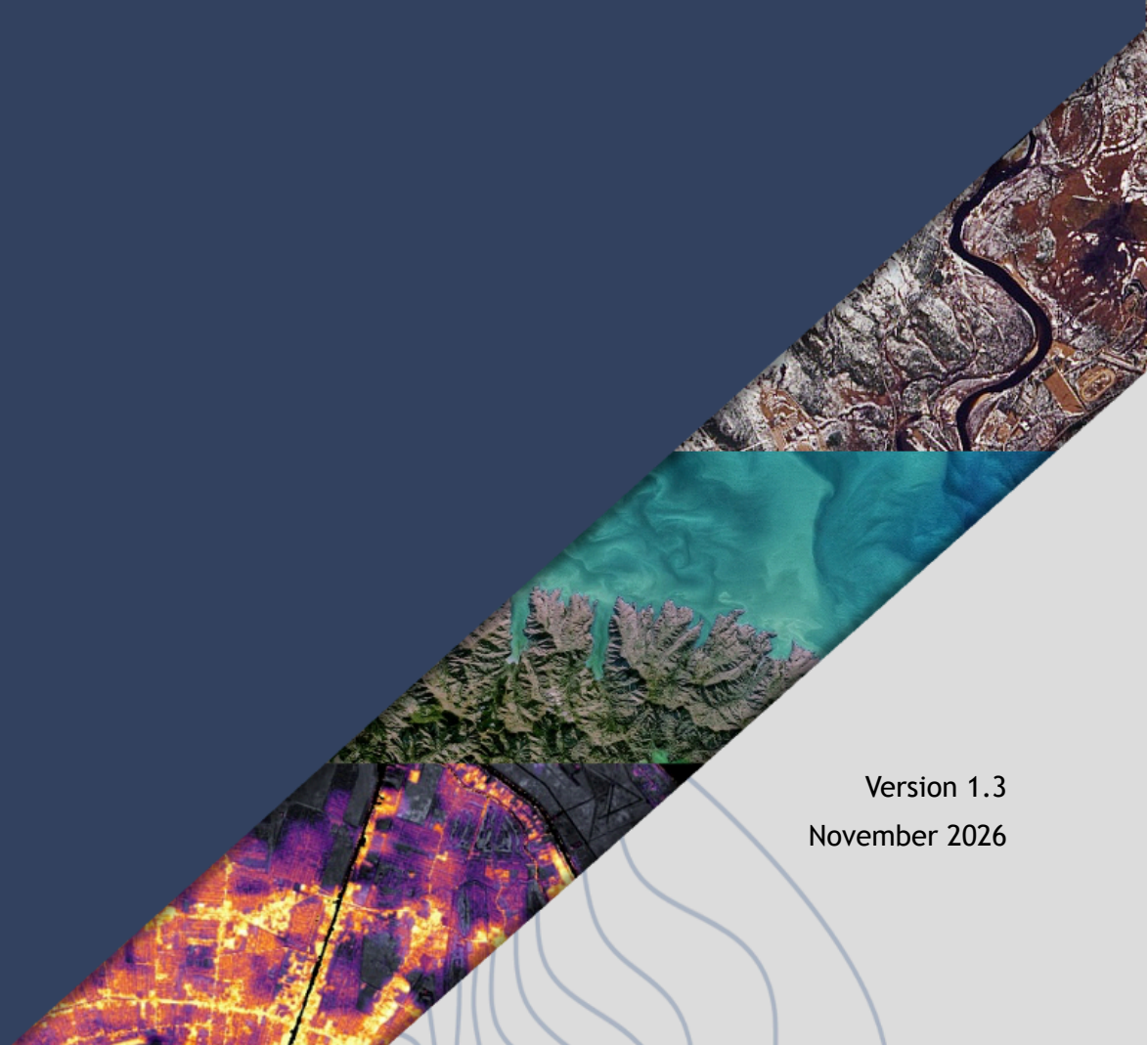
SPACE AGENCIES' RESPONSE TO THE 2022 GCOS IMPLEMENTATION PLAN



Version 1.3

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Note on Version 1.3

V1.0 of the Space Agency Response to the GCOS Implementation Plan 2022 was delivered to GCOS in April 2025. To inform discussions at the joint WGClimate-GCOS meeting in February 2026, WGClimate undertook a minor update to the Response, in light of recent satellite launches, new product availability, and other progress made. Notable updates since version 1.0 include:

- Biomass launched in April 2025, affecting activities A2.3, C5.6
- GOSAT-GW launched in June 2025, affecting activities A3.4, A3.5, B9.4, F2.4 and F4.5
- NISAR launched in July 2025, affecting activities A2.3, A3.5, B9.4, C5.6 and F3.1
- Sentinel-5A launched in August 2025, affecting activities B3.1 and F5.2
- The CDR Inventory, an evolution of the previous ECV Inventory, launched in December 2025. It includes an improved user interface designed to simplify access and enhance the experience for users, as well as a new rolling update model, allowing continuous integration of new CDRs.
- The production of ERA6 and EAC5 are both due to commence in Q1 2026, with the first data to be released in the second half of 2027.
- The MERRA-21C is in production and will finish processing in mid 2026.
- NASA selected the EDGE (Earth Dynamics Geodetic Explorer) and STRIVE (Stratosphere Troposphere Response using Infrared Vertically-resolved light Explorer) missions for continued development as part of NASA's Earth System Explorers Program, affecting activities A2.4, A2.7, and F2.3. ODYSEA was not selected, affecting activity B3.3.
- NASA announced the FALCON mission, an evolution of the Atmospheric Observing System (AOS), affecting activities A3.2 and A3.3.
- NASA announced the EAGLE mission, an evolution of the Surface Biology and Geology (SBG) mission, affecting activity F2.4.
- NASA and USGS announced the Landsat 10 mission, an evolution of the planned Landsat Next mission, affecting activities A3.5, C5.1, C5.3, F2.4 and F2.6.

Introduction

Background and Purpose

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

At the 7th Conference of the Parties (COP 7) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2001, the UNFCCC Subsidiary Body on Scientific and Technological Advice (SBSTA) invited the Global Climate Observing System (GCOS) to consider an integrated observational approach—combining satellite and in situ methods. This initiative aimed to leverage new and emerging observational techniques to better measure climate change.

At COP 9 in 2003, GCOS was further invited to develop a phased 5-to-10-year implementation plan. Subsequently, at COP 10 in 2004, Parties with Space Agencies were urged to direct those agencies to provide a coordinated response to the recommendations outlined in the 2004 Implementation Plan.

The purpose of this report is to present a consolidated response from Space Agencies to the actions outlined in the 2022 GCOS Implementation Plan (GCOS-244), addressing key priorities and ensuring alignment with international climate observation objectives.

Role of Satellites in a Global Climate Observing System

Earth observation satellites provide an essential means of obtaining observations of the Earth system from a global perspective, enabling the comparison of conditions and changes across different regions of the globe for many of the Essential Climate Variables (ECVs). Their global scope distinguishes satellite observations from ground-based and airborne measurements, which, while more spatially limited, are indispensable for constraining and validating satellite-derived information and capturing data for variables that satellites cannot measure from space.

Satellite climate data records that meet the GCOS requirements support a wide range of critical activities, including climate monitoring, trend and variability analysis, climate research, and the assimilation of data into numerical weather prediction models to produce long-term reanalyses of Earth System components. These records are also vital for providing boundary conditions for, and verification of, climate models, as well as climate impact modelling. Ultimately, they inform decision-making across numerous societal sectors, such as agriculture, water resource management, coastal planning, forestry, transportation, and insurance.

Furthermore, satellite observations play a pivotal role in leveraging Earth observations and geospatial information to support global initiatives. These include the UNFCCC Paris Agreement and UN 2030 Agenda for Sustainable Development, highlighting the integral contribution of satellites in addressing climate challenges and fostering sustainable development worldwide.

The Joint CEOS-CGMS Working Group on Climate

The Joint Committee on Earth Observation Satellite (CEOS) and Coordination Group for Meteorological Satellites (CGMS) Working Group on Climate (WGClimate) was established in 2013 to enable major Space Agencies to collectively contribute to the implementation of the Architecture for Climate Monitoring from Space through a coordinated CEOS-CGMS approach.

The primary objective of WGClimate is to improve the systematic availability of Climate Data Records, including the GCOS ECVs, by supporting the coordinated implementation and further development of the Architecture for Climate Monitoring from Space. A cornerstone of this effort is the creation of the ECV Inventory (available at climatemonitoring.info/ecvinventory), which compiles climate data record holdings of all ECVs across space agencies.

WGClimate supports GCOS in defining and delivering the ECVs needed by the UNFCCC and facilitates CEOS' broader engagement with the UNFCCC, its subsidiary bodies, and the Intergovernmental Panel on Climate Change (IPCC). Additionally, WGClimate is tasked by CEOS and CGMS to coordinate Space Agency responses to the GCOS Implementation Plan (this document) and to report CEOS-CGMS climate actions to SBSTA/UNFCCC.

WGClimate and its member agencies remain committed to applying the GCOS Climate Monitoring Principles and guidelines. Beyond the space segment, the group recognizes the vital role of Space Agencies' resource data management systems, which enable access to, use of, and interpretation of climate data and products as essential elements of comprehensive climate monitoring systems.

Response to Theme A: Ensuring Sustainability

Action A2: Address gaps in satellite observations likely to occur in the near future

Activity A2.1

Altimetry in the polar regions

Means of assessing progress: Established plans of Space agencies that ensure the continuation of satellite missions for **altimetry**, gravimetry, biomass, limb-sounding, sea surface salinity, wind lidar, global scale ice surface elevation

Activity A2.1 focuses on ensuring the continuation of satellite missions dedicated to altimetry in the polar regions. Altimetry plays a critical role in monitoring several Essential Climate Variables (ECVs), including Ice Sheets and Shelves, Glaciers (specifically polar glaciers), Sea Level (in polar oceans), Surface Currents (in polar oceans), Sea State (in polar oceans), and Sea Ice. Additionally, altimetry provides valuable data for the Snow ECV and holds potential for high-resolution observations relevant to the Permafrost ECV in the future.

Polar orbiters in sun-synchronous orbits, with an inclination of approximately 98.5º and an altitude of 800 km, provide measurements up to 81°–82° latitude. These include historical missions such as ERS-1, ERS-2, and Envisat, as well as current missions like SARAL/AltiKa (Ka-band altimeter), Sentinel-3A/B (Ku-band SAR altimeter), and HY-2C/D (Ku- and C-band altimeter). The Sentinel-3 and HY-2 satellites are part of operational programmes designed to ensure sustained, long-term observations.

The Sentinel-3 mission, part of Europe's Copernicus programme, has a well-established continuity plan for the coming decades. Sentinel-3C is scheduled for launch in Q3 2026, followed by Sentinel-3D in 2028, with both satellites already procured. Additionally, the next-generation Sentinel-3 Topography (S3NG-Topo) mission is under development by ESA, the agency responsible for the Copernicus space segment. Meanwhile, the HY-2 series will continue with HY-2E planned for launch in July 2026, followed by HY-2F in 2027. With five altimeters currently in orbit and plans for Sentinel-3C/D, S3NG-Topo, and future HY-2 platforms, no observational gaps are anticipated.

Dedicated missions for Arctic Ocean and polar land ice, operating at an altitude of around 700 km with a 92º inclination in non-sun-synchronous orbits, include CryoSat-2 (radar altimeter) and NASA's ICESat-2 (laser altimeter). These missions provide near-complete coverage of polar oceans, polar ice sheets, and sea ice. The Copernicus programme is also implementing the operational polaR Ice and Snow Topography ALtimetre (CRISTAL) mission, which includes two satellites. CRISTAL A is slated for launch in 2028, followed by CRISTAL B in 2034.

The GCOS requirements for ice sheets and sea ice have guided CRISTAL's mission design. CRISTAL will incorporate a dual-band approach (simultaneous Ka and Ku bands) to directly measure snow depth on sea ice, significantly enhancing sea ice thickness observations.

ICESat-2 is expected to last until mid 2030s, and its record will be continued by CRISTAL. Proposed solutions in the GCOS Implementation Plan, such as launching S3NG-Topo early to

replace CryoSat-2, are unsuitable due to differences in inclination and mission objectives. Similarly, maneuvering existing satellites into high-inclination orbits is not feasible due to physical constraints and satellite design limitations.

Sentinel-3C/D, S3NG-Topo, and CRISTAL A/B will collectively sustain observations of sea level and sea state in polar regions for oceanographic and climate applications. The European Union's Copernicus missions benefit from the collaboration between ESA and EUMETSAT, ensuring the operational delivery and regular reprocessing of data products across all levels.

Activity A2.2

Gravimetry missions

Means of assessing progress: Established plans of Space agencies that ensure the continuation of satellite missions for altimetry, **gravimetry**, biomass, limb-sounding, sea surface salinity, wind lidar, global scale ice surface elevation.

The GRACE (2002–2017) and GRACE Follow-On (2018–present) missions, developed and operated by NASA in collaboration with the German Aerospace Center (DLR) and GeoForschungsZentrum Potsdam (GFZ), measure monthly variations in Earth's gravity field caused by mass transport within the Earth system. These changes, reflecting mass redistribution across Earth's atmosphere, oceans, groundwater, and ice sheets, are critical indicators of large-scale planetary dynamics.

By observing Earth's water movement and monthly surface mass changes, GRACE and GRACE-FO contribute to the understanding of 15 Essential Climate Variables (ECVs). These observations have far-reaching implications, offering an integrated global view of Earth's evolving water cycle and energy balance. Applications include monitoring changes in ice sheets and glaciers, terrestrial water storage, groundwater reserves, large lakes and river systems, sea levels, and ocean currents. The data are essential for addressing pressing issues such as drought and flood monitoring, as well as climate risk and mitigation assessments.

In addition to their contributions to hydrology and climate science, GRACE and GRACE-FO provide unique insights into solid Earth processes, including glacial isostatic adjustment and earthquakes. These findings have been prominently featured and widely utilized in the IPCC's 5th and 6th Assessment Reports.

NASA and DLR are planning to launch a continuity mission, the Mass Change mission (GRACE-C), as part of NASA's Earth System Observatory in 2028. GFZ will continue to deliver geophysical products for this mission. GRACE-FO, having completed its prime mission phase in May 2023, is now in its extended operational phase. Based on current solar cycle forecasts and fuel reserves, GRACE-FO is expected to remain operational until 2028–2029. The GRACE-C mission, if launched as planned, will ensure data continuity and extend the consistent climate data record established by GRACE and GRACE-FO.

To further guarantee the long-term continuity of gravimetric measurements, NASA and ESA have initiated the Mass-Change and Geosciences International Constellation (MAGIC) and developed

the concept for a Next-Generation Gravity Mission (NGGM). Scheduled for a tentative launch in 2031–2032, NGGM will feature an inclined, non-polar orbit. When combined with a polar satellite pair such as GRACE-C, NGGM will significantly enhance the temporal and spatial resolution of mass transport observations. However, a single inclined satellite pair alone would be insufficient to ensure global gravity and mass change continuity or to maintain a consistent climate data record.

Activity A2.3

Biomass measurements

Means of assessing progress: Established plans of Space agencies that ensure the continuation of satellite missions for altimetry, gravimetry, **biomass**, limb-sounding, sea surface salinity, wind lidar, global scale ice surface elevation

Earth observation (EO) satellites have been collecting global data on the state and dynamics of landscapes for over 40 years. Their critical role in understanding climate change, greenhouse gas (GHG) emissions, and the requirements for mitigation and adaptation has become increasingly recognized. The 2019 update to the IPCC guidelines on AFOLU (Agriculture, Forestry, and Other Land Use) highlighted significant advancements in EO applications for monitoring land use and land cover changes, as well as directly quantifying atmospheric GHG concentrations. The guidelines also provided generic recommendations for incorporating biomass density maps into GHG inventories.

The CEOS AFOLU team organized four dedicated sub-teams of experts focusing on Agriculture, Land Cover and Forests, Above Ground Biomass (AGB), and Wetlands and Mangroves. These teams, comprising longstanding contributors to space-based datasets, have demonstrated the value of EO-derived AGB maps in supporting GHG inventories.

EO data has enabled the development of biomass estimates ranging from local to global scales, leveraging sensors such as radar, lidar, and optical systems. However, many of these datasets face limitations, including signal saturation (common in optical and Synthetic Aperture Radar (SAR) data, depending on radar frequency and polarization) and partial observations (e.g., lidar data, which depend on footprint size and sampling relative to vegetation distribution in vertical and horizontal dimensions). These challenges have historically restricted the operational use of sensors, particularly in high-biomass regions. Nevertheless, the insights gained have informed the design of next-generation biomass missions and products, such as GEDI, ICESat-2, NISAR, and BIOMASS, which aim to reduce uncertainties in AGB estimates and enhance country-level and global forest carbon monitoring. These advancements, along with pilot studies demonstrating their policy applications, are accessible through the Multi-mission Algorithm and Analysis Platform (MAAP).

Recent and upcoming biomass missions (post-2019) represent a significant leap in EO capabilities. Missions such as GEDI, ICESat-2, BIOMASS, NISAR, and ALOS-4 PALSAR-3 are poised to revolutionize biomass monitoring and will likely be complemented by additional missions like MOLI and ROSE-L. While each mission is expected to release its own biomass products, further

advancements are anticipated through data fusion approaches, as exemplified by ESA's CCI Biomass project. This initiative integrates biomass retrievals from C- and L-band radar with spaceborne optical and lidar data.

GEDI, hosted on the International Space Station (ISS), and MOLI share the limitation of being unable to observe high-latitude regions. ICESat-2, as the only other spaceborne lidar mission, fills this observational gap. To address global ecosystem monitoring comprehensively, future terrestrial lidar missions prioritize high-latitude coverage.

GEOTREES complements these spaceborne efforts by providing high-quality ground data through a global network of long-term forest inventories and permanent plots. These data sets support calibration and validation of EO sensors and align with the CEOS Aboveground Biomass Land Product Validation protocol recommendations.

