; EU's twin green and digital transition.

		VWC from coarse scale microwave observations (ASCAT, SMOS and SMAP) via vegetation optical depth; brightness temperature (e.g. SMOS and SMAP, and multi-frequencies in the upcoming CIMR), backscattering coefficient in C- (SAR and ASCAT) and L-band (e.g. ROSE-L); GNSS Groundwater: observations from mass change missions (GRACE and GRACE-FO); A new mission with much improved resolution in space and time will further advance the observations of terrestrial water storage.	10 ~100 km at weekly to monthly steps for groundwater;	Groundwater: change detection using time series of observation data; retrievals algorithms	
	B) Soil moisture profile as control of photosynthesis rates in vegetation canopies	Evaporation (and transpiration): observation of evaporation needs to cover the whole spectrum from	Evaporation: hm ~km at diurnal (half hourly) steps for **water potential** as well as full spectrum observation (incl. fluorescence)	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical,	

		optical to thermal range and the retrievals need to consider the involved essential physical and biochemical processes (coupling water, energy, and carbon cycles). Transfer of water through the soil, roots, stem and leaves can be quantified by measuring and simulating **water potential** and link the change of water potential to external forcings of radiation, precipitation and meteorology, the growth of above and below ground plant biomass, and the extraction of water by the growing roots. The direct observables are soil moisture, vegetation water content and near surface atmospheric water content.		TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	

	C) Quantify impacts of surface soil moisture and that of rooting depth soil moisture on surface-air exchanges	Quantify simultaneously SM, SIF, surface radiation fluxes (shortwave and longwave), sensible and latent heat fluxes	Sensible heat and latent heat fluxes (Evaporation): hm ~km at diurnal (half hourly) steps for **water potential** as well as full spectrum observation (incl. fluorescence), LST	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical, TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	
	D) Quantify the contribution of latent heat flux from bare soil and canopy to total surface-air exchanges, as well as that of groundwater level	Quantify simultaneously SM, SIF, surface radiation fluxes (shortwave and longwave), sensible and latent heat fluxes, together with TWS	Sensible heat and latent heat fluxes (Evaporation): km at monthly and seasonal steps: spectrum observation (incl. fluorescence), LST, TWS from GRACE and GRACE-FO and follow-on missions	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical, TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	

Narrative:

Recent floods and droughts in Europe have shown how the effects of climate change can be acerbated by unhealthy, i.e., compacted, sealed, eroded, and carbon-poor soils. It has been assessed 60-70% of soils in Europe are in an unhealthy condition. In the book “Collapse: How Societies Choose to Fail or Succeed”, authored by the “Pulitzer Prize” and “Wolf Prize in Agriculture” winner Jared Mason Diamond, soil problems (erosion, salinization, and soil fertility losses), water management problems, deforestation and habitat destruction are deemed the top environmental problems contributed to the collapse of past societies, and are the environmental problems facing humankind today.

Healthy soils are therefore not only essential for all life-sustaining processes on our planet, but also necessary for the successful implementation of EU’s Green Deal, providing ecosystem services, which include: Nutrient cycling, and producing safe and nutritious food; Storing and purifying water, regulating flows and recharging aquifers, as such providing a ‘buffer zone’ to reduce the impact of droughts and floods, contributing to climate adaptation; Sequestrating carbon from the atmosphere and reducing emission of GHG from soils, thus contributing to climate mitigation; Preserving biodiversity and supporting the quality of landscapes.

It is with the above context, European Commission launched ‘A Soil Deal for Europe’ which aims to pioneer, showcase and accelerate the transition to healthy soils at the level in line with Green Deal commitments and targets by 2030, via establishing a robust, harmonised soil monitoring framework (EU Soil Observatory), as well as 100 living labs and lighthouses within territorial settings. This mission is also essential for the success of the 2030 EU Soil Strategy, EU Nature Restoration Targets, and Circular Economy Action Plan. There are also political “buy-in” from across the European Commission to the Soil Deal mission: Farm to Fork Strategy, and EU Biodiversity Strategy for 2030; Climate Adaptation Strategy; New EU Forest Strategy; Long-term Vision for Rural Areas; Organic Action Plan; Common Agricultural Policy; EU’s twin green and digital transition.

With the foregoing, it is clear that the concept of ‘soil health’ is gaining momentum, and the Soil Deal mission will give visibility to soils as a crucial, yet widely ‘unrecognised’ societal asset and public good.

In 2019, ESA organized the World Soil User Consultation Meeting, with the aim to discuss the necessary steps to develop a soil monitoring system utilizing space-based EO data with in-situ data and modeling (http://worldsoils2019.esa.int/index.php). There are operational passive and active remote sensing platforms that can be applied to observe soil properties (e.g., soil organic content, clay, particle size, soil roughness, soil moisture, and many other soil attributes): from the passive optical (e.g., both multi-spectral and hyperspectral), thermal and microwave systems to the active SAR and LiDAR systems (Ben-Dor et al. 2018, CRC). Although optical remote sensing techniques for soil monitoring are available, their applications to retrieve soil properties are constrained by the mixed coverage of bare soil and vegetation, as well as the need to refine models capable of resolving the signal from such mixed pixels, since the factors affecting soil reflectance include: (high/low) vegetation, soil cover and crust, soil moisture, and atmosphere’s gases and aerosols.

Despite the above mentioned challenges, soil spectroscopy has been profoundly developed for estimating soil properties, since its cost-effective nature and its high reliability (Viscarra Rossel, et al. 2022). The new sensors of the Copernicus Programme, LSTM (6 VNIR + 5 TIR) and CHIME (spectral sampling interval <=10nm for the range 400-2500nm), are deemed particularly relevant for monitoring soil properties, thanks to their spectral coverage but also the growing availability of soil spectral library.

Terrestrial spectral libraries are important databases for the analysis of hyperspectral remote sensing information, since they provide the spectral features of a collection of soil material from different horizons with detailed metadata consisting of exact location, pedogenic characterization, and measurement protocol in both field and laboratory. The common soil attributes in SSLs are: mechanical composition (clay, silt, and sand content), organic matter, carbonate, iron oxides, hygroscopic moisture, and specific surface area (as in the LUCAS SSL and global SSL). SSL is the basis for developing proxy models for soil property quantification, classification, mapping, and monitoring, and, therefore, directly linked to the development of remote sensing technology for soil monitoring.

Microwave remote sensing products of surface soil moisture (SSM) and root zone soil moisture (RZSM) (e.g., from radiometers and scatterometers) have long been used for drought monitoring and climate studies. Nevertheless, most of microwave SSM data are at regional scales (25km) and the 'root zone' is fixed as 1m globally by model inversion. While we know in reality, root growth is a dynamic process and, consequently, the depth of root water and nutrient uptakes vary over the growing season, affecting the water/carbon use efficiency, and therefore, the drought response of plants and ecosystems. There are now a plethora of SSM products at 1km generated with machine learning algorithms (Han et al., 2023). However, the physically consistent set of SSM and RZSM are still lacking at field and plot scales for tracking the soil water stress and its impacts on ecosystem functioning. Soil physical and thermal properties can also be retrieved by assimilating microwave observation signals into a land surface model (e.g. Zhao et al., 2023).

At the timescale of multiple years to decades, the averaged VWC measurements can be used to quantify ecological dynamics related to biomass and structure at biome, continent, and global scales. For example, the disturbance (e.g., fire, extreme drought) and land use dynamics can be informed by the sensitivity of VWC to aboveground biomass. Therefore, the remote sensing of VWC, SSM/RZSM, and SIF can be used to monitor the disturbance on soil properties at these large scales. At the scale of weeks to months, the interactions between SSM/RZSM, xylem hydraulic functions, and VWC come into play, and are useful to assess the risk of drought-induced mortality and flammability risk. At this level, the VWC, SSM/RZSM, and SIF data can be used to derive regional scale soil properties. While at diel timescales, VWC, SSM/RZSM, SIF measurements reflect the coordinated responses of root, xylem, and stomatal conductance to drying soil and air, and therefore, can be used to detect water stress before it is detectable through other leaf properties. As such, the diel monitoring of VWC, SSM/RZSM, and SIF hold promise as early warning signals for drought risks, and to derive Ψ_{soil} which dominates the soil hydrological process. Capabilities in simulating the various observed signal from both passive and active microwave sensors (e.g. Zhao, et al., 2022) will enable the use of such observation in land surface models and climate simulations.

An observation system as outlined above will provide measurements of soil reflectance, SIF, LST, SSM/RZSM, and VWC across different spatiotemporal scales. It will enable process-level understanding of drought responses of agriculture and nature ecosystems, and correspondingly the soil properties across different scales. Nevertheless, deriving process understanding from soil reflectance, SIF, LST, SSM/RZSM, and VWC observations will require the establishment of a Digital Twin of Soil-Plant system. This soil-plant digital twin will facilitate the assessment of evolution and health of plants and ecosystems and their interactions with soil properties, by optimally integrating multi-wavelength satellite (future) observations, in situ measurements, analytical- and physically-based models, data assimilation as well as machine learning algorithms.

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CSQ-42

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
1. To what extent can we predict the Earth's water cycle closure in space and time?	**A) 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	1a)Fast reservoirs: atmospheric water vapor (WV), soil moisture (SM), vegetation water content (VWC), and surface water storage (SWS) (in lakes, man-made reservoirs and rivers); WV profile and its changes in response to temperature; Column WV from observations in microwave, infrared, optical, and UV spectrum. SM from passive microwave observations (SMOS and SMAP) and follow-on high resolution mission; VWC from coarse scale microwave observations (ASCAT,	1)WV: Changes from diurnal to daily and weekly time scale at hm to 10 km spatial resolution; Atmospheric WV profile (2m, 100m vertical resolution) SM & VWC: kilometer scale (e.g. 1 - 10 km) at daily to diurnal time steps - a future higher resolution L-band space mission is highly desirable;	WV: Atmospheric water vapor retrieval algorithms; inverse radiative transfer models; data assimilation; coupling the observation of humidity and temperature to generate a consistent dataset. SM & VWC: Retrievals algorithms (0^{th} order RT models); Combination with SAR and scatterometer data; GNSS and bistatic retrievals; use of auxiliary data by means of machine learning;	CC mitigation and adaptation policy Climate finance Green deal Water and food security Agriculture transition

		SMOS and SMAP) via vegetation optical depth; brightness temperature (e.g. SMOS and SMAP, and multi-frequencies in the upcoming CIMR), backscattering coefficient in C- (SAR and ASCAT) and L-band (e.g. ROSE-L); GNSS SWS: extent of surface water bodies and the changes in water levels (Optical and SAR sensors for surface water extent, radar altimetry and interferometry for water levels; SWOT for observation of rivers, lakes and inundation plains) 1b)Slow reservoirs: groundwater, snow, glaciers and ice caps, ice sheets and sea ice, and freeze and thaw and permafrost.	 SWS: 10s of meters at daily to weekly time steps	in-situ data for validation from e.g. International Soil Moisture Network (ISMN) SWS: retrieval algorithms; change detection algorithms Groundwater, snow, glaciers and ice caps, ice sheets and sea ice: change detection	

		Groundwater: observations from mass change missions (GRACE and GRACE-FO); A new mission with much improved resolution in space and time will further advance the observations of terrestrial water storage. Optical, thermal and microwave observations for snow, glaciers and ice caps, ice sheets and sea ice, and permafrost.	10 ~100 km at weekly to monthly steps for groundwater; 10s of meters at weekly to monthly steps for snow, glaciers and ice caps; km~10 km at monthly to seasonal steps for ice sheets and sea ice; km~10km at diurnal to daily steps for freeze and thaw and (seasonally) permafrost;	using time series of observation data; retrievals algorithms	

		1c)Other relevant variables: sea level and sea surface salinity	10km for sea level and sea salinity;		
	B) 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)	2) Observation of clouds and precipitation processes by CloudSat and EarthCARE on polar orbits (full global coverage of vertical profiles of clouds and light and solid precipitation) and Global Precipitation Measurement (GPM) for solid and liquid precipitation observations Observables for clouds and precipitation are optical properties in the optical and thermal spectrum and microwave brightness temperature and radar backscatters. New and novel observations, for example for marine stratocumulus, may	2) global precipitation dataset (e.g. the IMERG, half hourly and 0.1°x0.1° and aggregates at longer time scale). 10km clouds properties at hourly scale	Clouds and precipitation: retrieval algorithms based on radiative transfer; Bayesian retrievals; Machine learning algorithms; Validation by in-situ data collected by GPCC (global Precipitation Climatology Center)	

		be formulated due to their strong impact on radiation balances. Evaporation (and transpiration): observation of evaporation needs to cover the whole spectrum from optical to thermal range and the retrievals need to consider the involved essential physical and biochemical processes (coupling water, energy, and carbon cycles). Transfer of water through the soil, roots, stem and leaves can be quantified by measuring and simulating **water potential** and link the change of water potential to external forcings of radiation, precipitation and meteorology, the growth of above and below ground plant	Evaporation: hm ~km at diurnal (half hourly) steps for **water potential** as well as full spectrum observation (incl. fluorescence)	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical, TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	

		biomass, and the extraction of water by the growing roots. The direct observables are soil moisture, vegetation water content and near surface atmospheric water content. Discharges: Observation of surface water discharges by the SWOT mission (surface water levels and the slopes of water elevation in large rivers) by its Ka-band SAR interferometry; No currently obvious viable means for observation of groundwater discharges (from one river basin to another, or from river basins to ocean) but analysis of GRACE and GRACE-FO data and higher resolution	Discharges: 10~100m horizontal, ~cm vertical and quasi instantaneous in time	In-situ measurements (collected by GRDC-Global Runoff Data Center); Retrieval algorithms; Model simulations	

		observation may reveal future potential of such observation.			
	C). 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)	Regional climate systems and local topographical and land use features dependent precipitation extremes (intensity-duration- frequency) Flood extent and frequency and severity of floods (return period);	Measure precipitation intensity at mm water depth per half hour (currently at 3-hourly) and its duration of different occurrence; Mapping post flood extents by high resolution optical and SAR sensors (hm~km at daily-weekly steps);	GPM-IMERG data series for global scale applications; integration of other observation techniques (e.g. geostationary observations and microwave links from commercial telecommunications, for local precipitation extremes; validation by dedicated in-situ observation (ground radar and microwave links) Embedding a hydrological model in an ESM for prediction of precipitation extremes and floods at the same time; Integrating real time space observation of	

			Estimation of frequency and severity of floods using precipitation (extremes) in a hydrological model.	these events into an ESM by means of data assimilation and machine learning for a true DTE	

Narrative: To what extent can we predict the Earth's water cycle closure in space and time?

In order to determine the extent to which Earth's water cycle can be predicted, observation and modeling capabilities are needed to be able to quantify the reservoirs (where is the water on Earth?), the fluxes (how it moves?) and extremes (what are the largest magnitudes and when and where do they occur?).

Quantitative progress need to be made in terms of the following specific questions:
1). **Reservoirs:** What is the rate of expansion of the fast and slow reservoirs (in the atmosphere, on the land surfaces and in the oceans), what is its spatial character, what factors determine this and to what extent are these changes predictable?

The fast reservoirs include atmospheric water vapor, soil moisture, surface water (in lakes, man-made reservoirs and rivers), and vegetation water content in terms of changes from diurnal to daily and weekly time scale; other reservoirs that may be considered the slow changing ones include groundwater, snow, glaciers and ice caps, ice sheets and sea ice, and permafrost. The impacts of changes in these slow reservoirs on water cycle dynamics usually manifest at a longer time scale from weekly to seasonal and multiannual scales. Other relevant water cycle related geophysical variables are sea level and sea surface salinity.

The geophysical variables of interest in the atmosphere are the distribution of atmospheric water vapor in the troposphere and stratosphere and its changes in space and time in response to atmospheric temperature (profile). Column water vapor products have been generated from observations in microwave, infrared, optical, and UV spectrum. Accurate observation of the profile of atmospheric relative humidity (from land and ocean surface up to lower stratosphere) may be achieved by coupling the observation of humidity and temperature to generate a consistent dataset. Datasets on atmospheric temperature and humidity profiles have been identified as a critical issue for more than 30 years (WMO, 2012).

