EUROPEAN SPACE SCIENCES COMMITTEE

Earth Observation

Groundbreaking Science Discoveries

This document was prepared by the Earth Sciences Panel of the European Space Sciences Committee in response to the ESA contract 500104016 entitled "Ground-breaking science discoveries and successes enabled by ESA Earth Observation satellites".

Front and back-cover showing an image of the Earth compiled using tens of thousands of images from the Copernicus Sentinel -2 mission acquired during 2019-2020.

Table of Contents

Foreword

Urgency and agency:
Earth observations from space for science and society

In 2025, the European Space Agency celebrates its 50th anniversary. European scientists provide, in this brochure, a remarkable gift to decision makers.

They explain, with simple words and compelling visuals, how twelve scientific discoveries and their benefits for society have been made possible thanks to the European Space Agency and its Earth Observation programme.

For the first time, in 2024, the Earth's global surface temperature has exceeded 1.5°C above pre-industrial levels. The rate of human-caused heat uptake is still increasing, causing fast changes across the whole climate system – the atmosphere, ocean, cryosphere and biosphere, leading to an acceleration of global sea level rise, and an intensification of the water cycle. Every world's region is facing an escalation of adverse and severe impacts and losses and damages, hitting hard those most vulnerable.

Space observations play a key role in tackling climate science knowledge gaps, diagnosing the processes at play, sharpening our scientific understanding of the Earth system, and advancing confidence in future projections.

Space observations also play a critical role by informing our responses to a changing climate, including risk management and progress towards carbon neutrality. Real time atmosphere, land and ocean observations improve weather and air quality forecasts, which are critical for early warning systems and disaster relief.

Advanced weather forecasts also support efficiency in energy and transport systems. Global space observations are essential for tracking emissions that impact both climate and air quality, as well as for monitoring forest health, and to inform policy responses.

These twelve scientific success stories, providing vital information for society, would not have been possible without European cooperation, leadership, vision, and support for innovative Earth space observations.

We urgently need to advance our understanding of amplifying processes within the climate system – including the recent decline of Antarctic sea-ice, changing cloud patterns, signs of loss of efficiency of the ocean and land carbon sinks, changes in ocean circulation, or the onset of Antarctic ice sheet instabilities.

50 years after the start of the European Space Agency, choices for its Earth Observation programme package will be crucial for future advances in the understanding of the Earth system, supporting well-informed action.

Valérie Masson-Delmotte
Senior scientist,
Laboratoire des Sciences du Climat
et de l'Environnement,
Institut Pierre Simon Laplace

Former Co-Chair of IPCC Working Group I
for the 6th Assessment Cycle (2015-2023)

Introduction

The advent of polar-orbiting and geostationary satellites has revolutionised our ability to study the Earth as an interconnected system. We are no longer restricted to geographically scattered measurements of individual components such as the ocean, atmosphere, cryosphere, biosphere, land, and solid Earth. Remote sensing from the vantage point of space, using instruments that exploit light, radio waves, and gravity, has revealed the intricate anatomy and interconnected dynamics of our living planet.

This has transformed our awareness of the rapidly accelerating scale and pace of the climate and environmental crises, underscoring the urgent need for collective human action to address them. The ESA Earth Observation programme has been instrumental in these advances.

This brochure showcases 12 ground-breaking scientific discoveries and successes enabled by the programme. These are divided into 3 cases for each of the 4 main thematic domains of the Earth sciences: atmosphere, ocean, land, and polar regions. The criteria used to define a "groundbreaking science discovery" include a clear "elevator pitch", the "degree of astonishment", and the jump in knowledge that the scientific discovery represents. All the cases illustrated are based on a discovery as described in the list of references at the end of the document. They draw primarily on data from ESA missions (ERS-1, ERS-2, ENVISAT, and Earth Explorers) and the European Commission's Copernicus programme (Sentinels), but with additional insights gained from European national and NASA missions.

Together with in-situ data and modelling, these findings form a vital foundation for informed decision-making to address and adapt to the profound changes humanity is driving within the Earth system.

At the ESA Ministerial Conference in 2022 (CM-22), the European Space Sciences Committee (ESSC) noted: "*The Earth Observation package (proposed) further consolidates Europe's pre-eminent position in providing vital information for society to address the climate and environmental crises, while also laying new scientific and technological foundations for understanding the Earth system. Given (its) highly integrated nature, we draw attention to the disproportionate effect of even small funding reductions.*" Our recommendation was to fund this package in full, and we were disconcerted at the eventual undersubscription. As we prepare this contribution to the European Space Science Committee's evaluation of the ESA Earth Observation programme package for CM-25, we strongly reaffirm our previous recommendation. There has never been a more critical time to support the ESA Earth Observation programme and its ability to deliver fundamental scientific insights.

Prof. Chris Rapley CBE MAE
Chair, European Space Sciences Committee

ESA Perspectives

We are very happy to present the highlights of the scientific results enabled by European Space Agency's Earth Observation satellites which you will discover in the following pages.

When informed that a team of European scientists had decided on their own initiative to analyse the record of groundbreaking scientific discoveries delivered over the last decades thanks to the ESA Earth Observation satellites, I was very enthusiastic. I strongly commend the Earth Sciences Panel (ESP) of the European Space Sciences Committee (ESSC) on the initiative, its thorough assessment and commitment to bring forward simple explanations to the scientific discoveries. These discoveries provide compelling evidence of a rapidly changing and complex Earth system and of the need to not only sustain but accelerate and enlarge the Earth Observation programmes of ESA and other institutions to face the scientific and societal challenges.

The climate and environmental crises which humankind must collectively confront and the objective of sustainability on Earth for the future generations can only be addressed through an increasing understanding of Earth's complex systems. In this context, Earth Observation data not only opens up new frontiers of scientific knowledge but contributes to vital information for society, informed by observations and facts, to manage its way into a better future.

Our motivation to continue on this path of groundbreaking discoveries and successes is now stronger than ever.

Simonetta Cheli

Director of ESA Earth Observation Programmes

1 Atmosphere

1

1.1

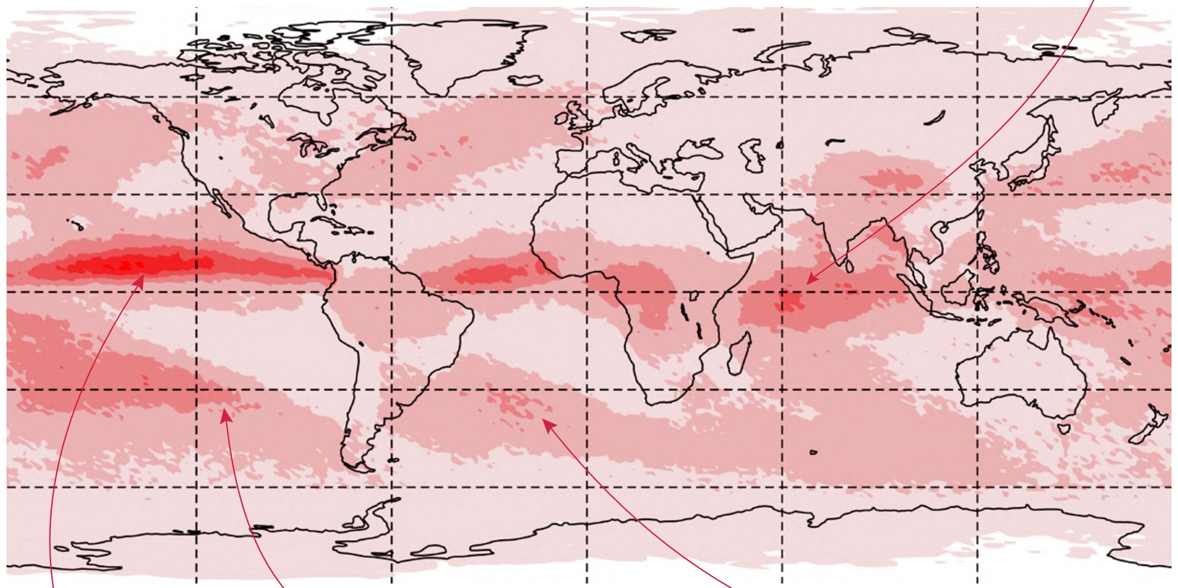
Harnessing the Winds

The Aeolus Mission's Breakthrough in Global Wind Mapping

Aeolus

Improvement of wind forecasts with Aeolus

The influence of the Aeolus data is seen in improvement of wind forecasts at 7 km altitude throughout the globe (indicated in red). The largest effects are seen in the equatorial and tropical areas as well as over the oceans.



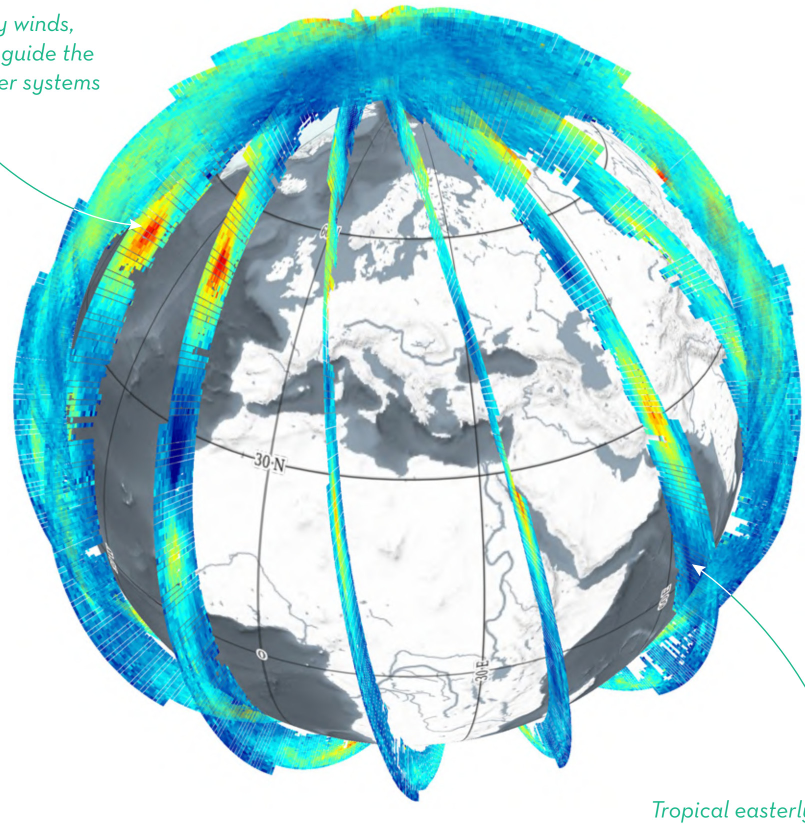
The ability to predict winds has been a longstanding concern for humanity, and even today many regions around the world have limited time to prepare for extreme weather events. Aeolus has transformed our capability of observing Earth's winds, revealing how precision from space can bring life-saving foresight to weather prediction and new resilience against extreme climate events.

ISSUE

Historically, global wind patterns were charted through a patchwork of ground stations, weather balloons, and aircraft and satellites tracking clouds. Yet vast swathes of Earth—especially over oceans and the remote Southern Hemisphere—remained unexplored. ESA's Aeolus mission transformed this reality as the first satellite purpose-built to measure wind profiles from the troposphere to the lower stratosphere, reaching heights up to 30 kilometres. With Aeolus, scientists gained an unprecedented, sweeping view of the atmosphere's rhythms, illuminating areas once out of reach and providing a comprehensive, real-time grasp on Earth's atmosphere.

Aeolus wind profile measurements

Aeolus measures winds at various altitudes, from the surface to the lower stratosphere, with a horizontal resolution of about 87 km along the satellite's orbit (coloured cross sections). Aeolus offers real-time data for operational weather forecasting, typically within a few hours of measurement.



DISCOVERY

Aeolus significantly enhanced the accuracy of weather forecasts by providing critical wind data, particularly in regions where observations were sparse or unavailable, such as over the tropics, oceans, and polar areas. This data filled an important gap, improving weather forecasts up to nine days in advance and supporting better community preparedness for severe weather events, including storms, hurricanes, and other extreme phenomena. The satellite's data proved especially valuable for real-time input into numerical weather prediction models, enabling more precise tracking of weather systems. Beyond short-term forecasting, Aeolus also contributed to a deeper understanding of long-term atmospheric dynamics, such as the global circulation of heat and moisture that drive climatic patterns. This increased forecast accuracy will help to protect lives, livelihoods, and infrastructures across the globe.

IMPACT

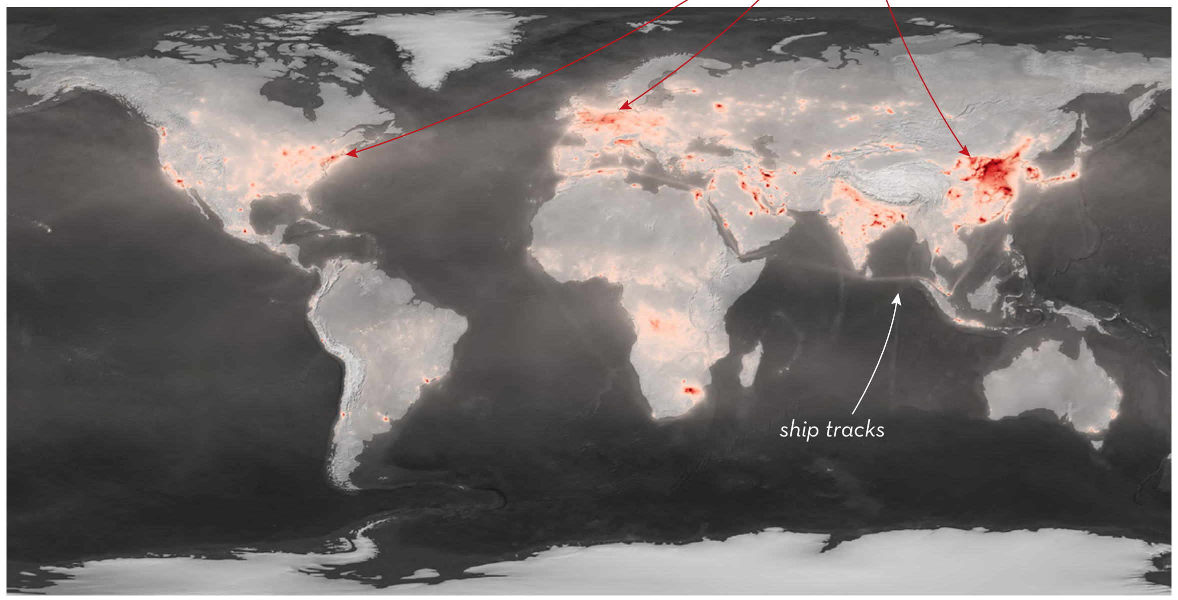
Launched in 2018, Aeolus carried ALADIN, an innovative Doppler wind lidar that emitted ultraviolet light pulses into the atmosphere. This revolutionary technology calculated wind speed and direction by analysing the Doppler shifts of backscattered UV-light from air molecules and particles such as dust, creating detailed profiles of wind patterns across the globe. Beyond weather, Aeolus delivered tangible benefits to the aviation and maritime industries by supporting safer, more fuel-efficient route planning. Though Aeolus is no longer in orbit—designed for 3 years but operating flawlessly for over 4.5—its legacy lives on through its successor, EPS-Aeolus, which will monitor Earth's winds to protect communities, boost economic resilience, and enhance understanding of our planet's complex systems.

