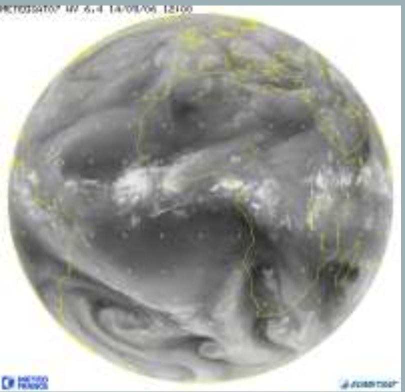
MONITORING THE CLIMATE AT A GLOBAL SCALE WITH SATELLITE OBSERVATIONS

TOOLS AND SOME CHALLENGES

Hélène Brogniez

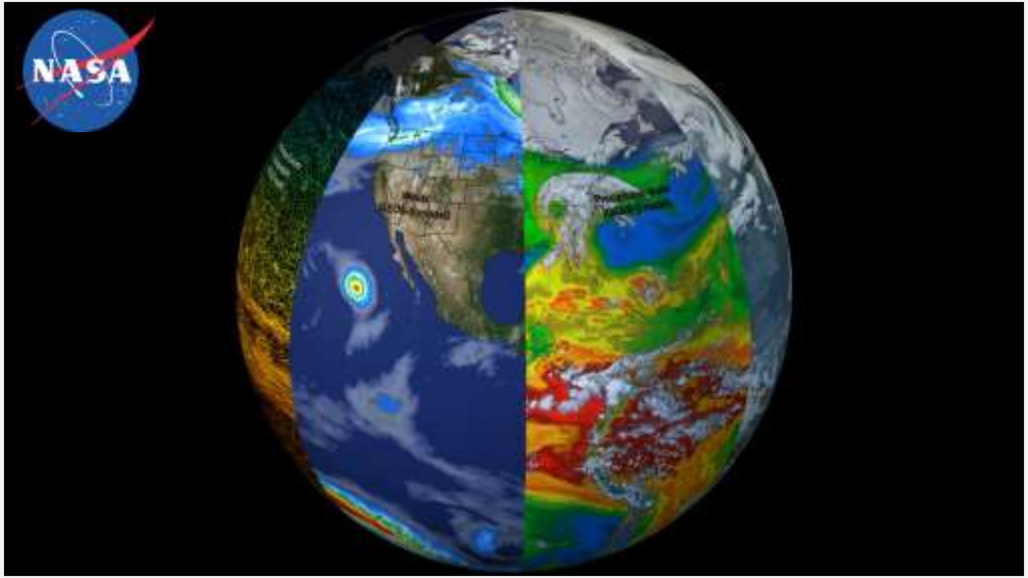


Rencontres de Noirmoutier – 3rd June 2026

PLAN OF THE PRESENTATION

1. Monitoring the Earth for meteo and climate
2. Some examples of satellite measurements
3. Data analysis and usage of IA
4. One observational challenge

A glimpse of Earth surface and fluids

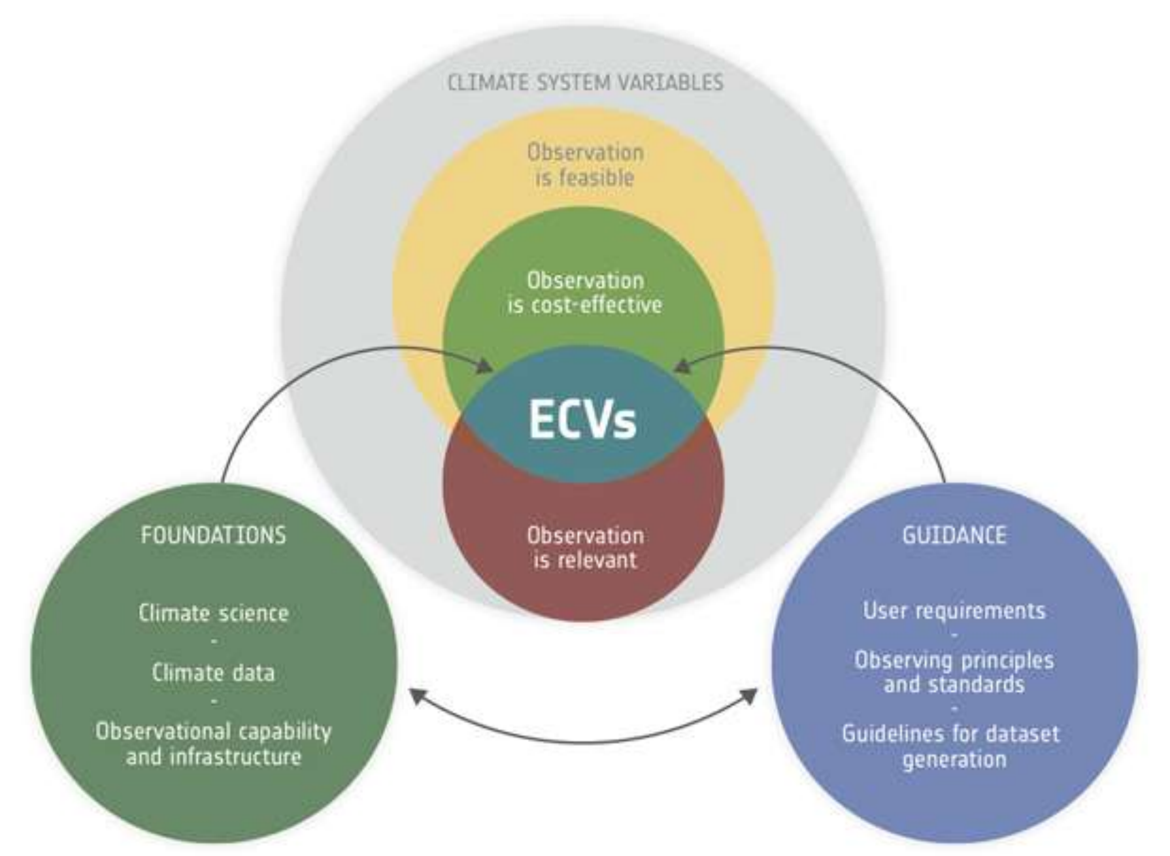


1. MONITORING THE EARTH FOR METEO & CLIMATE

1. The global observing system
2. For numerical weather prediction
3. For climate studies

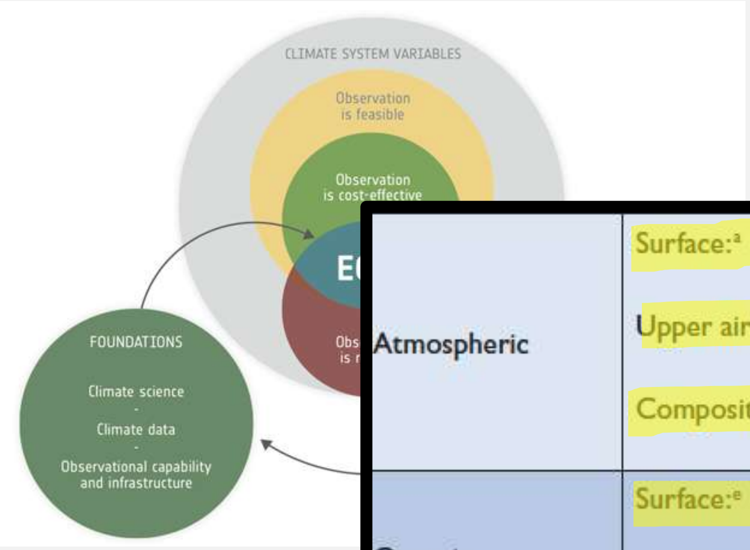
1. The global observing system

Monitoring "Essential Climate Variables" = ECV



[Bojinski et al. (2014)]

Monitoring of "Essential Climate Variables" = ECV

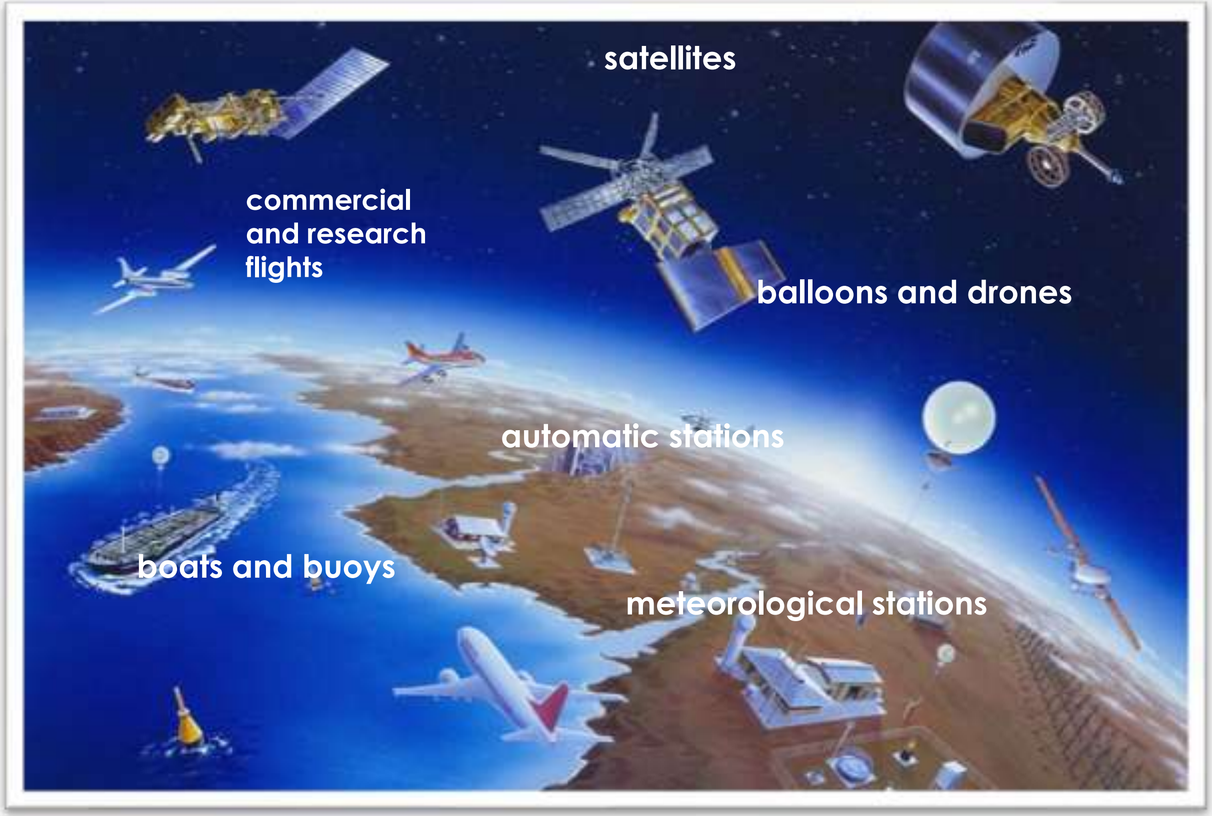


⇒ 50 ECVs have been identified

[Bojinski et al. (2014)]

Atmospheric	Surface:[a]	Air temperature, wind speed and direction, water vapor, pressure, precipitation, surface radiation budget
	Upper air:[b]	Temperature, wind speed and direction, water vapor, cloud properties, Earth radiation budget (including solar irradiance)
	Composition:	Carbon dioxide, methane, other long-lived greenhouse gases,[c] ozone and aerosol supported by their precursors[d]
Oceanic	Surface:[e]	Sea surface temperature, sea surface salinity, sea level, sea state, sea ice, surface current, ocean color, carbon dioxide partial pressure, ocean acidity, phytoplankton
	Subsurface:	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial		River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture

The Global Climate Observing System combines



© ECMWF

⇒ GCOS role is to ensure the availability and quality of observations necessary to monitor, understand, and predict the global climate.

300+ satellites have a mission for Earth Observation

Program for innovative observation methods

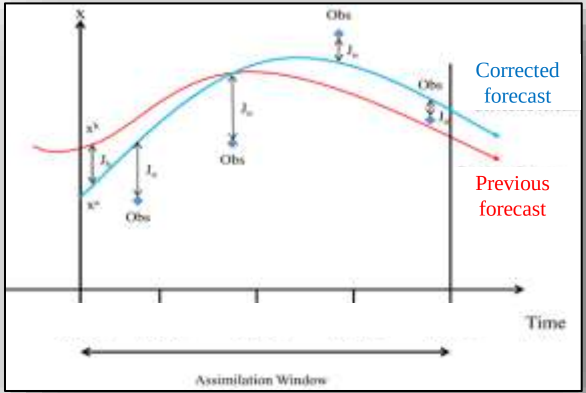
Obs to monitor the Earth's environment

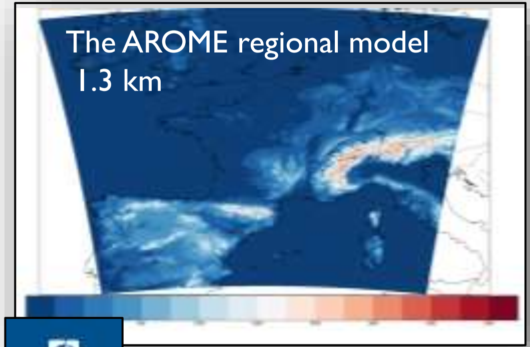
Program for numerical weather forecast

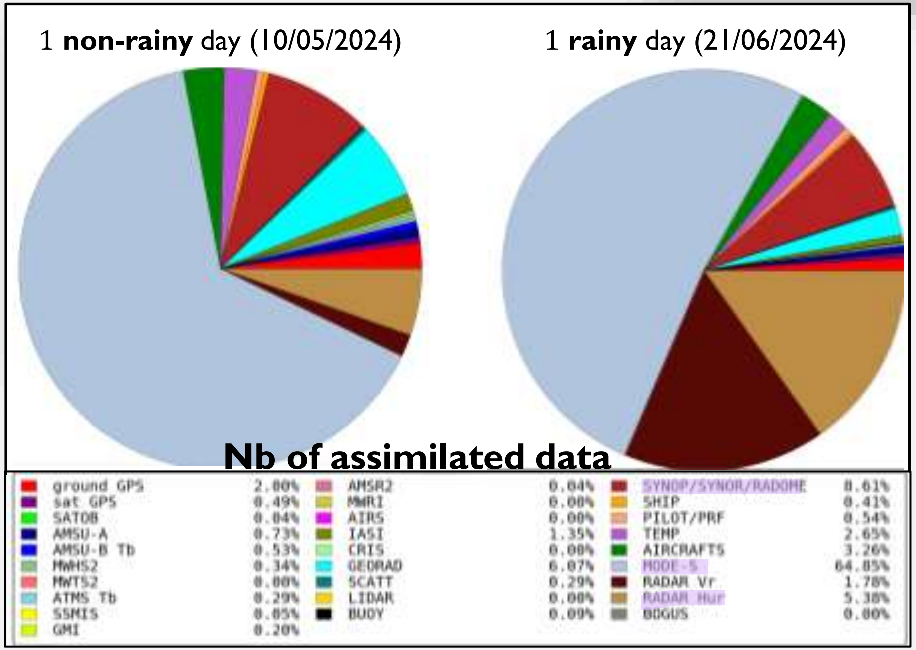
⇒ Key role of the satellites to provide a global coverage

2. For numerical weather prediction

⇒ Relies strongly on the Global Observing System trough variational assimilation **4D-VAR**







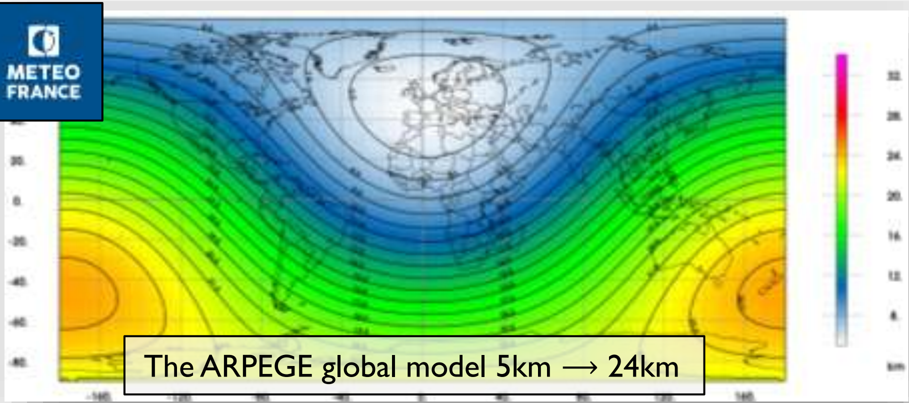
© Météo-France DIROP/COMPAS

<u>regional scale</u>

(scene dependant)

1st : conventional obs (aircraft + synop)