On the land surface, soil moisture, groundwater, surface water (in lakes, reservoirs and rivers), and vegetation water (water storage in biosphere, e.g. vegetation water content and their diurnal and seasonal changes) are the needed geophysical variables.

The observations of soil moisture have made major advances by the proven capability of passive microwave observations provided by SMOS and SMAP missions. Although other observation have also been used to retrieve soil moisture (e.g. combined with SAR and scatterometer data, e.g. Bauer-Marschallinger, 2018; and the use of auxiliary data by means of machine learning, e.g. Han et al., 2023), coarse scale microwave observations (ASCAT, SMOS and SMAP) also provide relevant estimates of vegetation water content (in terms of vegetation optical depth, e.g. Frappart et al., 2020).

The evaluation of global satellite soil moisture products primarily relies on in-situ data from contributing networks coordinated and quality controlled by the International Soil Moisture Network (ISMN) (Dorigo et al., 2023).

The observables relevant to soil moisture are brightness temperature in L-band (e.g. SMOS and SMAP, and multi-frequencies in the upcoming CIMR), backscattering coefficient in C-and (SAR and ASCAT) and L-band (e.g. ROSE-L). Next advances can be expected by generating higher resolutions data products at the resolution of kilometer scale (e.g. 1 - 10 km) at daily to diurnal time steps. Given the proven capabilities of passive microwave observation at L-band by SMAP and SMOS, a future higher resolution L-band space mission would be highly desirable.

For groundwater, observations from mass change missions like GRACE and GRACE-FO (Rodell and Reager, 2023) have made the most impact in detection of groundwater depletions. A new mission with this technology but much improved resolution in space and time will further advance the observations of terrestrial water storage.

For monitoring surface water storages, the extent of surface water bodies and the changes in water levels need to be determined. Optical and SAR sensors can effectively measure the surface water extent, while radar altimetry and interferometry have successfully measured water levels. The recent launch of the Surface Water and Ocean Topography (SWOT) mission is expected to make major advances in observation of rivers, lakes and inundation plains.

The observation of snow, glaciers and ice caps, ice sheets and sea ice, and permafrost have been conducted by using optical and SAR and passive microwave sensors. A variety of challenges exist in observing each of these geophysical variables. Advances in sensing technology, e.g. those of SMOS and SMAP capabilities but with higher resolution in space can be expected to help generate the much needed datasets.

2). **Flux exchanges**: To what extent are the fluxes of water between Earth's main reservoirs changing and to what extent in space and time scale can these changes be predicted?

The flux exchanges between the different reservoirs on Earth can be characterized by precipitation, evaporation, water vapor convergence and surface and groundwater discharges. The observation of precipitation is often considered together with the observation of clouds because of the tight links between clouds and the precipitation processes. CloudSat and EarthCARE on polar orbits provide full global coverage of vertical profiles of clouds and light and solid precipitation, while the Global Precipitation Measurement (GPM) mission have been providing solid and liquid precipitation observations that have enabled to generate consistent global precipitation dataset (e.g. the IMERG, half hourly and 0.1°x0.1° and aggregates at longer time scale). The observables for clouds and precipitation are optical properties in the optical and thermal spectrum and microwave brightness temperature and radar backscatters. New and novel observations, for example for marine stratocumulus, may be formulated due to their strong impact on radiation balances.

The observation of evaporation (including transpiration which is technically the water transpired by plants from soil to the atmosphere) has been approached so far by semi-empirical approaches, largely because it has been difficult to observe near surface water vapor gradients from space which are needed to quantify evaporation (such as done by in-situ observation using eddy covariance and Bowen ratio methods). However because evaporation couples water cycle and energy cycle over water surfaces and water, energy and carbon cycles over vegetated surfaces, major progress can be made in quantifying water cycles by achieving better observation of evaporation. Due to the aforementioned coupling, the observation of evaporation needs to cover the whole spectrum from optical to thermal range and the retrievals need to consider the involved essential physical and biochemical processes.

For observation of surface water discharges, the SWOT mission is expected to make major advances, thanks to its ability to observe surface water levels and therefore the slopes of water elevation (which can be translated to flow rates) in large rivers by its Ka-band SAR interferometry technology. There is currently no viable means for observation of groundwater discharges (from one river basin to another, or from river basins to ocean), however analysis of GRACE and GRACE-FO data and higher resolution observation may reveal future potential of such observation.

3). **Extremes in precipitation and floods:** How will local rainfall and its extremes change under climate change across the regions of the world? And what are the associated flood extremes (frequency, extent and severity)?

Precipitation extremes are determined by both regional climate systems and local topographical and land use features. While the GPM-IMERG data series are the state-of-the-art for global scale applications, integration of other observation techniques (e.g. geostationary observations and microwave links from commercial telecommunications, see e.g. Kumah et al., 2022) may provide the much needed local information for observing the precipitation extremes. While the flood extent may be observed post floods by high resolution optical and SAR sensors, the frequency and severity of floods must be estimated using precipitation (extremes) in a hydrological model. The embedding of a hydrological model in an Earth System Model can enable the prediction of precipitation extremes and floods at the same time. When real time space observation of these events can be integrated into such an ESM by means of data assimilation and machine learning enabled by High Performance Computing, a true Digital Twin Earth can be created for these tasks.

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CSQ-43

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models
What are the main coupling determinants between Earth's energy, water and carbon cycles and how accurately can we predict the forcings and feedbacks between the different components of the Earth system?	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. A). Advance f**orcing-feedback understanding**: What are the main climate forcings and feedbacks formed by energy, water and carbon exchanges?	All variables in coupling of the energy and water cycles with the carbon cycle: observation and description of photosynthesis in response to changes in temperature, CO_2 concentration and water stress	Field scale (hm -km) at half hourly time step; Better than 10% uncertainty (currently 20%) in fluxes (sensible, latent heat, and carbon fluxes – Gross Primary Productivity and Net Ecosystem Exchange)	Retrieval algorithms for reflectance (albedo), vegetation parameters, LST, fluorescence, and SM, VWC, WV (profile of relative air humidity); Coupled model of energy, water and carbon process in ESM and DTE (coupled surface and atmospheric models); Validation by in-situ flux observations (e.g. Fluxnet)
	B). Quantify **role of surface and UTLS forcings in ABL processes**: - role of sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere (i.e., horizontal advection and upper troposphere - lower stratosphere (UTLS) exchanges)	Surface observables: same as above; UTLS observable: T, P, u, q (temperature, pressure, wind and specific humidity)	UTLS: km – 10km at half hourly step profile (T,P, u, q)	Validation by radiosoundings; Reanalysis based on data assimilation

	C). Quantify **circulation controls:** influence of the large-scale circulations of the atmosphere and oceans on exchanges between water, energy and carbon	Simultaneous observation of surface and atmospheric variables: radiation fluxes, LST, SM as well as clouds and precipitation patterns	10 – 100km at half hourly step	Comparison to reanalysis; CDR (climate data records)
	D). Quantify **land-atmosphere interactions**: What are the role of land surface-atmospheric interactions in the water, energy and carbon budgets across spatiotemporal scales?	Multiscale observations of radiation, heat, water and carbon fluxes (H, LE, CO2 - sensible, latent and carbon fluxes) and surface states (albedo, LST, LST, SM, VWC)	hm – 10km at half hourly step	Comparison to 3D lidar observation at super observation sites; LES (large eddy simulation); ML algorithms

Narrative: What are the main coupling determinants between Earth's energy, water and carbon cycles and 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.

The coupling of the energy and water cycles with the carbon cycle need 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 for devising adaptation alternatives to these changes.

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CSQ-44

Question	**Knowledge Advancement Objectives**	**Geophysical Observables**	**Measurement Requirements**	**Tools & Models**
3. How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?	A). Quantify **anthropogenic forcing of continental scale water availability**: extent to which the changing greenhouse effect modified the water cycle over different regions and continents	Observables: land cover changes (at seasonal to annual scale), changes in water levels in lakes and man-made reservoirs (at weekly to seasonal scale), as well as irrigated areas.	10-100km at seasonal and annual steps	Time series analysis of observation; Scenario simulations with coupled ESM models; Use of DTE for decision support
	B). Detect **water management influences:** extent to which water management practices and land use changes (e.g., deforestation) modified the water cycle on regional to global scales	Estimate the water used for irrigation by estimating the cumulative difference between evaporation and precipitation of an area.	1km at daily-weekly step	Time series analysis of precipitation and evaporation products; Comparison of observation products to reanalysis
	C). Quantify **variability and trends of water availability:** effects of water and land use and climate changes on the variability (including extremes) of the regional and continental water cycle	Irrigation water use by extracting groundwater by GRACE observations (depletion of groundwater levels for large regions).	10km at weekly – monthly step	Availability of management data and coupled water cycle modelling (incl. groundwater, SM, discharge and evaporation and precipitation)

Narrative: How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?

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.

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 lynch-pinning 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.

Diurnal observations appear necessary to observe water potential at scales of half-hourly to hourly in time and kilometer to hectometer 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).***

(Full text on Water Cycle)

I). Societal relevance of water cycle

Viewed from space, the most striking feature of our planet is the water. In liquid and frozen form, water covers 75% of the Earth's surface and in gas form it fills the sky with clouds. Water is practically everywhere on Earth, from inside the planet's crust to inside the cells of the human body (NASA). The water cycle describes where water is on Earth and how it moves. Water is stored in the ocean, in the atmosphere, on the land surface, and below the ground as a liquid, a solid, or a gas. Water moves between the places where it is stored, and at large scales, through watersheds, the atmosphere, and below the Earth's surface. Water moves at very small scales too. It is in humans, plants, and all other organisms. Human activities impact the water cycle, affecting where water is stored, how it moves, and how clean it is (USGS).

The impacts of climate change on humans occur primarily through changes in the water cycle and the cycling of water is intimately linked with energy exchanges among the atmosphere, ocean, and land (including biosphere) that determine the Earth's climate and cause much of natural climate variability. "Water is at the heart of both the causes and effects of climate change." (NRC, 1999). The cycling of water through the biological systems is mainly in the way of photosynthesis by which plants, algae and cyanobacteria use sunlight, water, and carbon dioxide to create oxygen and energy in the form of carbohydrate. Photosynthesis provides the oxygen, food and energy needed to maintain animal life on the present Earth system and powers 99 percent of Earth's ecosystem. It is therefore through photosynthesis that Earth's water, energy and carbon cycles are coupled in terms of forcings and feedbacks. Recent droughts and floods in Europe have highlighted the urgency in observing, simulating and predicting, and adapting to the changes in the water cycle.

A few examples of recent droughts and floods in Europe

During the summer of 2022, parts of Europe experienced drought conditions exacerbated by heat waves, which was suggested and confirmed to be Europe's worst drought in 500 years. The drought had serious consequences for hydropower generation and the cooling systems of nuclear power plants, as the drought reduced the amount of river water available for cooling. Agriculture in Europe was also negatively affected by the drought (wikipedia).

While the Netherlands is known for its water management infrastructure, the extreme droughts of 2018-2020 in the Netherlands still induced huge economic damages in agricultural production, disrupted river navigation and damaged buildings and unique nature. The drought-related damage in 2018 alone was estimated between 900 and 1,650 million Euro (Kramer et al., 2019) and as a result the minister of agriculture has established an action programme for climate adaptation in agriculture (LNV, 2020).

In July 2021, several European countries were affected by severe floods. Some were catastrophic, causing deaths and widespread damage. At least 243 people died in the floods, including 196 in Germany, 43 in Belgium, two in Romania, one in Italy and one in Austria. The floods are estimated to have cost up to 2.55 billion Euro in insured losses, with the total damage costs being much higher, at a minimum of €10 billion (wikipedia).

II). Science questions that are directly relevant to European policy making

The knowledge and capability in observing, analyzing and predicting water cycle changes are directly relevant to societal needs related to water use, prevention of damages by and adaptation to extremes manifested in floods, droughts and fires. In addition to ensuring water security for drinking water and industrial and environmental water use, water availability is most critical to food security because ca. 80 percent of freshwater resources are used in agricultural irrigation. Quantification of carbon sequestration capacity of land and oceans will also contribute to the Paris Agreement and EU Green Deal and Digital Europe Programme and provides scientific foundation for implementing other EU initiatives such as 'carbon farming' and 'farm to fork'.

Despite the advances in our knowledge about the Earth's water cycle, it remains extremely challenging to accurately observe, explain, simulate and predict water availability and extremes (in the form of floods and droughts), such that our societies can adequately plan, construct, manage and adapt our infrastructure and management systems to ensure sufficient water availability (for domestic use, industrial use and irrigation and environmental use) and to prevent and reduce such adverse climate change impacts (storms and floods, droughts, and forest fires and heat waves). The figure below illustrates the challenges in simulating the occurrence of droughts by the state-of-the-art Earth System Models (ESMs).

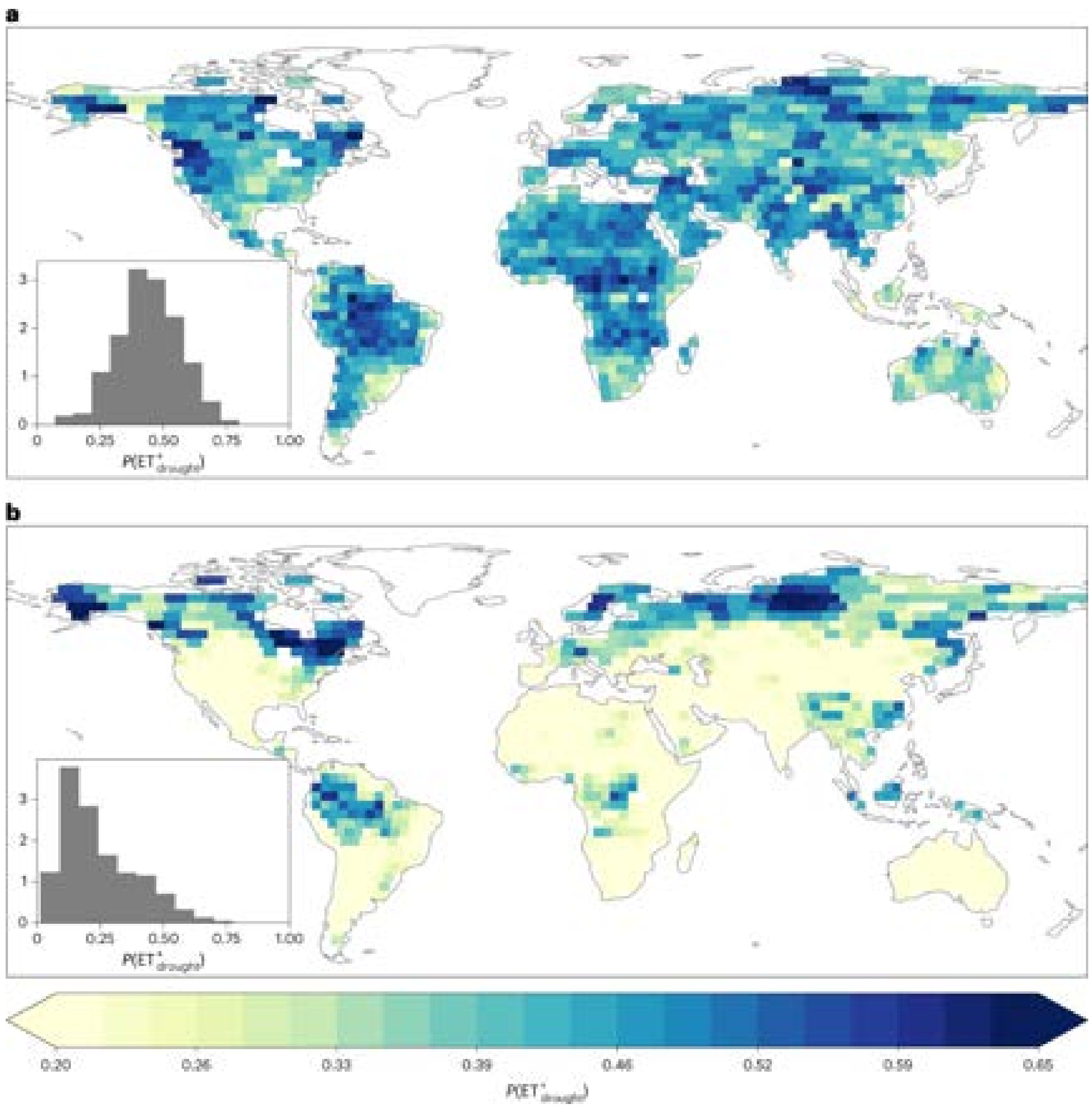

Figure 1. CIMP6 ESMs significantly underestimate the probability of drought-driven increases in ET. *a) Observed p(ET+$_{drought}$) during droughts between 2003 and 2020, b) p(ET+$_{drought}$) based on the CMIP6 ESM ensemble mean. Insets in a) and b) show probability density function (PDF) of each location's p(ET+$_{drought}$) across the globe (Zhao, et al., 2022).*

To this end, the major scientific questions that need to be answered according to the Global Energy and Water Exchanges Project of the World Climate Research Programme (GEWEX, 2021; Stephens, et al., 2023) are as follows:

1. To what extent can we predict the Earth's water cycle closure in space and time?

2. What are the main coupling determinants between Earth's energy, water and carbon cycles and how accurately can we predict the forcings and feedbacks between the different components of the Earth system?