Air Pollution: the Human Impact

Detecting Covid-19 Lockdown Effects on Air Pollution

SENTINEL-5P

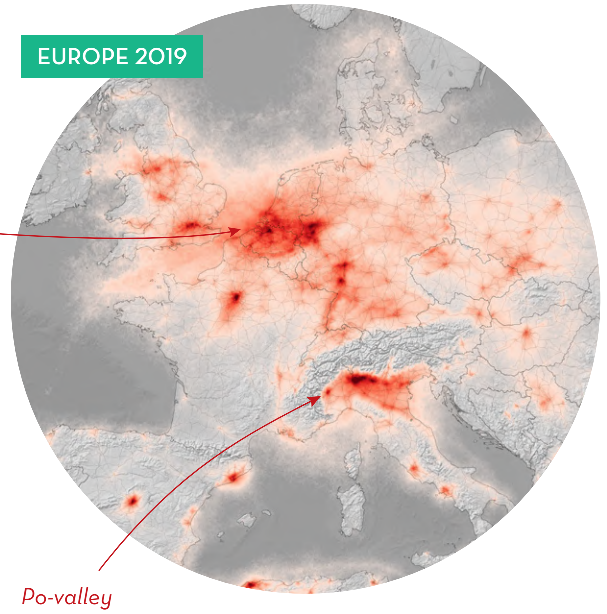
Nitrogen dioxide mean tropospheric column

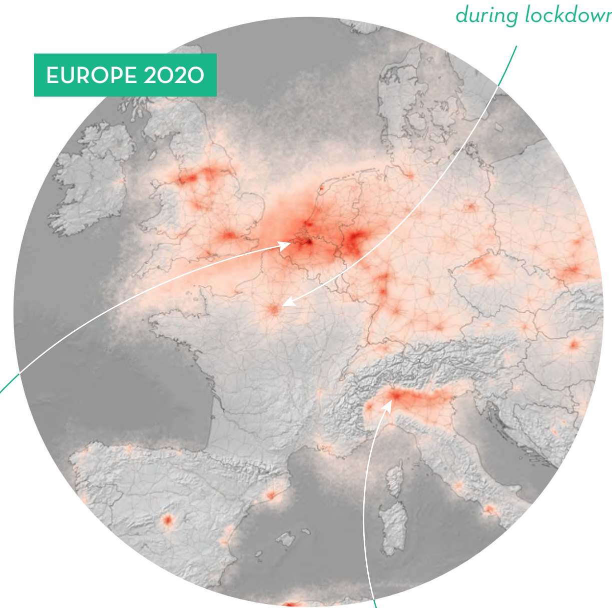


Highlight of most polluted regions in the world, including major cities and industrial areas. Cleanest air is seen in sparsely populated areas far from industrial emissions.

Air pollution before and after the COVID pandemic

The Covid-19 lockdown in 2020 provided a unique experiment to study atmospheric pollution. Atmospheric concentrations of the air pollutant NO2 reveal a drastic decrease between 2019 and 2020, resulting from reduced traffic and industrial emissions due to lockdown measures.





During the most efficient lockdown period the concentrations were considerably lower in several cities across Europe

Whilst some voices in the climate conversation have questioned the extent of human impact on our planet, advances in Earth Observation, particularly during the COVID-19 pandemic, have provided compelling evidence through continuous monitoring.

● ISSUE

Air pollution is a major threat to human health and a global crisis, with 99% of the world's population in 2019 residing in areas that did not meet WHO air quality guidelines. It is imperative that we deepen our understanding of this issue and implement decisive measures to address it. Nitrogen dioxide (NO_2) from fossil fuel combustion is a major contributor, especially in densely populated urban areas where it is primarily generated by traffic and industrial activity. For years, monitoring air quality at a high resolution and on a global scale has been challenging; ground-based sensors provided only sparse data, leaving vast regions inadequately monitored. To address this, the European Space Agency launched TROPOMI in 2017 aboard the Sentinel-5P satellite, ushering in a new era of high-resolution, daily, space-based air quality observations.

●● DISCOVERY

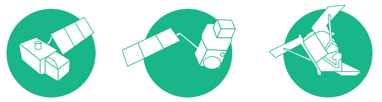
TROPOMI, with its exceptional sensitivity and ability to detect air pollutants across a 3.5 x 5.5 km grid, now scans the Earth daily with unprecedented clarity. Its sharp eye captures a multitude of pollutants, from nitrogen dioxide to sulfur dioxide, carbon monoxide, and formaldehyde, revealing the sources of these emissions and their movements through the atmosphere. During the COVID-19 lockdowns, TROPOMI tracked dramatic drops in NO_2 levels—up to 70% in some major cities—directly reflecting reductions in traffic and industry. This satellite's fine-tuned measurements enabled scientists to explore the impacts of varying lockdown measures around the world, as well as the subtle interplay of local weather and atmospheric chemistry in shaping pollution levels.

●●● IMPACT

The insights TROPOMI provides have far-reaching implications. The lockdown findings underscored the tangible benefits of reduced emissions on air quality, illustrating the responsiveness of our environment to immediate changes in human activity. For policymakers, these insights are invaluable: TROPOMI's data reveal how targeted actions—such as reducing vehicle emissions or controlling industrial output—can yield significant air quality improvements. As the science continues to unfold, TROPOMI stands as a powerful reminder that in protecting the air we breathe, we hold the tools and data to shape a cleaner, healthier future.

Our Climate Versus the Super-Emitters

Mitigating Climate Change by Revealing Methane Super-Emitters and Methane Leakages

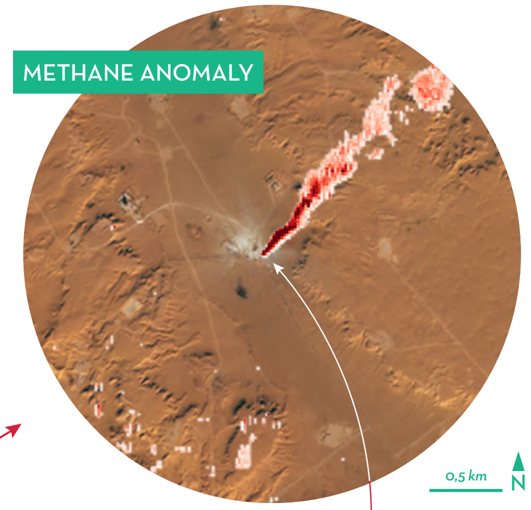


SENTINEL-2 SENTINEL-3 SENTINEL-5P

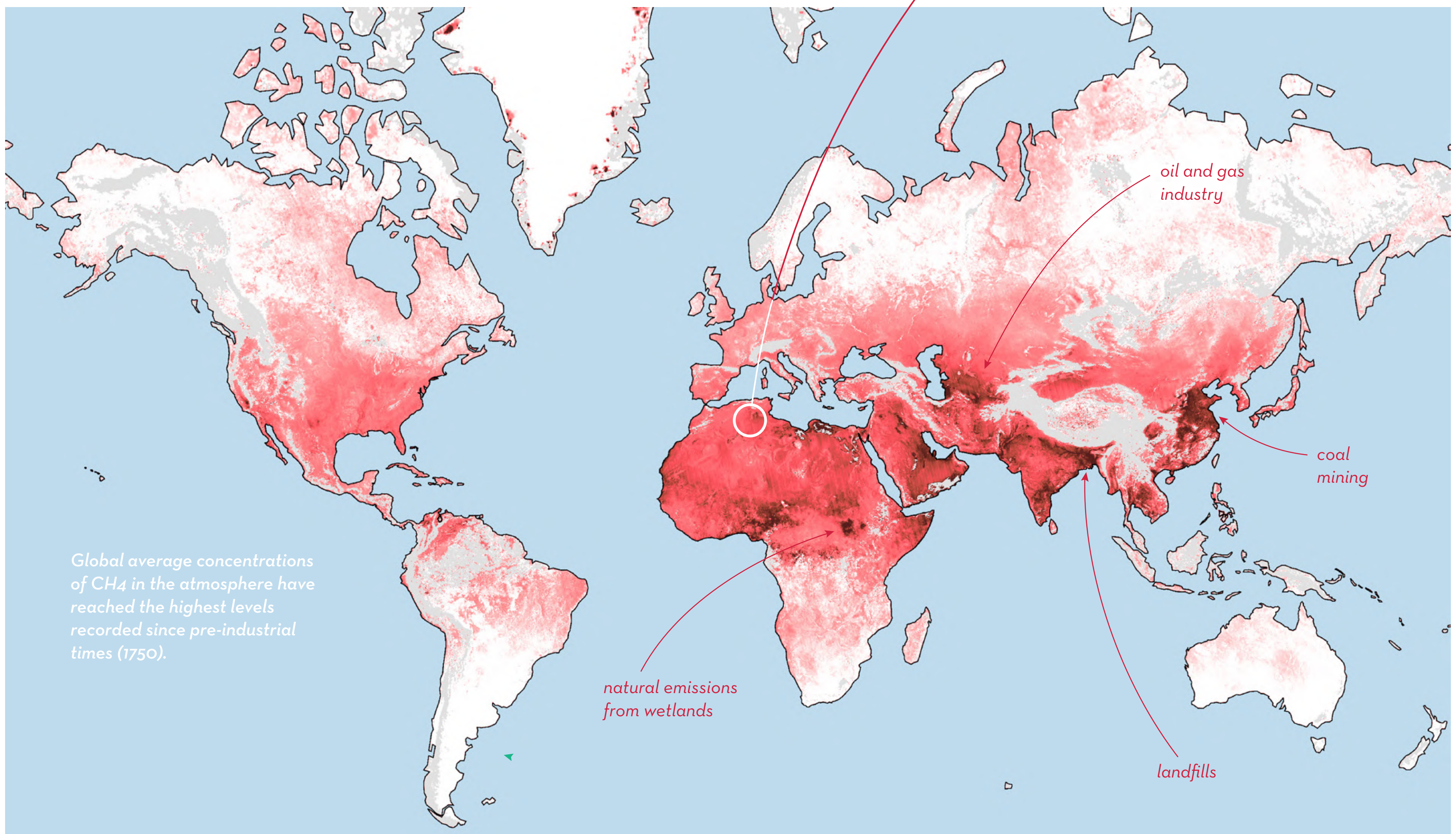
Global average concentrations of methane (CH4) in the atmosphere

Global average distribution of methane measured by TROPOMI. Regions with elevated methane concentrations are linked to methane's natural emissions from wetlands and anthropogenic emissions from rice cultivation, oil and gas industry, coal mining, livestocks, landfills.

Methane is an 80 times more potent greenhouse gas than carbon dioxide, and yet little was known about the scale of the problem. Earth observation technology has allowed up to pinpoint "super-emitters" so that we may tackle the problem head on.



Methane leak at more than 3ppm in Algeria, January 4, 2020



ISSUE

For decades, scientists have recognised that methane as a greenhouse gas is over 80 times more potent than carbon dioxide in the short term, significantly driving global warming. Tracking methane emissions is challenging due to their variability, stemming from natural sources like wetlands, and human activities such as agriculture, waste, and fossil fuel extraction. Additionally, substantial emissions often go unreported, particularly from leakages from oil and gas industry, coal mines and landfills. With the Sentinel-5P satellite and its advanced TROPOMI instrument, we can now monitor global methane concentrations daily, identifying persistent emissions and transient leaks. This unprecedented precision is a critical step in mitigating climate impacts.

DISCOVERY

The TROPOMI instrument aboard Sentinel-5P scans Earth's surface in cloudless conditions from space, capturing global methane levels with a fine spatial resolution of 5.5 by 7 kilometres. This vantage point enables it to zero in on methane "super-emitters"—highly concentrated local sources of emissions that exceed 10 tonnes per hour—from oil and gas infrastructure, landfills, coal mines, and other industrial sites. Often, these emissions sources are unrecorded, meaning they had slipped through the cracks of greenhouse gas inventories until now. TROPOMI's regular, global scans make it possible to identify unexpected leakages and track emissions across various sectors, even providing information on the frequency and location of emissions down to individual facilities, when combined with data from high-resolution sensors like those on Sentinel-2 and Sentinel-3.

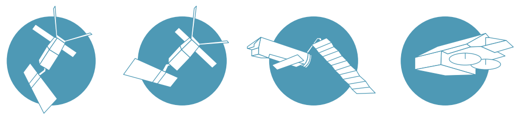
IMPACT

By exposing methane leaks and super-emitters with such precision, Sentinel-5P has brought invaluable data to the fight against climate change. TROPOMI's findings allow regulators, industry leaders, and policymakers to address previously unknown methane sources swiftly, reducing emissions that not only harm the environment but also waste valuable resources. This rapid-response capability offers governments and industries a practical means to monitor progress on emissions reductions and ensure regulations are working effectively. As we look to the future, Sentinel-5P's data can be a cornerstone of climate policy, helping reduce warming impacts quickly and providing a clearer path toward sustainable industry practices worldwide.