2nd : radar networks



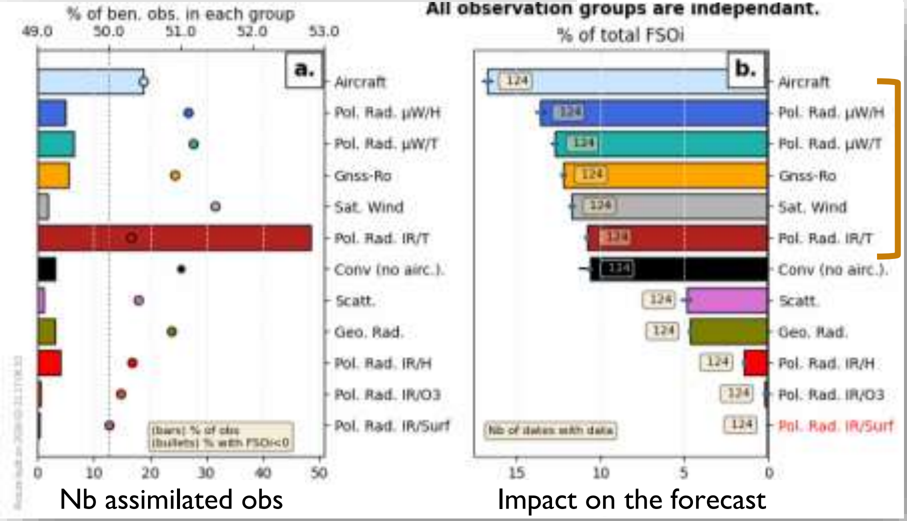
The ARPEGE global model 5km ⟶ 24km

global scale (all situations)

1st : conventional obs (aircraft + synop)

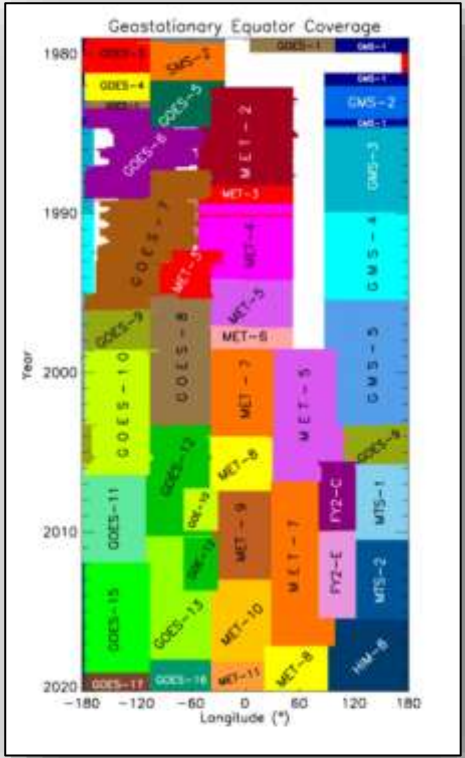
2nd : satellite (μW + GNSS+wind+IR)

Scores for January 2026

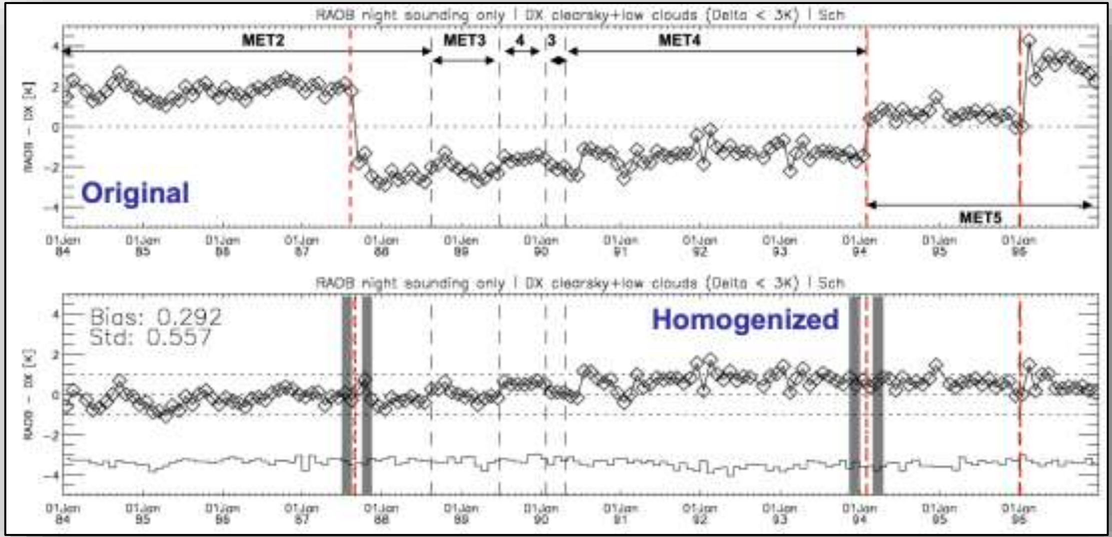


3. For climate studies

Multiple series of satellites with instrument upgrades / differences in spectral bands …



Ex: METEOSAT WV channel (6.3μm)



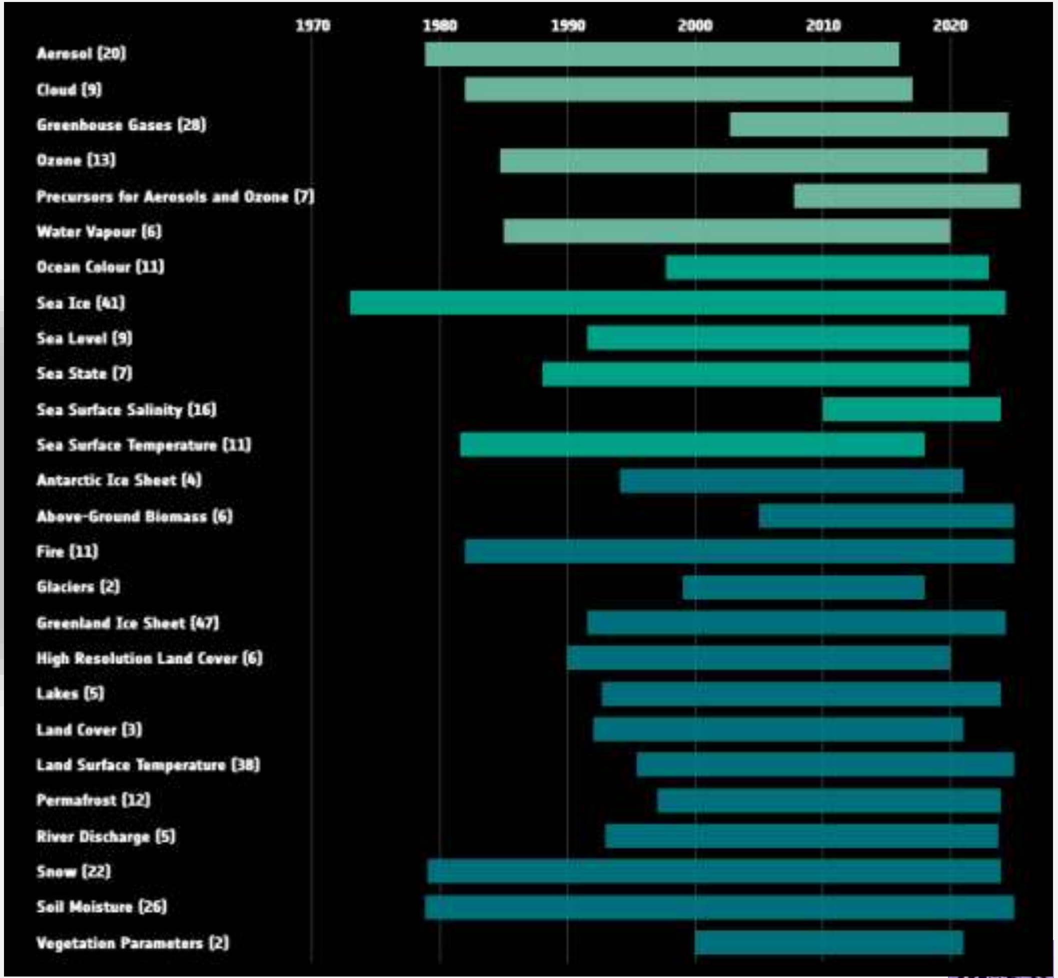
[Roca & Brogniez (2005)]

esa

European Space Agency

40-year satellite archive
+ current missions (ESA missions mostly)

⇒ Intercalibration of instruments, bias corrected, gridded data, validated with in-situ, uncertainy characterized (per pixel), fully documented, tested by users etc…



26 thematics & several datasets

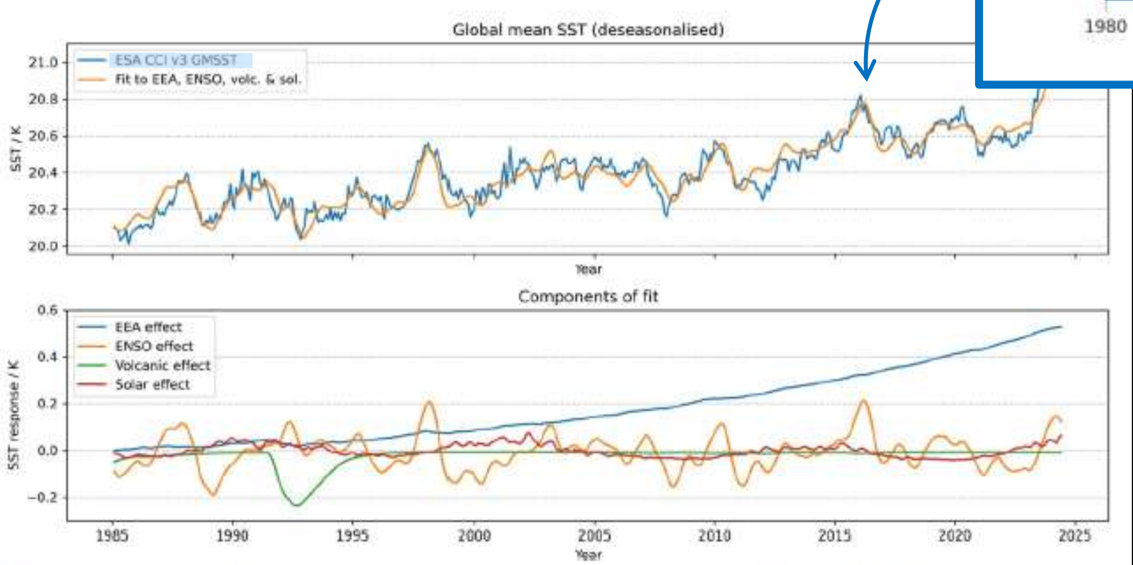
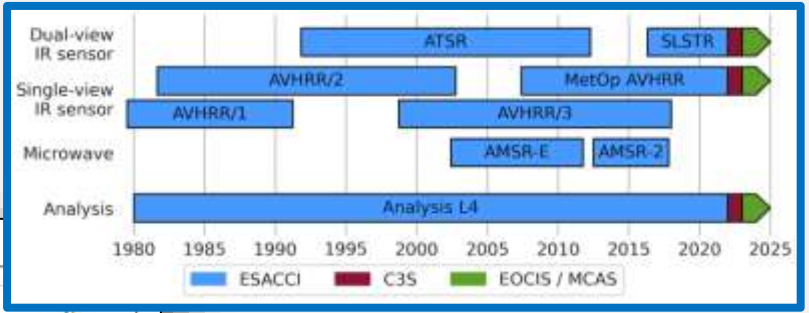


Figure 2. (a) Deseasonalised monthly mean sea surface temperature between 60°N and 60°S (GMSST). Blue line: observed timeseries from the European Space Agency Climate Change Initiative (ESA CCI). Orange line: fit to observed timeseries using Earth Energy Accumulation (EEA), El-Niño Southern Oscillation (ENSO) index, volcanic stratospheric aerosol and top-of-atmosphere total solar irradiance as predictors. (b) The components of the fit, i.e. the scaled predictors that (with an offset parameter not shown) sum to give the fitted curve in panel (a).

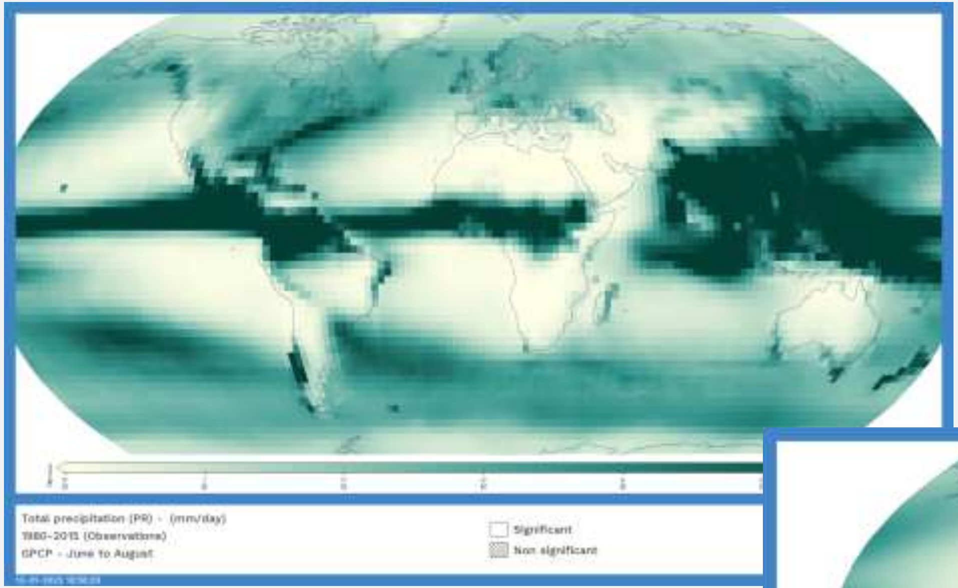


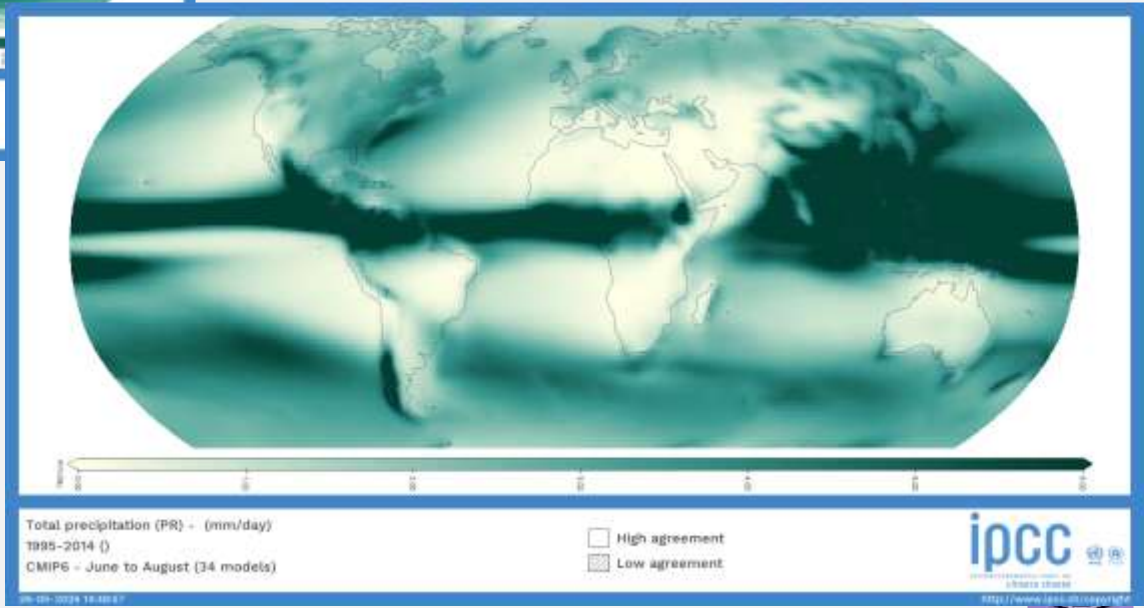
Contribution to various components of the natural variability to the global signal

[Merchant et al. (2025)]

Rainfall climatology
1980-2015
(blend of ground networks + geostationnary & inclined-orbit satellites)

https://interactive-atlas.ipcc.ch/





Gobal Climate Models
1995-2014

II. SOME EXAMPLES OF SATELLITE MEASUREMENTS

1. Passive instruments for weather & climate

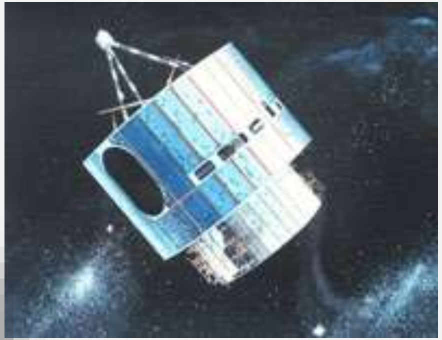
2. Enhanced instruments for the detection pollutants and GHG

