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Earth Observation

in the Era of Climate Overshoot

By Benjamin Poulter

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Cover
An illustration of Copernicus Sentinel-1 (credit: ESA/ATG medialab) superposed onto the Earth, which contains modified Copernicus Sentinel data (2019–20), processed by ESA and cloud layer from NASA, and blended over by the Climate Stripes (from s-ink.org/warming-stripes) with a hypothetical extension from 2026 to the future showcasing the potential Climate Overshoot.

Editorial

We have not been there. Yet, we know it is coming: the warmer world we are now, in all likelihood, heading towards. The challenge for humanity as a whole. Our challenge. What do we have to meet it? – It is a fleet of satellites watching over a planet‘s surface layer we have pushed past the safe zone.

This edition „Earth Observations in the Era of Climate Overshoot“, comes from Ben Poulter, ISSI‘s 2025 Johannes Geiss Fellow. Over several months at ISSI, Ben has made real contributions to our mission and helped sharpen ISSI‘s standing in the Earth and climate science communities. His scientific work reflects exactly the kind of collaborative, cross-disciplinary view we believe the field needs.

Broad views like his matter because our changing climate demands it: observation that is accurate and reliable, global and continuous, open and accessible. Understanding a system this intricate, and reacting to it in time, takes collaboration that crosses disciplines, borders, and generations. Few places are better suited to host that kind of work than ISSI, where international diverse teams already come together daily in a neutral, welcoming setting.

The space science angle matters too: it is how we understand our own position, as passengers on a planet that may not always be forgiving. There are signs that we will temporarily blow past the safe 1.5 °C Paris limit, pushing the climate to a higher peak, before *hopefully* bringing it back down using greenhouse-gas-removal technology. This scenario now has a name: „Climate overshoot“. It is what Ben lays out firsthand, clearly, through the lens of Earth observation.

Satellites are the climate‘s thermometer. They are sea-level rulers. They are the ice-sheet scale. Instruments named like ICESat-2, GRACE, and CERES, and upcoming missions going by the acronyms NISAR and MERLIN, are the tools that will tell us whether recovery from overshoot is actually working. Today, we observe the hundreds of thousands of square kilometres of coastline that sit below one metre of elevation, exposing tens of millions of people to near-term flood risk. Accurately tracking the Earth‘s energy imbalance has reveiled that it doubled in just two decades, even outpacing what climate models had predicted.

Ben does not promise that overshoot is reversible. Ice sheet loss and ocean warming unfold across centuries, far beyond a human lifetime. What he offers instead is a clearer view on the environment we all live so we widen our knowledge and sharpen our understanding to act more wisely. While satellites cannot undo the physics, they can tell us how much time we have, and whether our interventions are working, or not.

As Ben explains, what is needed now are new ways of designing and interpreting Earth observations because we are, genuinely, in uncharted territory. And that fleet of satellites we opened with? It is up there, watching, giving us our best chance to see where we are headed before we get there.

Now onward, with eyes open!

– Fabio Crameri

Earth Observation
in the Era of Climate Overshoot

Planetary sustainability and climate overshoot

The remaining carbon budget to avoid dangerous global warming continues to shrink as international efforts to reduce greenhouse gas emissions struggle to meet the ambition required for reaching net-zero emissions required for climate stabilization. Since 2023, for example, changes in temperature have now come close to, or exceeded, 1.5 °C warming (above pre-industrial era), the lower temperature limit that the Paris Agreement deemed 'safe' and was designed to avoid when it went into effect in 2016. Warming temperatures are now driving melting ice-sheets and rising sea-levels, as well as causing climate extremes that include more frequent heatwaves, droughts, and flooding. These events in turn are leading to increases in greenhouse gas emissions from permafrost, wetlands, wildfire, and impacting human well-being and social and economic systems.

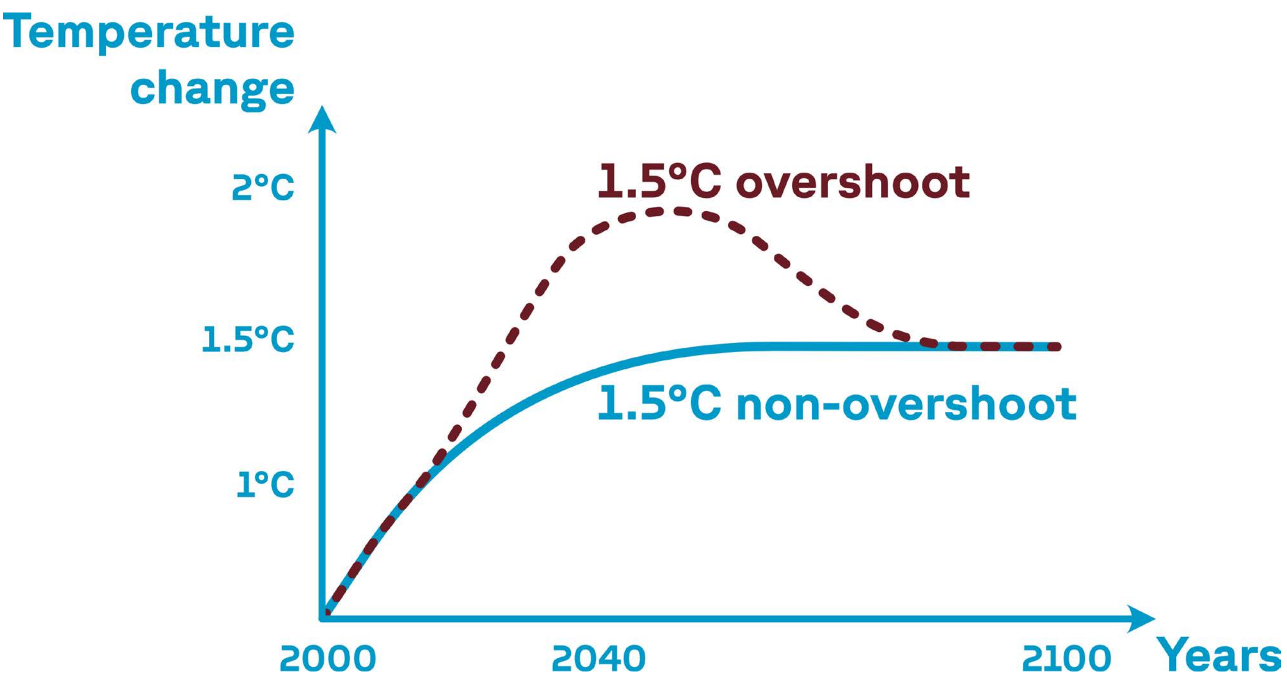


Figure 1. *Idealized depiction adapted from Rogelj (2023) of a climate 'overshoot' scenario (dashed line), where because of continued growth in net greenhouse gas emissions, global air temperature change exceeds 1.5 °C. Air temperature, in this example, peaks close to 2 °C for a specific duration before negative emissions (where greenhouse gases are taken out of the atmosphere) return temperature back to a stabilization level of 1.5 °C. Any possible number of climate overshoot scenarios exist and the scenario society currently follows will depend on the pace of the transition from fossil fuels to renewable energy sources.*

While the deployment of new energy technologies to transition society away from fossil fuels toward renewable sources of energy is underway, the pace of deployment is likely to be too slow to avoid cumulative greenhouse gas emissions that maintain temperature change to below 1.5 °C. The exceedance of 1.5 °C warming means that the Earth's climate system is now more likely to enter a new era, referred to as **'climate overshoot'**, locking in a reliance on costly negative emissions solutions to return the climate to lower temperatures and ultimately back to a safe and stable state (**Figure 1**). This new climate reality has no analogue in the past to compare to, and will require new ways of thinking about how we use existing, and design new, Earth observing systems to understand changes in the planet's atmosphere, ocean, land, and cryosphere systems.

The technical definition of climate overshoot is a greenhouse-gas emissions scenario that leads to an exceedance of a specific temperature for only a temporary period of time and is characterized by the peak temperature reached, the duration of time the peak is exceeded, and the return pathway back to a temperature stabilization target. First explored as hypothetical emissions scenarios by climate scientists in the mid-1990s[1] to understand the economic impacts of delayed climate action, climate overshoot is now a key knowledge area for the **Intergovernmental Panel on Climate Change (IPCC)** with an entire chapter (Chapter 9: Earth system responses under pathways towards temperature stabilization, including overshoot pathways) dedicated to this topic in the Seventh Assessment Report (AR7) by Working Group I.

