OCEANOGRAPHIC OBSERVATIONAL AND MODELING PRODUCTS AVAILABLE FOR MARINE RESEARCH

Sea Surface Temperature and Ocean Colour

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Ministero dell'Università e della Ricerca

Italiadomani

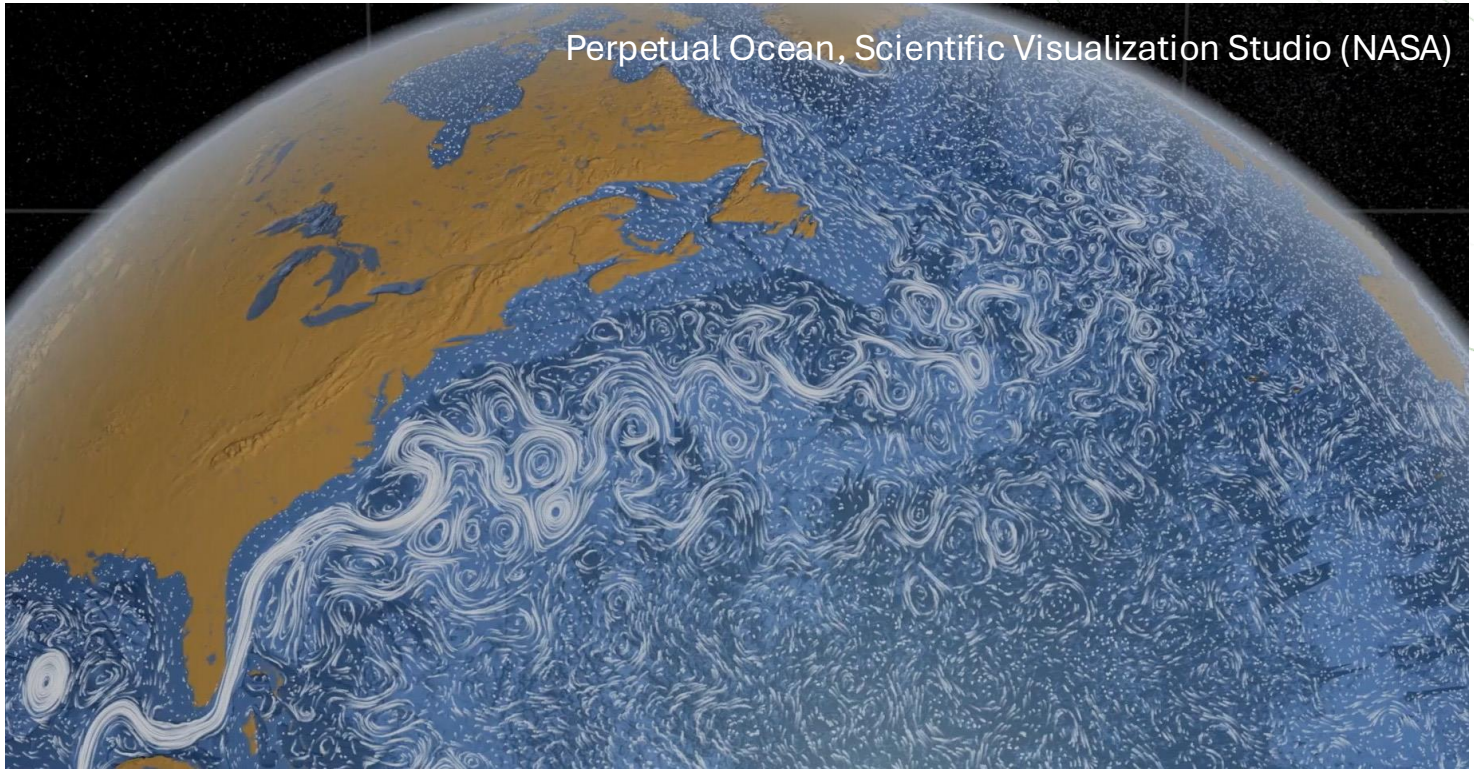
Outline

- Introduction to Remote Sensing
- Data providers and the Copernicus Marine Service
- Different products and processing levels
- Sea Surface Temperature
- Ocean Colour

Remote sensing

Advantages:

