Science Perspectives for the European Earth Observation Ecosystem in 2040+

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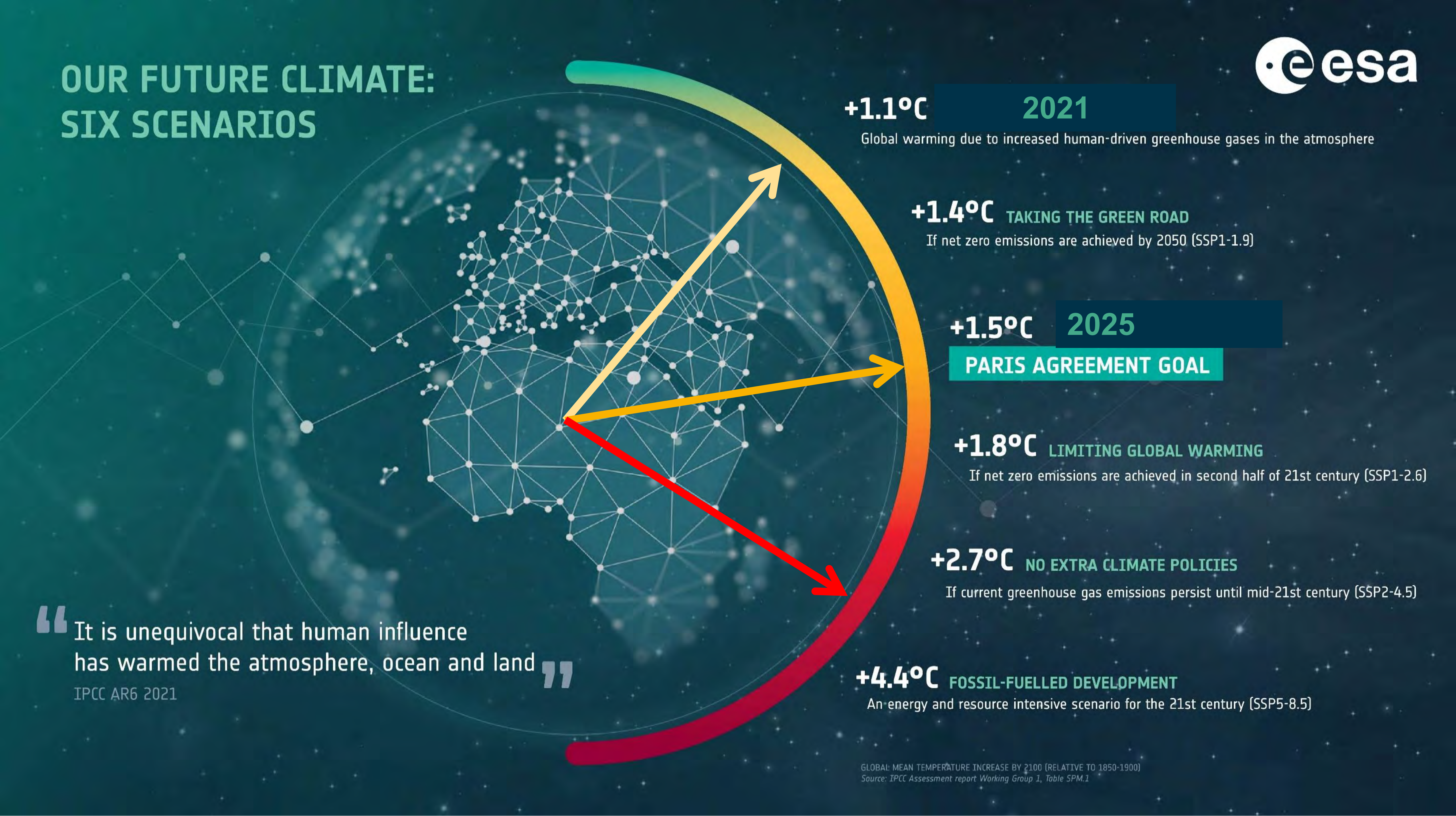
OUR FUTURE CLIMATE:
SIX SCENARIOS
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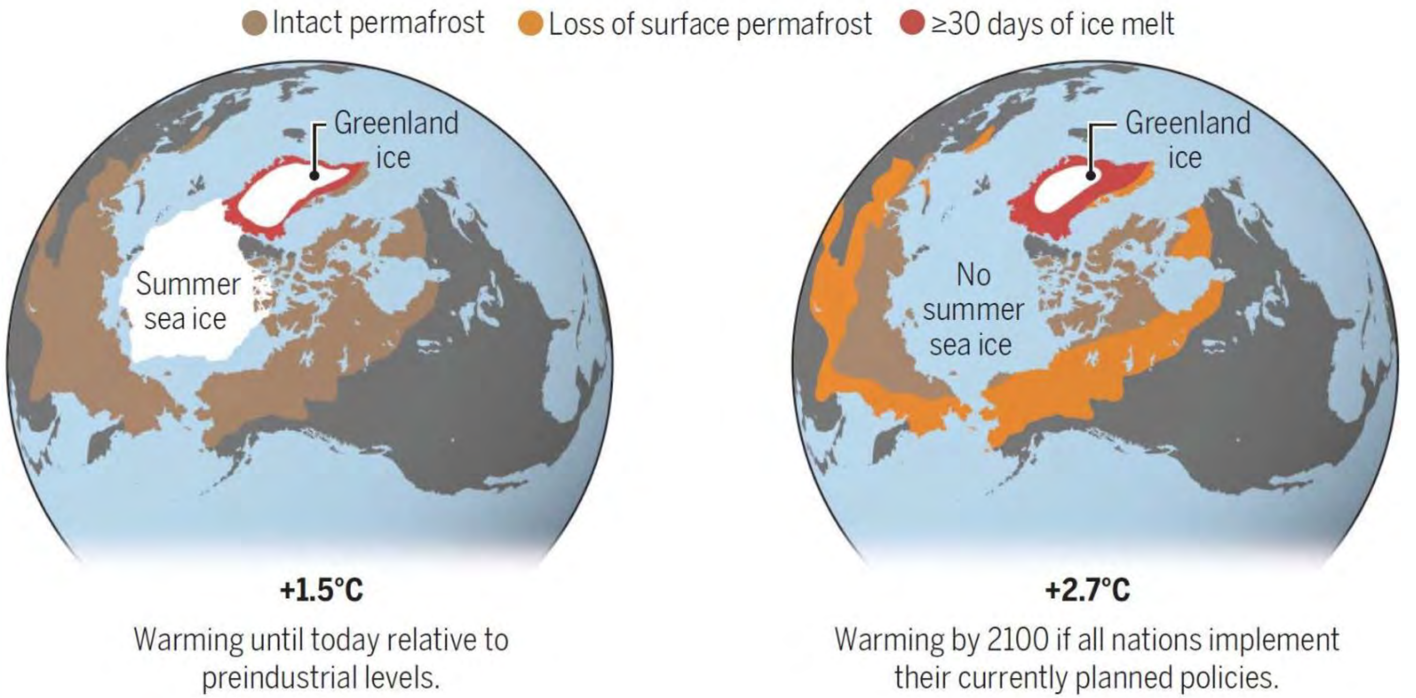
+1.1°C 2021
Global warming due to increased human-driven greenhouse gases in the atmosphere
+1.4°C TAKING THE GREEN ROAD
If net zero emissions are achieved by 2050 (SSP1-1.9)
+1.5°C 2025
PARIS AGREEMENT GOAL
+1.8°C LIMITING GLOBAL WARMING
If net zero emissions are achieved in second half of 21st century (SSP1-2.6)
+2.7°C NO EXTRA CLIMATE POLICIES
If current greenhouse gas emissions persist until mid-21st century (SSP2-4.5)
+4.4°C FOSSIL-FUELLED DEVELOPMENT
An energy and resource intensive scenario for the 21st century (SSP5-8.5)
"It is unequivocal that human influence has warmed the atmosphere, ocean and land"
IPCC AR6 2021
GLOBAL MEAN TEMPERATURE INCREASE BY 2100 (RELATIVE TO 1850-1900)
Source: IPCC Assessment report Working Group 1, Table SPM.1

