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Research and Systematic Observation (RSO)

Views on possible themes for the eighteenth meeting of the Research Dialogue

Submission from WMO

Introduction

The eighteenth meeting of the Research Dialogue, to be held in conjunction with SBSTA 64 (June 2026), provides an important opportunity to exchange research findings and lessons learned from international and regional programmes and supports the identification of research priorities and capacity-building needs, particularly in developing countries.

In line with the conclusions on RSO adopted at COP30 (FCCC/SBSTA/2025/L.8), and building on the draft conclusions considered at SBSTA 62 (FCCC/SBSTA/2025/L.5), WMO is pleased to provide its views on possible themes for the eighteenth meeting of the Research Dialogue, drawing on its global mandate in weather, climate and water, and its coordination of international research and observing systems.

WMO views on possible themes

- (1) **Strengthening Observation Systems, Attribution Science, and Research Capacity to Address Extreme Events and Climate Tipping Points in Developing and Data-Sparse Regions**
- (2) **Role of Artificial Intelligence (AI) and Machine Learning (ML) in advancing climatological research and modelling**

Key research questions

- (a) ***How can systematic and sustained weather and climate observation systems be strengthened in data-sparse regions to improve the monitoring and characterization of extreme and compound climate events?***

- A [landmark study by the European Centre for Medium-Range Weather Forecasts \(ECMWF\)](#) in 2025 provides the **strongest scientific evidence to date that investments in the global observing system significantly improve weather forecast accuracy**, both locally and globally. The study demonstrates that investing in systematic observations in developing countries, which often have the biggest data gaps, brings the greatest reductions in global forecast uncertainty. Observations from Small Island Developing States (SIDS) and Least Developed Countries (LDCs) are especially critical as data from remote, data-sparse locations have substantial impact on the quality of forecasts. Results highlight significant impact over Africa and the Pacific region, where forecast uncertainty decreases by up to 30% with new investments. The Systematic Observations Financing Facility (SOFF) supports SIDS and LDCs to generate and internationally exchange observations in line with the Global Basic Observing Network (GBON) of WMO.

- Recent assessments (for example, Otto, F.E.L., 2023)¹ indicate important **observational gaps** persist in geographical coverage and applicability, particularly in vulnerable and data-sparse regions. As reflected in the Sixth Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR6), limited observations, short records and high natural variability continue to constrain confidence in attribution results across many regions.
- The Global Climate Observing System (GCOS) is currently identifying the principal **gaps and threats affecting the global climate observing system** and developing priority actions to address them. This work will culminate in the joint publication of a new GCOS Status Report and a High Priority Action Plan in early 2027, timed to inform the next Global Stock Take (GST) and support Parties in meeting their commitments under the UNFCCC. These include insufficient geographical coverage, an inadequate number of in situ monitoring stations, sustainability challenges for monitoring stations, data repositories, quality assurance facilities, lack of secure long-term planning for satellite missions, and restrictive data access policies. These shortcomings are particularly acute in LDCs and SIDS, limiting the full usability of climate observations in support of Nationally Determined Contributions (NDCs) and broader Paris Agreement goals.
- Improved observational systems, data integration and modelling are therefore critical as they improve **extreme events attribution science**, including the integration of in situ measurements, satellite observations, and reanalyses. Artificial Intelligence (AI) and Machine Learning (ML) techniques can complement physically based models by supporting pattern recognition, multivariable analysis and downscaling, particularly in data-sparse regions.

(b) How can advances in attribution science – supported by strengthened observations, improved modelling and innovative techniques – address current research gaps, particularly in vulnerable and data-limited regions?