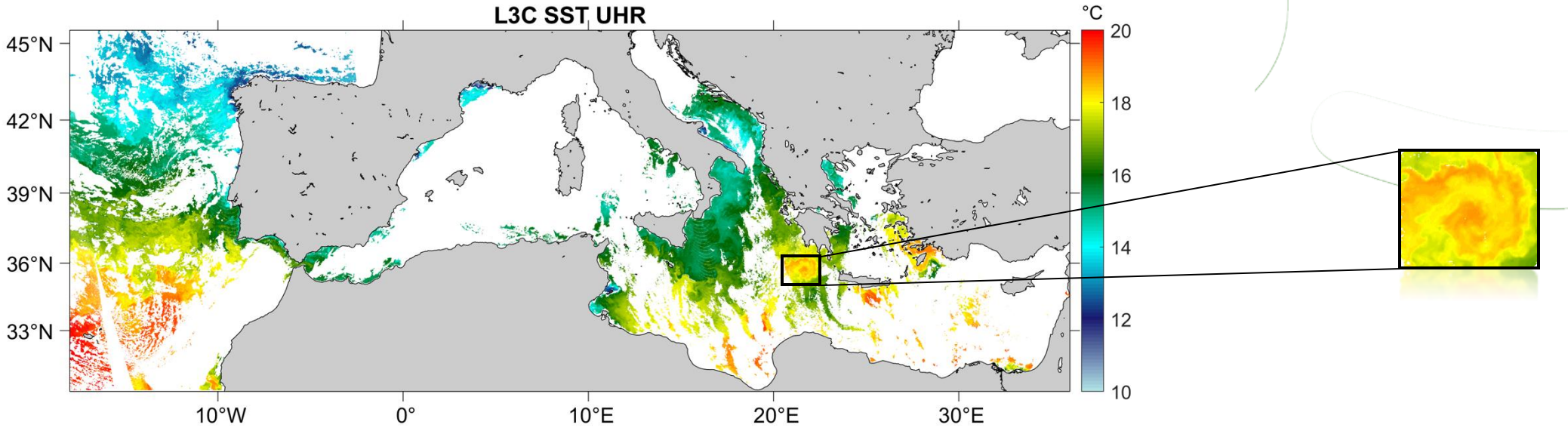
- Ocean coverage and global view



Remote sensing

Advantages:

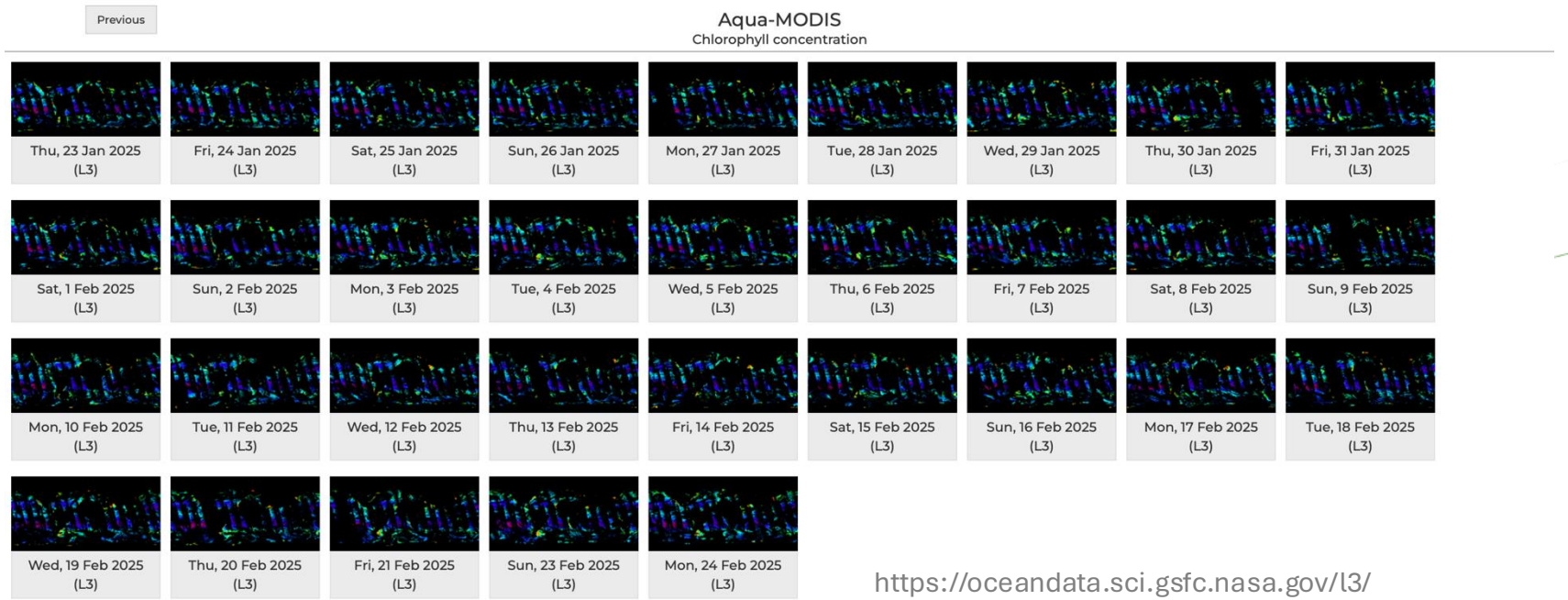
- Ocean coverage and global view
- Observations at different spatial scales