Impacts of 2.7°C Climate warming on a vulnerable Arctic



Ref: Stroeve et al (2025) [Disappearing landscapes: The Arctic at +2.7°C global warming]

2.7ºC warming will change the Arctic 'beyond recognition' with cascading risks and knock-on effects:

- ice sheet melting – and global impact from rising seas around the world (20 ± 0.9cm over next 80 yrs)
- Surface permafrost thaw: boreal becomes net source of carbon to the atmosphere
- Accelerating rate of global warming
- Fisheries impacted by ocean warming, acidification deoxygenation
- Consequences for Atlantic Meridional Overturning Circulation (AMOC)

Strategy Foresight Study: Towards 2040

ESA's Strategy 2040 Foresight Study identified four key Societal needs with significant contributions from space:

KEY EUROPEAN SOCIETAL NEEDS

- Sustainability of Life on Earth,
- Europe's Leadership in Science
- Resilience of the European Society and its Economy
- European Cohesion and Global Reach.

Five Goals expressed in Strategy 2040 aimed at ensuring ESA is preparing for the future of the European space sector:

ESA OVERARCHING GOALS

1. Protect our planet
2. Explore and discover
3. Strengthen European resilience, autonomy and security
4. Boost European growth and competitiveness
5. Inspire Europe

A strong Scientific element is fundamental to ESA strengthening its robustness and resilience in preparation for an uncertain future, applying EO based Earth science in support of sustainability of life on Earth

A Journey into the Future of ESA - University of Copenhagen Research Portal

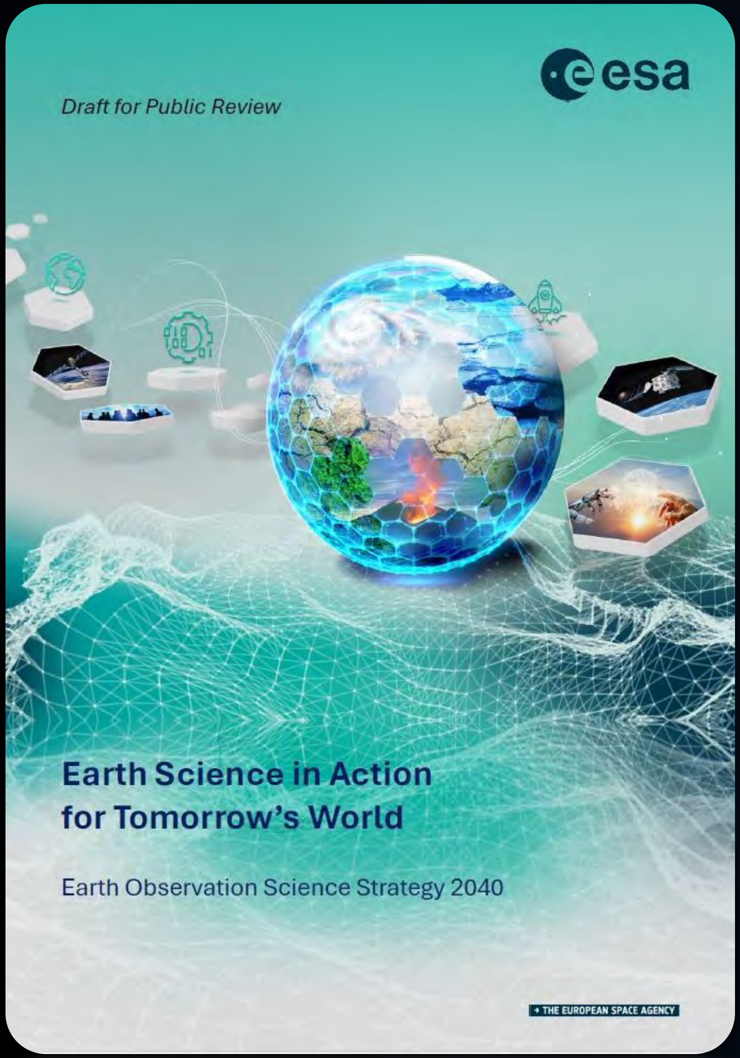
ESA Earth Observation Vision

To craft world-class Earth Observation capabilities and information products for informed decisions and actions that best respond to today's challenges of understanding, sustaining and improving the Earth and its environment.

Emphasis on:

- Discovery Earth system science
- Response to the global challenges faced by society today & preparing for tomorrow
- Actionable information leveraging the growing volumes of satellite data
- Action in support of mitigating and adapting to climate change and sustainable management of resources

Earth Observation Science Strategy



1) Frontier Science and Discovery: a strong foundation

2) From Science to Benefits: meeting society's needs

3) Reducing critical knowledge gaps: taking expedient action

4) Filling critical observation gaps: preparing for tomorrow starts today

6 overarching Earth Science Themes

1) Water Cycle; 2) Carbon Cycle and Chemistry; 3) Energy Fluxes;

4) Ecosystem Health; 5) Extremes and Hazards; 6) Interfaces and Coupling in Earth System

Relevance to International Treaties, Agreements and Conventions

Strategic Axes for EO-based Earth Action

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A1: **Frontier Science and Discovery**

- innovative/blue-skies, novel discovery science
- groundbreaking/technologically challenging
- serving as a foundation for all areas of action
- harnesses science knowledge, technical know-how at European level through ESA

A2: **From Science to Benefits**

- contribution to areas of societal benefits in the domains of international and national policy
- science basis for development of green solutions
- science relevant to informing, assisting, enabling monitoring of compliance, and evaluate policy impact
- support to evidence-based policy implementation

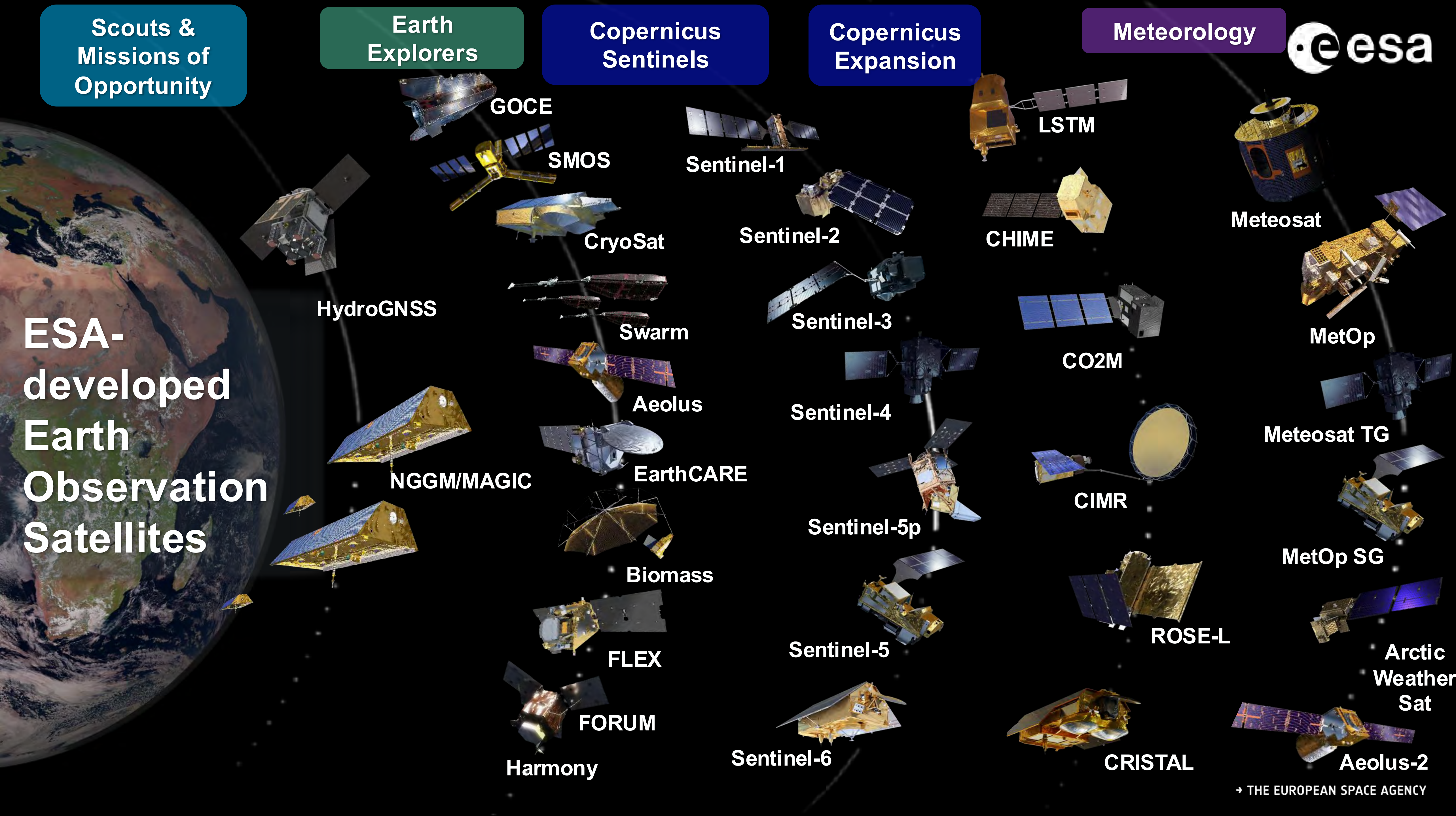
A3: **Reducing Critical Knowledge Gaps**