- Advances in attribution science are improving understanding of the role of climate change in extreme events. Advances in **probabilistic and process-based attribution methods** are improving understanding of how the occurrence, frequency and intensity of extreme events are changing under anthropogenic climate change. Initiatives such as World Weather Attribution demonstrate how robust, transparent attribution approaches can be applied to high-impact extremes, including tropical cyclones, monsoons² and heat-related events.
- Furthermore, coordinated science efforts, for instance, under the World Climate Research Programme³ (WCRP)'s Explaining and Predicting Earth System Change, help improve understanding of large-scale drivers and predictability across multiannual to decadal time scales. This strengthens confidence in attribution for circulation-driven extremes such as polar vortex variability.
- Addressing these gaps requires targeted **advances in observations, modelling and methodological approaches** suited to data-limited contexts, alongside coordinated synthesis across regions and hazard types. Regionally tailored attribution studies are essential to ensure equitable access to evidence that informs adaptation planning, risk management and climate

¹ Otto, F.E.L. (2023). Attribution of extreme events to climate change. Annual Review of Environment and Resources, 48, 813–828.

² See the WCRP's Monsoons group <https://www.wcrp-climate.org/mp-overview>.

³ An example is provided by the WCRP Lighthouse Activity on "Explaining and Predicting Earth System Change" which has as a key theme on Integrated attribution, prediction, and projection (including early warning and the potential for abrupt change) <https://www.wcrp-climate.org/epesc>.

services. The **WCRP Global Extremes Platform**⁴ contributes by coordinating cross-regional case studies, promoting methodological consistency and facilitating synthesis across hazards, thereby strengthening attribution where single-event analyses remain uncertain. In parallel, the **WCRP Global Precipitation Experiment** enhances the physical basis for attributing precipitation-driven extremes — including tropical cyclones (TC) and atmospheric rivers — through improved process understanding, targeted observations and process-based model evaluation in under-observed, high-risk regions.

- Advances in rapid and near-real-time attribution, supported by strengthened observations, improved modelling, and **AI and ML techniques**, are increasing the operational relevance of attribution science. National agencies are progressively integrating attribution into monitoring, seasonal outlooks and decision support before, during and after events. For example, rapid TC attribution embedded in outlooks or post-event risk bulletins can inform early action, reconstruction standards and risk-transfer mechanisms in cyclone-prone regions.

Key research question

(c) How can climate science improve the understanding of climate tipping points and their potential to trigger cascading, cross-sectoral impacts through non-linear and exponential changes?

- Advances in climate science are improving understanding of **tipping dynamics** by strengthening conceptual clarity and consistent definitions of tipping elements, tipping processes and impact tipping points. The recent IPCC-WCRP co-sponsored workshop on [High-Impact Climate Events, Tipping Points, and Irreversible Regional Impacts](#), and associated WCRP Assessment, emphasize the need for clearer typologies, harmonized terminology and better integration of tipping science across assessments to avoid conflation with extreme events and compound hazards.
- Improved detection of early warning signals requires **sustained, high-resolution observations** across oceanic, cryospheric, hydrospheric, atmospheric and biospheric systems. Long-term monitoring of tipping-relevant components — including the Atlantic Meridional Overturning Circulation, polar ice sheets, permafrost regions and major forest biomes — combined with novel statistical early warning techniques – can enhance detection of emerging instability and declining resilience, enabling earlier recognition of approaching thresholds.
- Advances in **Earth system modelling** are critical to better represent non-linear feedback, threshold behaviour and cross-system interactions. Targeted perturbation experiments, large ensembles under warmer scenarios, and improved representation of carbon–climate feedback and cryosphere–ocean coupling can help constrain the likelihood, timing and irreversibility of potential tipping transitions.
- Development of integrated analytical frameworks is essential for assessing **cascading and cross-sectoral risks** that account for interdependencies across physical and human systems. Recent scientific literature highlights the need to better characterize mechanisms of risk propagation, including nonlinear dynamics and interactions among climate system components.

⁴ <https://gep.wcrp-rifs.org/>

- The **Global Tipping Points Assessment 2025** (Lenton T.M. et al., 2025)⁵ notes that interacting tipping elements may alter system behaviour in ways not fully represented in conventional risk assessment approaches. Strengthened monitoring, improved representation of system interactions, and incorporation of these dynamics into risk assessment methodologies are therefore recommended. It also emphasizes clearer **integration of regional and local dimensions**, as tipping processes and their manifestations can vary across spatial scales.