3. How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?

III). Water cycle closure

The water cycle (also known as the hydrological cycle) is a biogeochemical cycle that describes the continuous movements and changes of water on, above and below the surface of the Earth. The water cycle closure can be written for a given region as:

$$\delta = v + \frac{dC_A}{dt} + P - ET - R + WT + \frac{dC_T}{dt} \tag{1}$$

$$\frac{dC_T}{dt} = \frac{\partial(SM+GW+SW+VWC+SWE+PI)}{\partial t} \tag{2}$$

Which include the **Fluxes**, v is the atmospheric water vapor convergence (or divergence, i.e. net flux of water vapor to the said region, which may be estimated as $\frac{dC_A}{dx}$ for the selected time period); P is precipitation; ET is evaporation/transpiration; R is runoff/discharge; WT is human water transfer, and the **Storages**, C_A is the atmospheric water vapor content; C_T is the total terrestrial water storage which may include, SM - soil moisture; GW - Ground Water; SW - Surface Water; VWC - Vegetation Water Content; SWE - snow water equivalent and PI - permanent ice (glaciers; ice sheet; permafrost) (x is the space coordinate, and t is the time variable; the fluxes can be expressed in water depth in e.g. mm per unit time and the storages in water depth in mm; runoff and human water transfers are commonly expressed as volume per unit time, but can be converted to water depth by dividing the surface area of interest).

To close the water cycle is to minimize δ for any given region and time period (δ is zero when the water cycle is closed). Assuming that the water cycle closure is achieved for a given region on land, the atmospheric part of water budget can be written as

$$v + \frac{dC_A}{dt} = -P + ET \tag{3}$$

Eq (3) indicates that the water vapor convergence (or divergence) and the changes in atmospheric water vapor content is balanced by precipitation out and evaporation into the atmosphere. Observation of the exchanges of water vapor in space ($v = \frac{dC_A}{dx}$) between the said region and its surroundings and water vapor changes in time within the region ($\frac{dC_A}{dt}$), as well as observation of precipitation (P) and evaporation (ET) will enable the closure of this part of the water cycle budget.

Similarly the terrestrial part of the water budget for a given region can be written as

$$\frac{dC_T}{dt} = -P + ET + R - WT \quad (4)$$

Which says that the changes in the total terrestrial water storage in time is balanced by the difference between the fluxes of precipitation, evaporation, discharge and human water transfer. However it is important to remember that human water transfer can significantly influence the amount of evaporation in arid and semi-arid regions where precipitation is usually very limited. Human water transfer may take place between regions (water diversion from one region to another) or by changes in storages (extraction of groundwater). This is usually to satisfy water needs for irrigation and other water uses. As a consequence, the different storage terms are also impacted (e.g. soil moisture, ground water and surface water), and these changes may also influence the precipitation through water (vapor) recirculation (i.e. the evaporated water vapor is condensed and falls back to the same region as precipitation).

For the whole earth system the water cycle is closed (meaning the total amount of water on Earth is conserved)

$$\frac{dC_A}{dt} + P - ET + \frac{dC_T}{dt} = 0 \quad (5)$$

or

$$\frac{dC_A}{dt} + \frac{dC_T}{dt} = ET - P \quad (6)$$

which says the change in the total storage in the atmosphere, ocean and land in time is equivalent to the difference in evaporation (and transpiration) and precipitation in the whole Earth system.

From an observational point of view, we can now directly observe the changes in storage ($\frac{dC_A}{dt} + \frac{dC_T}{dt}$) by GRACE and GRACE-FO missions, the precipitation (P) by the GPM and other microwave and optical missions, while the observations of evaporation (ET) can only be achieved via indirect retrievals that relay on other geophysical variables (radiation, albedo, land surface temperature and other vegetation properties, as well as meteorological variables). It is important to realize that the different observation technologies have very different spatial and temporal coverage and the resolved water cycle closure can only be assessed at the lowest spatiotemporal resolution. This is currently determined as 3° x 3° in space (ca. 300km by 300km at equator) and bi-monthly time intervals, determined by the characteristics of the GRACE and GRACE-FO missions. Downscaling techniques (data assimilation, or in a Digital Twin Earth framework) can then be used to downscale the water cycle components to higher spatiotemporal resolutions. It is also important to recognize that evaporation (and transpiration) is the variable that links the water cycle to the energy cycle over water and unvegetated surfaces, and it links the water cycle, energy cycle and carbon cycle over vegetated lands. By observing the water levels in rivers, we may estimate the discharges (R) by linking the water level and rivers cross sections to discharges (via so-called rating curves that convert water levels to water flow volumes). Altimeters and interferometers on missions like Sentinel-3 and SWOT shall help to improve the estimation of discharges. The more challenging component to observe is the human water transfer (WT), diversion of water from reservoirs and lakes may be estimated by altimeters, while the extraction of groundwater may be estimated as a consequence of changes in storage by GRACE and GRACE-FO missions. Next we shall discuss in more detail each of the science challenges.

IV). Geophysical variables, observables and observation methods

1. To what extent can we predict the Earth's water cycle closure in space and time?

In order to determine the extent to which Earth's water cycle can be predicted, observation and modeling capabilities are needed to be able to quantify the reservoirs (where is the water on Earth?), the fluxes (how it moves?) and extremes (what are the largest magnitudes and when and where do they occur?).

Quantitative progress need to be made in terms of the following specific questions:
1). **Reservoirs:** What is the rate of expansion of the fast and slow reservoirs (in the atmosphere, on the land surfaces and in the oceans), what is its spatial character, what factors determine this and to what extent are these changes predictable?

The fast reservoirs include atmospheric water vapor, soil moisture, surface water (in lakes, man-made reservoirs and rivers), and vegetation water content in terms of changes from diurnal to daily and weekly time scale; other reservoirs that may be considered the slow changing ones include groundwater, snow, glaciers and ice caps, ice sheets and sea ice, and permafrost. The impacts of changes in these slow reservoirs on water cycle dynamics usually manifest at a longer time scale from weekly to seasonal and multiannual scales. Other relevant water cycle related geophysical variables are sea level and sea surface salinity.

The geophysical variables of interest in the atmosphere are the distribution of atmospheric water vapor in the troposphere and stratosphere and its changes in space and time in response to atmospheric temperature (profile). Column water vapor products have been generated from observations in microwave, infrared, optical, and UV spectrum. Accurate observation of the profile of atmospheric relative humidity (from land and ocean surface up to lower stratosphere) may be achieved by coupling the observation of humidity and temperature to generate a consistent dataset. Datasets on atmospheric temperature and humidity profiles have been identified as a critical issue for more than 30 years (WMO, 2012).

On the land surface, soil moisture, groundwater, surface water (in lakes, reservoirs and rivers), and vegetation water (water storage in biosphere, e.g. vegetation water content and their diurnal and seasonal changes) are the needed geophysical variables.

The observations of soil moisture have made major advances by the proven capability of passive microwave observations provided by SMOS and SMAP missions. Although other observation have also been used to retrieve soil moisture (e.g. combined with SAR and scatterometer data, e.g. Bauer-Marschallinger, 2018; and the use of auxiliary data by means of machine learning, e.g. Han et al., 2023), coarse scale microwave observations (ASCAT, SMOS and SMAP) also provide relevant estimates of vegetation water content (in terms of vegetation optical depth, e.g. Frappart et al., 2020).

The evaluation of global satellite soil moisture products primarily relies on in-situ data from contributing networks coordinated and quality controlled by the International Soil Moisture Network (ISMN) (Dorigo et al., 2023).

The observables relevant to soil moisture are brightness temperature in L-band (e.g. SMOS and SMAP, and multi-frequencies in the upcoming CIMR), backscattering coefficient in C-and (SAR and ASCAT) and L-band (e.g. ROSE-L). Next advances can be expected by generating higher resolutions data products at the resolution of kilometer scale (e.g. 1 - 10 km) at daily to diurnal time steps. Given the proven capabilities of passive microwave observation at L-band by SMAP and SMOS, a future higher resolution L-band space mission would be highly desirable.

For groundwater, observations from mass change missions like GRACE and GRACE-FO (Rodell and Reager, 2023) have made the most impact in detection of groundwater depletions. A new mission with this technology but much improved resolution in space and time will further advance the observations of terrestrial water storage.

For monitoring surface water storages, the extent of surface water bodies and the changes in water levels need to be determined. Optical and SAR sensors can effectively measure the surface water extent, while radar altimetry and interferometry have successfully measured water levels. The recent launch of the Surface Water and Ocean Topography (SWOT) mission is expected to make major advances in observation of rivers, lakes and inundation plains.

The observation of snow, glaciers and ice caps, ice sheets and sea ice, and permafrost have been conducted by using optical and SAR and passive microwave sensors. A variety of challenges exist in observing each of these geophysical variables. Advances in sensing technology, e.g. those of SMOS and SMAP capabilities but with higher resolution in space can be expected to help generate the much needed datasets.

2). **Flux exchanges**: To what extent are the fluxes of water between Earth's main reservoirs changing and to what extent in space and time scale can these changes be predicted?

The flux exchanges between the different reservoirs on Earth can be characterized by precipitation, evaporation, water vapor convergence and surface and groundwater discharges. The observation of precipitation is often considered together with the observation of clouds because of the tight links between clouds and the precipitation processes. CloudSat and EarthCARE on polar orbits provide full global coverage of vertical profiles of clouds and light and solid precipitation, while the Global Precipitation Measurement (GPM) mission have been providing solid and liquid precipitation observations that have enabled to generate consistent global precipitation dataset (e.g. the IMERG, half hourly and 0.1°x0.1° and aggregates at longer time scale). The observables for clouds and precipitation are optical properties in the optical and thermal spectrum and microwave brightness temperature and radar backscatters. New and novel observations, for example for marine stratocumulus, may be formulated due to their strong impact on radiation balances.

The observation of evaporation (including transpiration which is technically the water transpired by plants from soil to the atmosphere) has been approached so far by semi-empirical approaches, largely because it has been difficult to observe near surface water vapor gradients from space which are needed to quantify evaporation (such as done by in-situ observation using eddy covariance and Bowen ratio methods). However because evaporation couples water cycle and energy cycle over water surfaces and water, energy and carbon cycles over vegetated surfaces, major progress can be made in quantifying water cycles by achieving better observation of evaporation. Due to the aforementioned coupling, the observation of evaporation needs to cover the whole spectrum from optical to thermal range and the retrievals need to consider the involved essential physical and biochemical processes.

For observation of surface water discharges, the SWOT mission is expected to make major advances, thanks to its ability to observe surface water levels and therefore the slopes of water elevation (which can be translated to flow rates) in large rivers by its Ka-band SAR interferometry technology. There is currently no viable means for observation of groundwater discharges (from one river basin to another, or from river basins to ocean), however analysis of GRACE and GRACE-FO data and higher resolution observation may reveal future potential of such observation.

3). **Extremes in precipitation and floods:** How will local rainfall and its extremes change under climate change across the regions of the world? And what are the associated flood extremes (frequency, extent and severity)?
Precipitation extremes are determined by both regional climate systems and local topographical and land use features. While the GPM-IMERG data series are the state-of-the-art for global scale applications, integration of other observation techniques (e.g. geostationary observations and microwave links from commercial telecommunications, see e.g. Kumah et al., 2022) may provide the much needed local information for observing the precipitation extremes. While the flood extent may be observed post floods by high resolution optical and SAR sensors, the frequency and severity of floods must be estimated using precipitation (extremes) in a hydrological model. The embedding of a hydrological model in an Earth System Model can enable the prediction of precipitation extremes and floods at the same time. When real time space observation of these events can be integrated into such an ESM by means of data assimilation and machine learning enabled by High Performance Computing, a true Digital Twin Earth can be created for these tasks.

2. What are the main coupling determinants between Earth's energy, water and carbon cycles and 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. More specific science questions can be formulated as follows.
1). **Forcing-feedback understanding**: What are the main climate forcings and feedbacks formed by energy, water and carbon exchanges?

2). **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 (i.e., horizontal advection and upper troposphere - lower stratosphere (UTLS) exchanges)?

3). **Understanding circulation controls:** To what extent are exchanges between water, energy and carbon determined by the large-scale circulations of the atmosphere and oceans?

4). **Land-atmosphere interactions**: What are 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 need 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 for devising adaptation alternatives to these changes. The importance of describing photosynthesis in a coupled dynamic water-energy-carbon system is illustrated in the following figures.