2 Polar Regions

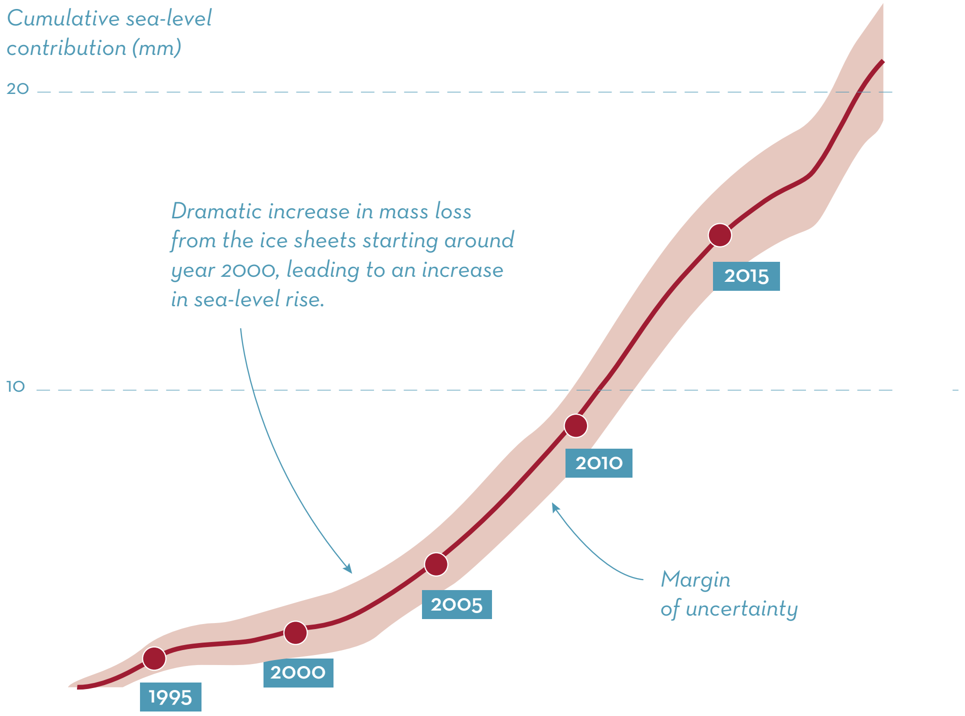
2.1 Mass Balance of the Great Ice Sheets

Assessing the Harsh Realities of Melting Ice Caps



Mass Loss from the Great Ice Sheets

from 1992 to 2021 as measured by CryoSat-2 and other satellite missions



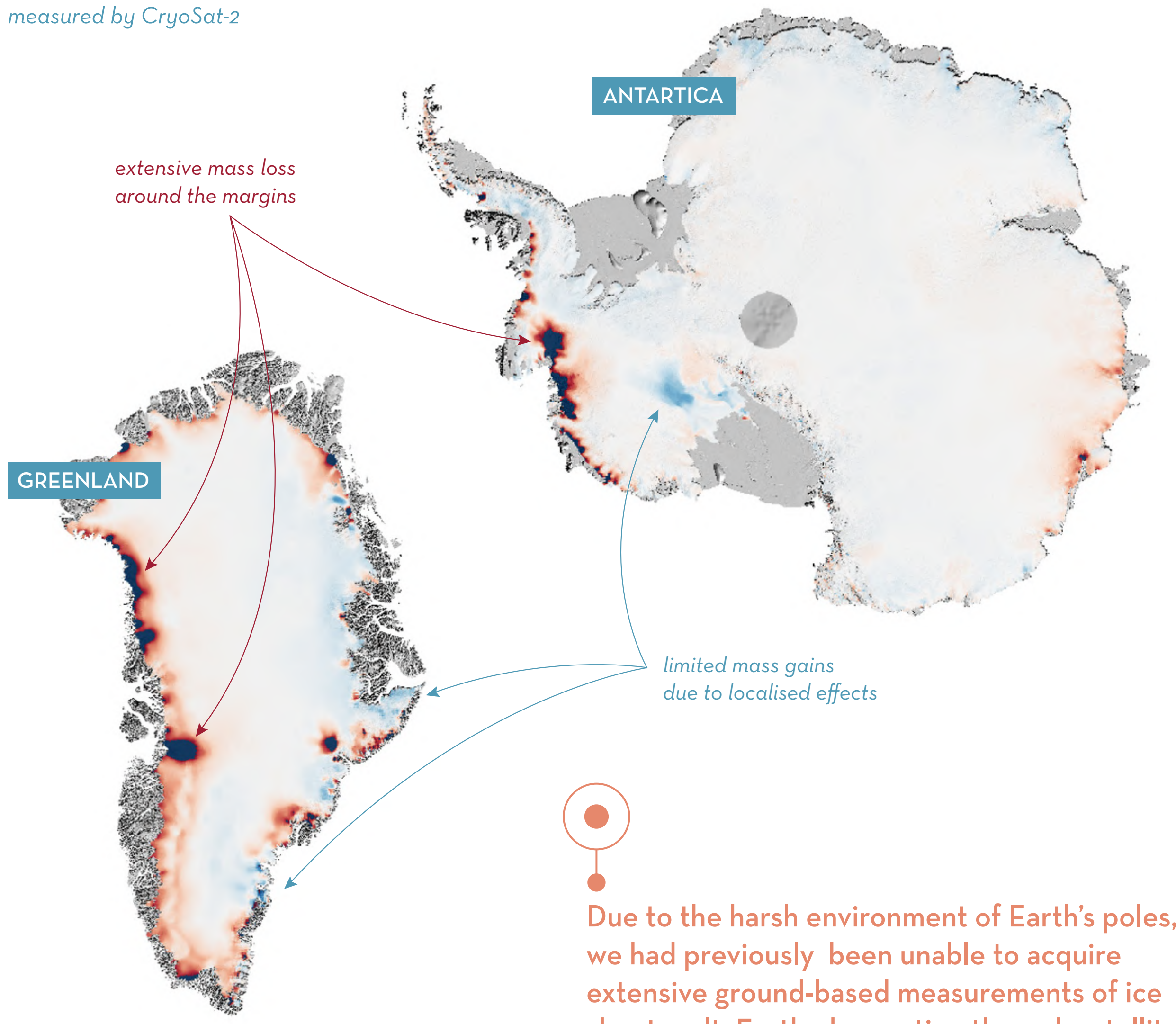
ISSUE

The Antarctic and Greenland ice sheets, together, store about 80% of the world's freshwater. If they were to melt completely, sea levels would rise by a staggering 65 metres. This makes even the slightest change in their mass balance—meaning the difference between the gains and losses of ice over time—an event with monumental consequences. It would first impact Europe's low-lying coastal regions, with countries like the Netherlands, Belgium, Denmark, the UK, and Italy facing increased flooding and erosion.

Major cities, critical infrastructure, and agricultural areas are at risk, threatening both economic stability and population safety. Despite the severity of this problem, understanding these changes is a challenge. The extreme cold, isolation, and vastness of these ice sheets make extensive on-the-ground measurements virtually impossible, leaving us with a critical blind spot in global climate monitoring. Before the advent of satellite technology, we had little understanding of how these icy giants were evolving.

Evolution of Great Ice Sheets

from 2010-2023 measured by CryoSat-2



Due to the harsh environment of Earth's poles, we had previously been unable to acquire extensive ground-based measurements of ice sheet melt. Earth observation through satellites is the only way we can grasp the full reality of melting ice caps, and take action.

DISCOVERY

This all changed with the launch of the ERS-1 satellite in 1991. For the first time, scientists could monitor nearly the entire Greenland Ice Sheet and 80% of Antarctica from space. Equipped with a radar altimeter designed to track elevation changes, ERS-1 was able to make precise measurements even in the harshest, cloud-covered conditions, thanks to a novel "ice mode" that adapted the instrument for the steep terrain at the edges of the ice sheets. This was the beginning of an era of continuous, reliable observations, with subsequent satellites such as ERS-2, ENVISAT, and CryoSat-2 enhancing our ability to track ice mass changes over time.

IMPACT

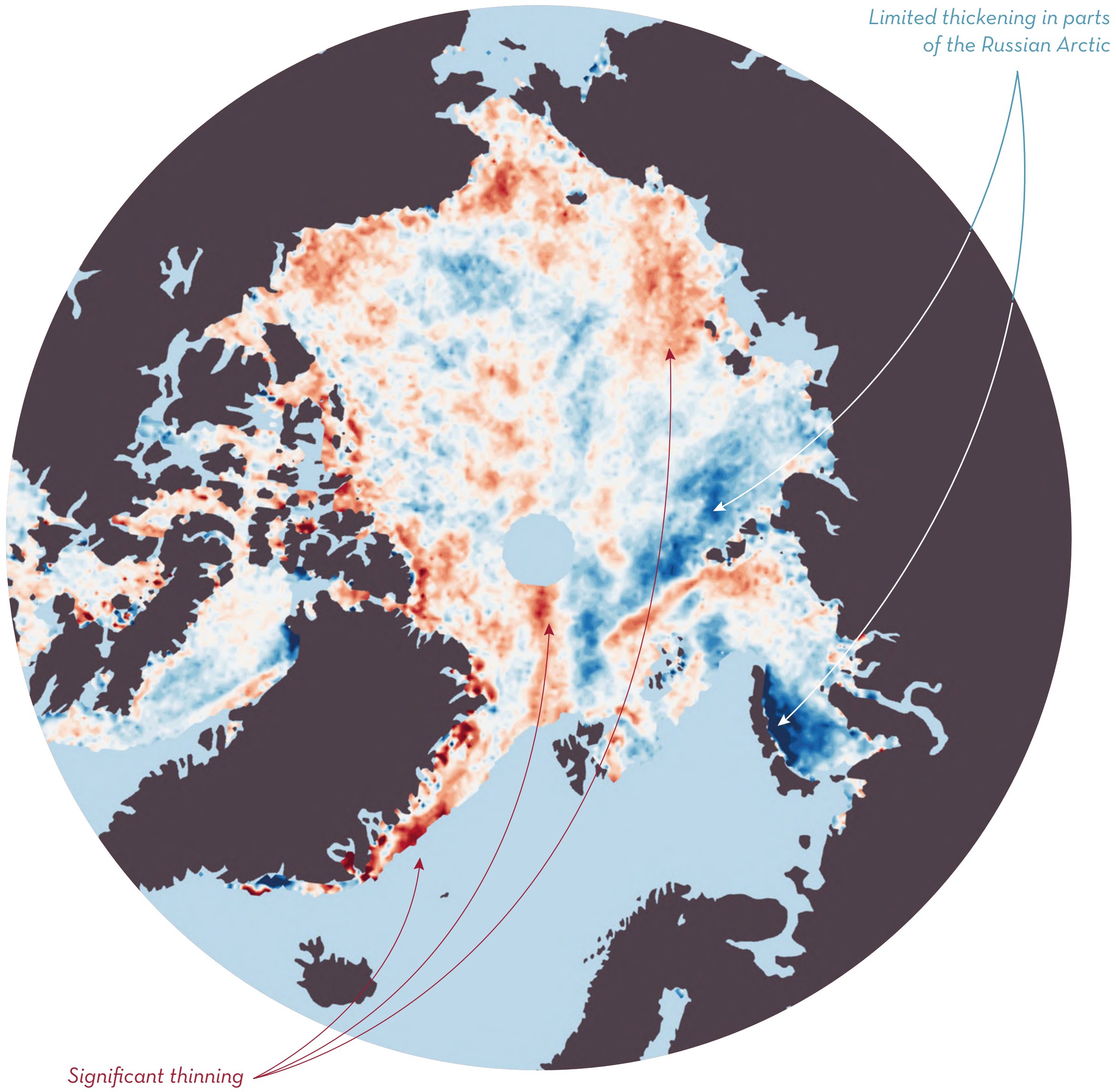
Today, satellite altimetry has provided us with a 33-year record of ice sheet mass balance, enabling scientists to measure their contributions to rising sea levels with unprecedented accuracy. Before this, the vast, remote regions of Antarctica had been shrouded in uncertainty, with estimates subject to wide margins of error. Now, thanks to these satellites, we have the tools to accurately quantify the role that melting ice is playing in global sea level rise, making it possible for policymakers to understand and address the urgent challenges posed by climate change in the polar regions.

2.2
Arctic Alarm
Unveiling Sea Ice Loss with ESA's Satellites

CRYOSAT-2 SMOS

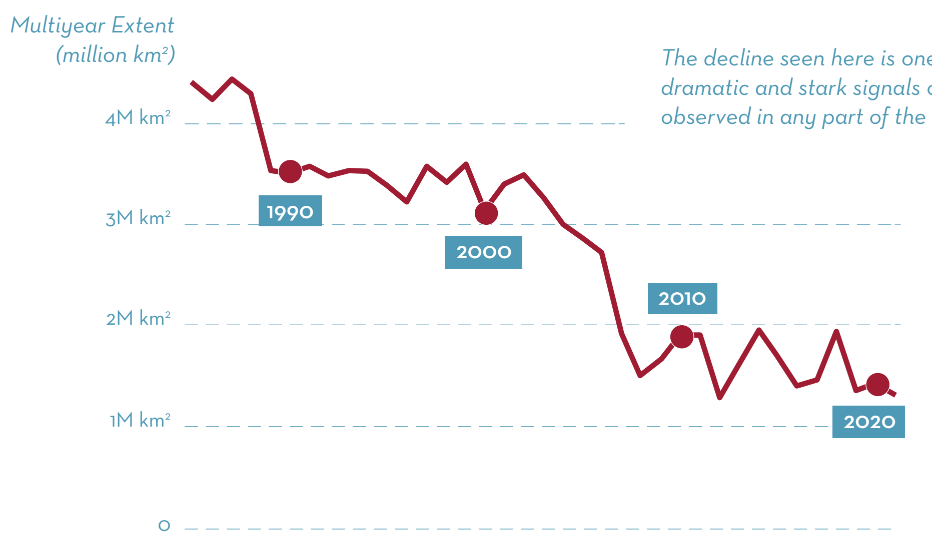
Arctic sea ice thickness change

Between 2010 and 2023 measured by CryoSat-2



Decline of multi-year sea ice (older than one year)

Since 1984 as measured by a suite of microwave imaging satellites



ISSUE

The Arctic is experiencing a climate crisis like no other, warming four times faster than the global average since the early 1980s. Central to this is the dramatic decline of sea ice, which plays a vital role in regulating the exchange of heat, moisture, and gases between the ocean and atmosphere. This thin ice layer, often described as the "poster-child" of climate change, is shrinking rapidly, underscoring the human impact on the climate system. Yet, this vast region, covering up to 2016 million square kilometres at its peak, has long been challenging to monitor due to its remoteness and extreme conditions.

DISCOVERY

Before the launch of advanced satellite systems, our understanding of Arctic sea ice was limited to surface area measurements, primarily from passive microwave radiometers. While these observations tracked the ice's extent, they couldn't provide the critical data on ice thickness, a key factor in determining how much thermal insulation the ice offers and its role in climate processes. That all changed in 2010 with the launch of ESA's CryoSat-2, which began offering unprecedented coverage of the Arctic, including detailed measurements of ice thickness using a novel radar altimeter system. Alongside CryoSat-2, the SMOS satellite has provided complementary data on thin ice, together offering a comprehensive picture of Arctic sea ice changes that was previously unattainable.

To see the most dramatic effects of the climate crisis, we should look no futher than the Arctic, as it is warming 4 times faster than the rest of the globe. For such a hostile environment, we require sophisticated satellites, such as those produced by ESA, to closely monitor this bellwether region.

IMPACT

The ability to measure both sea ice extent and thickness has transformed our understanding of the Arctic's evolving role in climate systems. Over the past decade, data from these satellites has shown a significant thinning in multi-year ice across the western Arctic, with some regions losing thickness at rates of up to 1.5 meters per decade. These data are crucial for refining global and regional climate models, which rely on accurate ice thickness to simulate energy, moisture and momentum exchanges between the atmosphere and ocean. More than just a scientific breakthrough, these observations carry vital implications for predicting the Arctic's future, including the potential for a "Blue Ocean" event, when the Arctic Ocean could become ice-free, profoundly altering global climate patterns and impacting industries like shipping and fishing.

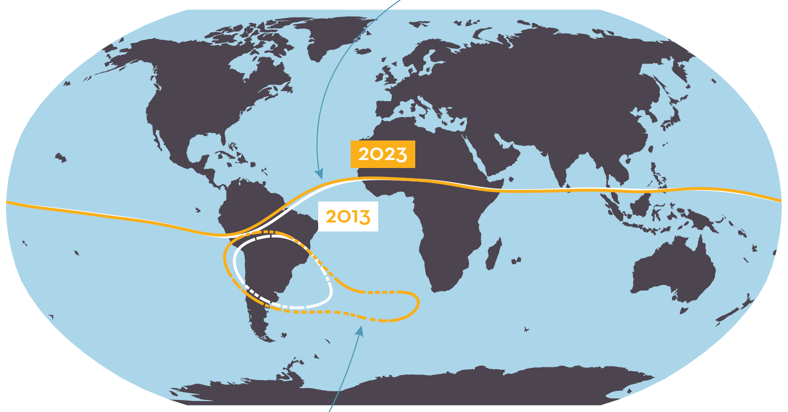
2.3 Tracking Earth's Magnetic Shifts

Safeguarding Technology and Navigation with ESA's Swarm

SWARM

Earth's magnetic field vitally protects us from dangerous cosmic radiation, but varies as a function of time, including a switch of the location of the North and South magnetic poles every 250'000 years or so. We need to be aware of when to expect this, as it will change the way our satellite, location, and communication systems function. ESA's Swarm mission does just this.