Key research question

(d) *How can advances in AI improve the speed, computational efficiency, spatial resolution and completeness of climate information derived from complex climate models and observational datasets, while ensuring scientific robustness and relevance for decision-making, particularly in data- and capacity-constrained regions?*

- **AI and ML** approaches have the potential to improve post-processing corrections on top of established physical models and observations, rather than replacements. In practice, this means starting from already evaluated products such as the Coupled Model Intercomparison Project (CMIP) and the Coordinated Regional Climate Downscaling Experiment (CORDEX) simulations or reanalyses and using AI to learn mappings from coarse to fine scales or from biased to bias corrected data. Embedding physical constraints directly in AI architectures is critical for scientific credibility, especially in data-sparse regions. Physics-informed or constraint-aware models can enforce already known teleconnections and covariances during training. By constraining what the AI is allowed to learn, these approaches reduce non-physical artefacts and help ensure that fine-scale structures remain consistent with large-scale dynamics.
- For bias-correction, AI/ML methods should complement, not replace, established statistical techniques. For example, classical methods such as quantile mapping provide a transparent baseline, while ML can add flexibility to capture non-linear relationships between model output and observations. Any AI-based bias-correction must be calibrated and independently validated, with performance metrics and assumptions clearly documented so that downstream users and assessors can judge its reliability.
- Gap-filling in **observational datasets** benefits from approaches that are both multivariate and physically interpretable. Methods that exploit relationships across variables and across space and time can reconstruct missing values in ways that maintain realistic dependence structures, for example, between temperature, precipitation and soil moisture. To retain scientific trust, gap-filled fields should be systematically evaluated against independent data and checked against process understanding, particularly where in-situ information is very limited.
- Maintaining **traceability and originality** is essential to keep AI-enabled data products usable for decision support and assessment processes. Each AI-enhanced dataset should carry metadata that records original inputs,

⁵ Lenton, T. M., Milkoreit, M., Willcock, S., Abrams, J. F., Armstrong McKay, D. I., Buxton, J. E., Donges, J. F., Loriani, S., Wunderling, N., Alkemade, F., Barrett, M., Constantino, S., Powell, T., Smith, S. R., Boulton, C. A., Pinho, P., Dijkstra, H. A. Pearce-Kelly, P., RomanCuesta, R. M., Dennis, D. (eds), 2025, The Global Tipping Points Report 2025. University of Exeter, Exeter, UK. The Global Tipping Points Report 2025, University of Exeter, UK.

training domains, versions of models and workflows, and information on where outputs are strongly constrained by observations versus largely model- or AI-driven. This transparency allows users in data- and capacity-constrained regions to understand the strengths and limitations of the information they rely on and supports reproducibility and iterative improvement over time.

- Effective regional and **South–South collaboration models** combine strong regional ownership with long-term institutional partnerships and shared digital infrastructure that supports co-production of climate information. Regional centres such as the **Southern African Development Community (SADC) Climate Services Centre**⁶ provide common data management, processing and early warning systems, enabling National Meteorological and Hydrological Services (NMHSs) to access operational tools while strengthening local capacity. Emerging initiatives also demonstrate how new technologies can help address capacity gaps. For example, WMO and the European Centre for Medium Range Weather Forecasting (ECMWF) are supporting a pilot project in Malawi to test **AI-based weather prediction systems** and “**forecast-in-a-box**”⁷ tools designed to run with relatively limited computational resources. Such systems aim to enable countries without advanced high-performance computing infrastructure to leapfrog to state-of-the-art forecasting capabilities and strengthen early warning systems for high-impact weather events. Broader South–South hubs and research partnerships— such as the Climate Research for Development (CR4D) partnerships in Africa and collaborative platforms—embed expertise within vulnerable regions, promote peer-to-peer exchange, and align research with regional service needs. Examples include the WMO Integrated Global Observing System (WIGOS), users interface platforms such as agroclimatic technical roundtables, such as the WCRP My Climate Risk Hubs⁸.
- **Digital platforms and shared data infrastructures** are also critical enablers of sustained capacity development and cross-disciplinary collaboration⁹. Open, regionally anchored platforms that integrate datasets, analytical tools and learning resources help overcome data gaps and scale up knowledge sharing. Initiatives such as global observing frameworks, user-interface platforms and capacity-building portals demonstrate how coordinated data access and digital cooperation can strengthen technological capability, particularly in data-sparse and climate-vulnerable regions.