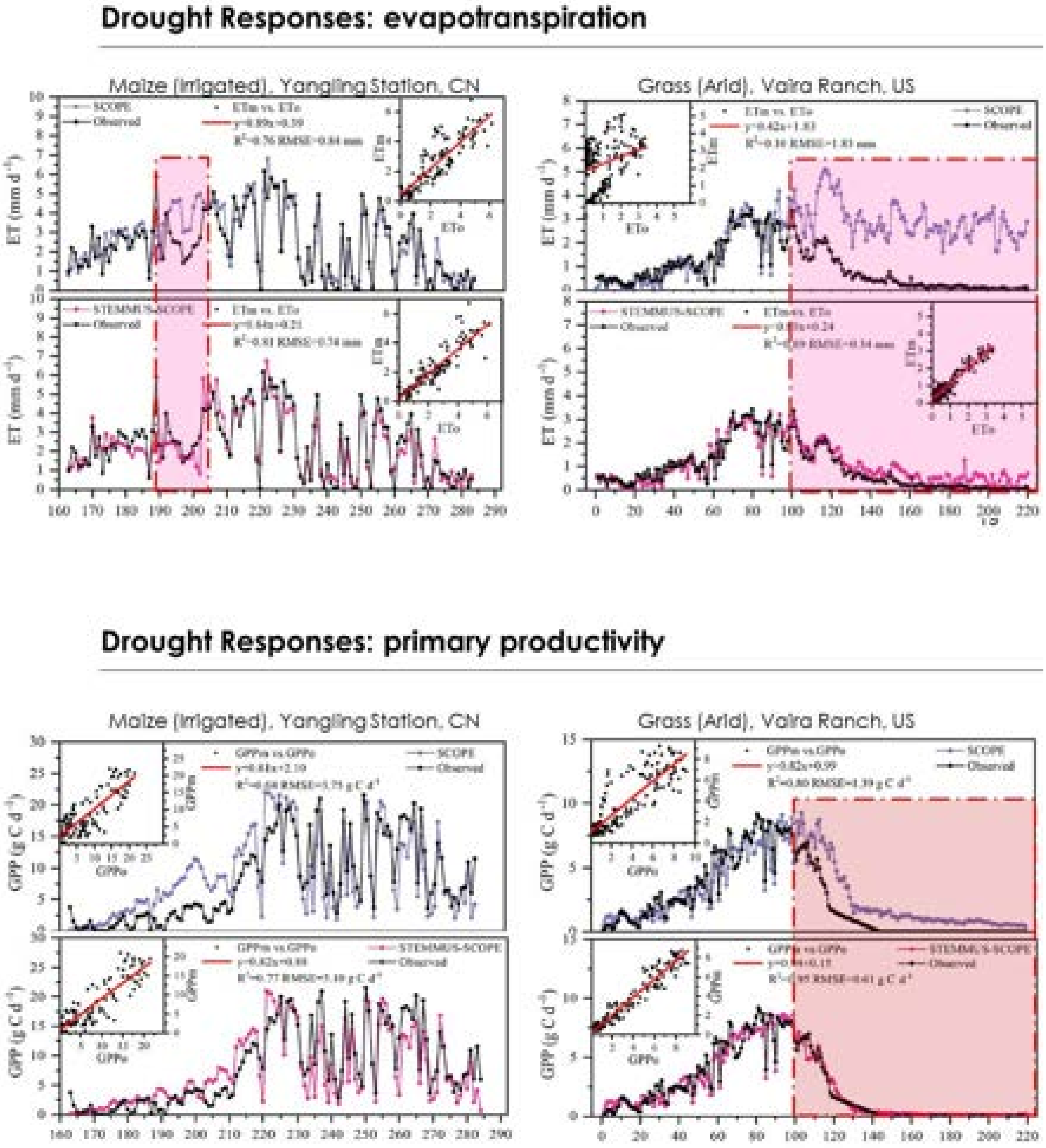

Figure 2. Simulations of drought responses in evaporation and transpiration (termed together as evapotranspiration, ET) and sequestration of carbon dioxide fluxes (gross primary productivity, GPP) of two sites: *one irrigated maize and another grassland in arid climate by two modelling systems (Wang et al., 2021).*

The modeling 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 modeling 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 achieved a much better fidelity compared to the observed fluxes. The major advances in the STEMMUS-SCOPE system are to describe 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 (in shoots and roots) and the extraction of water by the growing roots on the other. As such this dynamic system can be viewed as a digital twin that represents both the structure and function of the real water-soil-plant system and mimics the actual forcings and feedbacks. The STEMMUS-SCOPE also simulates and thus links satellite observables in the visible, infrared, and thermal spectrum (reflectance, leaf and soil temperatures and sun-induced fluorescence) to water-energy-carbon processes above- and below-ground and can be used to perform Observation System Simulation Experiments (OSSEs). The concept of digital twins is currently also pursued by WCRP in its new lighthouse activities and by the EU in the Destination Earth initiative (DestinE). These initiatives provide ample opportunities for integrating new EO observables into existing infrastructure for their best use in resolving the scientific questions related to water cycle identified in this note. They would also contribute to and be taken up by the CGMS-IESWG initiative (Coordination Group of Meteorological Satellites - the International Earth Surface Working Group) which aims to gather requirements specific to surface observations to enhance understanding and ability to monitor the components of the Earth system including land, vegetation, snow, ice, and coastal and open waters. It may be reasonably expected that the new capability demonstrated in Figure 2 can help improve the simulation capabilities of the CIMP6 ESMs as shown in Figure 1.

3. How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?

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. Specific questions need to be answered.

1). **Anthropogenic forcing of continental scale water availability**: To what extent has the changing greenhouse effect modified the water cycle over different regions and continents?

2). **Water management influences:** To what extent do water management practices and land use changes (e.g., deforestation) modify the water cycle on regional to global scales?

3). **Variability and trends of water availability:** How do water and land use and climate changes affect the variability (including extremes) of the regional and continental water cycle?

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.

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 lynch-pinning 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.
- Diurnal observations appear necessary to observe water potential at scales of half-hourly to hourly in time and kilometer to hectometer 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-45 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How can we improve estimates of the internal flow of energy within the climate system with respect to major uncertainties for equilibrium climate sensitivity evaluations?	A) Regional budget closure studies to further unravel regional uncertainties of surface observations, retrieval of energy flux and their parametrisation, and to allow for improved observational constraints for climate models	• Incoming solar (shortwave) radiation • outgoing reflected solar radiation outgoing thermal (longwave) radiation • surface temperature atmospheric temperature (vertical structure) • Radiative fluxes • Turbulent fluxes (e.g., Latent & sensible heat flux, evaporation, precipitation) • Ocean heat content • Atmospheric and oceanic planetary heat transport	• High-spatial resolution (e.g., , ¼°) • High-temporal resolution (e.g., daily, min. monthly) • Sustainability to improve climate change monitoring	Atmospheric & oceanic assimilation systems; Earth system models	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of CC prediction / climate models
	B) Study of cumulative regional cloud feedbacks, weighted by the global ratio of fractional coverage to evaluate the global cloud feedback	• Cloud properties (e.g., droplet concentrations, fractional coverage, vertical structure, type, height, Ice nucleating particles) • Water vapour, humitidy • Cloud liquid water path • Atmospheric temperature		Atmospheric assimilation systems Earths system models High-resolution cloud resolving models (CRMs) Large eddy simulations (LES) Aerosol reanalysis; multi-model ensembles (e.g., AEROCOM)	
	C) Study the causality in aerosol–cloud relationships, particularly for anthropogenic perturbations	• List above (cloud feedbacks) • Aerosols			

CSQ-45 Narrative

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., 2022). 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) (Raschke et al., 2016; Huang et al., 2019). 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} (Wild et al., 2017).

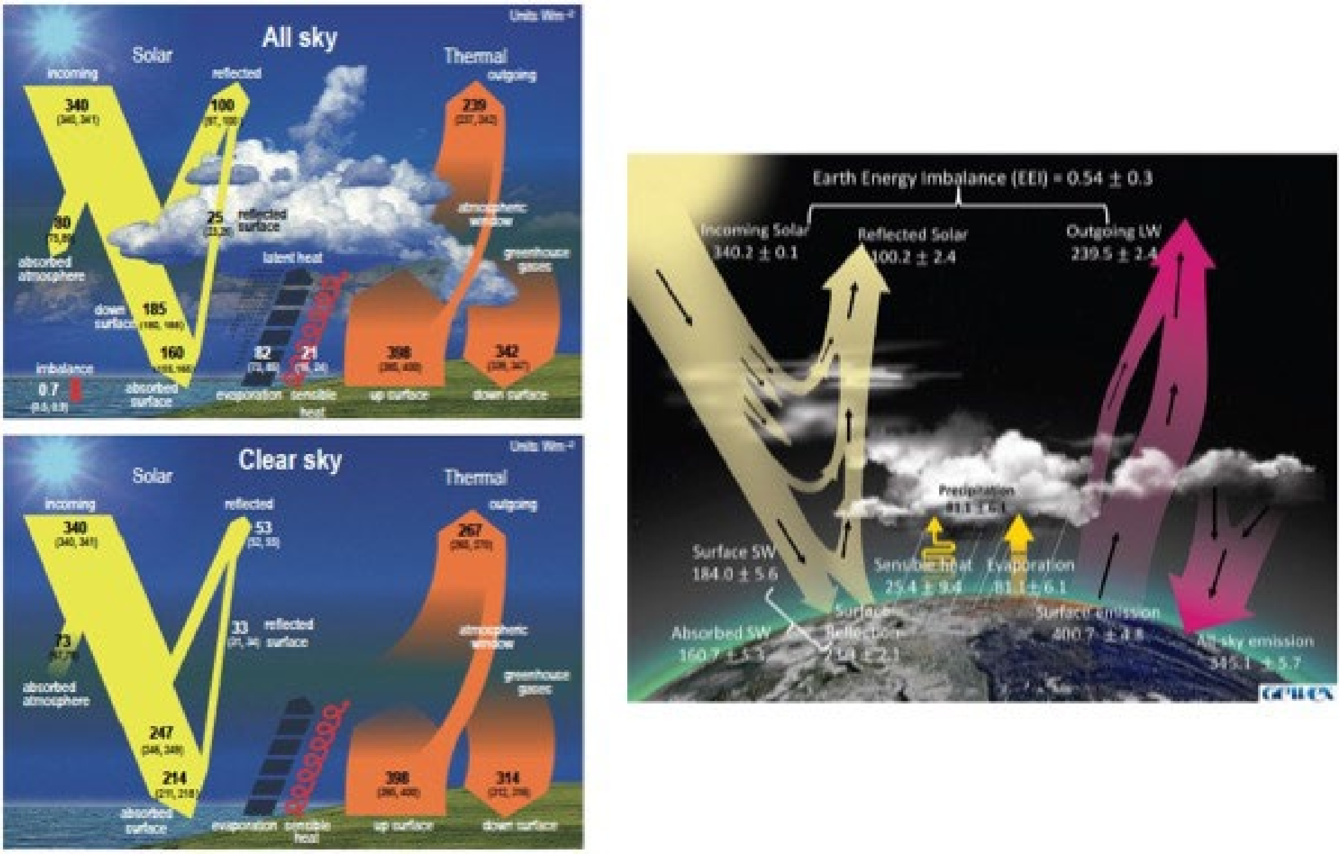


Fig. 1: *Schematic representation of internal flow of energy within the climate system for all sky (upper) and clear sky (lower) conditions (left panels) after Wild et al., 2020. Their difference is used to obtain the cloud radiative effect on Earth's energy budget. Right panel: mean annual fluxes of 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 (Loeb et al., 2014; L'Ecuyer et al., 2015; Kato et al., 2016), and associated uncertainties being area dependent with respect to the number of surface sites, regional uncertainty of surface observations (Kato et al., 2018; Previdi et al., 2015), the retrieval of flux-relevant meteorological variables, as well as from differences in the flux parametrizations (Yu, 2019). For example, uncertainties can reach up to 25 Wm^{-2} for latent heat and 5 Wm^{-2} for sensible heat over the ocean (Bentamy et al., 2017), 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 (Li et al., 2013; Wild et al., 2013; Boeke and Taylor, 2016; Wild, 2017, 2020; Zhang et al., 2018), often related to their representation of clouds (Trenberth and Fasullo, 2010; Donohoe and Battisti, 2012; Hwang and Frierson, 2013; Li et al., 2013; Dolinar et al., 2015; Wild et al., 2015).

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 (e.g., Wild et al., 2019, 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.

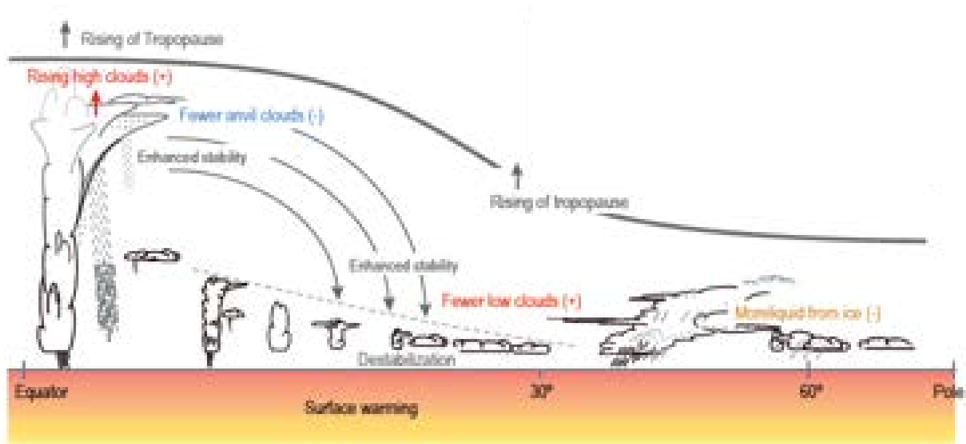


Fig. 2: *Schematic representation of cloud feedsbacks in different regimes from diverse cloud responses to surface warming. Adopted from Foster et al., 2021.*

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 (e.g., Gettelman and Sherwood, 2016; Boucher et al., 2013; Zhao et am., 2015; Sherwood et al., 2020), 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 (Stevens and Feingold, 2009). Multiple studies have found a positive relationship between cloud fraction and/or cloud liquid water pathway and aerosols (e.g., Nakajima et al., 2001; Kaufman and Koren, 2006; Quaas et al., 2009). 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).

CSQ-46 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How does the Earth energy imbalance and Earth heat inventory changes 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 to unravel how much and where surplus heat from climate change is going	• Ocean heat content (direct, indirect: ocean mass & sea level) • Land heat content (continental, permafrost and inland water bodies) • Atmospheric heat content • Heat available to melt ice (Ice shelf, sea ice, glaciers, snow cover)	• High-spatial resolution (e.g., ¼°, min. 1°) • High-temporal resolution to capture from extremes to long-term change (e.g., daily) • Multi-satellite approach • Multi-product approach (in situ, satellite, model)	Earth system models Atmospheric & oceanic & coupled assimilation systems	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of CC prediction / climate models (validation, parametrization, detection & attribution)
	B) Global budget closure studies for the global energy budget relation linking planetary heating, effective radiative forcing, surface temperature response and climate sensitivity to take stock on the long-term change in the Earth energy imbalance, further tackle underlying uncertainties.	• Net flux at the top of the atmosphere (incoming & outgoing radiation) • Effective radiative forcing • Climate sensitivity (indirect observed) • Earth heat inventory (see above)			
	C) Study the impact and causality of impacts of a changing Earth energy imbalance over time on planetary warming and associated implications for Earth system variability and change.	• Both lists above (inventory & constraint approach) • Ocean change (sea level, hydrography, carbonate system, mass) • Atmosphere change (hydrography incl. water vapor, radiative & turbulent fluxes, circulation) • Land (hydrography, incl. soil water, radiative & turbulent			

		fluxes, subsidence & erosion monitoring) • Cryosphere (Ice sheets, Sea ice, glaciers, snow cover)			

CSQ 46 Narrative

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. 2a) 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. 2b). Moreover, a quantification of the Earth heat inventory is also relevant for climate model constraint approaches, validations, and unraveling sources of uncertainties in the calculations such as for example on effective climate sensitivity (Gregory et al., 2002; Mauritzen and Roegner, 2020; Rugenstein et al., 2020). 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).