Activity A2.4

Limb-sounding missions capable of measuring several ECVs in the UTLS and stratosphere

Means of assessing progress: Established plans of Space agencies that ensure the continuation of satellite missions for altimetry, gravimetry, biomass, **limb-sounding**, sea surface salinity, wind lidar, global scale ice surface elevation

Several currently operational spaceborne instruments are well beyond their design lifetimes, and some are scheduled to be decommissioned in the next few years. Limb profiling instruments that will likely cease operations in the coming years are the Odin Optical Spectrograph and Infrared Imager System (OSIRIS) and Sub-Millimeter Radiometer (SMR), expected to reenter Earth's atmosphere in Q2 2026, the SciSat Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS), which has been operating beyond its design life since 2005, and the Aura Microwave Limb Sounder (MLS), which is expected to lose power by 2028. The loss of current limb-viewing capabilities will terminate vertically resolved global measurements of many trace gases relevant for stratospheric chemistry and dynamics, including reactive (chlorine monoxide, ClO) and reservoir (hydrochloric acid, HCl; chlorine nitrate, $ClONO_2$) chlorine species, water vapor, nitric acid (HNO_3), and long-lived transport tracers (e.g., nitrous oxide, N_2O; methane, CH_4; carbon monoxide, CO; methyl chloride, CH_3Cl). The impending cessation of these measurements, many of which have been taken continuously over the last several decades, will hamper the ability to reduce key uncertainties that remain in understanding stratospheric ozone depletion, including the lack of emergence of a clear signature of recovery in the Arctic, the potential influence of volcanic and wildfire emissions, and the role of very short-lived substances, among others.

The only planned limb sounder is the ESA EarthWatch mission ALTIUS (Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere) with an expected launch in 2027. The primary objectives of ALTIUS are to observe the global distribution of stratospheric ozone at high vertical resolution in support of operational services in near-real time and to contribute to stratospheric ozone long term monitoring. The secondary objective of ALTIUS is to provide profiles of mesospheric ozone and of other trace gases (H_2O and NO_2) and particles in the middle

atmosphere for scientific studies related to ozone chemistry, climate change and atmospheric dynamics.

In February 2026, NASA selected the Stratosphere Troposphere Response using Infrared Vertically-Resolved Light Explorer (STRIVE) for continued development under the Earth System Explorers Program. This mission will provide daily, near-global, high-resolution measurements of temperature, a variety of atmospheric elements, and aerosol properties from the upper troposphere to the mesosphere – at a much higher spatial density than any previous mission. It will also measure vertical profiles of ozone and trace gasses needed to monitor and understand the recovery of the ozone layer. STRIVE will launch no earlier than 2030. STRIVE is part of the FALCON mission.

Activity A2.5

Sea surface salinity (SSS) measurements

Means of assessing progress: Established plans of Space agencies that ensure the continuation of satellite missions for altimetry, gravimetry, biomass, limb-sounding, **sea surface salinity**, wind lidar, global scale ice surface elevation

Space agencies are actively exploring collaboration opportunities to address gaps in sea surface salinity (SSS) observations likely to occur in the future. The first aspect is to sustain the measurements from the currently existing SSS sensors (SMOS and SMAP). Although in orbit since 2009 and 2015, respectively, they are still being funded by the respective agencies, and continuous efforts are devoted to further improve the processing algorithms, address the existing issues, improve the validation chain, and derive additional products. Reprocessing campaigns to improve and homogenize the entire SSS archives are periodically performed. Merged SMOS and SMAP SSS datasets are also generated within the framework of the ESA CCI programme.

The first of China's Ocean Salinity Satellites (HY-4A) was launched in November 2024, and carries the Interferometric Microwave Radiometer (IMR) and the Microwave Imager Combined Active and Passive (MICAP). The European CIMR (Copernicus Imaging Microwave Radiometer) mission, led by ESA and jointly implemented with EUMETSAT, is planned to launch CIMR-A in 2029, which underwent Preliminary Design Review (PDR) in 2022, and is now in Phase C/D. A second instrument CIMR-B is planned to follow in 2035. The orbit is designed to synchronise with EUMETSAT's series of Metop-SG B satellites, particularly enhancing the overall coverage of Earth observation data. CIMR includes an L-band channel which will provide SSS measurements in the global oceans, with a distinctive focus on Polar regions. Although its spatial resolution is slightly coarser than the current measurements, CIMR will benefit from good accuracy, high temporal revisit and concurrent SST and wind speed measurements from additional bands available on the same platform. Bi-lateral NASA/ESA discussions of a potential collaboration in the context of CIMR are ongoing, and on other concepts for high-resolution SSS measurement. This collaborative effort also involves coordinating Calibration and Validation (CalVal) campaigns and maintaining the joint ESA/NASA effort on developing a multi-mission satellite SSS evaluation

Activity A2.6

Wind lidar

Means of assessing progress: Established plans of Space agencies that ensure the continuation of satellite missions for altimetry, gravimetry, biomass, limb-sounding, sea surface salinity, **wind lidar**, global scale ice surface elevation

ESA developed the Aeolus satellite mission that was launched on 22 August 2018 and operated it until 28 July 2023. Aeolus was the first satellite mission to acquire profiles of Earth's wind on a global scale. The Aeolus satellite carried just one large instrument – a Doppler wind lidar that measured the winds in the troposphere. Built to improve weather forecasts, it surpassed scientific expectations. The operational assimilation of its data by several major European Numerical Weather Prediction centers fully demonstrated the observational principle, critical technologies, and significant scientific impact.

EPS-Aeolus (Aeolus-2) will be the successor to ESA's Aeolus Earth Explorer mission. Aeolus-2 will allow the determination of wind vectors from the ground to 30 km altitude by measuring the Doppler shift of the signal backscattered by transmitted pulses from an ultraviolet laser. Exploiting an additional cross-polarisation channel, the new instrument - derived from the original Aeolus ALADIN instrument (Atmospheric Laser Doppler INstrument) - will also have an enhanced capability for aerosol profiling (linking with activity B3.1).

The Aeolus-2 implementation is progressing with the development entering Phase B2 in 2026. EUMETSAT would operate the ESA-developed instrument and satellite in the frame of the EPS-Aeolus programme which is under preparation. The launch of Aeolus-2 is currently planned for 2034, targeting 5.5 years of lifetime with consumables for 7 years of operations.

Activity A2.7

Global scale ice surface elevation – No follow up to Terra/ASTER

Means of assessing progress: Established plans of Space agencies that ensure the continuation of satellite missions for altimetry, gravimetry, biomass, limb-sounding, sea surface salinity, wind lidar, **global scale ice surface elevation**

The ASTER instrument aboard the Terra satellite will deorbit in the next few years. ICESat-2 is expected to last until mid 2030s and will provide continued global ice surface elevation

observations until the planned CRISTAL missions. One issue with the lack of follow up to Terra/ASTER is that we actually use DEM differencing as an independent technique to calculate ice surface elevation change. ASTER provided stereo sensor capabilities to calculate DEMs. With no continuation in sight, and no efforts being made to even consider a new stereo system, there will be many problems at several ends including poor orthorectification and geolocation for sensors using outdated or too coarse DEMs.

In February 2026, NASA selected the EDGE (Earth Dynamics Geodetic Explorer) mission for continued development as part of NASA's Earth System Explorers Program. EDGE will observe the three-dimensional structure of terrestrial ecosystems and the surface topography of glaciers, ice sheets, and sea ice, providing an advancement beyond the measurements currently recorded from space ICESat-2 and GEDI. EDGE will launch no earlier than 2030 and is part of the EAGLE mission.

Action A3: Prepare follow-on plans for critical satellite missions

Activity A3.1

Earth radiation budget measurements

Means of assessing progress: Established **long-term** plans of Space agencies demonstrating the continuation of satellite missions for earth radiation budget

Earth radiation budget (ERB) datasets are used to address many topics in climate science, including Earth's energy imbalance, climate feedback, aerosol radiative forcing, energy transport, and climate model evaluation. Climate science use of ERB data requires a long-term, integrated global climate data record (CDR) of the ERB from the surface to the top-of-atmosphere (TOA) together with the associated cloud, aerosol and surface properties. The Clouds and the Earth's Radiant Energy System (CERES) has been providing Level 1-4 ERB data products since 2000 from CERES instruments on Terra, Aqua, S-NPP and NOAA-20. The ERB CDR will be continued with Libera on JPSS-4 (launch planned for 2027).

Creating an ERB CDR involves integration of measurements from multiple instruments (e.g., CERES, MODIS, VIIRS, TSIS, geostationary imagers) and ancillary datasets to produce a seamless continuous record. The CERES CDR is the only dedicated global ERB CDR available for climate science research, as GERB and ScaRaB only provide regional measurements with higher uncertainty. The CERES framework has also been leveraged to provide additional data products for process studies (CALIPSO, Cloudsat, CERES, MODIS, C3M) and Applied Sciences (renewable energy and agriculture, CERES FLASHFlux). NASA is providing some funding to explore future use of small satellites and cubesats for ERB observations, but there are currently no plans to fly an ERB instrument after Libera. A data gap in the ERB CDR would significantly increase trend uncertainty.

The EarthCARE mission, launched in May 2024, has a broadband radiometer (BBR) with three fixed telescopes pointing forward, nadir, and backward. BBR will only provide along-track measurements, thus its spatial coverage is too limited for ERB studies. The Earth Radiation Measurement sensors on the FY-3 series have released L1 radiance data but have not released any higher level data. .

NASA's PREFIRE and ESA's FORUM mission focus on the far Infrared (FIR) spectral band. NASA's PREFIRE mission was launched in 2024 to measure the FIR radiation over the polar regions. ESA's FORUM mission will be launched in 2027 to measure Earth's outgoing radiation in the FIR range with high spectral resolution and radiometric accuracy. ERB measurements will benefit from the launches of absolute reference instruments (CLARREO-Pathfinder-ISS and Libera, see activity B1.5). This activity has strong links to activity B3.2 on EEI.

Activity A3.2

Cloud profiling

Means of assessing progress: Established **long-term** plans of Space agencies demonstrating the continuation of satellite missions for cloud profiling

NASA's CloudSat, with a 94-GHz nadir-looking cloud-profiling radar, has provided valuable cloud observations since its launch in 2006. After exiting the A-train constellation in 2018, CloudSat joined NASA/CNES's CALIPSO to form the C-train constellation, continuing cloud profiling science. CALIPSO ceased scientific data collection on August 1, 2023, and CloudSat was deactivated on December 20, 2023.

The joint ESA-JAXA mission EarthCARE, launched in May 2024, succeeds CloudSat and CALIPSO by providing advanced cloud profiling capabilities. EarthCARE combines JAXA's 94-GHz Doppler Cloud Profiling Radar with ESA's UV High Spectral Resolution Lidar (HSRL) to deliver high-quality cloud profile data and extend the observational record. Early cloud profiling data from EarthCARE mission looks promising for this purpose.

Cloud profiling observations will continue with NASA's FALCON missions - one will carry a lidar sensor, and the second will carry a cloud-profiling radar.

Activity A3.3

Cloud lidar

Means of assessing progress: Established **long-term** plans of Space agencies demonstrating the continuation of satellite missions for cloud lidar

CALIPSO ceased scientific data collection on August 1, 2023, after 17 years of operation. The ESA/JAXA EarthCARE mission, launched in May 2024, carries a UV (355 nm) HSRL lidar to measure cloud and aerosol profiles. NASA's FALCON mission, announced in April 2026, will include a cloud lidar, although the exact specifications are yet to be announced.

Activity A3.4

Global precipitation measurement consisting of a dual-frequency precipitation radar and passive microwave measurements to provide sufficient temporal and spatial sampling of rain areas

Means of assessing progress: Established **long-term** plans of Space agencies demonstrating the continuation of satellite missions for Global Precipitation Measurement

The Global Precipitation Measurement (GPM) mission continues the precipitation measurements framework initiated by the Tropical Rainfall Measuring Mission (TRMM). This is achieved by combining observations from a 13.6-GHz precipitation radar and a microwave radiometer

(10–89 GHz). GPM, launched in 2014, comprises the drifting low inclination NASA-JAXA Core Observatory, supported by a constellation of passive microwave imagers and sounders provided by international partners. The Core Observatory features JAXA's dual-frequency precipitation radar (14 and 36 GHz) and NASA's GPM microwave imager (10–183 GHz).

China's FY-3G, launched in 2023, is a precipitation measurement satellite with a drifting orbit carrying six instruments, including a 13.3- and 36-GHz precipitation radar and a microwave imager (10–183 GHz). Data from FY-3G is available from 23 October 2023, further enhancing global precipitation monitoring capabilities.

Looking ahead, the Precipitation Measuring Mission (PMM) satellite is planned for launch in 2030 as part of NASA's FALCON mission. PMM will feature JAXA's 14-GHz Ku-band precipitation radar with Doppler capabilities at nadir. The PMM satellite will also carry a high-frequency passive microwave sounder, C^2OMODO (operating at 3 frequency ranges: 89 GHz, 183 GHz and 325 GHz), provided by CNES.

Current and near-future satellites with passive microwave radiometers include:

- Passive microwave imagers on JAXA's GCOM-W and GOSAT-GW, EUMETSAT's EPS-SG-B, CMA's FY-3 series and US DoD WSF-M missions
- Passive microwave sounders on EUMETSAT's EPS-SG-A and NOAA missions
- Passive microwave sounders on smallsats/cubesats, such as EUMETSAT's AWS, NOAA's Quicksounder, and commercial entities (e.g. tomorrow.io).

Despite this robust network, significant temporal gaps remain, which could potentially be addressed through the deployment of small satellites or CubeSats, including those provided by commercial entities, provided they meet the required channel selection, resolution, and data quality standards. However, CGMS International Precipitation Working Group (IPWG) has done assessment of the timeline of precipitation-sensitive passive microwave radiometers, and indicated that use of an increasing number of CubeSat-sized passive microwave sounders, which only have high-frequency (>= 90 GHz) channels, will skew the derived precipitation estimates towards indirect, ice-based (scattering) retrievals, rather than the precipitation closer to the surface. In addition, there are currently no plans for low-inclination, wide-frequency-range passive microwave imagers in future mission concepts to serve as a reference standard, similar to the microwave imager onboard the GPM Core Observatory.

Activity A3.5

Sea ice and icebergs (or floating ice)

Means of assessing progress: Established **long-term** plans of Space agencies demonstrating the continuation of satellite missions for floating ice

Sea ice and icebergs or floating ice are defined as seven ECV products: Sea Ice Concentration; Sea Ice Thickness; Sea Ice Drift; Sea Ice Age; Sea Ice Temperature; Sea Ice Surface Albedo; and Snow Depth on Sea Ice. Different types of sensors are needed to observe each of those ECVs.

Microwave imagers are commonly used to observe daily global Sea Ice Concentration, Sea Ice Drift, Sea Ice age, Sea Ice Temperature, and Snow Depth on Ice by its cloud penetrating capability. Historical data by the US SSM/I series, Nimbus-7/SMMR, DMSP/SSM/I and DMSP/SSMIS (18-89GHz), has been available since 1978 to produce Climate Data Records (CDRs), but the last SSMIS is currently flying without a scheduled follow-on mission. Data from JAXA's AMSR series, Aqua/AMSR-E and GCOM-W/AMSR2 (6-89GHz), has been available since 2002 with finer spatial resolution than the SSM/I series by its 2-m diameter antenna, and is continued with the launch of AMSR3 (6-183GHz), on board GOSAT-GW, in 2025. Combined Sea Ice CDR of the SSM/I series and AMSR series are developed and released by several agencies. Europe is also preparing to launch two microwave imagers, MetOp-SG-B/MWI (18-183GHz) in 2026 and CIMR (1-36GHz) in 2029.

L-Band (1-2 GHz) microwave imager observations have been used to derive the thickness of thin (up to about 0.7 m) sea ice in the Arctic Ocean since winter 2009/2010. Derived sea ice thickness agrees with that from satellite altimetry very well. First attempts to derive thickness of thin sea ice in the Southern Ocean exist. The upcoming CMIR mission will succeed L-Band microwave observations.

Satellite laser and/or radar altimetry has been available since the early 1990s to estimate sea ice thickness. High inclination orbits are required to optimally monitor the Arctic Ocean's ice cover and have been used by NASA's ICESat (2003-2010) and ICESat-2 (2018-) and ESA's CryoSat-2 (2010-) sensors. The Copernicus CRISTAL mission will have similar coverage. All other past or existing (ERS1/2, Envisat-2, SARAL/AltiKa, Sentinel-3 A/B, HY-A/B) and future (e.g. Sentinel-3 C/D) radar altimeters leave a large part of the Arctic Ocean unobserved due to their lower inclination orbit but provide good spatial coverage for the Southern Ocean sea ice cover. New missions to monitor sea ice thickness should ensure complete coverage of both polar regions. The Copernicus programme is also implementing the operational polaR Ice and Snow Topography ALtimetre (CRISTAL) mission, which includes two satellites. CRISTAL A is slated for launch in 2028, followed by CRISTAL B in 2034. This activity is related to A2.1.

SAR is used to capture detailed structure of sea ice and icebergs with high-spatial resolution but with narrow swath width (e.g., sparse temporal sampling). For example, ESA's Sentinel-1 C-Band (4-8 GHz) SAR sensors have substantially increased the coverage in polar oceans, resulting in considerable enhancement of several sea ice products (i.e., sea-ice motion, sea-ice type, sea-ice age). New and upcoming SAR missions, such as NASA and ISRO's NISAR (launched in 2025), will provide frequent observation of Sea Ice in resolution of ~10m. NISAR will be also used for estimating Sea Ice Drift with requirement of 5-km grid with an average sampling capability of three days. The Canadian space agency provides ice services for operational monitoring from the RADARSAT constellation.

Imagers operating in the visible (VIS) and/or infrared (IR) part of the electromagnetic spectrum are used to infer sea ice temperature (IR imagers) and sea ice surface albedo (VIS imagers) when there are no clouds. VIS/IR data have been available from polar orbiting imagers by the NOAA satellite series since 1970 and NASA MODIS on Terra (since 1999) and Aqua (since 2002). These

missions have been succeeded by a series of JPSS/VIIRS satellite sensors (since 2012). EUMETSAT has been operating polar orbiting VIS/IR imagers on board the MetOp satellite series (since 2006). Observations will be continued by the MetOp-SG series currently in development, with the first platform launched in 2025. Several other agencies have been operating polar orbiting VIS/IR imagers and providing important sea ice observations (e.g., NASA/USGS's Landsat family, or ESA's Sentinel-2 MSI and Sentinel-3 OLCI) that, albeit less efficient in sampling frequency and coverage, offer substantially finer spatial resolutions and therefore have been, and will be, indispensable for sea ice ECV product development and evaluation and should be continued. Landsat 10 will improve its spatial resolution to 10-20 m visible to shortwave infrared, 60m thermal observations and 26 spectral bands. Landsat 8 & 9 have recently begun collecting more polar twilight and darkness data (See LEAP: Landsat Extended Acquisitions of the Poles Imaging Plan, 2024). Studies are ongoing to assess the feasibility of extending the Sentinel-2 and -3 coverage of sea ice monitoring using observations during twilight.