(3) **Advancing Climate Science for Measuring Progress and Effectiveness of Adaptation**

Key research question

(e) *How can consistency and comparability of climate indicators be ensured across diverse regional and national contexts and reporting frameworks?*

- Improving the consistency and comparability of climate indicators across regions and reporting frameworks requires research advances that help establish standards and methodologies, in particular with a focus on sector specific indicators that have consensus across the user community.
- A key research priority is the further refinement and consistent application of established climate analysis methodologies, such as those outlined in WMO-

⁶ [Home | SADC Climate Services Centre.](#)

⁷ <https://wmo.int/media/news/wmo-supports-artificial-intelligence-forecasting-pilot-africa>.

⁸ [My Climate Risk.](#)

⁹ See the WCRP Academy <https://wcrp-academy.org/>.

No. 1287¹⁰, to ensure coherence across global, regional and national assessments. This includes strengthening methodological comparability between global indicators and those used in National Adaptation Plans (NAPs) and other reporting instruments through consistent datasets, reference periods and analytical approaches.

- Research is also needed to improve **data quality, homogeneity and traceability**, particularly in data-sparse regions, building on robust historical baselines. Advances in integrating in **situ observations, satellite data, reanalyses and historical records**, together with clearer frameworks for indicator reproducibility, version control and uncertainty characterization, would further enhance comparability across countries with differing observational capacities.
- Another critical research need is the development of **scalable, interoperable indicator frameworks** that support a consistent global-to-national approach. Indicators should allow aggregation from national to regional and global assessments while maintaining scientific consistency and national relevance, enabling coherent reporting across WMO, IPCC, and UNFCCC processes, including State of the Climate reporting, climate services monitoring, and adaptation tracking under the Global Goal on Adaptation (GGA).

Key research question

(f) *What research advances are needed to improve the usability of climate indicators, including their translation from climate variables into indicators that are meaningful for users and decision-makers and more directly relevant for adaptation planning and action?*

- Improving the usability of climate indicators requires research that advances the **translation of climate science into decision-relevant information**, expanding on decision contexts, impacts, and adaptation pathways, in line with a shift toward policy relevance and user-centred reporting.
- A central research need is the development of **impact- and risk-oriented indicators** that go beyond describing climate variables to explain what climate change means for people, ecosystems, and sectors. Research is needed to systematically translate core climate indicators into impact-relevant metrics (such as heat stress, drought severity, flood risk drivers) while maintaining scientific integrity.
- Research advances are required in defining **thresholds** that matter for adaptation decisions—such as infrastructure tolerances, health risk thresholds, or ecosystem limits—and linking them consistently to climate indicators. For example, increasing ocean heat content drives thermal expansion and sea-level rise, influences marine heatwaves, and creates conditions for stronger TC. Similarly, extreme precipitation indicators can be linked to flood hazards, infrastructure exceedance, and landslide risks through hydrological and impact modelling. These cases show how improved physical understanding and modelling can make climate indicators operational for adaptation planning and decision-relevant thresholds.

¹⁰ WMO-GCF (2022), Developing the Climate Science Information for Climate Action. Available at: <https://library.wmo.int/records/item/53280-developing-the-climate-science-information-for-climate-action?offset=2>.

- Research is needed to further strengthen the **communication of uncertainty** and confidence in climate indicators, both for observed trends and future projections. In line with WMO methodology (No. 1287), which promotes the use of multiple scenarios and climate models to inform decision-making, continued advances can enhance the clarity and consistency with which uncertainty related to observational records, data constraints, trend detection, and projected risk ranges — including the likelihood of threshold exceedance — are conveyed.
- Another key research area concerns **co-production and user engagement** methodologies. WMO guidance highlights the importance of stakeholder engagement in shaping climate information. However, further research is needed to evaluate which co-production approaches most effectively improve indicator uptake, usability, and integration into adaptation planning and investment decisions. This includes strengthening engagement with NMHSs, Regional Climate Centres (RCCs) and WMO Regional Offices (ROs) to better understand region-specific needs, capacities and decision-making contexts, and also to ensure that co-produced indicators reflect local priorities, sectoral needs.