To better understand the impact of climate overshoot, the IPCC is currently reviewing a range of new emissions scenarios and how these impact temperature peak, duration, and the return to a stabilization target[2]. Earth system models with coupled land-ocean-atmospheric processes will be driven by these emission scenarios to simulate the impacts of climate overshoot and to explore whether the impacts on the atmosphere, ocean, cryosphere, and land are reversible or irreversible as temperatures follow the theoretical peak and decline.

Climate overshoot is also dependent on **'negative emissions' technologies** being available to reduce the concentrations of greenhouse gases in the atmosphere. Negative emission technologies include: carbon dioxide removal (CDR) using direct air capture, nature-based climate solutions, methane removal, and other interventions that are uncertain in terms of effectiveness, costly, and difficult to scale in practice. Climate overshoot also depends on the assumption that global temperatures can return to a safe and stable level when greenhouse gas concentrations decline, with Earth System Models (ESMs) suggesting that when emissions stop, temperatures stabilize shortly thereafter. These findings depend on how ocean heat content and land-CO_2 fertilization respond to declining greenhouse concentrations, and how other climate feedbacks associated with reversing the Earth's energy imbalance respond and at what timescales, and are covered through activities associated with **the zero-emissions commitment (ZEC)**.

1 Wigley, T., Richels, R. & Edmonds, J. Economic and environmental choices in the stabilization of atmospheric CO2 concentrations. Nature 379, 240–243 (1996).

2 Van Vuuren, D. P., O'Neill, B. C., Tebaldi, C., Sanderson, B. M., Chini, L. P., Friedlingstein, P., Hasegawa, T., Riahi, K., Govindasamy, B., Bauer, N., Eyring, V., Fall, C. M. N., Frieler, K., Gidden, M. J., Gohar, L. K., Högner, A., Jones, A. D., Kikstra, J., King, A., Knutti, R., Kriegler, E., Lawrence, P., Lennard, C., Lowe, J., Mathison, C., Mehmood, S., Nicholls, Z., Prado, L. F., Zhang, Q., Rose, S. K., Ruane, A. C., Sandstad, M., Schleussner, C.-F., Seferian, R., Sillmann, J., Smith, C., Sörensson, A. A., Panickal, S., Tachiiri, K., Vaughan, N., Vishwanathan, S. S., Yokohata, T., Zecchetto, M., and Ziehn, T.: The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7), Geosci. Model Dev., 19, 2627–2656, https://doi.org/10.5194/gmd-19-2627-2026, 2026.

Evolving Role of Earth Observations

Earth observations (EO) from space play a foundational role in our understanding of climate change through contributions made to measuring, monitoring, and quantifying changes. Since the 1970s, a growing constellation of research-grade and operational optical, microwave, radar, and lidar instruments have been launched to orbit our planet (**Figure 2**) in sun-synchronous, geostationary, and precessing orbits (i.e., where the orientation changes over time, on the International Space Station), each contributing in different ways to our understanding and perspective of the Earth's energy balance, and changes in atmospheric, cryospheric, ocean, and land processes.

Satellite missions typically include decades of planning before launch and operations. The mission lifecycle accounts for a large and complex number of development phases. They include advancing technologies to readiness levels that can operate in the space environment. This includes consulting with the science and applications community to define traceable mission objectives and science questions, to develop algorithms for processing binary information to complex geospatial geophysical variables, and to make appropriate decisions and 'trades' about spectral range, spectral resolution, signal-to-noise, spatial resolution, temporal revisit, and overpass time that meet budget constraints.

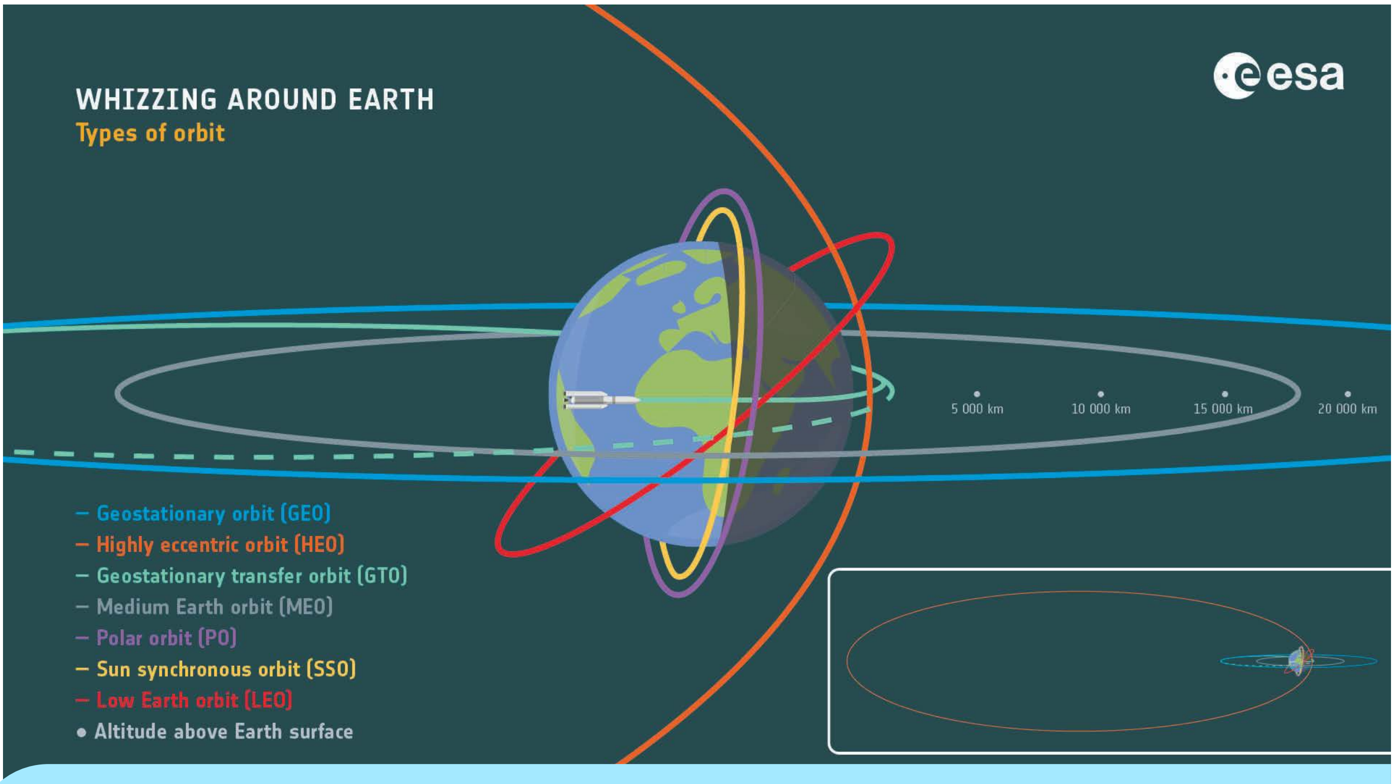


Figure 2. *Different types of orbits accessible for making Earth observations. The selection of orbit affects integration time of observations, temporal resolution, spatial resolution, and lifetime of the satellite. Figure by ESA.*

As our planet's climate enters the new era of climate overshoot, the Earth system is expected to respond in unique and unpredictable ways. This will require scientists to innovate and develop new approaches to interpreting existing observations and reconsidering the design and requirements of future satellite instruments and missions. The era of climate overshoot requires revisiting and tailoring Earth science objectives and questions often made decades ago for many of our current operational satellite missions. This includes reframing key objectives and questions about the Earth system in response to questions related to climate overshoot, and by developing traceability between effective spectral, spatial, and temporal observing requirements to address these questions.