South Atlantic anomaly



Westward movement of the magnetic equator of 42 km per year

Increase of the area with the lowest magnetic field intensity over that region between 2013 and 2023

ISSUE

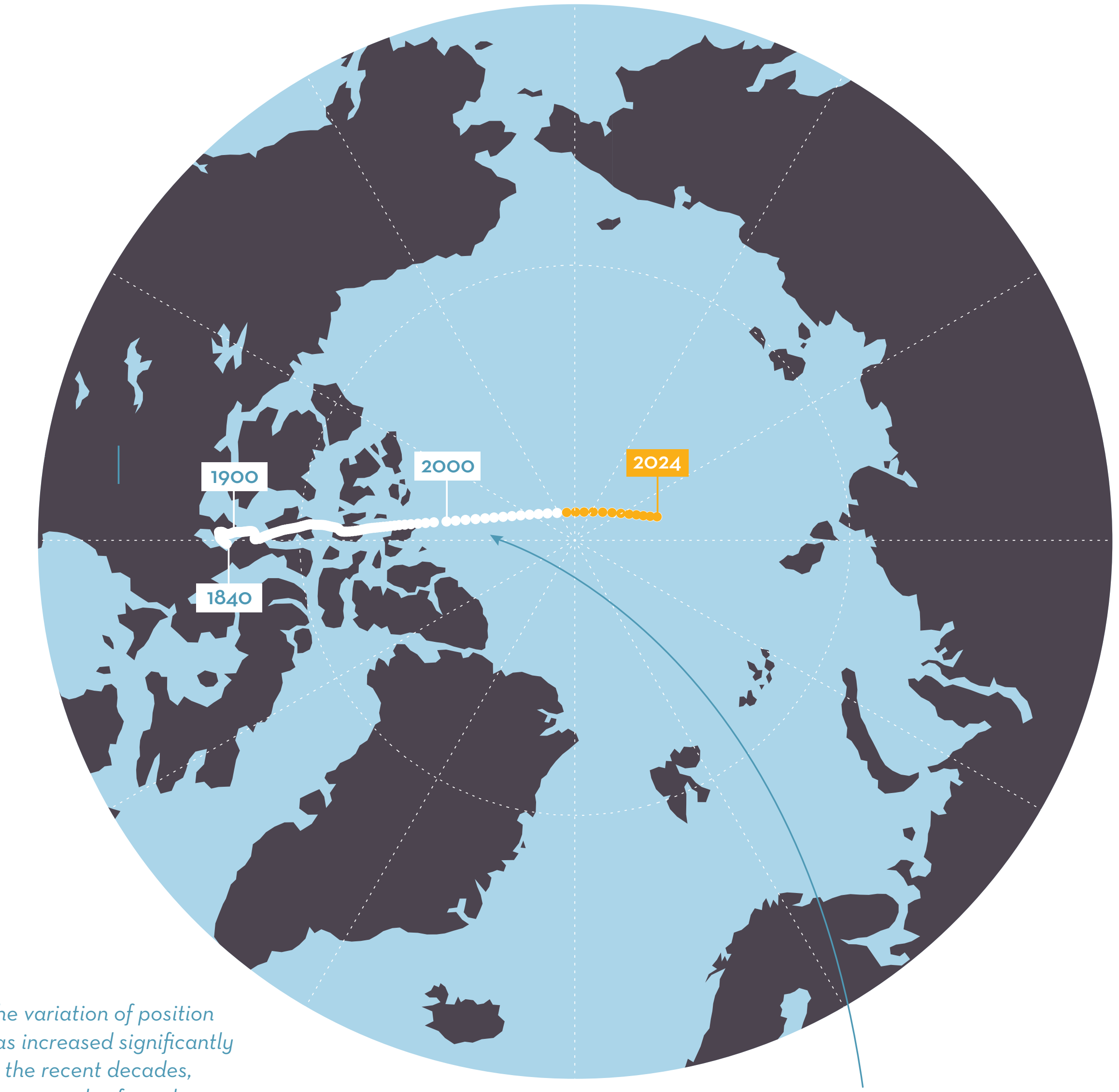
Earth's magnetic field, a powerful and dynamic force, plays a critical role in protecting life on our planet from harmful cosmic radiation. This radiation poses risks to human health, disrupts satellite systems, and can affect electronics and infrastructure such as aviation positioning. However, the field is constantly changing as the North pole is shifting significantly. These changes affect everything from navigation systems, used by organisations like NATO, to our everyday smartphone applications. Thanks to Earth observation satellites like the Swarm mission, we now have unprecedented insight into the behaviour of the Earth's magnetic field, enabling us to track these shifts with precision and accuracy.

DISCOVERY

Before the launch of dedicated satellites like Swarm, measurements of the Earth's magnetic field were limited to data gathered from ground-based observatories, which only provided accurate readings in regions with high coverage, such as North America and Europe. In contrast, satellite missions now offer a global perspective on geomagnetic dynamics, overcoming gaps in data from poorly covered areas. The combination of satellite and ground-based measurements has made it possible to map the movements of the magnetic poles and better understand the complex forces at play beneath the Earth's surface, such as the behaviour of liquid iron in the core. Notably, Swarm's data and numerous others have provided insights into the jet stream of liquid iron driving the acceleration of the magnetic North pole, now moving at a speed of 50-60 km per year. The ability to track this dynamic process provides invaluable information to better predict how these changes will impact life on Earth, particularly in areas where navigation and geospatial data are essential.

Wandering of the magnetic North

○ *historical land surveys*
● *using Swarm satellite data since 2014*



The variation of position has increased significantly in the recent decades, from speeds of 0-15 km per year in the past to current speeds of 50-60 km per year.

The magnetic North Pole has wandered more than 2500 Km from Northern Canada to the Arctic Ocean since the first measurement in 1840.

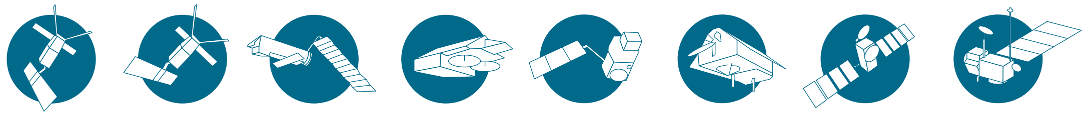
IMPACT

Scientific results obtained with Swarm data directly influences global navigation. For instance, the World Magnetic Model, used by billions around the world for GPS and navigation, now incorporates data from Swarm to ensure its accuracy. This model is critical for military, aviation, and maritime operations and requires constant updates to ensure precision. Additionally, the insights provided by the satellites into ionospheric and magnetospheric currents are improving predictions for space weather, offering vital information for satellite communication and aviation safety. This continuous, high-quality data stream from Swarm is not just a scientific breakthrough but a critical tool for enhancing global safety, operational efficiency, and our understanding of Earth's dynamic system.

3 Oceans

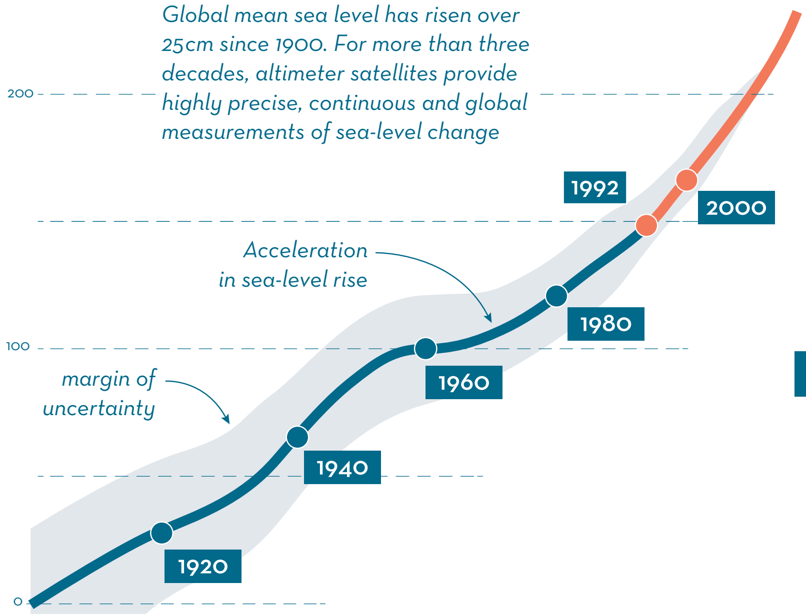
Rising Threats

Revealing Sea-Level Rise with Altimeter Satellites



Global mean sea level

mm



SATELLITE ALTIMETRY

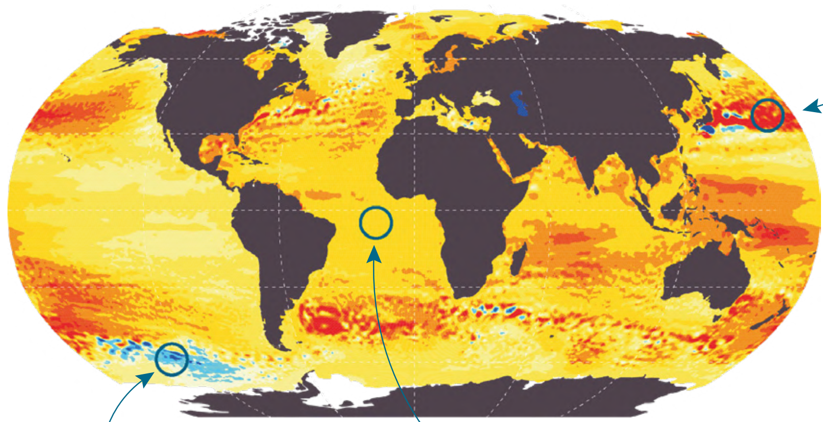
Satellite altimetry has revealed that sea level has risen faster in some regions (like the Tropical Pacific and the Indian Oceans) than in others in the last decades with already visible negative impacts on low-lying, highly populated coastal regions.

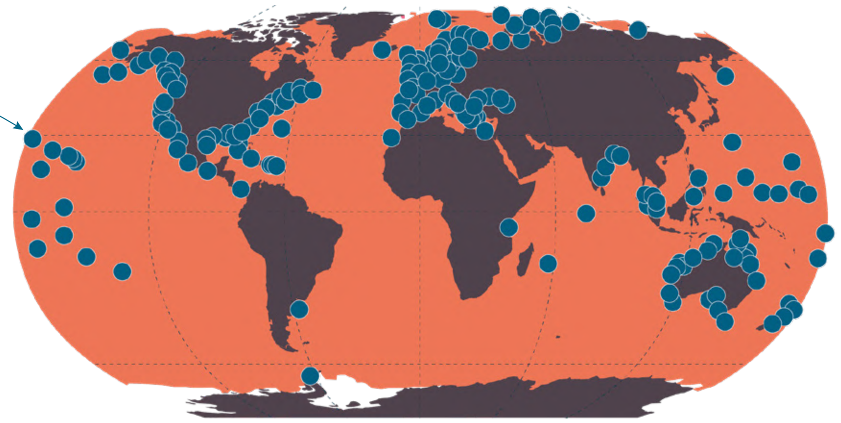
TIDES GAUGES

Unlike satellite altimetry, tide gauges cover only part of the world oceans, mostly in the northern hemisphere. But the few long records available provide useful historical information on past sea-level trends.

Regional sea-level trends

january 1993 - june 2024





Measurements of sea-level change across history have been limited to just some continental coasts, with large parts of our oceans not sampled. With the advent of satellites, we can now see the threatening reality of sea-level rise at planetary scale.

ISSUE

Long before the satellite age, sea-level changes were tracked by tide gauges along the coasts. These instruments provided precise, but only localised, measurements of how the sea level changed relative to the land. The limited and uneven geographic distribution of tide gauges made it challenging for scientists to estimate global sea-level rise across the world's vast oceans. As time marched on, and our climate began to warm, the clear scientific imperative was to develop a method of accurately mapping the worldwide sea levels.

DISCOVERY

The introduction of high-precision satellite altimetry in the early 1990s revolutionised our understanding of the oceans by providing continuous, near-global observations of sea level with remarkable precision and accuracy. The launch of NASA-CNES's TOPEX/Poseidon in 1992, followed by Jason-1, 2, 3 and Sentinel-6 missions, enabled routine monitoring of global sea level rise, revealing an average increase of over 3.4 mm per year with evidence for acceleration. Together with the ESA's complementary altimetry missions, they uncovered a critical finding: sea-level rise is uneven, with some regions, like the western tropical Pacific, experiencing rates up to three times faster than the global average—a trend that threatens low-lying tropical islands.

IMPACT

Over the past three decades, global sea levels have risen by more than 10 cm, with the annual rate now surpassing 4 mm due to ocean warming and land ice melt driven by greenhouse gas concentrations. By combining satellite records with tide gauge data, scientists have traced the acceleration in sea-level rise back to the late 1960s, well before satellite monitoring began. As seas continue to rise faster, the implications for coastal communities, infrastructure, and ecosystems are profound. Understanding the pace and drivers of sea level rise is essential to grasp how ice sheets, glaciers, and ocean waters are responding to climate change.