Remote sensing

Advantages:

- Ocean coverage and global view
- Observations at different spatial scales
- Frequent observations



https://oceandata.sci.gsfc.nasa.gov/l3/

Data providers

Several data providers (at different levels of processing):

- NASA
- NOAA
- EUMETSAT
- ESA
- …

Data providers

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- NASA
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- EUMETSAT
- ESA
- …

- Today focus: COPERNICUS

Copernicus programme

EUROPE'S EYES ON EARTH

In collaboration with:

*«Copernicus is the Earth observation component of the European Union's Space programme, **looking at our planet and its environment to benefit all European citizens**. It offers information services that draw from satellite Earth Observation and in-situ (non-space) data.»*

www.copernicus.eu

Copernicus programme

Copernicus
Europe's eyes on Earth

EUROPE'S EYES ON EARTH

European Commission

In collaboration with:

esa · EUMETSAT · ECMWF · EEA · MERCATOR OCEAN INTERNATIONAL · FRONTEX · SatCen · EMSA European Maritime Safety Agency

six thematic streams
of Copernicus services:

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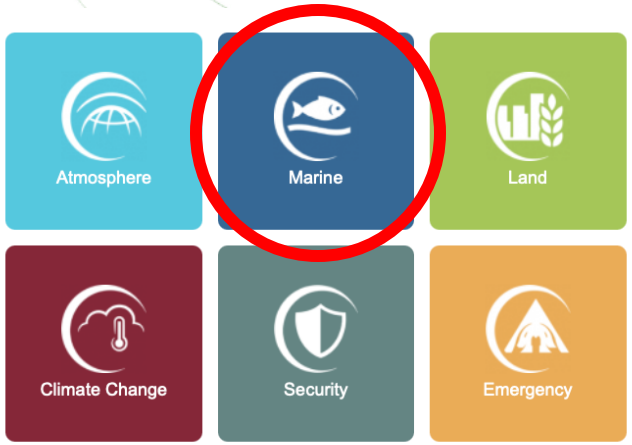