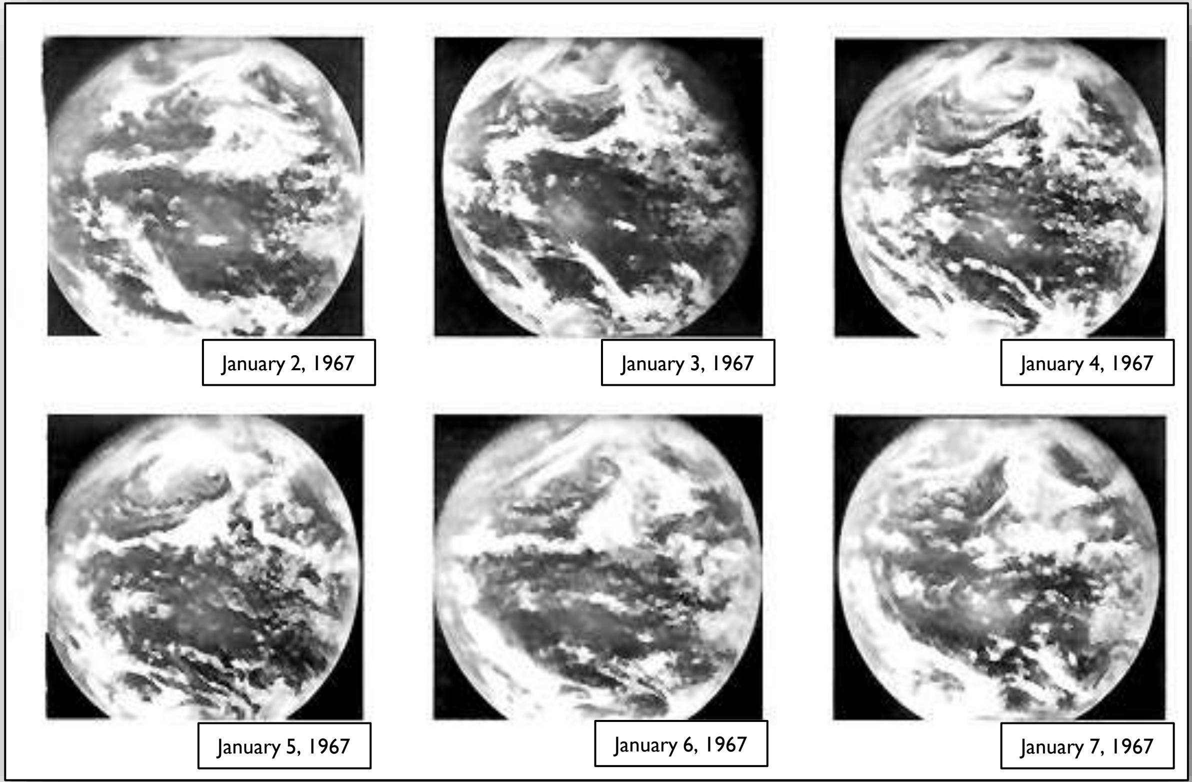
3. Radar & Lidar for 3D profiling

4. Gravimetry for the water budget

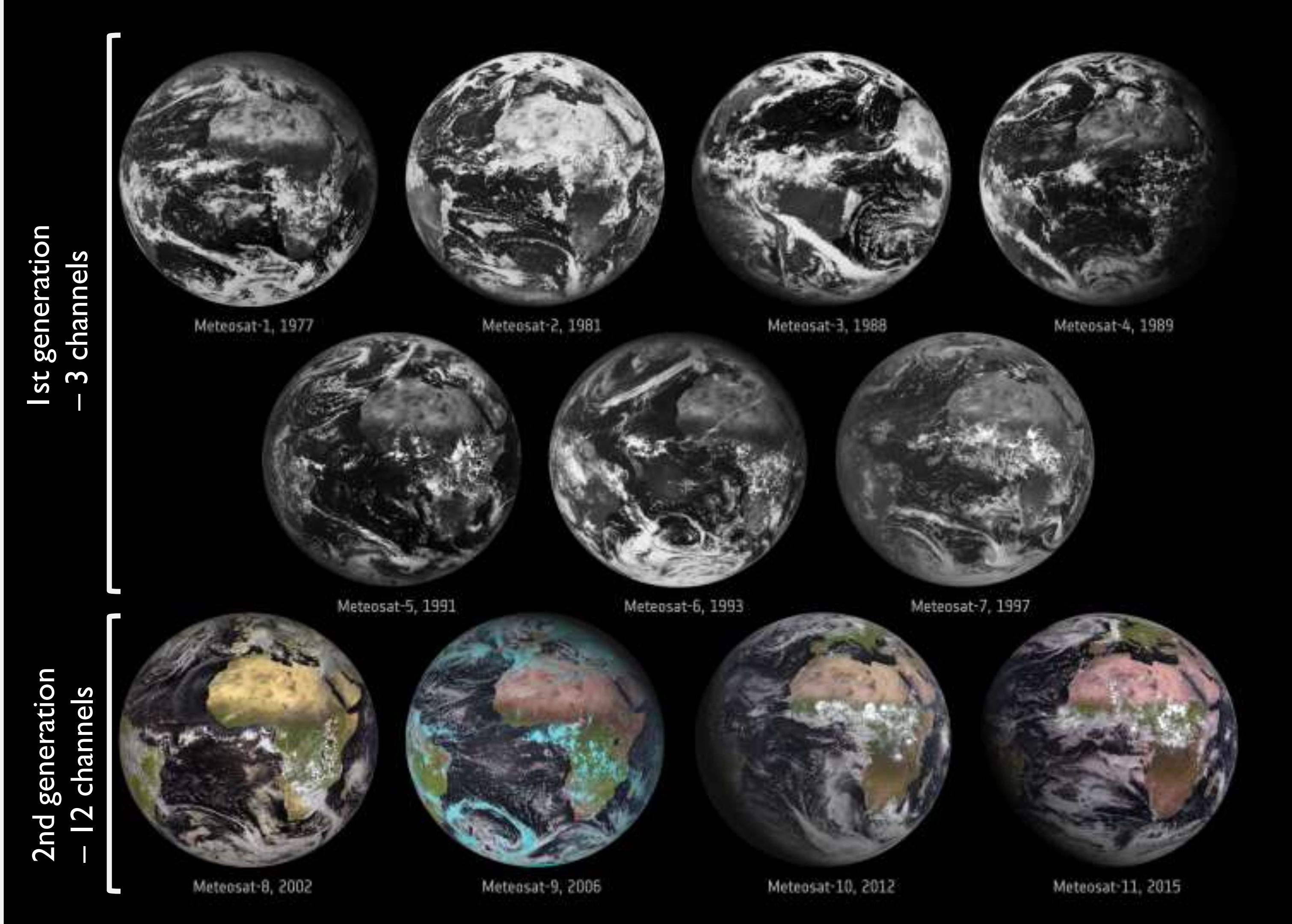
1. Passive instruments for weather & climate

1967-1975: GOES-1 (Geostationary Operational Environmental Satellite)
The 1st US weather monitoring platform in geostationary orbit (NASA)

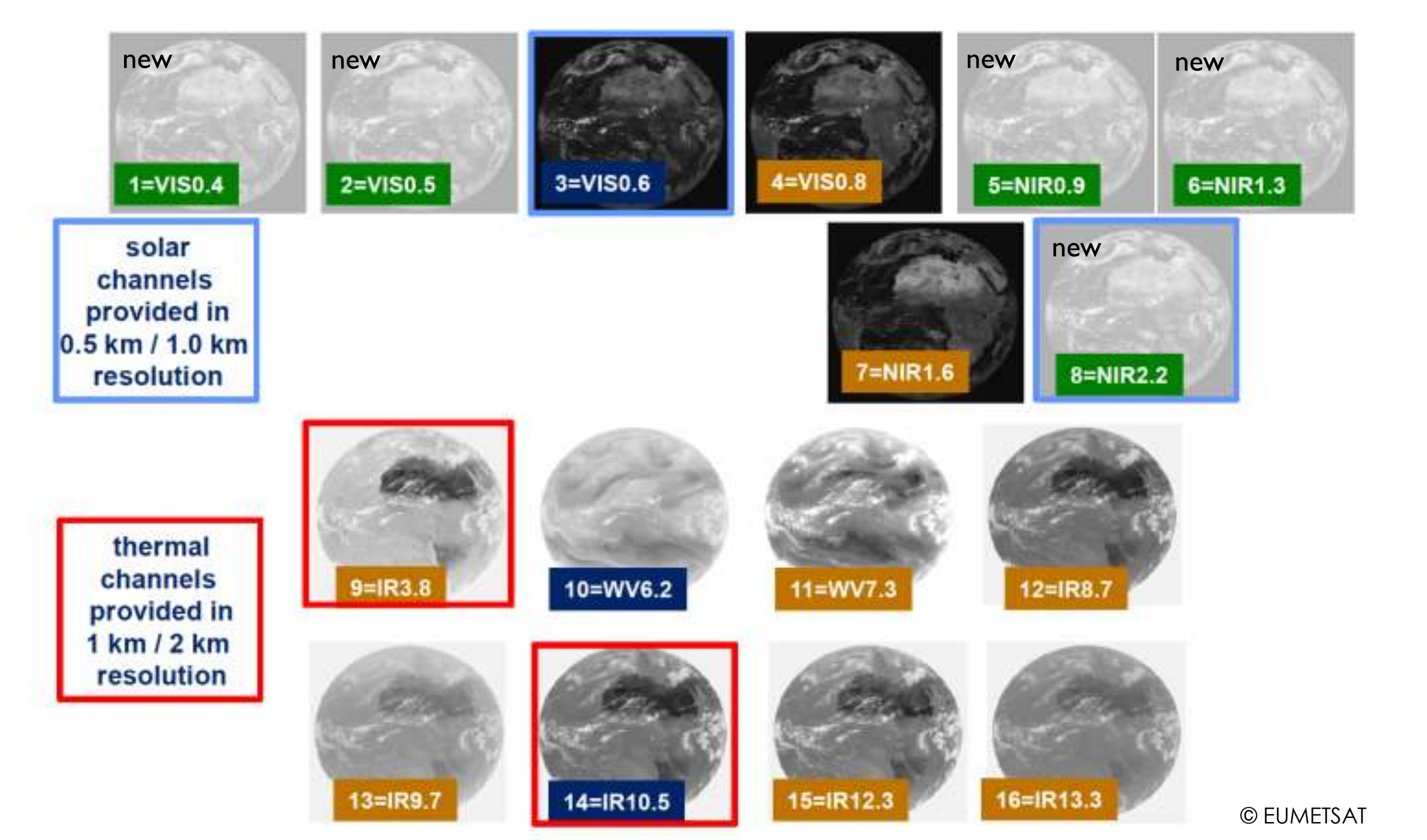




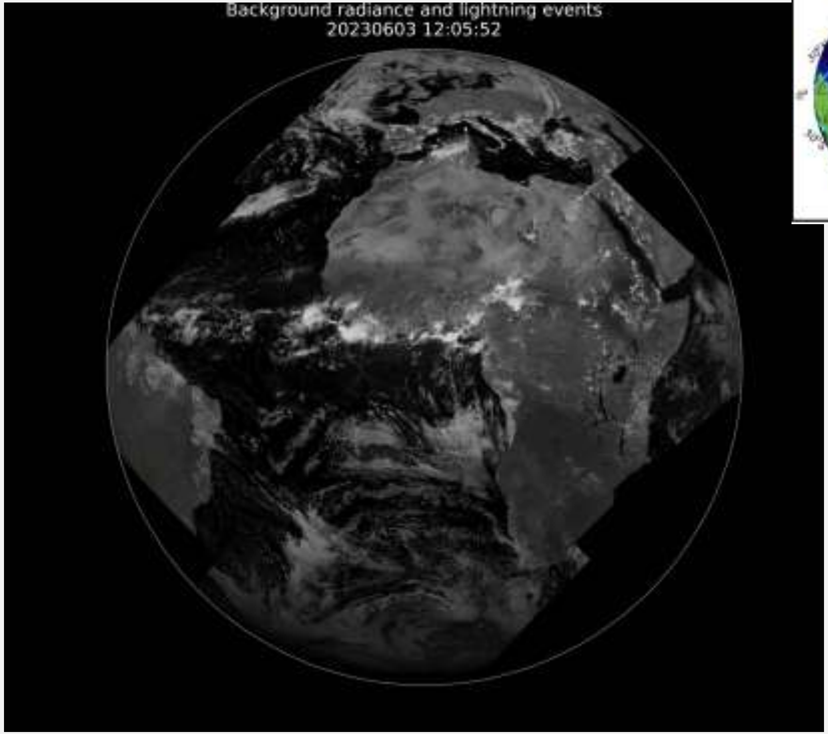
1977: METEOSAT-1 : The 1st european geostationary satellite

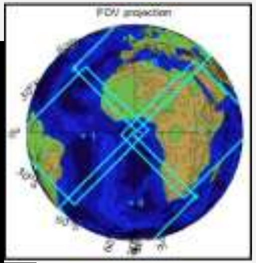


Since 2022 : 3rd generation – Flexible Combined Imager – 16 channels



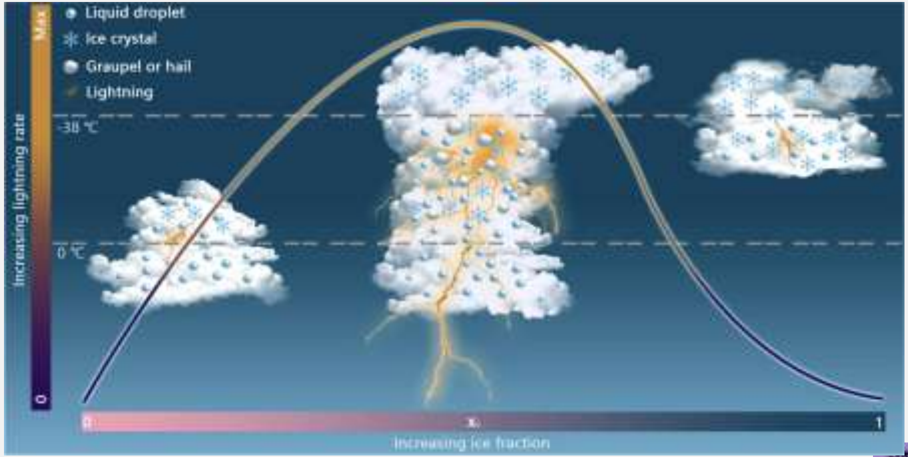
Since 2022 : 3rd generation – Flexible Combined Imager + Lightning Imager