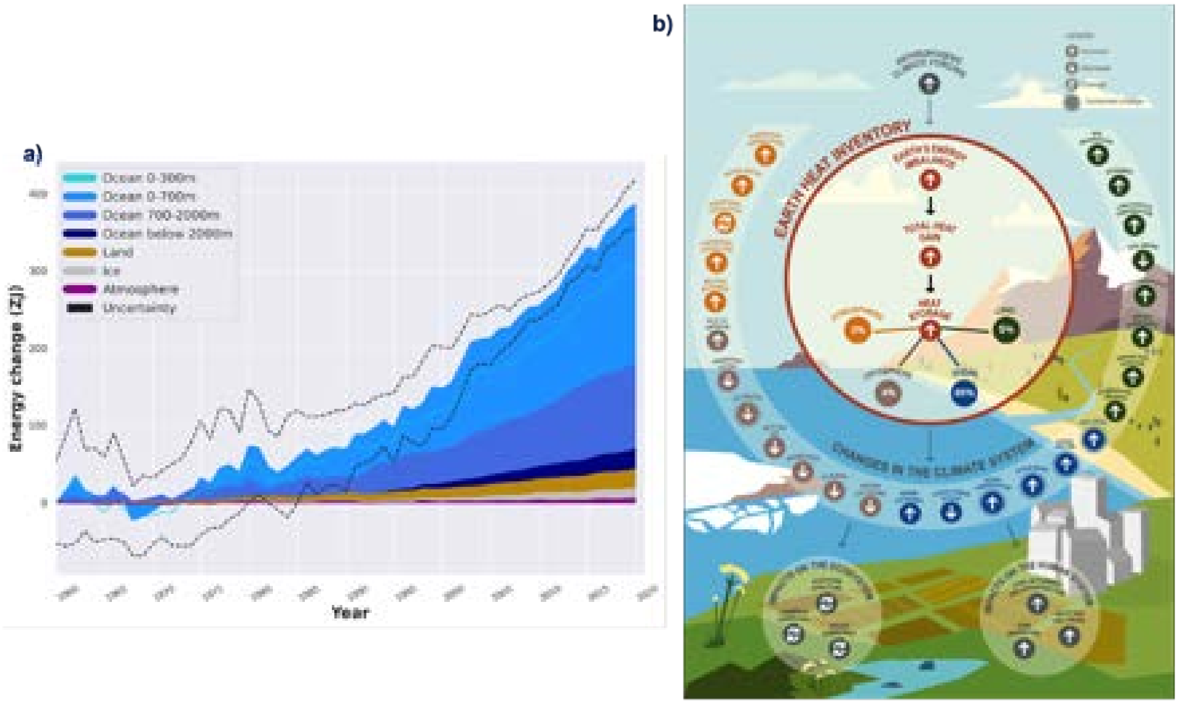


Figure 2: a) *Total Earth system heat gain in ZJ (1 ZJ =10^{21} J) relative to 1960 and from 1960 to 2020, with a total heat gain of 381±61 ZJ over the period 1971–2020, which is equivalent to a heating rate (i.e., the EEI) of 0.48±0.1 W m^{-2} applied continuously over the surface area of the Earth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

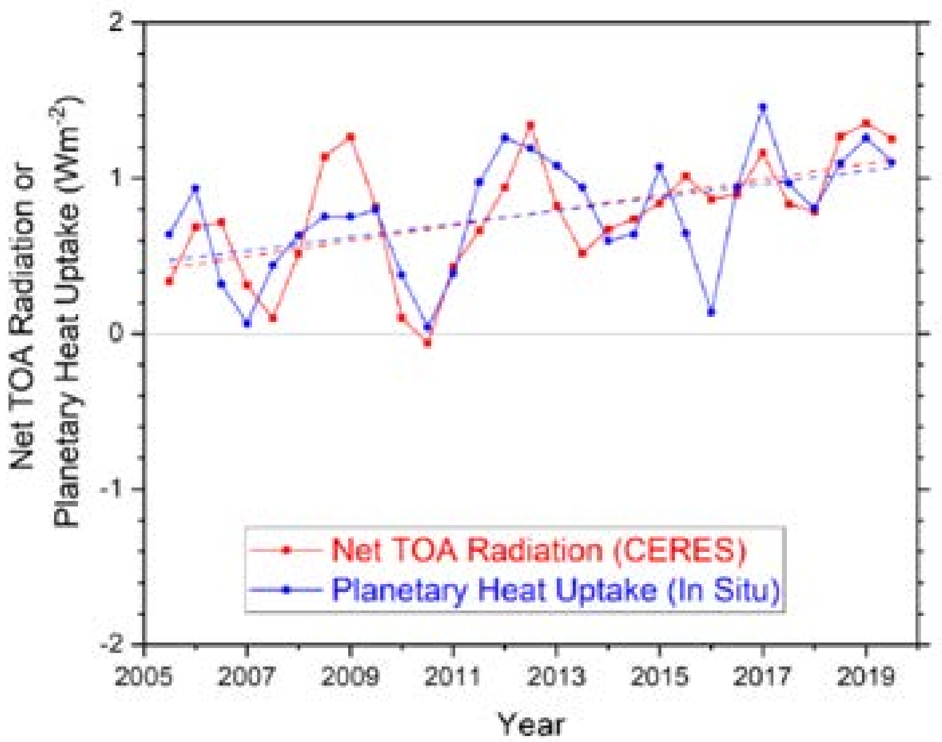


Figure 3: Comparison of overlapping one-year estimates at 6-month intervals of net top-of-the-atmosphere annual energy flux from CERES (red) and the uptake of energy by the Earth climate system. From Loeb et al., 2021.

As the ocean, the land, the cryosphere and the atmosphere warms from the anthropogenic surplus heat accumulated in the Earth system, 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. 2a) 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. 2b). Moreover, a quantification of the Earth heat inventory is also relevant for climate model constraint approaches, unraveling 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). 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).

CSQ-47 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
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 system cycles?	A) 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.	• Ocean heat content (direct, indirect: ocean mass & sea level) • Land heat content (continental, permafrost and inland water bodies) • Atmospheric heat content • Heat available to melt ice (Ice shelf, sea ice, glaciers, snow cover) • Net flux at the top of the atmosphere (incoming & outgoing radiation) • Effective radiative forcing • Climate sensitivity (indirect observed)	• High-spatial resolution (e.g., ¼°, min. 1°) • High-temporal resolution to capture from extremes to long-term change (e.g., daily) • Sustainability to improve climate change monitoring • Multi-satellite approach • Multi-product approach (in situ, satellite, model)	Earth system models Atmospheric & oceanic & coupled assimilation systems	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of CC prediction / climate models (validation, parametrization, detection & attribution)
	B) 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.				
	C) Identify and study feedbacks between climate change and the energy cycle, and between major Earth's system cycles	• List above • Recommendations for carbon & water cycle monitoring			

CSQ-47 Narrative

The Earth system cycles sustain life on Earth through the transfer, exchange & storage of heat, water, carbon, and other substances across all domains - the atmosphere, ocean, land, cryosphere and biosphere. Interactions are triggered and altered by natural variations of the climate system to maintain and balance the life-sustaining natural rhythm of the Earth system cycles, and are currently perturbed by human activities (IPCC, 2021), with adverse impacts on ecosystems and human systems (IPCC, 2022). The detection and attribution of this long-term impact is hence key, and systematic climate observations across all domains are the foundation for monitoring, understanding and predicting Earth cycles natural rhythm, their underlying processes, and future evolutions are needed to close knowledge gaps, and to support decisions on climate change action and sustainable development (Crisp et al., 2022; Dorigo et al., 2021; GCOS, 2021; von Schuckmann et al., 2020). With increasing warming, feedbacks between climate change and the Earth's system cycles become larger, intensifying related impacts and their severity (IPCC, 2021) (Fig. 4). An example of such feedback is the so-called ocean-heat carbon nexus: Carbon sinks set the airborne fraction, which sets radiative forcing that drives the additional heat in the atmosphere. The ocean sets the thermal response through ocean heat uptake. Ocean warming weakens the ocean sink, which increases the airborne fraction, and hence the radiative forcing (Forster et al., 2022). There are hence urgent advancements needed to enhance our understanding of both the natural variations and processes and the anthropogenic perturbation for the energy cycle, and the interference with other major Earth system cycles to accurately monitor, understand and predict the climate trajectory.

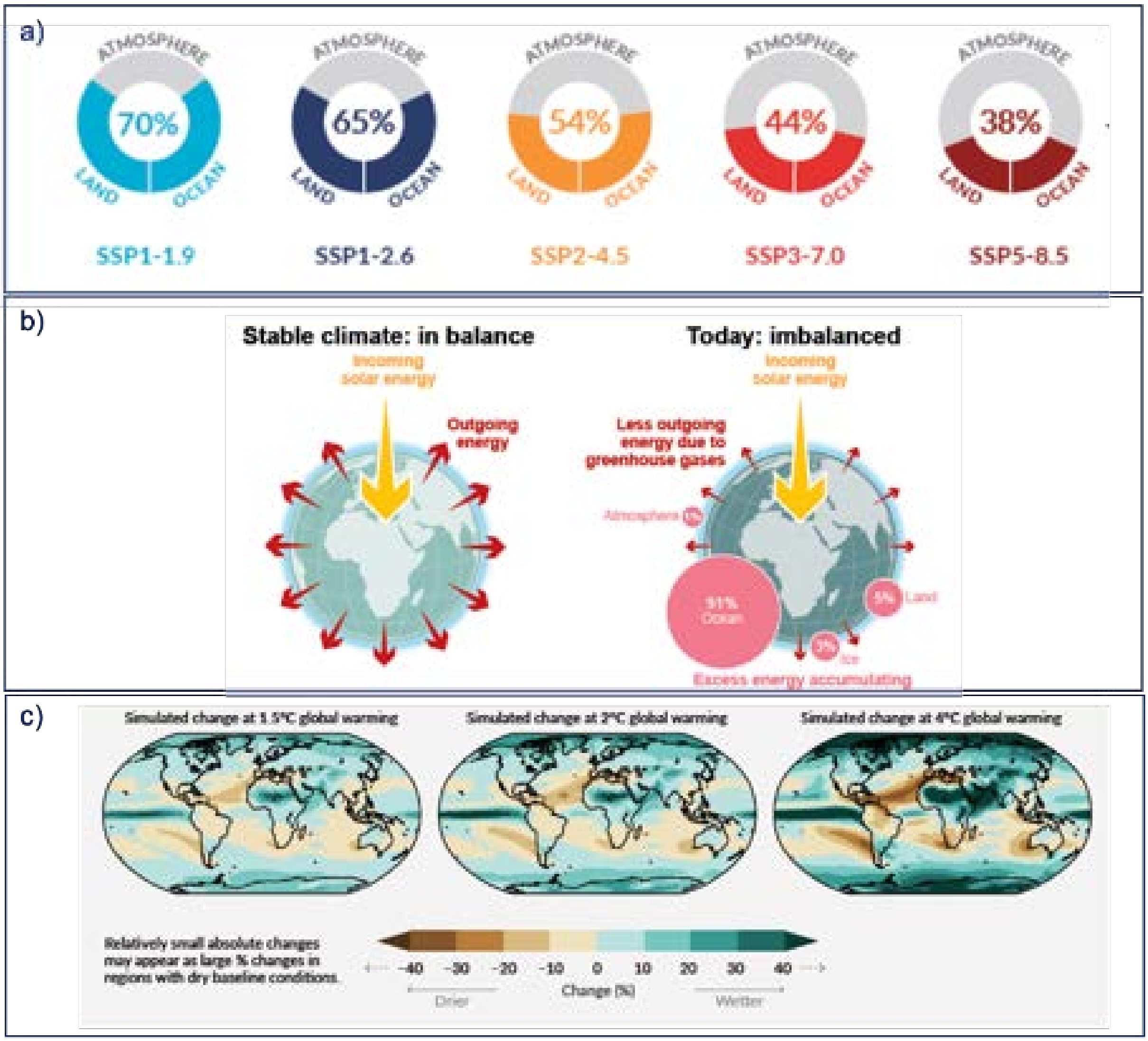


Figure 4: *Examples assessed in the IPCC 6th assessment report (Working Group I) of long-term pressure from climate change that affects the natural rhythm of all cycles across all domains. a) Carbon & nitrogen cycles: Human activity has caused an accumulation of well-mixed GHG (CO2: 47%, CH4: 156%, N2O: 23 %) (values above pre-industrial (1750) levels), lowering land & ocean sink dynamics. Figure adopted from* (IPCC, 2021)*(their Fig. SPM.7). b) Energy Cycle: Human activity has caused an imbalance of the natural energy flows, leading to an accumulation of surplus heat warming all domains: Ocean, Atmosphere, Land, Cryosphere Figure after* (Forster et al., 2022) *(Q&A 7.1). c) Water Cycle: Human activity has caused an intensification of the water cycle & is projected to further intensify, including its variability, global monsoon precipitation and the severity of wet and dry events (their Fig. SPM).*

CSQ-48 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	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) Thermodynamic coupling of the Earth's surface and the atmosphere to analyze critical feedback mechanisms, particularly for small-scale processes and variations to allow for improved weather and climate predictability B) Further develop better weather prediction on short time scales (2–12 weeks) aiming for advance warning of events such as heat waves and extreme precipitation, storms and long-term weather. C) Study the dynamic coupling for improved understanding of momentum and kinetic energy transfer between components of the Earth's system (ocean, atmosphere, cryosphere, land)	• Small scale (e.g., 25km resolution as discussed in Gentemann et al. 2021) measure of latent (e.g., wind speed, air-sea humidity difference) and sensible heat flux wind speed, air-sea temperature difference). • Near surface air temperature • Earth surface temperature, Sea surface temperature • Humidity • Wind (vector winds) • total ocean surface currents (e.g., 5km resolution as proposed under ODYSEA) • Ocean subsurface temperature • Planetary ocean and atmospheric heat transport • Net radiation	• High-spatial resolution (e.g., 25km) • High-temporal resolution to capture from extremes to long-term change (e.g., daily) • Sustainability to improve climate change monitoring	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

CSQ-48 Narrative

Regional scale exchanges at the interface between the Earth's surface and the atmosphere are a critical part of the global energy cycle, while fueling weather and climate variability and controlling important feedbacks such as for example through heat and moisture exchange (Bentamy et al., 2017; Cronin et al., 2019; Gulev et al., 2013). 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. 5a) to allow for predictability from mere days to weeks as these small-scale features can affect large-scale weather and climate (Penny et al., 2019; Saravanan & Chang, 2019). For example, better weather prediction on short time scales (2–12 weeks) provide advance warning of events such as heat waves and extreme precipitation (Vitart & Robertson, 2018; White et al., 2017), which are known to enhance and occur more frequently under global warming (IPCC, 2021), with severe impacts on human systems (IPCC, 2022a). 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. 5b). 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 (Bentamy et al., 2017), and remain a promising tool for regional energy budget closure approaches, process understanding and uncertainty evaluations (e.g., Loeb et al., 2022; Mayer et al., 2017; Trenberth et al., 2019).

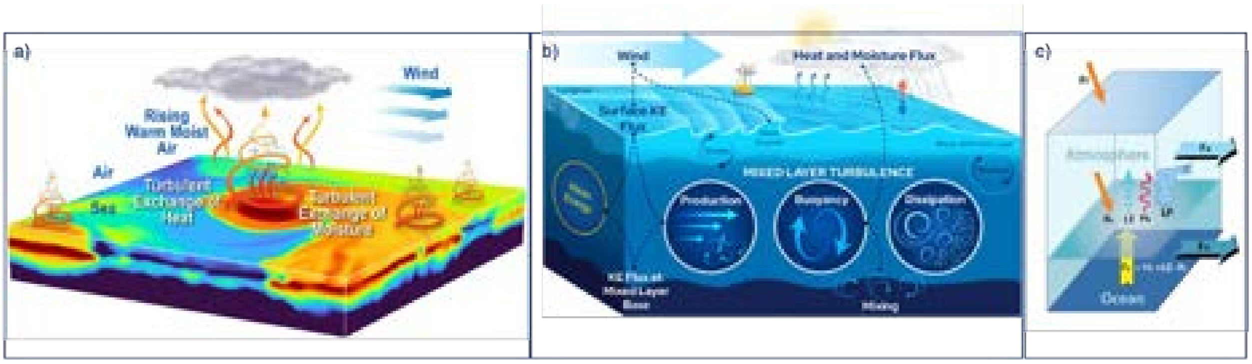


Figure 5: *a) Schematic representation of thermodynamic coupling and the role of turbulent fluxes at the air-sea interface. Figure from Genteman et al., 2021. b) Schematic representation of dynamic coupling highlighting surface processes and pathways for kinetic energy (KE) transfer between the atmosphere 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 tackeling 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.