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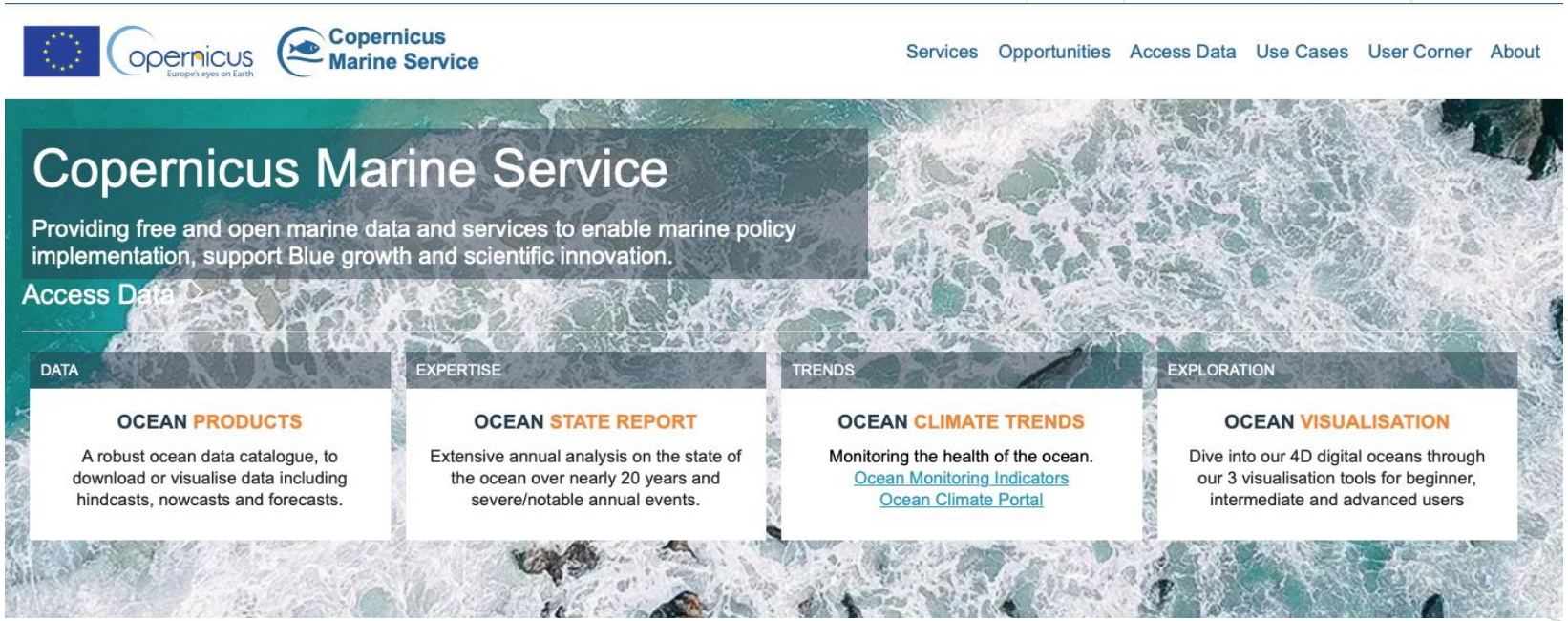
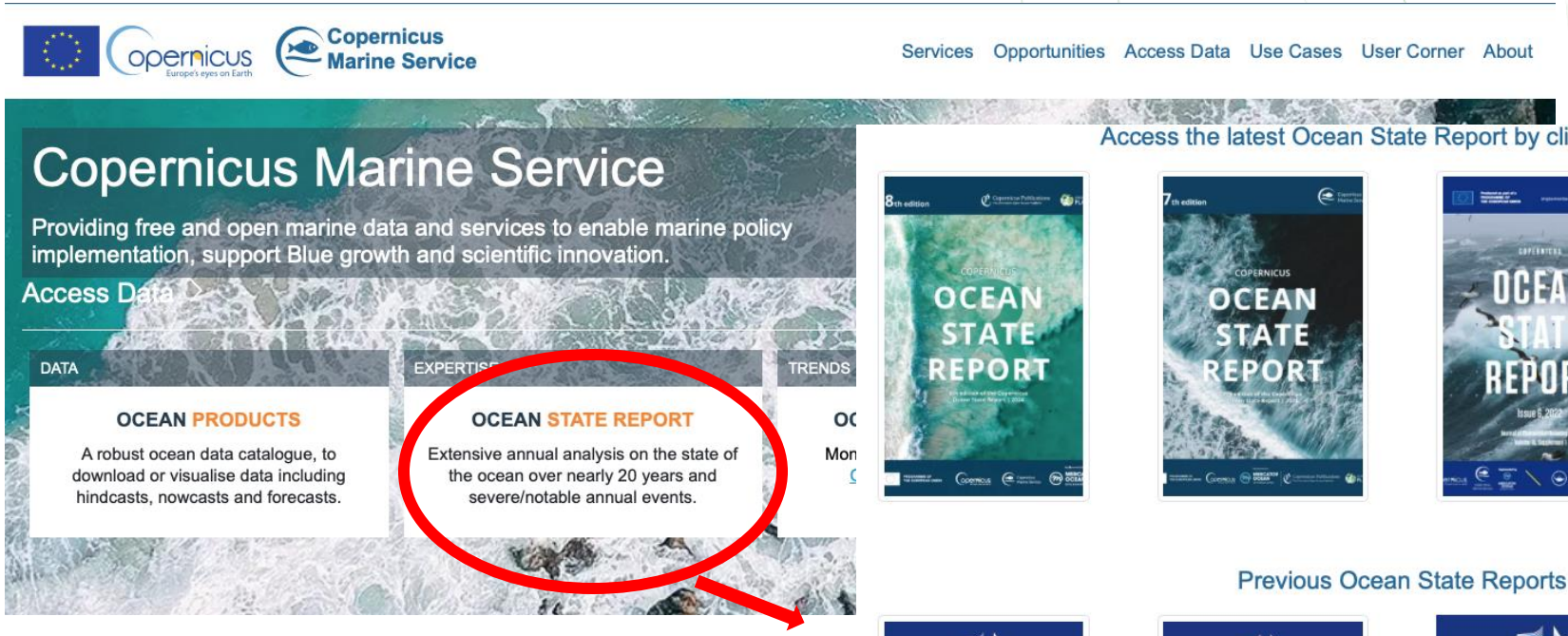
www.copernicus.eu