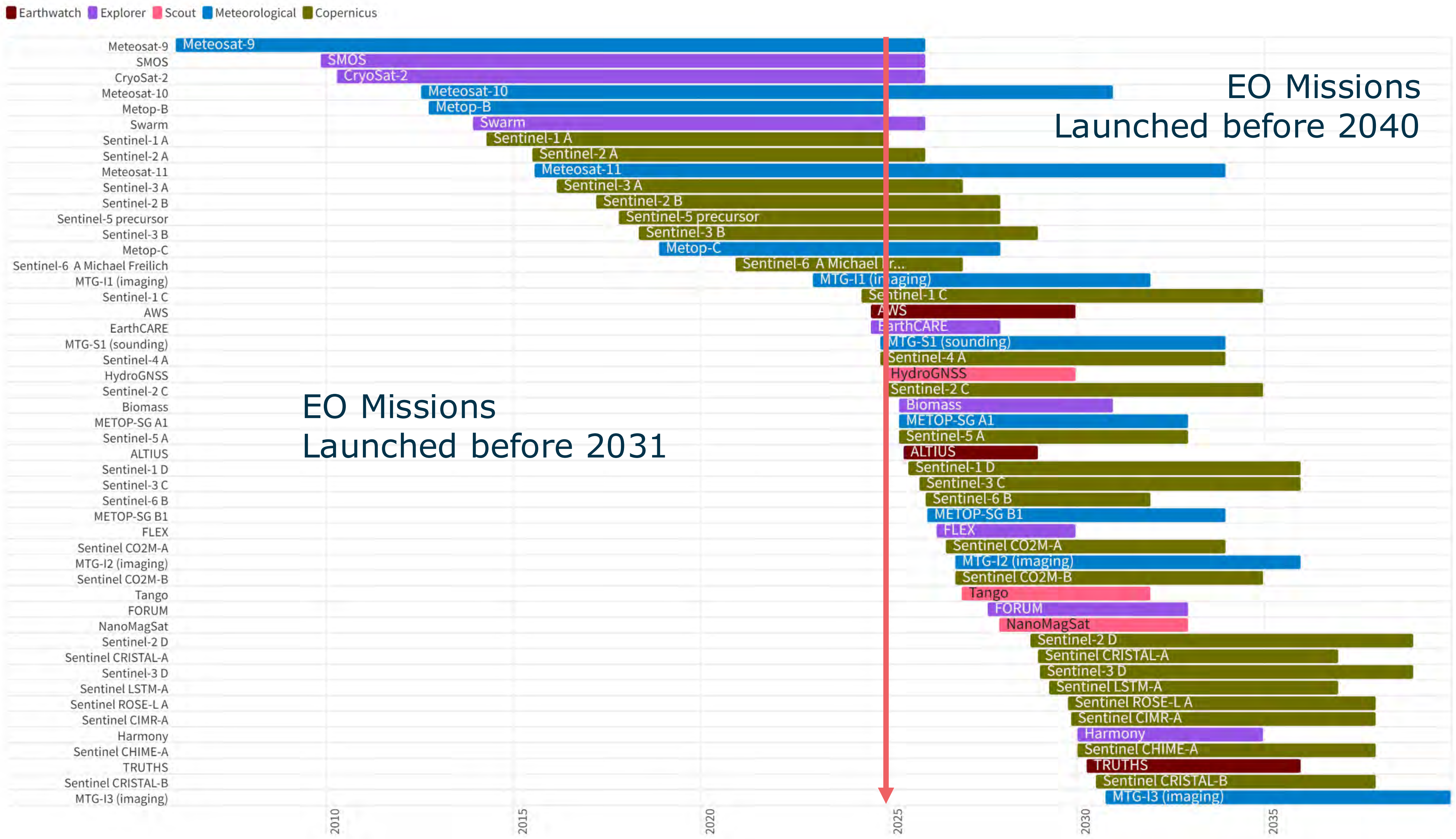
- uptake and contribution of existing/upcoming missions to science questions
- pursuit of multi-mission synergies
- agile Scout research missions for rapid return
- addressing high priority science through partnerships and institutional collaborations
- demonstrable progress made in 6 years

A4: **Filling Critical Observation Gaps**

- addressing crucial observation gaps with new technologies
- study and predevelopment of novel and improved observational capabilities
- requiring sustained science / technology development
- takes into account EO reference architecture

Science with Current and Planned Missions


Scouts & Missions of Opportunity
Earth Explorers
Copernicus Sentinels
Copernicus Expansion
Meteorology
esa
ESA-developed Earth Observation Satellites
HydroGNSS
NGGM/MAGIC
GOCE
SMOS
CryoSat
Swarm
Aeolus
EarthCARE
Biomass
FLEX
FORUM
Harmony
Sentinel-1
Sentinel-2
Sentinel-3
Sentinel-4
Sentinel-5p
Sentinel-5
Sentinel-6
LSTM
CHIME
CO2M
CIMR
ROSE-L
CRISTAL
Meteosat
MetOp
Meteosat TG
MetOp SG
Arctic Weather Sat
Aeolus-2
→ THE EUROPEAN SPACE AGENCY


Earthwatch
Explorer
Scout
Meteorological
Copernicus
Meteosat-9
SMOS
CryoSat-2
Meteosat-10
Metop-B
Swarm
Sentinel-1 A
Sentinel-2 A
Meteosat-11
Sentinel-3 A
Sentinel-2 B
Sentinel-5 precursor
Sentinel-3 B
Metop-C
Sentinel-6 A Michael Freilich
MTG-I1 (imaging)
Sentinel-1 C
AWS
EarthCARE
MTG-S1 (sounding)
Sentinel-4 A
HydroGNSS
Sentinel-2 C
Biomass
METOP-SG A1
Sentinel-5 A
ALTIUS
Sentinel-1 D
Sentinel-3 C
Sentinel-6 B
METOP-SG B1
FLEX
Sentinel CO2M-A
MTG-I2 (imaging)
Sentinel CO2M-B
Tango
FORUM
NanoMagSat
Sentinel-2 D
Sentinel CRISTAL-A
Sentinel-3 D
Sentinel LSTM-A
Sentinel ROSE-L A
Sentinel CIMR-A
Harmony
Sentinel CHIME-A
TRUTHS
Sentinel CRISTAL-B
MTG-I3 (imaging)
2010
2015
2020
2025
2030
2035
EO Missions
Launched before 2040
EO Missions
Launched before 2031