It is important to note that the success of continuing to monitor the polar regions requires careful thought in designing global satellite missions with synergies to ensure these are also applicable in the polar regions.

Response to Theme B: Filling Data Gaps

Action B1: Development of reference networks (in situ and satellite Fiducial Reference Measurement (FRM) programs)

Activity B1.3

Better align the satellite FRM program to the reference tier of tiered networks and enhance/expand FRM to fill gaps in satellite cal/val

Means of assessing progress: Alignment of FRM programs into the tiered network of networks concept; and additional FRM measurements to fill gaps to support satellite cal/val of ECVs such as Above Ground Biomass, albedo, FAPAR, LAI and burned area

The CEOS Working Group on Calibration and Validation (WGCV) provides quality references, methodologies, and protocols for calibration and validation (Cal/Val), along with tools and expertise. Its goals are to enhance confidence in satellite measurements, ensure traceability, and promote harmonisation. To support these objectives, the CEOS WGCV strives to align the satellite Fiducial Reference Measurement (FRM) program with the reference tier of tiered networks and to enhance and expand FRM efforts to address gaps in satellite Cal/Val. CEOS WGCV supports this initiative along three objectives:

1. Help in assessing the maturity toward FRM standard
2. Support activities to improve the quality measurements towards FRM
3. Support an FRM network

CEOS WGCV developed a roadmap towards an Assessment Framework for FRM. The purpose of the document is to propose a roadmap towards an assessment framework to endorse a specific class of measurements as a FRM. It provides the FRM definition and principles, the FRM endorsement process, the FRM maturity matrix and the FRM overall classification. Pilot projects were selected for the initial assessment, which include Pandonia Global Network, RadCalNet (Radiometric Calibration Network), ICOS (Integrated Carbon Observation System – Ecosystem Component), Ground-Based DOAS Air-Quality Observations, BAQUNIN (PREDE-POM LUNAR), CSIRO (DION), CEOS FRM MM - Brewer Spectrometer Measurements, and Hypernets. In addition, several projects for improving the measurements quality have been supported by CEOS, which includes FRM4SM (Soil Moisture), FRM4STS (Surface Temperature), FRM4SOC (Ocean Colour), FRM4DOAS (DOAS), FRM4GHG (Greenhouse gases), FRM4VEG (Vegetation), FRM4AQ (Air Quality supporting Pandora). These projects provide an intercomparison framework that facilitates a better understanding and characterisation of the measurements, including a proper uncertainty budget. A second FRM Assessment Framework pilot exercise is being conducted in 2026 with projects including NDACC (Network for the Detection of Atmospheric Composition Change), FRM4Drones, USGS, PGN, FRM4DOAS, Centre for Reactive Trace Gases Remote Sensing (CREGARS), and FRM4SM.

WGCV is developing the reference networks RADCalNet for radiometric calibration and validation, SARCalnet for SAR missions, and TIRCalnet for thermal infrared calibration and

validation. CEOS WGCV is also supporting several other networks, such as TCCON, COCCON, PGN, GBON, ICOS, and HYPERNETS.

Activity B1.5

Establish a long-term space-based reference calibration system to enhance the quality and traceability of earth observations. The following measurables are to be considered: high-resolution spectral radiances in the reflected solar and infrared wave bands, as well as GNSS radio occultations

Means of assessing progress: Implementation of CLARREO pathfinder pathfinder, TRUTHS and PREFIRE. Plans for long-term follow-on missions to the short-term (<1y) pathfinder missions (CLARREO and PREFIRE) and long-term continuous measurements

As of December 2024, the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder (CPF) payload was completed in October 2024 and is currently in storage at the Laboratory for Atmospheric and Space Physics in Boulder, CO. The mission is expected to meet the 0.3% (1-sigma) reflectance radiometric uncertainty requirement. Launch time frame is expected to be in 2026. Although just one year of operations is included in the scope of the mission, negotiations are ongoing to extend its scheduled occupancy and operations on ISS at least through the end of the current ISS schedule (approximately 2030). Mission extension for any NASA mission is subject to the senior review process, and this would include CPF's potential extension in mission operations. PREFIRE was launched in May 2024 and is measuring spectral radiances from 5 to 53 μm with a spectral sampling resolution of 0.84 μm to better understand polar far-IR radiation budget. ESA is planning to launch FORUM in 2027 to measure spectral far-IR radiation.

In 2025, the TRUTHS mission was defunded and the activities are now winding down. The science activities will be completed by Q2 2026, and an overview paper will be published.

The Chinese Space-based Radiometric Benchmark (CSRB) project has been under development since 2014 and the LIBRA satellite was planned to launch around 2025, however no plans for launch are yet available. LIBRA will offer measurements with SI traceability for the outgoing radiation from the Earth and the incoming radiation from the Sun with high spectral resolution.

Action B3: New Earth observing satellite missions to fill gaps in the observing systems

Activity B3.1

Improve diurnal sampling of observations and coverage of GHGs, precursor aerosols, and solar-induced fluorescence (SIF) to improve estimation of emissions and vegetation carbon update

Means of assessing progress: Feasibility studies addressing mission concepts relevant to observation and mission gaps. Solicitations by Space agencies for satellite mission development relevant to the above points.

Global and local (facility-scale) observations of greenhouse gases (GHGs) are anticipated to increase significantly in the coming years. The CEOS Atmospheric Composition Virtual Constellation (AC-VC) has been actively monitoring the expanding GHG satellite constellation annually to ensure these measurements are supported by robust calibration, validation, and evaluation efforts, while also addressing any measurement gaps.

For example, recent studies and growing consensus in the scientific community highlight the added value of integrating aerosol, precursor gases (e.g., SO_2, NOx), and solar-induced chlorophyll fluorescence (SIF) observations alongside GHG measurements. These additional capabilities are strongly encouraged for future missions and are already planned for inclusion in several upcoming ones. To maximize their utility, GCOS is encouraged to specify the product requirements for aerosols precursor gases to ensure their optimal implementation, as aerosols remain a critical priority. An operational framework is already envisioned, including instruments on MetOp-SG and the aerosol instrument aboard the Copernicus CO2M Mission.

The current generation of GHG satellites, such as GOSAT-1/-2, Sentinel-5 Precursor, and OCO-2, primarily have early afternoon overpass times. While this timing is optimized for capturing well-mixed planetary boundary layer conditions, it may be suboptimal for regions with increased afternoon cloud cover or other local retrieval challenges. Morning overpasses, such as those for the Sentinel-5 and CO2M Missions, could provide unique insights into processes like CO_2 uptake and CH_4 release, as well as diurnal concentration variations. Such data would enable divergence flux techniques and process-based analyses.

While missions in GEO, HEO, and MEO orbits could offer alternative solutions for diurnal sampling, each comes with significant trade-offs and differing performance compared to LEO satellites. Active GHG missions, typically in dusk-dawn orbits, do not provide nighttime observations. For CH4, the upcoming MERLIN mission, scheduled for launch in the late 2020s, will contribute valuable data. However, enhancing diurnal sampling remains a complex challenge. Close collaboration with GCOS is essential to clarify the objectives and use cases for enhanced diurnal sampling, particularly for global and local CO2 and CH4 observations.

Activity B3.2

Explore new ways to improve estimates of Earth's energy imbalance (EEI) with novel remote sensing techniques and with very well calibrated hyperspectral measurements over the full spectrum of the outgoing longwave and shortwave radiations

Means of assessing progress: Feasibility studies addressing mission concepts relevant to observation and mission gaps. Solicitations by Space agencies for satellite mission development relevant to EEI.

Despite that Earth energy imbalance (EEI) being the most important variable to monitor how the Earth system responds to natural and anthropogenic forcing, it cannot be determined directly from Earth radiation budget measurements at the top of the atmosphere (TOA) in an absolute sense. The magnitude of EEI is less than 1 Wm^{-2}, which is roughly 0.15% of the total incoming and outgoing radiation that is on the order of 340 Wm^{-2} at the TOA. The current state-of-the-art Earth radiation budget (ERB) instruments of total solar irradiance and outgoing radiation are not at the accuracy level to determine the EEI without applying constraints. The absolute uncertainty in solar irradiance alone is 0.13 Wm^{-2}. The actual uncertainty for the Clouds and the Earth's Radiant Energy Systems (CERES) resulting from calibration alone is 1% and 0.75% for shortwave (SW) and longwave (LW) radiation, which corresponds to 2Wm^{-2}, or 0.6% of the total TOA outgoing radiation.

Current approaches of determining the EEI are based on ocean heat uptake from satellite measurements using altimetry and gravimetry, and from in-situ ocean temperature measurements from the Argo network. These two approaches are regarded as the most accurate by the scientific community and indicate an EEI of 0.8±0.3 Wm^{-2} (at 90% confidence level) over the period of 2005-2020. Since the ocean absorbs more than 90% of the excess energy stored by the Earth system, estimating the ocean heat content change provides an accurate proxy of the EEI. The Earth radiation budget measurements at TOA (by the CERES instruments) provide the most precise quantification of the EEI variability and trend. It indicates a trend in EEI of 0.4±0.2 Wm^{-2} (at 66% confidence level) per decade over the period of 2005-2020. Continuity and improvement of the altimetry and gravimetry missions, and the ERB missions are critical for the long-term monitoring of EEI. Given that ERB measurements provide the most accurate EEI trend, it's most important to continue ERB measurements and ensure overlaps between successive ERB missions. Attributions of EEI changes may also benefit from reference measurements such as CLARREO.

This activity links strongly to A3.1 on ERB measurements.

Activity B3.3

Provide direct measurements of ocean surface currents from space

Means of assessing progress: Feasibility studies addressing mission concepts relevant to observation and mission gaps. Solicitations by Space agencies for satellite mission development relevant to ocean surface currents.

The current planning by space agencies regarding surface currents is as follows:

A CFOSAT follow-on mission will be launched no earlier than 2030, on the HY-2L mission (NSOAS, CAST). It is proposed to have Ku band Multi-beam Doppler Scatterometer for the Ocean Surface Current observation, measuring Ocean Surface Currents with an accuracy of 0.2m/s.

OSCOM was proposed as a candidate mission of the Chinese Strategic Priority Program on Space Science. It has reportedly been approved to be launched in 2026. It will directly measure ocean surface currents with a horizontal resolution of 5–10 km and a 3-day global coverage. The accuracy of currents is 0.1m/s in speed and 15° in direction.

After the SKIM and SeaStar proposals were not selected, Harmony (alternate reference) is an ESA Earth Explorer (EE10) mission planned to be launched in 2029. As a tandem mission for the Sentinel-1 SAR mission, it will not provide global coverage but focus on the acquisition of scenes with high resolution for the underlying ocean km-scale processes. In addition, a DopSCA feasibility study is being carried out by ESA. It aims to define requirements on surface currents retrieval and assess the feasibility of using the EUMETSAT EPS(MetOp)-SG SCAtterometer to retrieve surface currents. A follow-on study by EUMETSAT is also planned.

Activity B3.4

Explore and demonstrate the feasibility of satellite missions based on new satellite technologies for climate monitoring

Means of assessing progress: Number of publications on new potential satellite climate observations.

A technological revolution in Earth observation sensor design is underway, enabling measurements of many variables previously considered infeasible just a decade ago. Space agencies have made significant investments in advanced technologies, including precipitation radar, broadband radiometers, cloud profiling radar, imaging multispectral radiometers and sounders, and imaging microwave radars, among others. These advancements are driving sensor miniaturization, often resulting in reduced costs.

Emerging capabilities from these innovations present new opportunities for observing the Earth system at lower costs. One example is the evolution of the solar spectral irradiance measurements, which have progressed from the Spectral Irradiance Monitor on SORCE and TSIS-1 to compact spectral irradiance monitor, which is a 6U CubeSat. There are also other emerging capabilities using small sensors for cloud profile, rain, ocean color, and ocean winds.

One feature of the emerging landscape of small satellites is the increased role of the private sector. Companies such as GHGSat can operate constellations of small satellites that can provide (in this case) unprecedented coverage of methane emissions. Projects such as ESA's MEDUSA seek to underpin the dual role of the public and private sectors, by developing uncertainty frameworks and reference observations that can be used by both the public and private sectors to increase confidence in retrievals, developing the underpinnings for delivery to climate services such as UNEP's operational Methane Alert and Response System.

However, the extent to which these smaller, less expensive sensors can match or replace the capabilities of larger, more sophisticated counterparts remains unproven. When designing the future climate observing system architecture, it is essential to ensure that variables derived from these new sensor technologies maintain continuity with the climate data records produced by the current observation system.

Activity B3.5

Develop operational techniques to estimate permafrost extent

Means of assessing progress: Feasibility studies addressing mission concepts relevant to observation and mission gaps. Solicitations by Space agencies for satellite mission development relevant to permafrost extent.

Permafrost cannot directly be monitored from space as it is a subsurface condition. A number of different sensors can help monitor various land surface features that are associated with permafrost, and observations can be combined with model simulations of the ground thermal regime.

Key requirements for monitoring permafrost are therefore:

1. Ensuring systematic observations of ground displacement in permafrost regions using C- X- and L-band radar,
2. Improving the synergies with active and passive microwave sensors to better monitor wetland disturbances,
3. Continuing to provide high spatial resolution visible-thermal infrared multispectral radiometer data to monitor the land surface,
4. Continuing to leverage all possible missions for the scientific community.

CCI Permafrost targets primarily "ground temperature" and "active layer thickness". Permafrost extent is derived from the modeled ground temperature in addition, responding to e.g. requirements stated through WMO OSCAR, the WMO Polar Space Task Group (PSTG), the climate modeling user group (CMUG) etc. This is complemented by rock glacier kinematics, one of the permafrost ECV, based on SAR Interferometry in mountain regions.

As defined by GCOS, "Permafrost extent" is not a product of the ECV Permafrost like "Active Layer Thickness", "Permafrost Temperature" and "Rock Glacier Kinematics". However, the characterization of the permafrost extent has been employed for decades in the permafrost

community, e.g. in the classic IPA permafrost map displaying classes of continuous, discontinuous, sporadic and isolated permafrost. "Permafrost extent" has been further defined as required through WMO OSCAR as well as community discussions by European and US Agencies (European Commission Joint Research Centre, 2018; National Research Council, 2014) (Bartsch et. al., 2023). Therefore, we derive it as an additional product within CCI Permafrost, and it is the one which is most downloaded (among the CCI Permafrost products) and used by the community.

Now coming to the model used and further developed within CCI Permafrost (from CCI Permafrost ATBD v4.0):

"*CryoGrid CCI is a ground thermal model based on existing permafrost models, which is optimized for efficient computation to facilitate application for the entire permafrost domain. For each pixel, a model ensemble is computed in order to simulate the considerable subgrid variability (1km resolution) of the ground thermal regime observed in field-based studies. The model ensemble takes the spatial variability of landcover and ground stratigraphy, as well as snow depth into account, what allows for computation of a permafrost fraction. At the boundary of the permafrost domain, this makes it possible to quantitatively reproduce the well-established zonations in discontinuous and sporadic permafrost. The processing chain makes use of remotely sensed land surface temperatures (MODIS LST) and landcover (ESA CCI), which is supplemented within Permafrost_cci by a range of ancillary information, such as ground stratigraphies and fields of the ERA-5 reanalysis.*

The spin-up of the ground thermal profile is achieved by using reanalysis data from 1951 to 1980 which are statistically downscaled with MODIS LST using an overlap period from 2003 to 2021. Furthermore, the model is run twice for the five year period 1980 to 1984, allowing for the ground temperatures in the active layer and the uppermost permafrost to stabilize. The CryoGrid CCI model delivers the thermal profile from the surface downwards at sufficient temporal resolution to resolve the seasonal cycle. The output variables computed from the model state are mean annual ground temperature at different depths, annual active layer thickness and permafrost fraction within 1km pixels."

The CCI Permafrost project delivers 4 datasets for the Northern hemisphere:

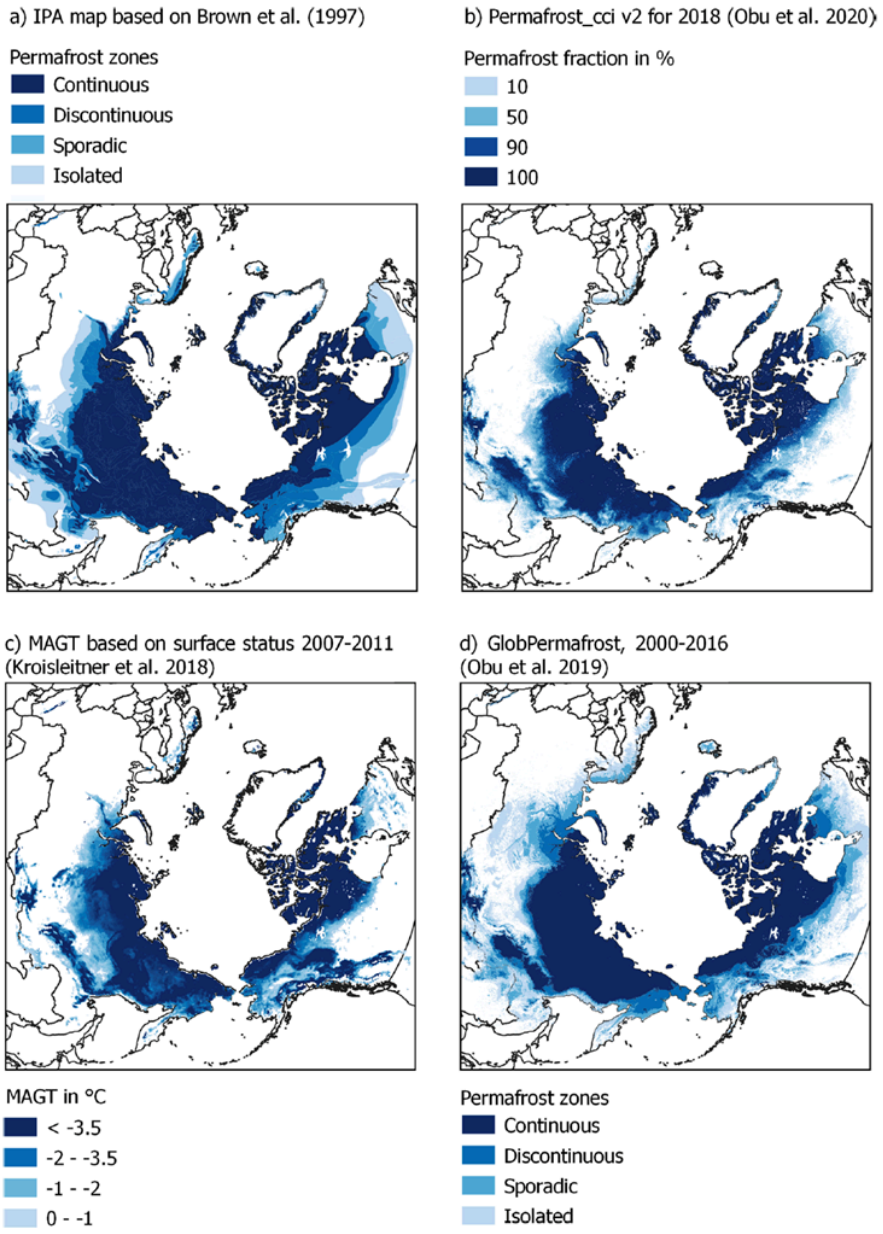
1. Permafrost Ground Temperature (ECV Permafrost product)
2. Permafrost Active Layer Thickness (ECV Permafrost product)
3. Permafrost Extent
4. Rock glacier kinematics (ECV Permafrost product)

1 to 3 are derived from the thermal model CryoGrid CCI, which is based on Earth observation data and value-added products (see above). Like all models it has its limitations (see CCI Permafrost ATBD v4.0, where more details of the model can be found). Uncertainties regarding parameterization of heat transfer as influenced by land cover, snow and soils are addressed and accuracies quantified across lowland and mountain regions (see CCI Permafrost PVIR v3.0).