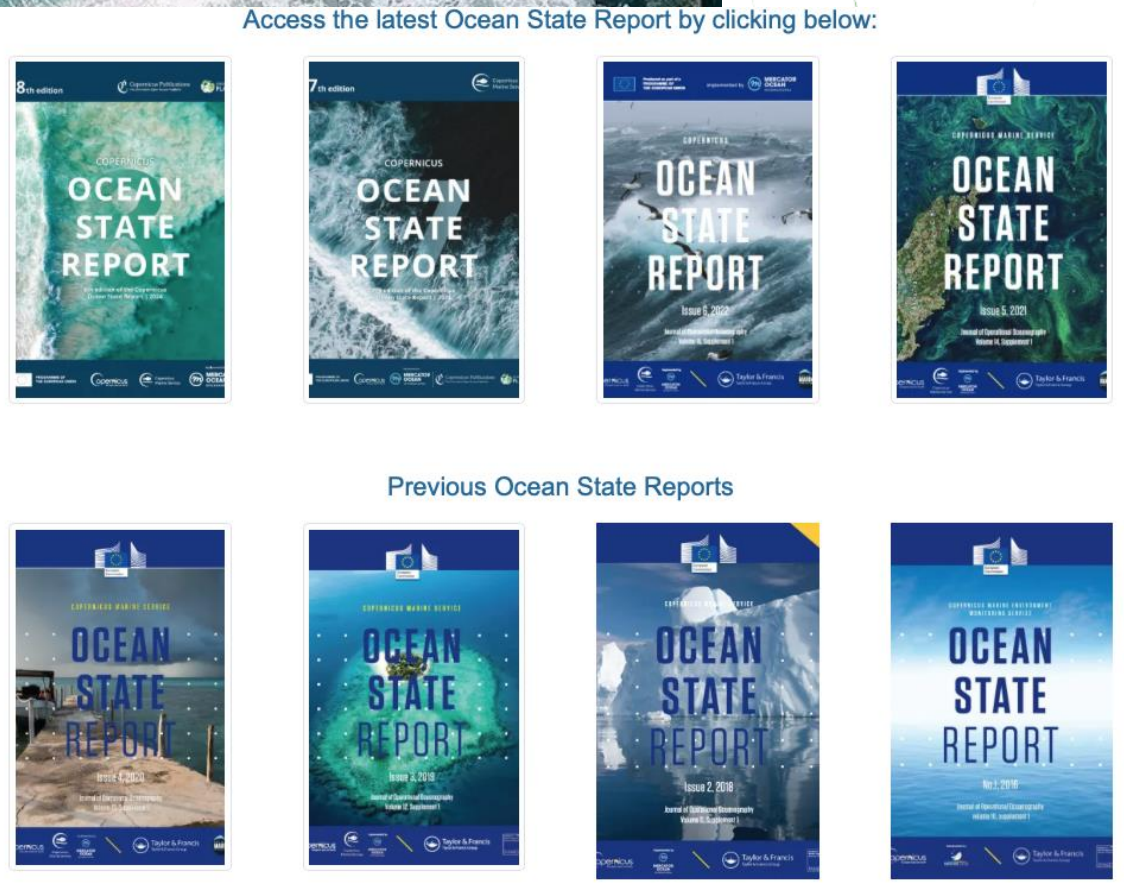
Copernicus Marine Service



www.marine.copernicus.eu

Ocean State Reports

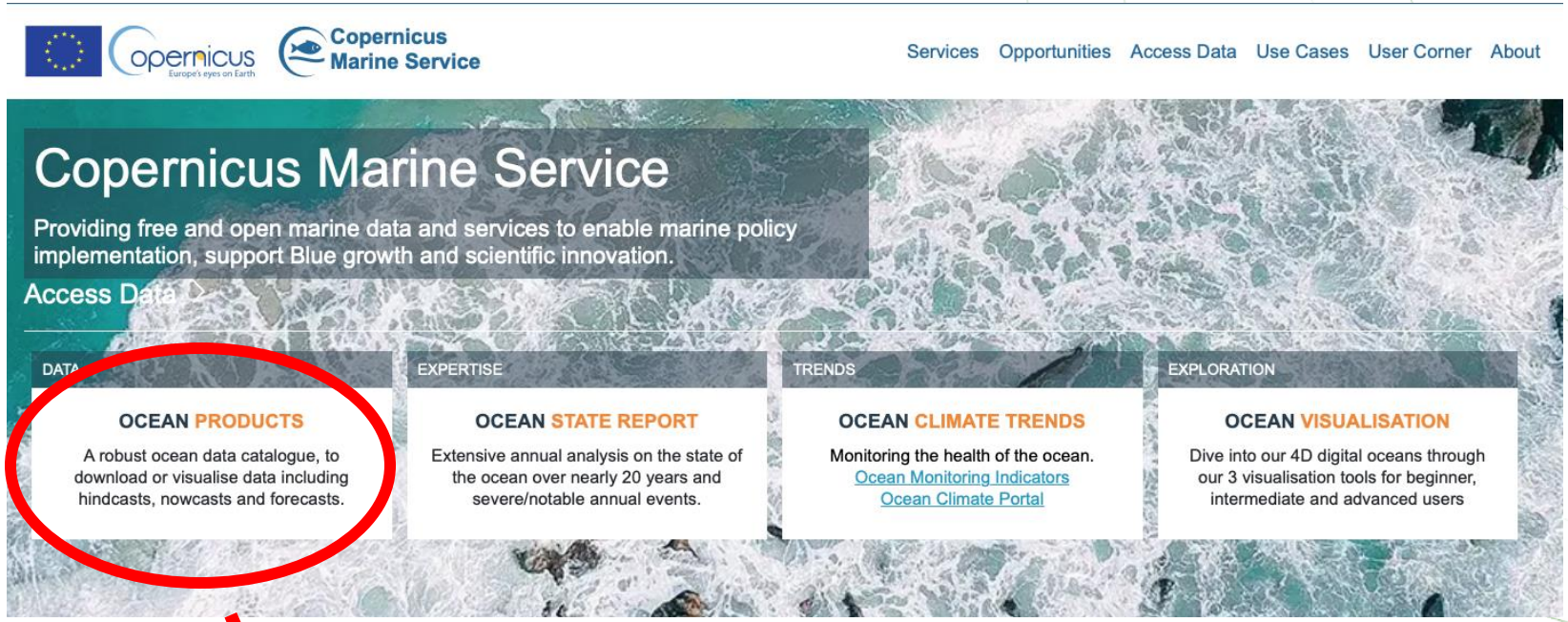


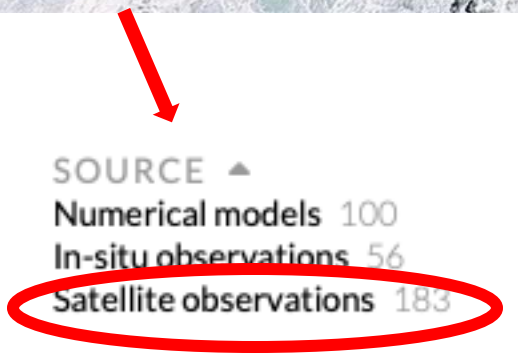


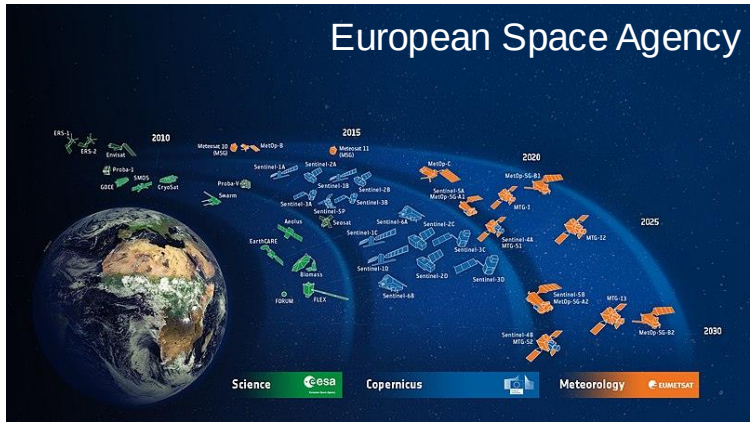
«The Copernicus Marine Service Ocean State Report is a Reference Report of the European Union.

It provides a comprehensive and state-of-the art assessment of the state of the global ocean and European regional seas for the ocean scientific community as well as for policy and decision-makers.»