Filling known gaps in satellite observing architectures, and helping provide these new observing insights, will come in part from newly launched public-agency satellite missions such as the European Space Agency's (ESA) **BIOMASS** mission that will support science and applications on forest structure, NASA's **Plankton, Aerosol, Cloud, ocean Ecosystem (PACE)** mission that will address questions related to atmospheric trace gases and ocean properties, and the **NASA-ISRO Synthetic Aperture Radar (NISAR)** mission that will provide information on surface water dynamics. In addition, a new series of commercial missions are providing key information, such as Planet's Tanager series (for both land surface dynamics and methane retrievals), HydroSat's VanZyl series (for soil moisture), and FireSat (for low-latency fire detections). Emerging technologies that will potentially help monitor climate overshoot are approaching readiness-levels for space applications. These include the development of active lidar, hyperspectral and thermal technologies, as well as "signals of opportunity" such as the use of **Global Satellite Navigation System (GNSS)** for sea-level, soil moisture and surface deformation monitoring. New orbital approaches are also being explored, such as polar-orbiting platforms or limb sounders. At the same time, rapid advances in cloud computing, machine learning, and artificial intelligence are being made. Combined, these developments offer a promising path toward successfully monitoring the Earth system under climate overshoot.

This article takes an EO perspective to explore concerns about how the Earth system will respond to climate overshoot related to 1) the response of land ecosystems to warming-induced emissions (WIE) such as the release of greenhouse gases from permafrost, wildfires, and wetlands, 2) the rate of sea-level rise and impacts on coastal environments, 3) losses of glaciers and ice sheets, and 4) reversibility of the Earth's energy imbalance, including ocean heat loss and land albedo shifts. Additionally, an increasing number of climate interventions are being considered to both avoid the worst of climate overshoot and to return temperatures back to stabilization levels that depend on solar radiation modification (SRM), carbon dioxide and/or methane removal (CDR and MR), ocean alkalinity enhancement (OAE), and other interventions where the impacts will need specific monitoring and measurement requirements. The following sections consider the design of Earth observing systems and considerations needed for the new era of climate overshoot.

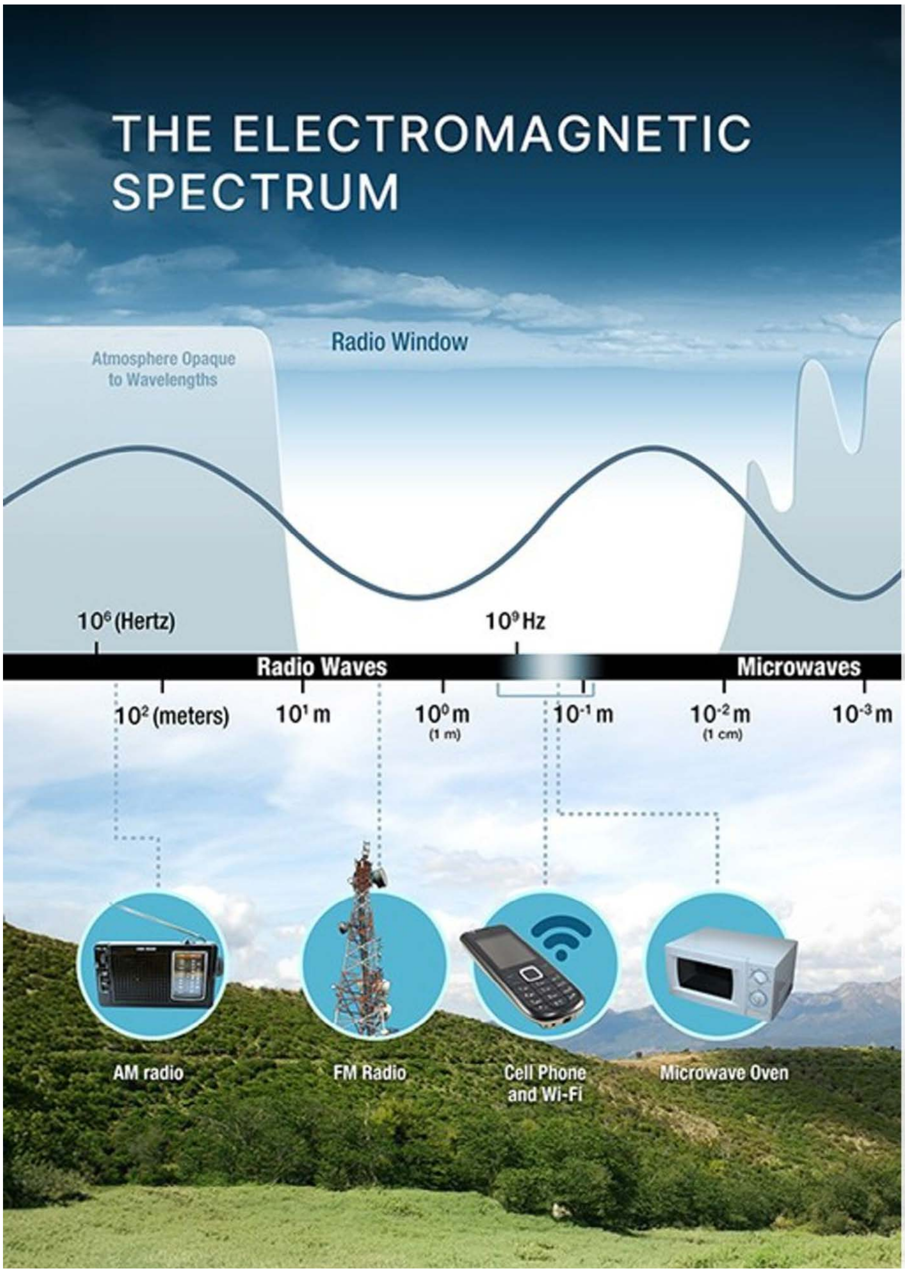
Earth Observations and Mission Design

Satellite mission design first consists of multiple steps driven by selecting observing requirements that meet all (i.e., baseline) or some acceptable minimum number (i.e., threshold) of science and applications objectives and questions. These involve, at a high-level, determining the geophysical parameter(s) that will be measured (i.e., land greenness or ocean height, etc.), then whether the instrument is passive (relies on sun's energy for retrieving radiance information) or active (energy source on-board the spacecraft generates retrieval information), determining spectral characteristics necessary to make retrievals, and then making trades on spatial and temporal characteristics and

Figure 3. *The NASA Earth Science Directorate (ESD) fleet of operational and planned Earth science missions (as of June 2025; figure by NASA). Equivalent figures for the European Space Agency can be viewed on their webpage (https://bit.ly/4vJiuGJ) and for the Japanese Space Agency (JAXA), on theirs (http://bit.ly/4ywAMxl). The public space agency fleets are accompanied by an increasing number of spacecraft from the private sector as described by Terrawatch (https://bit.ly/4pOtj9v).*

overpass time. Most of these observing requirements are interlinked, where 'trades' amongst each other also drive the type of orbit, altitude, and speed of the spacecraft (linked to integration time and signal-to-noise), the swath (linked to revisit), and the time of day (linked to cloud cover and also sun-sensor geometry effects that requires Bidirectional Reflectance Distribution Function, BRDF, corrections).

The current and planned Earth observing fleets managed by agencies like NASA (see **Figure 3**, for example), ESA, the Japanese Space Agency, the German Aerospace Centre (DLR), and commercial companies cover a very large number of combinations of observing requirements. These missions are designed to address objectives and scientific questions related to national priorities, commercial opportunities, and are also coordinated to a



certain extent with the United Nations through the Global Climate Observing System's (GCOS) set of **'Essential Climate Variables'** (http://bit.ly/4f7duH6). The most recent set of Essential Climate Variables, for example, includes 55 variables that cover atmosphere, ocean, cryosphere and land physical, chemical and biological properties.

According to the World Meteorological Organization's Observing Systems Capability Analysis and Review Tool (OSCAR; space.oscar.wmo.int), there are close to 400 operational missions carrying out various Earth science objectives, with ESA, NASA, JAXA, the Canadian and Indian Space Agencies (CSA, ISRO), and the US Geological Survey responsible for managing around a third of these. The instruments aboard these spacecraft are further characterized and described in the Committee on Earth Observing Satellites (CEOS) **eohandbook** (database.eohandbook.com) where broadly they can be categorized into optical imagers or sounders, radars (active) or radiometers (passive), and lidars (atmospheric and altimetry).