Key research question

(g) How can robust, science-based baselines be defined to measure progress on adaptation, and what role can the WMO play in supporting data-driven adaptation planning at national and global levels?

- Research is needed to define **climate-risk-informed baselines** further, grounded in observed climate trends, extremes, and variability. Baselines could reflect historical and current climate risk, enabling adaptation progress to be assessed relative to changing hazard conditions. This approach aligns WMO emphasis on historical climate analysis as the foundation for risk and vulnerability assessments.
- Another priority is research into **dynamic baselines** that can be periodically updated while preserving comparability over time. WMO methodologies recognize that climate baselines must evolve as new data become available; further work is needed to define best practices for updating baselines without undermining long-term monitoring of adaptation outcomes.
- Research is also required to integrate **physical climate indicators with socio-economic and impact data**, enabling adaptation progress to be measured in terms of reduced risk, avoided losses, or increased resilience rather than climate trends alone. This aligns closely with WMO promotion of impact-based approaches and climate services that link hazards to real-world outcomes.

(4) Enhancing the scientific understanding of climate change drivers, Earth system feedback mechanisms, and improved quantification of greenhouse gas emissions and removals

Key research questions

(h) What sustained global observations of the atmosphere, oceans, cryosphere and biosphere are required to improve understanding of climate change drivers (including Greenhouse Gases (GHGs) in the atmosphere), climate feedback mechanisms, natural variability, and their interactions? What infrastructure and systems are needed to produce such

measurements and answer relevant questions in a timely manner?

- (i) *What is required to fill gaps in understanding of carbon budgets (sources and sinks) across multiple time horizons, the role and limits of carbon dioxide removal (CDR) in saving carbon budgets, and the Earth system's capacity for long-term carbon storage?***

I. Climate forcing factors and change drivers

- Recent observed changes¹¹ in the climate have highlighted the importance of both developing and applying understanding of the Earth system to explain observed climatic change and, critically, implications for the future.
- This requires up to date information on climate forcing factors including greenhouse gases, aerosols (both natural and anthropogenic), and solar influences, as well as observations pertinent to any potential feedbacks such as concurrent changes in clouds or changes in the land or ocean carbon sinks. These need to be combined with monitoring of internal variability in the climate system, including the El Niño Southern Oscillation (ENSO) and other modes of variability. In addition, we need systems in place to ensure information is interpreted holistically to answer relevant questions in a timely manner.
- The recent increase in global mean temperature is¹² a clear example. A rapid increase in global temperature triggered global interest and multiple potential contributing factors were identified. These included changes in anthropogenic aerosols¹³, an unexpectedly strong solar cycle, volcanic aerosols and volcanic water vapour from the Hunga Tonga eruption¹⁴. Variability also played a role, with a relatively strong El Niño after a prolonged La Niña¹⁵, record low Antarctic sea ice extent¹⁶ (with changes in albedo and, possibly signalling changes in ocean currents¹⁷), unusually clear skies¹⁸ and low wind speeds¹⁹ over the Atlantic, changes in Saharan dust transport²⁰, aerosols from forest fires²¹, and strong stratification of the surface ocean²². This underscores the importance of observing and monitoring a wide range of phenomena in near real time to effectively explain changes in the climate system. The question of what all of this means for the magnitude and rate of current²³ and future warming is still unclear.
 - Atmospheric greenhouse gas levels reflect the combined influence of natural and anthropogenic sources and sinks. According to the WMO Greenhouse Gas Bulletin (2025)²⁴, the globally averaged surface concentrations of carbon

¹¹ <https://library.wmo.int/records/item/69455-state-of-the-global-climate-2024>

¹² <https://library.wmo.int/records/item/68835-state-of-the-global-climate-2023>.

¹³ <https://www.nature.com/articles/s43247-024-01324-8>.

¹⁴ <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104634>.

¹⁵ <https://acp.copernicus.org/articles/24/11275/2024/>.

