L'espace au service du climat

Vers une Planète Sous Surveillance : Le Rôle Émergent des Nano-Satellites

27 January 2025
Mustapha Meftah

Introduction

❑ Space for Climate Action

- **A Global Challenge:**
  The climate crisis requires innovative tools to monitor, understand, and mitigate its effects.

- **The Role of Satellites:**
  Satellites enable continuous, global observation of Earth, providing critical data for:
  - Monitoring greenhouse gases (CO_2, CH_4, etc.).
  - Predicting extreme weather events.
  - Analyzing changes in ecosystems and oceans.

- **The Small Satellite Revolution:**
  With reduced costs and increased flexibility, nanosatellites and microsatellites make these observations more frequent and accessible.

Introduction

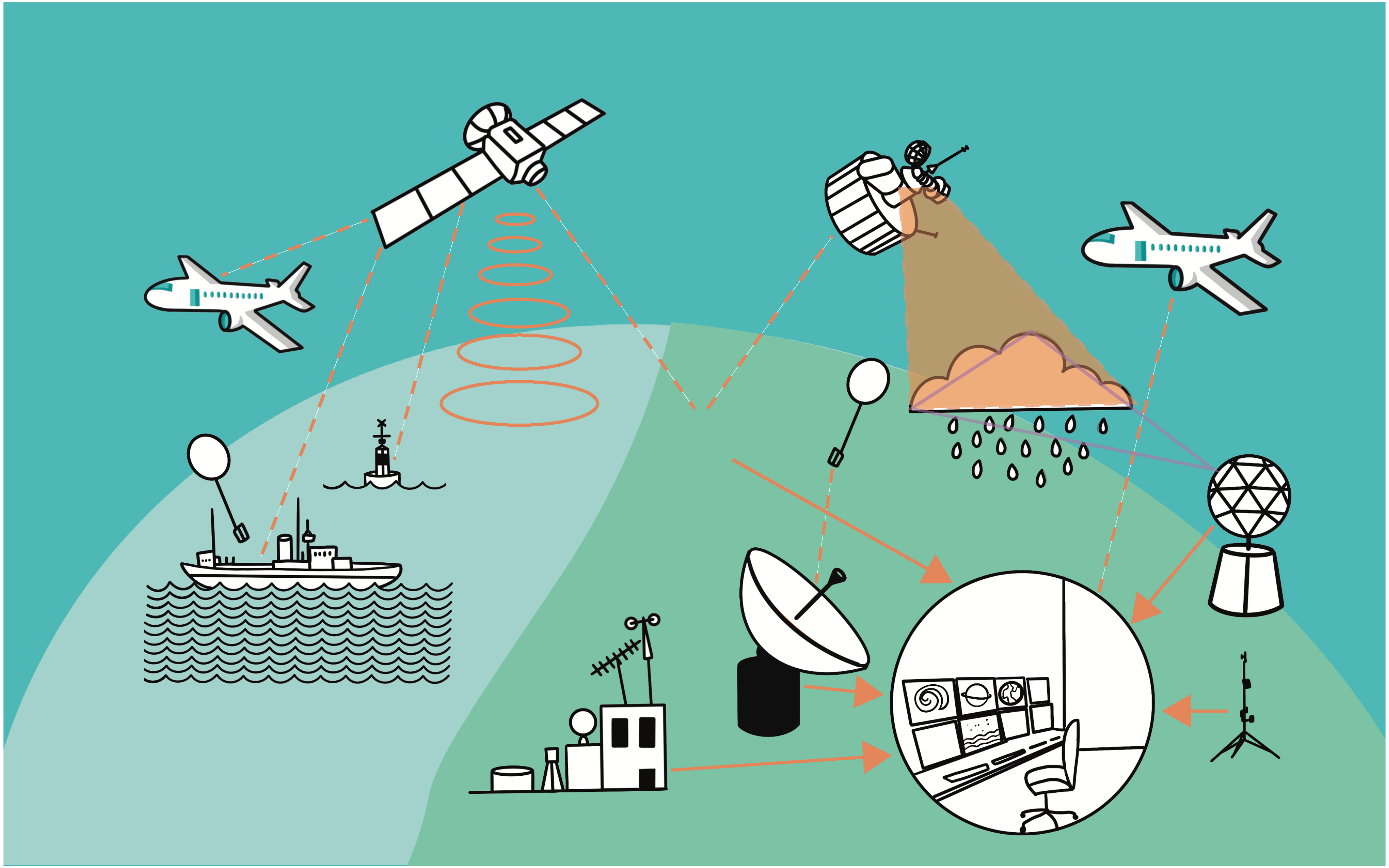
❑ <u>Nano-Satellites: A New Era for Earth Monitoring</u>

- **Why Nano-Satellites?**
  - Lower costs and rapid deployment.
  - Adaptability for specific scientific missions.
  - Capability to operate in constellations, enabling near real-time global coverage.

- **Practical Applications:**
  - Measuring industrial and agricultural emissions.
  - Tracking wildfires, polar ice, and rising sea levels.
  - Enhancing climate models with high-precision data.

- **A Promising Future:**
  Nano-satellites play a key role in the transition to a well-monitored planet, enabling climate policies to be based on reliable and accessible data.

Introduction



Introduction

Introduction

"All the News That's Fit to Print"

The New York Times

Late Edition

VOL.CXXXVII . . . No. 47,546 — NEW YORK, FRIDAY, JUNE 24, 1988 — 30 CENTS

Global Warming Has Begun, Expert Tells Senate

Sharp Cut in Burning of Fossil Fuels Is Urged to Battle Shift in Climate

Drought Raising Food Prices; Inflation Effect Seems Minor

IMMIGRATION LAW IS FAILING TO CUT FLOW FROM MEXICO

ECONOMIC FACTORS CITED

Illegal Entries Are on the Rise as More Come From Large Cities and Stay Longer

Cañon Zapata in Tijuana, Mexico, the busiest illegal crossing point.

High Court Getting Unusual Plea Not to Reverse Key Rights Ruling

Against Drug Tide, Only a Holding Action

The Crack Plague

Soviet Offers to Adjust Imbalance Of Conventional Forces in Europe

Interim District Attorney Drops Out of Bronx Race

Robert T. Johnson as he announced his candidacy.

Martin Out Again

INSIDE

Pope Meets With Waldheim

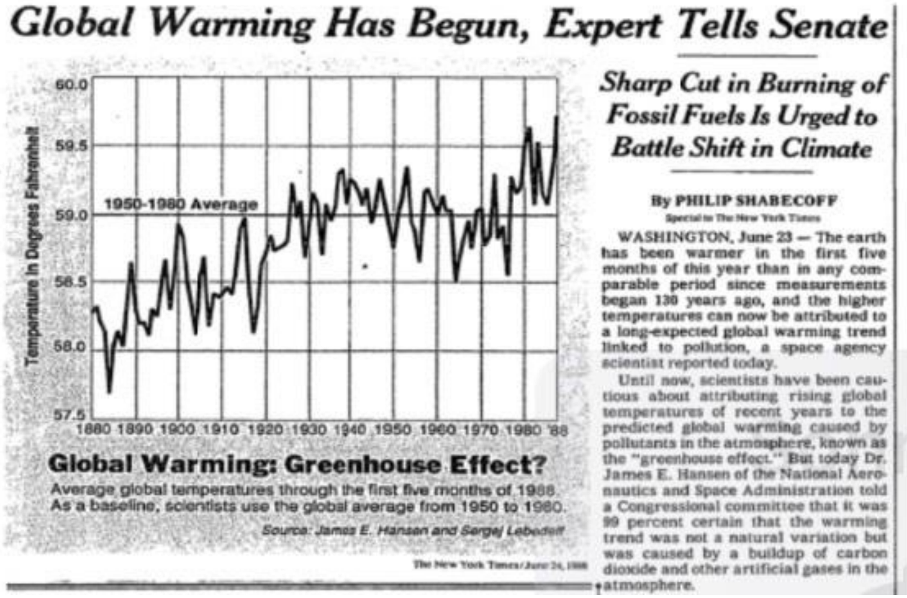
Reading Scores Improve

300 Feared Dead in Turkey

Veterans' Records Found

Dennis Day Is Dead

24 June 1988



Global Warming Has Begun, Expert Tells Senate

Global Warming: Greenhouse Effect?

Average global temperatures through the first five months of 1988. As a baseline, scientists use the global average from 1950 to 1980.

Source: James E. Hansen and Sergej Lebedeff

The New York Times / June 24, 1988

Sharp Cut in Burning of Fossil Fuels Is Urged to Battle Shift in Climate

By PHILIP SHABECOFF

Special to The New York Times

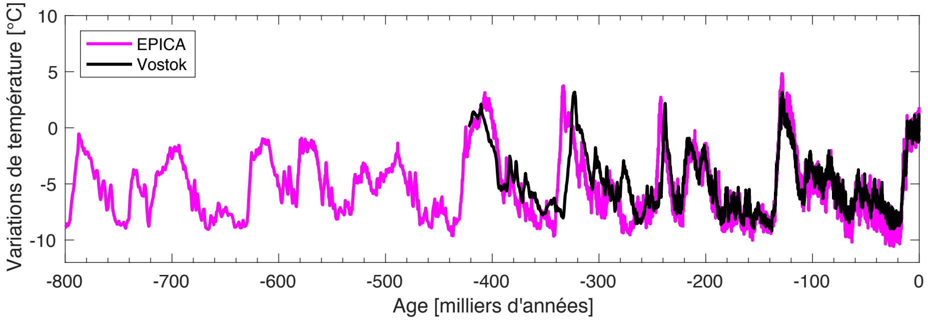
WASHINGTON, June 23 — The earth has been warmer in the first five months of this year than in any comparable period since measurements began 130 years ago, and the higher temperatures can now be attributed to a long-expected global warming trend linked to pollution, a space agency scientist reported today.

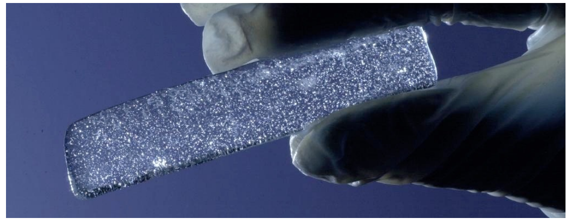
Until now, scientists have been cautious about attributing rising global temperatures of recent years to the predicted global warming caused by pollutants in the atmosphere, known as the "greenhouse effect." But today Dr. James E. Hansen of the National Aeronautics and Space Administration told a Congressional committee that it was 99 percent certain that the warming trend was not a natural variation but was caused by a buildup of carbon dioxide and other artificial gases in the atmosphere.

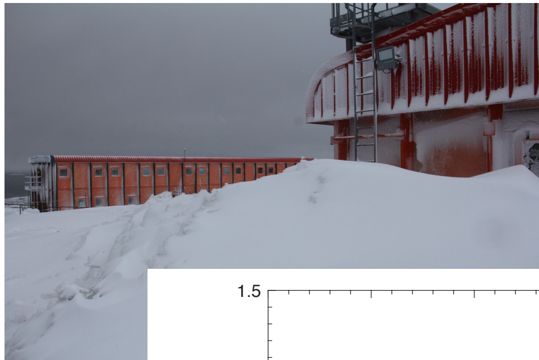
This is an issue that has been known for a long time.