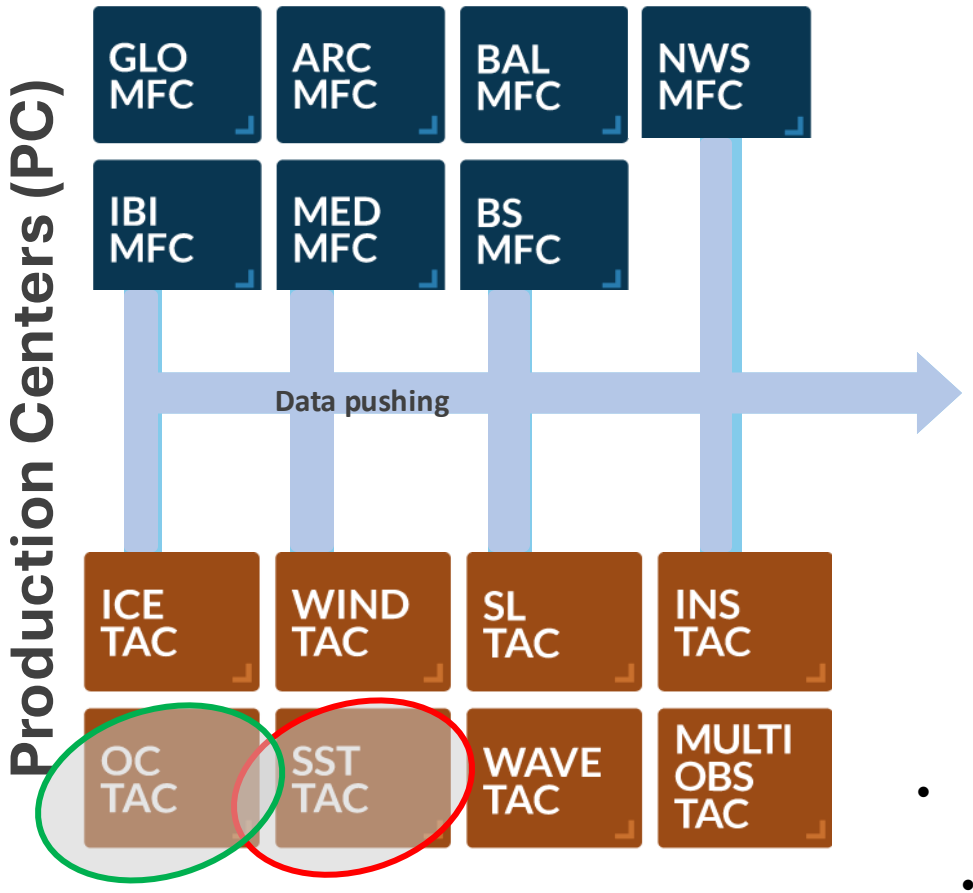
Copernicus Marine Service

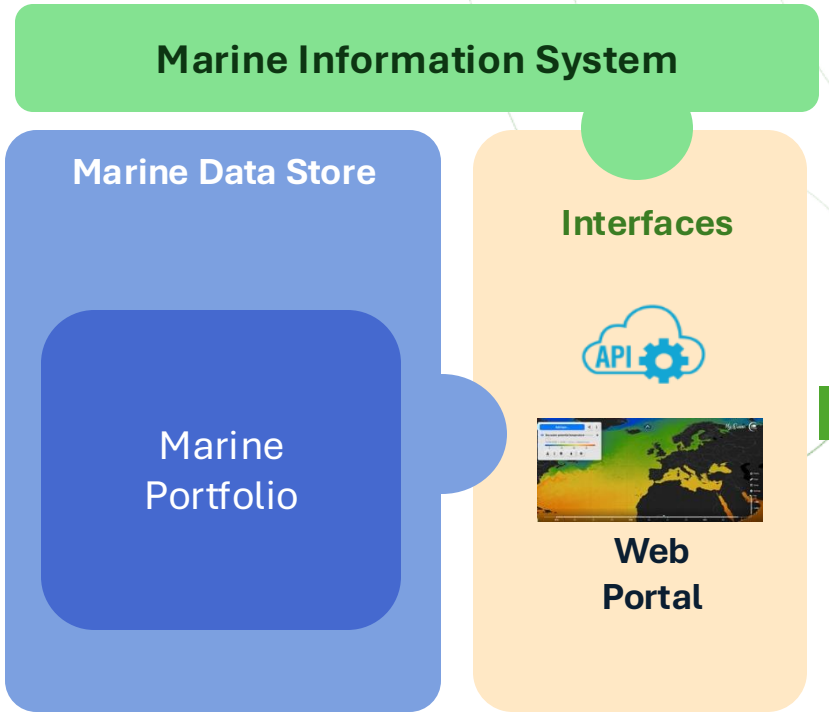


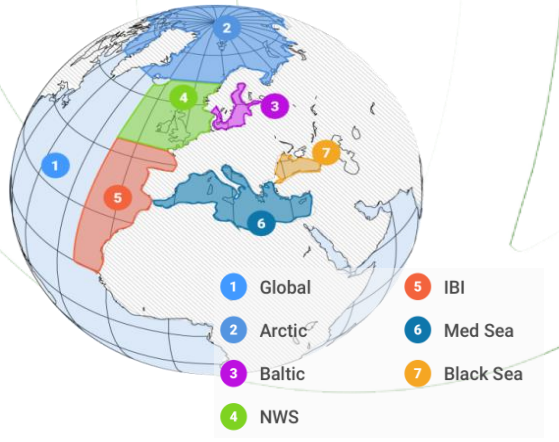




Copernicus Marine Service