Within this global constellation, spatial resolution varies between submeter (for commercial satellites) to 10–500 meters for optical instruments, and up to 25 km for radiometers, and temporal

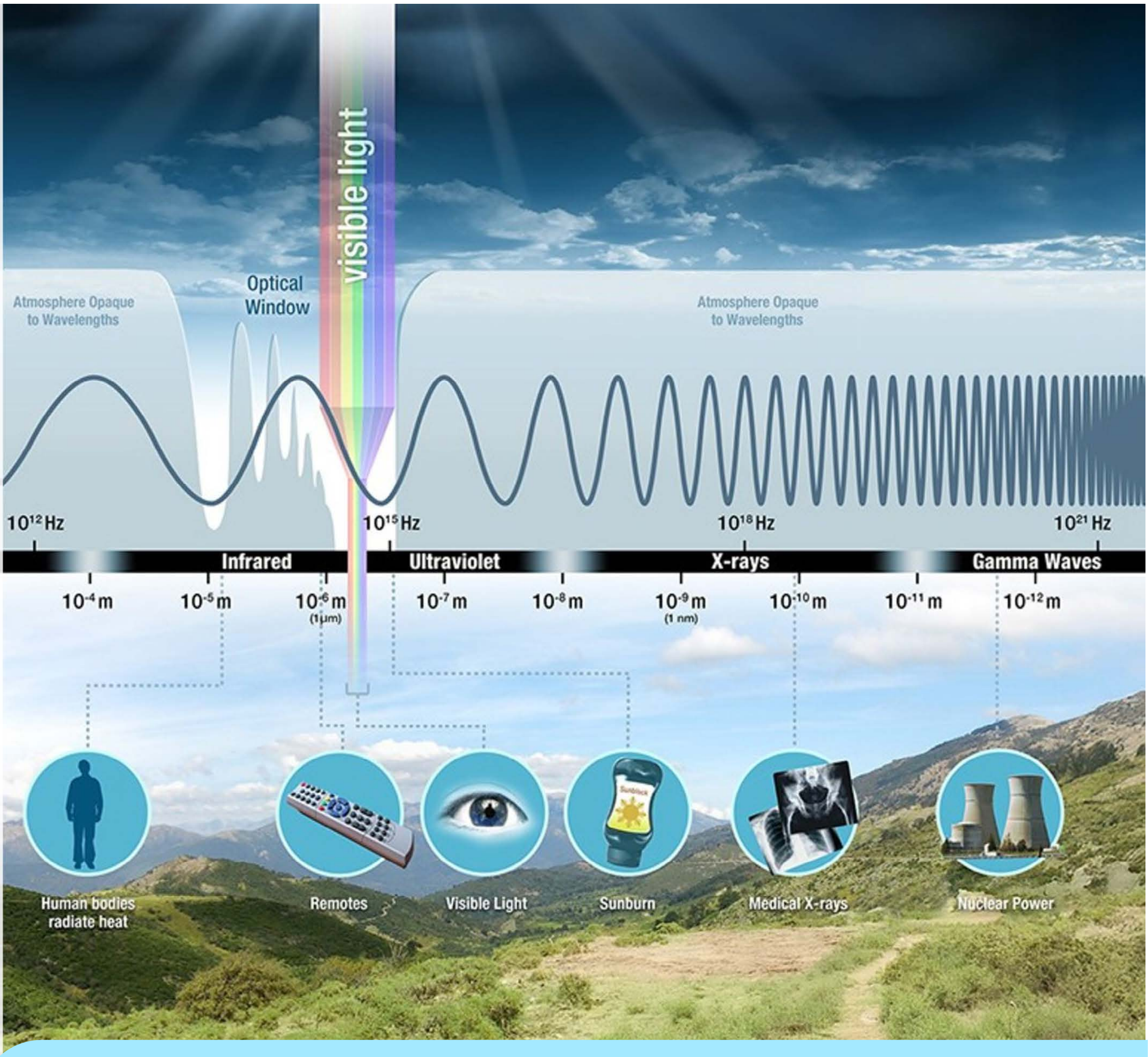


Figure 4. *Principles of remote sensing rely on fundamental understanding of the electromagnetic spectrum and how different surface and atmospheric properties reflect and affect radiances measured by instruments. Figure from NASA Science.*

revisit ranges from sub-daily for geostationary to daily, weekly or more for low-earth orbit missions. Spectral range (**Figure 4**) and resolutions also vary depending on whether geophysical properties can be retrieved using fine (i.e., chemical properties, greenhouse gases) versus broadband information (i.e., vegetation reflectance in infrared and red to derive leaf area index. Overpass time tends to be in the morning for optical missions, avoiding convective cloud formation that occurs in afternoons, but varies by mission and geophysical parameter (i.e., greenhouse gas satellites tend to have afternoon overpasses when the boundary layer conditions are more mixed). Mission lifetime is also highly variable, with many missions initially launched with 3–5-year operations but now in extended missions operations. For example, NASA Orbiting Carbon Observatory-2 (OCO2) is twelve years into a 3-year mission and OCO3 is similarly seven years into a 3-year mission lifetime.

Mission constellations, consisting of more than one spacecraft with the same or similar instruments are more commonly operated by private and commercial companies using SmallSats or CubeSats. The PlanetScope constellation currently includes over 430 Dove and SuperDove satellites providing global, high resolution multi-spectral information of the Earth's surface each day. GHGSat maintains a growing constellation of 14 satellites equipped with Fabry-Perot spectrometers designed to retrieve information on methane plumes from oil, gas, and some agriculture facilities. Hydrosat currently operates two satellites that provide thermal information used for agriculture decision support, and FireSat plans to have 50 satellites orbiting by 2030, ultimately providing sub-daily high-spatial resolution information on fire activity.

For space missions supported by public agencies, NASA develops its observing requirements through its Earth Science Decadal Survey, the most recent of which was published in 2018, titled 'Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space' (https://bit.ly/3TIEN1Y). The Decadal Survey is the result of a robust consultative process led by the US National Academies of Science, Engineering and Medicine. And for ESA, the 2024 Earth Science in Action for Tomorrow's World (https://bit.ly/4vJqaZR), developed through consultation with the Earth science community, was more recently developed to provide a vision for Earth science through 2040. While these reports highlight the need for satellite observing requirements to address a range of questions related to climate change, traceability to the needs for understanding Earth system responses to climate overshoot remains at an early stage.