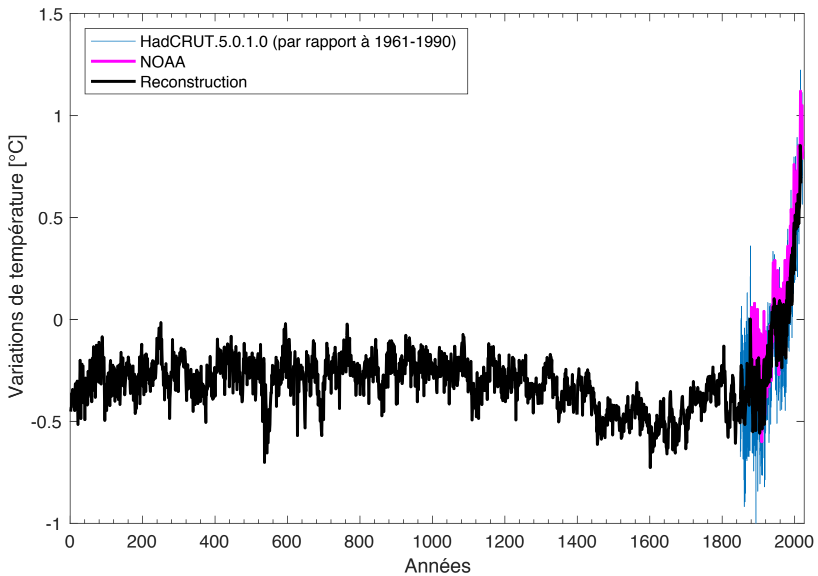
Some effects of climate change

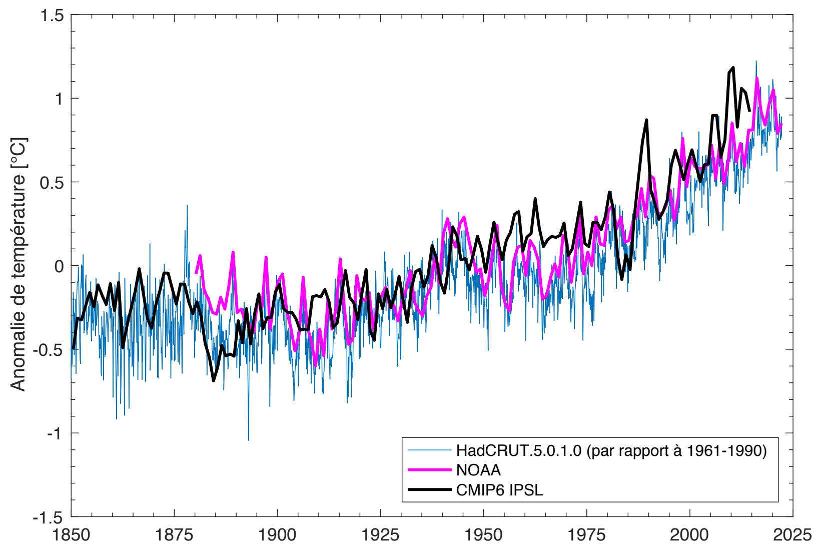
Temperatures





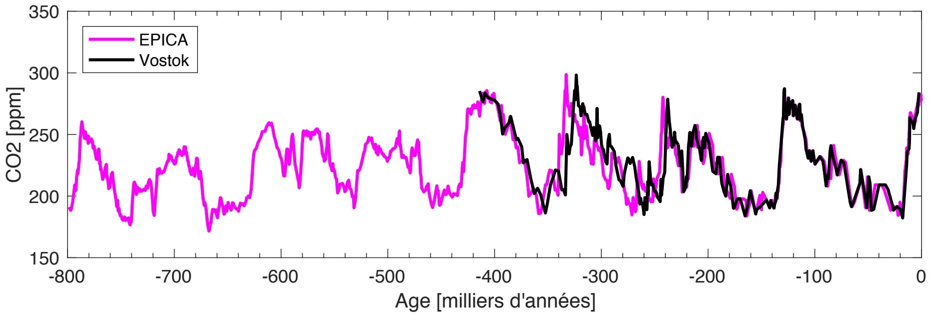


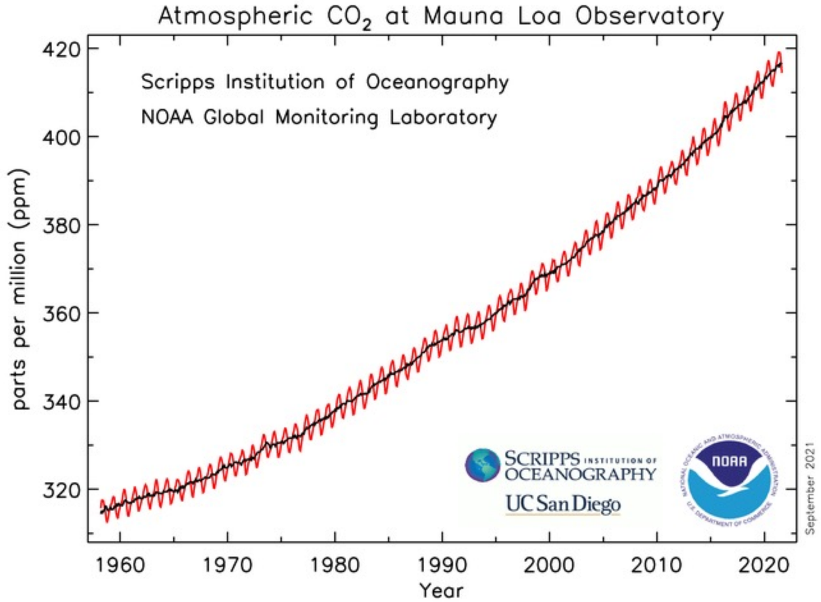


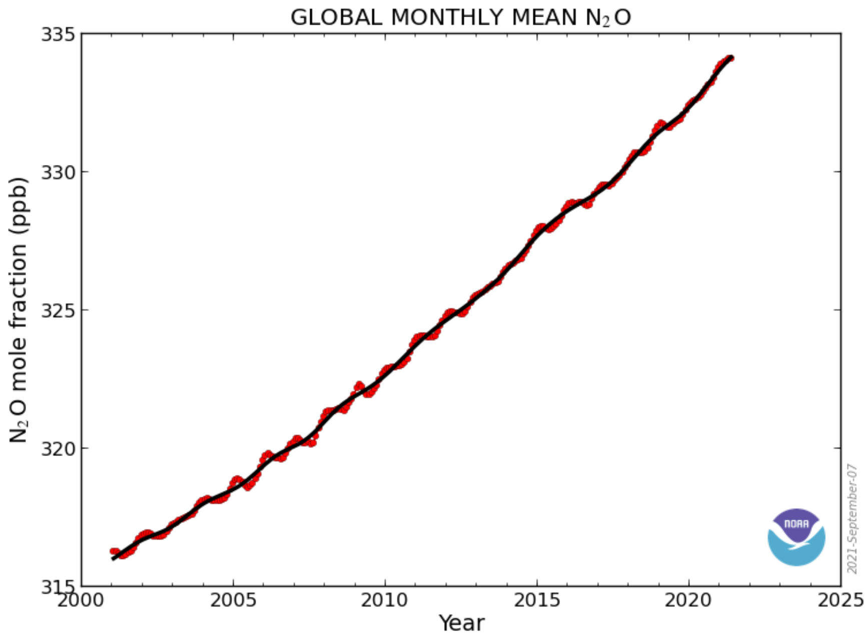


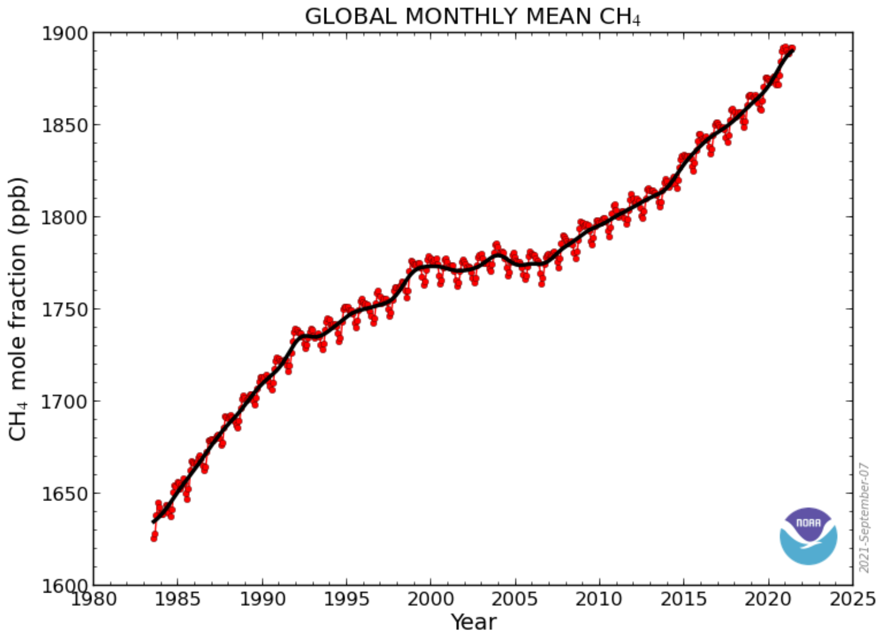
Some effects of climate change

GHG



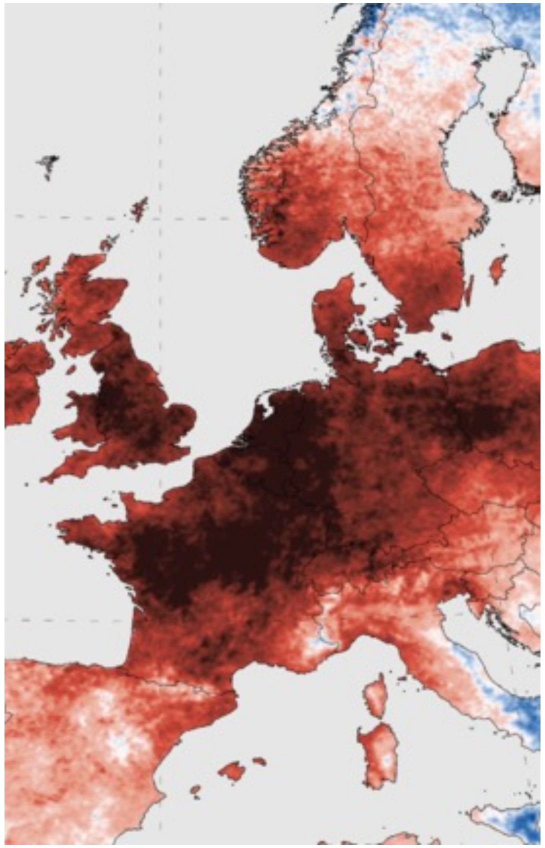






Some effects of climate change

Heat waves



European Heat Wave
EU 2006
(70'000 dead, €13 billion in damages)

Black Saturday bushfires
Australia 2009
(173 dead, > €2 billion in damages)

Californian Camp Fire
US 2018
(85 dead, > €6 billion in damages)

There is also the summer of 2021 when Algeria experienced devastating wildfires, exacerbated by an intense heatwave. The fires, particularly concentrated in the Kabylie region in northern Algeria, led to the tragic loss of numerous lives, including both civilians and soldiers who were trying to combat the flames.

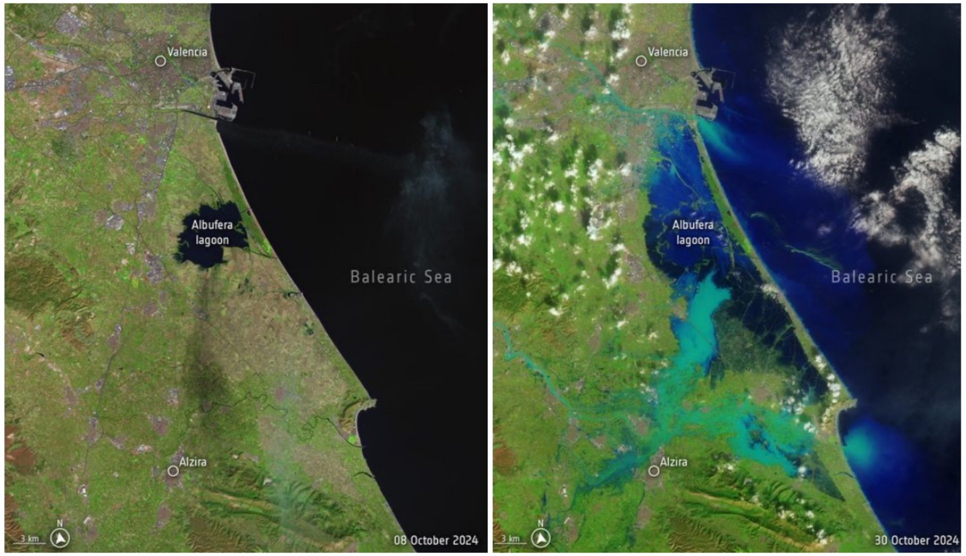
Some effects of climate change

Drought and Floods

Untold Human Suffering in Pictures

Drought | Floods

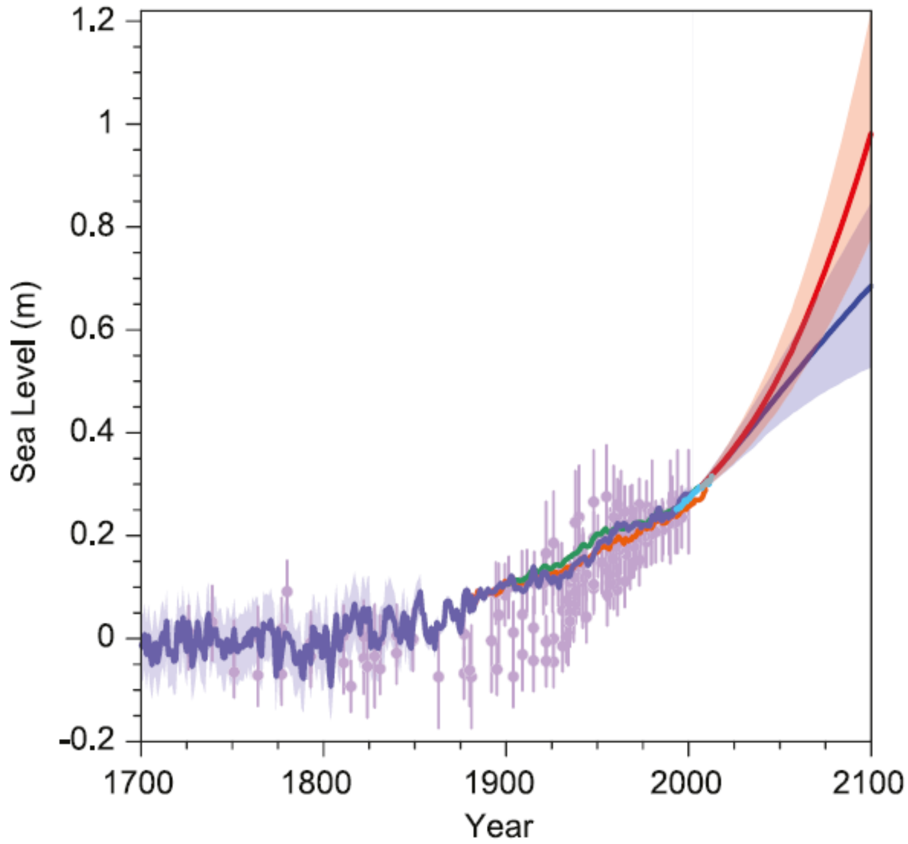
Figure 1. The impacts of climate-related droughts (left column) and floods (right column). Left column (top to bottom): "Children in dust storm" (Ethiopia, 2016; photograph: Anouk Delafortrie/EU/ECHO), a water hole that may have become empty because of drought (Mozambique, 2016; photograph: Aurélie Marrier d'Unienville/IFRC), drought-affected corn field in Paulding County, Ohio (United States, 2012; photograph: US Department of Agriculture/ Christina Reed), "Drought in Kenya's Ewaso Ngiro river basin" (Kenya, 2017; photograph: Denis Onyodi/Denis Onyodi/KRCS). Right column (top to bottom): houses are nearly submerged by flooding (Bangladesh, 2020; photograph: Moniruzzaman Sazal/Climate Visuals Countdown), "A girl, duck in hand wades through the water in Rwangara" (Uganda, 2020; photograph: Climate Centre), "two children a boy and a girl on a flooded riverbank" (Bangladesh, 2018; photograph: Moniruzzaman Sazal/Climate Visuals Countdown), "Residents wade through flooded streets to escape flood waters" (United Kingdom, 2008; John Dal). All photos are licensed under Creative Commons and all quotes are from the Climate Visuals project (https://climatevisuals.org). See supplemental file S1 for details and more pictures.

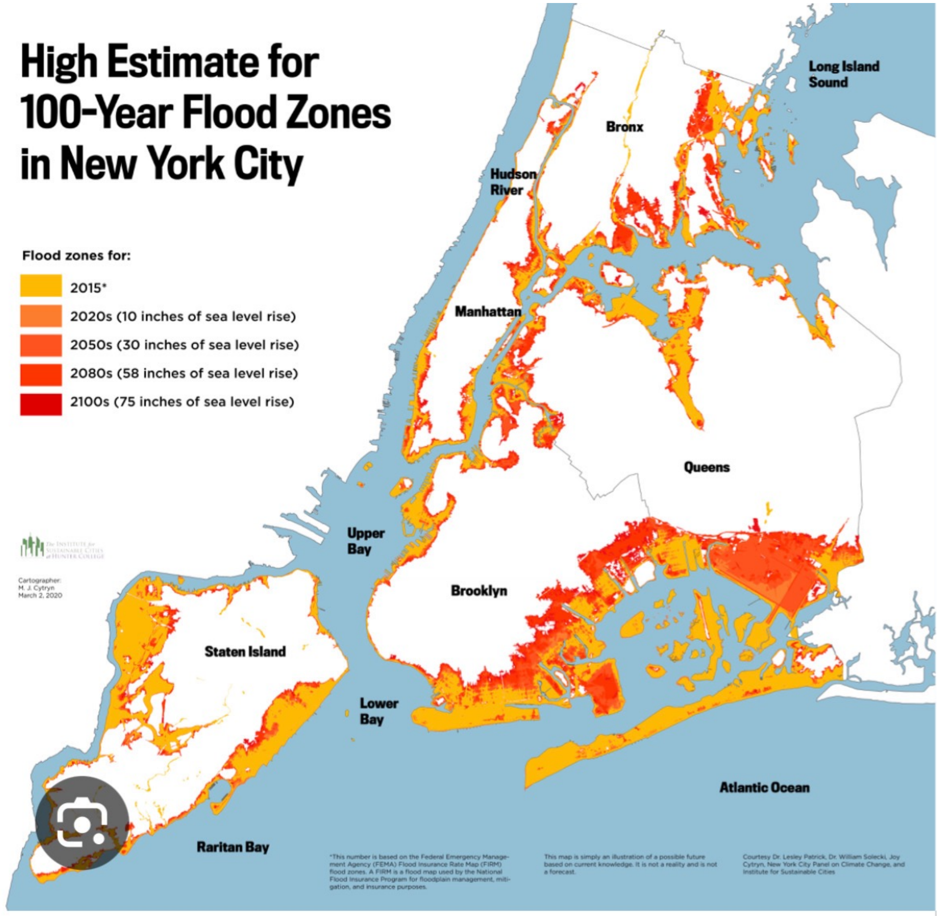


John Deere fait appel à SpaceX pour connecter ses tracteurs en toutes circonstances