3.2

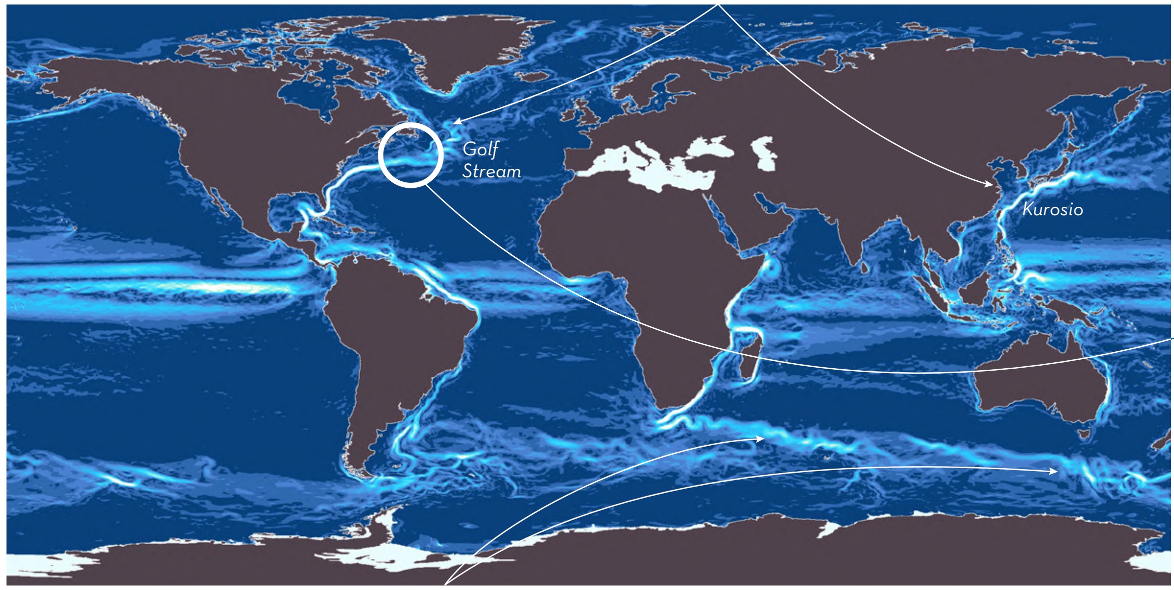
Mapping Ocean Surface

Unlocking the Secrets of Ocean Circulation with High-Resolution Satellites

GOCE SMOS

Ocean Circulation

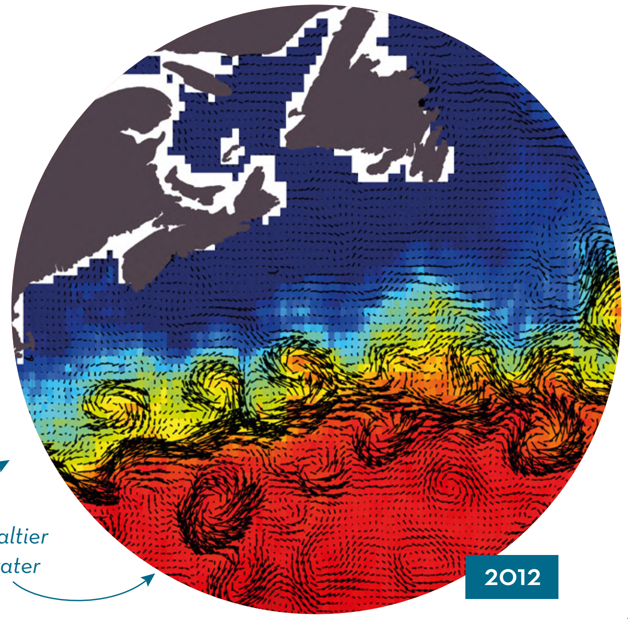
Western boundary currents are prevailing features



Examples of large scale wind-induced ocean circulation

Gulf Stream "Meanders"

Surface currents from altimetry and salinity from the SMOS satellite mission

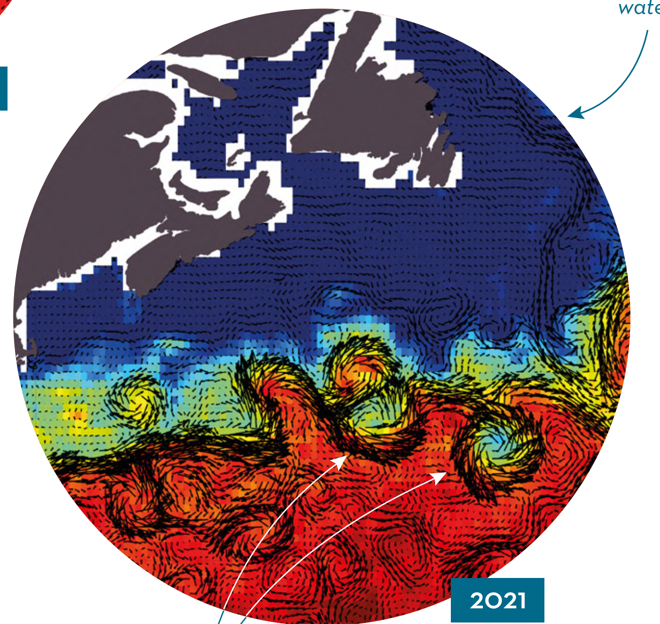


Saltier water

Surface dynamic topography allows calculating the complex structure of the Gulf Stream, the ocean current that transports immense amount of heat from the tropics to high latitudes in the North Atlantic.

Advances in satellite technology have revealed how precise measurements of sea surface topography—when combined with Earth's gravity field—unveil the intricate, global patterns of ocean currents, deepening our understanding of ocean circulation and its impact on climate and marine ecosystems.

Less salty water



The Gulf Stream consists of a succession of meanders of a few hundreds km size and a few months lifetime.

ISSUE

Before satellites orbited our skies, our understanding of the sea's movements was piecemeal, relying on fragmentary data from ships and buoys. Beneath and at the ocean surface lies a complex interplay of currents, driven by temperature, wind, and Earth's rotation. To fully understand these movements, scientists needed to measure the ocean's dynamic topography—the subtle differences in sea surface height relative to Earth's geoid, a mean shape influenced by gravity that varies across the planet.

DISCOVERY

The speed and direction of surface currents are determined by the slope of this topography. Mapping it with altimeter satellites unveils powerful currents like the Gulf Stream and Kuroshio, while revealing deeper ocean circulations that impact global climate. Using satellite data to chart both sea surface height and the geoid with remarkable accuracy has revolutionized our knowledge of ocean currents and eddies. This challenge indeed required nothing short of a revolution in space-borne gravity observation. ESA's Gravity and Steady-State Ocean Circulation Explorer (GOCE) mission, launched in 2009, was that revolution, transforming our ability to measure Earth's gravity field to unprecedented accuracy. When combined with satellite altimetry, GOCE mission opened an unprecedented window onto the patterns and flows of ocean currents, illuminating them with newfound clarity.

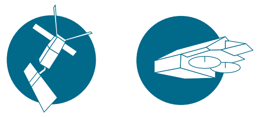
IMPACT

This detailed mapping of global ocean circulation has profound implications—enhancing weather forecasts, deepening climate insights, and supporting everything from commercial navigation to fishing and emergency response in environmental crises like oil spills. On a larger scale, ocean mapping also fine-tunes GPS calibration, critical for satellite navigation. With missions like GOCE, we've uncovered a hidden world, bringing us closer to understanding the vast forces that shape our oceans, our climate, and our shared future.

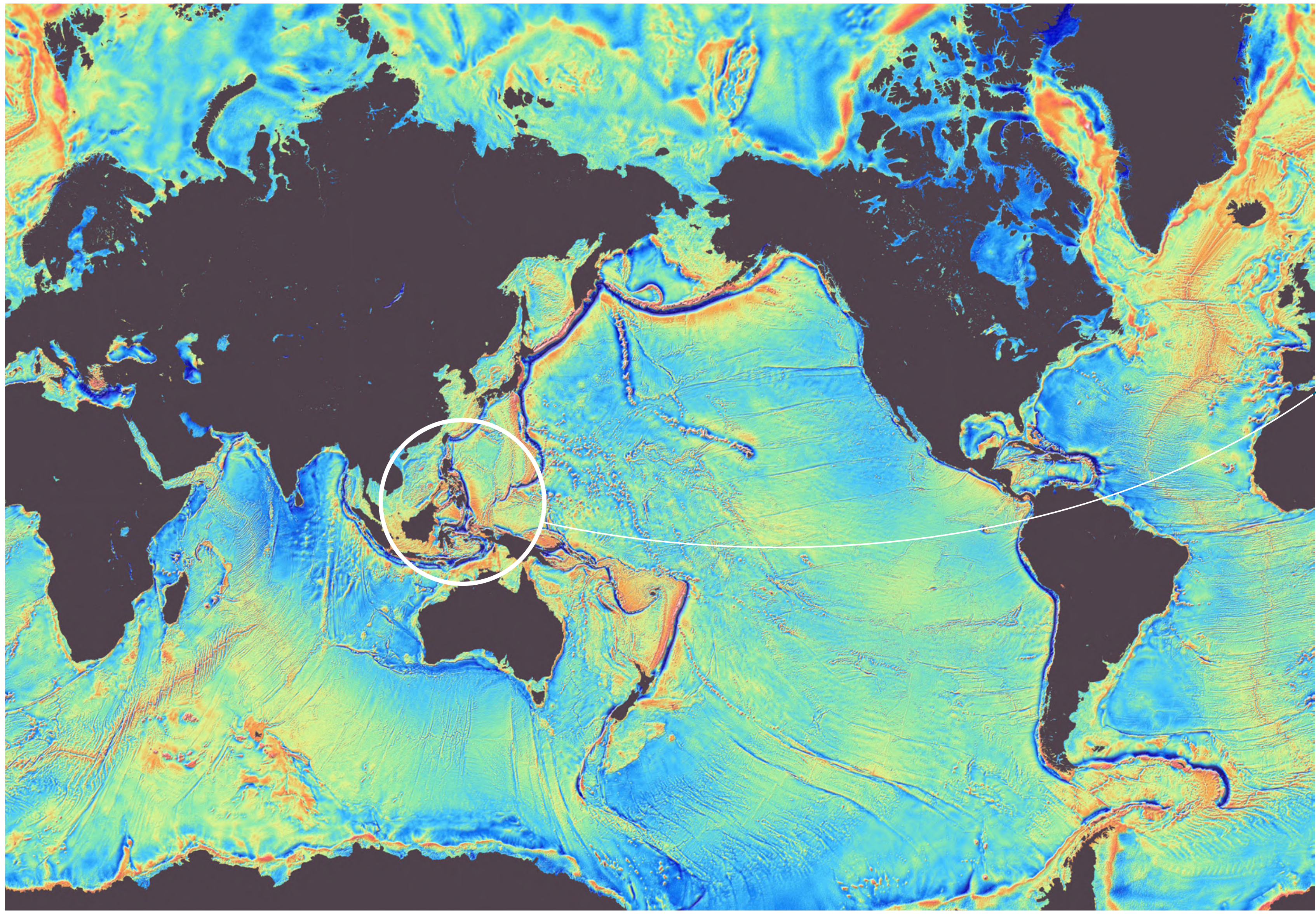
3.3

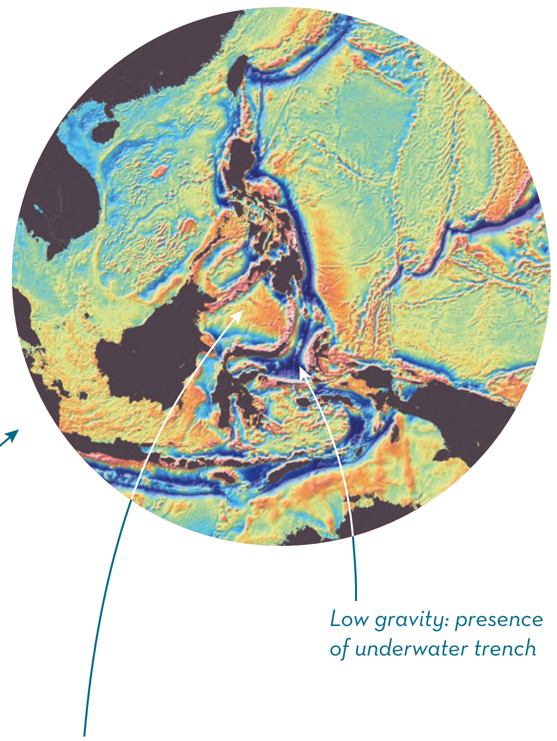
Beneath the Ocean Surface

Mapping the Ocean's Hidden Depths with Satellite Altimetry



Altimetry-based
Earth gravity map





ISSUE

Earth's vast ocean surface has two key components: a stable "base topography" shaped by Earth's gravity, featuring broad, stationary highs and lows, and a time-variable component, influenced by tides, currents, and changing sea levels. The stable features, which undulate up to 100 meters over large distances, mirror Earth's gravitational variations, influenced by mantle processes and seafloor topography. Until the mid-1990s, seafloor topography mapping (or bathymetry) depended on limited ship-based sonar surveys, leaving large areas, especially in the Southern Hemisphere, largely unmapped. Accurate seafloor topography mapping supports marine geophysical sciences, submarine navigation, deep-sea resource exploration, and submarine cable routing.

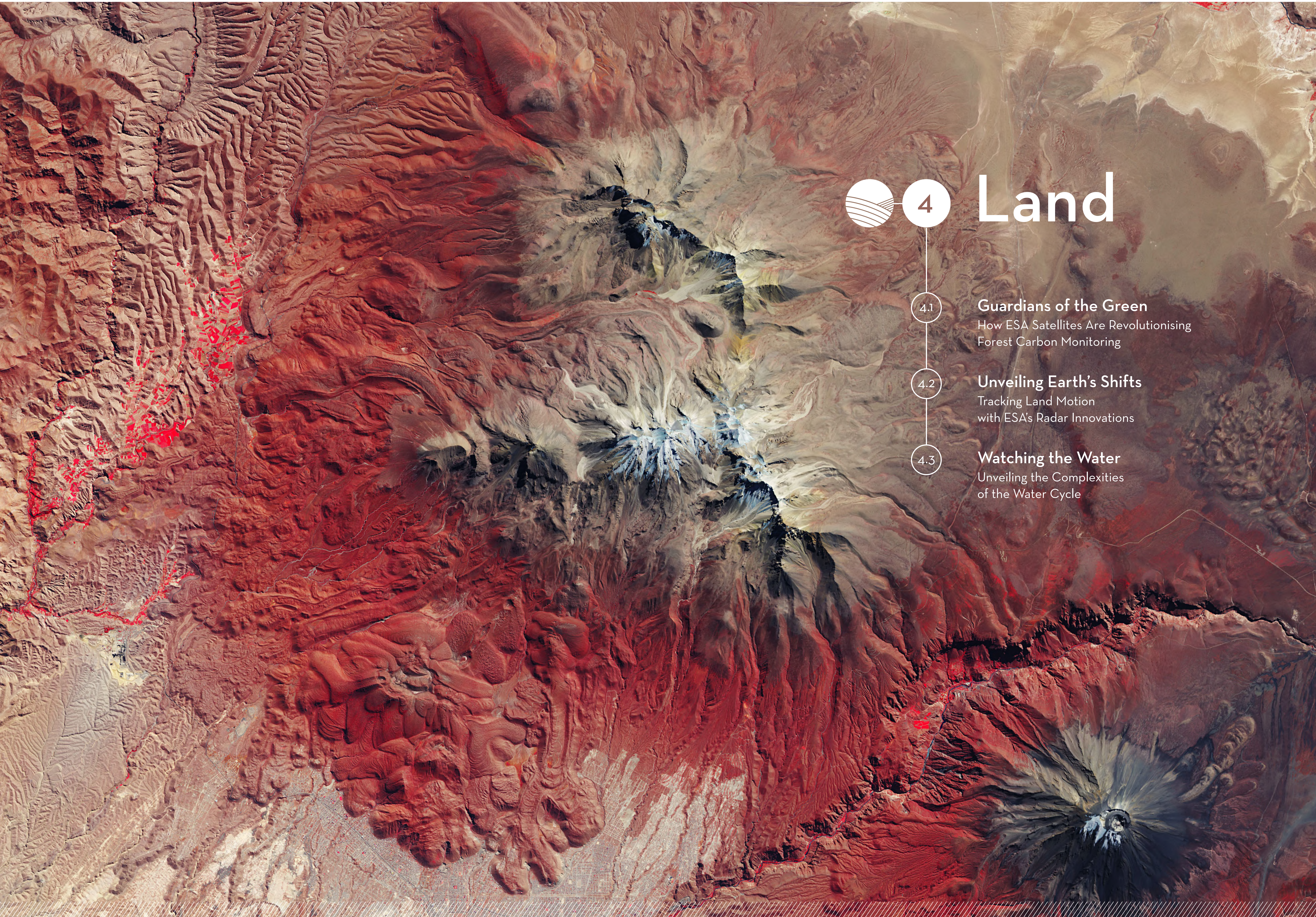
DISCOVERY

ESA's ERS-1 satellite, launched in 1991, revolutionised seafloor mapping by using a radar altimeter to capture sea surface topography across the globe. By shifting ERS-1 to a drifting orbit in 1994-1995, scientists mapped the permanent sea surface topography at unprecedented resolution. Combining ERS-1 data with the U.S. Navy's GEOSAT satellite data, they created the first detailed, altimetry-based global bathymetric maps, a process later advanced by ESA's CryoSat-2 in 2010, which mapped seafloor features down to 2.5 km ground resolution. Together with data from NASA-CNES's Jason-1 mission, CryoSat-2 produced the sharpest view of the ocean floor yet, highlighting complex seafloor features.