¹⁶ <https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/wea.4518>.

¹⁷ <https://www.nature.com/articles/s43247-023-00961-9>.

¹⁸ <https://www.science.org/doi/10.1126/science.adq7280>.

¹⁹ <https://climate.copernicus.eu/record-breaking-north-atlantic-ocean-temperatures-contribute-extreme-marine-heatwaves>.

²⁰ <https://www.sciencedirect.com/science/article/pii/S0169809524003764>.

²¹ <https://atmosphere.copernicus.eu/aerosols-are-so2-emissions-reductions-contributing-global-warming>.

²² <https://link.springer.com/article/10.1007/s00376-024-3378-5>.

²³ <https://www.nature.com/articles/s43247-024-01711-1>.

²⁴ WMO (2025), WMO Greenhouse Gas Bulletin (2025) WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2024, No. 21 – 16 October 2025.

dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) reached unprecedented highs in 2024, with CO₂ at 423.9±0.2 ppm, CH₄ at 1942±2 ppb and N₂O at 338.0±0.1 ppb. These values constitute, respectively, increases of 52%, 166% and 25% above pre-industrial (before 1750) levels. The record increase in CO₂ from 2023 to 2024 (3.5 ppm) was most likely due to a combination of natural variability and continued emissions of fossil fuel CO₂. The levels of these gases continued to increase through 2025. However, the evolving influence of climate change on natural emissions and sinks is not yet fully integrated into most accounting frameworks.

I. Earth system feedback mechanisms

- Several processes impact natural emissions and removals of GHG to/from the atmosphere, depending on the specific gas. CO₂ is the main anthropogenic greenhouse gas, which has the largest individual contribution to radiative forcing. According to the most recent analysis of the Global Carbon Project (Friedlingstein et al., 2025)²⁵, natural removals are taking about 50% of the anthropogenic emissions (21% by land and 29% by the ocean averaged over 2015–2024 period), with the remainder being accumulated in the atmosphere. The processes that may impact these percentages are discussed below.

II.I Biomass burning

- Most of the wildfire carbon emissions are in the form of CO₂, so the intensity of the fires has a sizable impact on the CO₂ budget and growth rate, and will significantly influence its future growth because of the impact of fires on land use, which in turn will affect the net CO₂ land sink. Carbon monoxide (CO), produced by incomplete burning and later converted – through oxidation – into CO₂, is an important indicator of atmospheric pollution and wildfire smoke. The exceptionally high fire emissions in South America in 2024 may have contributed to the extremely high CO₂ growth rate.
- Recent analysis (Kelley et al., 2025)²⁶ shows that climate change greatly increased the likelihood and severity of extreme fire weather: 30–70 times more likely in Northeast Amazonia (with about four times more area burned), around 25 times more likely in Southern California, and 3–8 times more likely in the Congo Basin (with nearly three times more area burned). More frequent and intense fires will add further CO₂ to the atmosphere while weakening the natural carbon sink provided by forests and other vegetation.

II.II Droughts and forest sink

- In the context of climate change, the Amazon is a specific ecosystem that is considered as a climate tipping point²⁷. Hence, observing changes in the Amazon carbon cycle is particularly important for understanding the global system. WMO is working closely with Brazil's National Institute for Space Research to understand the long-term changes in the Amazon Carbon Balance. Over the past 15 years, the Amazon has been heavily affected by

²⁵ Friedlingstein, P. et al. Global Carbon Budget 2024. *Earth System Science Data* 2025, 17 (3), 965–1039. <https://doi.org/10.5194/essd-17-965-2025>.

²⁶ Kelley, D. I. et al. State of Wildfires 2024–2025, *Earth Syst. Sci. Data*, 17, 5377–5488, <https://doi.org/10.5194/essd-17-5377-2025>, 2025.

²⁷ <https://esd.copernicus.org/articles/15/41/2024/esd-15-41-2024.html>.

deforestation, fires, and worsening climate conditions. Forest loss has reduced rainfall and increased temperatures, creating longer, hotter dry seasons that make the forest more flammable. Severe drought in 2023 led to exceptionally high fire emissions, based on long-term atmospheric measurements from the Long-term Study of the Amazon Carbon Balance (CARBAM) project operated by Brazil's National Institute for Space Research (Gatti et al., 2021; Gatti et al., 2023)^{28,29}.