Some effects of climate change

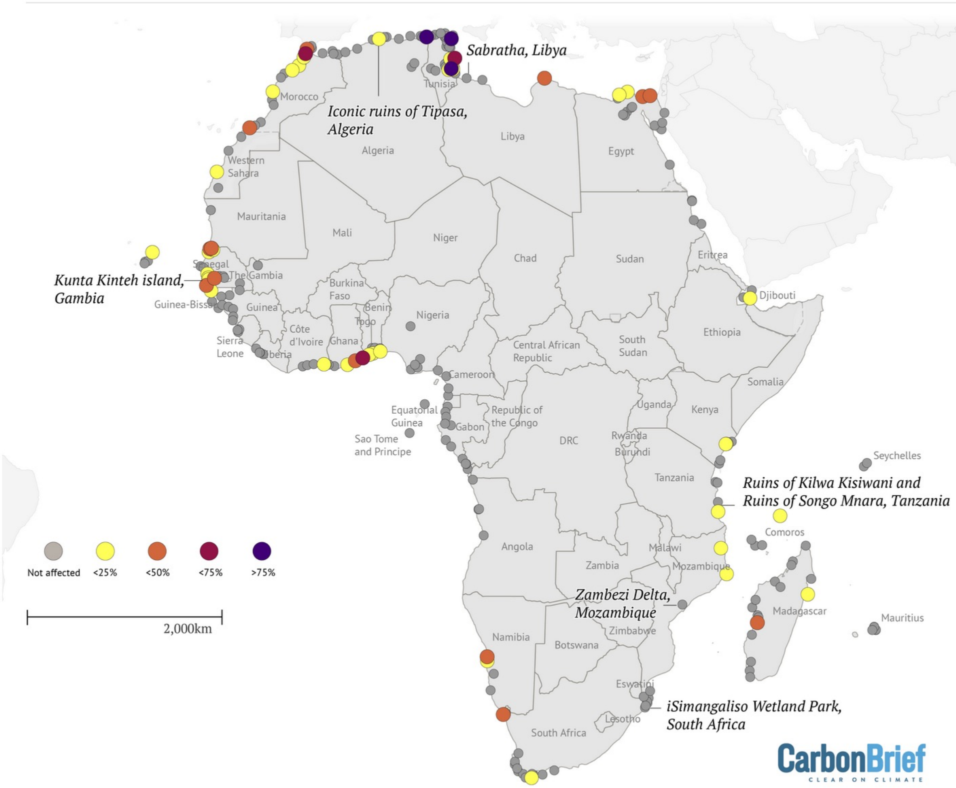
<u>**Rising sea levels**</u>

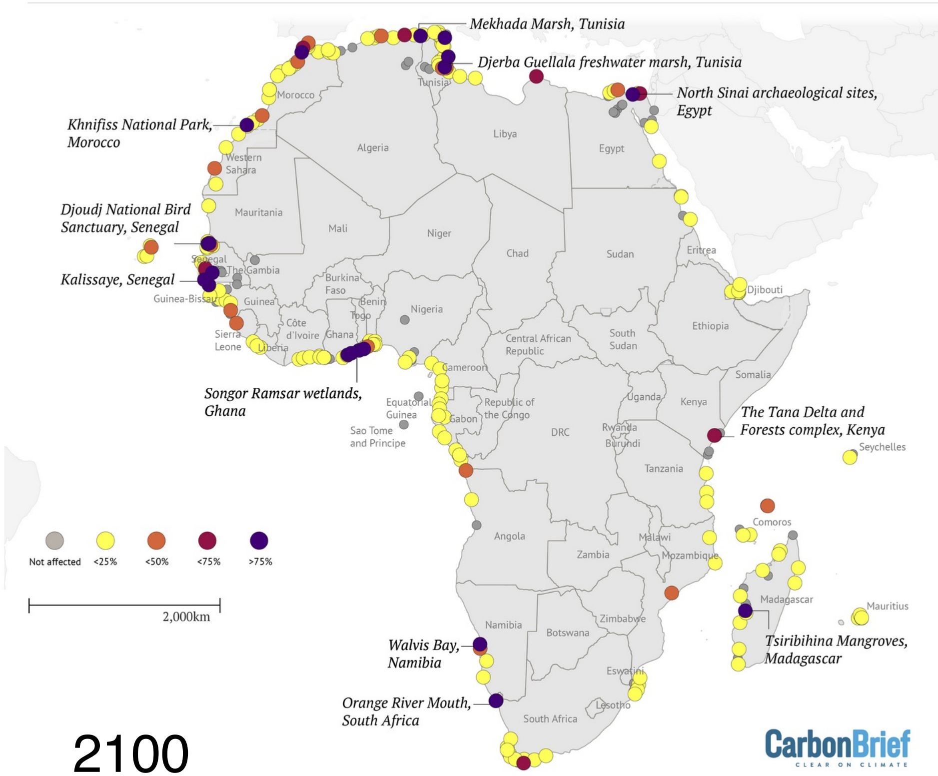




Some effects of climate change

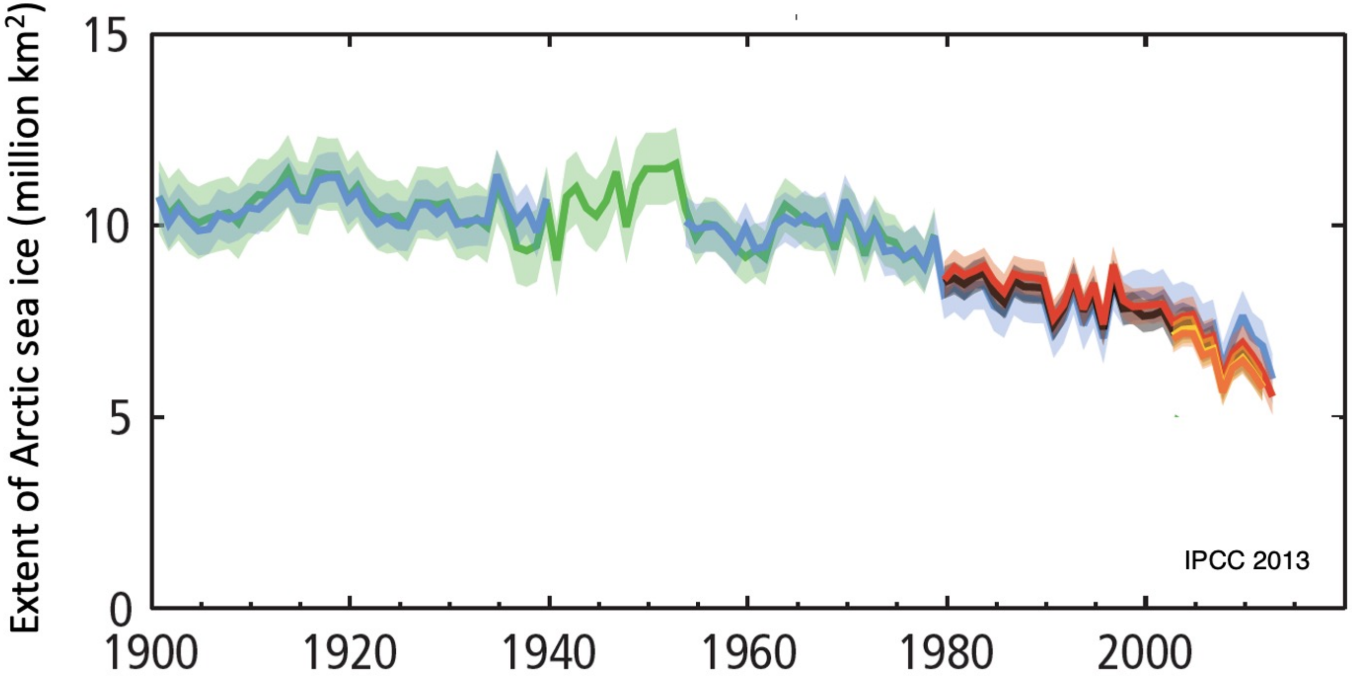
Rising sea levels

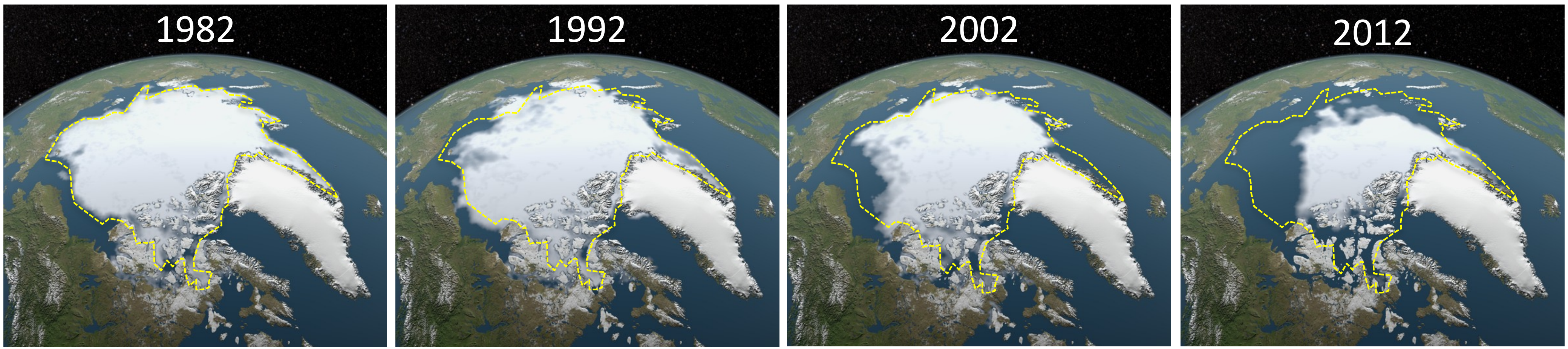




Some effects of climate change

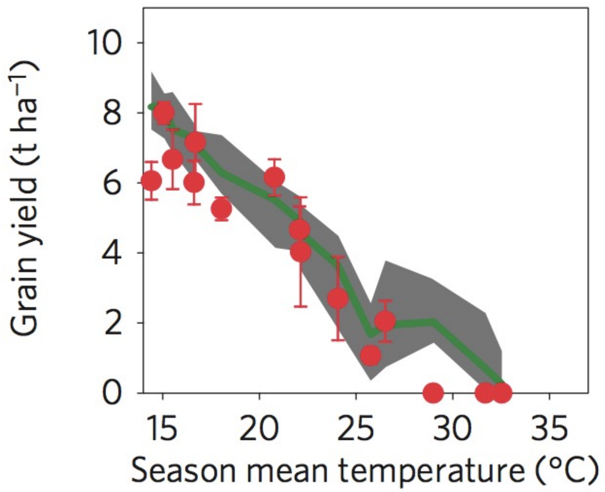
Sea ice

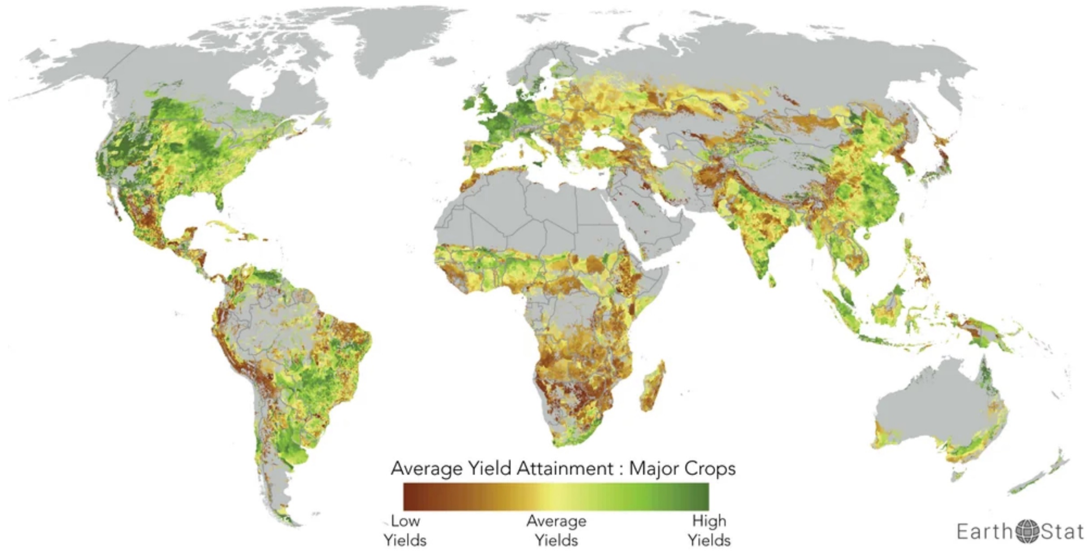


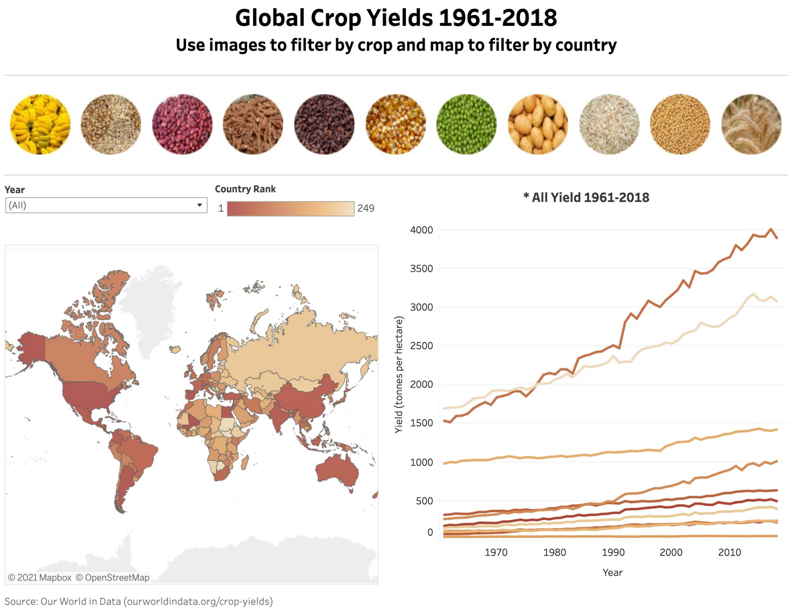


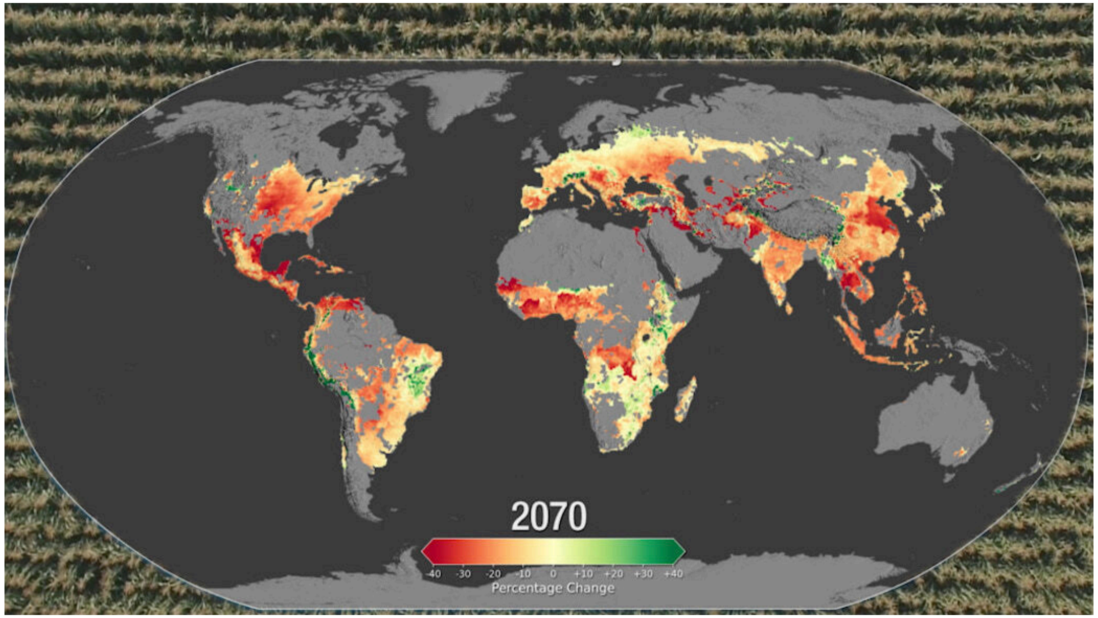
Some effects of climate change

Crops yields





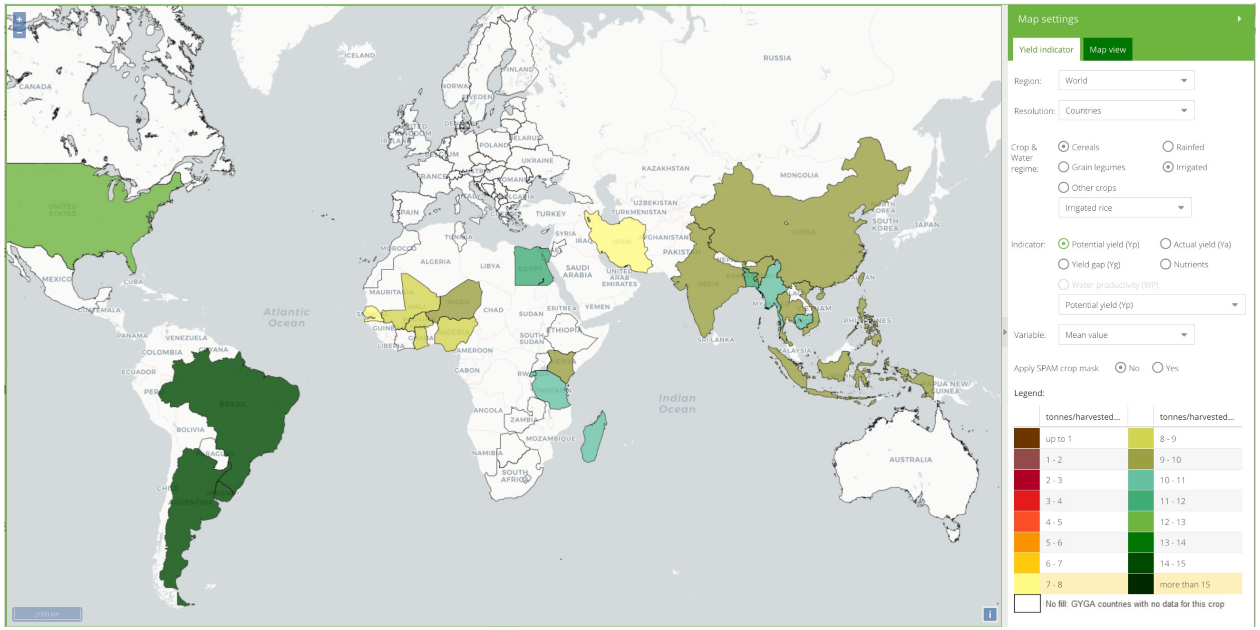


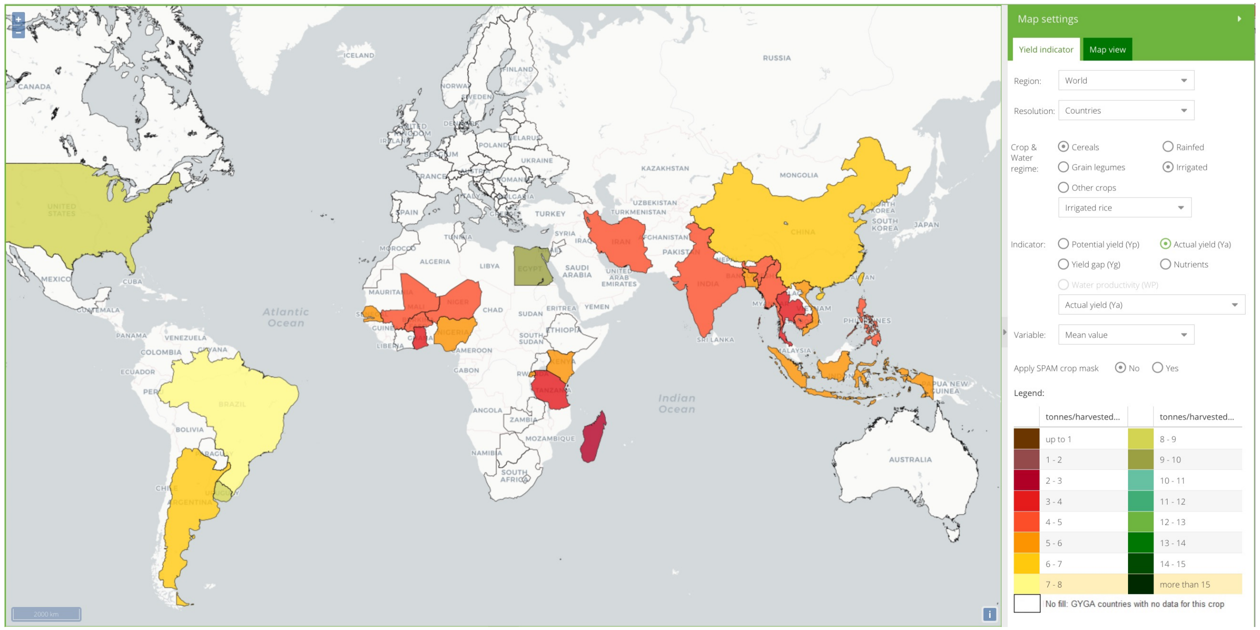


Flat map of the world showing in red where decreases in corn yields are projected to occur in 2071: parts of North america, South America, West Africa, Central Europe, India, China. Credit: NASA/Katy Mersmann