Despite electromagnetic waves being unable to penetrate the ocean, satellite technology has finally revealed Earth's last frontier, mapping the ocean floor with unprecedented detail—from towering seamounts to ancient tectonic scars—and transforming both scientific understanding and practical uses for this hidden landscape.

IMPACT

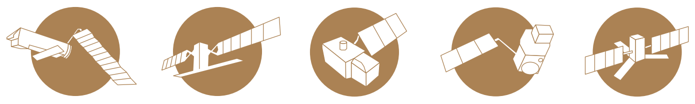
Decades ago, satellite altimetry revealed an unexplored world beneath the ocean surface, uncovering thousands of previously unknown submarine volcanoes and ancient tectonic remnants. These high-resolution seafloor maps have far-reaching applications, supporting safe navigation, efficient fisheries management, and exploration of marine resources, in addition to marine geology and geophysics. Satellite-driven insights into this hidden landscape have transformed our understanding and use of Earth's submerged realms.



4 Land

Guardians of the Green

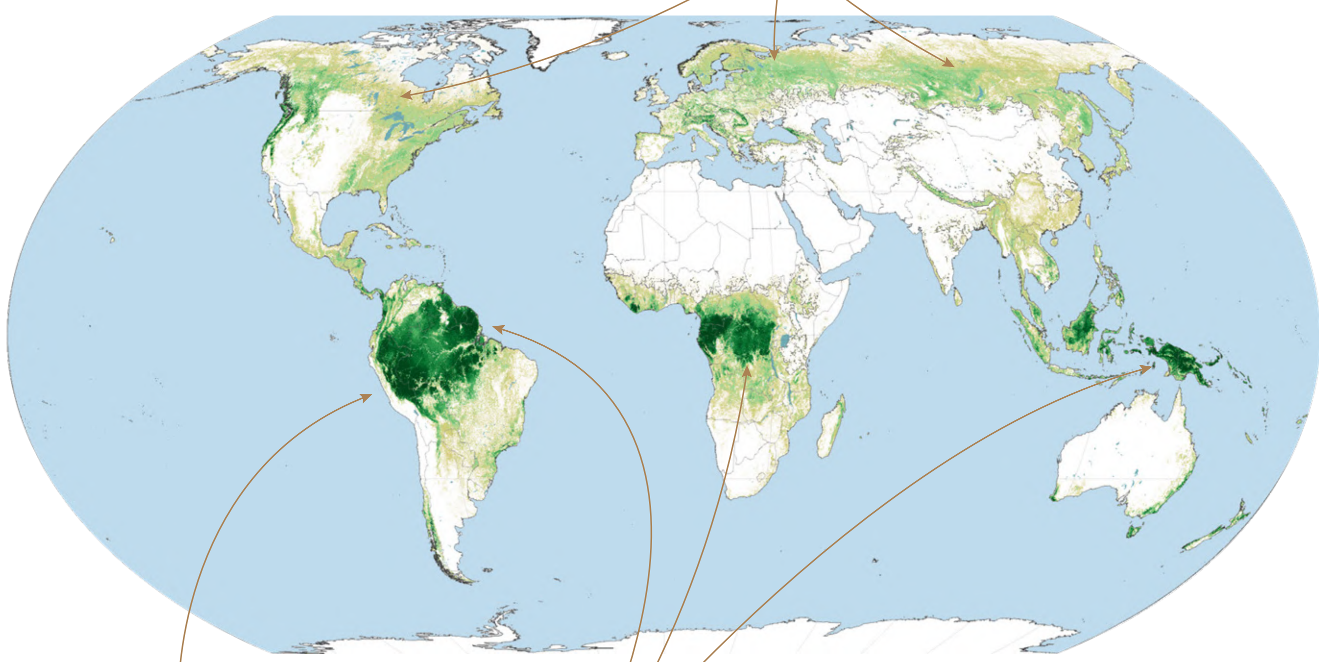
How ESA Satellites Are Revolutionising Forest Carbon Monitoring



ESA's satellites are transforming our understanding of forests, revealing their vital role in the carbon cycle and equipping us to monitor the health of these "green lungs" of the planet in the fight against climate change.

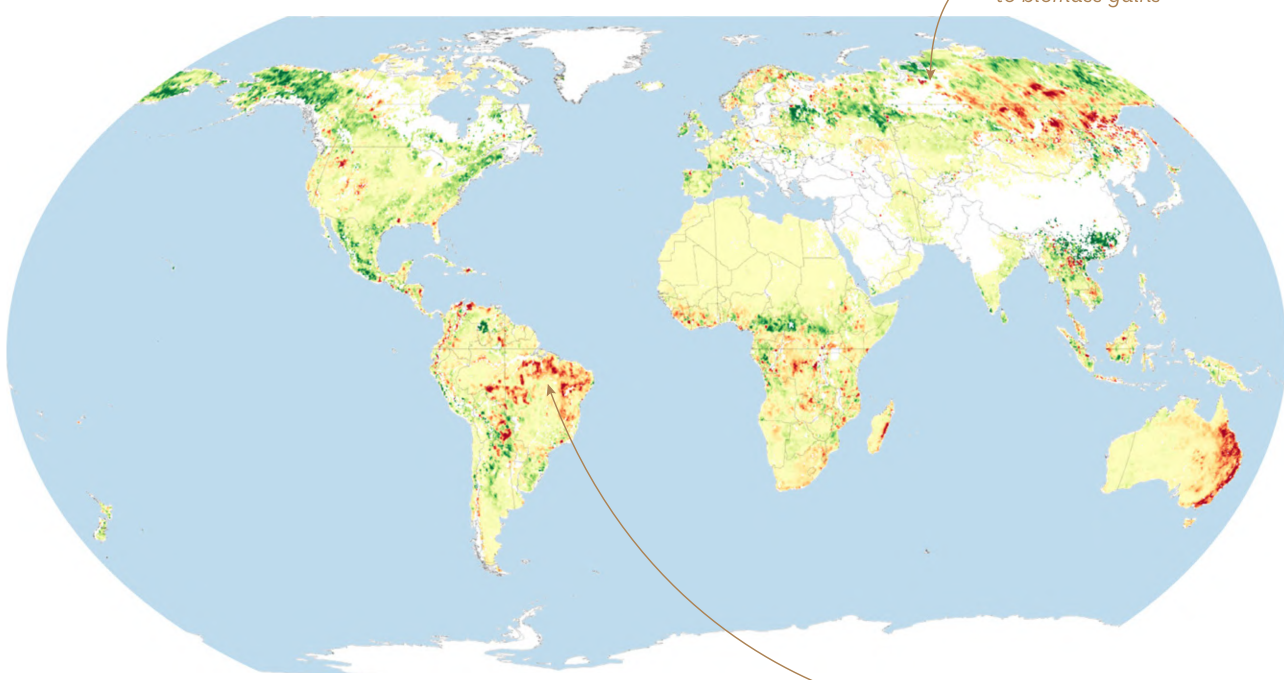
Above Ground Biomass

2020



Biomass changes

2010-2019



ISSUE

Forests absorb about 8 gigatonnes of carbon dioxide annually, weaving themselves into the planet's carbon cycle and stabilising its climate. Yet these carbon stores are perilously close to becoming carbon sources as fires, deforestation, and land degradation—especially in tropical regions—release vast amounts of stored carbon back into the atmosphere, fuelling climate change. To grasp the full scope of this delicate balance, we need constant, precise data, far beyond what ground-based methods alone can provide.

DISCOVERY

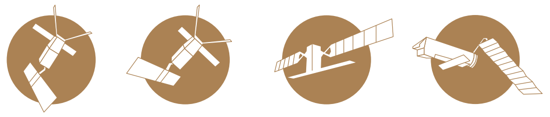
ESA's satellites—Envisat, Sentinel-1, and Sentinel-2,—have been reshaping our view of the world's forests, painting detailed, high-resolution maps that reveal forest growth, biomass, and carbon storage with unparalleled clarity. The SMOS satellite has shown that young and middle-aged forests are the most active carbon absorbers, while older forests are close to carbon-neutral. Satellite-based microwaves can even penetrate thick cloud cover, allowing Sentinel-1 to track disturbances in tropical forests on a 6–12-day cycle, an invaluable tool for detecting subtle changes due to small-scale agriculture and logging.

IMPACT

With the launch of ESA's Biomass satellite set for 2025, the future of forest monitoring promises to be more insightful than ever. Using breakthrough radar technology, Biomass will measure not only the towering forest canopy but also the trunks, branches, and even leaves, capturing the full scope of a forest's carbon potential. As these instruments sharpen our understanding of forest dynamics, they will reveal new insights into the global carbon cycle, enriching our stewardship of the planet's green lungs as they breathe, grow, and change.

4.2 Unveiling Earth's Shifts

Tracking Land Motion with ESA's Radar Innovations



ESA's advanced radar satellites reveal Earth's subtle movements, transforming how we monitor tectonic shifts, resource-driven subsidence, and urban stability, ensuring a safer, more informed future.

ISSUE

The Earth's surface is in a state of perpetual motion, shifting and settling in response to natural forces like tectonic shifts and volcanic activity, as well as human actions such as mining and groundwater extraction. These subtle but far-reaching movements can alter landscapes, affect infrastructure, and disrupt ecosystems. Yet, tracking these shifts with traditional ground-based methods, such as GPS or topographic surveys, remains limited, providing only fragmented snapshots of change and leaving much of the broader dynamics of land deformation unexplored.

DISCOVERY

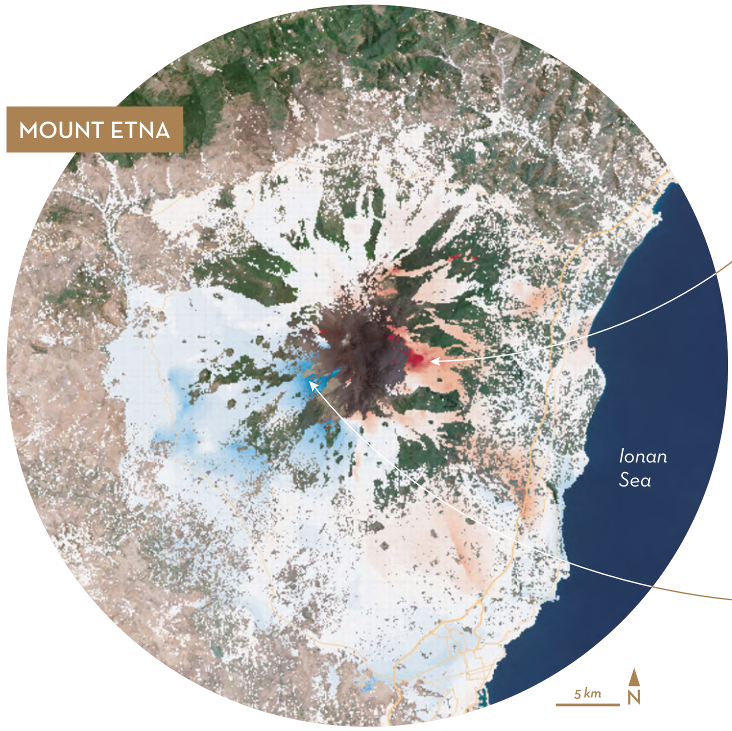
ESA's advances in Synthetic Aperture Radar (SAR) interferometry, beginning with the ERS-1 and ERS-2 missions in the 1990s, revolutionised our ability to measure land motion from space. Techniques like Permanent Scatterers (PS) and Small Baseline Subset (SBAS) emerged, offering precise monitoring of ground shifts as slight as 1 mm per year. The innovative SqueeSAR algorithm later unified these methods, improving our ability to map deformation at fine scales across expansive areas. Today, Sentinel-1's SAR data has brought these capabilities to an operational level, enabling the European Ground Motion Service (EGMS), a public resource that provides insights into subsidence and land shifts across Europe.

IMPACT

By using radar interferometry, ESA satellites can now detect minuscule ground movements with remarkable precision, allowing scientists to monitor even millimetre-scale changes. This capability has significant applications, from tracking seismic and tectonic activity to mapping subsidence caused by resource extraction, all of which have direct implications for urban planning, resource management, and public safety. With EGMS, Europe now has a powerful tool to visualise land deformation over time, transforming our understanding of the shifting Earth beneath us and enhancing our ability to adapt to these subtle yet impactful changes.