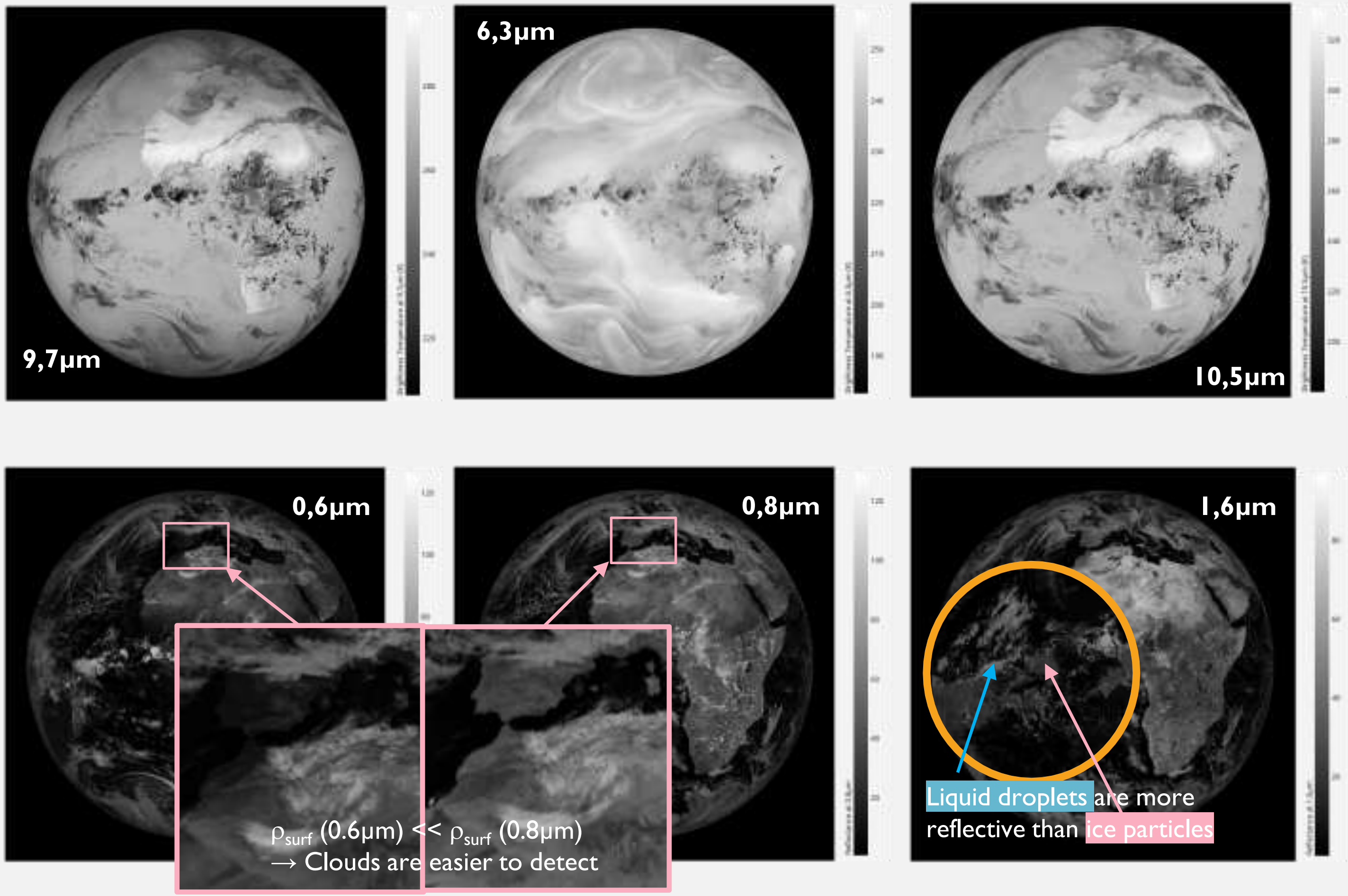
4 cameras @ 777.4 nm
Integration time of 1ms

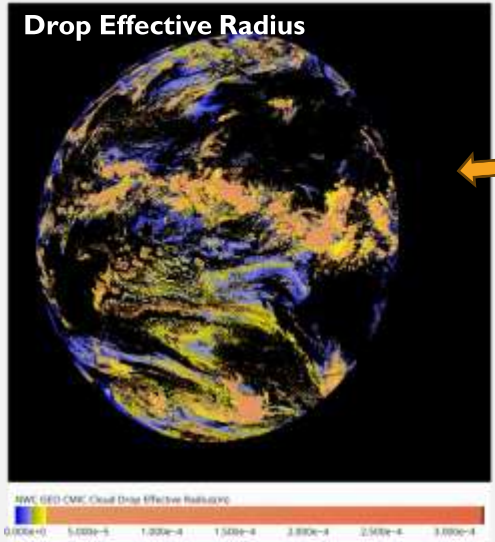
⇒ Indicator of storm development

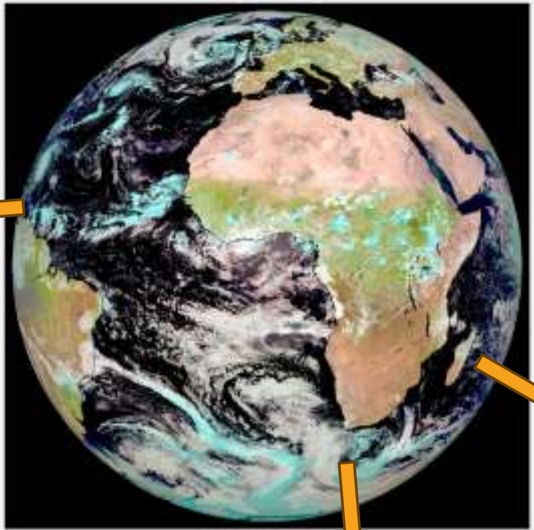


[Han et al. (2021)]

(MTG) - 30/03/2026 @ 12:00 UT





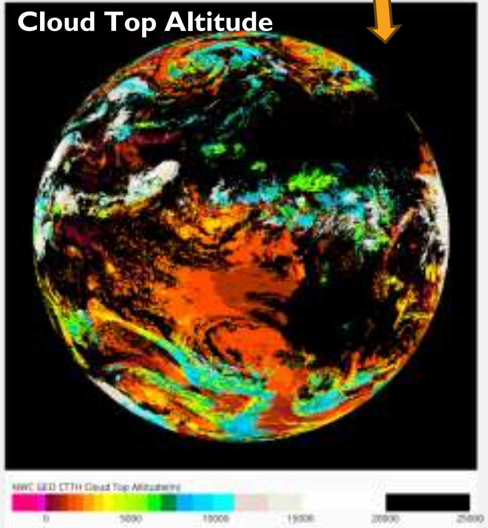


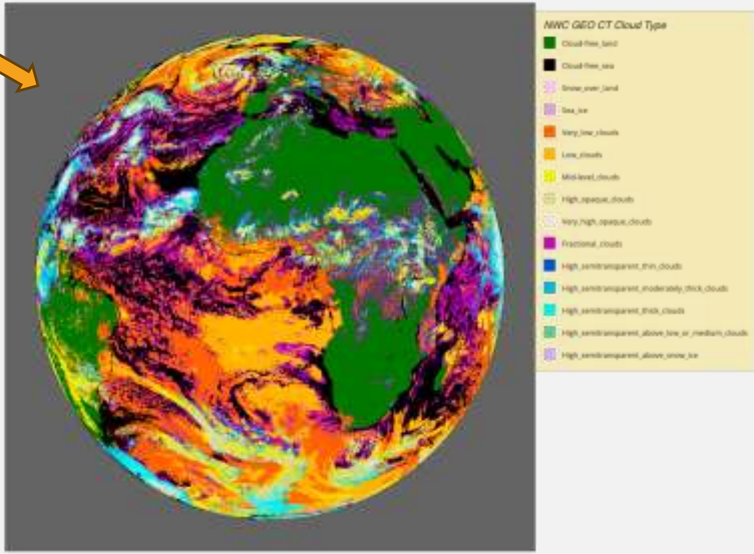
05/09/2020 @ 14:00 UT

Red (1.6µm)

Green (0.8µm)

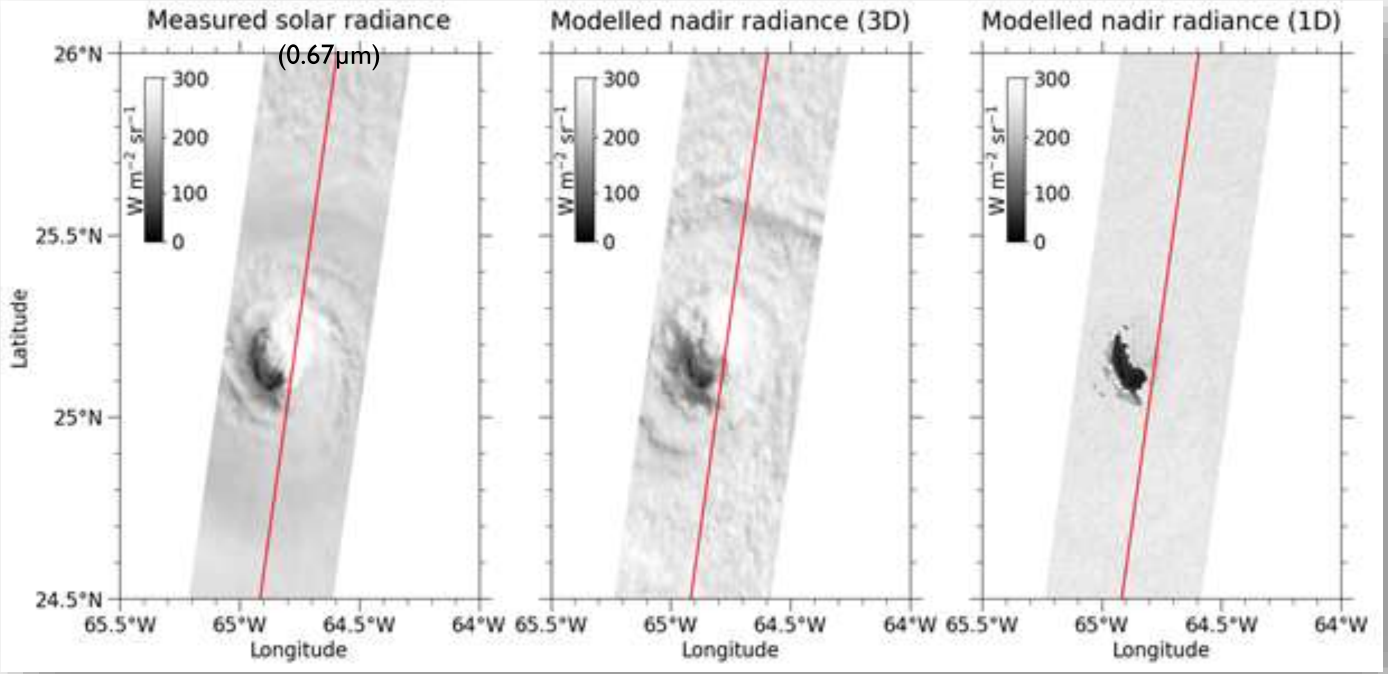
Blue (0.6µm)





Use of **3D radiative transfer model** to represent the structure of clouds

Example: View of Hurricane Humberto (25/09/2025) by the Multi-Spectral Imager (EarthCARE)



[ex: Cole et al. (2022)]

⇒ this 3D cloud representation is used to estimate how incoming sunlight is scattered by cloud

2. Enhanced instruments for the detection of pollutants and GHG

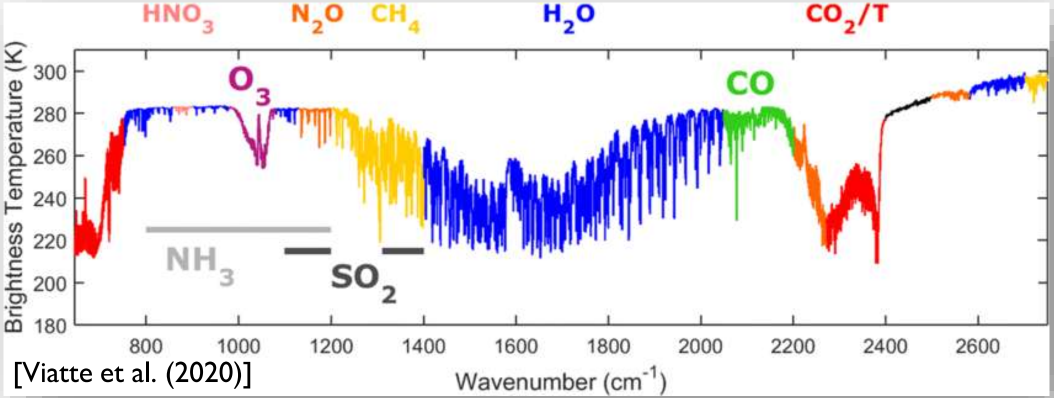
The **IASI** instrument *(Infrared Atmospheric Sounding Interferometer)*

First designed for Numerical Weather Prediction & for Atmospheric Chemistry

with a Climate Monitoring application (target length of the mission= 50+ years)

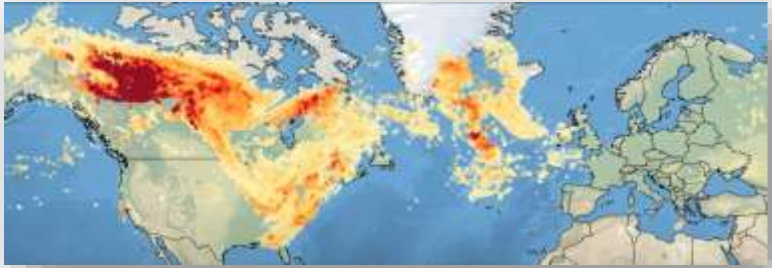
Curtesy C. Crevoisier @ LMD

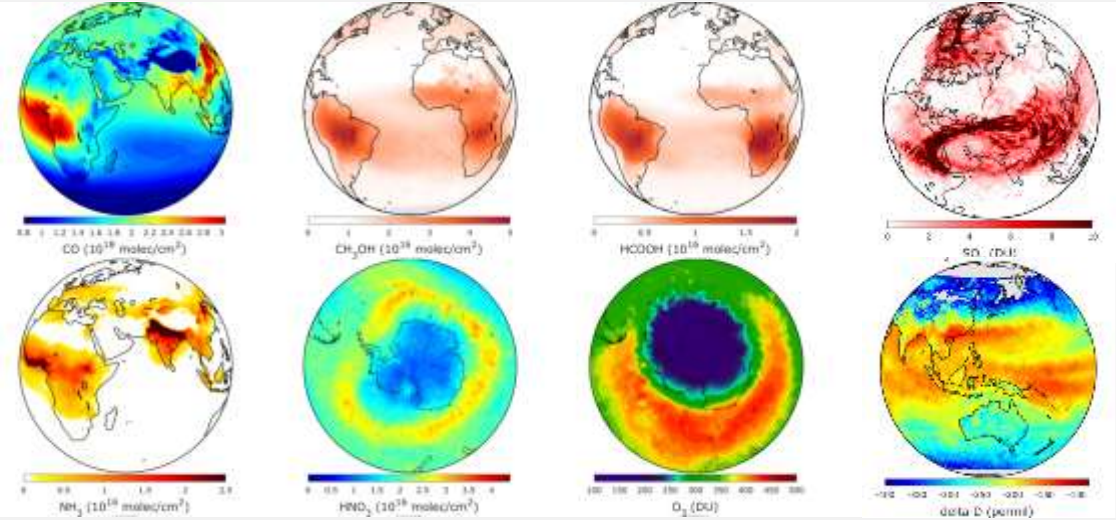
IASI spectra > 33 atmospheric parameters *(cloud-screened situations)*



[Viatte et al. (2020)]

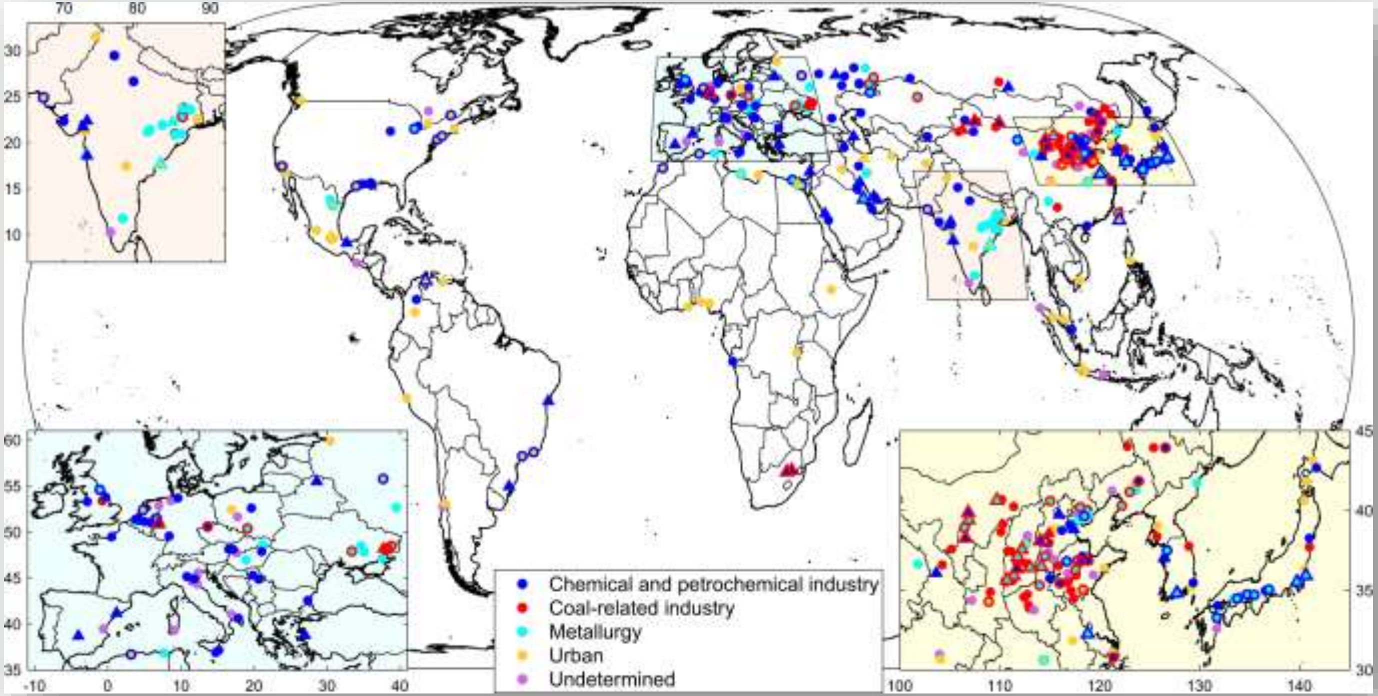
[CO] from Canadian mega-fires – 18/07/2023