Some effects of climate change

Rice production





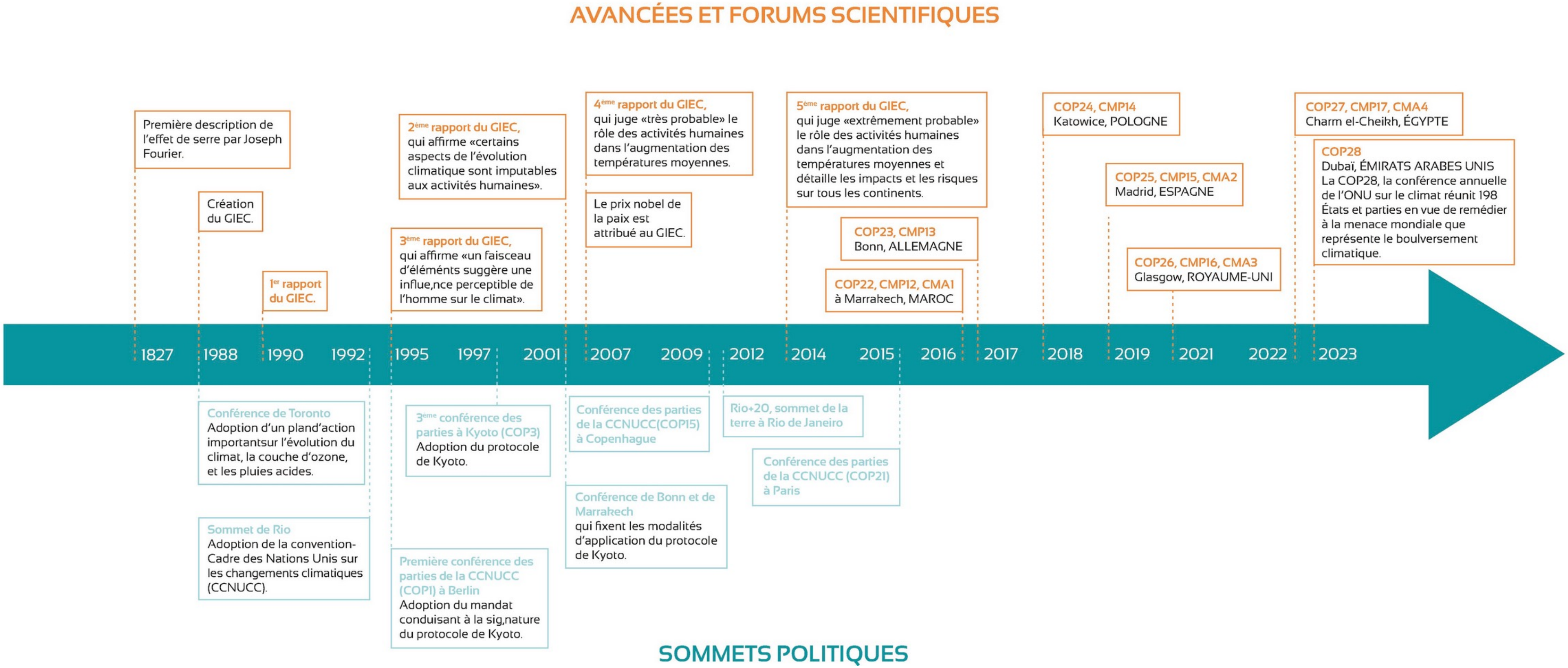
Some effects of climate change

Reducing biodiversity

Least concern	Vulnerable	Endangered	Extinct
Happy	Soon endangered?	70% dead in 3 generations (habitat < 5000 km^2) (population< 2500))	Dead
Example: pigeon, brown rat, pavement ant	Example: Koala, African elephant, panda, …	Example: Gorilla, black rhinoceros, blue whale…	Example: Dinosaurs, dodo…

Some effects of climate change

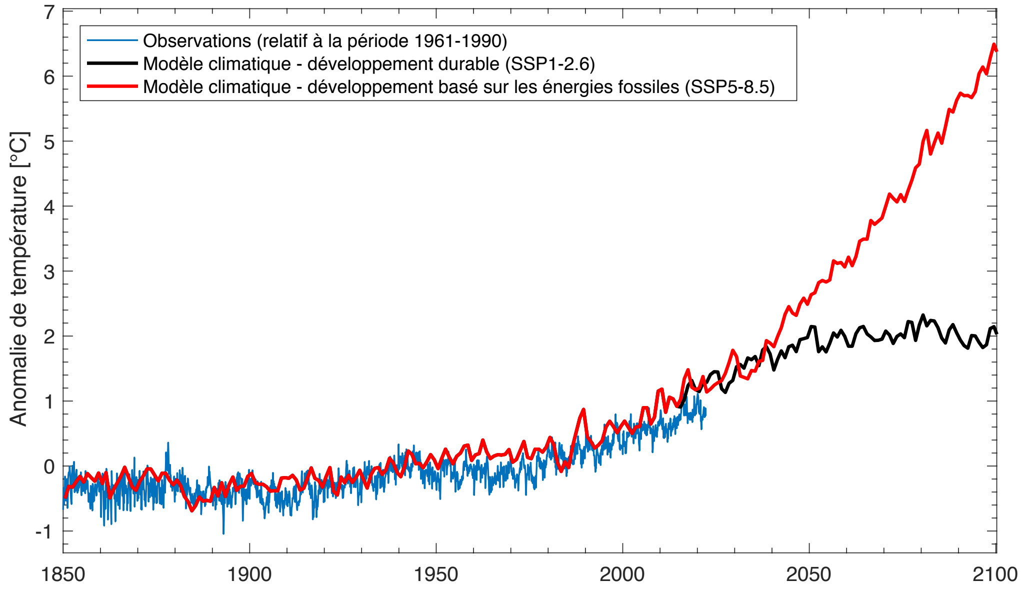
Forums

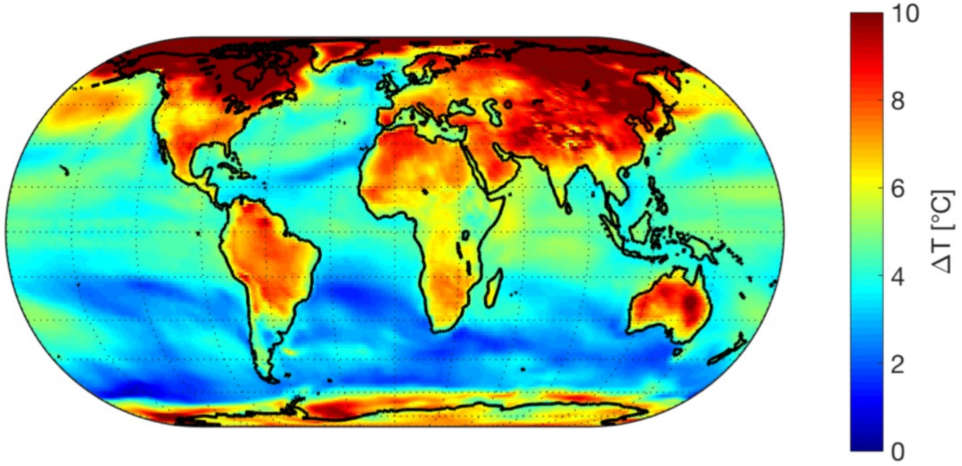


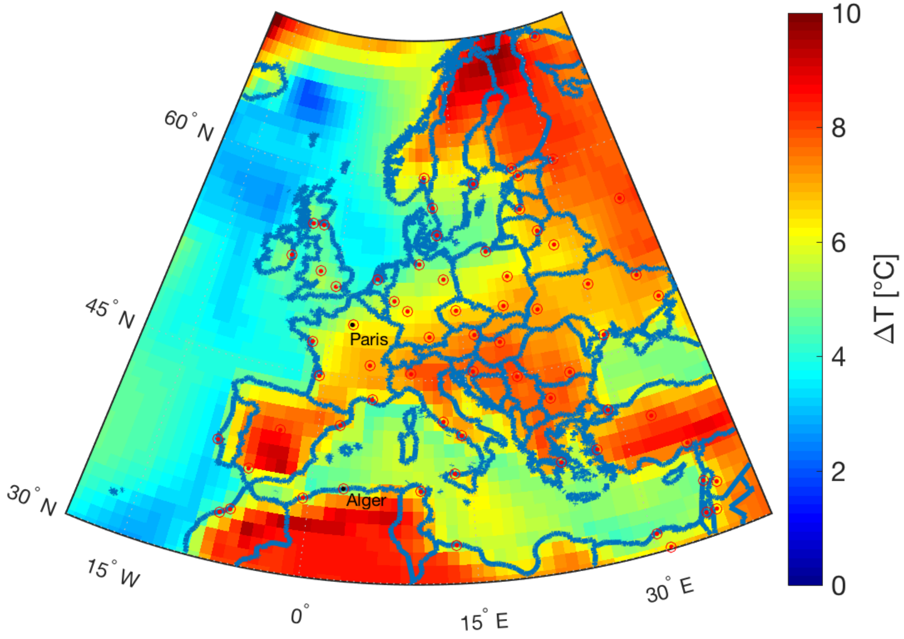
Models


Institut Pierre Simon Laplace
Institut Pierre Simon Laplace
Laboratoire des Sciences du Climat et de l'Environnement
Laboratoire de Météorologie Dynamique
Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques
cea
Direction des Sciences de la Matière

Models

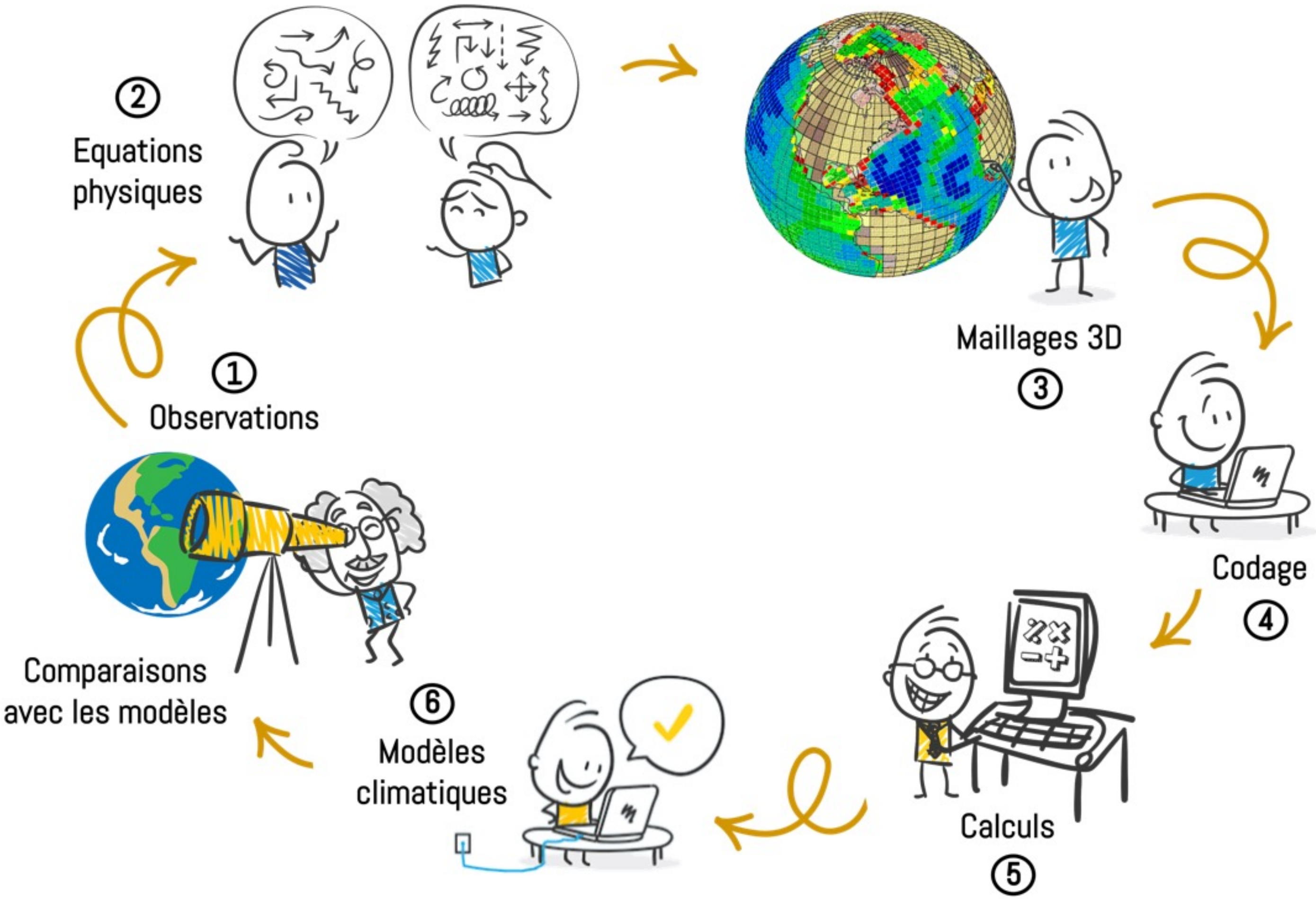






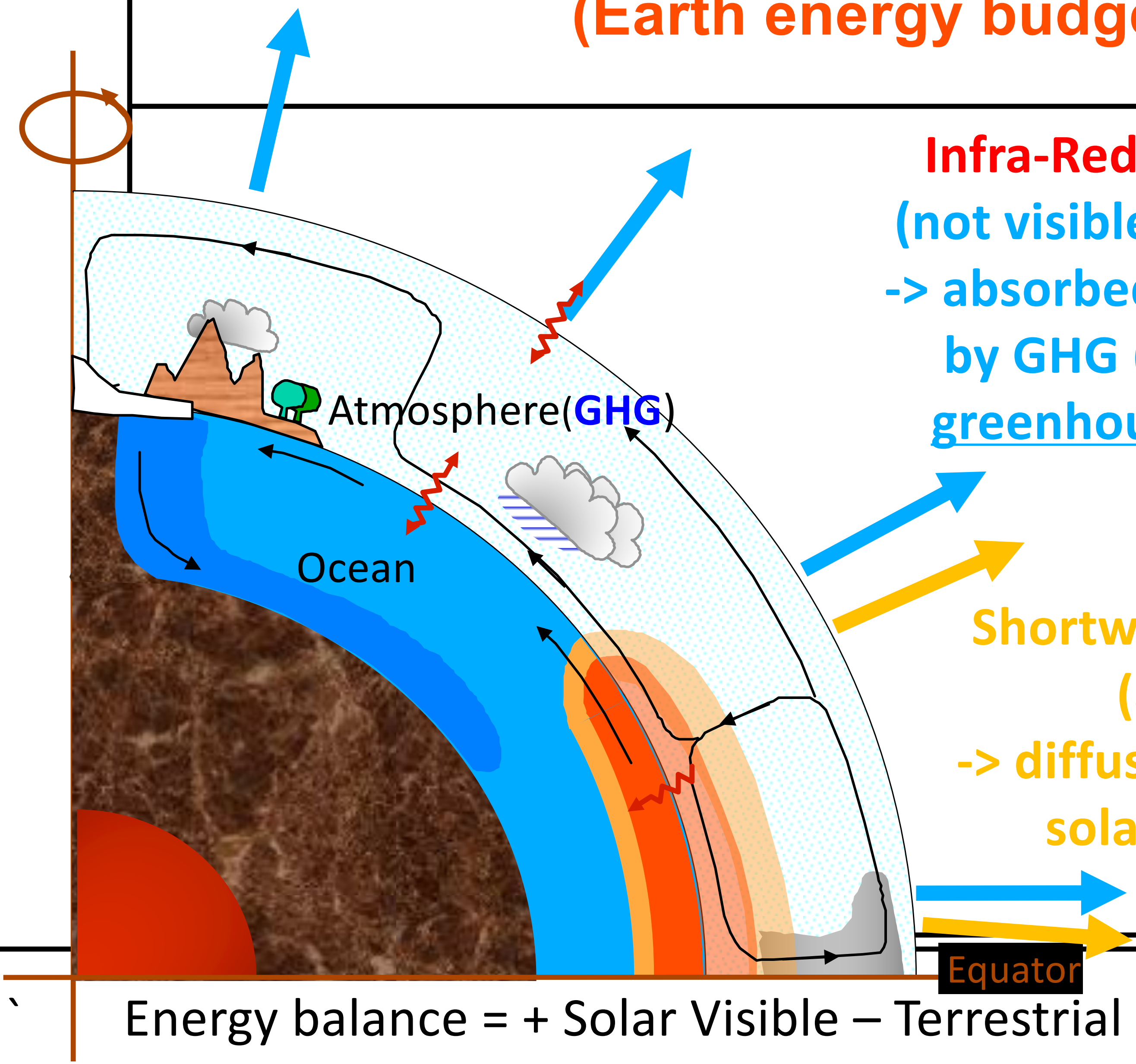
Horizon 2100

Models and satellites observations



L'espace et le NewSpace au service du climat,
Meftah M., 2023.