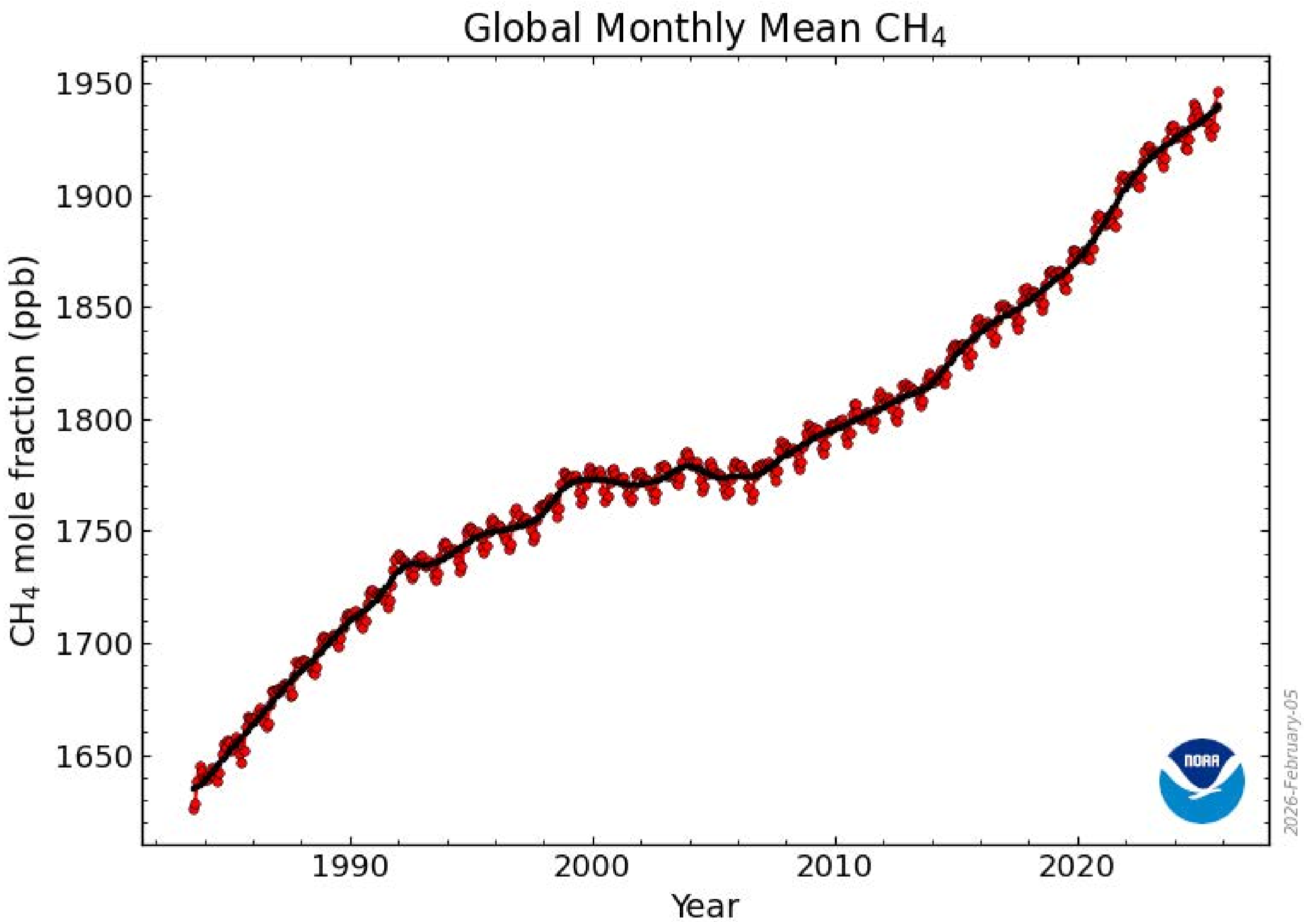


Figure 5. *Observations of atmospheric methane concentrations show an acceleration in growth since 2007, attributed in part to increasing emissions of methane from warming wetlands. Figure by NOAA.*

Expected climate overshoot response – four case studies

The following four case studies are used to illustrate observing architecture considerations under climate overshoot for key Earth system components. For each case study, the satellite observing characteristics are considered from the point of view of spectral, spatial and temporal resolution, and other mission characteristics, taking into account the program of record and emerging technologies.

1) Case Study 1:

Warming Induced Emissions

Forty years ago, computer models designed for the Arctic first warned that the warming of the planet might release more greenhouse gas emissions from thawing permafrost[3]. In recent years, with the growth of carbon dioxide and methane concentrations in the atmosphere accelerating (**Figure 5**), evidence is emerging that indeed the **'warming is feeding the warming'**. Increasing emissions of carbon dioxide, methane and nitrous oxide from permafrost, warming wetlands, and wildfires and drought caused declines in tropical forest productivity, have now been documented by numerous satellite, modeling, field, and experimental studies[4,5]. Wetland methane emission feedbacks are particularly concerning given the warming potency of methane, as by 2100 the additional methane released could increase warming by 0.1 to 0.2 °C[6].

Wetlands are the largest single source of methane emissions, producing over one third of total emissions each year, but are also the largest uncertainty in the global methane budget. Wetlands are located in remote tropical and arctic regions making ground-based measurements challenging and thus providing a relevant application for satellites to make remote observations. However, making satellite observations is also challenging in the tropical and arctic regions. This is due to the presence of cloud cover, the presence of dense vegetation obscuring surface water detection, and the presence of low-sun angles in high-latitude fall, winter, and spring seasons limiting the use of passive remote sensing. In addition, many vegetated wetland systems are characterized by inundated vegetation interspersed by small ponds and streams that are difficult to isolate and classify using moderate resolution remote sensing, which makes modeling of specific methane emission pathways more challenging.

Under climate overshoot, the warming phase can be expected to result in an increase in wetland methane emissions. In the tropics, warming is expected to stimulate methane producing microbes, and in the high-latitude boreal and arctic region, warming is expected to increase the growing season length, or the number of days that microbes are active before the soils freeze up in winter. Thawing permafrost is expected to make frozen carbon available to microbes to decompose, releasing an uncertain mix of carbon dioxide, methane, and

3 Woodwell, G. M. 1983. Biotic effects on the concentration of atmospheric carbon dioxide: A review and projection. In Changing climate. National Academy Press, Washington, DC, USA. 216–241.

4 Ciais P., Zhu Y., Cai Y., Lan X., Michel S. E., Zheng B., Zhao Y., Hauglustaine D. A., Lin X., Zhang Y., Sun S., Tian X., Zhao M., Wang Y., Chang J., Dou X., Liu Z., Andrew R., Quinn C. A., Poulter B., Ouyang Z., Yuan W., Yuan K., Zhu Q., Li F., Pan N., Tian H., Yu X., Rocher-Ros G., Johnson M. S., Li M., Li M., Feng D., Raymond P., Yang X., Canadell J. G., Jackson R. B., Yu X., Li Y., Saunois M., Bousquet P., Peng S.. Why methane surged in the atmosphere during the early 2020s. Science. 2026 Feb 5;391(6785):eadx8262. doi: 10.1126/science.adx8262. Epub 2026 Feb 5. PMID: 41642995.

5 Ciais, P., Ke P., Yao Y., Sitch S., Li W., Xu Y., Du X., Gui X., Bastos A., Zaehle S., Poulter B., Colligan T., van der Woude A.M., Peters W., Liu Z., Jin Z., Tian X., Wang Y., Liu J., Pandey S., O'Dell C., Bian J., Zhou C., Miller J., Lan X., Goncalves De Souza J., O'Sullivan M., Friedlingstein P., van der Werf G. R., Peters G. P., Chevallier F., Low latency global carbon budget indicates reduced land carbon sink in the year 2024, National Science Review, Volume 13, Issue 2, January 2026, nwaf594, https://doi.org/10.1093/nsr/nwaf594

6 Buma, B. Frumhoff P.C., Rogers B. M., Sartzetakis S., Phillips C. A., Schädel C., Treharne R., Natali S. M., Alpert A., Goldberg M., Holdren J. P., Canadell J. G., Dooley K., Kurz W. A., Nobre C., Ury E., and Hamburg S. P.. Policy solutions to better assess progress toward Paris goals given warming-induced ecosystem emissions, which shorten timelines by 2–5 years. One Earth, Volume 0, Issue 0, 101571

nitrous oxide back to the atmosphere. In addition, changing precipitation patterns will cause wetland areas to expand or contract, affecting the surface area available to produce methane emissions.

To better quantify the expected responses of wetlands to climate overshoot, improved observations are needed, particularly given the challenges of present-day observing conditions. Instruments and mission designs that can detect sub-canopy conditions, while maintaining high spatial resolution and operating under difficult light and albedo levels, could better reveal wetland processes and help monitor methane emissions. NASA's NISAR mission, with 10-meter resolution, is expected to provide invaluable information and new insights on wetland area, wetland type and dynamics. If combined with active lidar greenhouse gas instruments that will retrieve greenhouse gas information during polar autumn, winter and spring seasons, such as the Centre national d'études spatiales (CNES/DLR) MEthane Remote sensing Lidar MissioN (MERLIN), the uncertainties of wetland methane emissions and response to warming could be expected to be reduced, producing new constraints on column methane concentrations (XCH_4), source areas, and improved emission estimates.

To track the response of wetland methane emissions to peak and decline characteristics of climate overshoot, long-term and sustained observations are a key component of an observing system. Successive satellite follow-on missions, such as Landsat, the Gravity Recovery and Climate Experiment (GRACE), and GRACE-Follow On (FO), have demonstrated the importance of continuity in monitoring long term change, and this will become an increasingly important component of climate overshoot observing systems.