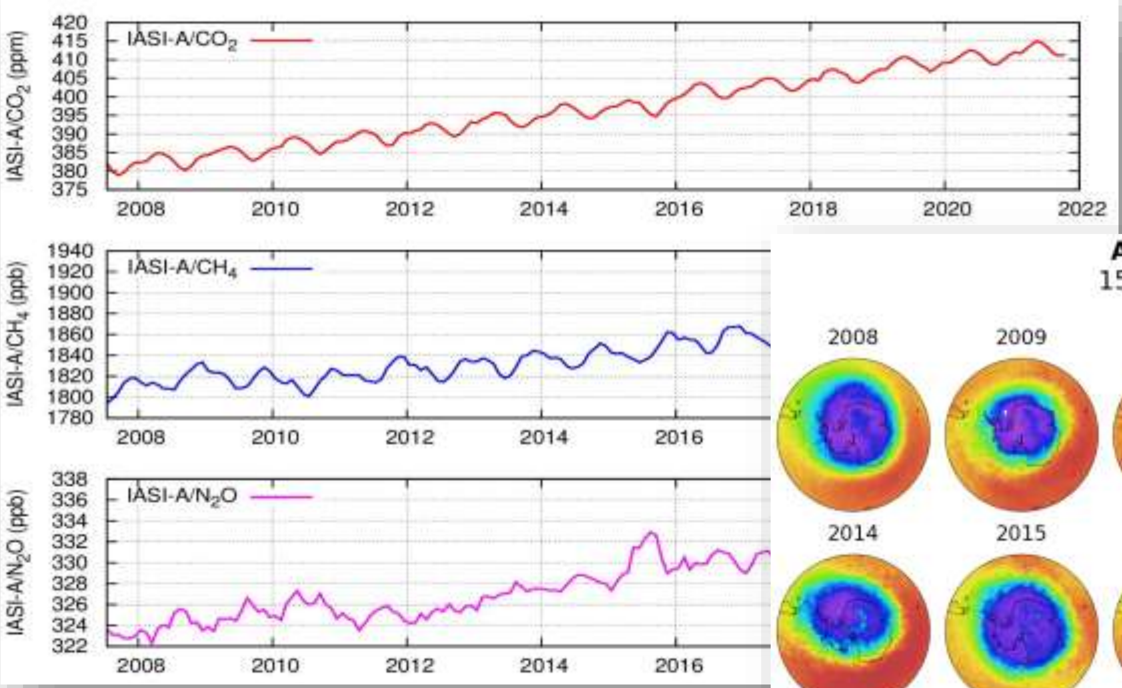


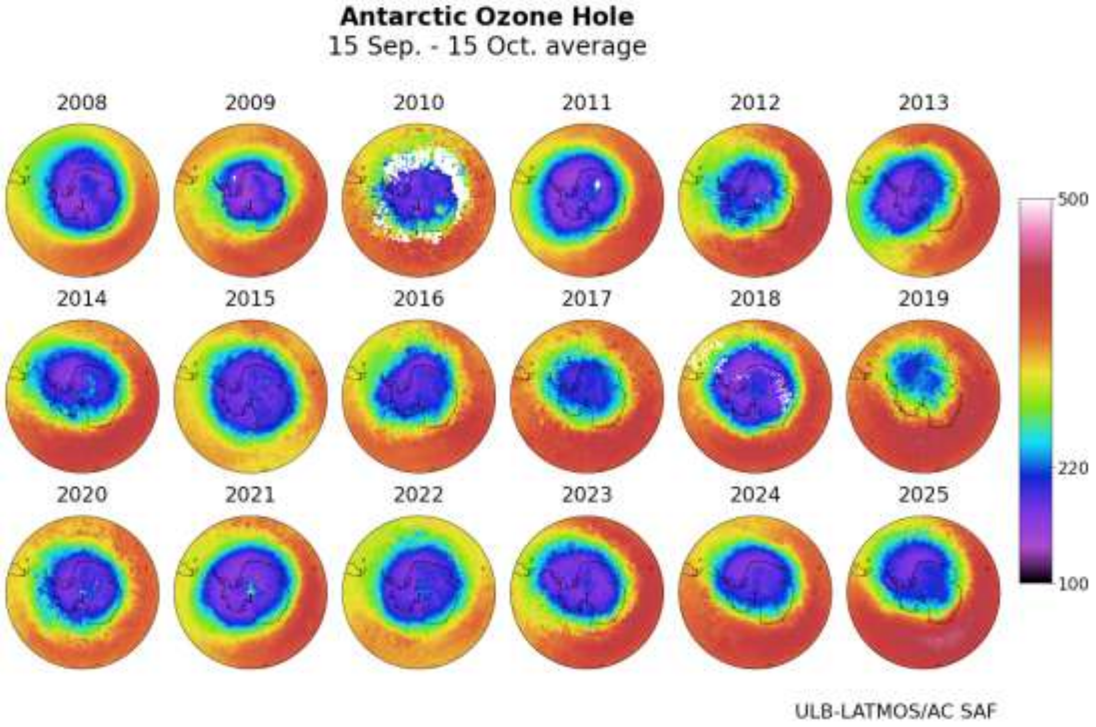
Global distribution of C_2H_4 (940–960 cm^{-1}) point-sources detected by IASI 2008 -2020

[Franco et al. (2022)]



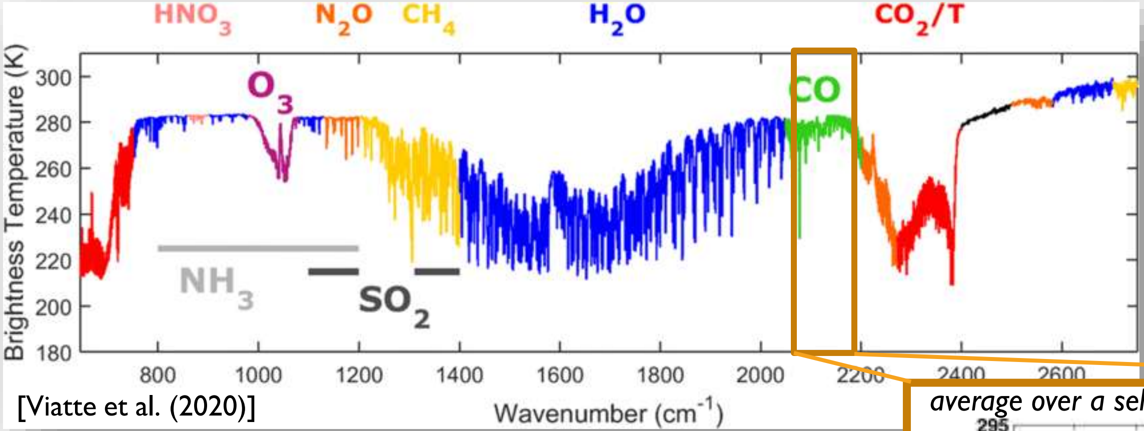
Climate Monitoring of GHG





Curtesy C. Crevoisier @ LMD

IASI spectra > 33 atmospheric parameters *(cloud-screened situations)*

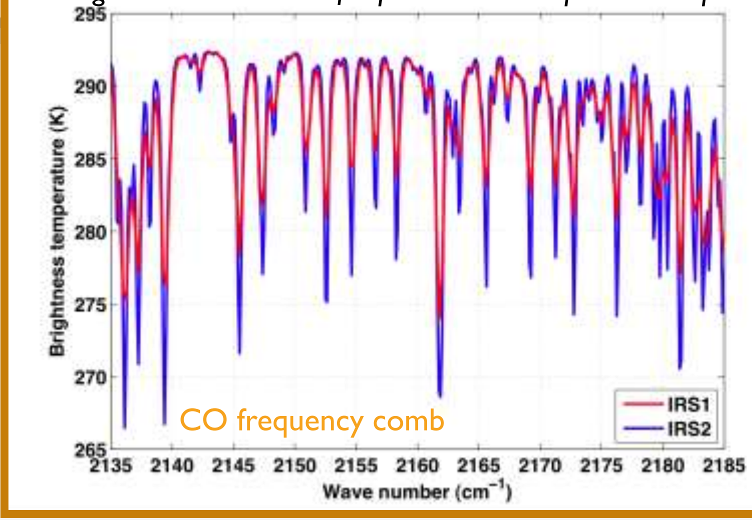


[Viatte et al. (2020)]

increased spectral resolution (/2)
+ reduction of radiometric noise (/2 to 4)

IASI - 0.5 cm^{-1}
IASI-NG - 0.25 cm^{-1}

average over a selection of representative tropical atmospheres



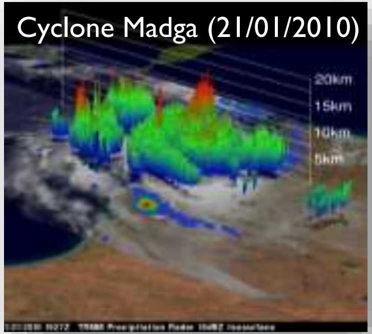
IASI-NG launch : 12/08/2025
Release of first data : 05/05/2026

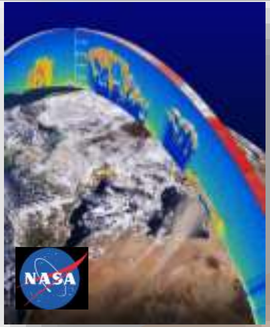
Curtesy C. Crevoisier @ LMD

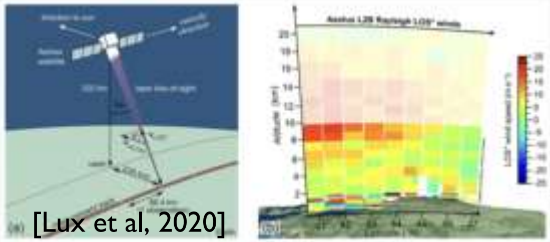
https://4aop.aeris-data.fr
https://geisa.aeris-data.fr

3. Radar & Lidar for 3D profiling of the atmosphere

Designed for Earth Observation







1978 (3m)
1st radar altimeter + SAR
SeaSat 1

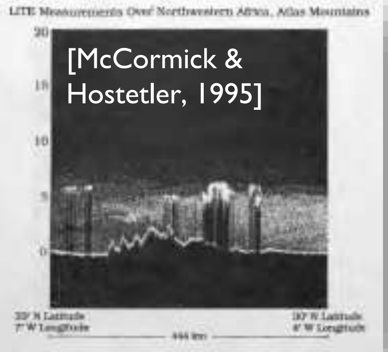
1994 (10d)
lidar (355, 532+1064 nm)
ISS

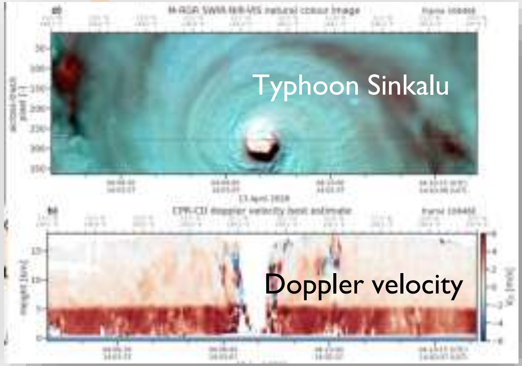
1997→2015
precipitation radar (13,8GHz)
TRMM

2006→2023/2025
lidar (532 + 1034nm) & cloud radar (94GHz)
A-Train

2018→2023
doppler lidar (355nm)
ADM-Aeolus

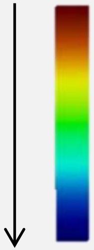
2024 →
lidar (355nm) & doppler radar (94GHz)
EarthCare





… monitoring sea surface height with radar altimetry ….

High concentration
of droplets/cristals



Low concentration
of droplets/cristals

Example 1: Physics of cloud

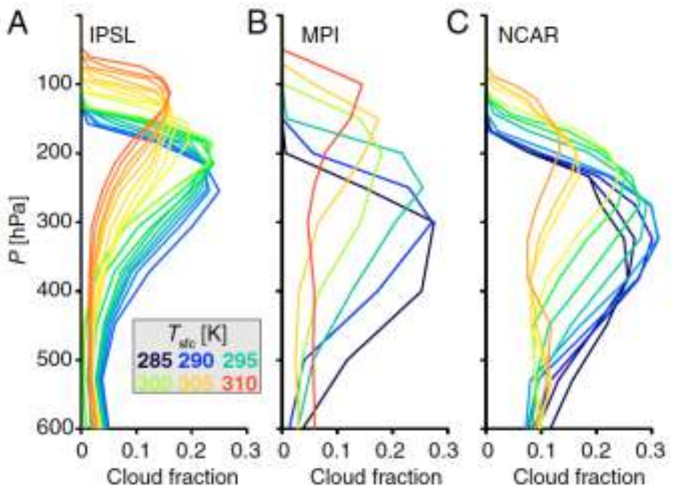
2006-2011 CloudSat radar data

> Used to test theories of tropical cloud evolution with surface warming

Ex: the Fixed Anvil Temperature assumption

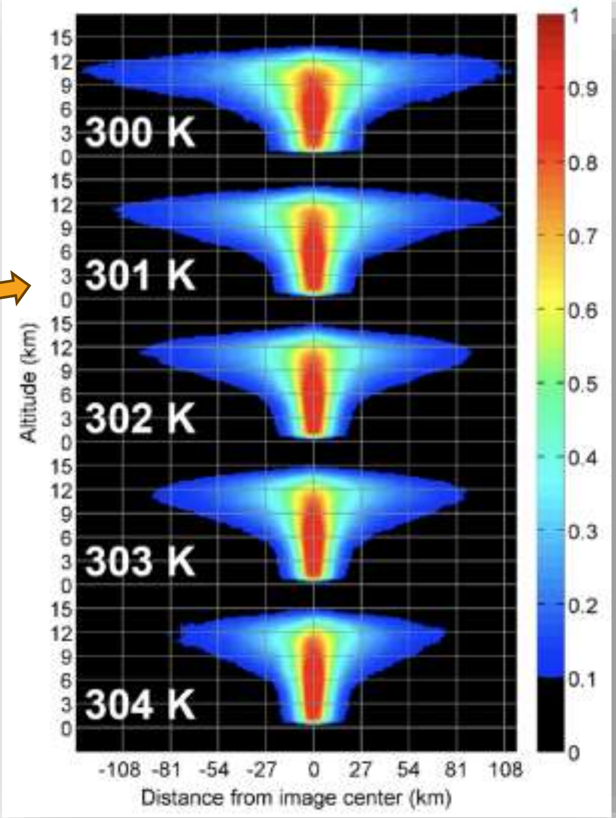
in models

3 Global Climate models – RCE mode



[Bony et al. (2016)]

in obs



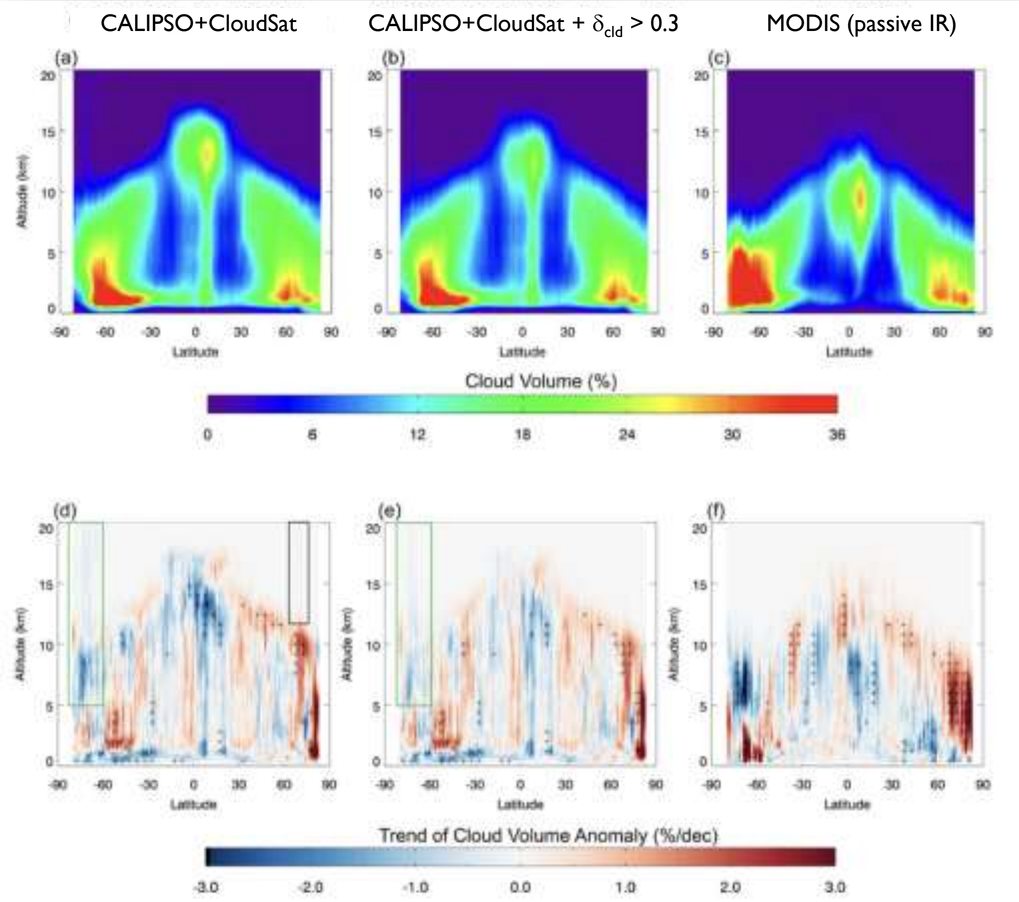
[Igel et al. (2014)]