Climate: thermal machine (Earth energy budget)



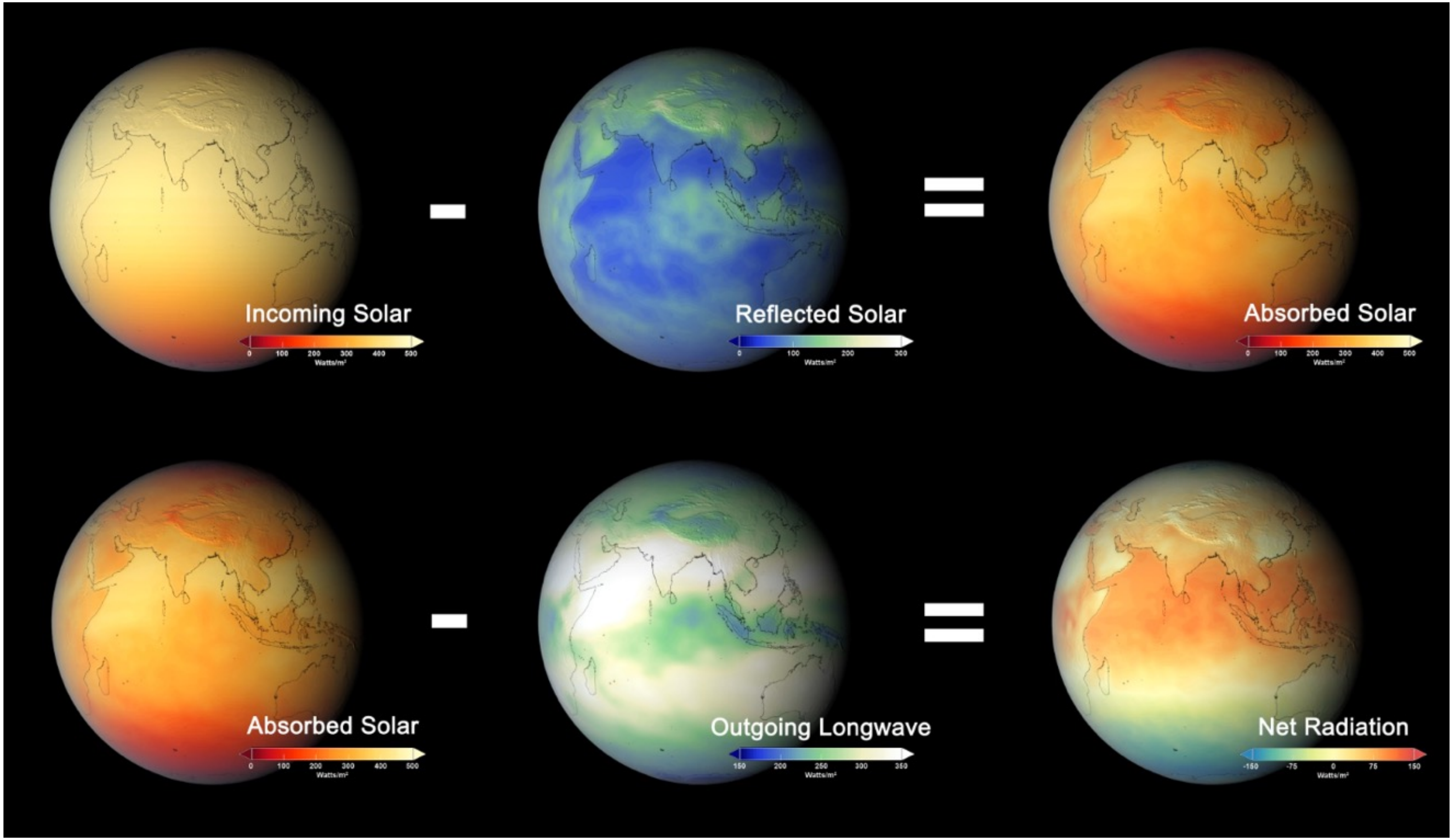
Infra-Red Radiation
(not visible with eyes)
-> absorbed/reemitted
by GHG (so-called
greenhouse effect)

Shortwave Radiation
(albedo)
-> diffuse reflection of
solar radiation

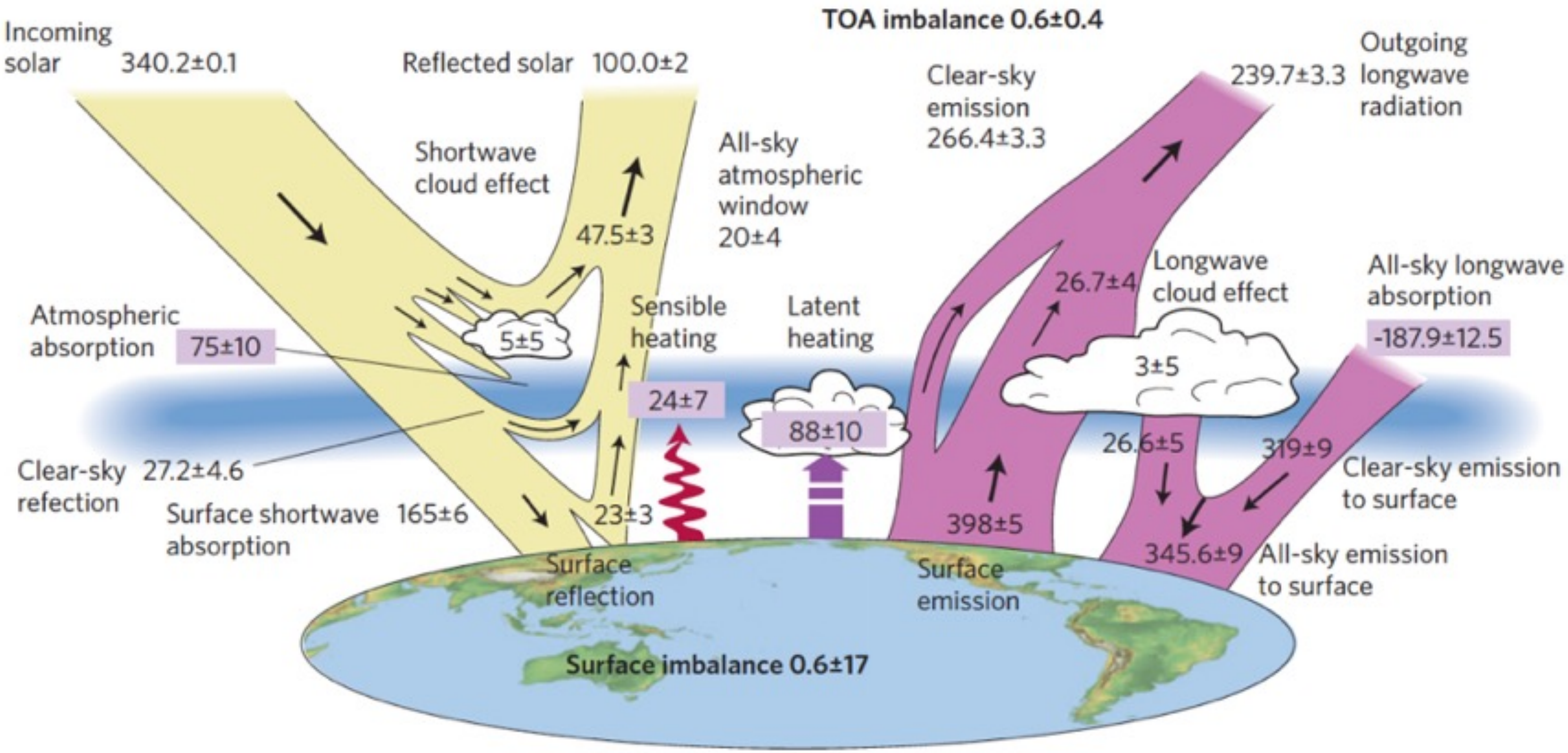
Energy balance = + Solar Visible – Terrestrial Infra-Red

Difference between incoming solar radiation and outgoing radiation

Importance of the key components of the Earth energy budget

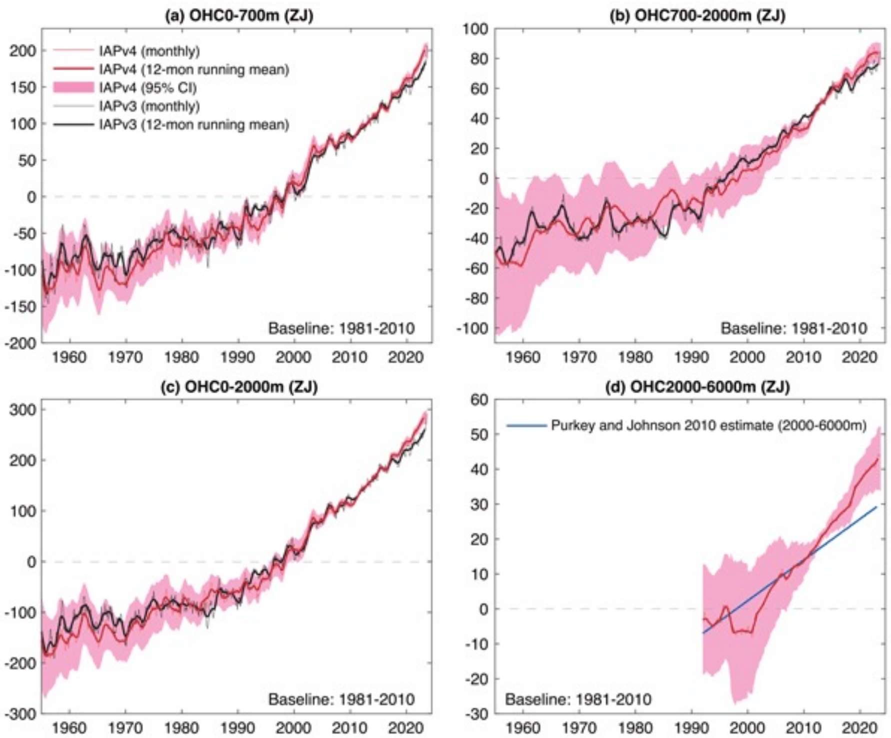


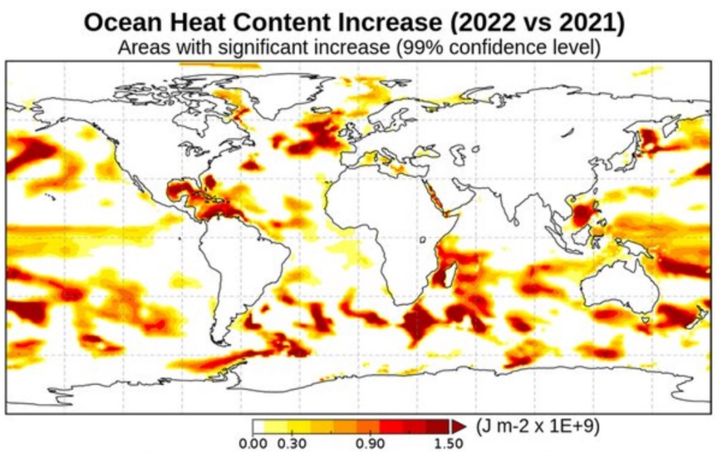
Importance of the key components of the Earth energy budget



Earth Energy Imbalance = Incoming solar –
[Reflected solar (OSR) + Outgoing longwave radiation (OLR)]

Importance of the key components of the Earth energy budget





To estimate the temperature increase due to an energy imbalance of **0.6 W/m²** over a decade, we need to account for the distribution of this energy within the climate system, particularly in the oceans, which absorb about 90% of the excess heat. Here's how to proceed:

Calculation Steps

1. **Total Accumulated Energy**: An energy imbalance of **0.6 W/m²** sustained over a decade (10 years) results in an accumulation of energy.

$$\text{Total Energy} = 0.6\,\text{W/m}^2 \times 10\,\text{years} \times 3.15 \times 10^7\,\text{s/year} \approx 1.89 \times 10^9\,\text{J/m}^2$$

2. **Surface Area of Earth**: The total surface area of Earth is approximately $5.1 \times 10^{14}\,\text{m}^2$, so the total accumulated energy is:

$$\text{Total Energy} = 1.89 \times 10^9\,\text{J/m}^2 \times 5.1 \times 10^{14}\,\text{m}^2 = 9.64 \times 10^{23}\,\text{J}$$

Converting this to zettajoules (1 ZJ = 10^{21} J):

$$\text{Total Energy} = 9.64 \times 10^{23}\,\text{J} = 964\,\text{ZJ}$$

3. **Distribution of Energy (90% in the Oceans)**: Since the oceans absorb about 90% of this energy, we have:

$$\text{Ocean Energy} = 0.9 \times 9.64 \times 10^{23}\,\text{J} \approx 8.68 \times 10^{23}\,\text{J} = 868\,\text{ZJ}$$

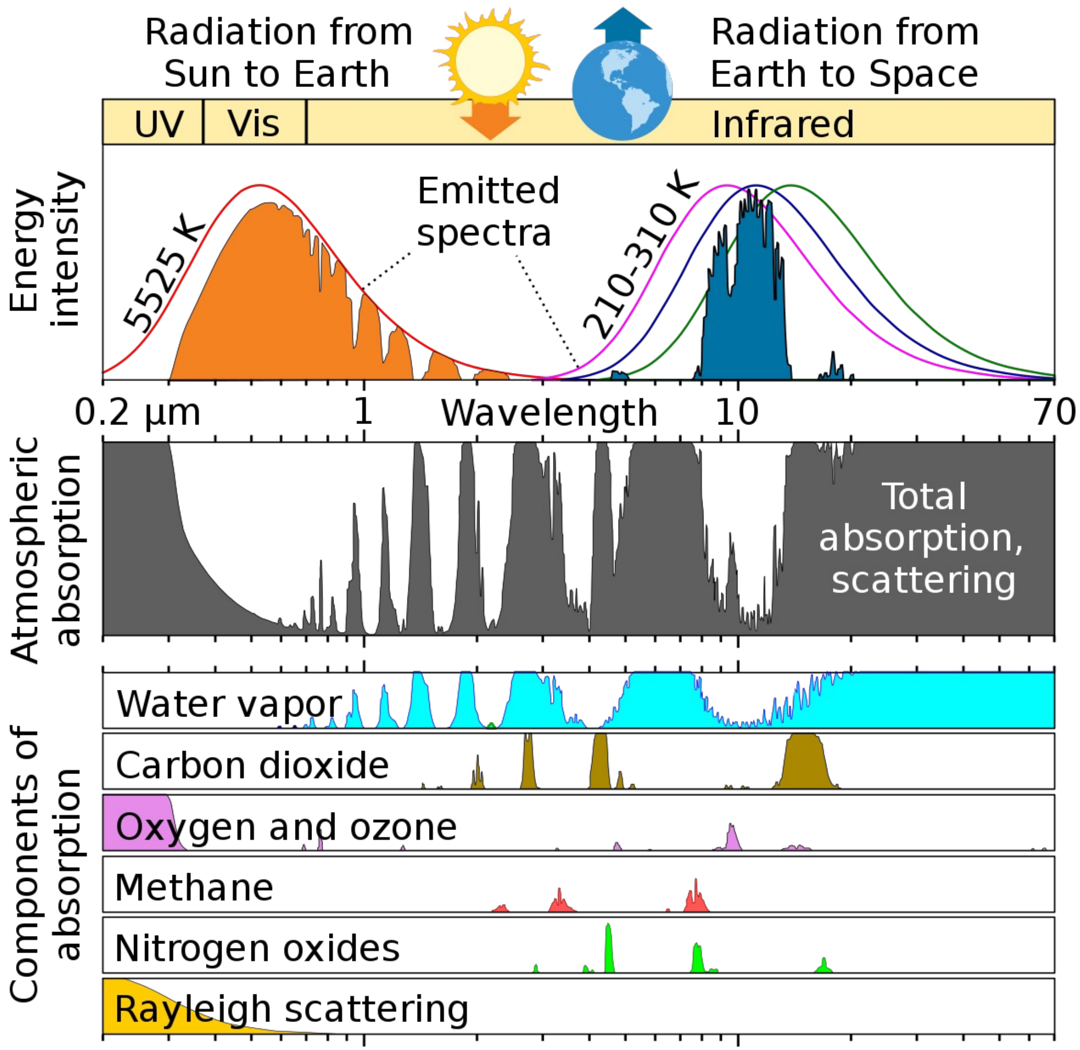
4. **Temperature Increase of the Oceans**:
   - The volume of the upper 700 meters of the ocean, which responds most quickly to climate changes, is approximately $3.6 \times 10^{17}\,\text{m}^3$.
   - The specific heat capacity of seawater is about $4.18 \times 10^3\,\text{J/(kg K)}$.
   - The density of seawater is around $1025\,\text{kg/m}^3$.