- Total CO₂ emissions, fire CO₂ emissions, and net biome exchange (NBE) were estimated from these 15-year observations. In 2024, total and fire-related CO₂ emissions in the Amazon reached their highest levels, linked to low precipitation and high temperatures (WMO, 2025). Over 2010–2022, the Amazon acted as a net carbon source, with emissions increasing in recent years. Extreme droughts associated with El Niño and unusually warm North Atlantic conditions contributed to particularly high emissions in 2010, 2015–2016, and 2024 (Franco et al., 2025)³⁰.
- Similar patterns are observed elsewhere. In 2022, severe heat and drought across Europe significantly reduced summer carbon uptake in the affected regions—by an amount exceeding the Netherlands' total annual emissions and equivalent to about 80% of France's annual emissions (van der Woude et al., 2022)³¹.

II.III Ocean carbon uptake and ocean–atmosphere interactions

- Oceans are absorbing most of the excess heat from the atmosphere, which leads to the warming of ocean water. Warming of the ocean water triggers several changes related to carbon exchange between the ocean and the atmosphere, both through physical and biological processes.
- In 2023, sea-surface temperatures (SSTs) reached record highs, partly due to a strong El Niño. Based on historical responses to elevated global mean SSTs, oceanic CO₂ uptake in 2023 should have increased, driven by reduced outgassing in the tropical Pacific Ocean. However, using observation-based estimates of ocean CO₂ fugacity, Müller et al. (2025) demonstrated that the global non-polar ocean absorbed about 10% less CO₂ than expected. This weakening was caused by the anomalous outgassing of CO₂ in the subtropical and subpolar regions, especially in the Northern Hemisphere, driven primarily by elevated SSTs, reducing the solubility of CO₂. In most regions, this SST-induced outgassing was mitigated by the depletion of dissolved inorganic carbon in the surface mixed layer. While some chemical feedback limited the overall impact, this resilience may not persist under continued warming.
- Large-scale ocean–atmosphere modes of variability, such as the El Niño–Southern Oscillation (ENSO), can strongly influence regional carbon fluxes and climate feedback, highlighting the importance of sustained observations of ocean–atmosphere interactions. Research and coordination on these processes are promoted through the WCRP and its Climate and Ocean

²⁸ Gatti, L. V. et al. Amazonia as a Carbon Source Linked to Deforestation and Climate Change. *Nature* 2021, 595, 388–393. <https://doi.org/10.1038/s41586-021-03629-6>.

²⁹ Gatti, L. V. et al. Increased Amazon Carbon Emissions Mainly from Decline in Law Enforcement. *Nature* 2023, 621, 318–323. <https://doi.org/10.1038/s41586-023-06390-0>.

³⁰ Franco, M.A. et al. How climate change and deforestation interact in the transformation of the Amazon rainforest. *Nat Commun* 16, 7944 (2025). <https://doi.org/10.1038/s41467-025-63156-0>.

³¹ van der Woude, A.M. et al. Temperature extremes of 2022 reduced carbon uptake by forests in Europe. *Nat Commun* 14, 6218 (2023). <https://doi.org/10.1038/s41467-023-41851-0>.

II. Remaining carbon budget

- Climate feedback has implications for mitigation actions as they impact the remaining carbon budget (RCB). The IPCC AR6 estimates (50% likelihood) that 85, 180 and 315 gigatonnes of carbon (305, 655 and 1 155 gigatonnes of carbon dioxide) remain for limiting warming to 1.5°C, 1.7°C and 2°C, respectively. A recent assessment (Forster et al., 2024)³³ supported by the [Global Carbon Project](#)³⁴ in partnership with WCRP, suggests smaller budgets—45, 140 and 290 gigatonnes of carbon (160, 510 and 1 060 gigatonnes of carbon dioxide)—reflecting updated methods and recent warming. Both estimates account for uncertainties in the climate response to cumulative carbon dioxide emissions, non-carbon dioxide forcing, and other factors, and their ranges overlap when these uncertainties are considered. Reducing these uncertainties will require sustained observations and continued improvements in modelling tools.