CSQ-49 Summary

Question 1	**Knowledge Advancement Objectives**	**Observables**	**Measurement Requirements**	**Tools & Models**	**Policies / Benefits**
Could we improve the observations of active boundary areas dynamics?	A) Knowing better seismic cycles, both in spatial and time scale	• interseismic, deformation ground velocity • coseismic, deformation Ground velocity Acceleration • postseismic deformation Ground velocity • Map surface rupture events • Map surface temperature anomalies along fault zone	Observed area: 100km Spatial resolution 100-10 m Accuracy <10 mm Deformation on all 3 directions N-S, E-W, Vertical Surface temperature variations with high spatial (<30 m) and radiometric accuracy (0.1 k)	InSar Techniques Optical techniques to measure surface deformation. Seismic source models, models to estimate evolution of fault scarp with time Temperature-emissivity separation techniques, time series analysis using AI and machine leraining techniques	Improve the knowledge of earthquake risk in high populated areas Improve planning to strengthen infrastructures and buildings Study better evacuation plans
	B) improve systematic measurements of changes in topography associated to active tectonics	• Map active fault zones at different scales • Measure systematically change in topography associated to active tectonics	DEM and DTM at different scales High Spatial resolution <0,5 m Vertical resolution <1 m Update every 6 months	Photogrammetric Techniques Structure from motion techniques	

	C) Improve the study soil gas change and isotopic signatures during seismic sequences	• Methan(CH4), hydrogen (H2) carbon dioxide (CO2), radon in soils	CO2, CH4 flux Radon flux	FTIR, LIDAR, Optical imagery in SWIR- Dilatancy-Diffusion (DD) model (Sholz et al. 1973).	

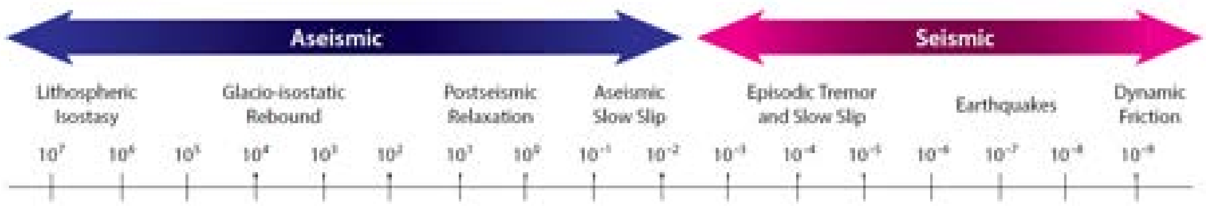
CSQ-49 Narrative

The study of earthquake sources and their relationship to the active fault structures seen at the surface has made a significant contribution to our understanding of plate tectonics, as well as determining where strain is currently building up in the crust. Geodetic systems are particularly suited to determining how much of a fault surface is locked and accumulating strain, as opposed to releasing it aseismically. Establishing this is a critical constraint in assessing the seismic potential for a fault system (Avouac 2015). The relatively new field of seafloor geodesy is opening up our ability to use GNSS to observe deformation underwater (Bürgmann and Chadwell 2014), which is particularly important for the Earth's subduction zones that cause the largest earthquakes and associated tsunamis.

Earthquakes produce two major sets of measurable physical phenomena Firstly, seismic waves propagate from the earthquake source, radiating outwards, and can be measured globally by seismometers. It is these waves that are the source of the ground shaking (accelerations) that comprise the bulk of the hazard to buildings in major earthquakes. Secondly, a permanent displacement of the Earth's surface occurs due to the change in the accumulated elastic energy that results from the sudden slip across the fault surface (which in itself can be a direct hazard if buildings straddle the fault rupture). This static displacement leads in the long-term (after many earthquake cycles) to the permanent deformation of the crust, accommodating the translation of plates and crustal blocks,as well as resulting in the growth of geological structures and mountains

The availability of topographic and geodetic information at fine spatial and temporal scales enabled a new researches on active faults in recent decades, and these data continue to fuel discoveries. Beyond simply documenting earthquake rupture, Earth-surface changes recorded by InSAR and GPS can document aseismic "afterslip" in the ensuing days to months

The Earth-surface record of fault zone evolution allows us to examine processes over timescales ranging from a single earthquake rupture to the integrated effects of faulting over millions of years



Duration (years)

CSQ-50 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How we could Improve The large-scale bathymetry of the deep oceans?	A) 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	• Sea floor tectonic active areas • Active volcanoes underwater • Sea floor structures and channels	Bathymetry maps of coastal areas Spatial Res:<50 m(global) Bathymetry on deep ocean Spatial Res: <1km Update frequency <1 year	Altimetry measurements High resolution Stellite and airborne Optical imagery Airborne LIDAR	Improve the knowledge of tsunami risk in coastal areas. Improve models for probabilistic tsunamic hazards
	B) improve modeling of tsunami run-up and its impact on coastal populations.	• Wave velocity • Depth of the water • Wave heights	Radar altimeters measurements continuously	Models for Time Variations of Tsunami Height and Wavelength in Distant Tsunami Propagation	
	C) Improve the systematic measurements of sea floor seismicity along marine active faults	• earthquake magnitude • fault mechanisms • fault displacement	Seismic networks on land and on sea floor. GPS data networks Gravity field data	Probabilistic tsunami hazard and risk analyses as PTHA and PTRA (Basili et al., 2021)	

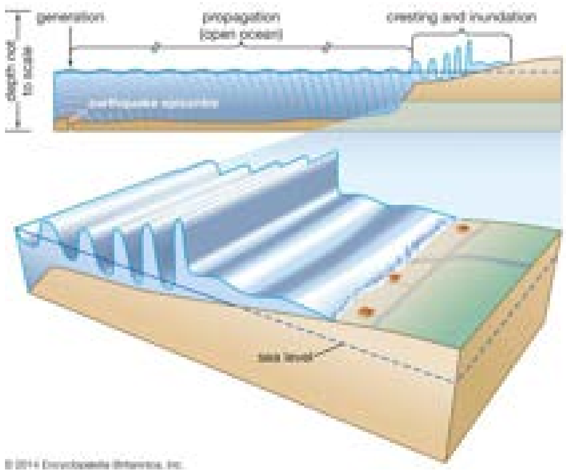
CSQ-50 Narrative

Tsunami (from Japanese "harbor wave") is an unusually large wave occurring in a result of the displacement of a large volume of water. Tsunamis are usually produced by submarine earthquakes but can also be generated by landslides or underwater volcanic eruptions. The tsunami propagation speed depends on the depth of the ocean/sea and can be approximated by the following formula:

$$v \approx \sqrt{gb} \qquad (1)$$

where b is the depth of the ocean, and $g \approx 9.8ms^{-2}$ is the force of gravity. As such, tsunamis in deep water move very fast – speeds such as 500 kilometres per hour (300 miles per hour) are quite typical; enough to travel from Japan to the US, for instance, in less than a day.

Tsunamis are one of the most destructive hazards on Earth, yet satellites are only peripheral in monitoring their generation and propagation. Mapping ionospheric waves has recently provided some limited information on tsunami propagation. Improved models of the shape of the seafloor as well as high-resolution coastal topography are critically needed to improve modeling of tsunami run-up and its impact on coastal populations. The topography of the deep ocean floor (>1,000 m) affects the overall velocity, focusing, and amplitude of the wave as it propagates across an ocean basin. The detailed topography of the shallow ocean floor (<1,000 m) and coastal areas affects the velocity, amplitude, and inundation of the wave as it flows over the land.

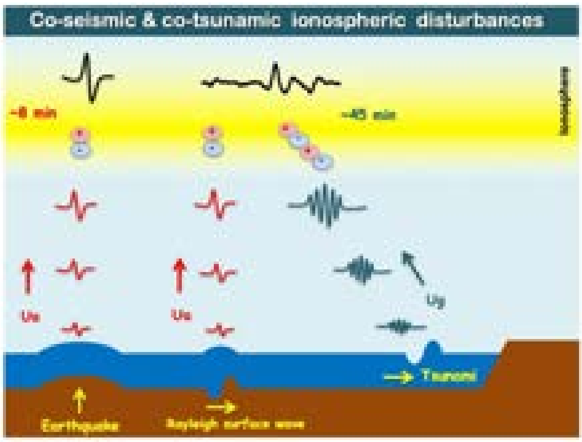


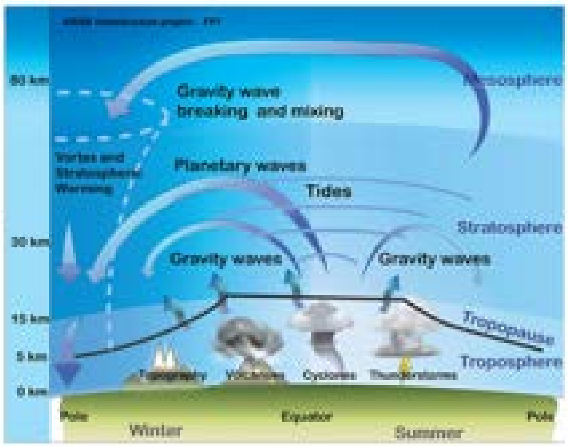
CSQ-51 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How we can improve the understanding of lithosphere-atmosphere-ionosphere coupling mechanisms?	A) high spatial resolution measurements of the total electron content of the ionosphere	• **Gravity waves** • **Acoustic waves** • **Ionosphere density**	measurements at frequency of higher than ~3.3 mHz measurements every 1min	GNSS receivers, Ionosonde networks and airglow cameras Gravimeters	Support the emergency plans during large earthquake and tsunami And major Volcanic eruption Improve the knowledge of interactions between lithosphere-atmosphere-ionosphere
	B) improve the measurements of Atmospheric anomalies (short term)	• Atmospheric temperatures • Clouds shapes	Atmospheric profiles from different sources	Atmospheric profiles Polar and Geostationary meteorological satellites	
	C) Measure short term atmospheric pressure waves triggered by earthquakes, explosions, volcanic eruptions, tsunamis,	• Atmospheric pressure	Atmospheric profiles from different sources		

CSQ-51 Narrative

Tsunami Early Warning System for the Indian Ocean (https://www. gitews.org/; Falck et al., 2010), and so forth. These systems 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).





CSQ-52 Summary

Question	**Knowledge Advancement Objectives**	**Observables**	**Measurement Requirements**	**Tools & Models**	**Policies / Benefits**
How can we help predict a volcanic event through the detection of thermal transient phenomena, gas emissionis and surface deformation evidences	A) 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	• Surface deformation vertical and horizontal • Surface velocity • Surface topography	• < 10 mm • < 1 cm/year • <50 cm horizontal • < 1m vertical	Insar techniques GNSS networks High resolution visible images	Emergency planning and volcanic eruption forecast Climate effects of large volcanic eruptions
	B) Assessment of surface vertical deformation extent and atmospheric contamination, and composition and temperature of volcanic products following volcanic eruption	• Surface Deformation • Atmospheric composition at different distances from the volcano (columnar content and vertical distribution) • Surface topography	• <10mm • <100m resolution • 200 km observed area • hourly to daily sampling • <50 cm horizontal • <1 m vertical	Optical and IR sensors to measure optical depth, ash content, particle size	
	C) Measurement of the composition and quantity of the gas emitted prior to and during an eruption as well as the composition of any ash.	• Volcano degassing plume composition • Aerosols • Volcano eruptive plume composition	• Every 2-3 days pre-eruptive • (ppmTBD) • Hourly during eruption	Measure columnar content and flux of gas species emitted by volcanoes (CO2, SO2, H2S, KCL) and H2O Develop suitable atmospheric Radiative transfer models	
	D) Inference of changes at shallow depths as magma reaches the uppermost plumbing system prior to an eruption	• Ground Surface Temperature • Lava Lake Temperature	• <0.5 K • < 3 K • Weekly to daily		

	E) Capturing transient behaviour in an ongoing eruption to model the vent-scale processes	• Volcano Surface structure / composition imagery	High temporal repeat (hours to days)		
	F) 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.	• Surface deformation Composition of emissions	time scale of days to weeks.	Photogrammetric Techniques Structure from motion techniques	

CSQ-52 Narrative

Volcanic unrest is a complex multi-hazard phenomenon of volcanism. Although it is fair to assume that probably all volcanic eruptions are preceded by some form of unrest, the cause and effect relationship between subsurface processes and resulting unrest signals (geophysical or geochemical data recorded at the ground surface, phenomenological observations) is unclear and surrounded by uncertainty (e.g., Wright and Pierson 1992). Unrest may, or may not lead to eruption in the short-term (days to months). If an eruption were to ensure it may involve the eruption of magma or may be non-magmatic and mainly driven by expanding steam and hot water (hydrothermal fluids). These conundrums contribute significant uncertainty to short-term hazard assessment and forecasting of volcanic activity and have profound impact on the management of unrest crises (e.g., Marzocchi and Woo 2007).

Figure 34: Volcano processes and distribution

While institutional and individual decision-making in response to this unrest should promote the efficient and effective mitigation or management of risk, informed decision-making is fundamentally dependent on the early and reliable identification of changes in the subsurface dynamics of a volcano and their “correct” assessment as precursors to an impending eruption. However, uncertainties in identifying the causative processes of unrest impact significantly on the ability to “correctly” forecast the short-term evolution of unrest.

The interaction between hydrological and volcanic systems is an important element in volcanic unrest. Changes in hydrological behaviour, such as water table elevation, spring discharge, temperature and chemistry, at an active volcano can provide early indications of changes in volcanic activity. Hydrological interactions can also alter and augment the existing volcanic hazard. Chemical and physical interactions between host rocks and different fluid types can modify fluid degassing pathways, generating dynamic pressure distributions within a volcanic edifice
A magmatic hydrothermal system is composed of three main elements: a host rock (or reservoir), which contains a circulating fluid, set in motion by an igneous heat source. While the difference in relief between stratovolcanoes and calderas can lead to contrasting hydrological systems, secondary processes (e.g. hydrothermal system perturbation, meteorological forcing) modify primary signals from deeper-seated magmatic processes.

Gas and aerosol emissions
Volcanic gases are one of the main tools used to monitor changes in the activity of volcanoes and forecast their eruption. This approach is rooted in the strong pressure dependence of the solubility of volatiles (mainly H_2O, CO_2, SO_2, H_2S, Cl) in silicate melts. Accordingly, magma ascent toward the surface is associated with the exsolution of volatiles initially dissolved in the melt, a process designated as “magma degassing”. The different volatiles have contrasted solubilities in silicate melts and, therefore, are expected to react differently to decompression. This forms the basis for using volcanic gas ratios to infer magma ascent and depth of gas segregation in volcanic conduits. For example, the sudden increase of gas CO_2/SO_2

ratio has been used as an indication for deep magma recharge at Stromboli (Aiuppa et al. 2010). At Soufriere Hills volcano (Montserrat), a correlation has been noted between gas HCl/SO2 and the level of shallow activity as marked by the rate of lava extrusion and dome growth (Christopher et al. 2010; Edmonds et al. 2010).

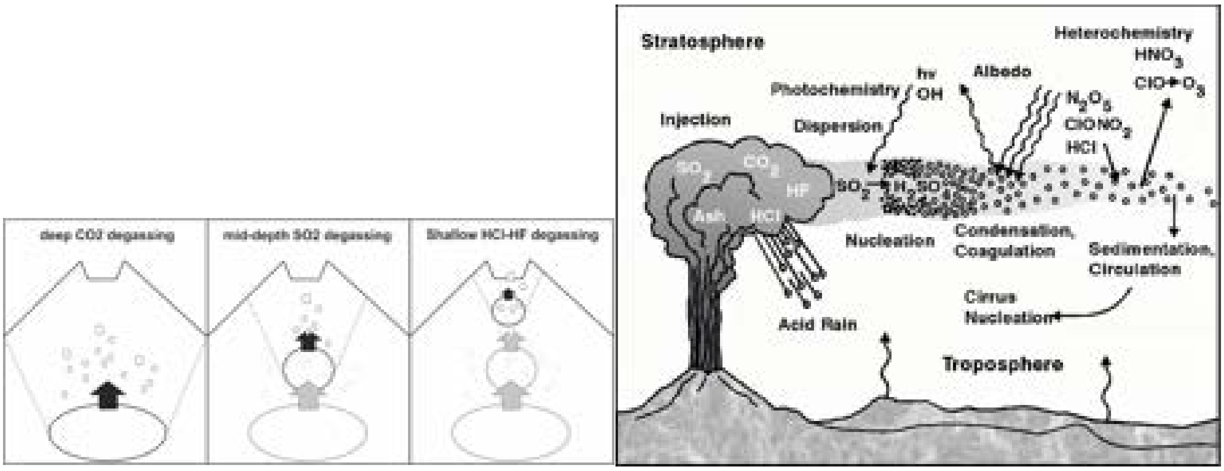


Figure 35: Volcano gas and aerosol emissions

Which gas species are released, how much and when? When a magma starts to degas, by any of the above processes, the less soluble species is released first (i.e. at higher confining pressure in the magma chamber). The order in solubility of indicative magmatic gas species is $CO_2 < SO_2 < HCl < HF$; the order of release when a magma progressively degasses is "CO2-first till HF-last"

Temperature characteristics
Some volcanoes have thermal features such as smoking vents, geysers, hot springs, lava flows or lava domes. Surface temperature changes at these thermal features sometimes occur before a volcanic eruption. Recognition of these "thermal anomalies" can be useful in predicting changes in activity.