Earth Explorer 11 Candidate Research Missions

CAIRT:

limb observations of atmospheric composition, structure and dynamics from mid-troposphere to lower thermosphere

WIVERN:

- observations of in-cloud horizontal atmospheric motion and microphysical properties

Earth Explorer 12 Candidate Research Missions

ECO:

measuring the Earth Energy Imbalance (difference between incoming solar radiation and outgoing radiation)

Hydroterra+:

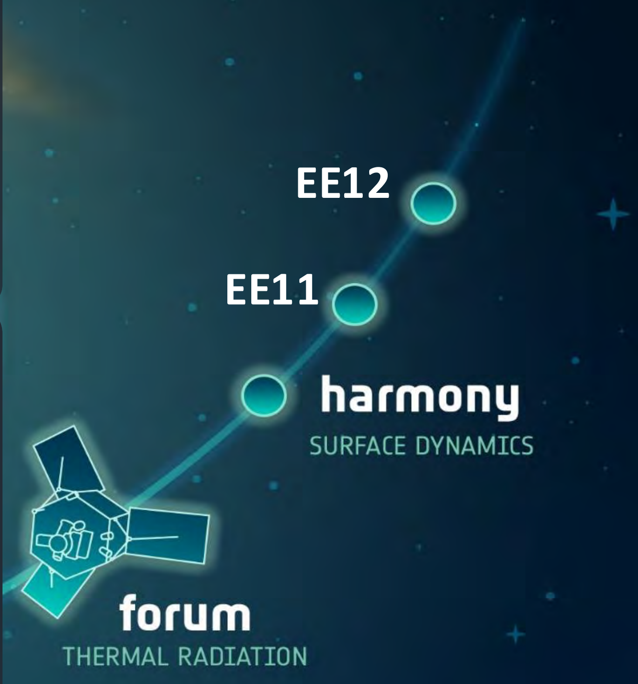
geosynchronous Earth-science radar mission for water cycle and tectonic movement

CryoRad:

novel broadband radiometer for cryosphere observations

Keystone:

first direct observations of atomic oxygen in the altitude range of 50–150 km



Development of a world-class European EO system

Over the last decades - progressive infusion of operational reference missions with scientific and technical capabilities from demonstrated research missions.

Some Examples:

Atmospheric composition:

ERS-2 (GOME) → Envisat (Sciamachy, GOMOS, MIPAS) → MetOp (GOME2, IASI) → Aura (OMI) → Sentinel-5p (TROPOMI) → MTG (Sentinel-4 UVN) → MetOp-SG (Sentinel-5 UVNS→ Scout TANGO) → MicroCarb → ALTIUS → CO2M

Ocean/Ice/Hydrology Altimetry:

ERS-1/2 (RA) → Topex/Poseidon → Jason-1/2 → Envisat → CryoSat-1/2 (SIRAL) → Sentinel-3 (SRAL) → Sentinel-6 (Pos4) → SWOT → CRISTAL (IRIS) → Sentinel-3 NG Topo (Pos 5) → Sentinel-6 NG

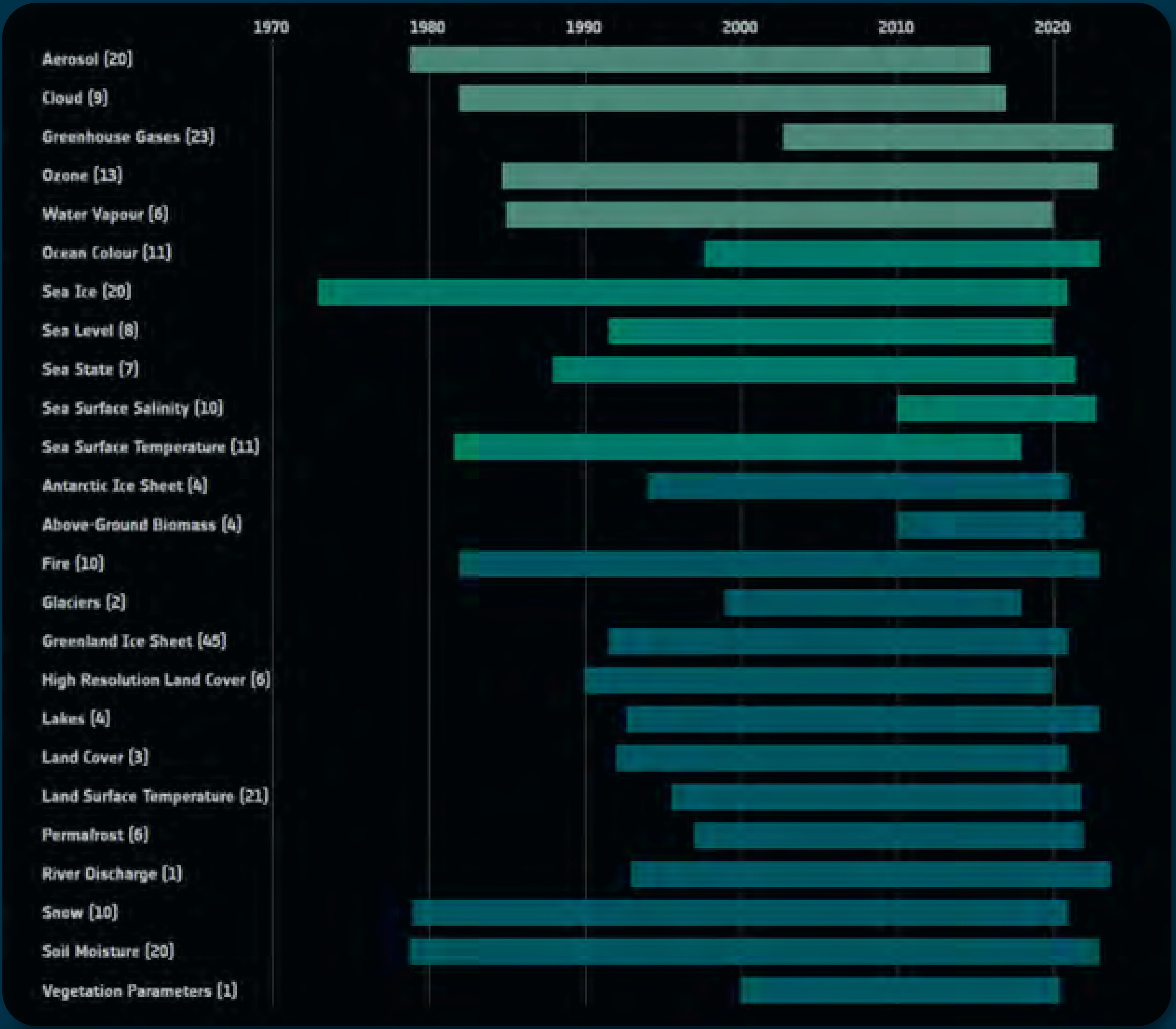
Ocean/Land Optical Imaging:

SPOT → ERS-1/2 (ATSR) → Envisat (MERIS/ AATSR) → Sentinel-2 (MSI) → Sentinel-3 (OLCI/SLSTR) → Sentinel-2 NG → PRISMA → EnMAP → CHIME → Sentinel-3 NG Opt (AOLCI/ASLSTR)