III. Land-use change, albedo and cryosphere feedbacks

- Land-use and land-cover change influence climate not only through greenhouse gas emissions but also by modifying surface properties such as albedo, evapotranspiration and surface roughness, which affect the Earth's energy balance and regional climate. Deforestation, agricultural expansion and urbanization can alter the reflectivity of the land surface and influence temperature, precipitation patterns and ecosystem carbon uptake. In high-latitude and high-mountain regions, changes in snow cover, sea ice and glaciers strongly affect planetary albedo. The loss of highly reflective snow and ice surfaces exposes darker land or ocean surfaces, increasing solar absorption and amplifying warming through the ice-albedo feedback.
- Improved understanding of these feedbacks requires sustained observations of land cover, surface albedo, snow and ice extent and glacier mass balance. The Global Cryosphere Watch³⁵ is working to consolidate access to cryosphere observations by coordinating existing monitoring networks and data systems. This includes facilitating the integration of research datasets with operational meteorological observations. Addressing these challenges also requires the combined use of in-situ and Earth- and space-based observations, particularly in data-sparse polar and high-mountain regions.

IV. Carbon dioxide removal

- CDR comprises deliberate approaches to remove CO₂ from the atmosphere and store it durably. IPCC AR6 indicates that CDR may complement deep emissions reductions, although large-scale deployment of CDR faces substantial biophysical, technical, monitoring, and governance constraints and cannot replace rapid and sustained emissions reductions to limit warming

³² https://www.clivar.org/research-foci/enso?utm_source=chatgpt.com.

³³ Forster, P. M. et al. Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence, Earth Syst. Sci. Data, 16, 2625–2658, <https://doi.org/10.5194/essd-16-2625-2024>, 2024.

³⁴ <https://www.wcrp-climate.org/news/wcrp-news/1146-wcrp-gcp-partnership>.

³⁵ <https://wmo.int/activities/global-cryosphere-watch-gcw/global-cryosphere-watch>.

(Hurrell et al., 2024)³⁶.

- Current CDR is mostly land-based and small-scale, while novel methods remain minimal (<0.1% of total CDR) (Smith et al., 2024)³⁷. Key challenges include limits to durable geological storage, inconsistent reporting, and significant land and water demands that may conflict with ecosystems and food security. For example, afforesting 2.1 million km² to remove ~1.6 GtCO₂/year would require over 1,000 km³ of water annually (United Nations-Water, 2024)³⁸. Understanding the impact of the removals is also complicated, as reporting is not consistent.

Research question

(j) How can atmospheric greenhouse gas observations, including through the Global Atmosphere Watch, be more effectively integrated with national and global GHG emission evaluation to strengthen science-based greenhouse gas monitoring, reporting and verification?

- At present, progress in monitoring GHG concentrations is mainly assessed through self-reported national emission inventories prepared under IPCC guidelines. The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories recognizes atmospheric concentration measurements as an independent tool for verifying emissions, as they do not rely solely on activity data and emission factors. In 2025, WMO produced good practices for utilization of atmospheric observations to improve evaluation of emissions and removals on a national and urban scale. These techniques allow for improved timeliness of the emission data and provide the most direct quantification of the mitigation impacts.
- More broadly, understanding climate drivers and feedback depends on sustained, high-quality observations. Large uncertainties in carbon budgets and climate impacts persist, especially in poorly monitored and climate-sensitive regions. Strengthening and expanding observing systems is therefore critical to detect emerging risks early and avoid delayed responses.

³⁶ Hurrell, J.W. et al. (2024) Climate intervention research in the World Climate Research Programme: a perspective. *Front. Clim.* 6:1505860. doi: 10.3389/fclim.2024.1505860.

³⁷ Smith, S. M. et al. The State of Carbon Dioxide Removal 2024 – 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024).

³⁸ United Nations-Water (2024), United Nations-Water Analytical Brief on Water for Climate Mitigation. Geneva, Switzerland.