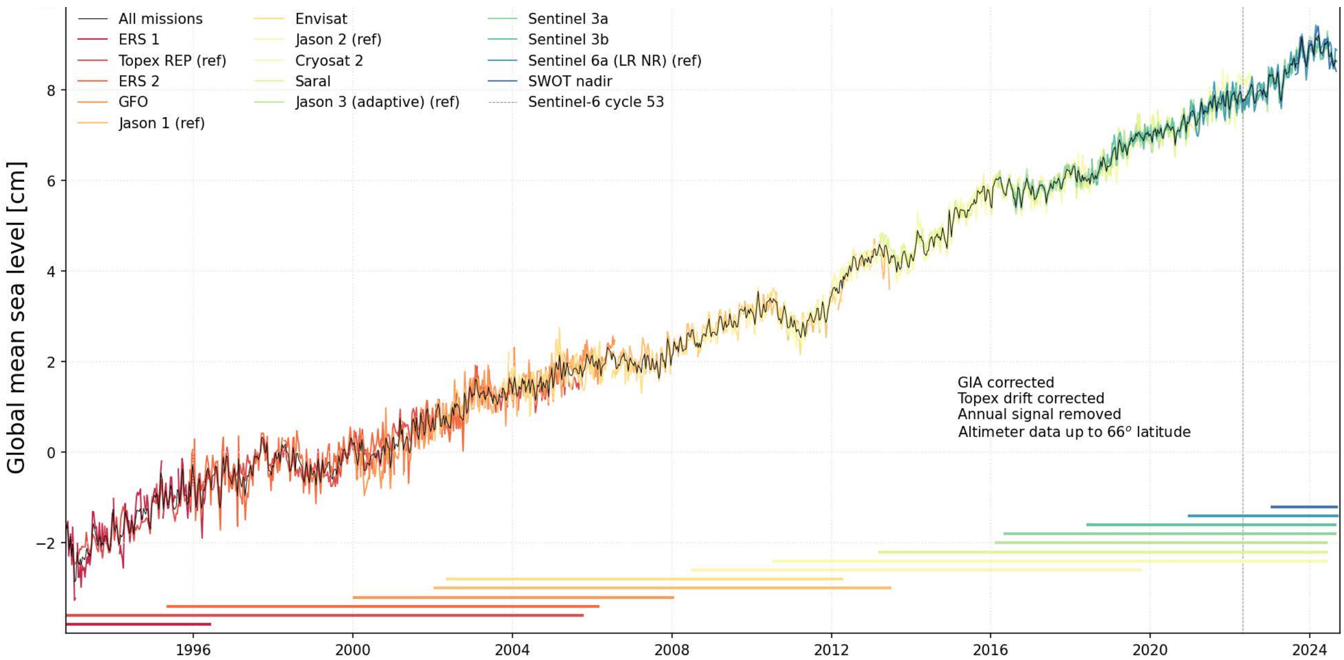


Figure 6. *Global mean sea level tracked through successive altimetric missions showing around a 10–12 cm rise in sea-level since the mid 1990s. Figure by EUMETSAT.*

2) Case Study 2:

Sea-level rise and coastal impacts

Warming affects sea level in two ways, the first is that the volume of water expands as it warms, a process known as **'thermal expansion'**. And the second is that warming increases the contribution of ice via melt from glaciers, ice caps, and ice sheets. Combined, eustatic processes have led to an increase in sea level of 20–24 cm since the mid-1800s, with roughly equal contribution from thermal expansion and ice melt. Sea level is measured through a network of surface stations and satellite altimeters. Satellite altimeters transmit microwave pulses from the instrument to the Earth's surface and the time it takes for the transmission to return to the spacecraft is used to determine sea-surface height. These instruments provide millimeter scale precision and have been used since the early 1990s to provide a continuous record of global and regional sea level change (**Figure 6**).

Rising sea level impacts low-lying regions and small island states through a combination of gradual submergence and through increasing the severity of flooding associated with storms and high-tide events. Between 460,000 to 670,000 km^2 of coastal land area is below 1 m elevation, exposing 77 to 130 million people to the near-to-medium-term risks of sea-level rise[7]. Improved mapping of coastal vulnerability to sea-level rise can be accomplished through a combination of improved digital elevation models combined with high-resolution land-cover change assessments.

Under climate overshoot, the rate of change in sea-level-rise growth and the reversibility of sea levels are major concerns. Melting ice from glaciers and ice-sheets is irreversible on time scales relevant for society, with recovery taking centuries to millennia to recover back to pre-industrial conditions. Similarly, the warming of the ocean that contributes to eustatic rise will take multiple decades to centuries to reverse, given the time involved in ocean currents transporting and releasing energy back to the atmosphere.

Main components of ocean observing systems for sea-level change involve continuity, improved spatial resolution, and connecting physical responses of the ocean (i.e., sea-surface temperature and ocean heat content) with sea level itself. The Copernicus program's Sentinel-6b satellite forms part of this critical long-term program of record for measuring sea-surface height and changes in sea level.

Coastal adaptation will likely be the primary response of society to manage sea-level rise under climate overshoot. Planned retreat, shoreline protection, and hydrologic management are some options available. These options will require satellite data to help integrate information across science and application domains to understand vulnerability to sea-level rise, to monitor impacts, and to help inform decisions to slow or prevent the impacts of flooding, salt-water intrusion, and losses of social and ecological services as sea level rises.

3) Case Study 3:

Ice sheet loss

The partial loss of the Greenland and Antarctic ice sheets is projected to contribute to between **one to five metres of sea-level rise between 2100 and 2300** under current emission scenarios. Greenland is responsible for almost two thirds of the total sea-level rise from ice sheet loss since 1992, around 13.5 mm (the equivalent of 169±9 Gt of ice per year). The West Antarctic Ice Sheet (WAIS, **Figure 7**), in particular, the Thwaites glacier, shows signs of instability, with collapse of the complete WAIS contributing to potentially three to five metres of sea-level rise and the Thwaites glacier could contribute to ~0.6–0.7 metres.

The most effective Earth observing systems for ice sheet loss are lidar altimetry and microwave interferometry for tracking of gravitational anomalies (measuring the distance between two spacecraft). Altimetric missions, such as NASA's Icesat-2, use photon counting laser altimeters using multiple beams to provide wider spatial coverage. The GRACE satellite program, using microwave

7 Seeger, K., Minderhoud, P.S.J. Sea level much higher than assumed in most coastal hazard assessments. Nature 652, 667–674 (2026).