- Steam, or vapor-dominated features such as gas vents, fumaroles, and mud pots range in temperature from boiling up to several hundred degrees (about 400 °C or 750 °F).
- Water-dominated features include geysers, hot springs/pools, crater lakes, elevated sea surface temperature (e.g., from underwater or island volcanic activity), and even melting ice (e.g., sub-glacial volcanoes). These range in temperature from freezing to boiling.
- Lava-dominated features include lava lakes, lava flows, lava domes, and pyroclastic flows, and can reach temperatures up to about 1200 °C (2200 °F).

Deformation monitoring in volcanic areas
Volcanic eruptions are often preceded by small changes in the shape of the volcano. Such volcanic deformation may be measured using precise surveying techniques and analysed to better understand volcanic processes. Complicating the matter is the fact that deformation events (e.g., inflation or deflation) may result from magmatic, non-magmatic or mixed/hybrid sources. Using spatial and temporal patterns in volcanic deformation data and mathematical models it is possible to infer the location and strength of the subsurface driving mechanism.
Detectable changes in volcano shape, gas emissions, and thermal output prior to a new eruption event occur over time scales ranging from months to minutes. The relevant length scales are 10 m to 200 km for surface and plume measurements, with most shape changes occurring over length scales greater than 1km.

The necessary vertical precision (1-10 mm) and the temporal frequency need to be adjusted to match the activity of a particular volcano.

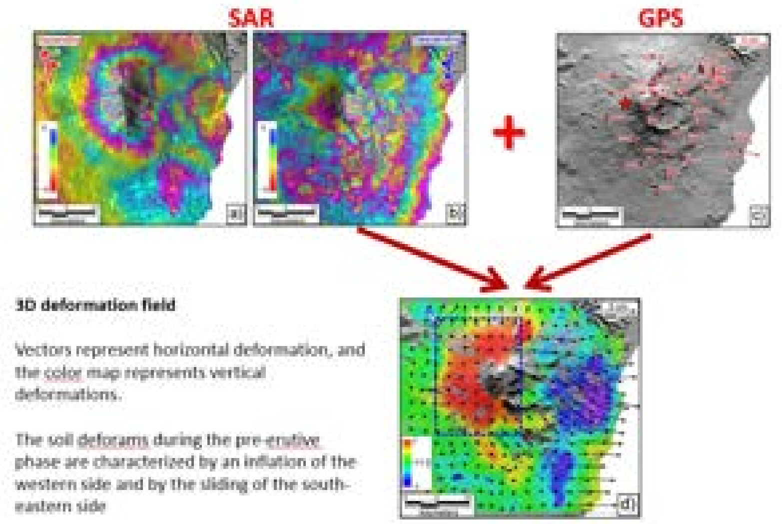


Figure 36: Volcanic monitoring of the pre-eruptive phase of Mt Etna (INGV)

CSQ-53 Summary

Question	**Knowledge Advancement Objectives**	**Observables**	**Measurement Requirements**	**Tools & Models**	**Policies / Benefits**
Can we map topography, surface mineralogic composition and distribution, thermal properties, soil properties/water content?	A) 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	• Mineralogical species in natural outcrops for mining interest • Surface composition in urban environment • Spectral emissivity of surfaces • Spectral reflectance of surfaces • Surface texture • Particle dimensions • Physical characteristics • Surface morphology • Surface deformations	imaging spectrometers and cameras VNIR >200 spectral channels 1-10 m spatial resolution measurements SWIR and MWIR-LWIR 10-200 spectral channels spatial resolution > 30m Laser scanners Measurements frequency <1 day MWIR-LWIR night acquisitions DTM with >0,5 m spatial and vertical resolution Deformation >10 mm/yr), and 5-50 m spatial resolution deformation monitoring	Radiative transfer models improvements (3D) Use of AI and machine learning techniques for mineral species detection using satellite o airborne hyperspectral images. Atmospheric modelling for dust transportations	Improve policy for soil protection and agriculture development Mining activity planning and control Support Air pollution control (better understand of particles sources) Plans to protect human healt
	B) Improve the measurement of quality of soils which are very important ingredients	• Soil component mineral and organic	imaging spectrometers and cameras VNIR >200 spectral channels		

	for agriculture and ecology	• Water content nutrients, permeability, thickness	1-10 m spatial resolution measurements SWIR and MWIR-LWIR 10-200 spectral channels spatial resolution > 30m		
	C) Measure the composition of dust sources in atmosphere and AOD and particle size parameters analysis to sand/dust storms	• Mineral composition • Extension of source areas • Aerosols particles characteristics • Particle shape and dimension • Optical characteristics			

CSQ-53 Narrative

Spectroscopic information about the mineral content of the ground, whether soft sediment, regolith or hard rock, constitutes a great tool in numerous geological, geomorphological and soil studies. It includes mapping of rocks and mineral

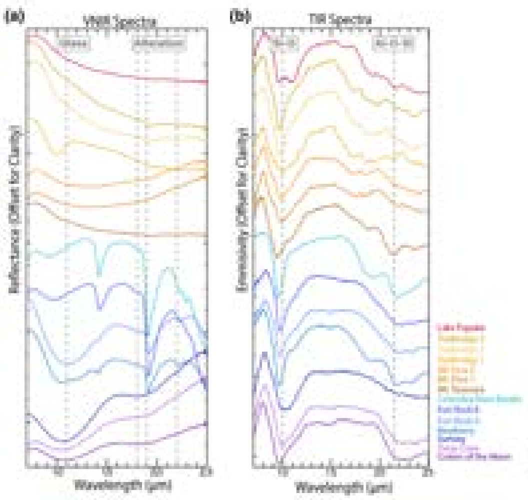
outcrops, assessment of rock weathering degree, soil studies, analysis of minerals, protection of the natural environment, analyses of geothermal deposits and studies of meteorites.

New spectroscopic measurements of the Earth's exposed surface to derive mineralogy are required to address key science and application targets. These measurements will advance understanding of fundamental geological processes, natural and anthropogenic hazards, soil geochemistry and evolution, and the location of energy and mineral resources

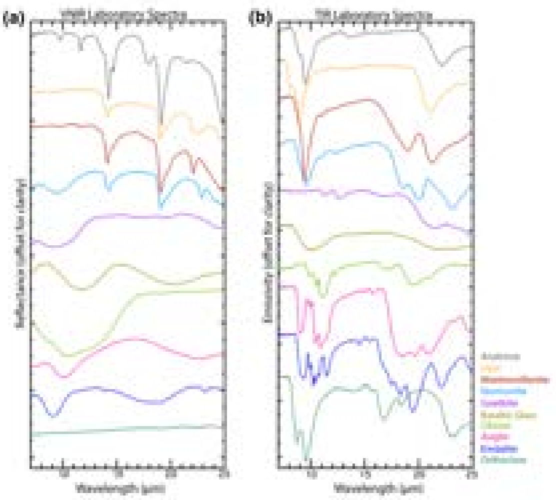
In the last few decades, hyperspectral imaging (HSI) has evolved as a method for remote detection with many applications, including identification of plants, earthen materials, and natural events as volcanic eruptions.

Surface spectroscopy in the full spectral range of VIS-SWIR and MWIR-LWIR is very important reconstruct the eruption historical phases. Hyperspectral MWIR-LWIR (3-5 and 8-12 microns) spaceborne instruments are not yet available but should be considered as a goal as future missions

Spectral analysis by means of laboratory instruments and remote sensing data is also very important to better understand geology and lithology in fault areas



(a) Visible/near-infrared (VNIR) reflectance spectra and (b) thermal infrared (TIR) emission spectra of volcanic tephra samples, ordered by X-ray diffraction (XRD) crystallinity, decreasing from top to bottom, and colored by eruption type (purple = magmatic cinders, blue = phreatomagmatic, yellow/orange/red = magmatic). Dashed lines indicate wavelength positions of major absorption bands.

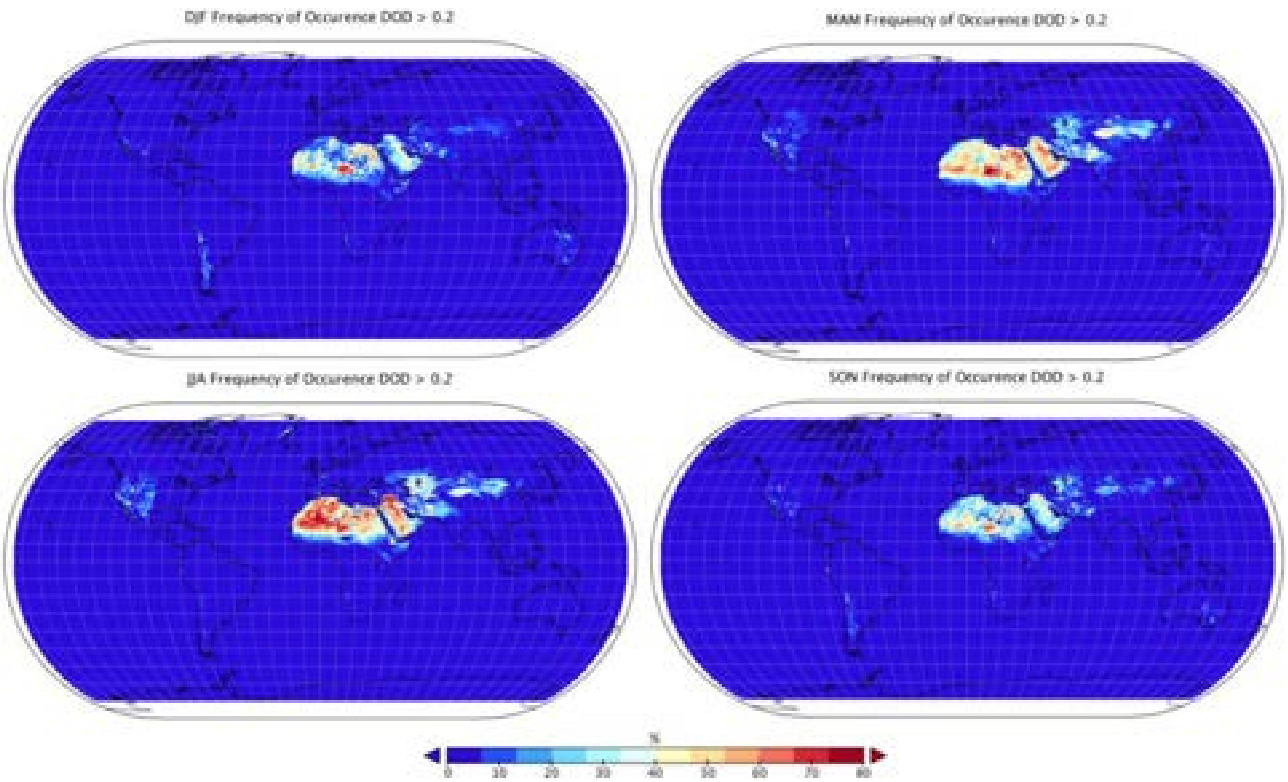


Laboratory reference spectra of minerals common in volcanic environments in the (a) visible/near-infrared (VNIR) (Horgan et al., 2017, Kokaly et al., 2017) and (b) thermal infrared (TIR) (see citations in Table 2).

Reference: Henderson, M. J. B., et al. 2020 https://doi.org/10.1029/2019EA001013

Dust sources

Oceans and arid regions provide most of the atmospheric aerosol load of the Earth, with 6.3–10.1 and 1.2–1.8 Giga (109)-tons (t)/year (yr) of sea salt and PM10 soil dust, respectively, emitted into the troposphere. Sea salt is made of PM derived from sea/ocean droplets suspended into the atmosphere that are subsequently evaporated and yielding salts, such as sodium, chloride, magnesium, calcium, potassium, and sulphate. Soil dust aerosols are created by wind erosion within arid regions, where soil particles are loosely bound by the low soil moisture and absence of vegetation. Dust sources have been identified empirically from satellite radiance measurements over the last few decades



Frequency of occurrence of dust optical depth (DOD) > 0.2 by season. Aerosol optical depth was retrieved at 10 km resolution using the MODIS Deep Blue algorithm

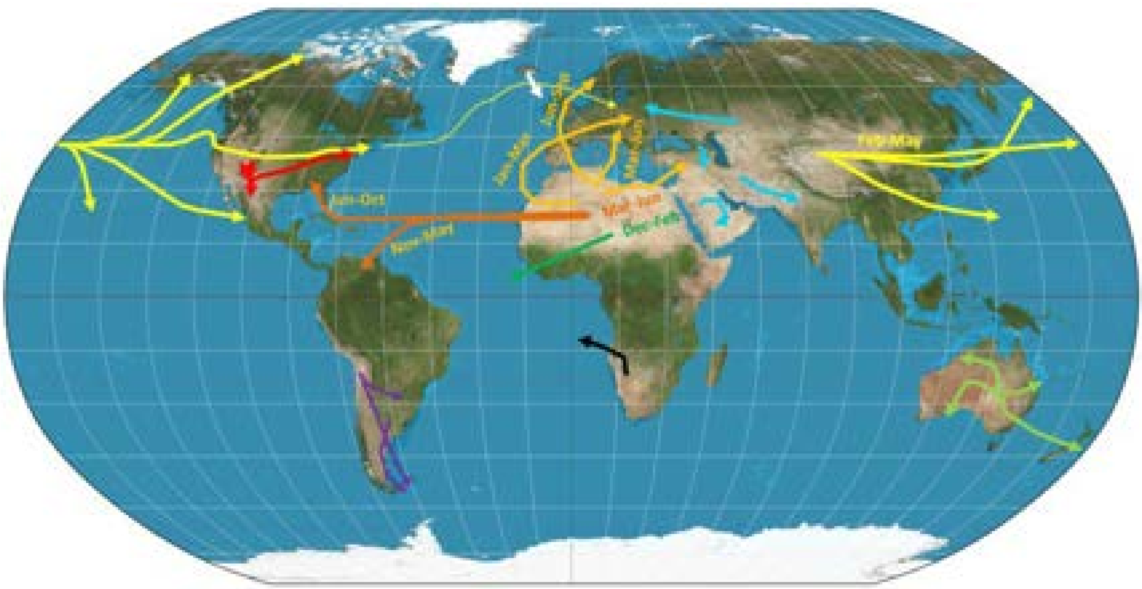


Figure Major desert dust transport fluxes, modified from Griffin (2007).