Rock glacier kinematics derivatives (stable/moving) as observable through SAR missions can be used as indicators for permafrost presence in mountain regions and thus can complement permafrost extent modelling efforts. InSAR subsidence analyses in permafrost lowland regions can provide to some extent information on ground ice conditions, but the interpretation is

complex. It is potentially relevant for characterizing the active layer/permafrost soils as needed for permafrost modelling. This is explored in Permafrost CCI targeting improved descriptions of ground stratigraphies in CryoGRID in addition to improving land cover as proxy for subground conditions. As ground subsidence related to freezing and thawing is limited to frost susceptible soils and is not limited to permafrost regions it cannot be used to derive permafrost extent. Also creep in mountain regions is not exclusive to rock glaciers/permafrost areas. Nevertheless, ground displacements derived from InSAR can provide valuable information in order to address various aspects of the Permafrost ECVs. The previously reported impact by the loss of Sentinel-1B concerns both rock glacier monitoring as well as subsidence analyses as auxiliary information.

Regarding permafrost extent, a purely EO based approach using land surface freeze/thaw state has been tested in CCI Permafrost. Freeze/thaw information has been shown to be suitable as a proxy for sub-ground conditions (Park et al. 2016; Kroisleitner et al. 2018). The number of frozen days per year is summed up and converted to potential ground temperature (empirical model calibrated with borehole in situ measurements). The performance depends on land cover, wavelength, acquisition timing and the algorithm used to derive the surface state. Results based e.g. on Metop ASCAT (C-band) provide similar results compared to equilibrium modeling using LST (as used in DUE Globpermafrost) for lowland regions. Regions with specifically mountain ranges show larger deviations. In general freeze/thaw-based MAGT has often a negative bias as the insulating effect of snow is not considered in such a simple approach. A further disadvantage is the comparably coarse spatial resolution, which does not meet user requirements.



Circumpolar representation of permafrost: a) permafrost zones based on traditional mapping (Brown et al. 1997), b) Transient modelling of permafrost fraction using satellite-derived land surface temperature representing a specific year (Obu et al. 2021b), c) satellite radar-derived surface status converted to mean annual ground temperature (MAGT) (Kroisleitner et al. 2018) and d) Equilibrium modelling of permafrost probability converted to permafrost zones using satellite-derived land surface temperature representing an average of several years (Obu et al. 2019). Source: Bartsch et al. (2023)

Action B5: Implementing global hydrological networks

Activity B5.1

Increase the number of in situ river level observations that are exchanged internationally and can be used to calibrate satellite observations of water levels

Means of assessing progress: Increased availability of calibrated satellite estimates of water levels in rivers

The CEOS Working Group on Calibration and Validation (WGCV) actively supports several initiatives aimed at enhancing in situ river level observations and ensuring their international exchange. These efforts are crucial for calibrating satellite observations of water levels and improving the accuracy of hydrological measurements worldwide. Key Initiatives include:

1. **St3TART**:
   This project focuses on developing protocols and procedures for Fiducial Reference Measurements (FRM) to support satellite altimetry missions. These efforts span critical domains, including sea ice, land ice, and inland water, ensuring robust calibration standards that enhance the reliability of satellite-derived data.
2. **AquaWatch Australia**:
   AquaWatch is working toward establishing an integrated national water quality monitoring system in Australia. By combining satellite sensors with in situ water quality measurements, advanced data analysis, and artificial intelligence, AquaWatch provides accurate monitoring and forecasting of freshwater and coastal water quality. This initiative not only safeguards water resources in Australia but also contributes to a global framework, strengthening networks of ground-based water quality sensors.
3. **USA Water Data for the Nation (WDFN)**:
   Managed by the U.S. Geological Survey (USGS), WDFN provides high-quality, discoverable, real-time water data across the United States through an accessible online platform. This system plays a pivotal role in sharing hydrological data, enabling its use in satellite calibration efforts and broader water resource management (https://waterdata.usgs.gov).

A few other databases are openly accessible which increase the number of data that are available to the community:

1. **So HYBAM:**

   Daily water level of the Solimões River is provided by the Observation Service SO HYBAM ”Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basins” (https://hybam.obs-mip.fr/)

2. **SWORD:**

   The SWOT River Database (SWORD) provides the foundation for SWOT river vector products including elevation, slope, width, and discharge. It combines multiple global river- and satellite-related data sets into a congruent product designed to integrate satellite observations (https://zenodo.org/records/14727521).

The increasing integration of ground-based networks with space-based observations is driving a new era in hydrological science (Altenau et al., 2021; Nielsen et al., 2022). By fostering international and national (e.g. subalpine lakes in Italy, laghi.net) collaboration and standardizing calibration practices, these initiatives address critical gaps in global water data availability and usability. Further development in machine learning and artificial intelligence can leverage this wealth of data to predict and mitigate water-related challenges, including droughts, floods, and pollution.

Virtual station water level time series have been developed based on Jason, Sentinel-3A, and SWOT measurements:

1. Database for Hydrological Time Series of Inland Waters (DAHITI): https://dahiti.dgfi.tum.de/en/
2. Sentinel-3A virtual station water level time series: https://github.com/cavios/tshydro
3. The hydroweb.next platform has a mission to centralize a maximum amount of satellite data, models and in-situ data for hydrologists: https://hydroweb.next.theia-land.fr

Continued support and expansion of these programs are essential to achieving comprehensive, accurate, and actionable water monitoring at regional and global scales.

Action B9: Improve estimates of latent and sensible heat fluxes and wind stress

Activity B9.4

Develop new approaches and improved methods to better exploit relevant ECV measurements to estimate ocean surface heat, moisture and momentum flux including:

- Better integration of in situ and satellite measurements, data assimilation, fusion techniques, ensuring consistency between different types of measurements and their harmonization
- Development and deployment of new satellite missions that are tuned to maximize the sensitivity to the state variables needed to estimate heat flux over the ocean and land
- Increase and improvements in satellite observations that target both the surface parameters and the near-surface air-parameters
- Simultaneously use of an approach based on high resolution numerical models (LES) to augment satellite product validations
- Included in future intercomparison campaigns of latent and sensible heat fluxes measurements inferred from simultaneous observations with a water vapor differential absorption lidar, a doppler wind lidar and temperature from rotational Raman lidar.

Means of assessing progress: Reduced uncertainty in both air-sea and land-atmosphere flux products; Scoping and development of satellite missions to better optimise measurements in the Planetary Boundary Layer.

Satellite observations have played a pivotal role in advancing our understanding of turbulent air-sea fluxes of heat and moisture. Traditional approaches leverage instruments such as VIS/IR imagers, sounders, microwave imagers, scatterometers, radar altimeters, and Synthetic Aperture Radar (SAR) to measure key variables including sea surface temperature (SST), precipitation, wind speed and direction, sea surface height, and planetary boundary layer (PBL) parameters like air temperature and specific humidity. These observations, processed through parameterization models such as the COARE algorithm, form the backbone of flux estimation.

Microwave SST, due to its cloud-penetrating capability, has emerged as a critical parameter in these models. However, the availability of suitable microwave imagers with C- and X-band channels has been limited, covering only short periods in the past. Promising advancements include JAXA's AMSR3, launched in 2025, and the European Commission's CIMR mission, with launches planned for 2029 and 2035. These missions aim to overcome challenges such as radio frequency interference by incorporating advanced detection methods.

While traditional methodologies offer robust solutions, alternative approaches seek to address their limitations. Current PBL temperature and humidity estimates, derived from correlations with thicker atmospheric layers, often lack precision. An ideal solution would involve a single microwave imaging instrument capable of simultaneously observing all variables required for flux computations. Although the proposed Butterfly mission aimed to achieve this, it has yet to secure funding. Similarly, microwave hyperspectral sounders hold promise for improving PBL estimates but are still in conceptual stages with uncertain launch timelines.

Emerging strategies also focus on integrating raw microwave and infrared measurements into coupled global reanalyses. These models, which interpolate physical processes with high temporal and spatial resolution, could offer the most consistent global flux estimates. Future

reanalyses are expected to achieve spatial resolutions of less than 10 km, surpassing the capabilities of standalone mission proposals. LES simulations recommended in the GCOS Implementation Plan could further validate parameterization models used in reanalyses.

To ensure the continuity and enhancement of ocean datasets, a range of satellite missions and initiatives are underway. The CIMR mission, launching later this decade, will enhance SST and salinity measurements, crucial for heat flux estimates in polar regions. Meanwhile, NISAR, a joint NASA-ISRO mission launched in 2025, will provide high-resolution data on surface conditions to refine estimates of land-atmosphere heat exchange.

Other missions, such as CERES and CLARREO Pathfinder, focus on radiative heat fluxes and Earth's energy budget. CLARREO, planned for deployment in 2026, aims to enhance the accuracy of climate records through precise radiation measurements. Additionally, geostationary programs like GOES-R, MTG, and Himawari, operational well into the 2030s, provide continuous monitoring of SST, land surface temperature, and atmospheric conditions, critical for diurnal heat flux analysis.

Advances in data processing and integration are equally transformative. Improved assimilation techniques are incorporating real-time satellite data into coupled models, reducing uncertainties and refining predictions of climate variability. Emerging tools like AI and machine learning are further enhancing data analysis, extracting nuanced insights and improving heat flux estimates.

Aircraft-based observations offer valuable transitional data, bridging the gap between satellite and in situ measurements. These datasets provide three-dimensional views of ocean-atmosphere interactions, aiding parameterization in coupled models.

The combined efforts of space agencies, innovative mission designs, and cutting-edge data processing techniques are reshaping the landscape of heat flux estimation. These developments promise to deepen our understanding of Earth's energy balance, drive improvements in climate models, and enhance predictions of weather and climate variability.

Response to Theme C: Improving Data Quality, Availability and Utility, Including Reprocessing

Action C2: General improvements to satellite data processing methods

Activity C2.1

Improve radiance measurement records and Radiative Transfer models for simulating them

Means of assessing progress: New publications showing improvements in radiative transfer and uncertainty characterisation.

The scientific community continues to make significant strides in advancing radiative transfer (RT) models and refining the understanding of gas absorptions, as well as aerosol and cloud optical properties. Recent efforts to benchmark the RT models include RAdiation transfer Model Intercomparison (RAMI) and RAMI4ATM. Current RT models align well with observations across the ultraviolet to infrared spectrum, but recent comparisons have exposed discrepancies in the microwave region, particularly in the 183.31 GHz water vapor absorption line. When comparing spaceborne measurements of this line with RT model calculations based on numerical weather prediction or radiosonde profiles, a channel-dependent bias has been observed. Differences between channels near the line center and those on the line wings can be as large as 3 K, highlighting areas that can benefit from further investigation.

One of the primary sources of this discrepancy lies in uncertainties related to spectroscopy, especially the water vapor continuum, which includes both foreign and self-continuum components. These spectroscopic issues appear to have a more pronounced impact on the discrepancies than the inherent limitations of the RT models themselves. Addressing these challenges involves improving the underlying spectroscopic data and ensuring its proper implementation within the RT models. Recent intercomparison studies between RT models of varying complexity—ranging from detailed line-by-line models to computationally efficient fast models—indicate that the models themselves are generally consistent. This finding emphasizes the importance of integrating improved spectroscopic knowledge rather than overhauling the models.

Fast RT models, such as RTTOV, play a crucial role in operational applications, particularly in numerical weather prediction and climate reanalysis, where computational efficiency is essential. While RTTOV is a standard model used in data assimilation of IR and MW instrument data, it was not capable of being used for simulating UV-VIS spectra. Recently, the EUMETSAT Numerical Weather Prediction Facility added this ability to RTTOV enabling an easier use of such data in data assimilation and assessment of measurement quality for many sensors operating at this spectral range. These models are also instrumental in characterizing historical satellite observations, especially in cases where reference measurements are unavailable. However, the functionality of these models must continue to evolve by incorporating advancements from research-grade RT models, ensuring that they remain accurate and reliable.

In comparisons involving data from various sources, such as satellites, radiosondes, and aircraft, understanding the differences between RT models is vital. For instance, the optical depth

parameterization used by RTTOV makes it unsuitable for interpreting aircraft measurements, underscoring the need for context-specific approaches in RT modeling.

Ultimately, addressing biases in RT model outputs will require a concerted effort to enhance spectroscopic data while ensuring that improvements in research models are effectively transferred to operational fast RT models. These efforts will strengthen the accuracy of satellite calibration, atmospheric measurements, and long-term climate reanalysis, furthering our understanding of the Earth's atmosphere and climate system.

Activity C2.2

Improve uncertainty quantification of satellite retrievals

Means of assessing progress: New publications showing improvements in radiative transfer and uncertainty characterisation.

Action C2.2 concerns uncertainty quantification at all processing levels and its suitability for downstream users. Therefore the issue of uncertainty propagation through retrievals is key to this action. This response addresses first efforts relating to Radiative Transfer Models (RTMs) and secondly those relating more to downstream propagation.

Projects such as FIDUCEO and Analysis of the uncertainty of the stability of the altimeter measurement of sea level rise (ASeLSU) have made important advances in the representation of uncertainty in satellite retrievals. The FIDUCEO project developed the understanding and characterization of uncertainty in Climate Data Records (CDRs) and Fundamental CDRs (FCDRs) (*Radiance Uncertainty Characterisation to Facilitate Climate Data Record Creation*). These methodologies then propagate through to the CDR community as in e.g. *Satellite-based time-series of sea-surface temperature since 1981 for climate applications*.

There are a number of activities developing radiative transfer for CDRs. New methods looking backwards in time can be used to develop CDRs from historical EO data as in *Climate Data Records from Meteosat First Generation Part I: Simulation of Accurate Top-of-Atmosphere Spectral Radiance over Pseudo-Invariant Calibration Sites for the Retrieval of the In-Flight Visible Spectral Response*. These projects carried out basic research, and the findings should be used, with sustained funding, for a systematic implementation of the techniques to a wide range of instruments. This is, for example, happening at EUMETSAT, who have plans to systematically use the FIDUCEO method and advancements of it in future creations of FCDRs, and in projects such as ESA's CCI programme..

NOAA, NASA, EUMETSAT, and their associated research institutions are focusing on enhancing radiative transfer models and retrieval algorithms, which are critical for interpreting satellite observations accurately. These efforts include refining the physical models that describe how radiation interacts with the Earth's atmosphere and surface, improving the representation of clouds, aerosols, and greenhouse gases, and using advanced statistical techniques to better quantify uncertainty in satellite-derived climate variables.

Recent advancements include the development of next-generation radiative transfer models (see Activity C2.1) that account for complex atmospheric conditions, and the implementation of machine learning approaches to improve retrieval accuracy. For example, NASA's work on the Goddard Earth Observing System (GEOS) and NOAA's use of the Community Radiative Transfer Model (CRTM) are geared towards improving the precision of radiative transfer calculations. Additionally, collaboration with the international community on projects like the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder is expected to provide benchmark measurements that will be crucial for reducing uncertainties (SI Traceable reference satellite missions are addressed in more detail in B1).

FIDUCEOs wider applicability highlights that, for comprehensive uncertainty characterisation, the mapping and modelling of all relevant (error-causing) processes is a prerequisite to their subsequent propagation – i.e. this process is a requirement for subsequent consideration of error correlation and propagation of (non-) gaussian processes. The principles developed in FIDUCEO have been adopted by the wider community including for processes downstream of FIDUCEO's initial Level 1 remit, and are instrumental to many recent projects on derived EO products. (e.g. Graf et al., 2023, Guerou et al., 2022).

Some types of uncertainties and propagation continue to present a challenge to the EO community – for example, the literature on trend uncertainties. In these cases, developments may begin in one sub-community of remote sensing but be shared via the literature for wider applicability (e.g. Godin-Beekmann et al., 2022, Bulgin et al., 2020, Guerou et al., 2022)

Spatially correlated errors also continue to present a challenge to the community. The minimum description possible is a generic correlation length scale for a variable in a dataset. Within that length scale, the errors are not independent, which reduces the "effective number" of observations. Some ECVs such as SST can report these uncertainties. Temporally correlated errors should also be considered alongside spatially correlated errors.

Uncertainty characterisation for data assimilation is an advanced subfield, with many earth observation providers liaising directly with data assimilation teams (e.g. Boersma et al., 2024, Inness et al., 2022). However, FIDUCEO style uncertainty estimates are not straightforward usable in assimilation frameworks such as 4D-VAR, which would need research funding to realize. The situation may change if these uncertainty estimates can be used in observation based machine learning approaches for weather and decadal scale climate prediction. Further development of all of the above can be improved with sustained funding and coordination between data producers and data users.