⇒ Suggests that, on average over the tropics, the **anvil cloud amount** **decreases** as the surface temperature increases

Example 2: documentation of trends in 3D cloud distribution

[Ham et al. (2025)]

2008-2017 data records



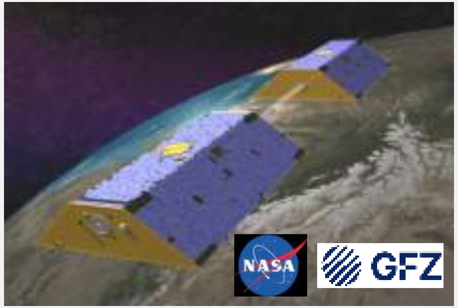
- Lidar (CALIPSO) detects thin clouds
- Passive IR (MODIS) detects the cloud top near IR emission center

'+' where trends ≥ 2σ

- Decrease over the Antarctic (5–10km)
- Increase over the Arctic
- Increase in upper tropospheric clouds (N.H.)
- Desagreements

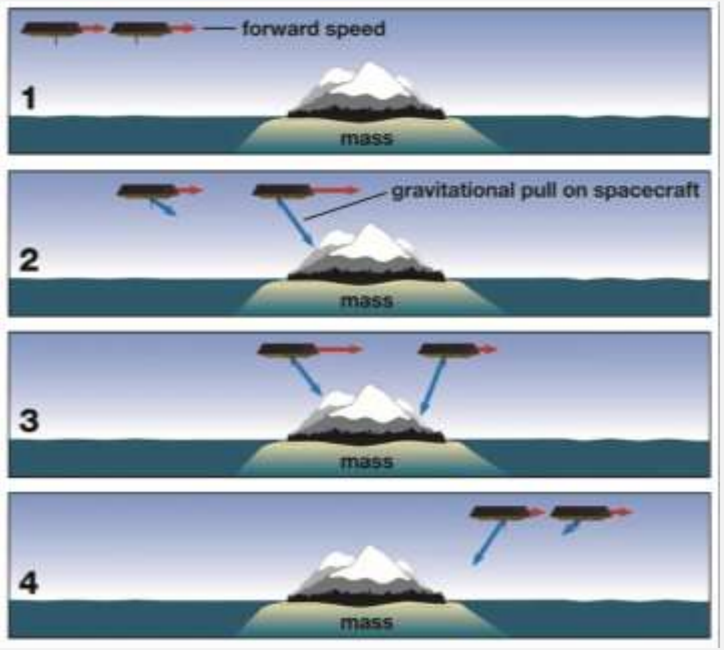
  ⤇ differences in cloud detection

4. Gravimetry for the water budget

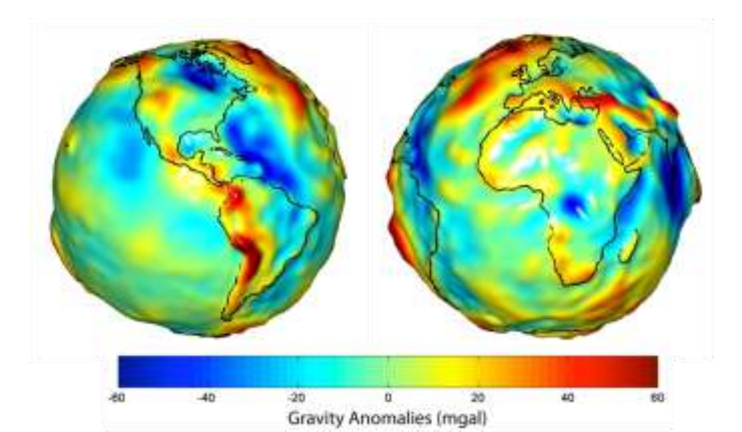


GRACE & GRACE-FO: Gravity Recovery and Climate Experiment

(2002-2017) (2018 →)



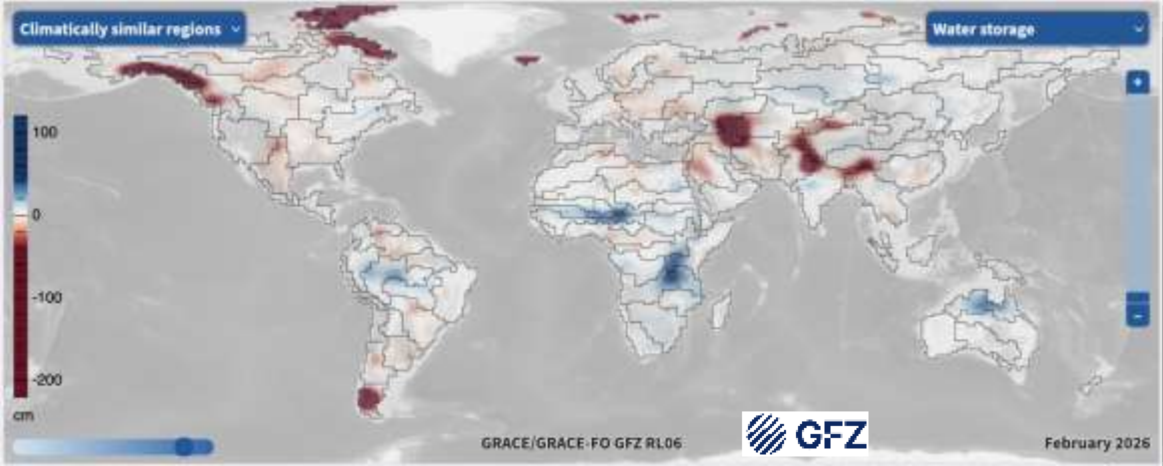
Measurement of disturbances in the Earth's gravitational field caused by mass anomalies.



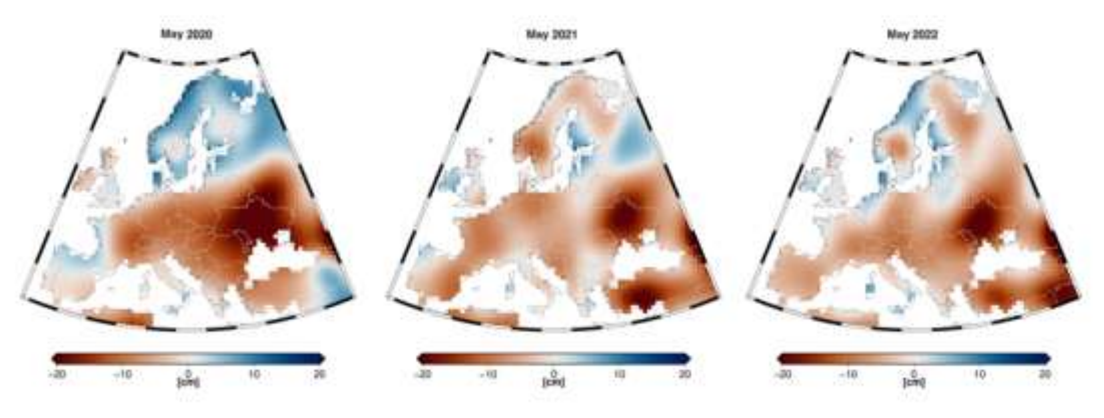
⇒ Variations are interpreted as variations in the continental stock of water (surface & subsurface)

Terrestrial Water Storage *(anomalies wrt 04/2002 – 03/2020)*

https://gravis.gfz.de/tws



Monthly
50km x 50km



⇒ Since 2018, most summers in Europe have been far too dry.

⇒ This leads to dramatic groundwater deficits

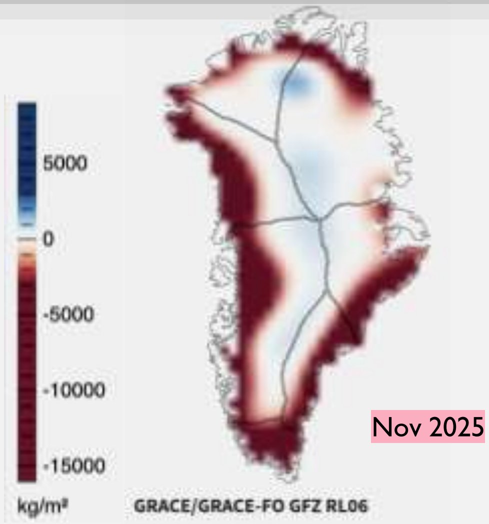
© Eva Börgens
GFZ

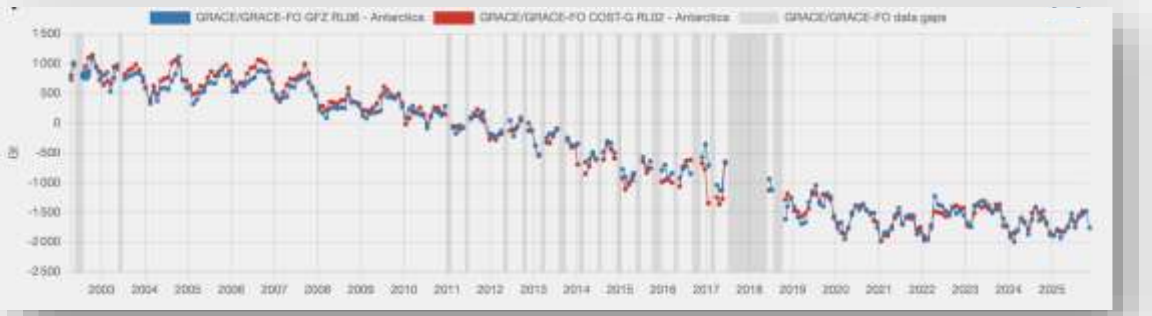
Terrestrial Water Storage *(anomalies wrt 04/2002 – 03/2020)*

Greenland ice-mass change

Antarctic ice-mass change

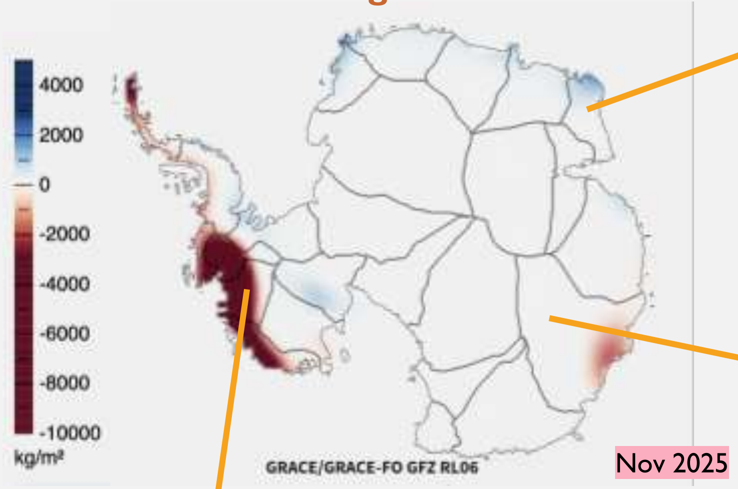
Nov 2025





Terrestrial Water Storage *(anomalies wrt 04/2002 – 03/2020)*

Antarctic ice-mass change



IV. DATA ANALYSIS AND USAGE OF **IA**

1. Spatialization of data for the monitoring of biomass

2. Properties of meso-scale convective systems

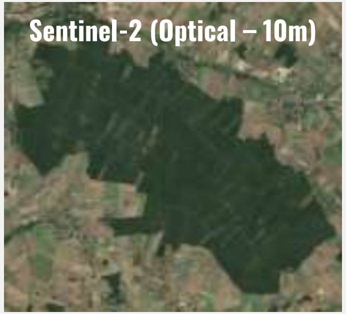
3. Identification of pollutant plumes

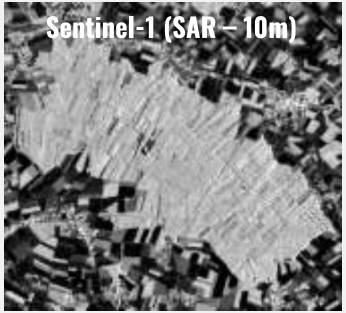
I. Spatialization of data for the monitoring of biomass

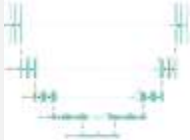
The forest is an important natural carbon sink ⇒ forest inventories at a large scale to perform a monitoring of the global carbon budget

Forêt de Crécy, Somme

High-resolution satellite images

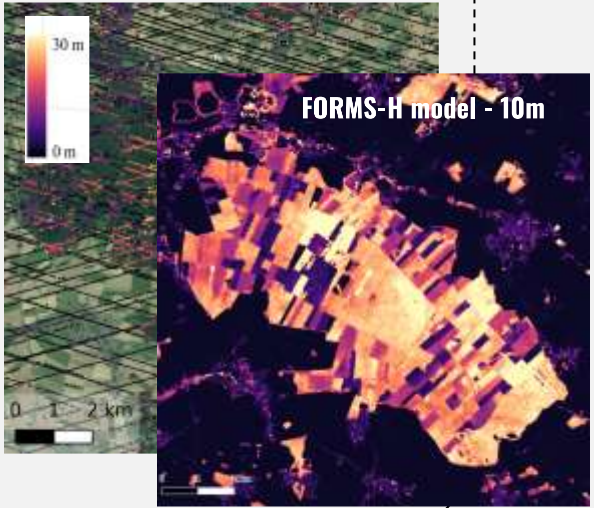






U-Net
Convolutional
Neural Network

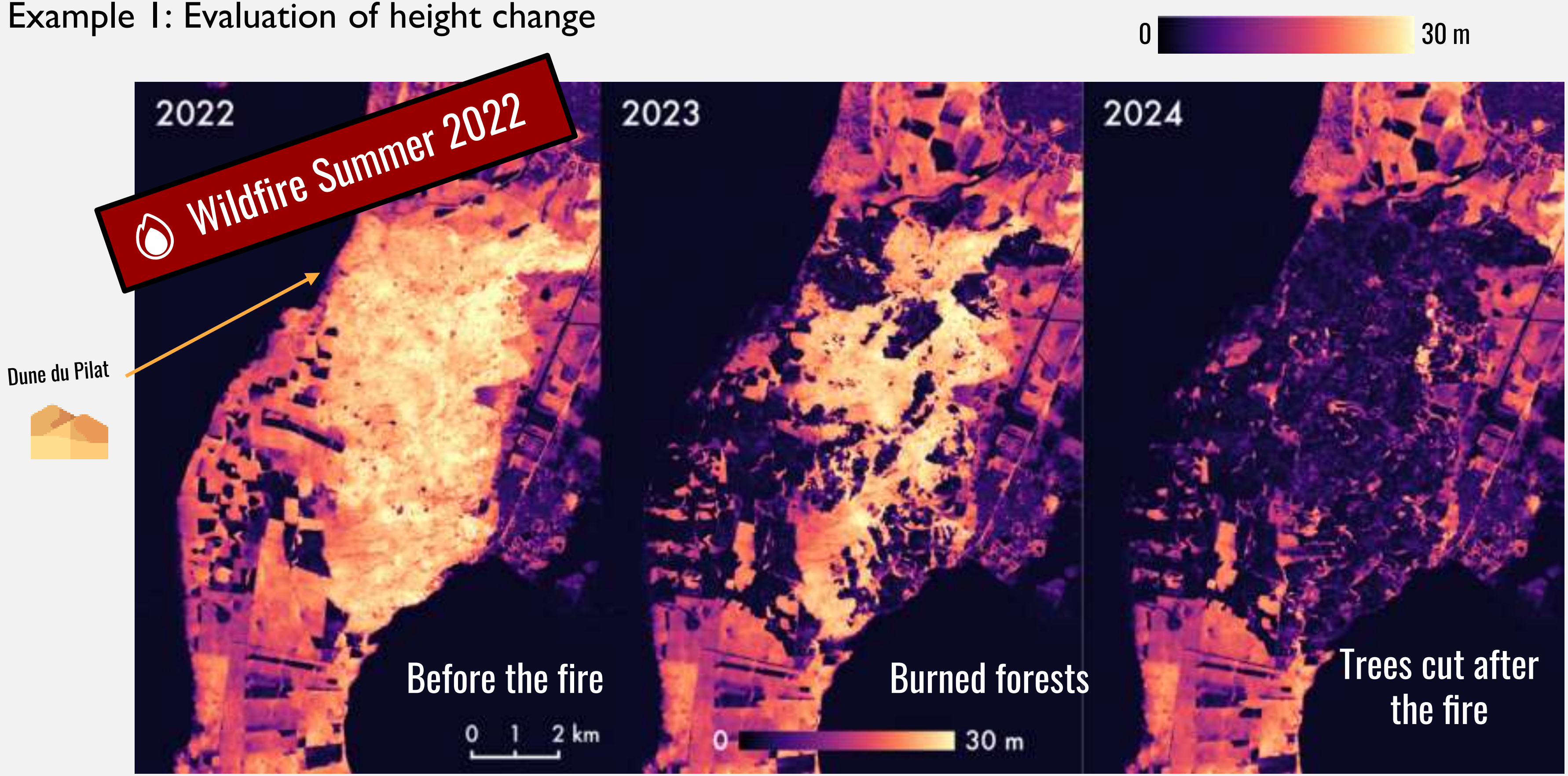
Canopy Height
- 30m



[Schwartz et al. (2025)]