CSQ-54 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How different drivers and threats effect the integrity of ecosystem?	A) Long-term, global land use and land use change monitoring	• Land cover and land use change types including, agricultures, pastures (grazing), urban and its relationship with changes	• Using various optical/SAR time series data available in the long-term (i.e. Landsat, Sentinels)	• Different change detection and time series analysis • AI for inferring land use patterns	• UNCBD • IPBES • Nature-based solutions • Restoration efforts
	B) Monitoring direct exploitation patterns worldwide	• Tracking different extraction, production, and consumption patterns (incl. mining, infrastructures, subsidence)	• using optical time series, very high-resolution data, subsidence/ structural changes (SAR/LIDAR)	• Various EO data analysis methods • AI for integrating different EO data and inferring specific extraction types	
	C) Explore different approaches for monitoring environmental pollution and invasive alien species	• Different environmental pollution processes (i.e. air quality, waste sites etc.) • Tracking of invasive species (although limited EO opportunities	• using optical time series, very high-resolution data, subsidence/ structural changes (SAR/LIDAR)	• Various EO data analysis methods • AI for integrating different EO data and inferring specific extraction types	
	D) Monitoring ecosystem integrity	• “integrity”, also naturalness or intactness to be assessed by quantifying the human pressures (land use, extractions etc.) and/or by quantifying ecosystem properties (structure, function,	• High resolution space-based LIDAR and RADAR measurements	• Various EO data analysis methods • Statistical and AI methods for integrating EO	

		and composition) compared to a “natural” state regionally	• Optical EO time series (i.e. Sentinels) • Quality ground reference networks (i.e. plot networks)	with innovative ground data	

CSQ-54 Narrative

How different drivers and threats effect the integrity of ecosystem?

A recent synthesis of direct drivers of recent global anthropogenic biodiversity loss showed that land/sea use change has been the dominant direct driver, followed by direct exploitation of natural resources, pollution; while climate change and invasive alien species have been significantly less (Jaureguiberry et al., 2022).

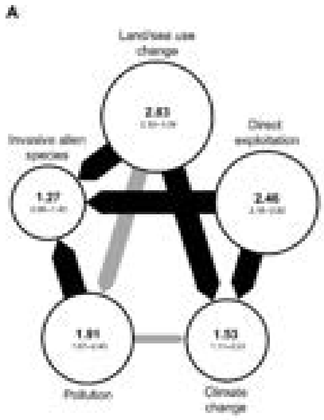


Fig. Dominance hierarchies of the five studied direct drivers of biodiversity loss (N=154, Jaureguiberry et al. 2022)

This study has been based on meta-analysis of different regional studies, while at the same time there is potential for using different EO-approaches to better map and constrain the various drivers and threats, for example:

1. Land use change monitoring (using optical/SAR time series)
2. Direct exploitation incl. extraction, production, consumption (using optical time series, very high-resolution data, subsidence/structural changes [SAR, LIDAR])
3. Climate change (using various ECV data records)
4. Pollution (some opportunities using hyperspectral, SAR, atmospheric monitoring)
5. Invasive alien species (limited remote sensing possibilities)

At least for the first three and most important drivers and threats a new systematic global and regional assessments across multiple drivers and including temporal trends could be advanced and provide consistent information suited for assessing ecosystem impacts and integrity. Considering and comparing with the series of local/regional case studies (that is current scientific base, Jaureguiberry et al., 2022) is important.

Improved spatial and temporal data on drivers can underpin an improved analysis of their impacts on ecosystem integrity. Ecologists associate the term “integrity” with naturalness or intactness and that can be assessed by quantifying the human pressures (land use, extractions etc.) and by quantifying ecosystem properties (structure, function, and composition) compared to a “natural” state regionally (Hansen et al., 2021). This assessment can benefit from improved EO-based mapping of ecosystem structure and composition when analyzed together with the new data on drivers. This approach is a practical way forward since the full complexity of Ecosystem and Biodiversity characteristics cannot be fully capture by observational methods, but tracking the key changes and using the concept of Ecosystem Integrity allows to quantify the most important patterns and trends.

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CSQ-55 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What are local patterns of ecosystem structure and composition worldwide?	A) Quantifying three-dimensional vegetation structure at high resolution and at scales that also relate to ongoing on the ground ecological and forest monitoring networks	• Vegetation structure, height, cover, biomass • Fragmentation and connectivity • Related dynamics over time • Focus on related EBVs not covered by ECVs	• High resolution space-based LIDAR and RADAR measurements • Very high-resolution optical data • Quality ground reference networks (i.e. plot networks, GEOTREES) • Interoperability of different EO sensors and ground networks is important	• Various EO data analysis methods • Processing tools to allow for interoperability • Statistical and AI methods for integrating EO with innovative ground data	- UNCBD - IPBES - Nature-based solutions - Restoration efforts
	B) Characterizing ecosystem composition based on space-based imaging spectroscopy combined with ground reference data	• Species composition and biophysical/trait characteristics	• High-spectral-resolution / hyperspectral • Very high-resolution optical data • Innovative ground data (i.e. eDNA, sound sensors, citizen science)	• Various hyperspectral data analysis methods • AI for integrating EO with innovative ground data (i.e. eDNA, sound sensors, citizen science)	

CSQ-55 Narrative

What are local patterns of ecosystem structure and composition worldwide?

While ecosystems are undergoing rapid changes worldwide, a consistent, accurate and spatially detailed characterization of ecosystem structure and composition 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).

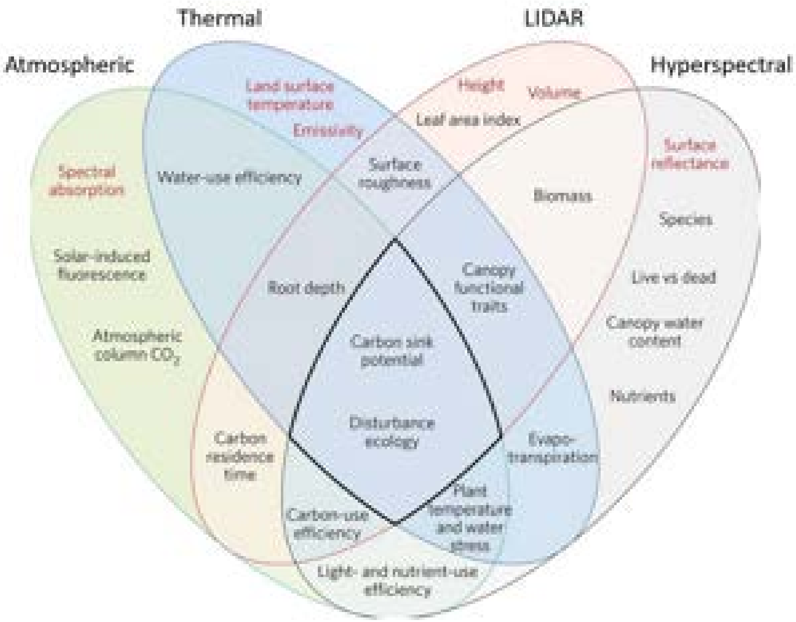

Fig. Synergy of different EO-based approaches for characterizing Ecosystems and Biodiversity (adapted from Stavros et al., 2017).

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). Quantify the structure as key feature of many terrestrial ecosystems and forest, 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 ongoing on the ground 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 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.

These approaches should be leveraged for a new global effort for a characterizing both ecosystem structures and composition and its relationships at local and regional level. From an observation perspective, most opportunities exist for forests and vegetated ecosystems; but under-studied ecosystems (IPBES, 2019) such as freshwater systems, Arctic, marine/ocean, seabed, and wetlands should also be considered with priority.

From an observation perspective, using EO-system operating now or in the coming years provide a lot of additional new information that still needs to 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. The same is true for integrating with space-based on on-the ground monitoring. 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, the use of optical and SAR-based systems with a longer time series record is required.

In the longer term, a more precise and repeatable (i.e., revisiting the same areas every year) space-borne LIDAR system could be developed to track ecosystem structure increasingly through time.

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CSQ-56 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
Where and how are ecosystems undergoing critical transitions?	A) Assessing ecosystems heterogeneity (that is, spatial and temporal variation in ecological processes) for improved understanding of ecosystem resilience	• Vegetation structure and cover • Related dynamics over time	• Dense, long time series based on datasets that provide continuity and consistent of all observations from Landsat and Sentinels 1,2	• Various EO time series analysis methods	- UNCBD - IPBES - Nature-based solutions - Restoration efforts
	B) Comprehensive assessment of ecosystem dynamics including the identification of critical changes in ecosystem resilience directly through monitoring disturbance frequency and recovery rates over time	• Vegetation structure and cover • Soil moisture • Disturbances (types and frequency)	• Dense, long time series-based datasets from Landsat, S1/2, SMOS etc.	• Temporal autocorrelation or mapping the rate and speed of recovery after disturbances to quantify resilience directly from remotely sensed data	
	C) Approaches for rapid/near real time monitoring and development of early warning signals for critical transitions to occur	• Disturbance and dynamics monitoring at high frequency and with rapid updating	• Dense time series (daily, weekly coverage) at high spatial resolution)	• Different near/real time/anomaly detection methods	

CSQ-56 Narrative

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. With satellite-based time-series from sensors like Landsat and Sentinels 1 and 2 becoming increasingly long and temporally dense, studying ecosystems heterogeneity (that is, spatial and temporal variation in ecological processes) can be improved and leads to a substantially improved 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 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).

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 consistent of the all observations from Landsat and Sentinels 1,2 to capture vegetation dynamics and using various sensors (like SMOS) capturing soil and soil moisture dynamics globally.

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CSQ-57 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How vegetation and climate interactions vary across scales?	A) Linking vegetation characteristics to climatic conditions at detailed/plot level often monitored by ecologists	• Vegetation structure and cover • Land surface temperature, albedo, soil moisture, water vapor • Related dynamics over time	• Sentinel 1 / 2 time series, high resolution data • LSTM / Landsat (LST) • ENMAP/CHIME (albedo) • S1/SMOS (soil moisture)	• Various EO time series analysis methods • ICOS site networks	- UNCBD - IPBES - Nature-based solutions - Restoration efforts - UNFCCC and climate science
	B) 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 individuals	• Vegetation structure and cover • Land surface temperature, albedo, soil moisture, water vapor • Related dynamics over time	• EO data at different resolutions (10 m – 1 km resolution) covering Land surface temperature, albedo, soil moisture, water vapor	• Various EO time series analysis methods • ICOS (and other) site networks	

CSQ-57 Narrative

How vegetation and climate interactions vary across scales?

The better understanding of vegetation-climate interactions at macro-climatic levels 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 and to take the vegetation climate interactions to a level of detail considering climate conditions that is experienced by most terrestrial species. Micro-climate is often regulated by vegetation and spatially detailed remote sensing data of land surface temperature, albedo, water vapor and soil moisture can help linking vegetation characteristics to local climatic conditions and help to scale from plot level often monitored by ecologists to more macro-Earth System models. Bridging information and understand across scales will improving monitoring the impacts of changing climates at the level of species and individuals.

From a sensing perspective, land surface temperature (i.e. Landsat, LSTM), 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. The use of soil moisture information (i.e. from SMOS) is also very important.

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CSQ-58 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
Are nature-based solutions delivering on multiple benefits?	A) 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	• Vegetation structure and cover • Land surface temperature, albedo, soil moisture, water vapor • Related dynamics over time	• Landsat, Sentinel 2 time series, • Very high resolution data • ROSE-L, BIOMASS, GEDI • ENMAP/CHIME • S1/SMOS	• Various EO time series analysis methods • Interoperability • Ground networks covering different nature-based solutions	- UNCBD - IPBES - EU policy (i.e. nature restoration law, climate law, EUDR) - National action plans/policies - Nature-based solution and restoration efforts frameworks (i.e. private sector, NGOs) - UNFCCC and climate science
	B) Monitor and assess the local and regional impacts considering different nature-based solution and different areas of "benefits" (i.e. climate, biodiversity, livelihoods)	• Vegetation structure and cover • Land surface temperature, albedo, soil moisture, water vapor • Related dynamics over time	• Landsat, Sentinel 2 time series, • Very high resolution data • ROSE-L, BIOMASS, GEDI • ENMAP/CHIME • S1/SMOS • Several ECV products	• Various EO time series analysis methods • Interoperability • Ground networks covering different nature-based solutions	

CSQ-58 Narrative

Are nature-based solutions delivering on multiple benefits?

Activities for improving ecosystems are stimulated by various international and national policy frameworks. These are commonly referred to as “nature-based solutions” and proposed and implemented by countries, private sector actors, NGO’s etc.. They include various landscape/ecosystem restoration efforts, the establishment of sustainable supply chains (for commodities, raw materials), different environmental certification schemes, and pursuing environmental/economic assessment frameworks. Nature-based solutions serve different purposes including benefits for climate, biodiversity, livelihoods etc. An important scientific question is whether these activities are actually providing the impacts and benefits they were set out to achieve; in particular whether they create synergies or trade-offs given their multiple objectives. Any independent and comparative scientific assessments require quality monitoring data that allow for tracking these activities, their impacts and performance over time. Such data can help to answer questions whether the activities are actually doing the right thing, at the right time and in the right place, and underpin up to date and robust scientific analysis and synthesis for future IPBES assessments for example.

The observation needs depend on type of activity and ecosystems characteristics but using Landsat, Sentinels and related data provide a good base for tracking activities. Different data streams can be useful for assessing impacts on climate (i.e. carbon), biodiversity (i.e. structure, conditions) . Essential is to time series that provide information on the scales where these activities are happening on the ground. Providing data in free and open manner should ensured to enhance transparency for the multiple stakeholders concerned with nature-based solutions. Geographically, the implementation and impact of nature-based solution can be clustered in areas where humans are most active (like in cities or production landscape) and these regions would need to receive specific attention.

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CSQ-59 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How can we leverage EO data from tracking animal counts and behavior?	A) Demonstrate the use of EO date for animal counting in different ecozones and types of fauna (i.e. large mammals, penguins, cows)	• Various detection options for different types of animal individuals and environments	• Very-high resolution satellite data (<1 m) • New sensing concept by new space actors and sensing concepts (i.e. constellations, thermal etc.)	• Statistical and AI approaches for detecting and counting individuals	- UNCBD - IPBES - National action plans/policies - Animal conservation efforts
	B) New approaches for tracking animal behavior to understand species–environment interactions and for generating and analyzing animal movement data	• Ecosystem structure and conditions • Climate/environmental characteristics • Related dynamics over time	• Link with animal tracking networks • Landsat, Sentinel 2 time series, • Very high resolution data • ROSE-L, BIOMASS, GEDI • ENMAP/CHIME • S1/SMOS • Several ECV products	• Various EO time series analysis methods • Interoperability • Integration with animal tracking data	

CSQ-59 Narrative

How can we better leverage satellite data from tracking animal counts and behavior?

The accurate estimation of animal populations and their behavior using ground-based or conventional methods has its challenges and require considerable investment in resources and time. Aerial surveys have been demonstrated as an alternative approach to detect large mammal populations and generate statistical estimates of their abundance in open areas and are commonly used to detect wildlife such as elk or deer. In developing countries with their large share of endangered and threatened fauna and in remote areas (i.e. the Arctic) it is particularly relevant to develop alternative approaches for conducting accurate and timely wildlife population counts using satellite data as potential source (Xue et al., 2017). Satellite remote sensing for detecting and counting animals has its challenges and have mostly been working well in small area studies and/or in homogenous (background) environments such as sea ice. Major limitations seen in other studies are the relatively low accuracy of automated detection techniques across large spatial extents, false detections, and the cost of high-resolution data (Hollings et al. 2018). With the increasing availability of high-quality remote sensing data and analysis methods, there are opportunities to improve detection capabilities and population counting efforts.

In addition, satellite technologies are a relevant tool for studying animal behavior providing ecologists with the means to understand species–environment interactions in combination with generating and analyzing animal movement data. Satellite are useful in different ways. Data from GNSS systems are critical for animal tracking devices and provide quality space-time data of individuals and their dispersal and migrations. Satellite are also very relevant to characterizing habitat characteristics and changes that can relate animal behavior to context and track critical changes related in environments due to land use change (e.g., deforestation and expansion of agriculture) or wildlife management actions (e.g., reintroductions and translocations), and to keep track large migrations (i.e. insects) and any shifts in migration patterns.

Using satellite data towards detecting and monitoring "individuals" requires high-resolution satellite data. Such sensor data are currently provided by commercial data providers with spatial resolutions less than 1 m, with different constellations allowing for more detailed temporal coverage and for developing different sensing concepts (i.e. thermal, hyperspectral) at higher resolution. For animal tracking the use of quality GNSS data is important. General ecosystem characterization and environmental conditions takes advantage of many remote sensing sensing data streams.

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