Note that emerging fields of research relevant to retrieving emission fluxes from satellite measurements (particularly from methane point sources) are a rapidly developing area. From the metrological and FRM communities, NIST (USA), NPL (UK), BIPM and ESA have all in 2024 held workshops or conference sessions directly addressing uncertainty quantification in the retrieval of methane fluxes from space. Projects such as ESA's MEDUSA project aim to develop techniques both for routine validation and development of intercomparable prognostic uncertainty estimates.

This action links to other C2 actions, and also actions concerning reference and validation observations, and associated projects such as the ESA FRM4 series (e.g. FRM4DOAS).

Activity C2.3

Periodically reprocess full satellite data records whenever an update of underlying methods occurs, especially when those risks introducing discontinuities into the time series.

Means of assessing progress: Increased number of available reprocessed Fundamental Climate Data Records (FCDRs).

Satellite data reprocessing plays a pivotal role in generating long-term climate data records that ensure spatial and temporal consistency, a critical requirement for advancing climate science. The process is both strongly supported and inherently complex, reflecting the scientific and operational challenges of harmonizing diverse datasets across decades of satellite observations.

Institutional Leadership in Data Reprocessing

Major space agencies have taken a leading role in satellite data reprocessing, contributing to the development and maintenance of high-quality climate records.

- NOAA (National Oceanic and Atmospheric Administration):
  NOAA leads efforts in creating Climate Data Records (CDRs) by ensuring the consistency and quality of datasets across multiple satellite generations. These CDRs are regularly updated and sustained to meet the needs of stakeholders. NOAA's focus lies in operationalizing climate data for routine use.
- NASA (National Aeronautics and Space Administration):
  NASA's Earth Science Division emphasizes the development of advanced algorithms and technologies for reprocessing satellite data. While its efforts prioritize reliability over decades, NASA's role complements NOAA by contributing less to routine updates and more to refining methodologies through programs like ROSES MEaSUREs.
- USGS (U.S. Geological Survey):
  Through its Landsat program, USGS reprocesses satellite data to support long-term environmental and climate records. These records are crucial for land-use studies and monitoring climate change. The USGS also aids in data curation and delivery of several other national land data sets, including from the MODIS, ASTER, ECOSTRESS, GEDI and EMIT sensors via the Land Processes DAAC (See https://www.earthdata.nasa.gov/centers/lp-daac).
- ESA (European Space Agency):
  ESA's Climate Change Initiative (CCI) generates long-term, stable datasets for Essential Climate Variables (ECVs), often spanning multiple satellite platforms. In addition, as part of the Long Term Data Preservation activities, ESA runs several projects such as FDR4AVHRR that support the generation of FCDRs from historical mission data. Both activity lines include harmonization across platforms and producing operational versions maintained by the Copernicus Climate Change Service. The current CCI phase addresses 27 GCOS ECVs while advancing actionable climate information.
- EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites):
  EUMETSAT is integral to the creation of Fundamental Climate Data Records from multi-decadal inputs of raw data from its own missions but also from other space

agencies. This is especially used as input into global reanalysis at ECMWF and for generating high-quality climate records for ECVs. It delivers low-latency data record extensions to serve national and European Copernicus climate services. Reprocessing efforts are carefully prioritized based on their potential to improve applications or enable new uses.

Funding and Resources

- Federal and Programmatic Funding:
  In the United States, satellite data reprocessing relies on federal budgets allocated to agencies like NOAA and NASA. In Europe, funding is secured through ESA's CCI program, EUMETSAT's satellite programs, and Copernicus initiatives.
- Technological Investments:
  Significant investments in cloud computing and advanced algorithms, such as machine learning, enhance the ability to manage large datasets and complex processing needs. For instance, NOAA's Big Data Project leverages commercial cloud services, while European initiatives like the EUMETSAT-ECMWF European Weather Cloud and the EU's DestinE infrastructure integrate observational and model data efficiently.

Advancements in Algorithm Development and Data Consistency

- Advanced Algorithms:
  Continuous innovation improves anomaly detection, sensor drift correction, and inter-satellite calibration. Reference sites and models are extensively used to maintain data consistency.
- International Collaboration:
  Collaborative efforts between agencies ensure harmonized datasets across missions. For example, NOAA, EUMETSAT, and JMA satellites share data frameworks, while Sentinel-6 altimeter records are jointly distributed by EUMETSAT and NASA.

Challenges and Future Directions

- Sustaining Long-Term Records:
  The continuity of climate data records across multiple satellite generations is essential for understanding long-term trends. Agencies can address challenges like sensor changes and platform transitions.
- Addressing Data Gaps:
  Historical data inconsistencies, caused by issues such as orbit drift and sensor variability, require sophisticated reprocessing and validation techniques to integrate them into long-term records.
- Meeting Evolving Data Needs:
  The growing demand for higher-resolution datasets and new types of observations, such as hyperspectral imaging and active sensors, drives the need for ongoing reprocessing efforts to ensure older datasets meet modern scientific standards.

The commitment of space agencies to satellite data reprocessing underscores its importance for producing reliable, long-term climate records. These efforts are crucial for advancing climate science and informing policy decisions. However, their success may depend on sustained

funding, technological innovation, and robust international collaboration. By addressing challenges and adapting to evolving needs, agencies ensure that these invaluable datasets continue to support global climate research and applications.

Activity C2.4

Consolidate satellite observations into instrument-independent space-time grids for easy intercomparisons and fusion

Means of assessing progress: Increased number of available consolidated gridded satellite datasets.

CEOS and CGMS, supported by the Joint Working Group on Climate (WGClimate), are making significant strides in advancing Climate Data Records (CDRs) to support global climate monitoring and research. A key aspect of this progress is the expansion and evolution of the Essential Climate Variable (ECV) Inventory. Since its initial publication in 2017, the Inventory has grown from 917 CDRs to 1304 in 2025. In 2025, the ECV Inventory transitioned to the new CDR Inventory - with a new user interface designed to simplify access and enhance the experience for users, as well as a new rolling update model, allowing continuous integration of new CDRs. This comprehensive resource also includes metadata for planned CDRs, enabling detailed searches by GCOS ECV, product, and other criteria. Most CDRs are offered on regular equal-area or equal-angle grids.

WGClimate has conducted three gap analyses focused on energy, water, and carbon cycle ECVs. These studies have provided critical insights, guiding the development of its Coordinated Action Plan to address identified gaps.

Significant efforts are also underway to advance geostationary CDR development. The NOAA/EUMETSAT GEO-Ring project is creating a fundamental climate data record of infrared radiances and visible reflectances from historical meteorological geostationary satellites. This record, spanning the early 1980s to the present, includes key spectral channels such as visible (~0.7 µm), infrared window (~11 µm), and infrared water vapor (~6.7 µm), along with data from other bands. Each participating agency is contributing calibrated FCDRs that will be merged into a comprehensive GEO-Ring product.

Building on this foundation, the ISCCP Next Generation (ISCCP-NG) project is leveraging GEO-Ring data to provide higher spatiotemporal sampling using modern geostationary satellites. While initially focused on atmospheric parameters, the project's scope is expanding to include other variables such as land and sea surface temperature, evapotranspiration, precipitation, and aerosol optical depth. These advancements promise to deliver geostationary data on globally complete gridded fields with unparalleled temporal and spatial resolution.

Efforts to harmonize satellite records are also central to this work. Programs like ESA's Climate Change Initiative (CCI) aim to align data across time and platforms, ensuring temporal and spatial stability while addressing robust uncertainty characterization. For example, the CCI ozone precursor project harmonizes data from multiple polar-orbiting instruments to create consistent, long-term CDRs.

Recognizing the need for modern tools and accessibility, agencies are exploring the development of analysis-ready data (ARD) formats. These initiatives aim to make CDRs more accessible for automated processing using contemporary tools, such as Python libraries in cloud environments. ESA's RECCAP-2 project exemplifies this effort by building a data cube of Earth observation datasets that adheres to CCI standards while aligning with CEOS's ARD vision.

The development of the CDR Inventory, advancements in geostationary CDRs, harmonization of datasets, and exploration of ARD formats all reflect the commitment of CEOS and CGMS agencies to providing comprehensive, reliable, and accessible climate data. These ongoing efforts are critical for supporting climate research and addressing the evolving needs of stakeholders and the global scientific community.

Action C4: New and improved reanalysis products

Activity C4.1

Implement new production streams using improved data assimilation systems and better collections of observations, particularly aiming at:

- Further increasing resolution;
- Improving handling of systematic observational and model biases;
- Providing (improved) estimates for the uncertainty in the mean state;
- Improve quality control in data sparse areas.

Means of assessing progress: Publications describing new reanalysis production streams and their validation with improved estimation of uncertainty of reanalysis data products.

The state-of-the-art in reanalysis (covering atmosphere, ocean, land and composition) was the focus of the ECMWF flagship Annual Seminar, 4-8th September 2023 in Reading (UK) attended by around 100 experts in the field. This covered several aspects highlighted in this activity as priority areas for research, including results on the proposed approach to model bias correction in the stratosphere for ERA6, ECMWF's next generation global reanalysis. All presentations and recordings are available here.

More recently, the 6th WCRP International Conference on Reanalysis (ICR6) took place in Tokyo on 28/10 to 1/11/2024, hosted by the University of Tokyo and JMA. The ICR is the main forum for bringing together most of the scientists and institutions involved in reanalysis efforts worldwide. This edition had over 200 participants from 30 countries and regions. The oral and poster presentations as well as the active panel discussions (see the programme and session timetable) provided a good overview of the state-of-play as well as new insight. Compared to the previous conference ICR5, the increasing importance of reanalysis production and applications from operational, scientific, and social perspectives was highlighted. The ICR6 International Program Committee members, session chairs, and rapporteurs are currently working together to summarize the outcome of this conference. A summary of ICR6 will be submitted to the Bulletin of the American Meteorological Society (BAMS).

The performance of the ERA5 global reanalysis, covering the period 1940-2022, has been analysed by the ECMWF reanalysis team and the findings summarized in Soci et. al., 2024 (QJRMS 2024). The paper compares the performance of ERA5 with several independent datasets and with other contemporary reanalyses. It follows the papers by Hersbach et. al., 2020 (QJRMS 2020, covering 1979-2019) and Bell et. al., 2021 (QJRMS 2021, covering 1950-1979).

Preparations are underway for the next generation ECMWF global reanalysis, ERA6, due to commence production in Q1 2026. Horizontal resolution will be 14km, alongside the configuration of the accompanying ensemble of data assimilations – which will provide synoptic uncertainties in the ERA6 product. ERA6 will include an ocean and ice model. The initial state of these extended domains will be provided via a one-way coupling with the ORAS6 ocean reanalysis. The latest and best (conventional and satellite) observations and forcing datasets will be ingested; model bias in the stratosphere is addressed as well as several other ERA5 known issues will be alleviated. ERA6 data will be released by tranches of one or two decades (after undergoing evaluation and quality control) - the first tranche will be released in the second half of 2027 and production is expected to be completed by mid- to end 2028.

Preparations are also well underway for the new ECMWF/CAMS global reanalysis of atmospheric composition EAC5 (including greenhouse gases). Production is also due to start in Q1 2026 and the same IFS model cycle as ERA6 will be used. A key improvement over the predecessor reanalysis EAC4 will be detailed stratospheric chemistry. The plan is to complete and release EAC5 to users by the end of 2027 or in the first months of 2028.

The Japan Meteorological Agency (JMA) has developed the third Japanese global atmospheric reanalysis, the Japanese Reanalysis for Three Quarters of a Century (JRA-3Q). JRA-3Q is based on the TL479 version (a horizontal resolution of approximately 40 km) of the JMA global Numerical Weather Prediction (NWP) system as of December 2018 and uses results of developments in the operational NWP system, boundary conditions, and forcing fields achieved at JMA since the previous Japanese 55-year Reanalysis (JRA-55). It covers the period from September 1947 and uses rescued historical observations to extend its analyses backwards in time about 10 years earlier than JRA-55. The initial quality evaluation revealed major improvements from JRA-55 in the global energy budget and representation of tropical cyclones (TCs). One of the major problems in JRA-55—global energy imbalance with excess upward net energy flux at the top of the atmosphere and at the surface—has been significantly reduced in JRA-3Q. Another problem—a trend of artificial weakening of TCs—has been resolved through the use of a method that generates TC bogus based on the JMA operational system. The specifications and basic characteristics of JRA-3Q are described in the JRA-3Q comprehensive report (Kosaka et al. 2024).

The latest reanalysis of the NASA Global Modeling and Assimilation Office (GMAO), MERRA-21C, is currently in production, with an estimated completion in the summer of 2026. MERRA-21C is an atmosphere-only reanalysis that focuses on early 21st century instruments and the transition to NASA's post-EOS observations and covers the period of 1998-onward. Produced at 25 km horizontal resolution and using a hybrid-4DEnVar data assimilation strategy, it introduces the assimilation of microwave radiance measurements in cloudy and precipitating conditions from AMSR-E, AMSR2, TMI, GMI, and MHS, assimilates homogenized ozone observations to reduce the impact on ozone trends, as well as on-line interactive aerosols with an updated modeling capability GOCART-2G. Land processes are driven with corrected precipitation measurements from NASA's Integrated Multi-satellitE Retrievals of GPM (IMERG). Uncertainty estimates are provided for most atmospheric fields and added diagnostic collections target user communities like the wind energy and the cryosphere. Preliminary internal evaluation shows overall improvements over MERRA-2 reanalysis, especially in areas of known biases.

GMAO is also preparing to produce three off-line follow-on reanalyses:

- M21C-Polar, a global 7km down-scaling of MERRA-21C that introduced updates to the representation of cryospheric processes in the downscaling model. Production to start in Q4 of 2026.
- An all-atmosphere chemistry reanalysis, driven by the atmosphere of the climate reanalysis, and using the chemistry model GEOS-Chem and a newly developed constituents data assimilation system (production to start in Q4 2026). This reanalysis is a follow-on to the current stratosphere-only chemistry reanalysis (MERRA-2 Stratospheric Reanalysis with MLS, M2-SCREAM).
- M21C-Land: and offline land data assimilation (or soil moisture and surface fluxes) driven by the atmosphere of MERRA-21C. Production is expected to start in Q4 of 2026.

Activity C4.2

Develop coupled reanalysis (ocean, land, sea-ice)

Means of assessing progress: Demonstrated benefits of coupled reanalysis

ECMWF has developed a coupling mechanism for its upcoming reanalysis ERA6. This entails using a prior ocean reanalysis. In each assimilation window of the ERA6 reanalysis, the atmospheric model is to be run in coupled mode with the ocean, starting from the ocean conditions determined by the ocean reanalysis. In this fashion, the reanalysis will represent diurnal cycles in surface temperatures at the sea interface, in the air and in the water. Also, one expects to find the 'cool trail' effect observed when tropical cyclones dump heavy precipitations (substantial amounts of fresh water) over warm tropical seas, or to see the influence of ocean currents. Coupling with the land component is being investigated in the context of the European research project CERISE (https://www.cerise-project.eu/), with the objective to gain enough maturity for ERA7.

Future GMAO reanalysis will assimilate observations in multiple components of the Earth system, first including the atmosphere and land (MERRA-3, c.2027), and then the atmosphere, land, ocean, and sea-ice (MERRA-4, c.2030).

Activity C4.3

Improve the capability of sparse-input reanalysis that covers the entire 20th century and beyond

Means of assessing progress: New versions of sparse-input reanalysis products.

ECMWF has not produced any new 20th century reanalysis since (C)ERA-20C(M). These reanalyses were decommissioned in 2023, but remain available from other sources, such as NCAR. However, preparations have been made to extend the observational coverage to support such activities in the future and/or by any international partner. The observation datasets prepared are served freely and openly on the climate data store. A comprehensive dataset of upper-air balloon-borne observations is also being finalized.

Activity C4.4

Develop and implement regional reanalysis and other approaches to regionalization

Means of assessing progress: Number of in-depth performance assessments of regional reanalyses and other regionalised datasets.

The Copernicus Climate Change Service continues to implement, through partners at SMHI and MetNo, two high resolution regional reanalyses spanning Europe and the Arctic regions. The performance of these reanalyses, and the incremental value over and above that provided by coarser resolution global reanalyses were presented at the 2023 ECMWF Annual Seminar.

The Copernicus Atmosphere Monitoring Service delivers annual reanalyses of air quality over Europe. These are based on assimilation of surface observations of the main pollutants, while satellites are assimilated into the ECMWF global system, which provides the lateral boundary conditions. Data and documentation are available here.

The ClimCORE project led by the University of Tokyo is conducting production of regional atmospheric reanalysis data (RRJ-ClimCORE) for Japan and its surrounding domain under the official collaboration with JMA. The data can reproduce the past atmospheric conditions four-dimensionally at hourly intervals with 5-km horizontal resolution for recent decades, by assimilating various conventional and satellite observation data as well as radar-raingauge-blended precipitation data into the latest version of the JMA regional forecast system.

Activity C4.5

Reduce data latency

Means of assessing progress: Reduced latency of data product updates

The ECMWF global product ERA5 is distributed within 5 days behind near-real-time. The JRA-3Q product is made available within 5 days behind real time for non-commercial purposes. NASA GMAO's GEOS-IT is produced for instrument teams with a latency of a few hours.

Action C5: ECV-specific satellite data processing method improvements

Activity C5.1

Generate timely permafrost, land cover change, burnt area, and fire severity/burning efficiency products from high resolution satellite observations (e.g. Sentinel-1 /-2 and Landsat)

Means of assessing progress: Improved and validated permafrost, land cover and change products and updated, and higher resolution, burnt area and fire severity products

Activity C5.1 focuses on generating timely, high-resolution products for permafrost, land cover change, burned area, and fire severity/burning efficiency using satellite observations from platforms such as Sentinel-1/-2 and Landsat. These products are essential for developing effective climate adaptation and mitigation strategies and rely on accurate, frequent, and global satellite-derived data. While such products have existed for many years, the need for global coverage at higher spatial and temporal resolutions remains a priority.