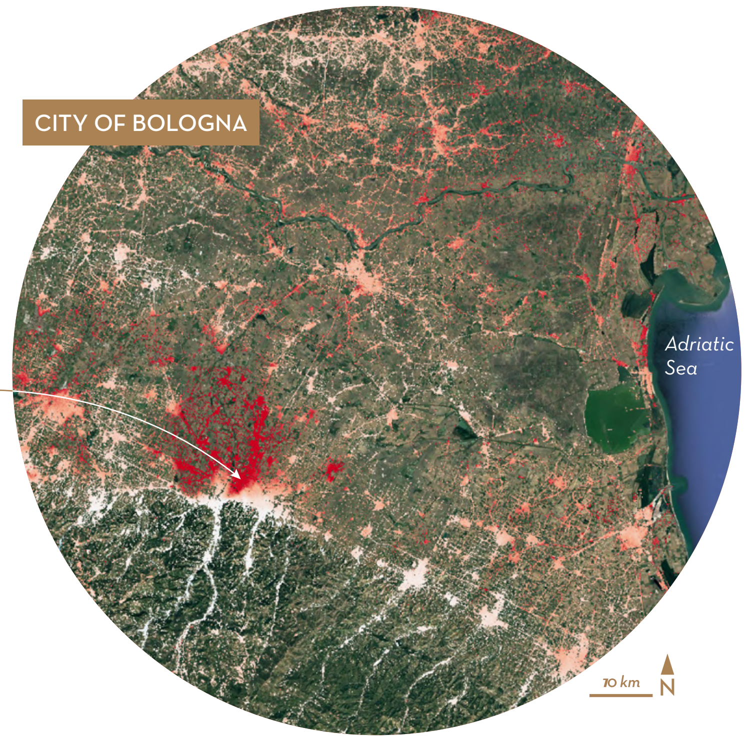
Rate of ground displacement around Mount Etna and surroundings

Italian island of Sicily between 2015 and 2020



Land subsidence rate in Bologna and surrounding areas

North Italy, between 2019 and 2023

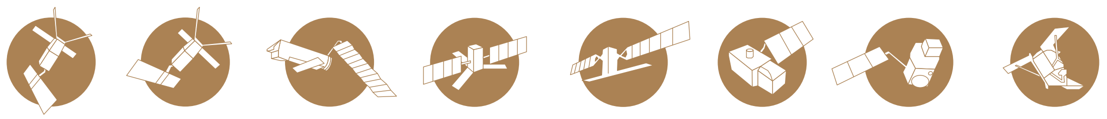


4

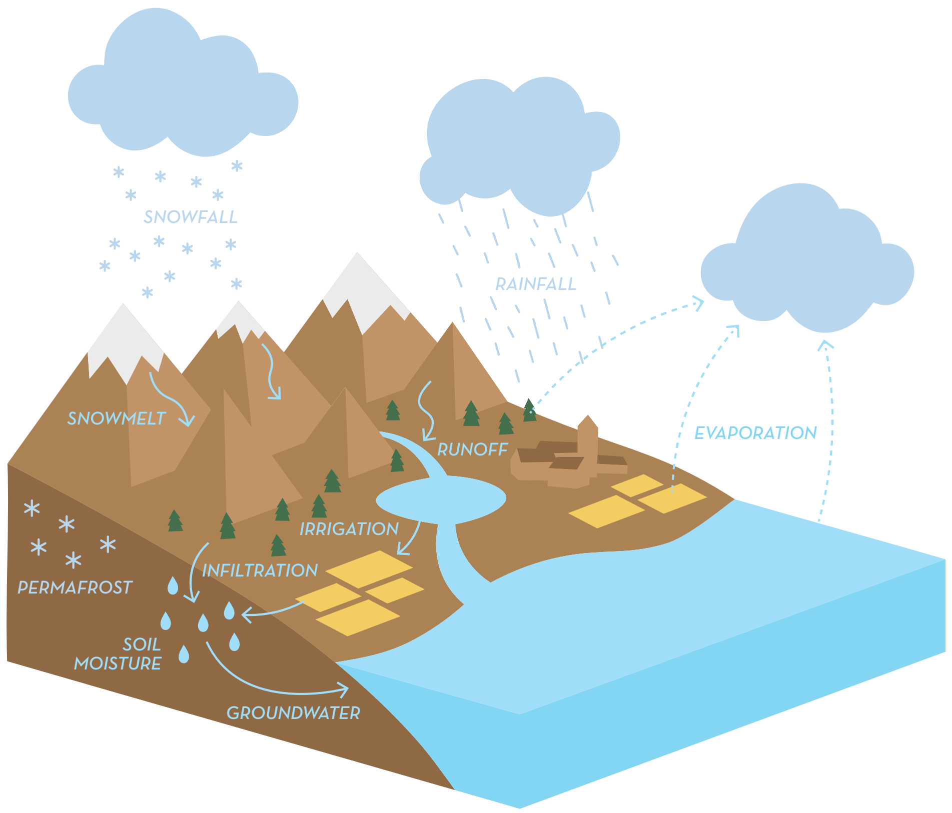
4.3

Watching the Water

Unveiling the Complexities of the Water Cycle



Water Cycle

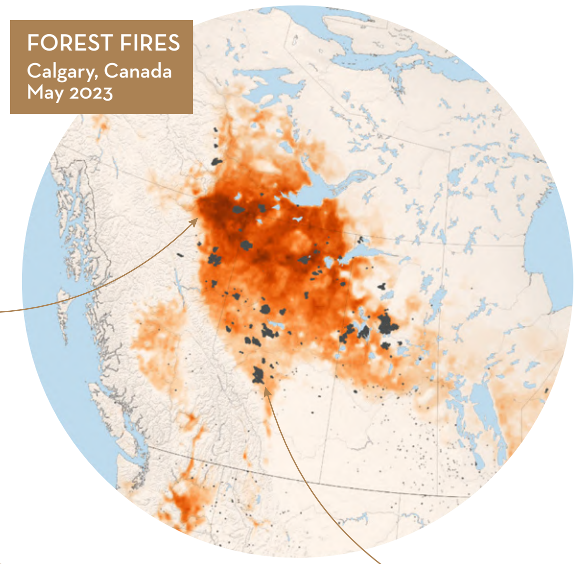


ESA's satellite missions, including ERS-1, ERS-2, ENVISAT, SMOS, Sentinel-1, Sentinel-2, Sentinel-3, and Sentinel-5P, have revolutionised our understanding of the water cycle by providing global insights into soil moisture, flooding, and irrigation. Through high-resolution data integration, ESA has created virtual models—Digital Twins—empowering planners to better manage water resources and prepare for future climate scenarios.

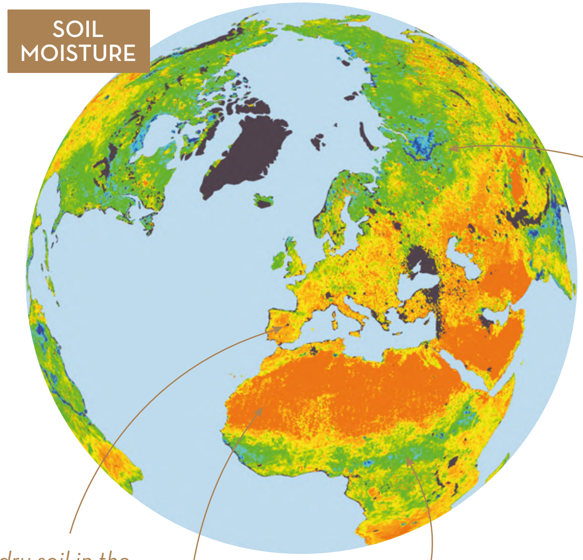
ISSUE

The water cycle, fundamental to life and a key regulator of our climate, is still not fully understood, particularly in relation to extreme events such as droughts and floods. Traditional monitoring of the water cycle has relied heavily on ground-based measurements, which are often limited in coverage and struggle to account for human-driven changes like irrigation. Meanwhile, hydrological models face uncertainties, especially in data-scarce regions, leaving gaps in our knowledge about the global dynamics of water.

High probability of fire occurrence for enery day of the month. The probability of fire occurrence index considers the avaibility of fuel and soil dryness from SMOS data, on top of classical indicators.



Fire hotspots

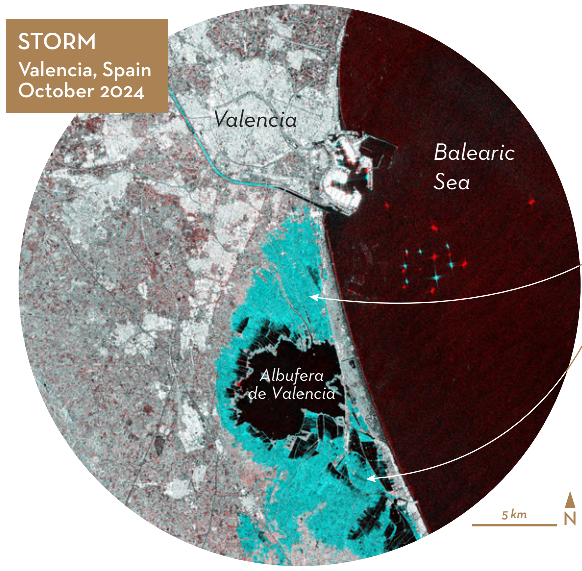


flooded areas

dry soil in the Mediterrenean

tropical wet region during monsoon

Sahara desert



Flood

DISCOVERY

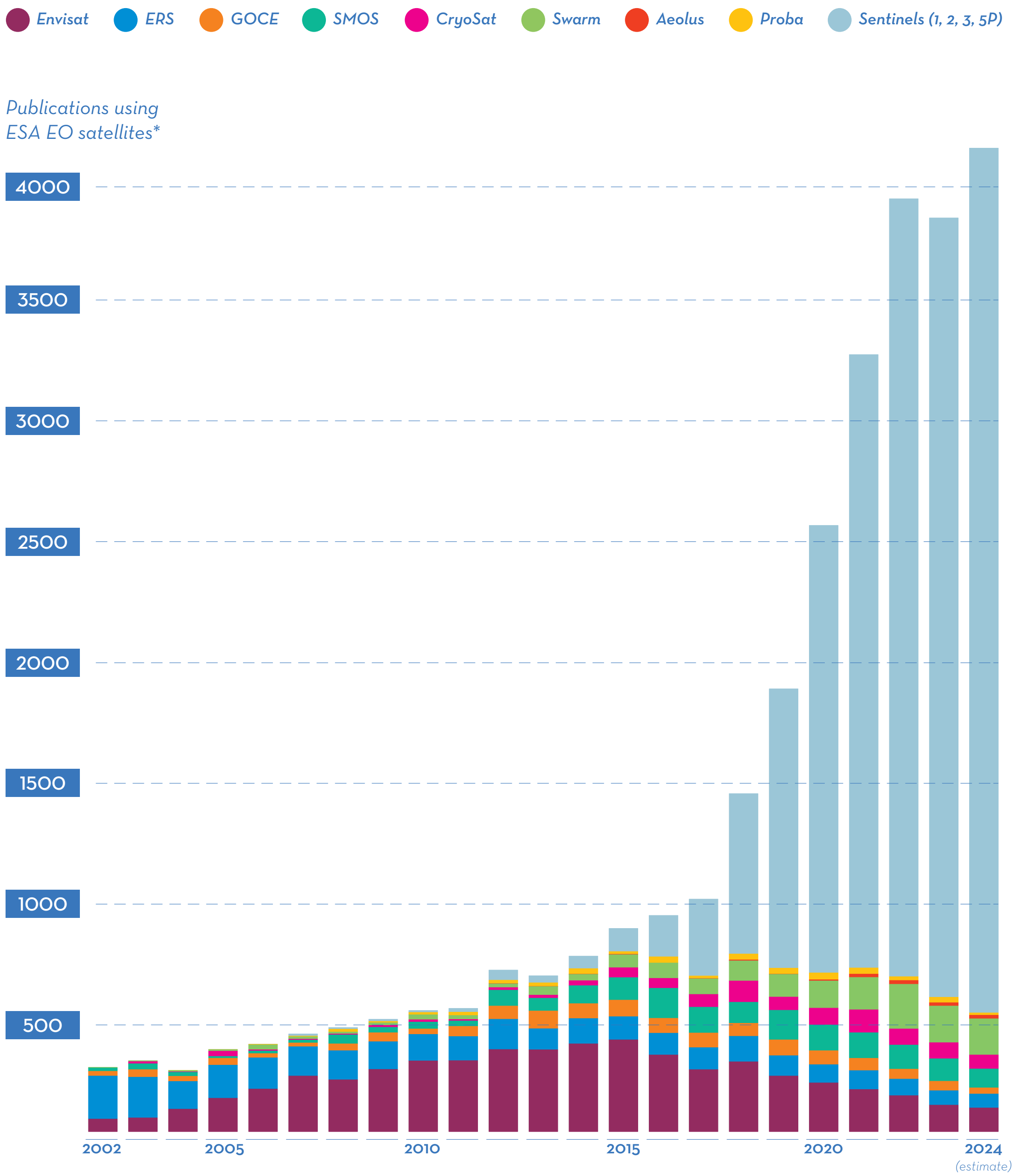
By integrating data from Sentinel -1 and -2, as well as Sentinel-3 and -S5P to retrieve evapotranspiration, ESA has created a profound shift in our ability to observe and understand the water cycle on a global scale. The SMOS mission, launched in 2009, became the first satellite dedicated to measuring soil moisture from space, enabling scientists to monitor water in soil across large areas, improve drought, forest fire, and flood forecasting, and assess the impact of intensive irrigation. Complementary data from Sentinel-1 and Sentinel-2 have transformed our capacity to assess flood impacts, allowing detailed mapping of flood extents and the resulting alterations to landscapes across Europe.

IMPACT

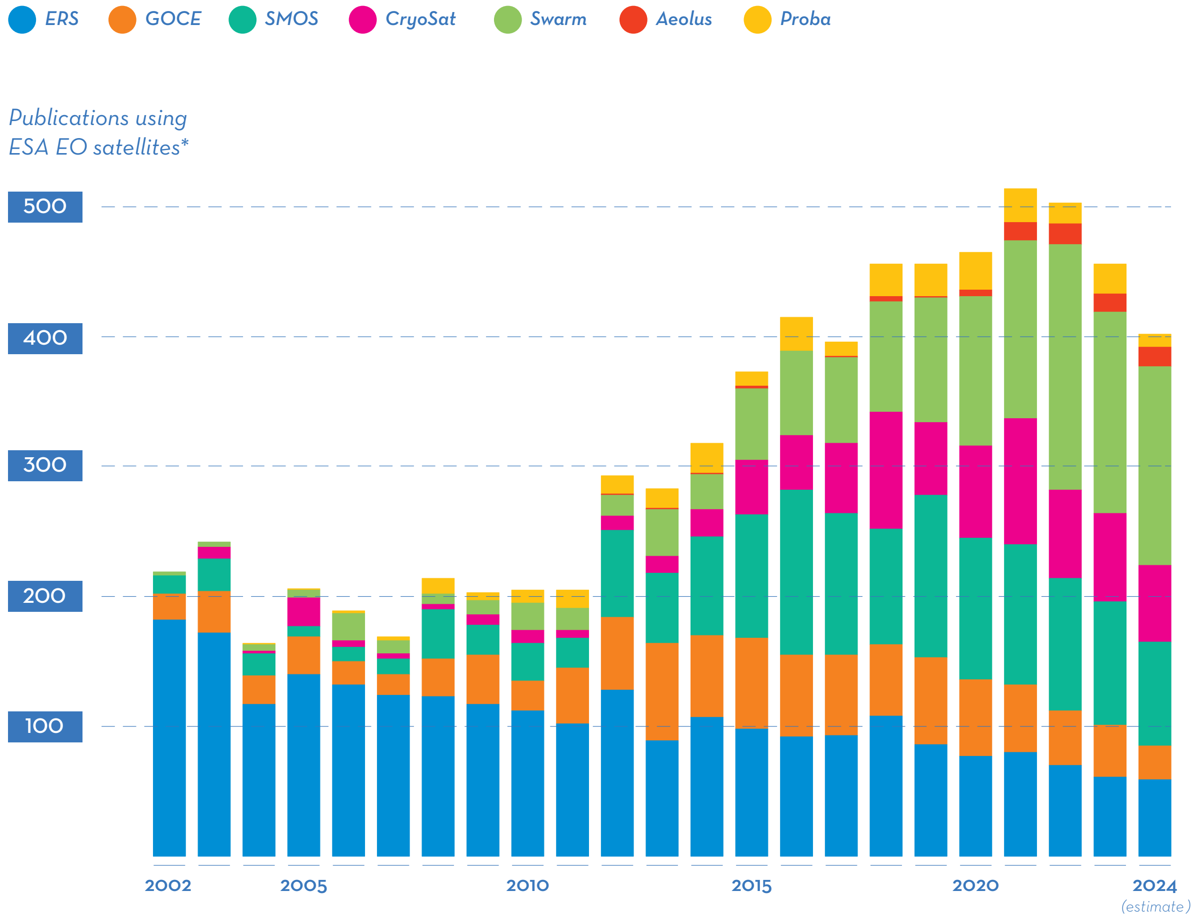
Integrating data from Sentinel missions 1, 2, 3, and 5P, ESA has created high-resolution reconstructions of the water cycle, offering unprecedented insights into precipitation, soil moisture, evaporation, irrigation, and river discharge. Within initiatives such as ESA's WACMOS-MED, 4DMED and DTE-Hydrology, these virtual models of the water cycle serve as essential tools for planners, enabling them to simulate future scenarios, design targeted interventions, and explore critical data. These "Digital Twins" of the water cycle represent a breakthrough in our quest to understand and manage Earth's precious water resources effectively.