Using these values, we calculate the average temperature increase in the upper 700 meters of the ocean:

$$\Delta T = \frac{8.68 \times 10^{23}\,\text{J}}{3.6 \times 10^{17}\,\text{m}^3 \times 1025\,\text{kg/m}^3 \times 4180\,\text{J/(kg K)}}$$

$$\Delta T \approx 0.55\,^\circ\text{C}$$

Importance of GHG and role in Earth enegy budget



At ~1.6 µm, the entire CO_2 column is measured. Whereas at ~15µm, it's sensitive to the temperature of the stratosphere.

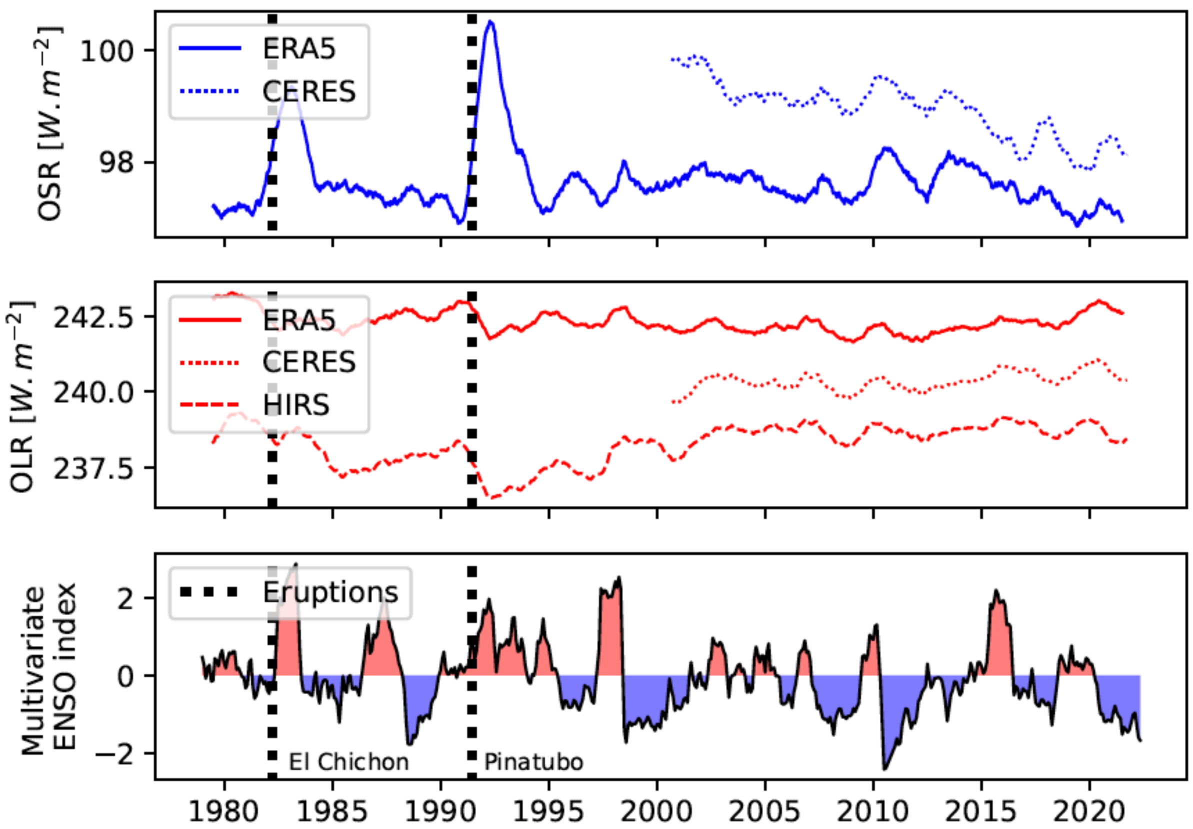
The ~8 µm band is sensitive to silicates (deserts).

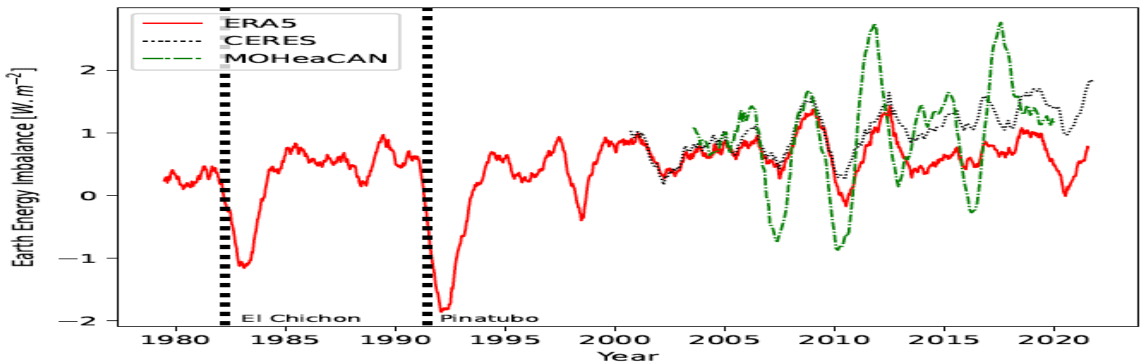
The ~10µm band is sensitive first to the surface temperature and then to emissivity.

At ~19.2 µm, it's sensitive to the presence and characteristics of high cirrus clouds.

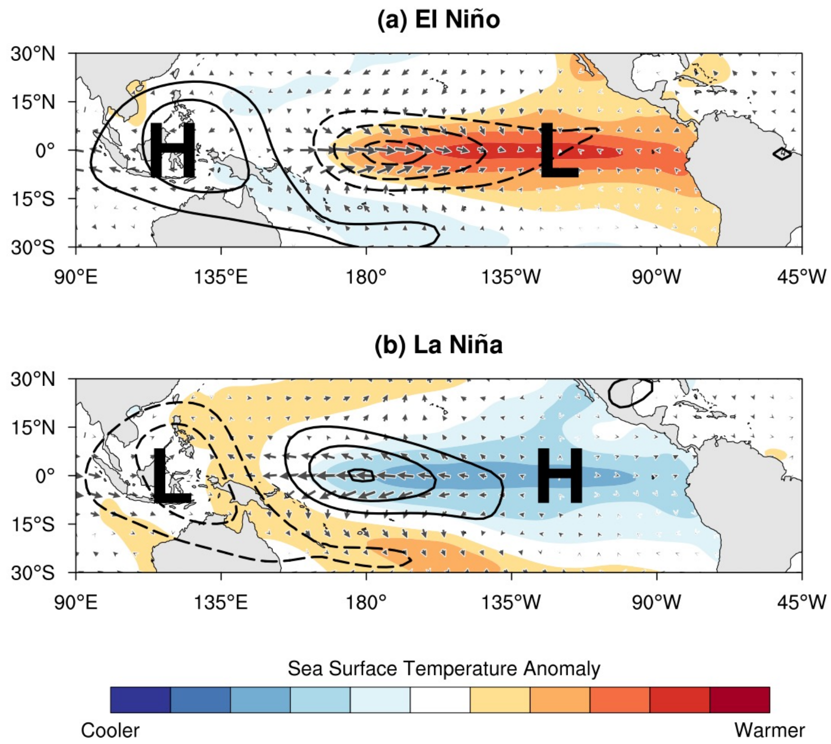
At ~40 µm, it depends on stratospheric water vapor.

Importance of OLR and OSR observations





Finance (Phd thesis), 2023



The El Niño–Southern Oscillation (ENSO) recurring climate pattern causes fluctuations in heat storage in the ocean, leading to temporary global warming during El Niño phases (recent major events: 1982–1983, 1997–1998, and 2014–2016) when the ocean surface warms up in the central and eastern tropical Pacific Ocean, removing heat by radiating it back to space. Since May 2023, negative OLR anomaly values indicate the return of El Niño to the tropical Pacific after seven years.

Satellites constellation

❑ Importance of satellite observations.

- Satellite observations are useful for:
  - Understanding how clouds and aerosols influence Earth's energy balance from the top of the atmosphere to the surface.
  - Better determining atmospheric and oceanic circulations.
  - Better understanding the processes related to large tropical convective systems and their life cycle.
  - Understanding trends and patterns of change associated with sea ice and snow cover in polar regions.
  - Improving seasonal to interannual forecasts, ...

- To improve our understanding of Earth's energy balance, observations are needed over several time scale ranges (multi-decadal variations, annual, seasonal, monthly, and the diurnal cycle of these different systems).

- This information/observations are important for refining models.

Satellites constellation

❑ Importance of Earth radiative budget at the top of the atmosphere

- The first challenge comes from the studies by Lindzen in 1994 and 1998. These studies argue that the response time of surface temperature isn't just influenced by λ (the climate feedback parameter that accounts for individual feedback processes) and the ocean's mixed layer heat capacity. The diffusion coefficient k, found at the base of the mixing layer, also plays a crucial role. This coefficient, however, is not well-understood. The deep ocean and the oceanic mixing layer are pivotal in determining how surface temperature reacts over time. The climate feedback parameter measures how Earth's climate reacts to energy changes entering and exiting the planet. **To accurately determine λ, another separate observation is essential**.

- **The second challenge involves the unpredictability in historical measurements of radiative forcing, particularly from aerosols, which counterbalance some of the radiative forcings from CO_2**. The accurate values for k and λ remain elusive. To address these uncertainties, Hansen et al. in their 2005 and 2011 studies suggest utilizing precise ocean heat content measurements. This approach offers a way to tackle the uncertainties in assessing historical radiative forcing and the vertical heat diffusion in the ocean over past periods.

Satellites constellation

❑ Requirements

Produit	Fréquence	Résolution	Incertitude de mesure requise	Stabilité par décennie
Tableau de synthèse – Bilan radiatif de la Terre				
Rayonnement à ondes longues sortant (OLR)	Mensuel (résolution du cycle diurne), 3 heures	10-100 km / NA* * Non applicable	Exigences en moyenne globale : 1,0 W/m²	0,1 W/m² par décade
Rayonnement à ondes courtes sortant (OSR)	Mensuel (résolution du cycle diurne)	10-100 km / NA	Exigences en moyenne globale : 1,0 W/m²	0,1 W/m² par décade
Irradiance solaire totale (TSI)	Journalier	NA / NA	0,54 W/m²	0,1 W/m² par décade
Irradiance solaire spectrale	Journalier	1 nm < 290 nm ; 2 nm 290-1000 nm ; 5 nm 1000-1600 nm ; 10 nm 1600-3200 nm	0,3 %	1 % par décade

M. Meftah, 2023.
Livre : L'espace et le NewSpace au service du climat.

Produit	Fréquence	Résolution	Incertitude de mesure requise	Stabilité par décennie
Tableau de synthèse – Atmosphère				
Profil de température troposphérique	3 heures	25 km / 1 km	0,5 °C	0,05 °C
Profil de température stratosphérique	3 heures	100 km / 2 km	0,5 °C	0,05 °C
Tableau de synthèse – Composition atmosphérique				
CO_2	3 heures	2-10 km / NA	1 ppm 0,2 ppm biais interrégional	0,2 ppm par décade
Colonne de CO_2 troposphérique	3 heures	2-10 km / NA	1 ppm	1,5 ppm par décade
CO_2 troposphérique	3 heures	2-10 km / 5 km	1 ppm	1,5 ppm
Colonne de Méthane troposphérique	3 heures	2-10 km / NA	10 ppb	7 ppb
Méthane troposphérique	3 heures	2-10 km / 5 km	0,5 ppb	0,7 ppb
Méthane stratosphérique	Journalier	100-200 km / 2 km	5 %	0,30 %

- **To achieve these performance levels (time criteria), it is necessary to implement satellite constellations.**
- **Spatial resolution (< 30 km for Earth radiative budget, <10 km for convective cells and water vapor, etc.) and temporal resolution (3 hours).**

Satellites constellation

Scientific issue:

Earth's energy imbalance (Climate change), including radiative impacts of aerosols and clouds (highly variable spatially and temporally), key uncertainties in climate sciences.