Current products derived from Earth observation (EO) data are available at local, regional, and global scales, including those from the ESA Climate Change Initiative (CCI), such as Permafrost, Snow, Glacier, High-Resolution Land Cover, and Fire datasets. Other notable contributions include ESA's WorldCover land cover products, the University of Maryland's Global Land Analysis and Discovery (GLAD) Landsat Analysis Ready Data (GLAD ARD) for land cover mapping, the United States Geological Survey (USGS) LCMAP products, and the USGS Burned Area Science Products. While these datasets provide valuable information, there is room for improvement, particularly in delivering global products with higher spatial and temporal resolutions. Current limitations in spatial resolution often fail to capture fine-scale variations in permafrost thaw, land cover changes, or fire severity, while higher temporal resolution is critical for monitoring rapidly evolving environments and extreme events, such as wildfires.

A number of these products (land cover and burned area), from the ESA Climate Change Initiative are designed to be pre-operational and are then taken up by services such as C3S, who produce iCDRs at low-latency (typically a few weeks).

The upcoming next generation of Sentinel and Landsat satellites is poised to address these challenges. For example, Landsat 10 will offer significant enhancements, including an additional 15 spectral bands and up to 10-meter resolution (compared to the current 30-meter standard). Sentinel-2 Next Generation is planned to fly with additional bands in the VIS and SWIR, suitable for burned area and active fire monitoring, with improved spatial resolution of up to 5m in the VNIR. These advancements will enable the production of higher-quality, more timely datasets, offering improved spectral and spatial detail for monitoring environmental changes.

Collaboration with GCOS on this activity is crucial, as permafrost, land cover, burned area, and fire are recognized as Essential Climate Variables (ECVs) due to their critical role in understanding and characterizing Earth's climate system. Strengthening partnerships and focusing on monitoring advancements in these areas will ensure the development of more accurate, reliable, and actionable data products, supporting the global effort to mitigate and adapt to climate change.

Activity C5.2

Aligning and validating AGB map products from different space agencies to IPCC guidelines and methodologies, to enhance their use in policy reporting and increase the precision of AGB estimation at national and sub-national scales.

Means of assessing progress: Validated AGB estimates from various maps at national/subnational levels; Production of higher-level products from the AGB map estimates as direct input to IPCC methodologies; Generation of case-studies for the integration of national forest inventories (NFIs) with AGB maps.

The CEOS Biomass Harmonisation team, operating under the CEOS AFOLU Roadmap team (LSI-VC Forest & Biomass Subgroup), comprises members from NASA, NOAA, ESA, JAXA, and several prominent research institutes, including WRI, Conservation International (CI), the University of Maryland, and Wageningen University. This team has been working collaboratively to better understand and compare the various Above Ground Biomass (AGB) maps currently being developed. These efforts include evaluations of the ESA CCI Biomass Map, NASA JPL Biomass Map, NASA GEDI and ICESat-2 Biomass Map, and the NCEO Africa Biomass Map. The harmonization initiative is conducted as an open science activity on the NASA-ESA Multi-Mission Algorithm and Analysis Platform (MAAP).

The biomass products are validated using the Plot2Map tool and analyzed across continental, biome, national, and sub-national scales for partner countries. Reference data for product evaluation are drawn from the GEO-TREES Biomass Reference System, which adheres to the CEOS Aboveground Biomass Land Product Validation Protocol established in 2021. The GEO-TREES network aims to establish 100 sites worldwide to directly link ground measurements to satellite biomass product evaluations. However, significant challenges remain, as each product's error properties vary widely. Substantial effort is required to ensure comparisons and harmonization adequately account for these differences.

A new web-based dashboard has been developed to facilitate the exploration of biomass products and share insights from product developers and country users. Use cases have been developed in collaboration with stakeholders from countries such as Paraguay, Peru, Wales (UK), Japan, and the Solomon Islands. These cases allow potential users to visualize methods for incorporating EO-based AGB estimates into national reporting, exploring their role—whether as standalone or harmonized products—in supporting Nationally Determined Contributions (NDCs). This initiative aims to engage countries in leveraging biomass estimates effectively and comprehensively.

Despite these advancements, challenges persist. Many countries are unlikely to use satellite biomass products without national validation or updates. Barriers include a lack of transparency in product uncertainties, differing forest definitions among countries and biomass products, and insufficient guidance on applying biomass products to policy reporting. The harmonization activity focuses on aligning biomass products and algorithms with policy requirements, acknowledging that a single, universal estimate is unlikely to meet all countries' needs.

Activity C5.3

Ensure that the Bidirectional Reflectance Distribution Function (BRDF) parameters are provided together with surface albedo.

Means of assessing progress: Provision of the isotropic BRDF spectral parameters used in surface albedo retrieval at the same spatial and temporal scale of the products and the uncertainties error budget associated with the surface albedo products.

Accurate retrieval of land surface albedo, which represents the fraction of radiative flux reflected by a surface to the atmosphere, plays a crucial role in understanding Earth's energy budget and climate system. Incorporating Bidirectional Reflectance Distribution Function (BRDF) parameters alongside surface albedo measurements enhances our ability to assess the uncertainty associated with these products.

NASA's MODIS BRDF and albedo parameters have provided both BRDF coefficients and albedo measurements. They provide coefficients for the BRDF of each pixel in the seven MODIS 'Land' bands, albedo measurements derived simultaneously from those bands, and three broad bands. However, with the discontinuation of MODIS land products, alternative sources for such data will be explored. VIIRS has been used to continue the BRDF and albedo datasets. Utilizing higher-resolution satellites like Landsat and Sentinel-2 for BRDF retrieval poses challenges due to limited multi-angular observations (Lin et al., 2022).

USGS is actively investigating the production of BRDF products, particularly with the upcoming release of Landsat Collection 3. The Landsat 10 instrument will leverage new atmospheric and surface spectral measures on-board.

Despite advancements, uncertainties persist in surface albedo products, stemming from sensor noise, atmospheric effects, calibration errors, and retrieval algorithms. Addressing these uncertainties is paramount for researchers and policymakers relying on these products for climate studies and ecosystem monitoring.

While there's recognition of the need for BRDF parameters alongside surface albedo, progress remains limited. Ongoing efforts can help overcome challenges and ensure reliable data availability for various climate research applications and beyond.

Activity C5.4

Reprocess the NASA LEO 25+ year Lightning Imaging Sensor (LIS) dataset from the Optical Transient Detector (OTD, 1995-2000), LIS on TRMM (1997-2015) and ISS (2017-present).

Means of assessing progress: Validated and updated 0.1 x 0.1 deg product for satellites and ground-based lightning RF data sets (GLD360, WWLLN); and ThunderHour grids (derived from the satellite lightning detection) for GLD360, ENGLN, WWLLN, GLM.

There is an existing effort to merge the OTD, TRMM LIS, and ISS LIS data into a long-term (~25-year) climatology record. This includes a significant effort to improve the algorithms so that the three datasets can be processed and merged in a more consistent manner. The improvements include correcting known issues in the TRMM LIS dataset, adapting a more

consistent geolocation approach to all datasets, accurately calculating and correcting for any sensitivity degradation in ISS LIS relative to TRMM LIS, improving the accuracy of the group and flash radiance data products, making the application of processing filters in the data more consistent across all datasets, and updating and unifying all datasets' metadata to make them friendly to climatological use. These improvements will be able to produce more consistent Level 2 products across all three sensors. These Level 2 data will be used to produce gridded climatologies including annual mean flash rate on a 0.5° grid, mean diurnal cycle of flash rate on a 2.5° grid with 24 hour resolution, mean annual cycle of flash rate on a 0.5° or 2.5° grid with daily, monthly, or seasonal resolution, mean annual cycle of the diurnal cycle on a 2.5° grid with two hour resolution for each day, and time series of flash rate over the ~25- year record with roughly three-month smoothing (with a data gap between 2015 and 2017). These merged datasets are expected to be available in 2026.

Recently updated data sets to this end are now available and are included in the CDR Inventory, including the Quality Controlled Lightning Imaging Sensor (LIS) on International Space Station (ISS) Science Data V2 (Lang, Timothy. 2022). This dataset is available online from the NASA Global Hydrometeorology Resource Center DAAC, Huntsville, Alabama, U.S.A. doi: http://dx.doi.org/10.5067/LIS/ISSLIS/DATA111).

Activity C5.5

Reprocess the GEO Geostationary Lightning Mapper (GLM) on GOES-16/17/18 (2017-present).

Means of assessing progress: Validated and updated space and RF ground-based lightning data at 0.1 x 0.1deg grids.

Two Agencies are, or will be, providing lightning data from geostationary satellites. First, NOAA's GOES-R team is currently developing a system to process GOES Lightning Mapper (GLM) data, converting raw L0 files into L2 products, including events, groups, flashes, and backgrounds. Initially based on Matlab, the code is being transitioned to C for improved speed. Enhancements are being made to the coherency filter, which helps distinguish lightning from noise, by increasing the time window and allowing forward-looking checks to include early pulses. Improvements are also underway for filters that reduce false alarms, such as the blooming and event artifact filters.

The geolocation process is being revised to use results from the operational code, allowing for better alignment of lightning detections between the operational and reprocessed datasets, as well as improved detection efficiency for new lightning events. The team has secured approval to publicly release the reprocessing code, with final confirmation pending the production of the Algorithm Theoretical Basis Document (ATBD). Code conversion and improvements are expected to be completed by the end of the year, with a no-cost extension available until June 2025 if needed. The GLM Thunder Hours (2017-Present) dataset is available online from the NASA Global Hydrometeorology Resource Center DAAC, Huntsville, Alabama, U.S.A. DOI: http://dx.doi.org/10.5067/GLM/DATA101).

Second, EUMETSAT is committed to performing regular reprocessing of the Meteosat Third Generation Lightning Imager (MTG-LI) data throughout and after the mission. The first of these are planned for 2026/27 to consolidate first mission data, including useful data obtained in the commissioning phase. It will most likely use the EUMETSAT algorithms, but applying a community algorithm can be considered. The GEO-Ring of lightning measurements is also listed for a potential extension of the GEO-Ring imager radiances for the future.

Activity C5.6

Improve consistency of the inter-dependent land products.

Means of assessing progress: Maps of all biospheric ECVs using a common geographic definition, at the same temporal/spatial scale as climate models with plant functional types.

Space agencies have made significant strides in mapping biospheric Essential Climate Variables (ECVs) using a unified geographic framework that aligns with the temporal and spatial scales of climate models incorporating plant functional types (PFT). These efforts focus on monitoring parameters such as land cover, LAI, fAPAR, and carbon fluxes at scales compatible with Dynamic Global Vegetation Models (DGVMs), facilitating the estimation of ECVs like biomass and vegetation types (de Paula et al., 2018). The resulting high-resolution maps provide valuable insights into ecosystem dynamics and their interactions with the climate system. Moreover, advancements in Earth observation technologies, including improved sensor capabilities and enhanced data processing, are expected to yield even more detailed and accurate maps, supporting climate research, resource management, and policy decision-making.

Several ESA Climate Change Initiative (CCI) projects utilize data from the CCI Land Cover project, which includes tools for converting land cover data into PFT equivalents. The globally harmonized assessment of above-ground biomass, conducted through the Multi-Mission Algorithm and Analysis Platform (MAAP) from NASA and ESA, incorporates data from numerous extant and former satellite missions, via initiatives like NASA's Global Ecosystem Dynamics Investigation (GEDI) and the joint NASA/ESA AfriSAR campaign. Future enhancements will integrate data from new missions, such as NASA-ISRO SAR (NISAR) and ESA's BIOMASS mission. Additionally, global Leaf Area Index (LAI) maps are being developed through the European GEOV2 project and NASA's MODIS data.

Ensuring that maps of biospheric ECVs align with the temporal and spatial scales of climate models is vital for compatibility in broader climate studies and predictions. Initiatives like CEOS Analysis Ready Data (CEOS-ARD) are fostering the use of standardized formats and geographic projections, thereby enhancing consistency and interoperability. These efforts aim to integrate land products seamlessly with climate models, providing a more comprehensive understanding of the biosphere-climate interactions.

Despite these achievements, challenges persist. Integrating data from diverse sources and sensors remains complex, as each comes with unique characteristics and limitations. Moreover, more advanced modeling techniques are required to accurately link satellite observations with climate models, capturing the nuanced interactions between the biosphere and the climate

system. For instance, comparisons of converted CCI Land Cover data to PFTs with existing PFT maps used by Earth system modeling teams reveal substantial discrepancies (Poulter et al., 2015). Similarly, algorithmic enhancements are needed for GEOV2 (Copernicus Land Monitoring Service) and MODIS LAI products to improve cross-sensor performance and address uncertainties over time (Fang et al., 2021).

Overcoming these challenges can be improved with continued collaboration and investment. Groups like CEOS and the Group on Earth Observations (GEO) play a pivotal role in advancing these products and fostering innovation. Closer cooperation with GCOS is particularly critical in refining ECVs, underscoring the importance of these datasets in understanding and addressing climate change.

Response to Theme D: Managing Data

Action D4: Create a facility to access co-located in situ cal/val observations and satellite data for quality assurance of satellite products

Activity D4.1

Improve access to co-located satellite and reference quality in situ observations, as well as tools for evaluation purposes. This facility will use data from reference networks and FRM programs for a broad range of ECVs for cal/val of satellite programs.
Develop tools to use the co-located data collection developed under activity 1 to undertake various analyses of satellite-based measurements.

Means of assessing progress: Establishment of a unified database of and access to co-located, reference quality, ground-based measurements suitable for satellite cal/val.

Various facilities exist to support this action, including QA4SM (for soil moisture), EVDC (for atmospheric data) and FRM4SST (for SST). However, a single facility is likely unfeasible due to the complex nature of these facilities, and the different communities they support. CEOS Working Group on Calibration and Validation (WGCV) is looking at establishing a central list of facilities, perhaps within the CalVal Portal, however it is unlikely the list will ever be exhaustive.

WGCV also supports various calibration networks for different sensors, including RadCalNet, SARCalNet and TIRCalNet (in development), which provide databases of calibration and validation data.

In 2025, WGCV published the CEOS Product Validation Platform (ceos-pvp.org), which allows satellite data providers, CEOS agencies and others, to evidence the quality of their data in a consistent manner through comparison to a community agreed reference using a minimal set of established calibration sites.

Response to Theme F: Other Emerging Needs

Action F1: ECV-specific satellite data processing method improvements

Activity F1.2

Improve biomass, land cover, land surface temperature, and fire data with sub-annual observations and improved local detail and quality

Means of assessing progress: Availability of key terrestrial ECVs at resolutions of 10-30 m stored in long term archives; Availability of Near Real Time (NRT) sub-annual data for critical land changes and to identify extremes stored in long term archives.

Above-ground biomass (AGB) is a critical ecological metric, representing the mass of living biological organisms in a given area at a specific time. The U.S. Oak Ridge National Laboratory (ORNL) DAAC hosts numerous datasets describing terrestrial vegetation biomass and its changes over time. These datasets include analysis-ready, multi-resolution vegetation structure metrics derived from NASA's Global Ecosystem Dynamics Investigation (GEDI) Level 2 and 4A products. GEDI, a lidar-based instrument aboard the International Space Station (ISS), measures ground elevation and vegetation using eight laser beams spaced 60 meters along-track and 600 meters across-track. The GEDI datasets include raster grids at resolutions of 1 km, 6 km, and 12 km, offering metrics such as canopy height, canopy cover, plant area index, foliage height diversity, and plant area volume density at 5-meter strata. These metrics are valuable for applications in carbon and water cycling, forest management, biodiversity modeling, and habitat assessment. The data, provided in cloud-optimized GeoTIFF format, delivers near-global vegetation structure profiles validated with independent datasets.

The Copernicus Land Monitoring Service (CLMS) provides a global land cover dataset with seasonal/annual land cover/land use change both at 100 m resolution and at an improved resolution of 10 m. The first release (2020 base year) was published in June 2025. The data are updated annually and will be available for the 2020-2026 years.

The ESA Climate Change Initiative (CCI) produces datasets for several key environmental variables, including fire, land surface temperature (LST), above-ground biomass (AGB), and land cover. These datasets are often generated at lower spatial resolutions to provide long-term and global coverage, while higher-resolution products are developed for pilot regions. Over time, some of these regional high-resolution datasets, e.g. land cover, are expanded to cover continental or global scales and longer temporal periods. Temporal resolutions vary across datasets, with Fire CCI offering monthly updates and LST CCI providing daily products.

The Fire CCI project has produced regional burned area datasets for Subsaharan Africa with a spatial resolution of 20 meters. Comparisons between these high-resolution maps and lower-resolution 250-meter maps reveal nearly double the burned area in the former, highlighting the benefits of improved resolution. Current efforts aim to expand this regional mapping to global coverage in the near future. Similarly, the Land Cover CCI has created a 20-meter resolution regional product, currently available as a static map for 2016 through an interactive viewer. Plans are underway to extend this high-resolution product across both time and space, complementing the existing time-series maps at moderate resolution.

For fire monitoring, the VIIRS Active Fires data (VNP14IMGT) represents the latest product available through the Fire Information for Resource Management System (FIRMS). This data identifies global fire locations in near-real time. VIIRS improves on its predecessor, MODIS, with a higher spatial resolution of 375-meter pixels (compared to MODIS's 1-kilometer pixels), enabling better detection of smaller fires and more reliable fire perimeter estimates. Additionally, VIIRS is calibrated to detect fires at night, further enhancing its utility for global fire monitoring. The Sentinel-3 mission includes a dedicated fire detection band, used day and night, and the next generation Sentinel-3 will continue these fire detection capabilities at improved spatial resolution. Active fire detection data from five geostationary instruments (GOES-16, GOES-18, Himawari-8, Meteosat 9, and Meteosat 11) are available in FIRMS. These geostationary instruments provide outstanding temporal resolution acquiring imagery for their entire field of view at 10 to 15 minute intervals or better. This enables geostationary instruments to potentially detect more fire events and capture their growth and change, particularly between fire detection observations conducted by sensors on polar-orbiting platforms. However, geostationary instruments have a much coarser spatial resolution than polar-orbiting instruments and can be less sensitive to detecting relatively smaller fires.

These advancements in Earth observation technologies and datasets underscore their critical role in understanding and managing environmental and climatic changes. They provide high-quality, accessible data for researchers, policymakers, and resource managers worldwide.