Copernicus Space Component

Sustained Observation Infrastructure for Earth Action

- Critical need to identify the essential elements of Space infrastructure – and to sustain key observations
- Extension of critical ECVs out to 2040 would secure a 60yr climate record
- All CDRs are available via [STAC/APIs and open source tools](#)through [federated interoperable EO ecosystem](#)
- Foundation for Policy implementation via key sustained datasets
- New ECVs recently added (e.g. TWS from gravimetry; ocean currents)



https://climate.esa.int/en/odp/#/dashboard

Critical Gaps and Strategic Science Priorities

Guiding Scientific Questions – by Earth Science Domain

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Frontier Science and discovery	Domains	
SQ-02	Atmosphere, Land	Land biosphere response to CC
SQ-03	Atmosphere, Ocean	Ocean carbon cycle responses to climate change
SQ-45	Atmosphere, Land, Ocean, Cryosphere	Internal energy flux estimates
SQ-46	Atmosphere, Land, Ocean, Cryosphere	Earth energy imbalance
SQ-55	Land	State of Land ecosystems

Reducing critical knowledge gaps	Domains	
SQ-02	Atmosphere, Land	Land biosphere response to CC
SQ-20	Ocean, Cryosphere	Ice mass balance
SQ-46	Atmosphere, Land, Ocean, Cryosphere	Earth energy imbalance
SQ-45	Atmosphere, Land, Ocean, Cryosphere	Internal energy flux estimates
SQ-43	Atmosphere, Land, Ocean	Coupling between energy water and carbon cycles

From science to benefits	Domains	
SQ-01	Atmosphere, Land	Anthropogenic influences on the carbon cycle
SQ-5	Land, Ocean	Sea level change in the coastal ocean
SQ-44	Atmosphere, Land	Anthropogenic influences on the water cycle
SQ-55	Land	State of Land ecosystems
SQ-56	Land	Land ecosystem critical transitions

Filling critical observation gaps	Domains	
SQ-07	Atmosphere, Land, Ocean	Coastal interfaces with land atmosphere and ocean
SQ-45	Atmosphere, Land, Ocean, Cryosphere	Internal energy flux estimates
SQ-46	Atmosphere, Land, Ocean, Cryosphere	Earth energy imbalance
SQ-51	Atmosphere, Solid earth	Lithosphere-atmosphere-ionosphere coupling
SQ-52	Solid earth	Volcanic Hazards

Atmosphere Land Ocean Solid earth Cryosphere

Critical Observables for addressing Science Questions

Top 20 (non exhaustive) priority Geophysical Observable identified as 'critical' (Ref: Science Strategy Foundation Study)
Letters indicate C - CEOS Database, O - OSCAR Variable, or N - New)

Geophysical Observables			
Gravity Field	C	Land Surface Temperature	C
Gravity gradients	C	Ocean Surface Vector Currents	C
Ice sheet topography	C	Ocean suspended sediment concentration	C
Land Surface imagery	C	Ocean temperature	C
Ocean Chlorophyll concentration	C	Chorophyll Fluorescence from Vegetation on Land	C
Land Surface topography	C	Vegetation Canopy	C
Atmospheric specific humidity (column/profile)	C	Sea Surface Salinity	C
Atmospheric temperature (column/profile)	C	River discharge	O
Above Ground Biomass (AGB)	C	Vegetation Water Content	N
Sea Surface Temperature	C	Coastal sea level	C

Ref: Candidate Science Questions, Geophysical Observables and EO mission capabilities – Science Strategy Foundation Study Report

Preparing Technology for Frontier Science and Discovery in the 2040s

Capabilities to unlock Frontier Science Discoveries

- Operational NRT gravimetry to monitor water/mass exchange
- Geostationary Ocean/Land Colour – aquatic ecosystems and disaster monitoring
- LIDaR profiling of atmosphere/ocean/forests
- High resolution Thermal Imaging for land surface/urban areas
- SAR Ocean Vector Currents
- Passive Microwave Subsurface Temperature Sounding
- SAR Tomography for sub-surface structure and dynamics
- Geosynchronous SAR for hydrology and tectonics

………

- Formation Flying: for aperture synthesis/ multi-point SAR tomographic imaging
- Constellations to address time/space sampling

Advanced Atmospheric LIDaR

Scientific Gap:

Profiling of tropospheric water vapour (WV) and cloud properties with high vertical resolution, and sensitivity to the lowermost troposphere and Planetary Boundary Layer (PBL)

Science Progress:

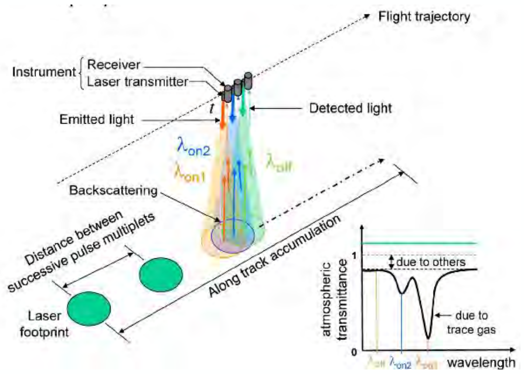
- Understanding of deep convection, radiatively driven circulation, subtropical humidity inversion, but also climate-related warming affecting WV in the (lower) troposphere, and PBL structure.
- Benefits for improvements in future Numerical Weather Prediction

Payload:

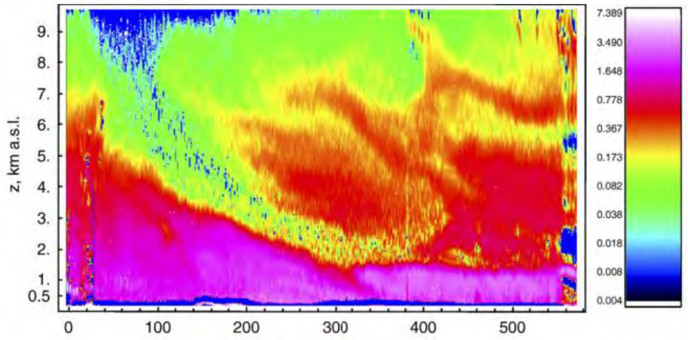
Differential absorption Lidar (DIAL) in the WV absorption band (935 nm) or Raman Lidar

DIAL demonstrated during using DLR airborne WALEX instrument

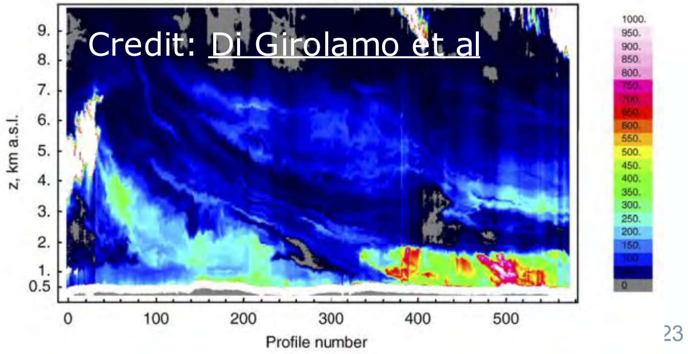
Alternative Solid-state laser technology suitable for space environment



WALEX Campaign
Water Vapour Mixing Ratio (g/kg)



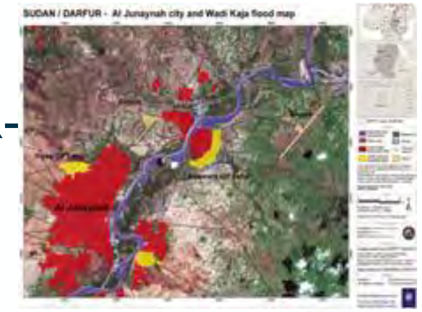
Backsc. coeff. 955nm, Walex, 020515

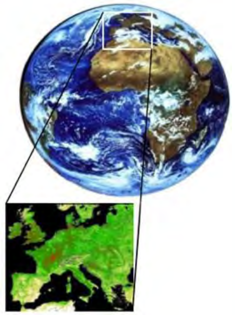


Advanced Geostationary Ocean/Land Colour

Scientific Gap:

Persistent, sub-daily, fast response, 10-100m spectral imaging (UV-VNIR, MWIR-TIR, and Pan) to improve understanding of inland/coastal waters and aquatic ecosystems and for Fire/Extreme event monitoring

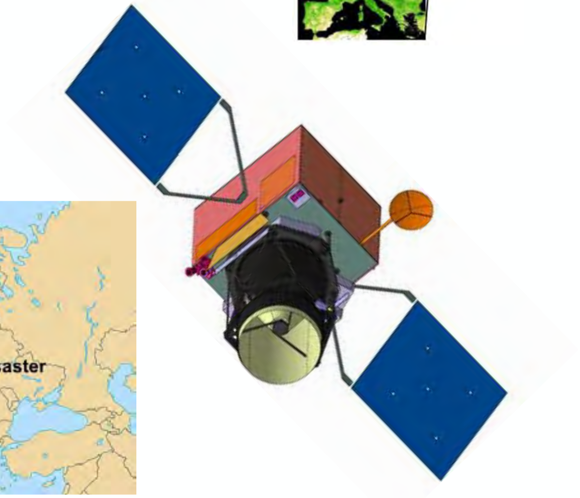




Science Progress:

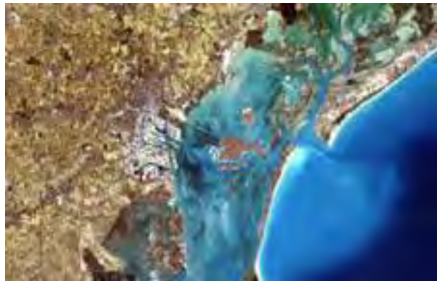
Coastal zones account for 30% of global ocean production, and inland waters play a crucial role in the carbon cycle despite their small surface area. No European EO mission is dedicated to studying coastal ecosystems.

- Variability in Biodiversity
- Land-ocean carbon and sediment fluxes
- Water Quality (Algal Bloom) – for European regulation



Payload:

- Agile pointing, step and state, high performance multi-instrument (Pan, UV,VNIR, SWIR-MWIR, TIR) and Radiometric reference
- Extensive Geo-Oculus concept study activities

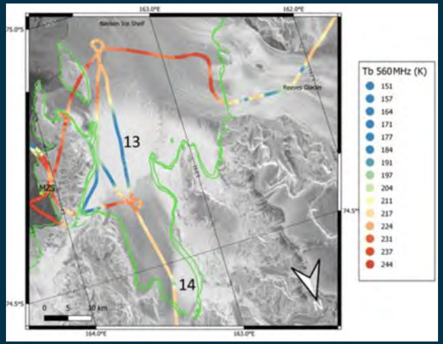


Low Frequency Microwave Sub-surface Thermometry

Scientific Gap:
Space-based capability does not exist today to deliver sub-surface temperature sounding/profiling – as analogue to atmospheric sounding

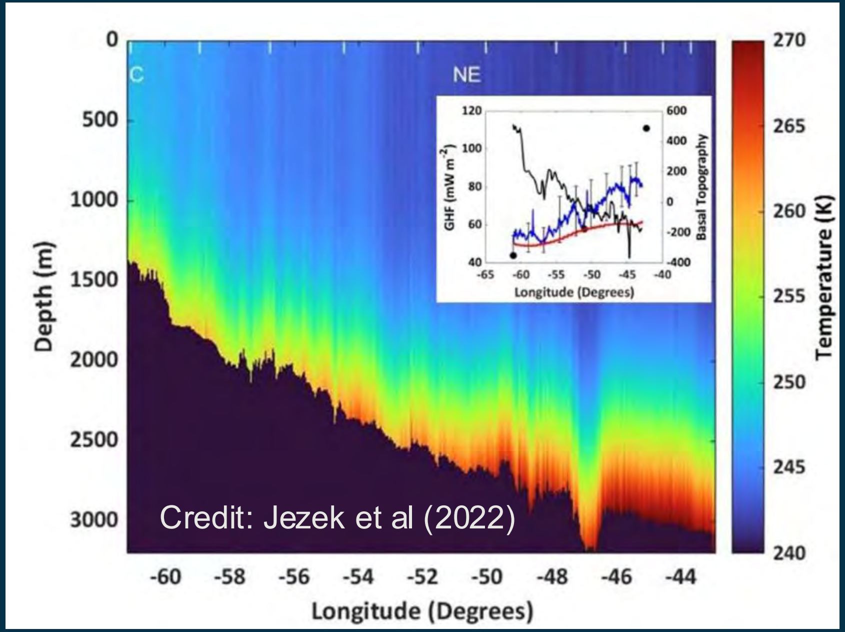
Science Progress:
Potential for top to bottom ice sheet/ice shelf thermometry - as constraint for thermodynamic state in coupled ice-sheet models; to estimate basal geothermal heat flux; and to improve climate model forecasts of rate of sea-level contribution.
Additional retrieval of sea-ice thickness/salinity, and ocean salinity

Payload:
0.4 MHz - 2GHz wide-band passive microwave radiometer with RFI mitigation and filtering
Airborne/tower prototype experiment campaign demonstrations of UWBRAD

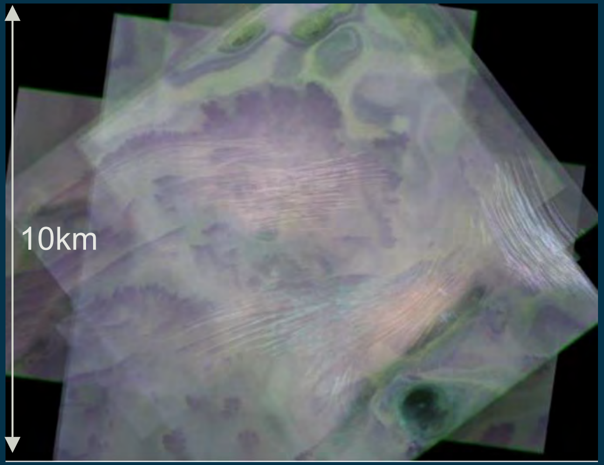


Credit: Brogioni et al (2023)

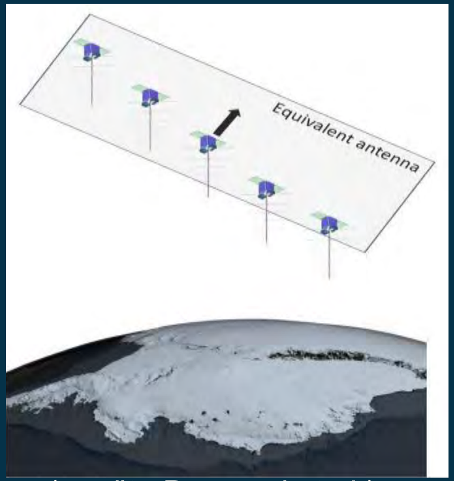
Greenland ice sheet temperature profile from airborne UWBRAD



Sub-Surface SAR 3d Tomography

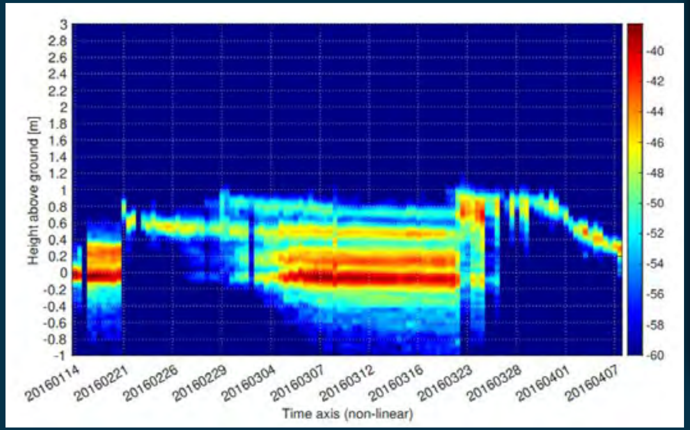


Greenland P-band SAR Images (credit; ONERA)



(credit: Bruzzoni et al.)