Curtesy M. Schwartz & P. Ciais @ LSCE

Example 1: Evaluation of height change



Forest of la Teste de Buch, Landes, France

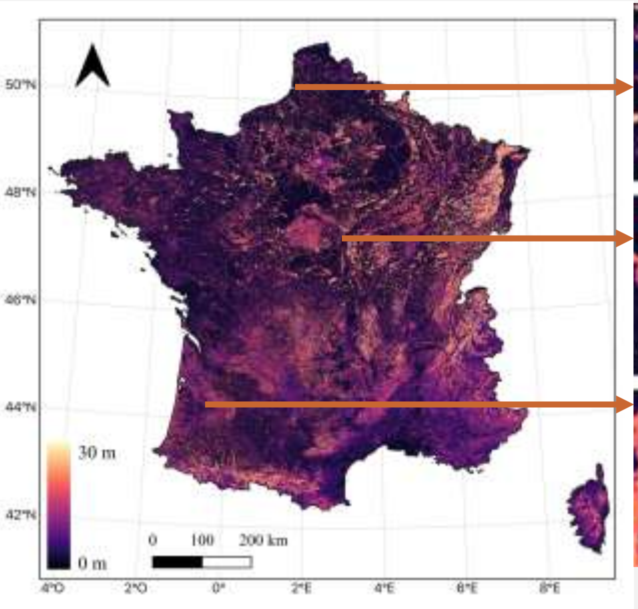
[Schwartz et al. (2025)]

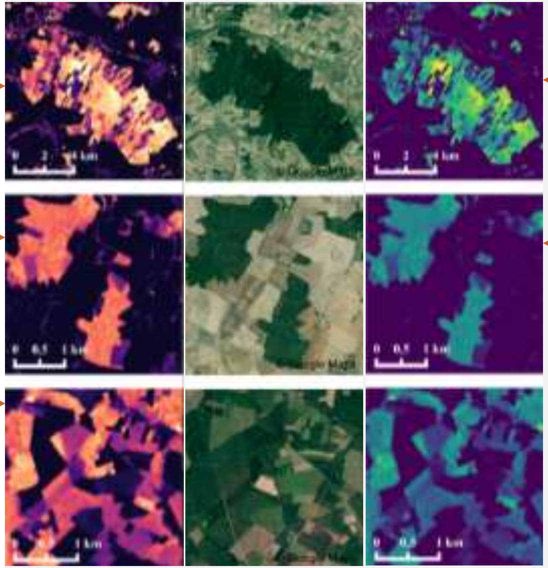
LSCE *Curtesy M. Schwartz & P. Ciais @ LSCE*

Example 2: Evaluation of Biomass

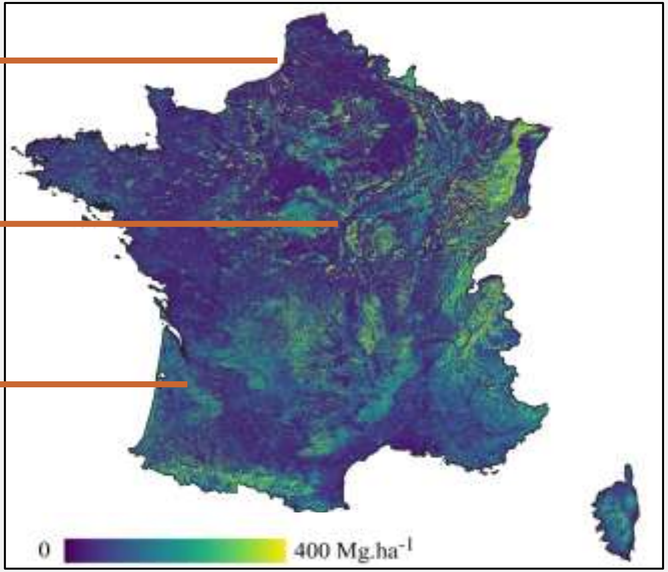
Height map (2020)

Biomass at 30 m resolution from height-biomass equations





Google map

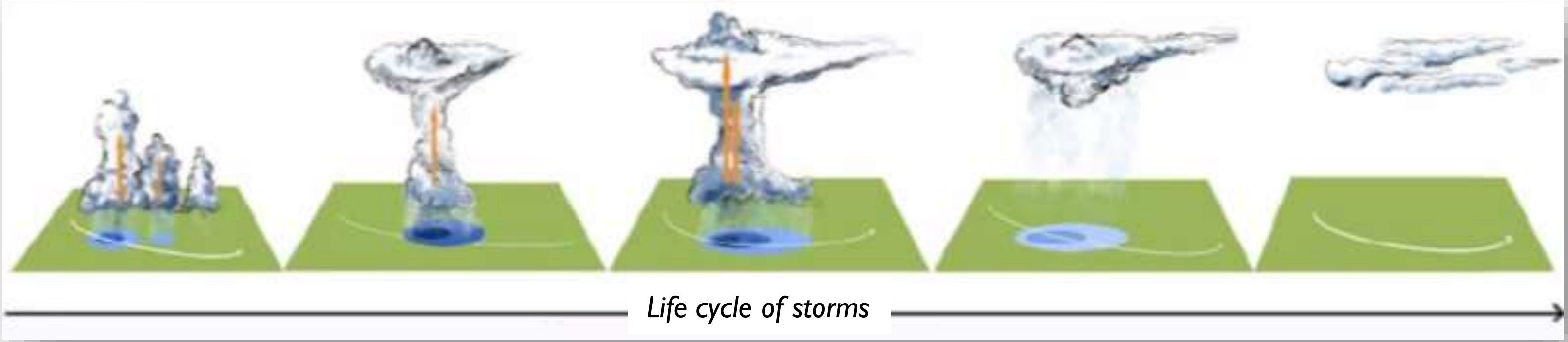


LSCE *Curtesy M. Schwartz & P. Ciais @ LSCE*

[Schwartz et al. (2023 & 2025)]

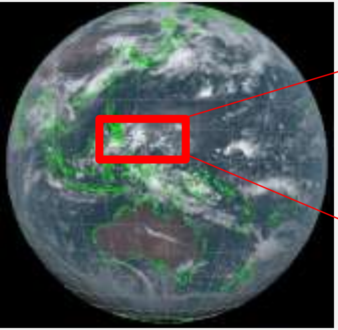
2. Properties of Meso-scale Convective Systems

Storm systems are central to the global water and energy cycles ⇒ their properties are driven by the magnitude of the updraft

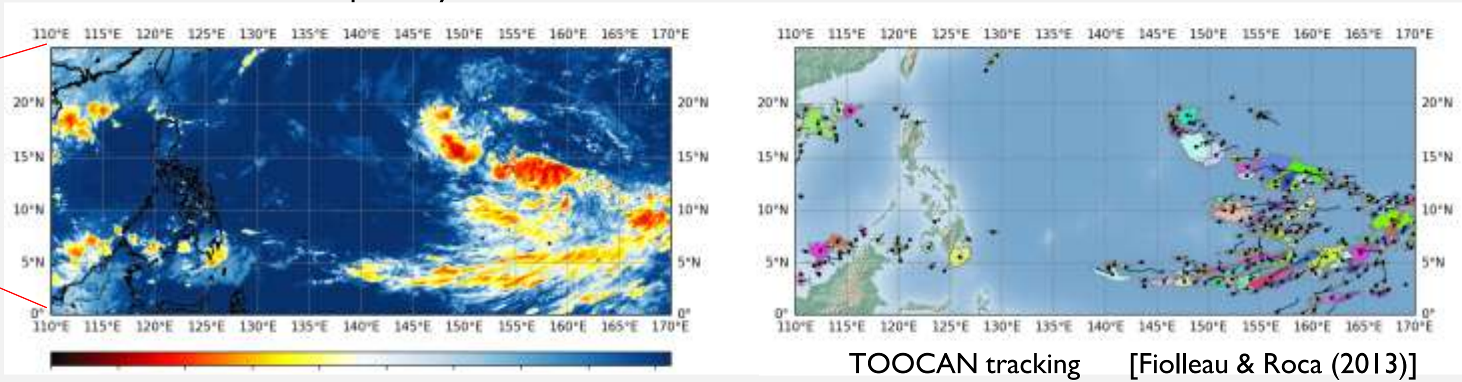


+ the stages of storm's development have different radiative (LW & SW) signatures

Storms can be tracked thanks to the high revisit time of geostationary satellites



Tropical Cyclones in West Pacific – 11 to 18 Oct. 2015



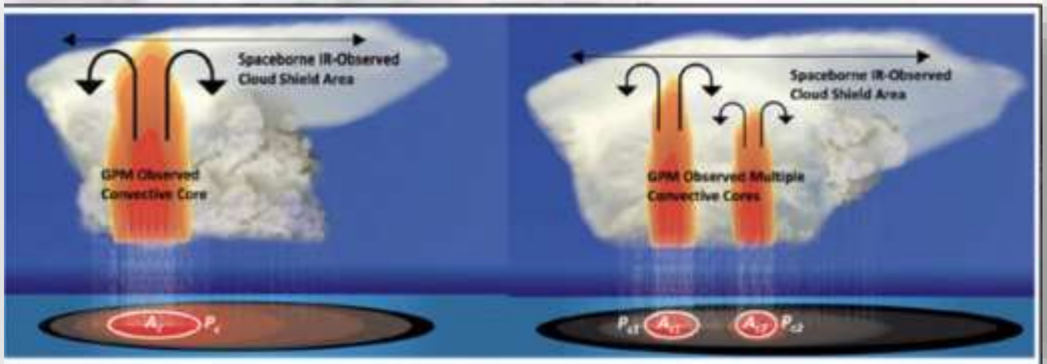
TOOCAN tracking [Fiolleau & Roca (2013)]

-100 °C 10.8µm BT +20°C

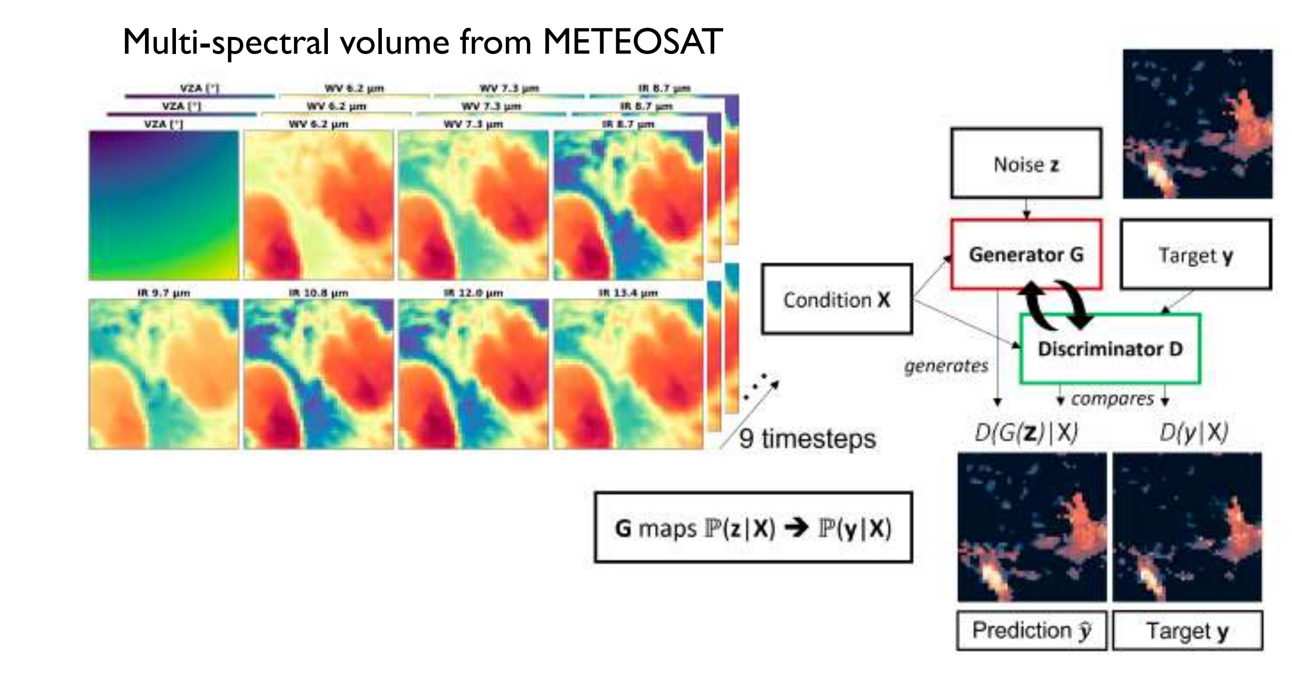
⇒ Temperature of cloud top / Horizontal extent / Life time

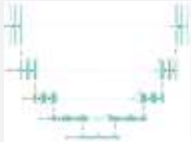
+ use of precip radars to get the inner properties

⇒ Vertical extent of the convective core



IA to associate macro properties (IR, frequent obs) ⇔ inner properties (radar, sparse obs)



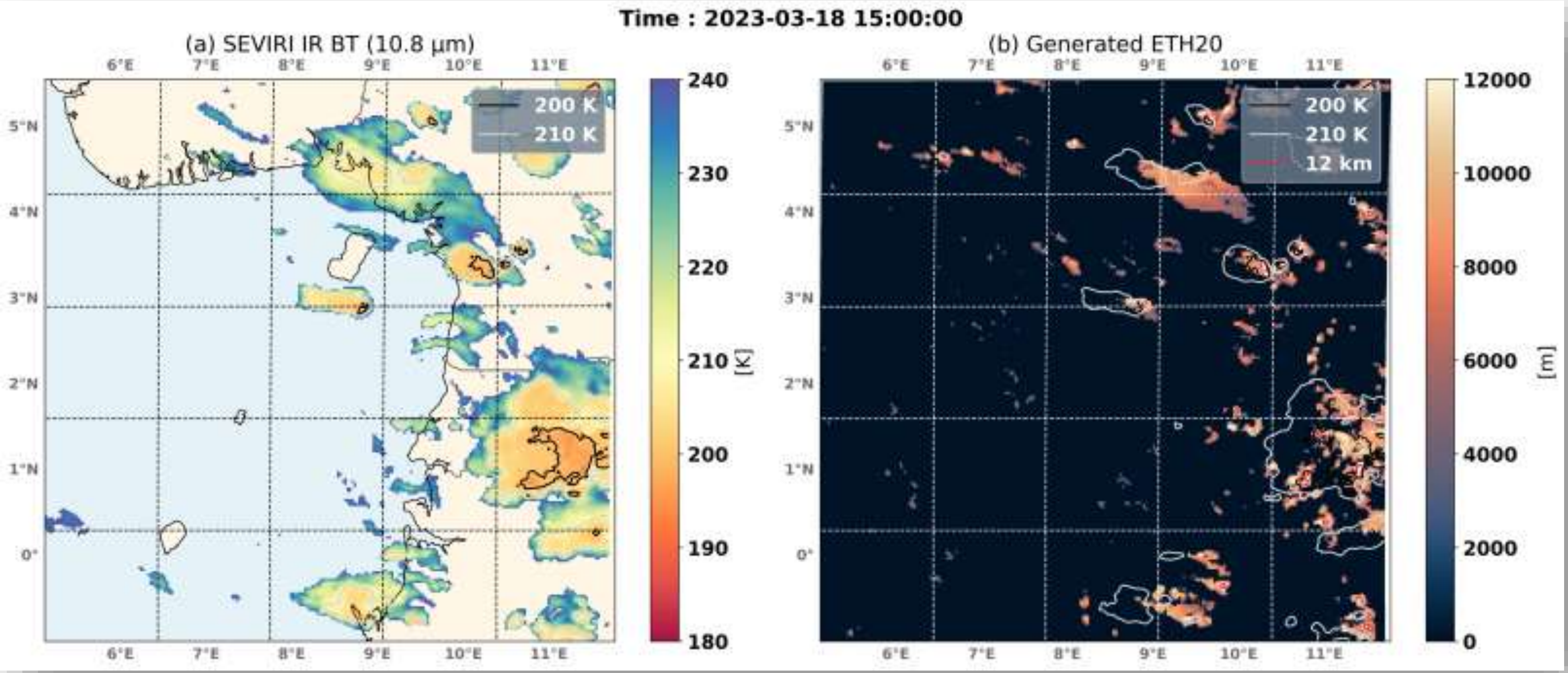


U-Net
Convolutional
Neural Network
2D+3D

Curtesy L. Netz @ LEGOS

[Netz et al. (sub. 2026)]