Action F2: Improved ECV satellite observations in polar regions

Activity F2.1

Sea surface salinity of polar oceans

Means of assessing progress: Proof of concept for new technologies and new methodologies to measure SSS

Space agencies are coordinating their plans to improve SSS retrievals in polar regions using existing satellite platforms. The first aspect is a close monitoring to the currently existing satellite SSS measuring sensors (SMOS and SMAP) activities. Although in orbit since 2009 and 2015, respectively, they are still being funded by the respective Agencies, and continuous efforts are devoted to further improve the processing algorithms, address the existing issues, improve the validation chain, and derive additional products. Reprocessing campaigns to improve and homogenize the entire SSS archives are periodically performed. Merged SMOS and SMAP SSS datasets are also generated within the framework of the CCI programme. Dedicated activities to improve SSS estimates in Polar oceans (both Arctic and Antarctic) are being held in specific projects such as “Arctic+ Salinity”, “SO-FRESH” or within the frame of the “CCI salinity High-latitudes”.

NASA has been actively engaged in a two-year study to explore the potential of a joint future satellite mission, including enhanced hardware contribution of the upcoming European CIMR (Copernicus Imaging Microwave Radiometer) mission, dedicated to the high-latitude regions. In particular, bi-lateral NASA/ESA discussions of a potential collaboration in the context of CIMR are ongoing, and also on other concepts for high-resolution SSS measurements that would allow improvement of SSS retrievals in polar regions in particular by leveraging NASA’s expertise in broadband multi-frequency radiometry technology development and the knowledge in polar regions gained from field campaigns like Salinity and Stratification at the Sea Ice Edge (SASSIE).

Regarding the continuation of satellite SSS measurements, ambitious plans lie in the European CIMR mission, led by ESA and jointly implemented with EUMETSAT, is planned to launch CIMR-A in 2029, which underwent Preliminary Design Review (PDR) in 2022, and is now in Phase C/D. A second instrument CIMR-B is planned to follow in 2035. CIMR includes an L-band channel which will provide SSS measurements in the global oceans, with a distinctive focus on Polar regions. Although with a spatial resolution which is slightly coarser than the current measurements, CIMR will benefit from good accuracy, high temporal revisit and concurrent measurements of SST and Wind Speed from additional bands available on the same platform. This would represent a solid and feasible plan to grant continuation of satellite SSS measurements, with minimum (if not absent) measurement gaps. The first of China’s Ocean Salinity Satellites (HY-4A) was launched in November 2024, and carries the Interferometric Microwave Radiometer (IMR) and the Microwave Imager Combined Active and Passive (MICAP).

Additional efforts are being devoted by the satellite salinity community to explore technical solutions for future satellite missions which would specifically target higher-resolution SSS measurements with specific focus on coastal regions.

Activity F2.2

GHG at high latitudes with a focus on the permafrost regions in wintertime

Means of assessing progress: Proof of concept for new technologies and new methodologies to measure GHGs at high latitudes, particularly in wintertime.

This activity is specifically for methane observations at the high latitude, as up to half of the emissions emitted at high latitude polar ecosystems take place during the autumn and spring 'shoulder' seasons. In general, the carbon cycle is expected to be significantly slowed down in wintertime and it will be more difficult to observe changes from satellites even without considering observational limitations.

The darker seasons are times of year when the sun-sensor geometry is suboptimal or inadequate for passive greenhouse gas retrievals to be made within uncertainty requirements for atmospheric inversions. Current and future satellites have the capability to measure in so-called glint mode. This mode can produce much larger signals over snow-covered regions and would extend the coverage into the shoulder seasons. For example, the Copernicus CO2M Mission will be composed of three satellites in a constellation flying in an 11:30 LTDN Sun-synchronous orbit, which improves high latitude coverage and glint observations are performed over snow-covered areas to further improve retrievals over high latitudes. Due to cloud coverage in autumn, the main improvements are in early spring. The specific capability to measure in the polar night is offered by lidar, but this technology has not yet been widely used for GHG observations, as it is expensive and is expected to remain limited. The upcoming MERLIN mission (scheduled for launch in 2029) will be the first to provide this capability.

Close collaboration with GCOS is essential to clarify the objectives and use cases for CO2 and CH4 observations in high latitudes in wintertime.

Activity F2.3

Sea ice thickness

Means of assessing progress: Proof of concept for new technologies and new methodologies to measure sea-ice thickness

Sea ice thickness is most directly estimated via altimeters. An altimeter emits a signal from above the ice and measures the time for the signal pulse to be reflected back to the sensor. Knowing the altitude of the altimeter, the height of the surface can be estimated. For sea ice, this is the height above the local sea level, which is denoted as "freeboard". There are two primary types of altimeters: radar and laser. Laser altimeters use visible light pulses to estimate height. If snow is present on the sea ice, the photons of visible light primarily reflect off the top of the snow surface so that the actual observation is a "snow+ice" freeboard. Radar signals generally penetrate through the overlying snow cover and reflect from the snow-ice interface, yielding an ice freeboard. However, particularly for radar, the actual reflecting layer may not be the snow-ice interface, depending on the character of the overlying snow.

Sea ice thickness can be derived from the freeboard using hydrostatic equilibrium if the snow and ice densities are known. Snow density in particular can be highly variable. Sea ice density can also vary, with the primary difference coming from the ice type. Seasonal or first-year ice (ice that has not survived a summer melt season) contains pockets of entrained brine. The summer melt season flushes out much of the brine, leaving air pockets in multi-year ice. Thus, multi-year ice is less dense than first-year ice.

Issues with uncertainties in snow depth and snow characteristics limit the accuracy of retrievals; there is ongoing research to obtain better estimates of snow and refinements to the algorithms to improve accuracy. Retrievals are limited during the summer melt season, particularly for radar altimeters, and for this reason estimates are generally not produced during summer. However, new methods are being developed that have the potential to estimate thickness year-round. Due to the character of Antarctic ice – thinner with heavy snow and flooded snow-ice formation – retrievals in the Antarctic are more challenging and, to date, less reliable. Thus, most of the focus has been on estimation of Arctic sea ice thickness.

The first altimeters that targeted sea ice were radar altimeters on the European Remote-Sensing Satellites (ERS) 1 and 2, which operated from 1991-2000 and 1995-2003 respectively. However, these sensors had limited coverage of the polar regions and did not retrieve data from the interior of the Arctic ice pack. Nonetheless, the sensors on ERS-1/2 were a proof-of-concept demonstrating that altimeters could retrieve reliable sea ice freeboard and thickness estimates and they did provide useful early information on changes in Arctic sea ice. Raw data of these satellites have been reprocessed and that studies are underway to extend the sea-ice thickness time series established using Envisat-RA2 and CryoSat-2 back in time.

The NASA Ice, Cloud, and land Elevation Satellite (ICESat) was launched in 2003 carrying a laser altimeter. Instrument issues limited the operation of the laser such that data was collected only over two 30-day periods per year. Still, this provided the first near-complete coverage of the Arctic sea ice region. ICESat operated until 2009.

NASA undertook an airborne mission, Operation IceBridge, carrying altimeters and other instruments to overlap with ICESat and future sensors and “bridge” the gap between satellite missions. Flights were conducted over the Arctic and Antarctic at least a couple times per year between 2009 and 2019.

ESA's Envisat radar altimeter that operated from 2002 to 2012 has been used to derive freeboard and sea ice thickness for Arctic and Antarctic. The ESA CryoSat-2 mission, carrying a radar altimeter, was launched in 2010 and continues to operate. CryoSat-2 has been the backbone to estimate the sea ice thickness distribution in the Arctic and Antarctic since 2010. CryoSat-2 is producing monthly composites of freeboard and thickness in the Arctic and Antarctic. While providing good coverage of the Arctic, the spatial resolution is relatively coarse, at about 15 km.

CryoSat-2 has provided new measurements that now form the backbone of monitoring. Its SARIn technology provides a completely new and more precise method to measure sea ice freeboard (and, as an aside, also land ice elevation). Further, the upcoming Copernicus CRISTAL mission will be a dual-frequency Ku- and Ka-band polar orbiting SAR enabled altimeter. (CryoSat-2 is Ku, AltiKa is Ka). The importance of this is related to being able to better measure and represent the air-snow interface and understand the snow loading on sea ice, and therefore improve the calculations of radar freeboard and sea ice thickness. Snow load is a huge question mark in the

calculations of sea ice thickness, because currently all products rely on what is called the Warren Climatology from the 90s, which a) are in situ measurements of snow depth from Soviet drifting stations on multiyear sea ice from 1954-1991, extrapolated to the entire Arctic basin, and b) also basically no longer holds true in the current climate.

In 2018, NASA launched ICESat-2 with a more advanced "photon-counting" laser altimeter with three pairs of beams with <70 m sampling. However, spatial coverage is sparse with a 91-day repeat cycle, though it is higher near the poles and monthly composites of freeboard and thickness are being routinely produced.

Beginning in 2020, the CryoSat-2 orbit was modified to allow near-coincident observations with ICESat-2 during parts of some orbits. The combination of radar altimeter (penetrating through snow to the snow-ice interface) and laser altimeter (reflecting from the top of the snow) has potential to improve both snow depth on sea ice and sea ice thickness retrieval and yield better understanding of both instruments.

Both ICESat-2 and CryoSat-2 are beyond their nominal mission lifetimes, but continue to operate effectively and have enough fuel to potentially operate for several more years. CRISTAL is designed as a follow-on to CryoSat-2 and will entail two satellites carrying radar altimeters, with the launch of the first satellite currently planned for 2028 and the second satellite for 2034. CryoSat-2 was launched in 2010 and a potential gap could occur if it fails before 2028.

In February 2026, NASA selected the EDGE (Earth Dynamics Geodetic Explorer) mission for continued development as part of NASA's Earth System Explorers Program. EDGE will observe the three-dimensional structure of terrestrial ecosystems and the surface topography of glaciers, ice sheets, and sea ice, providing an advancement beyond the measurements currently recorded from space ICESat-2 and GEDI. EDGE will launch no earlier than 2030.

Altimeters are relatively less accurate for thin ice, due to a lower instrument precision for ice less than about 20 cm. Microwave emission from the surface is dependent on the phase state of water, with ice substantially more emissive than liquid water. Passive microwave sensors have long been employed to estimate sea ice concentration. However, at low frequencies, e.g., 1.4 GHz, the emission correlates well with thickness until a saturation point is reached. This allows sea ice thickness to be accurately estimated up to at least 0.5 m and potentially 1 m. The ESA Soil Moisture Ocean Salinity (SMOS) satellite was launched in 2009 with a 1.4 GHz microwave radiometer capable of estimating thin ice thickness. Because SMOS is limited to thin ice and CryoSat-2 is most optimal over thick ice, a combined CryoSat-2/SMOS product has been developed, which can yield thickness and volume estimates across the entire range of sea ice thickness. The 1.4 GHz microwave radiometer capability is continued on the EU Copernicus polar expansion mission Copernicus Imaging Microwave Radiometer (CIMR), jointly implemented by ESA and EUMETSAT. Two satellites are planned to be launched in 2029 and 2035.

Higher frequency passive microwave channels are generally used only for surface properties (concentration, melt detection, snow cover), but with quality information on the ice emissivity and temperature, thickness can potentially be derived. Thermal infrared sensors have also been employed with radiative transfer models and surface flux information to estimate thickness. Both of these approaches incorporate substantial modeling and their use has been limited within the sea ice community.

Activity F2.4

Surface temperature of all surfaces (sea, ice, land)

Means of assessing progress: Feasibility study for true pole-to-pole orbital mission to measure changes at the very high latitudes for a set of targets ECVs.

Thermal infrared (IR) imagers have been used for surface temperature of sea, ice, and land by offering higher spatial resolutions, albeit with limitations under cloudy conditions. Sensors like VIIRS, MODIS, SLSTR, AVHRR, and METimage deliver SST and LST data with spatial resolutions ranging from 750 m to 1.1 km. JAXA's Global Change Observation Mission - Climate (GCOM-C), launched in 2017, bridges traditional IR sensors and emerging ultra-high-resolution technologies, providing data at 250–1000 m resolution with a focus on coastal and global applications.

For land and land-ice LST, operational products are available from Sentinel-3 SLSTR (A and B), with additional modules (C and D) planned for launch in the near future. Landsat satellites continue to provide critical thermal IR LST data, with Landsat 8 and 9 offering 100 m native resolution and Level 1 and 2 data products resampled to 30 m. The upcoming Landsat 10, scheduled for launch in 2031, will further improve native resolution to 60 m across five thermal IR bands. Specialized products, such as MODIS and VIIRS polar-region datasets, and next-generation instruments like the Advanced SLSTR, are being designed to enhance LST and ice surface temperature monitoring capabilities.

Recent advancements in thermal IR radiometer missions have enabled ultra-high-resolution (less than 100 m) retrievals of LST and coastal SST. Key missions include:

- NASA ECOSTRESS (2018): 69 × 38 m resolution, 384 km swath.
- CNES/ISRO TRISHNA (2026): 57–90 m resolution, 1062 km swath.
- ESA LSTM (2028, 2030): 50-m resolution, 1–3 day repeat cycle.
- NASA EAGLE-TIR (launch date TBD): details to be confirmed

These missions are designed to complement one another, and product harmonization efforts, including format standardization, calibration, and algorithm development, are underway. GHRSST and SST-VC are encouraging agencies to adopt GDS-compliant formats for SST products.

Microwave imagers play a crucial role in observing the Earth's surface under cloudy conditions, particularly in high-latitude regions. However, their coarse spatial resolution compared to optical imagers remains a significant limitation. Advances are being made to improve the utility and resolution of these observations, while integrating them with complementary thermal IR datasets to support diverse applications, from climate monitoring to resource management.

Microwave imagers like JAXA's Advanced Microwave Scanning Radiometer (AMSR) series have provided long-term, all-weather global SST and Land Surface Temperature (LST) measurements since 2002. The AMSR series measures SST at 30–50 km and LST at 15 km spatial resolution, and is continued by AMSR3 aboard the GOSAT-GW satellite launched in 2025. ESA's Copernicus Imaging Microwave Radiometer (CIMR), slated for launch in 2029, will further enhance microwave-based SST observations with a 15-km spatial resolution.

The Group for High-Resolution Sea Surface Temperature (GHRSST), in collaboration with the CEOS SST Virtual Constellation (SST-VC), has standardized the format for satellite-based Sea

Surface Temperature (SST) datasets, including both IR and microwave imagers, under the GHRSST Data Specification (GDS). This enables the integration of these datasets into Level 4 (merged multi-satellite SST) products, which are operationally used by meteorological agencies worldwide.

Projects such as ESA CCI SST, LST, and Lakes are developing improved global climate data records for sea, land, ice surface temperatures, and lake surface water temperatures using a variety of infrared and microwave instruments. Similarly, the CM SAF is generating long-term climate LST datasets from geostationary instruments. The CEOS Land Surface Imaging Virtual Constellation (LSI-VC), through the CEOS Analysis Ready Data (CEOS-ARD) initiative, has developed product family specifications (PFS) for Surface Temperature products, with Version 6.0 of the ST PFS including LST, Surface Brightness Temperature (SBT) and water surface temperature (WST). Landsat products have already been assessed as compliant with the specifications, while other products are in development.

These collaborative efforts are addressing challenges such as integrating data from diverse sensors and aligning them with standardized formats. By enhancing spatial resolution and data harmonization, these advancements are expected to significantly improve the utility of SST and LST observations for climate research, resource management, and policy decision-making.

Activity F2.6

Albedo for all surfaces (land and sea-ice)

Means of assessing progress: Feasibility study for true pole-to-pole orbital mission to measure changes at the very high latitudes for a set of targets ECVs.

CEOS and CGMS agencies produce multiple satellite-derived albedo products that include coverage at high latitudes. Without more specific information on the shortcomings in existing products or application and performance requirements for an improved product, the Agencies cannot assess if current or future albedo products would satisfy the GCOS community. Therefore, below we first address the GCOS orbit study request, then summarize several existing products that provide surface albedo in polar regions.

Pole-to-pole orbit consideration

The requested study of a 90-degree inclination orbit is neither clearly needed nor generally desired for two reasons. First, multiple visible/near-infrared imagers already observe the exact pole locations (+/-90 degrees) from existing orbits -- in fact multiple times per day. These non-nadir observations are far better for estimating albedo at the poles given the highly anisotropic bidirectional reflectance distribution functions of these surfaces, particularly for high solar zenith angles. Second, a satellite orbit with a 90-degree inclination angle would not precess, and therefore would not be sun-synchronous, a feature that enables the comparison and assessment of environmental conditions at consistent times and solar illumination conditions across the globe and over different days.

Existing albedo products

For albedo products over snow and ice, perhaps the greatest retrieval system challenge is discrimination of clouds from snow and ice surfaces given their similar spectral and bidirectional reflectance characteristics. Given this, the highly specular anisotropy of the surface reflectance distribution, and the high solar zenith angles associated with these regions, high latitude albedo performance is invariably lower than that over most mid- and low-latitude targets. With this key caveat in mind, we summarize below several leading albedo products.

As for existing climate-length records, NOAA has long-produced albedo as part of the 19-variable AVHRR/VIIRS Polar Pathfinder climate data record (APP-X, version 2). This product extends from 1982-present, approximately the longest satellite-derived albedo record length possible. The albedo product has been validated and is considered climate quality. NOAA continues to sustain and extend the length of this record in time. EUMETSAT has a similar surface albedo climate data record as part of the third edition of the CM SAF CLARA-A3 AVHRR-based clouds, radiation and surface albedo climate data record covering the period 1979 to 2023 (Karlsson et al., 2023). This product has been formally validated prior to its release by EUMETSAT. The Copernicus Climate Change Service produces 10-day gridded global surface albedo products from multiple platforms/sensors from 1981 to present. Current data is from Sentinel-3 OLCI/SLSTR with the heritage data coming from the AVHRRs. The product is independently validated through the Copernicus Land Monitoring Service Ground-Based Observations for Validation (GBOV) project.