SnowLab SnowScat setup



Tomographic snow profiles (Frey et al 2023)

Scientific Gap:
Radar sounding/tomography of 3d sub-surface structure and physical properties within reach

Science Progress:
Ice sheet/ice shelf physical structure and velocity required to understand impact of ice flow dynamics in coupled ice-sheet models.
Benefits: 3d structure, and basal topography of ice; or deserts; Depth/density/layers/water equivalent in snow

Multi-platform / Payload:
MIMO multi platform 3D SAR tomography of ice/snow/deserts
MHz for ice penetration & GHz frequencies for snow
Challenging large aperture antennas replaced by distributed architectures - close formation flight and antenna synthesis (e.g. STRATUS concept).
SnowLab Campaign demonstration of Snow tomography

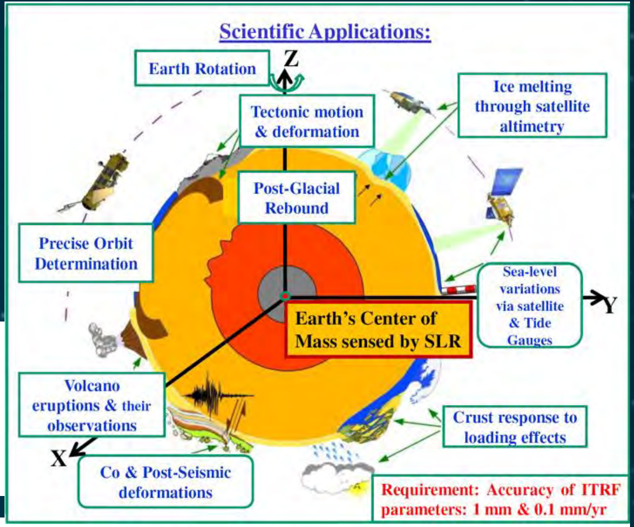
Critical Gap: Reference Frame Maintenance

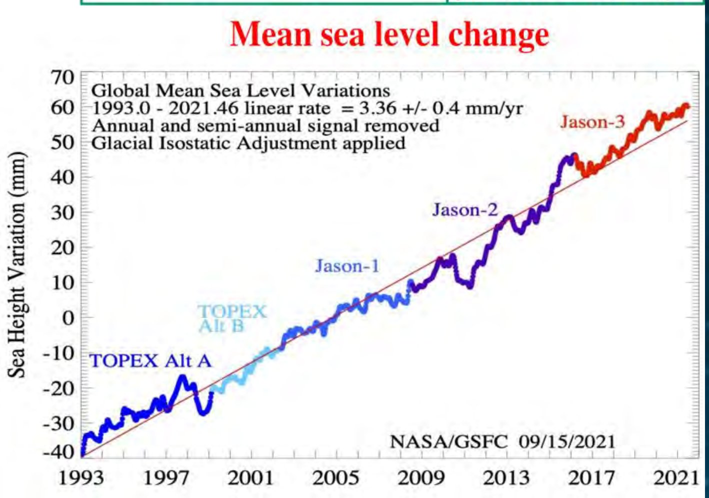
All EO metrology missions making precise range/position measurement rely on the International Terrestrial Reference Frame (ITRF)

- *A small drift of 1 mm/yr in the ITRF origin, translates into apparent 0.9 mm/yr sea level rise at high latitudes*

Operational geodetic applications depending on ITRF:

- National geodetic systems/frames
- Ground motion services
- Positioning: Real Time or *a posteriori*
- Navigation: Aviation, Terrestrial, Maritime
- GNSS requires availability of the orbits and the reference frame (ITRF)





Today Genesis is outside EO domain – yet critical to combining GNSS, SLR, DORIS, VLBI, Gravity data

→ **Need long term maintenance of ITRF for resilience of services delivered by operational metrology missions**

Other Key Enabling Elements for Science to Flourish

EO Orbit Diversity

- Earth-system processes remain chronicaly undersampled
- Polar (LEO) and Geostationary (GEO) orbits alone do not fulfil all user needs for global sub-daily, high time/space resolution data, particularly at high latitudes
- Future launch vehicles need to provide capability to deliver missions into:
  - Highly Elliptical Orbits (HEO) – enabling persistent coverage of poles – and dipping orbits that enable in-situ sampling (e.g. Daedalus concept)
  - VLEO (100-450km) – providing opportunities for low-cost systems and constellations to provide VHR imaging or more sensitive gravimetry/magnetometry
- Satellite platforms equipped to resist the space environment, with propulsion for active orbit maintenance, and handle downlink communication windows.

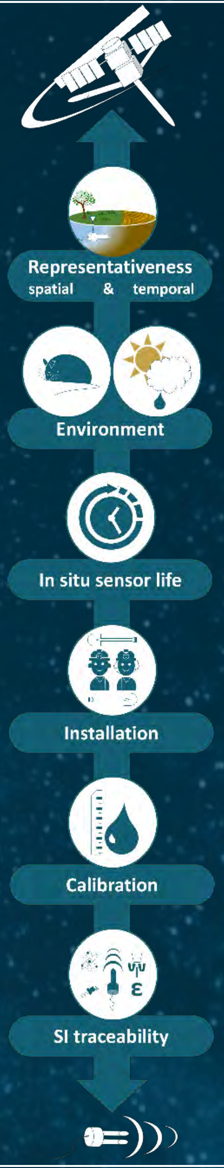
Fiducial Reference Measurements

Ground-based and airborne measurements known as Fiducial Reference Measurements (FRM) essential reference records in support of external calibration and product validation, ensuring accurate and reliable data

FRMs are characterised by:

- Independent from the satellite geophysical retrieval process;
- Documented with SI traceability using metrology standards and/or community-recognised best practices;
- Well documented and maintained uncertainty budgets;
- Measurement protocols, procedures, and community-adopted practices;
- Openly accessible to other researchers allowing independent verification of processing systems;
- be used to quantify the in-orbit uncertainty characteristics of satellite geophysical measurements via independent validation activities.

See examples at: QA4EO and QA4SM



HAPS: Sub-orbital persistent high-res. sampling

High Altitude Pseudo Satellites (HAPS) promise long duration, persistent stratospheric optical imaging (Fixed wing or Balloon).

e.g. AALTO Zephyr (solar powered fixed wing) has endurance of >1 month flying at altitude of ~20km