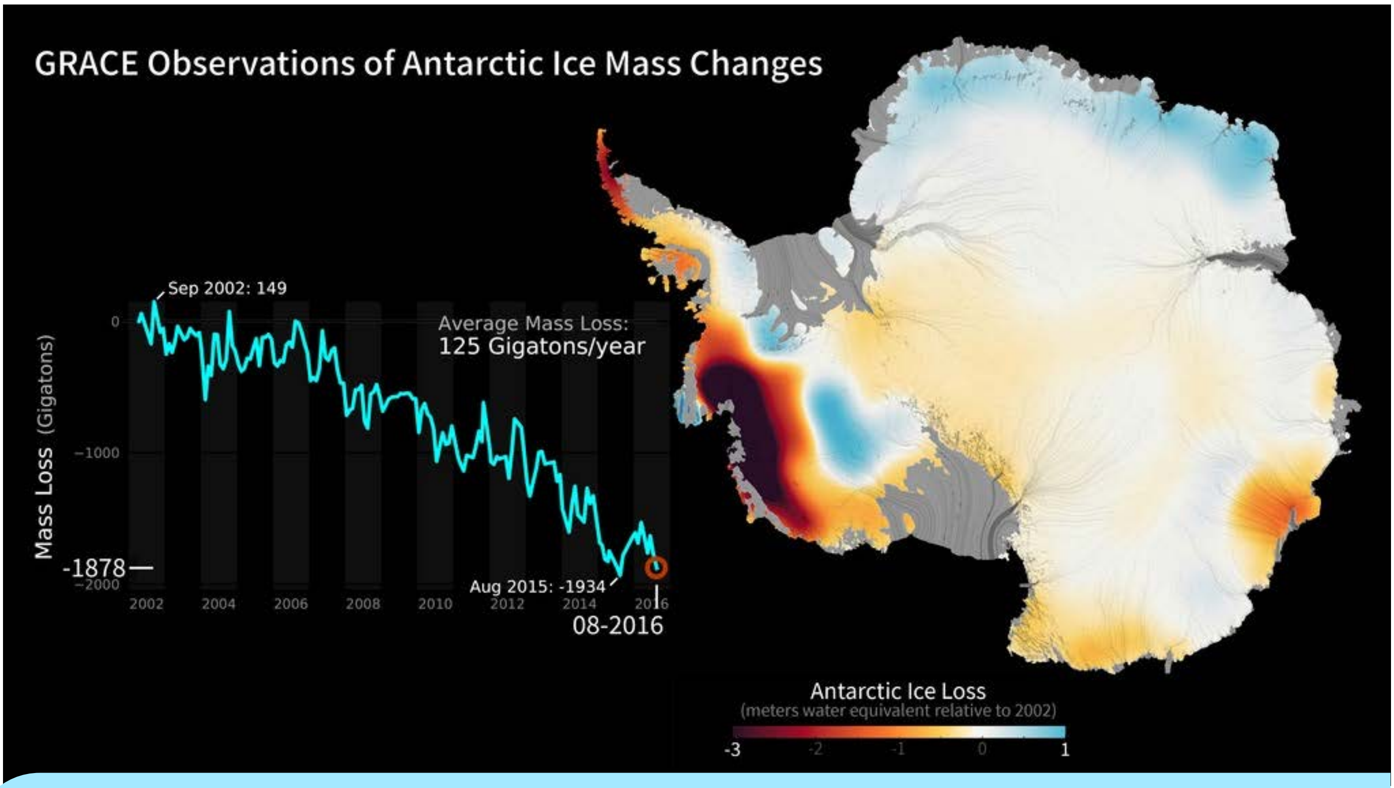


Figure 7. *Ice mass loss in Antarctica and other regions has been monitored by the joint NASA-DLR Gravity Recovery and Climate Experiment (GRACE) mission. Figure by NASA.*

interferometry, has provided an almost two-decade long data series on changes in total water storage that can be used to quantify changes in the Earth's hydrologic balance and ice movement. Both ICESAT-2 and GRACE have applications for other Earth system components beyond monitoring the cryosphere, including monitoring forest change and changes in biomass and the carbon cycle.

Some of the main uncertainties in projecting how ice sheets will respond to climate overshoot include how bedrock friction stabilizes shelf movement, the relationship between buttressing and ice flow, and interactions between the open ocean environment and ice loss. These processes determine the rate of ice loss under warming, and longer-term responses as climate overshoot peaks and declines. Satellite observations constraining bedrock processes are not possible given the depth of ice sheets, and so models rely on indirect observations of ice movement to parameterize model processes that are responsible for large-scale ice dynamics.

For the increase and peak phases of climate overshoot, the sensitivity, precision and temporal frequency of the program of record is likely sufficient for monitoring ice sheet responses to climate overshoot. The spatial resolution of missions like GRACE-FO is a fairly coarse 300 kilometres, but techniques for downscaling to 25 kilometres and potentially finer resolution are emerging[8]. Increased spatial resolution through higher spatial density of photon counting instruments would help provide better topographic information related to ice sheet calving, and improvements in fine-spatial resolution modeling. For the temperature decline and recovery phase, sustained, harmonized and well-calibration observations will be necessary to monitor processes related to ice-sheet stability.

8 Li, F., & Kusche, J. (2026). Reproducing GRACE total water storage change at finer spatial scales. Geophysical Research Letters, 53, e2025GL119881. https://doi.org/10.1029/2025GL119881

4) Case Study 4:

The Earth's Energy Imbalance

Anthropogenic greenhouse gases that accumulate in the atmosphere have led to an energy imbalance between shortwave radiation entering Earth's atmosphere and outgoing longwave radiation trapped by increasing carbon dioxide, methane, nitrous oxide, and other gases. This accumulation of energy leads to the warming of the land, ocean, atmosphere, and the melting of ice sheets. **In just two decades, the rate of increase in Earth's energy imbalance has doubled** (**Figure 8**), outpacing predictions made by climate models[9].

9 Mauritsen, T., Tsushima, Y., Meyssignac, B., Loeb, N. G., Hakuba, M., Pilewskie, P., et al. (2025). Earth's energy imbalance more than doubled in recent decades. AGU Advances, 6, e2024AV001636. https://doi.org/10.1029/2024AV001636

Radiometer instruments have played a pivotal role in observing the Earth's energy imbalance since the late 1990s, since the launch of the Clouds and the Earth's Radiant Energy System instruments (CERES) aboard NASA's Terra and Aqua spacecraft as part of their Earth Observing System program (EOS). Since then, the CERES instrument has flown as part of several other missions, including the joint NOAA-NASA Joint Polar Satellite System and Suomi NPP and NOAA-20. CERES uses a radiometer to measure reflected solar and emitted thermal infrared energy exiting the Earth–atmosphere system in three scanning modes to provide different view angles of radiance.

A key characteristic of radiation missions includes having a highlight calibrated and harmonized record of observations across different missions. The current fleet of CERES instruments are set to be decommissioned within the next decade, and

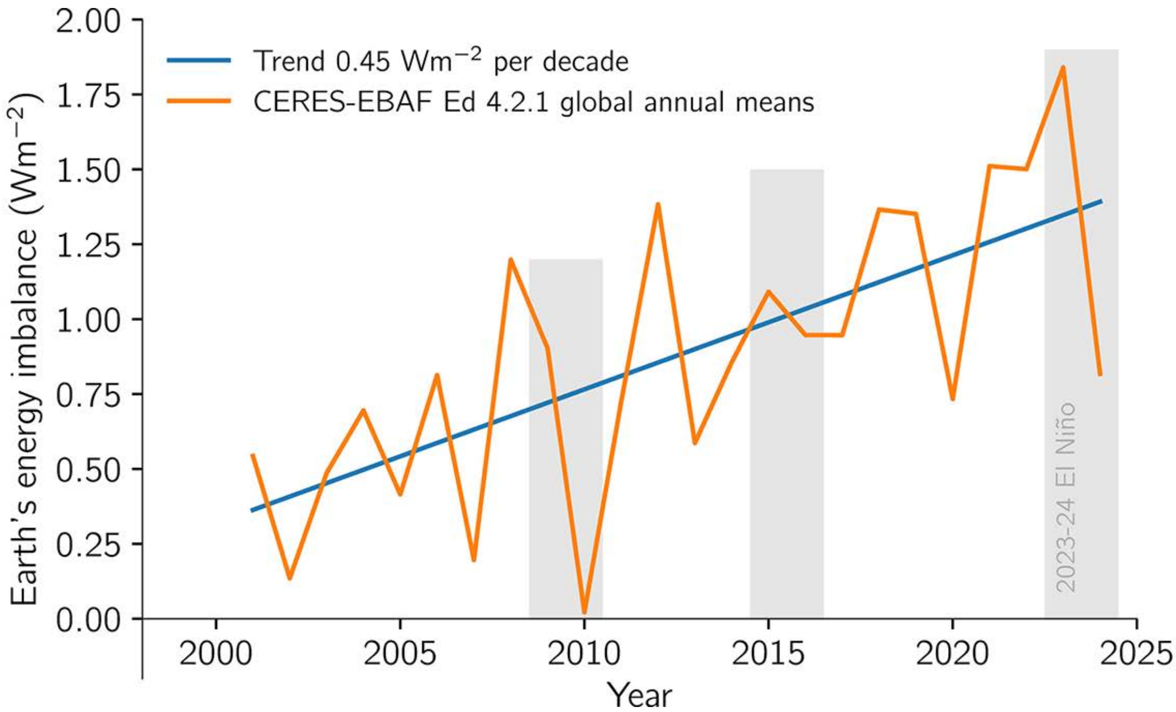


Figure 8. *As greenhouse gases trap heat in the Earth's atmosphere, the Earth's energy imbalance increases. Measurements made by NASA's Cloud's and the Earth's Radiant Energy System (CERES) have provided a time series since 2003. Figure by EOS.*

Figure 9. *The CNES/DLR Methane Lidar Remote Sensing Mission (MERLIN) will use an active lidar system, at 1.65 μm to retrieve column concentrations of methane. The active system will enable retrievals at nighttime and when the sun angles are low at high-latitudes. Figure by CNES/DLR.*

there are few options for replacement. One of these options includes NASA Libera mission, a more compact radiometer designed to extend the almost three decade record of radiation measurements.

Under climate overshoot, accurate, timely, and well-calibrated monitoring of the Earth's energy imbalance will help quantify and understand mitigation efforts as well as Earth system feedbacks that might emerge. The doubling of the rate of increase in the Earth's energy imbalance is currently being investigated, in order of priority, as due to unexpected changes in the Earth's surface albedo, interactions with eliminating high-sulfur diesel fuels and 'termination shock', and challenges with harmonization of data records. The latter arises as the Terra and Aqua missions are gradually deorbited.