⇒ A 3D description of clouds at the resolution of geostationnay data



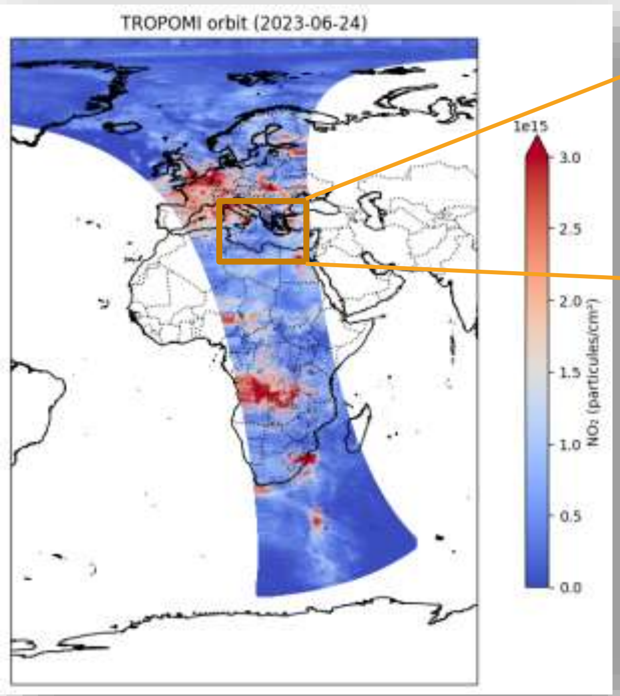
ETH20 = echo top-height at 20 dBZ ~ 12 km [Liu et al 2007]

= the altitude at which ice particles are deposited by the updrafts, which is linked to convective intensity

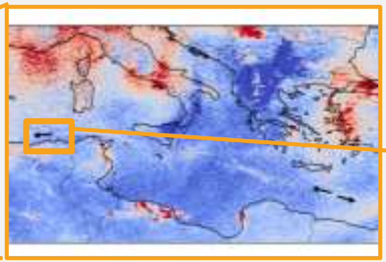
Curtesy L. Netz @ LEGOS

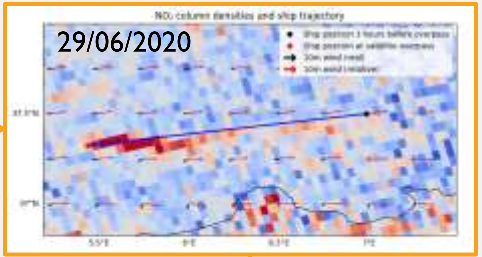
4. Identification of pollutant plumes for budget estimation

Assessment of national efforts to reduce the emissions of GHG ⇒ detection of plumes from hotspots requiring separation from background signal & observation errors



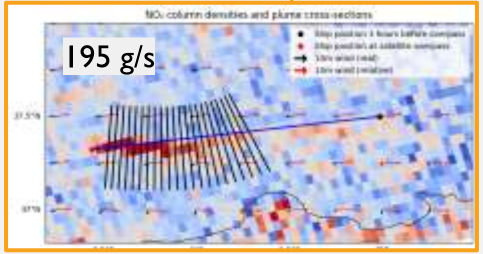
Example 1: ships and NO_2





plume segmentation with a clustering approach using wind (u,v) direction

⇒ total ship emission from cross sections along the track
+ atmospheric chemistry

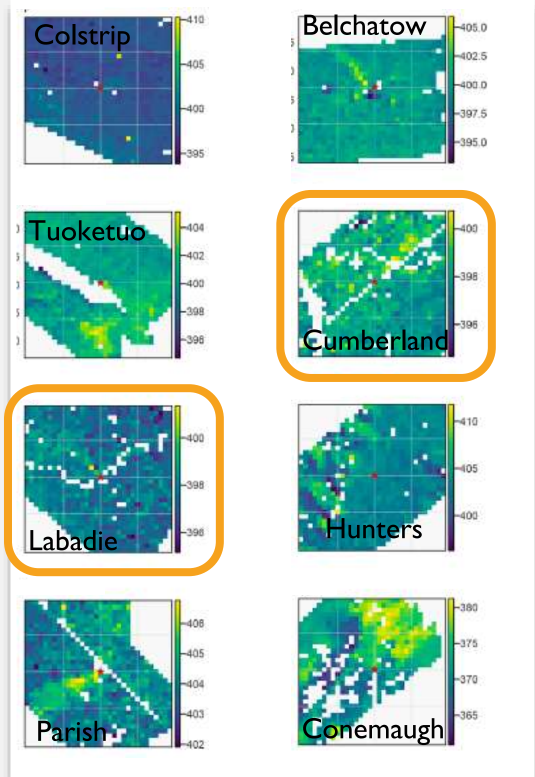


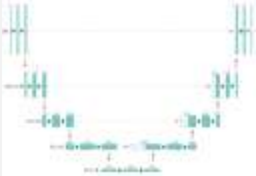
Curtesy H.Vignesoult & G. Broquet @ LSCE

Example 2: power plants and CO_2

⇒ Image segmentation with deep learning allowing a prediction of total emission

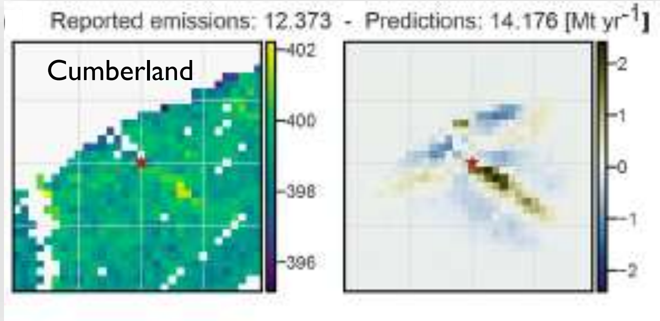
OCO-3 (2km) images of european power plants



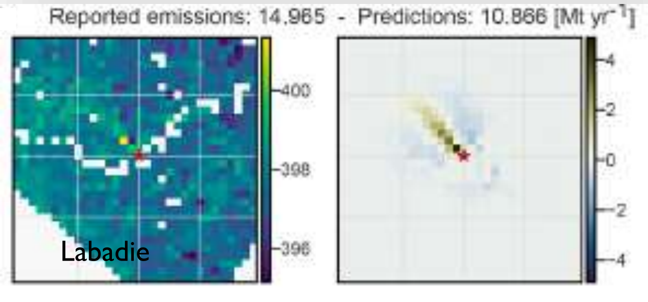


U-Net Convolutional Neural Network

Training with
- synthetic plumes
- background (biogenic + anthropogenic fuxes)
- instrument noise



Contribution of the pixel to the total prediction



[Dumont Le Brazidec et al. (2023, 2024, 2025)]

Curtesy G. Broquet @ LSCE

V. ONE OBSERVATIONAL CHALLENGE

km-scale measurements of clouds

km-scale measurements of clouds

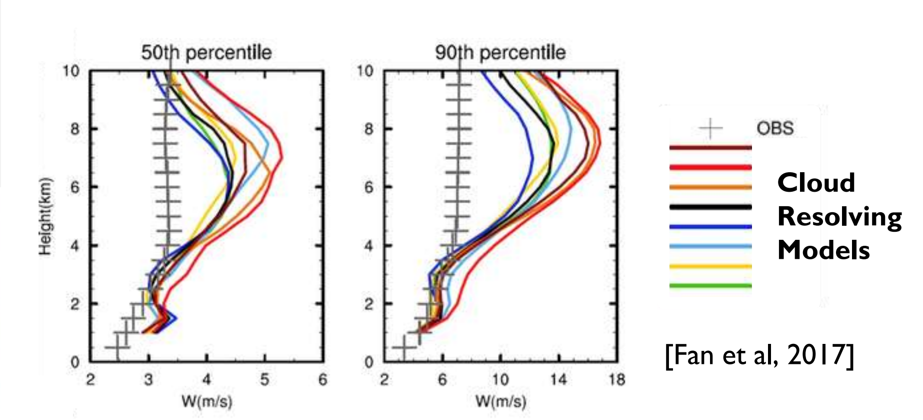
- **Rainfall forecasting** and **extreme rainfall events** are of major societal importance
- Need to **better understand**

  - physics of storm development and dissipation

  Where and **why** do they form where they form ?

  - role of the environment

  → Will support improvements in the modelling of atmospheric processes at the km-scale



[Fan et al, 2017]

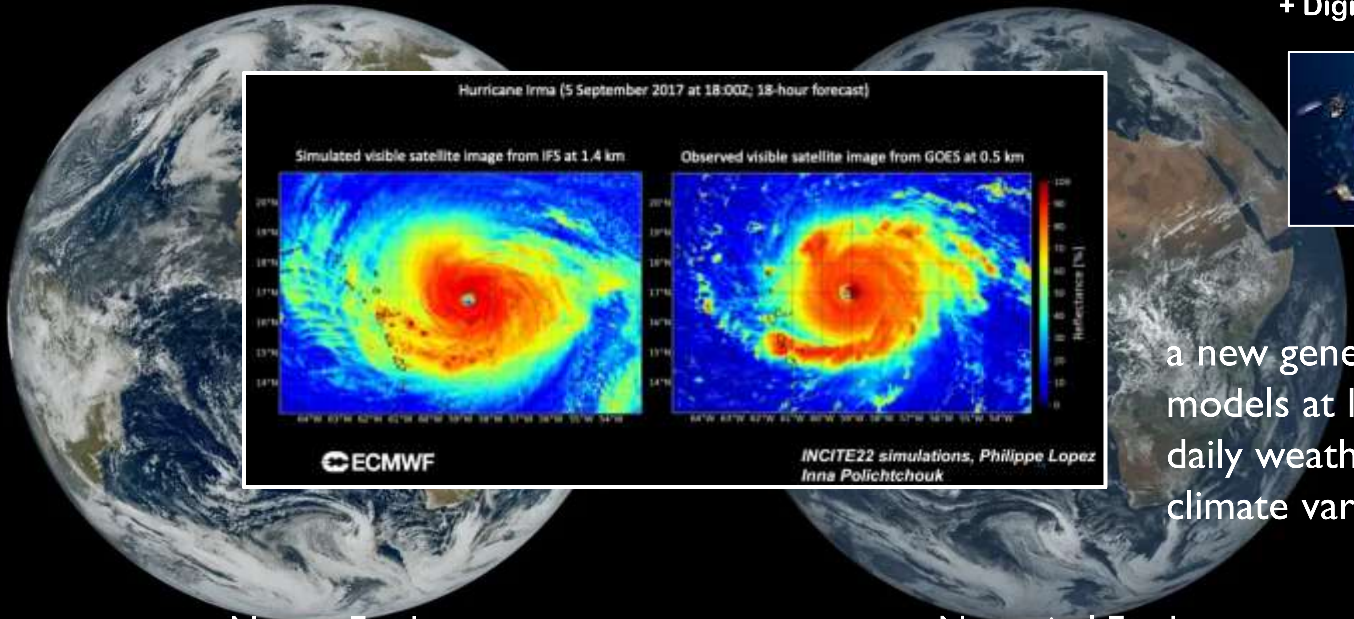
Destination Earth

+ Digital Twins of Earth

18 March 2023 at 12:00 UTC

MTG-I1 FCI

ECMWF IFS 2.8-km forecast



Nature Earth

Numerical Earth

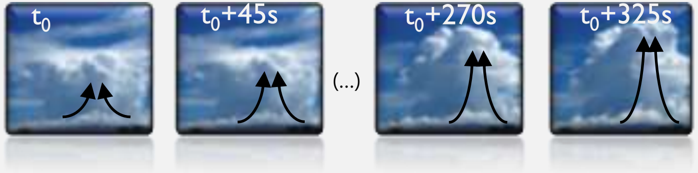
a new generation of models at km-scale from daily weather to decadal climate variability

⇒ Convergence on weather & climate modelling approaches

⇒ Allows to solve **explicitly** deep convection : vertical mass flux & dynamics within storms !

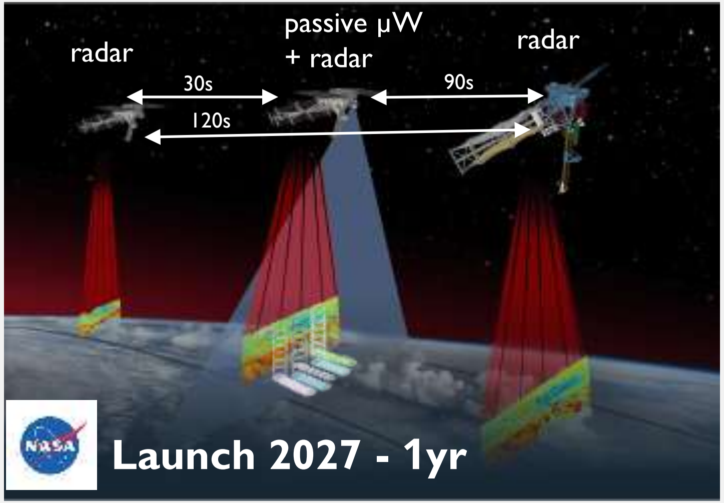
Observational requirements @ global scale !

⇒ Several satellite projects in the pipeline targeting in-cloud motion



« time-delayed » missions based on the fast growth of storm cells

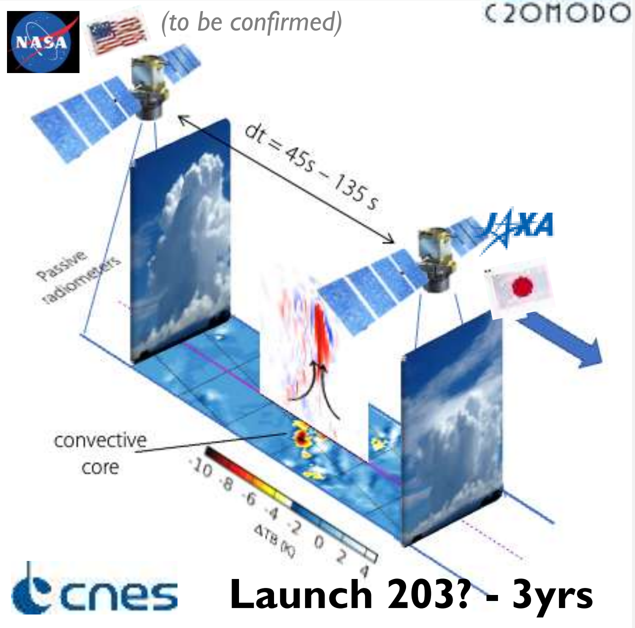
Investigation of Convective Updrafts



[Haddad et al (2022)]

Convective core observations trough microwave derivatives in the tropics

C2OMODO



[Brogniez et al (2022)]

Other challenges (not exhaustive) !

❖ Soil moisture estimation at a sub-daily scale :

⇒ source of atmospheric moisture (daytime) + energy constraint (latent & sensible heats)

⇒ several instruments (passive/active) at different local time / different frequencies…

❖ Chemistry of aerosols :

⇒ better cartography of natural and anthropogenic emissions: key of air quality + impact on formation of clouds and precipitations

⇒ black carbon, organic aerosols, sea salts…

❖ … and much more…

Thank you !