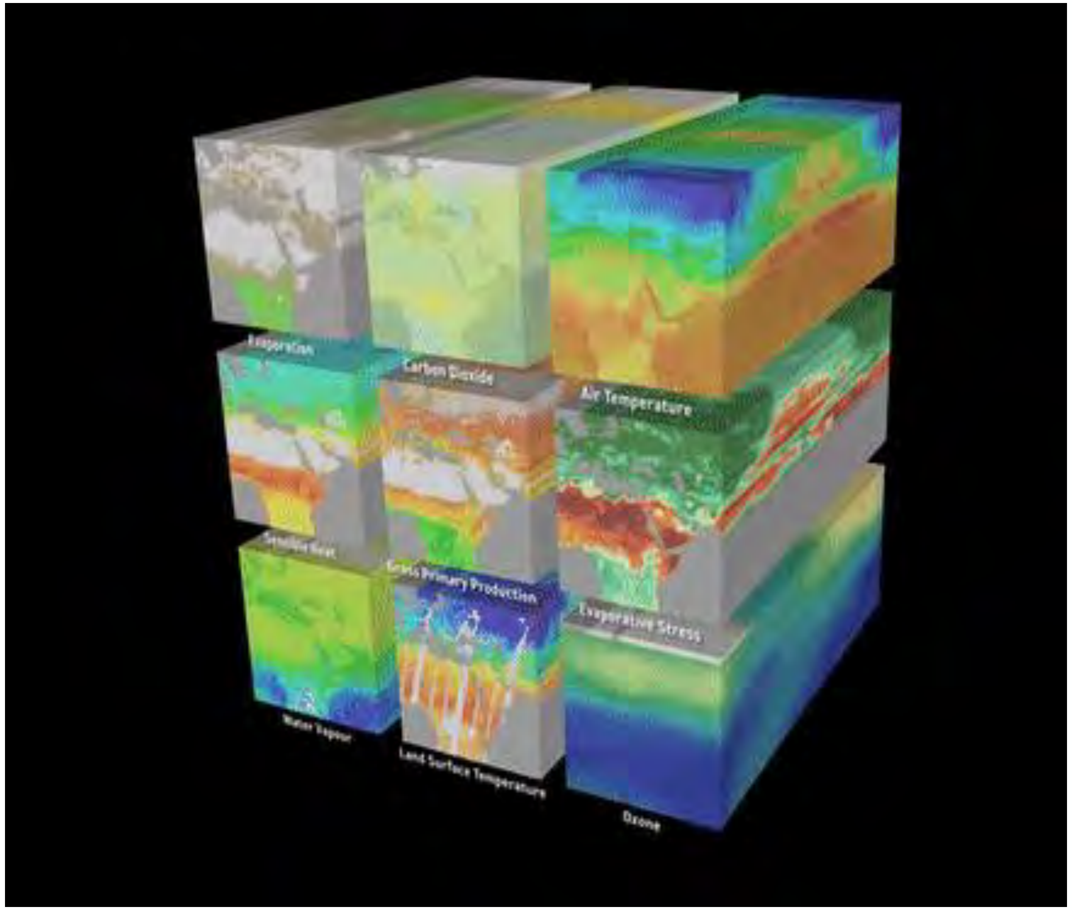
OPAZ payload: Steerable high-res. camera: 2500km^2/day, 1km footprint, 0.1m res. Vis, and MW IR images or video
Automatic Identification System (AIS)
Low latency monitoring data

New Applications:
Illegal fisheries, fire hotspot monitoring, border security, crisis response
Synergistic use of satellite and HAPS observations
Reference tool for performance evaluation of selected satellites

Data Cubes

Advanced Federated Global Data Cubes will become commonplace in 2040 – and continue to offer significant benefits by accelerating EO based scientific research:

- Lifts barriers to interdisciplinary research
- Enhanced Data Access (OGC standards) and Analysis Ready Data (ARD)
- Improved multi-source Data Integration (Research Operational and Commercial missions)
- Efficient multi-variate Time-Series Analysis
- Accelerated Data Processing
- Basis for Machine Learning
- Enhanced Collaboration and knowledge sharing



EO data cube - Euro Data Cube (credit: ESA)

Digital Twin of Earth in 2040

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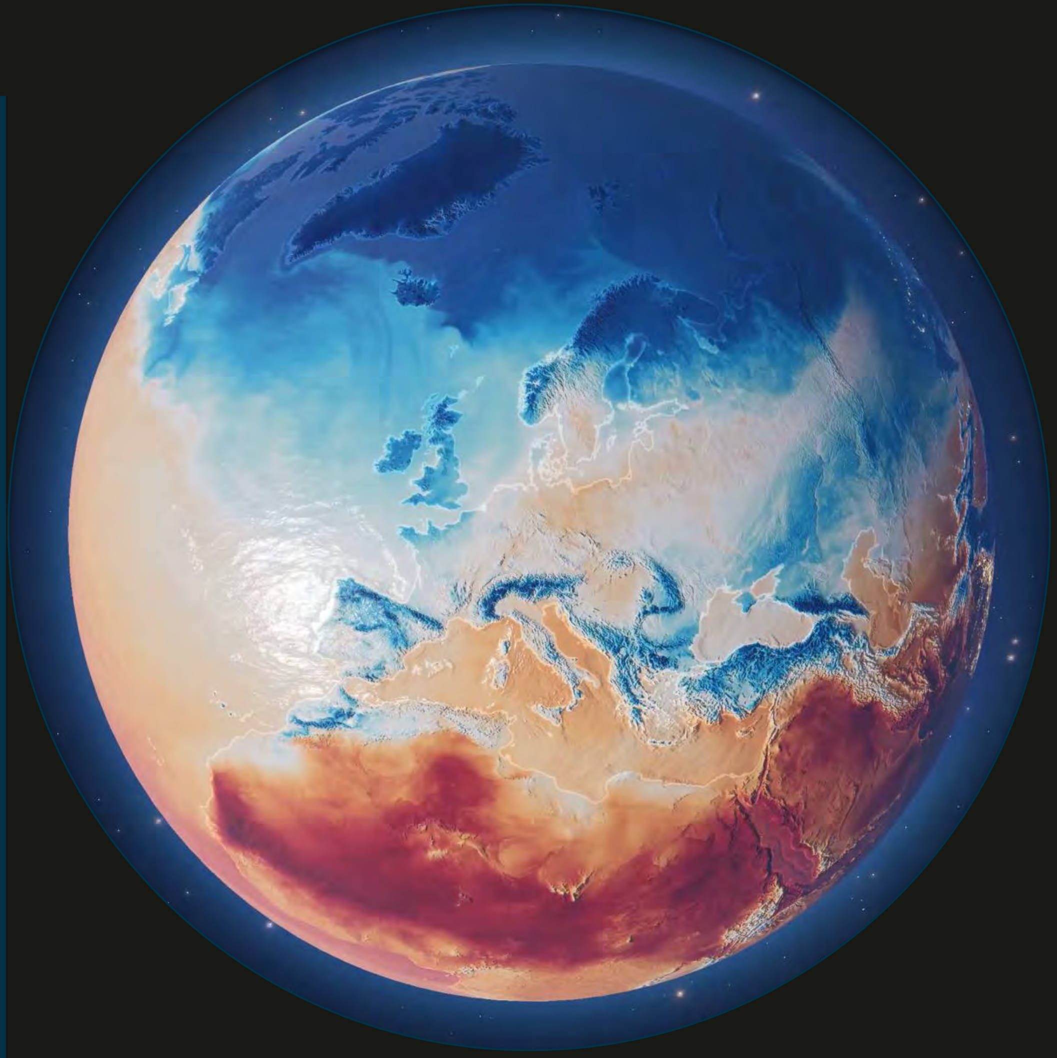
DestinE Platform

- EO Data driven models like DestinE are needed to deliver information and climate projections at local, societally relevant scales
- Quantum computing will replace exascale supercomputers enabling Model projections at < 100m scale
- DestinE will be driven by vast, growing EO data Lake
- Integration of refined Digital Twin capabilities will enable predictions of local climate extremes, and mitigation and adaptation DestinE and its Platform development enables a vibrant ecosystem of integrated services



https://platform.destine.eu/

Conclusions

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Undoubtedly the Earth system will look profoundly different in 2040, due to human impact on climate and the environment

The future EO ecosystem must serve frontier science and discovery – as a foundation for new operational capabilities

Science and new technology development must mature hand in hand to address known observation gaps and unlock new discoveries

The EO ecosystem shall be flexible and adaptable – enabling new research missions to exploit synergies with sustained data from reference missions

Continuity in critical EO measurements by reference missions sustains climate research, forecasting capability and underpins development of EO based services in the downstream commercial sector

The Ecosystem shall embrace combinations of satellite capabilities (public/private) to leverage the unique benefits from improved time/space sampling

Data quality must be assured based on independent Fiducial reference measurements, and with Calibration and Validation approaches following protocols and standards

Models remain of paramount importance as consumer of EO data and as a means of forecasting and building resilience to future climate change. Exascale and Quantum computing will revolutionise our ability to exploit the vast data Lake

Thank you Any Questions?

MAKE SPACE FOR EUROPE

www.esa.int/FutureEO