Science Publications Using ESA Earth Observation Satellite Data

Number of Peer-reviewed Publications using ESA EO Satellites since 2002



Number of Peer-reviewed Publications using Earth Explorer missions only



*Figures courtesy of ESA, based on metrics derived from Elsevier Scopus database

According to statistics provided by ESA, over 4,000 scientific publications utilising ESA and Sentinel satellites have been published in peer-reviewed journals in 2024 alone. While a significant portion of these publications is based on Sentinel measurements, it is important to acknowledge the vast quantity of dataw generated by the Copernicus programme—exceeding 570 PiB (1 PiB = 2^{50} bytes) between the launch of Sentinel-1A in 2014 and October 2023—compared to the comparatively smaller volumes collected by ESA's Earth Explorers, even when including ERS and ENVISAT.

Although Copernicus was not specifically designed to achieve scientific objectives, focusing instead on supporting EU sectoral policies such as fisheries, climate, and agriculture, the Earth science community increasingly leverages these datasets due to their high quality and the long-term perspective offered by the programme.

Nonetheless, the scientific value of data acquired by the Earth Explorers should not be underestimated, as these missions play a pivotal role in demonstrating innovative measurement techniques, retrieval methods, and applications, which are subsequently adopted within the Copernicus programme.

Conclusions

Since the launch of Meteosat-1 in 1977 and ERS-1 in 1991, Earth observation (EO) satellites built by the European Space Agency have been pivotal in various domains. These include pushing forward meteorology, creating innovative applications to tackle societal challenges, supporting disaster relief organisations, and fostering growth in the Earth observation commercial market.

At the core of these developments lies the urgency of a deeper scientific understanding of the Earth and its environment, encompassing the various disciplines within Earth sciences.

This document uses examples from the atmosphere, polar regions, oceans, and land domains of Earth sciences to explain, in straightforward terms, the ground-breaking scientific discoveries enabled by ESA Earth Observation satellites. Special attention has been given to "translating" complex scientific publications into accessible language, complemented by impactful visuals created through collaboration between scientists and professional graphic designers.

In reality, there are far more than the twelve examples presented here. However, our goal was to select a few key cases to highlight, focusing on the issues they address, the nature of the discoveries, and their impact on enhancing knowledge and understanding.

While the Sentinel missions of Copernicus remain the primary source of Earth observation data, ESA's Earth Explorers play a crucial role in boosting scientific understanding and demonstrating innovative science and technology, paving the way for the expansion of future Sentinel satellites and EO national missions.

Worth noting is the fact that examples from neither EarthCARE (launched in May 2024) nor Biomass (launch foreseen early 2025) have been included in this document, but data acquired by these two new Earth Explorers promise to be a source of invaluable information for the atmosphere and land thematic domains.

Many scientific challenges remain, as highlighted in the recent ESA Earth Observation Science Strategy, underscoring the commitment to continue nurturing new Research and Development satellites, including future ESA Earth Explorers and Missions of Opportunity.

With the combined efforts of Earth Explorers, Copernicus, and national EO missions, Europe, has established itself as a global leader in satellite-based Earth observation. Achieving this leadership has relied on pushing the boundaries of science and leveraging cutting-edge technologies to develop innovative EO satellites.

As critical decisions are made about the future of this domain in Europe, it is essential to remember the importance of these advances and the need to sustain progress in this vital field.

Maurice Borgeaud
Panel Chair, Earth Sciences Panel
of the European Space Sciences Committee

References

1 Atmosphere

1.1 Harnessing the Winds

IMAGE CREDITS

Wind speed graphic adapted from ECMWF Newsletter 173 "Aeolus positive impact on forecasts with the second reprocessed" (© Creative Commons Attribution 4.0 International Public License)

BIBLIOGRAPHY

Rennie and Isaaksen, 2024, *The NWP impact of Aeolus Level-2B winds at ECMWF*

Global Wind Energy Council, 2021, *Harnessing the Winds: The Benefits of AEOLUS in Global Forecasting*

European Space Agency, 2020, *AEOLUS: ESA's Wind Mission*

World Meteorological Organization, 2020, *Global Impact of the AEOLUS Satellite on Weather Forecasting*

Dabas, Flamant and Weiss, 2018, *Understanding Doppler Wind Lidar Technology: The AEOLUS Mission*, Journal of Atmospheric Sciences, 75(2), 231-242

1.2 Air Pollution

IMAGE CREDITS

Global average concentration of methane, © FMI (Anu-Maija Sundström), based on TROPOMI data

Methane detection in Algeria, © ESA (Emmanouil Lagoudakis)

BIBLIOGRAPHY

Fisher et al., 2024, *Revised estimates of NO2 reductions during the COVID-19 lockdowns using updated TROPOMI NO2 retrievals and model simulations*

Levelt et al., 2022, *Air quality impacts of COVID-19 lockdown measures detected from space using high spatial resolution observations of multiple trace gases from Sentinel-5P/TROPOMI*

1.3 Our Climate Versus the Super-Emitters

IMAGE CREDITS

Nitrogen dioxide concentration, © ESA (Emmanouil Lagoudakis)

BIBLIOGRAPHY

Schuit et al., 2023, *Automated detection and monitoring of methane super-emitters using satellite data*

Varon et al., 2023, *Continuous weekly monitoring of methane emissions from the Permian Basin by inversion of TROPOMI satellite observations*

Pandey et al., 2023, *Daily detection and quantification of methane leaks using Sentinel-3: a tiered satellite observation approach with Sentinel-2 and Sentinel-5P*

2 Polar Regions

2.1 Mass balance of the Great Ice Sheets

IMAGE CREDITS

Evolution of the Great Ice Sheets, © Otosaka et al., 2023, Surveys in Geophysics (adaptation)

Mass Loss from the Great Ice Sheets, © Otosaka et al., 2023, Earth System Science Data (adaptation)

BIBLIOGRAPHY

Otosaka et al., 2023a, *Mass Balances of the Antarctic and Greenland Ice Sheets Monitored from Space*, Surveys in Geophysics 44, 1615–1652

Otosaka et al., 2023b, *Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020*, Earth System Science Data, 15(4), 1597-1616

Bamber and Dawson, 2020, *Complex evolving patterns of mass loss from Antarctica's largest glacier*, Nature Geoscience, 13(2), 127

Shepherd et al. (2020), *Mass balance of the Greenland Ice Sheet from 1992 to 2018*, Nature, 579(7798), 233-239

Shepherd et al. (2018), *Mass balance of the Antarctic Ice Sheet from 1992 to 2017*, Nature, 558(7709), 219-222

2.2 Arctic Alarm

IMAGE CREDITS

Arctic sea ice thickness change Map, © Landy et al. (2022)

Decline of multi-year sea ice, © Meier et al. (2023)

BIBLIOGRAPHY

Meier et al., 2023, *NOAA Arctic Report Card 2023: Sea Ice*

Landy et al., 2022, *A year-round satellite sea-ice thickness record from CryoSat-2*, Nature, 609, 517-522

Ricker et al., 2017, *A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data*, The Cryosphere, 11(4), 1607-1623

Lenton et al., 2008, *Tipping elements in the Earth's climate system*, Proceedings of the national Academy of Sciences, 105(6), 1786-1793

2.3 Tracking Earth's Magnetic Shifts

IMAGE CREDITS

Wandering of the magnetic North, © ESA (Enkelejda Qamili and Anja Stromme)

South Atlantic anomaly and magnetic equator, © Finlay et al. (2020)

BIBLIOGRAPHY

Livermore, Finlay and Bayliff, 2020, *Recent north magnetic pole acceleration towards Siberia caused by flux lobe elongation*, Nature Geoscience. 13, 387–391

Finlay et al., 2020, *The CHAOS-7 geomagnetic field model and observed changes in the South Atlantic Anomaly*", Earth Planets Space 72, 156

Aubert and Finlay, 2019, *Geomagnetic jerks and rapid hydromagnetic waves focusing at Earth's core surface*, Nature Geoscience,12, 393–398

References

3 Oceans

3.1 Rising Threats

IMAGE CREDITS

Global mean sea level, © Dangendorf, et al. (2019).

Regional sea-level trends, © LEGOS (Anny Cazenave and Lancelot Leclercq)

BIBLIOGRAPHY

Dangendorf et al., 2019, *Persistent acceleration in global sea-level rise since the 1960s*, Nature Climate Change 9, 705–710

Cazenave et al., 2018, *Global sea-level budget 1993-present*, Earth System Science Data 10, 1551–1590

Church and White, 2011, *Sea-level rise from the late 19th to the early 21st century*, Survey in Geophysics 32, 585–602

3.2 Mapping Earth's Gravity

IMAGE CREDITS

Ocean circulation, © ESA (Marie-Helene Rio)

Gulf Stream, © IFREMER/LOPS (Nicolas Reul).

BIBLIOGRAPHY

Andersen et al., 2023, *The DTU21 global mean sea surface and first evaluation*, Earth System Science Data, 15, 4065–4075

Bingham, Haines and Lea (2014), *How well can we measure the ocean's mean dynamic topography from space?*, Journal of Geophysical Research: Oceans, 119, 3336–3356

Pail et al., 2011, *First GOCE gravity field models derived by three different approaches*, Journal of Geodesy, 85, 819–843, Springer, ISSN 0949-7714

3.3 Beneath the Ocean Surface

IMAGE CREDITS

Altimetry-based Earth gravity map, © Scripps Institution of Oceanography and National Oceanic and Atmospheric Administration (David Sandwell and Walter Smith)

BIBLIOGRAPHY

Calmant, Berge-Nguyen and Cazenave, 2002, *Global seafloor topography from a least-squares inversion of altimetry-based high-resolution mean sea surface and shipboard soundings*, Geophysical Journal International, 151: 795-808

Ramillien and Cazenave, 1997, *Global bathymetry derived from altimeter data of the ERS-1 Geodetic Mission*, Journal of Geodynamics, 23(2), 129 – 149

Sandwell and Smith (1997), *Marine gravity anomaly from Geosat and ERS-1 satellite altimetry*, Journal of Geophysical Research: Solid Earth, 102, 10,039 – 10,054

Sandwell, et al., 2014, *New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure*, Science 346 (6205), 65-6

4 Land

4.1 Guardians of the Green

IMAGE CREDITS

Biomass, © ESA (Chiara Luisa Ferrario)

BIBLIOGRAPHY

Yang et al., 2023, *Global increase in biomass carbon stock dominated by growth of northern young forests over past decade*, Nature Geoscience, 16(10), 886-892

Reiche et al., 2021, *Forest disturbance alerts for the Congo Basin using Sentinel-1*, Environmental Research Letters, 16(2), 024005

Brandt et al., 2018, *Satellite passive microwaves reveal recent climate-induced carbon losses in African drylands*, Nature Ecology & Evolution, 2: 827-835

Tian et al., 2018, *Coupling of ecosystem-scale plant water storage and leaf phenology observed by satellite*, Nature Ecology & Evolution, 2: 1428-1435

Bousquet et al., 2022, *Monitoring post-fire recovery of various vegetation biomes using multi-wavelength satellite remote sensing*, Biogeosciences, 19: 3317-3336

Fan et al., 2019, *Satellite-observed pantropical carbon dynamics*, Nature Plants, 5: 944-951

4.2 Unveiling Earth's Shifts

IMAGE CREDITS

Image and maps provided by ESA (Chiara Luisa Ferrario), the "land subsidence rate in Bologna" map was produced by Christian Massari

BIBLIOGRAPHY

Costantini et al., 2021, *European ground motion service (EGMS)*, IEEE International geoscience and remote sensing symposium IGARSS (pp. 3293-3296)

Ferretti et al., 2011, *A new algorithm for processing interferometric data-stacks: SqueeSAR*, IEEE Transactions on geoscience and remote sensing, 49(9), 3460-3470

Berardino et al., 2002, *A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms*, IEEE Transactions on geoscience and remote sensing, 40(11), 2375-2383

Ferretti, Prati and Rocca, 2001, *Permanent scatterers in SAR interferometry*, IEEE Transactions on geoscience and remote sensing, 39(1), 8-20

4.3 Watching the Water

IMAGE CREDITS

Image and maps provided by ESA (Chiara Luisa Ferrario), the "soil moisture" map was produced by Christian Massari.

BIBLIOGRAPHY

Massari et al., 2020), *A daily 25km short-latency rainfall product for data-scarce regions based on the integration of the Global Precipitation Measurement mission rainfall and multiple-satellite soil moisture products*, Hydrology and Earth System Sciences, 24: 2687-2710

Kerr et al., 2010, *The SMOS mission: new tool for monitoring key elements of the global water cycle*, Proceedings of the IEEE, 98: 666-687

Leduc-Leballeur et al., 2020, *Melt in Antarctica derived from Soil Moisture And Ocean Salinity (SMOS) observations at L band*, Cryosphere, 14: 539-548

Muñoz-Sabater et al., 2019, *Assimilation of SMOS brightness temperatures in the ECMWF integrated forecasting system*, Quarterly Journal of the Royal Meteorological Society, 145: 2524-2548

Tarpanelli, A., Mondini, A. C., & Camici, S., 2022, *Effectiveness of Sentinel-1 and Sentinel-2 for flood detection assessment in Europe*, Natural Hazards and Earth System Sciences, 22(8), 2473-2489

Imprint

This document was commissioned by the European Space Agency to the European Science Foundation and the European Space Sciences Committee (PO N. 5001040165).

AUTHORS

Earth Sciences Panel of the European Space Sciences Committee
Maurice Borgeaud (panel chair), Jonathan Bamber, Anny Cazenave, Michaela Hegglin, Yann Kerr, Marta Marcos, Christian Massari, Johanna Tamminen and Chris Rapley

European Science Foundation
Jonas L'Haridon, Courtney Allison

EDITORS

European Science Foundation
Jonas L'Haridon, Courtney Allison

ARTISTIC DIRECTION
GRAPHIC DESIGN

Carine Baudet

GRAPHIC DESIGN

Guillemette Crozet