Definition of parameters and performances requirements:

Resolve diurnal variations (e.g. every 3 hours) and small scales (ideally few km resolution)

"Small Sat" constellation for multi-point observations

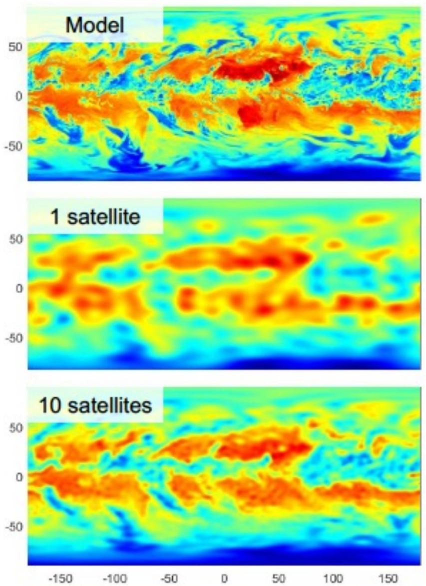
Instruments identification

Detailed instruments and subsystems modelling

- Diurnal variations (LTAN 3H00, 6H00, 9H00, 12H00)

- Few km for spatial resolution

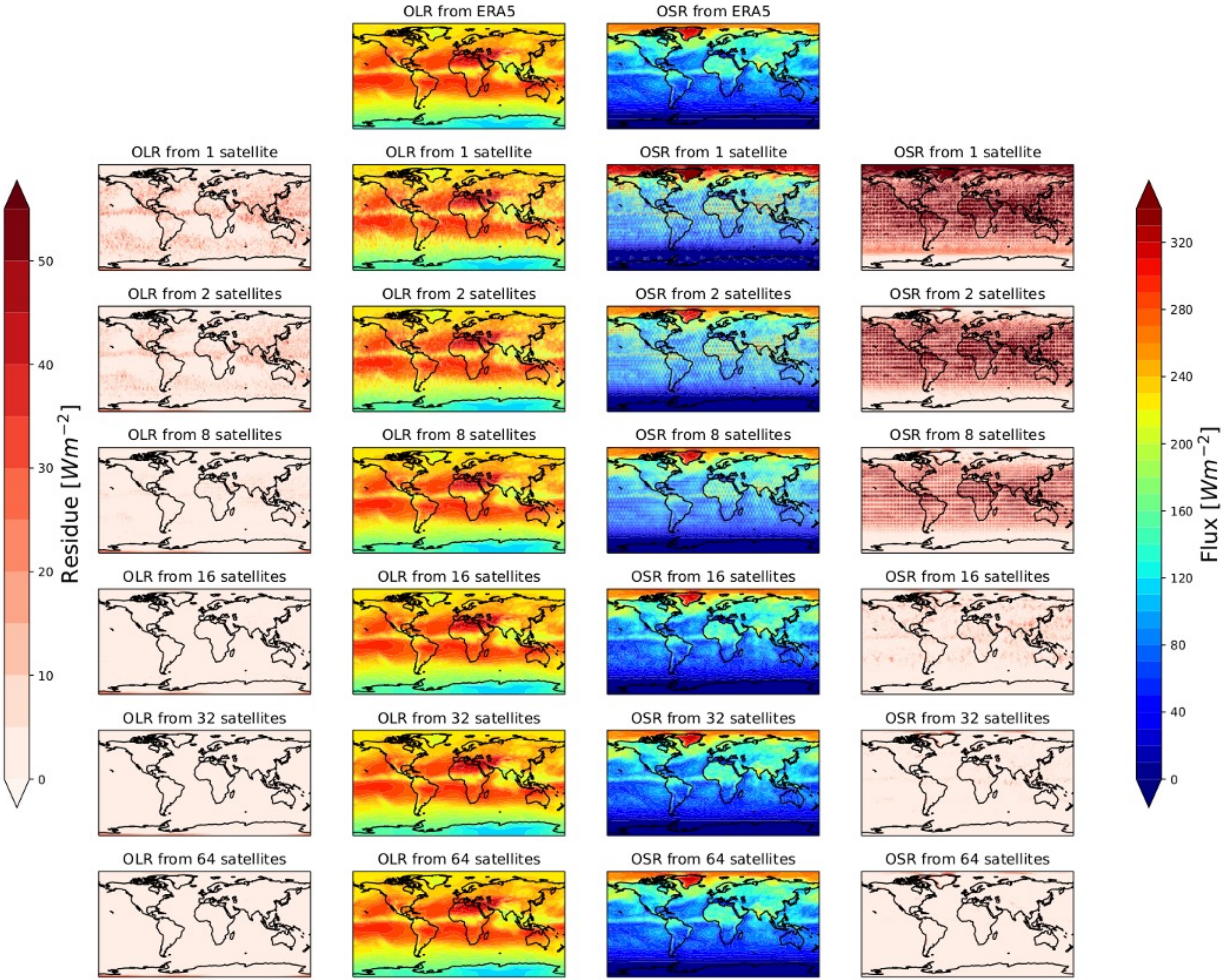
EEI has been identified as a fundamental diagnostic for analyzing climate variability and anticipating future climate changes. EEI direct measurement represents one of the greatest challenges in climate research.



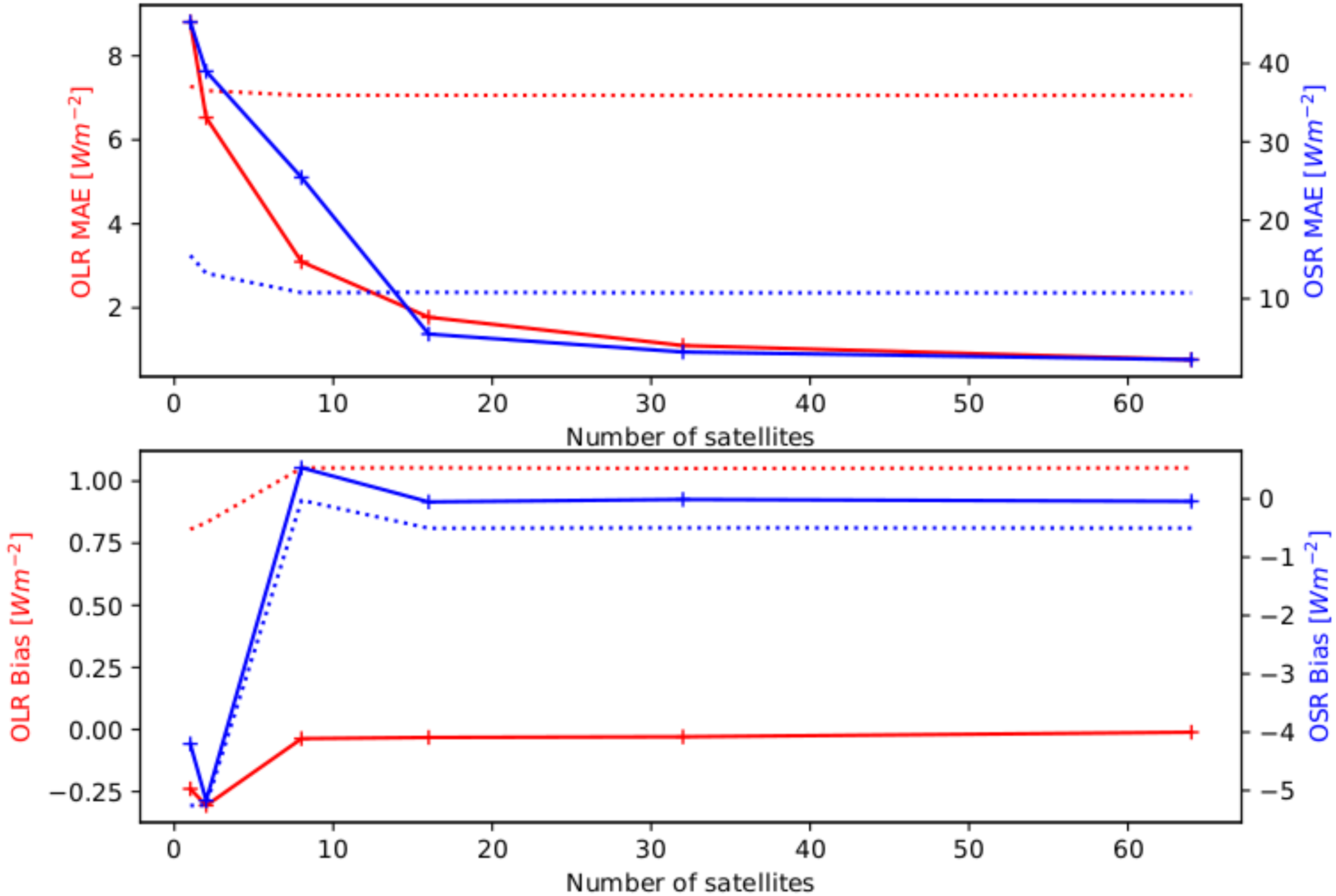
Performance analysis:

Revisit time and spatial resolution as as a function of instruments characteristics (including power and data storage) and configuration (e.g. number of satellites).