As for near-real-time operational albedo products over high latitudes, NOAA recently significantly improved its operational VIIRS SURFALB product, particularly for snow and ice albedo estimation, offering improved accuracy and temporal resolution over previous systems like MODIS and AVHRR (Peng et. al., 2023; Peng et. al., 2018). Key innovations include a Direct Estimation Method (DEM) that derives albedo directly from single-date observations of top-of-atmosphere reflectance, allowing for more accurate capture of dynamic snow/ice surface changes, particularly during melting or refreezing. SURFALB is based on specialized Look-Up Tables (LUTs) utilizing individualized bidirectional reflectance modeling for snow and sea-ice surfaces, enhancing albedo estimates in polar regions. The product is provided as daily near-real-time albedo estimations. Additionally, the product includes gap-filling techniques for cloudy-sky conditions, improving spatial data continuity. However, the current version (v2r2) has limitations, including a short product accumulation due to its recent operational release in December 2024 and reliance on historical climatology for cloudy-sky albedo estimations. NOAA plans to reprocess all VIIRS data to provide a complete consistent albedo product for the period-of-record. NOAA is considering additional enhancements such as blended albedo products using data from multiple satellites and improved climatology for more accurate cloudy-sky retrievals. Despite these challenges, VIIRS continues to represent a significant step forward in monitoring snow and ice albedo, with ongoing improvements poised to enhance its utility in climate science.

NASA is sustaining its daily MODIS- and VIIRS-derived research-quality albedo products, at least through 2026 (Román et. al., 2024). The 500- and 1000-m resolution products do well over mixed snow-forest mixed scenes and adequately for most purposes for highly specular surfaces like snow and ice. They are not provided for SZA>70 degrees because of the aforementioned highly anisotropic reflectance issue.

Several high resolution (~30m) Landsat 8/9 and Sentinel-2 A/B/C albedo products are available from the NASA USGS Land Processes Distributed Active Archive Center (LP DAAC) (Elms et. al.,

2021; Erb et. al., 2022). Because these instruments mostly sample near nadir, some of the albedo products leverage coarser-resolution bidirectional reflectance distribution information derived from MODIS or VIIRS to estimate the hemispheric albedo quantity. The resolution mismatch is a source of additional uncertainty in the retrieved product depending on the homogeneity of the target and its surroundings.

JAXA has produced albedo products from its GCOM-C/Second generation GLobal Imager (SGLI) instrument since December 2017. JAXA also produces and distributes albedo products from MODIS on Terra and Aqua since 2000 to be consistent to that of SGLI for climate studies and the algorithm for SGLI is also applied to VIIRS.

Finally, the Canadian Space Agency is studying development of an highly-elliptical orbiting mission called the Arctic Observing Mission which possibly would launch in the mid-2030s. The potential Canadian-led, international partner AOM would provide data to support the monitoring of the Arctic's atmosphere and ground conditions, and to help scientists monitor permafrost. The AOM may carry the NOAA ABI imager which would effectively stare at the north pole, however it would be at coarse spatial resolution.

This section summarized several of the more widely known and longer-duration albedo data sets which cover polar regions. It is not a comprehensive list, however it is a starting point for polar albedo studies and discussion of needs and requirements by the GCOS community.

Action F3: Improve monitoring of coastal and exclusive economic zones

Activity F3.1

Expand global ocean climate in situ observations and satellite products into exclusive Economic Zones (EEZs) and coastal zones.

Means of assessing progress: Increased density of observations and reprocessed products in EEZ and coastal waters, and related uncertainties.

Numerous national programs, such as Ocean Networks Canada, the US Ocean Observatories Initiative, and the Integrated Marine Observing System (IMOS) in the UK and Australia, provide near-real-time sensor data and quality-controlled archived datasets for coastal regions less than 2000 meters in depth. These networks utilize a combination of in-water fixed buoys and mobile assets, including gliders, wire-following profilers, and autonomous underwater vehicles (AUVs), to collect extensive observations.

The near-real-time observations vary depending on the program and location but typically include:

- Atmospheric and Meteorological Data: Measurements of atmospheric gases and weather conditions.
- Physical Oceanographic Data: Geolocated and depth-corrected parameters such as temperature, currents and flow rates, and wave height.
- Biogeochemical Oceanographic Data: Sensor-based measurements of:
    - Fluorometrically-derived Chlorophyll
    - Colored Dissolved Organic Matter (CDOM)
    - Total and particulate backscattering
    - Spectral Irradiance
    - Spectral Total Absorption and Absorption by Dissolved Materials
    - UV-Sensor Nitrate/Nitrite
    - Dissolved Oxygen
    - pH
    - Climate-quality Air/Subsurface Partial Pressure of CO_2 (pCO_2)

In addition to sensor-based data, these programs generate biological and advanced chemical datasets, such as environmental DNA (eDNA), extracted chlorophylls, and hydrophone acoustic recordings. However, these datasets often experience unpredictable and lengthy delays before becoming available due to the time-intensive nature of processing and analysis.

Existing and upcoming satellite missions will enhance foundational scientific discovery and routine monitoring. NASA's PACE (Plankton Aerosols Clouds and Ecosystems) mission is one of a kind for its hyperspectral and polarimeter capabilities, which enable phytoplankton community detection and improved harmful algal blooms assessment. The upcoming GLIMR mission (Geostationary Littoral Imaging and Monitoring Radiometer) is geostationary over the Gulf, providing hourly observations needed to detect rapid changes affecting fisheries, aquaculture, and oil industries, among others. The NISAR mission is a joint partnership between NASA and the Indian Space Research Organization, carrying dual-frequency synthetic aperture radar that can enable detection of surface water deformation near the coast, oil slicks and discoveries yet to

be made. NASA's SWOT (Surface Water Ocean and Topography) mission enables state of the art detection in sea level heights, enabling improved estimates of sea level rise and local current conditions. The Sentinel-2 next generation mission will expand coverage compared to the current generation to cover the maritime EEZs.

By integrating automated, high-quality data from a variety of platforms, these national networks significantly enhance our understanding of coastal ecosystems and contribute valuable information for research, resource management, and policy development.

Activity F3.2

Develop new satellite-based products for coastal biogeochemistry

Means of assessing progress: Number of global operational biogeochemical products in coastal areas.

Experimental products for several biogeochemical parameters, such as Suspended Particulate Matter (SPM) and Colored Dissolved Organic Matter (CDOM), are progressing but still require significant refinement. Similar challenges exist for chlorophyll products, particularly within 1 km of the coastline, where complex environmental factors influence accuracy. However, new missions like SWOT and PACE, along with the integration of commercial data, are expected to enhance capabilities for monitoring land use, water quality (e.g., chlorophyll, turbidity, CDOM), and sea surface temperature (SST).

The CEOS COAST-VC is actively building capacity and co-designing advanced coastal products in collaboration with stakeholders. Pilot regions include the Bay of Bengal, Chesapeake Bay, Rio de la Plata estuary, the west coast of continental Africa, and small island nations in the Pacific and Caribbean. These efforts aim to develop tailored solutions addressing regional and global needs.

In the United States, the Satellite-based Tool for Rapid Evaluation of Aquatic environMents (STREAM) (https://ladsweb.modaps.eosdis.nasa.gov/stream) provides rapid high-resolution water quality parameters from Landsat 8/9 and Sentinel-2. Sentinel-2 chlorophyll-a (Chl-a) products are also under development by NOAA but have not yet reached operational status. Collaborative efforts between NOAA and other federal agencies are focused on creating large-scale operational products for coastal biogeochemical processes across all U.S. coastal areas, with a particular emphasis on chlorophyll-a and turbidity. These products leverage data from Sentinel-2 satellites.

There are also many research products and applications ongoing using Sentinel 3 OLCI full resolution in coastal and inland water for water quality, chl-a and increasingly carbon cycle rates and stocks. In the Copernicus services S2 and S3 are used operationally for chl-a and turbidity. In the ESA PRIMUS project (2022-2024) a time series of primary production was computed based on Sentinel 3 OLCI 300m data for the NW Spanish rias (areas of significant mussel farming). Likewise, in other ESA projects various groups are investigating carbon cycle pools using 300m data: e.g., POC, PIC and DOC concentrations for the Spanish rias, western English Channel and Baltic Sea.

Additionally, there are ongoing efforts to evaluate the potential of the Landsat satellite series for water temperature monitoring, building on successful demonstrations in inland waters. These advancements hold promise for providing more accurate and comprehensive coastal and inland water assessments in the near future.

Activity F3.3

Produce land cover datasets in coastal areas without land surface masks and in near real time, including uncertainties

Means of assessing progress: Number of land-cover data sets produced without masks

The United States has approximately 95,000 miles of coastline. NOAA's National Geodetic Survey (NGS) surveys these coastal regions and provides the Nation with accurate, consistent, up-to-date national shoreline. These shoreline data are considered authoritative when determining the official shoreline for the United States. The method used to delineate the shoreline is stereo photogrammetry using tide-coordinated aerial photography controlled by kinematic Global Positioning System (GPS) techniques. This process produces a seamless, digital database of the national shoreline and a database of aerial photography. NOAA has produced coastal land cover data for the US at 30 m resolution, updated the data in 1985, 1996, 2001, 2011, and 2016.

NOAA's Digital Coast program is currently working to phase-in the next generation of high-resolution land cover data for US coastal areas. The new 1-meter products use advanced artificial intelligence combined with expert human analysis, review, and editing to produce high-quality, standardized, raster-based map products. Phase 1 Initial Layers and Phase 2 Expanded Categories data is now available for 2020 and 2021.

Europe's coastal regions are hotspots of biodiversity. Tens of thousands of plant and animal species rely on unique coastal ecosystems such as inland or salt marshes and intertidal flats, which are vital to the health of global oceans. The Copernicus Coastal Zones product provides detailed land cover/land use maps of Europe's coastal regions. This data is helpful for making informed decisions about coastal ecosystem management (e.g., identifying areas that require conservation), land-use planning (e.g., in areas with competing resource demands), and disaster management (e.g., forecasting the impact of storms and flooding). Land Cover/Land Use layer is extracted from Very High Resolution (VHR) satellite data and other available data. The Coastal Zones product covers the entirety of European coastal areas to an inland depth of 10 kilometers—a total area of roughly 730,000 square kilometers. The classification provides 71 distinct thematic classes with a Minimum Mapping Unit (MMU) of 0.5 ha and a Minimum Mapping Width (MMW) of 10 m. The product is updated every six years, and currently consists of three layers: a land cover/land use status layer for both 2012 and 2018, as well as change layer for the period between 2012 and 2018. Copernicus provides, at a global level, spatial information on different types (classes) of physical coverage of the Earth's surface, including forests, grasslands, croplands, lakes and wetlands for the 2019 base year. The data are updated annually and are available for 2015-2019. The next planned Dynamic Land Cover product update

addresses the generation of products for the time period from 2020 to 2026. The data contains coastal area land cover types and changes, with a spatial resolution of 100 m.

At local/regional level, projects such as ARGANS are producing maps of waterline, shoreline, land use classification maps, plus time series maps to assess the extent of coastal erosion. ESA's ULYSSES Project looks at Mediterranean soil sealing processes and develops land use maps based on Sentinel-1 and Sentinel-2 data.

With regards to longer term records, Space for Shore compiles 25 years of coastal monitoring to assess coastal erosion in Europe. A Space 4 Shore data portal has been developed, using a case study/end user approach to derive variables of interest. To date, most datasets are local or regional in nature as user needs vary widely based on the coastal context.

Action F5: Develop an integrated operational global GHG monitoring system

Activity F5.2

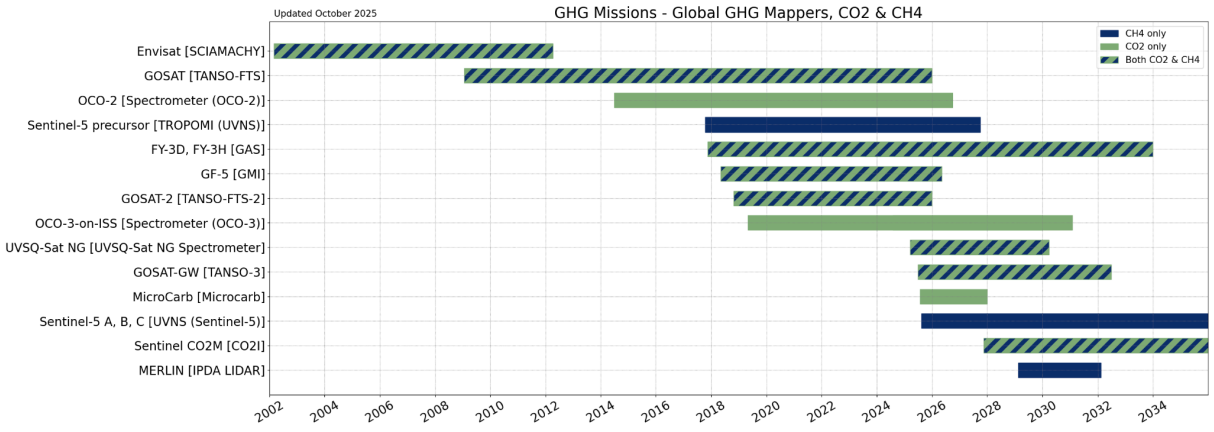
Design a constellation of operational satellites to provide near-real time global coverage of CO2 and CH4 column observations (and profiles to the extent possible)

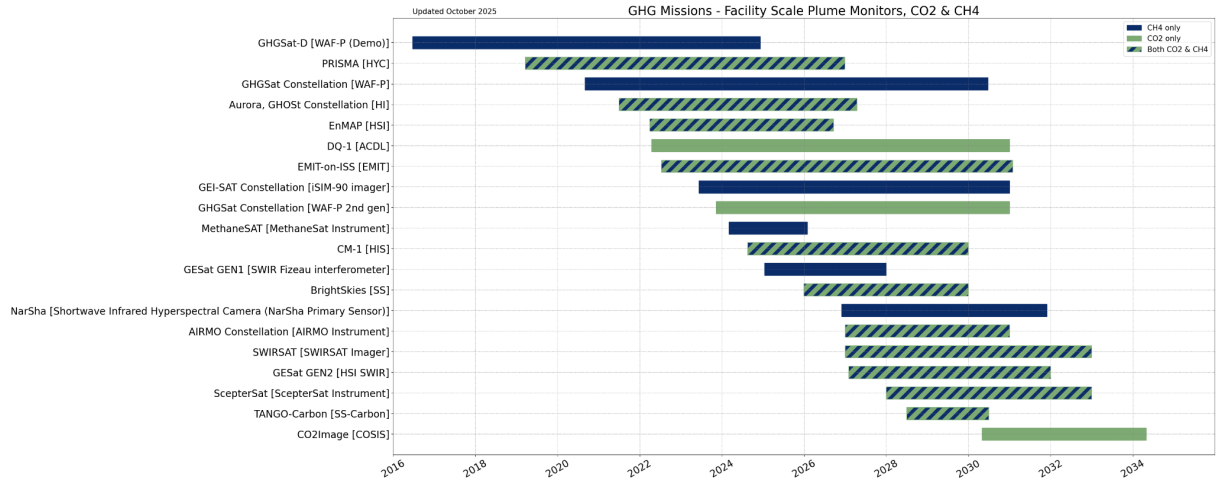
Means of assessing progress: Designs and plans for in situ and satellite observations.

CEOS and CGMS have been working towards establishing an integrated operational global GHG monitoring system. The current monitoring system, including OCO-2/3, GOSAT-1/-2/-GW and Sentinel-5A/-5P (TROPOMI), already provides good coverage. The near-future system is expected to provide global coverage by the end of 2026 with the launch of CO2M to provide operational GHG monitoring and services. For CO2M (and likely for Sentinel-5), these data will be delivered within 24 hours of observational time. Profiles are currently only feasible above the middle troposphere. There is currently no known remote sensing technology that can provide profiles between the surface and mid-troposphere. Close collaboration with GCOS is essential to clarify the objectives and use cases for providing CO2 and CH4 observations in near-real time, which need to be explicitly defined.

The charts below show current and planned wide area and facility scale missions that will operationalize the global GHG monitoring. A dedicated greenhouse gas satellite missions portal was established (here) and can be used to track status of current missions and planning of upcoming missions.

In 2024, CEOS and CGMS endorsed Issue 2 of the Greenhouse Gas Roadmap, reaffirming the commitment to space-based monitoring of CO_2 and CH_4.





Activity F5.4

Improve and coordinate measurements of relevant ECVs at anthropogenic emission hotspots (large cities, power plants) to support emission monitoring and the validation of tropospheric measurements by satellites

Means of assessing progress:

a) Improved satellite retrievals in the presence of varying aerosol loadings in urban and hotspot conditions. Improved uncertainty quantification of GHG retrievals in the presence of aerosols;
b) Number of emission detection studies using in situ and satellite data near hot spots.

This activity focuses on improving the quality of satellite-based emission estimates at urban and local scales, particularly for CO_2 (rather than CH_4). In 2024, CEOS and CGMS endorsed Issue 2 of the Greenhouse Gas Roadmap, reaffirming the commitment to space-based monitoring of CO2 and CH4.

a) Variations in aerosol loading can significantly impact satellite-based estimates of total column CO_2, especially when these data are used to evaluate natural fluxes, which vary by approximately 0.25 ppm per 100 km (Worden et al.,2017). However, in urban regions and around large facilities, CO_2 gradients are much larger, making aerosol variability a less critical factor. For example, CO_2 emission estimates from urban areas and large power plants observed by satellites such as OCO-2, OCO-3, and GOSAT are primarily affected by uncertainties in local wind field and aerosols (Nassar et al., 2017). The ESA AEROCARB study, conducted as part of the Copernicus CO_2 Monitoring (CO2M) mission, also reached a similar conclusion. Notably, the CO2M mission will feature an aerosol sensor to help correct for aerosol effects. The ESA SMARTCARB study, conducted as part of the CO2M mission, investigated the added value of coincident NO_2 observations for better locating emission plumes of CO_2 emission hotspots. The study concluded that such NO_2 observations greatly enhance the accuracy of CO_2 emission estimates of these hotspots. The CO2M and GOSAT-GW mission will also measure NO_2 alongside CO_2. Initial in-orbit experience has been gained by combining OCO-2 CO_2 with Sentinel-5 Precursor NO_2 data.

For plume mapping of CO_2, the influence of aerosols on retrieval accuracy is not well understood and requires further investigation. This will be part of a broader initiative within the CEOS

Atmospheric Composition Virtual Constellation (AC-VC) to promote greater transparency in plume-mapping products, particularly those from non-public datasets.

b) Several initiatives aim to establish city networks equipped with numerous sensors to provide more detailed insights into urban CO_2 emissions. To enhance the integration of ground-based and satellite data, it is recommended to co-locate aerosol sensors at these monitoring sites. This approach could facilitate better connections between satellite retrievals and ground-level observations, improving the accuracy and reliability of urban emission assessments.

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