New and more agile missions like Libera provide a model for sustained and resilient observations of Earth's energy imbalance (EEI). Sustaining observations with overlap between missions, and developing workflows that include consistent calibration, ground-based validation, and improved radiative transfer models, would be key features of such constellations that would help measure and monitor change in the Earth's energy imbalance under climate overshoot.

New observing requirements

Climate overshoot presents new challenges for the Earth observing community to **better characterize the timing, duration, and accuracy** needed from satellite based instruments. The current fleet of satellite missions have been designed to address directional changes in the Earth's climate, and the temperature peak and decline characteristics of the era of climate overshoot will require new observing and analytical approaches.

Key characteristics include 1) maintaining sustained and intercalibrated observations across successive missions or constellations of satellites, 2) expanding the revisit of satellite observations

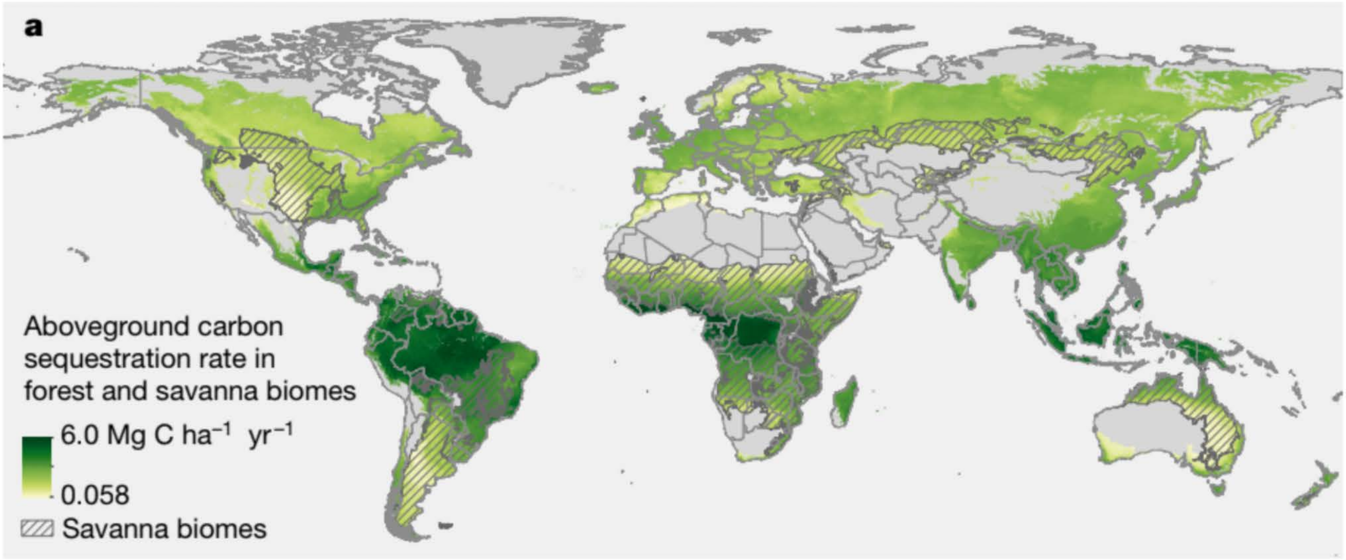


Figure 10. *Monitoring ecosystem carbon removals from nature-based carbon solutions projects will become increasingly important as the land sector's role in negative emissions is relied on to reach temperature stabilization targets. Figure from Patton et al. (2020).*

to daily and sub-daily observations, 3) increasing the accuracy of retrievals and derived products to be able to better detect smaller-scale impacts and the response of systems to climate mitigation, and 4) exploring new innovations in technology (i.e., active sensors) and orbital configurations (i.e., limb sounding, HEO, co-adding of higher spatial resolution information) to improve representation across critical regions where observations remain sparse.

The program of record for operational and planned missions covers much of the trade space necessary to understand Earth system changes under climate overshoot. Active missions, such as the CNES/DLR Methane Lidar Remote Sensing Mission (MERLIN), will contribute to year-round understanding of methane concentrations (**Figure 9**), contributing to improved assessment of emission sources. Partnerships between space agencies on hyperspectral and thermal missions will provide higher temporal frequency information on land-surface responses to diurnal, subseasonal-to-seasonal, and interannual variability. Improved coordination between ground networks will provide better characterization of satellite instrument calibration as well as retrieval performance for land, ocean, atmosphere, and cryospheric processes.

Additional considerations for climate interventions and negative emissions

Climate overshoot also brings a new reality where a range of climate interventions are being discussed to reduce temperatures and concentrations (for the decline phase) to return to safe and stable temperature targets. These interventions require their own specialized monitoring, measurement, reporting, and verification requirements. Because of the linear relationship of carbon dioxide with temperature and the long lifetime of carbon dioxide in the atmosphere (100s to 1000s of years) net-zero emissions generally means that the climate will stabilize, but technologies will be needed to reduce carbon dioxide (and methane) concentrations.

A range of direct air capture technologies are being explored for carbon dioxide, and more recently for methane, as well as nature-based climate solutions (including reforestation, afforestation), and alternative enhancements of carbon capture through, for example, ocean-alkalinity enhancement, biochar amendments, enhanced rock weathering.

The financing mechanisms for climate interventions include voluntary carbon markets, climate bonds, and other incentives to increase the volume of greenhouse-gas credits available for mitigation, as well as their quality. As these financial mechanisms mature, so will the need for appropriate and robust **Monitoring, Reporting, and Verification (MRV) technologies** to develop a framework for monitoring investments and to demonstrate their effectiveness. Carbon stocks for land ecosystems is an active area of research (**Figure 10**) where high-potential exists for drawing down atmospheric carbon concentrations through reforestation and afforestation and where high-potential also exists from a financing perspective. Earth observations presently play a role in understanding the locations for potential projects, providing baselines and reference cases necessary for developing financing portfolios.

Closing thoughts

Continued emissions of greenhouse gases from human activities means that temperatures will almost certainly exceed the 1.5 °C limit that the Paris Agreement intended to avoid. Indeed, recent warming anomalies suggest that the 1.5 °C limit has already been exceeded and the remaining carbon to avoid this level of warming already appears to have been consumed. From a climate policy perspective, exceeding 1.5 °C is expected to be temporary, meaning that **the Earth's climate system now enters a period of overshoot**, defined as a temporary peak temperature followed by a decline to some stabilization temperature.

Climate overshoot will present its own set of risks, including non-analog conditions [10] the potential for new biogeochemical feedbacks that are not well understood [11], and policy and mitigation challenges that far from guarantee a return back to a safe temperature stabilization level without additional ambition. While from a theoretical perspective, climate overshoot provides a convenient policy mechanism to compensate for delayed climate action, it may come at the cost of irreversible ecosystem damage, uncertainty in ecosystem recovery, and increased risks to trigger 'tipping points' in the climate system. **Earth observations from the program of record, from new missions, and new analytical methods will continue to play a key role in measuring and monitoring the Earth system response during this important phase of climate change.** However, new perspectives from climate overshoot science will continue to be needed to understand novel impacts during the phases of temperature peak and duration, and temperature decline, and whether impacts are reversible or irreversible and the climate system recovers.

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Dr. Ben Poulter is a Senior Scientist at Spark Climate Solutions, a non-governmental organization working to catalyze high-impact climate mitigation science and policy. Ben's background is in ecology, numerical modeling and remote sensing, receiving his PhD from Duke University, working in Europe as a Marie Curie Fellow, and then at the NASA Goddard Space Flight Center. He worked on early Free Air Carbon Dioxide Enrichment (FACE) experiments to understand ecosystem responses to elevated atmospheric carbon dioxide concentrations, he developed Dynamic Global Vegetation Models (DGVMs) to track global land carbon removals and wetland methane emissions, and designed new satellite architectures configured to monitor land-surface processes and greenhouse-gas (GHG) concentrations using hyperspectral instruments associated with the Surface Biology and Geology mission. In 2024, Ben worked at the White House Office of Science and Technology Policy as Deputy Director for GHG monitoring to implementation the coordination of a new national GHG monitoring program. He was the 2025 Johannes Geiss Fellow at the International Space Science Institute.

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