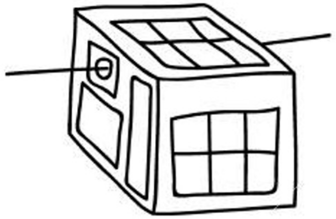
Satellites constellation

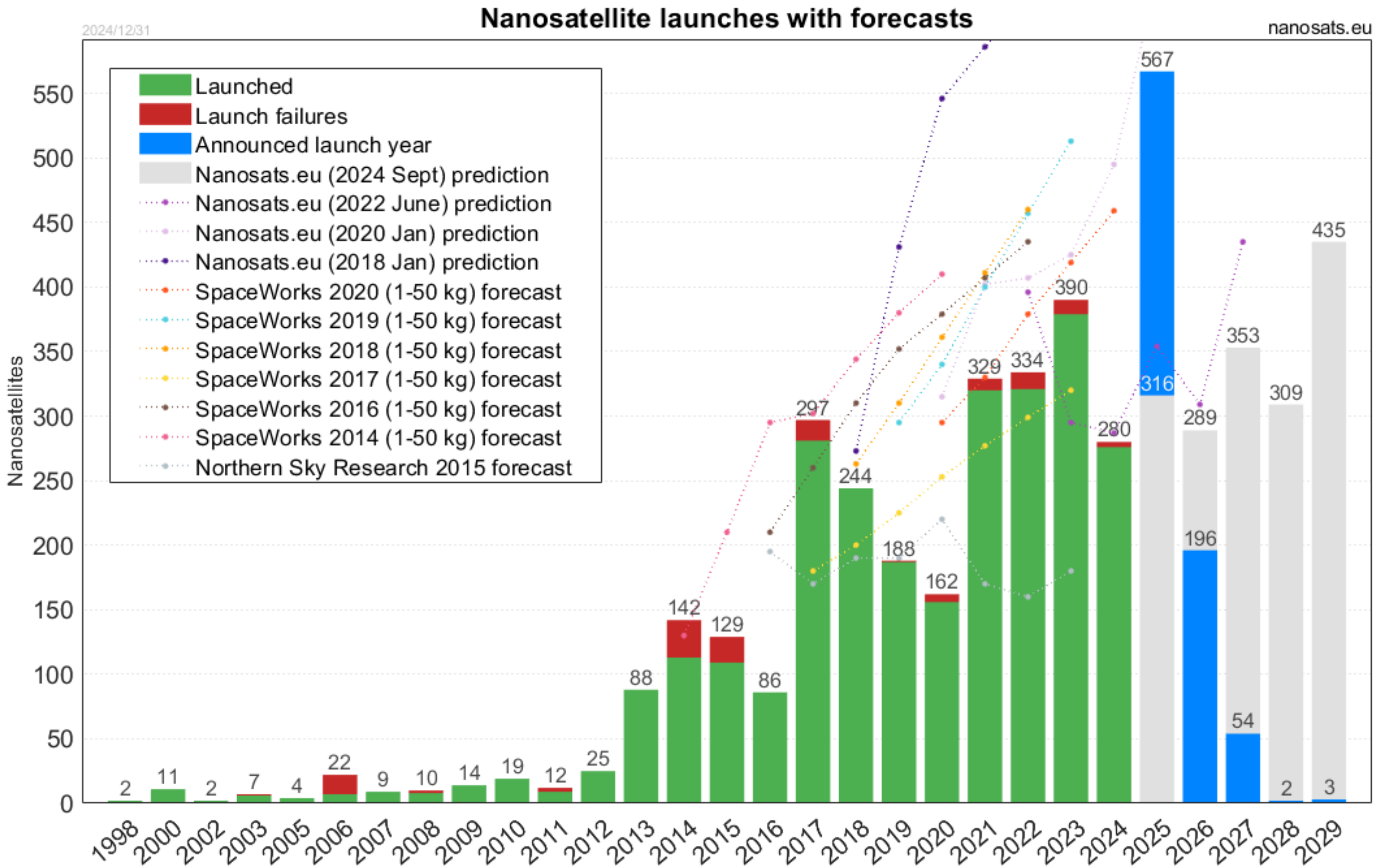


Satellites constellation

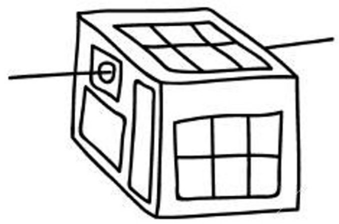


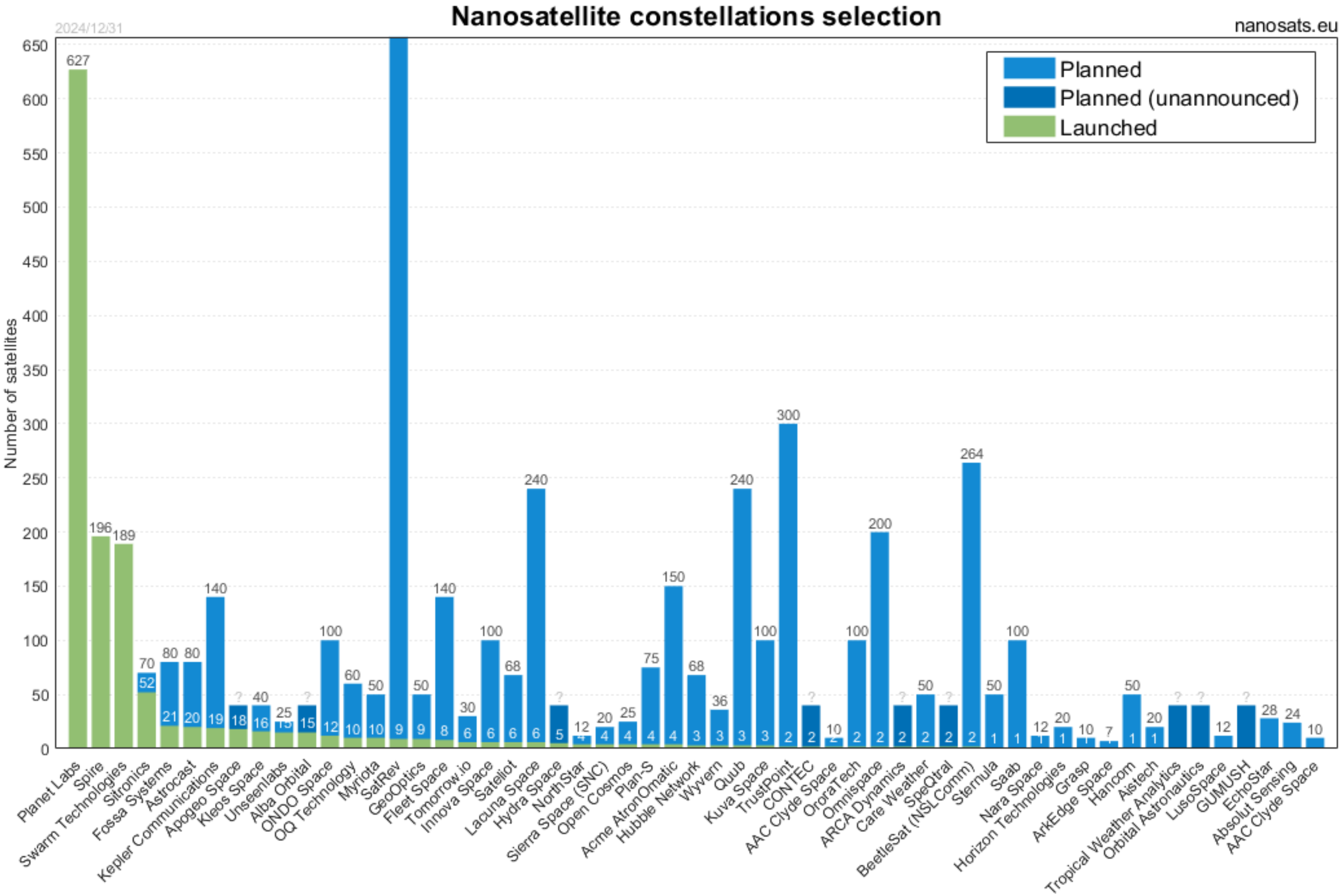
Satellites constellation



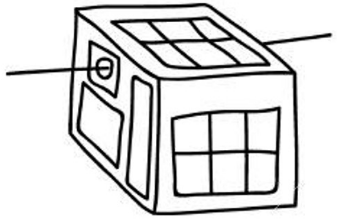


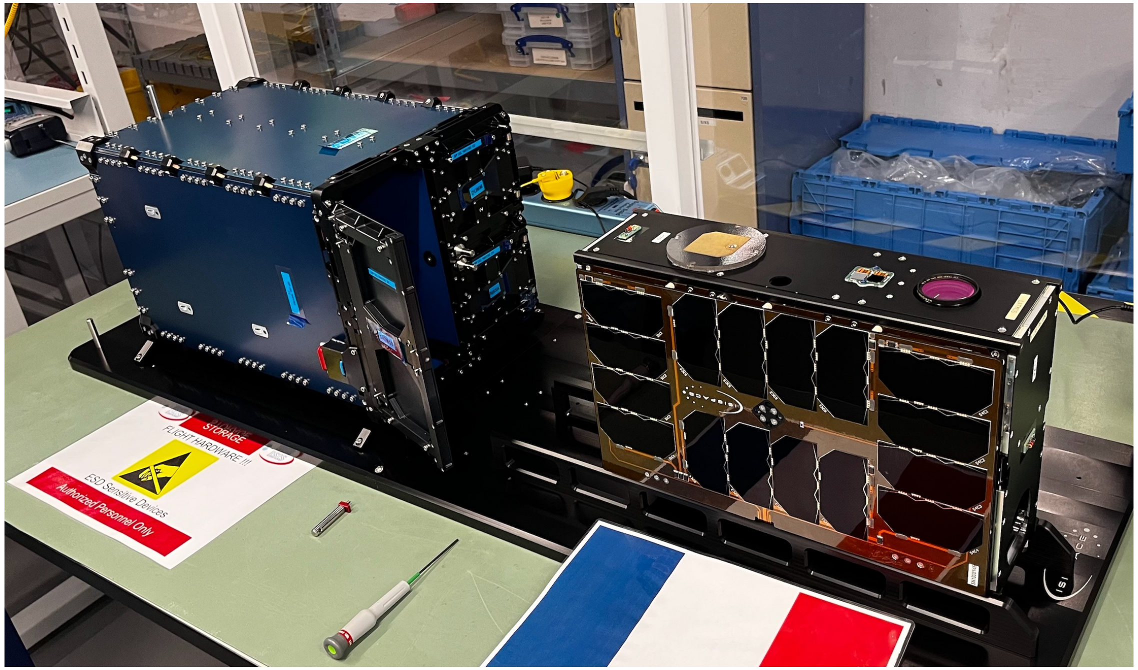
Satellites constellation

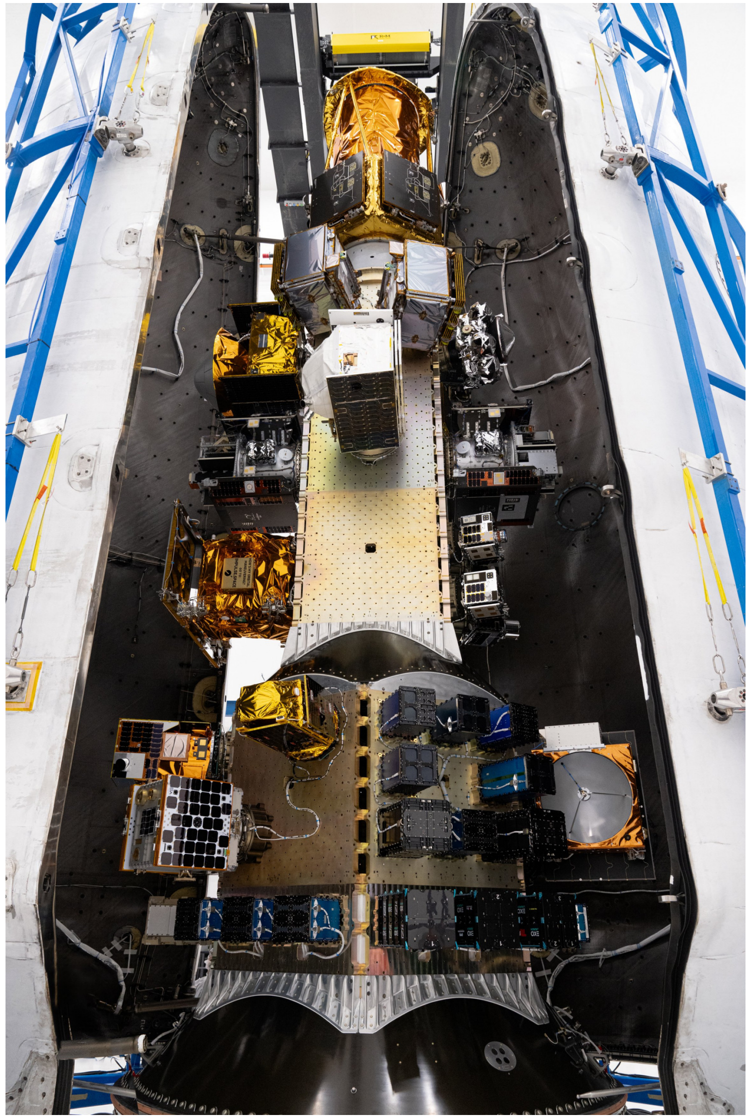




Satellites constellation



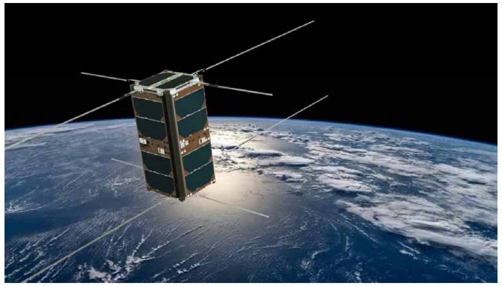




Satellites constellation

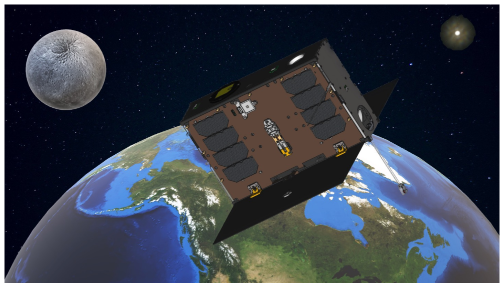
UVSQ-SAT (Inspire-Sat 5)

2018 — Studies ① + Manufacture ② Tests — 24/01/2021 — Exploitation ③ 13/03/2021 — End of Life 24/01/2024 ? — Data exploitation ④



Inspire-Sat 7

2020 — Studies ① + Manufacture ② Tests — 15/04/2023 — Exploitation ③ 15/05/2023 — End of Life 15/04/2026 ? — Data exploitation ④



UVSQ-SAT NG (Inspire-Sat X)

2021 — Studies ① + Manufacture ② Tests — 13/03/2025 — Exploitation — End of Life — Data exploitation ④

Phases 0/A, B, C, D — **Phase E** — **Phase F**

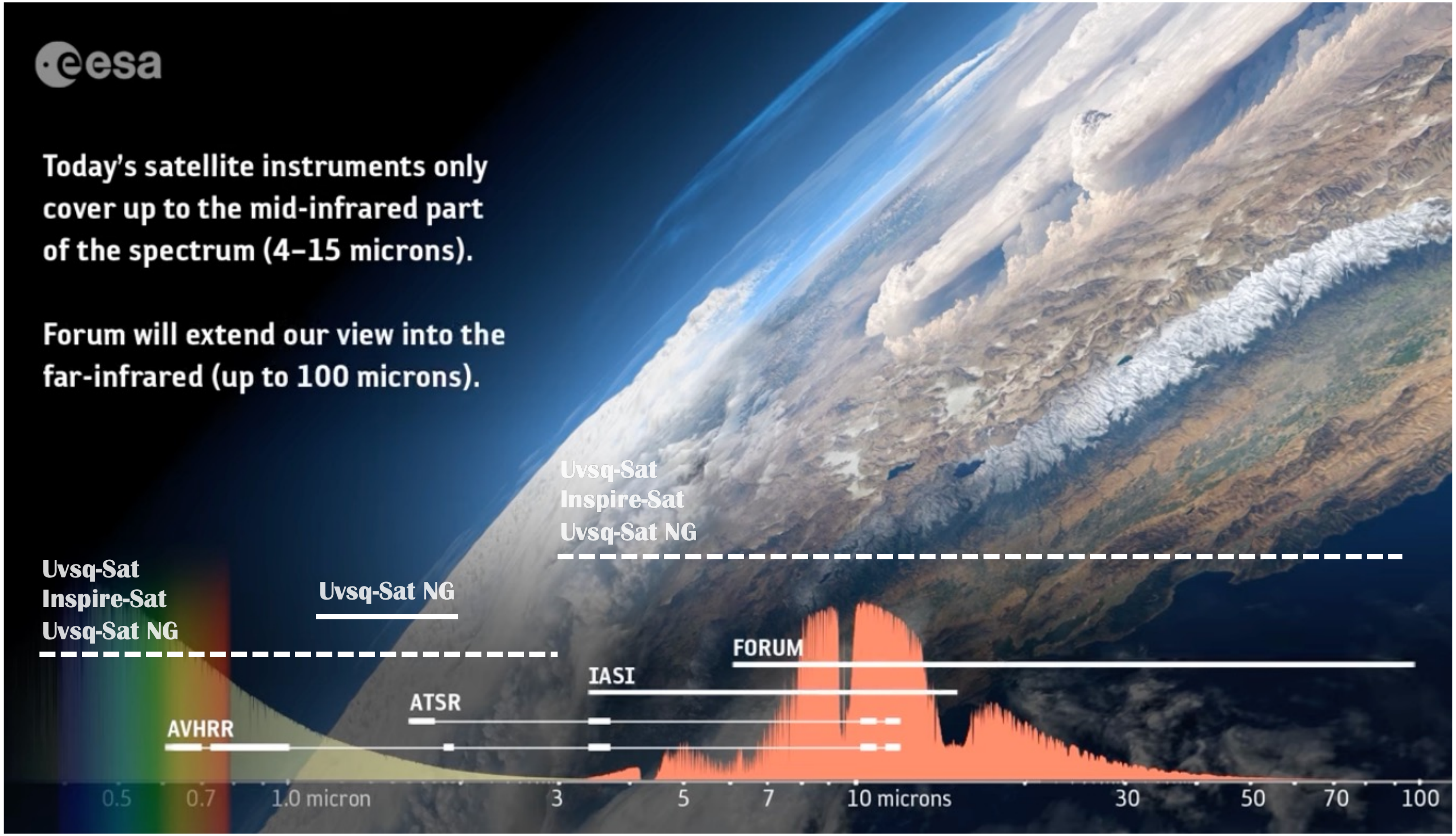
Satellites constellation

❑ Requirements

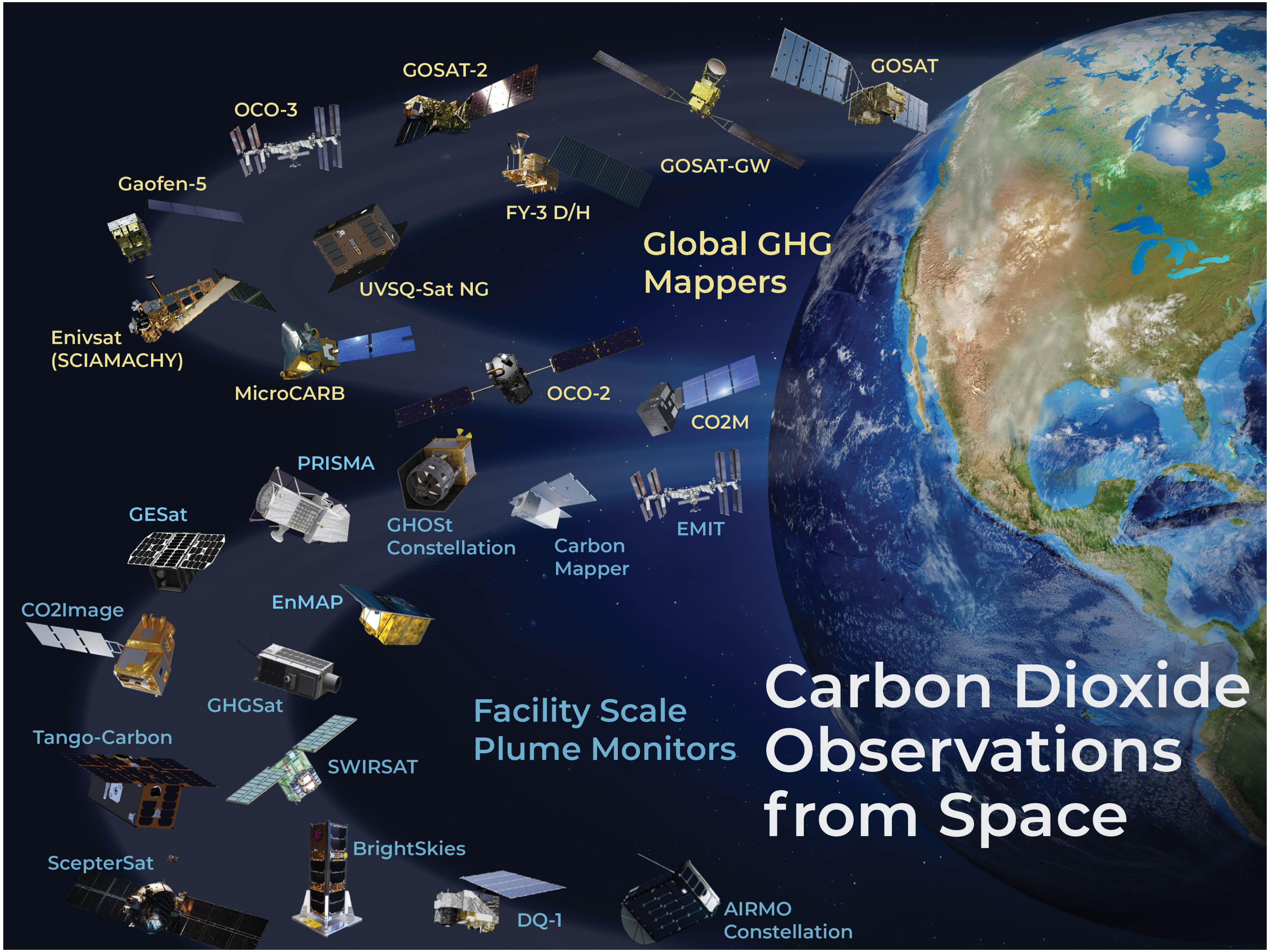
Requirements for Uvsq-Sat—Launched on 24 January 2021 from Cape Canaveral, Florida, USA				
ECV	Absolute accuracy	Stability per year	Spatial resolution	Temporal resolution (global map)
OSR	$\pm 10.00\ \mathrm{W m^{-2}}$	$\pm 5.00\ \mathrm{W m^{-2}}$	2500 km per element	30 days with one CubeSat
OLR	$\pm 10.00\ \mathrm{W m^{-2}}$	$\pm 1.00\ \mathrm{W m^{-2}}$	2500 km per element	30 days with one CubeSat
Requirements for Inspire-Sat 7—Launched on 15 April 2023 from Vandenberg, California, USA				
ECV	Absolute accuracy	Stability per year	Spatial resolution	Temporal resolution (global map)
OSR	$\pm 5.00\ \mathrm{W m^{-2}}$	$\pm 1.00\ \mathrm{W m^{-2}}$	2500 km per element	10 days with two CubeSats
OLR	$\pm 5.00\ \mathrm{W m^{-2}}$	$\pm 1.00\ \mathrm{W m^{-2}}$	2500 km per element	10 days with two CubeSats
Requirements for Uvsq-Sat NG—Launch Date in 2025 or in 2026				
ECV	Absolute accuracy	Stability per year	Spatial resolution	Temporal resolution (global map)
OSR	$\pm 3.00\ \mathrm{W m^{-2}}$	$\pm 1.00\ \mathrm{W m^{-2}}$	2500 km per element	5 days with three CubeSats
OLR	$\pm 3.00\ \mathrm{W m^{-2}}$	$\pm 1.00\ \mathrm{W m^{-2}}$	2500 km per element	5 days with three CubeSats
CO_2	±4.0 ppm	±1.0 ppm	2–10 km per pixel	> 30 days
CH_4	±25.0 ppb	±10.0 ppb	2–10 km per pixel	> 30 days
Requirements for a Hypothetical Satellite Constellation Named Terra-F—Horizon 2035				
ECV	Absolute accuracy	Stability per decade	Spatial resolution	Revisit time
TSI	$\pm 0.54\ \mathrm{W m^{-2}}$	$\pm 0.14\ \mathrm{W m^{-2}}$	–	24 h
OSR	$\pm 1.00\ \mathrm{W m^{-2}}$	$\pm 0.10\ \mathrm{W m^{-2}}$	10–100 km per pixel	3 h
OLR	$\pm 1.00\ \mathrm{W m^{-2}}$	$\pm 0.10\ \mathrm{W m^{-2}}$	10–100 km per pixel	3 h
EEI	$\pm 1.00\ \mathrm{W m^{-2}}$	$\pm 0.10\ \mathrm{W m^{-2}}$	–	24 h
CO_2	±1.0 ppm	±1.5 ppm	1–5 km per pixel	3 h
CH_4	±10.0 ppb	±7.0 ppb	1–5 km per pixel	3 h

Satellites constellation

- **Synergy with other space-based missions**



Synergy


GOSAT-2
OCO-3
GOSAT
GOSAT-GW
Gaofen-5
FY-3 D/H
Global GHG
Mappers
UVSQ-Sat NG
Enivsat
(SCIAMACHY)
MicroCARB
OCO-2
CO2M
PRISMA
GESat
GHOSt
Constellation
Carbon
Mapper
EMIT
CO2Image
EnMAP
GHGSat
Tango-Carbon
SWIRSAT
Facility Scale
Plume Monitors
Carbon Dioxide
Observations
from Space
BrightSkies
ScepterSat
DQ-1
AIRMO
Constellation

Conclusions

Our main scientific goal is:

- To observe essential climate variables with a constellation of small satellites.

The INSPIRE goals are:

- To initiate a Space Program, and to teach courses related to Space.
- To have Laboratory facilities for hardware development and specialized personnel for teaching.
- To have facilities for building and testing CubeSat/small Instruments.
- To have ground stations for satellite operations.

Our positions are:

- To Design for simplicity and robustness:
  – Assume designs will fail and then prove they will work.
  – Design the satellite for easy assembly and disassembly.
  – Have respectable margins, robust safe modes, few deployables, graceful performance. degradation, and frequent preventative satellite resets.
- To Build an experienced team—it matters:
  – A successful team has veteran member(s) and frequent informal peer reviews (discussions) with proven subject matter experts.