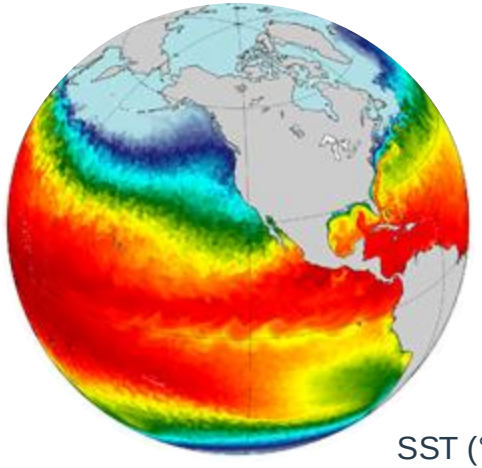


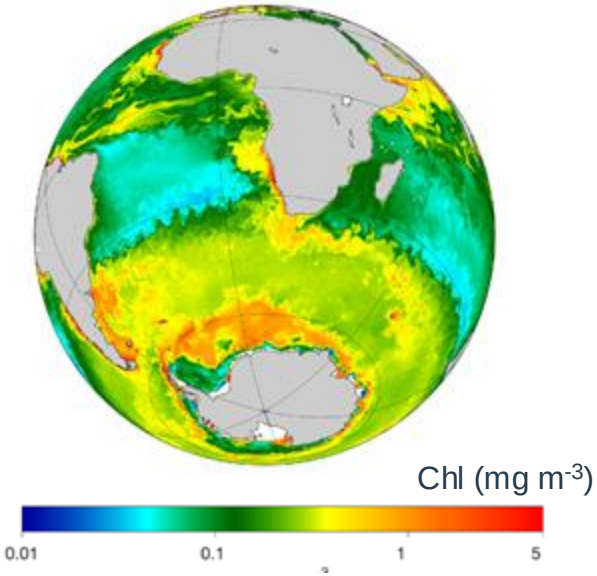


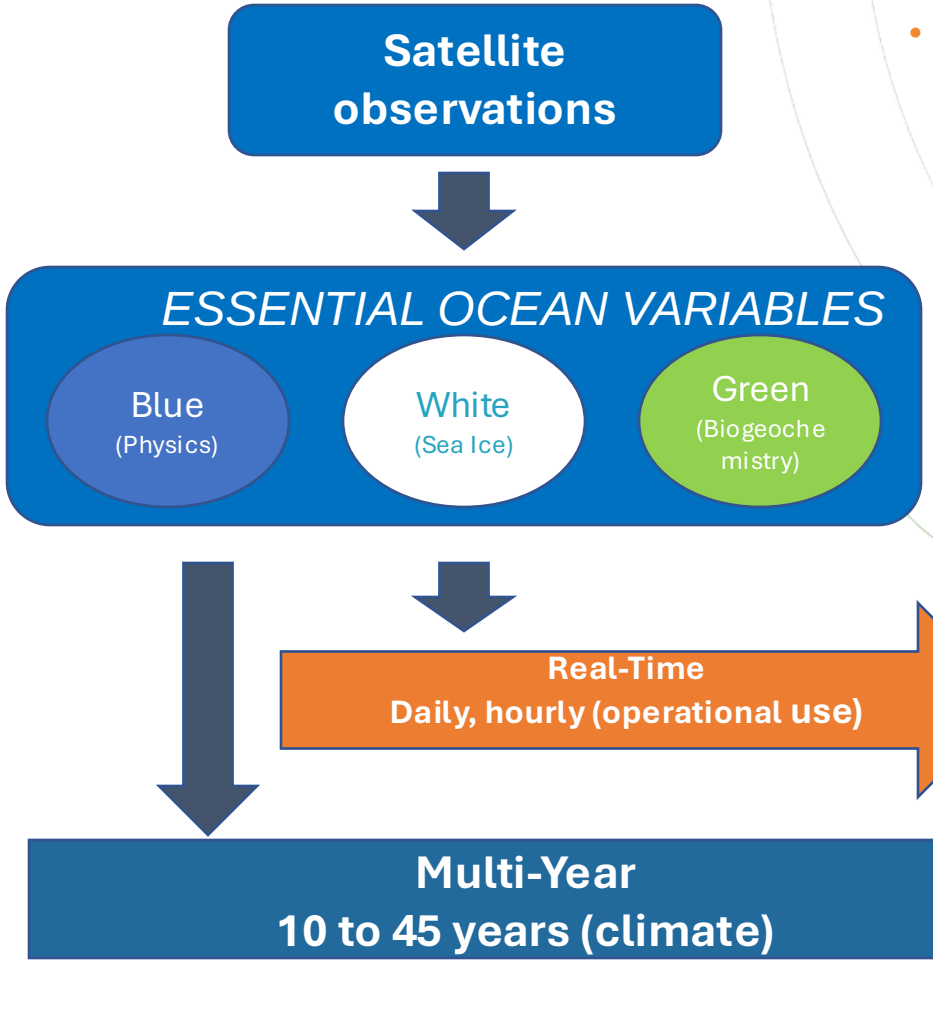


- **PCs – 7 MFCs (model data) & 8 TACs (observations)**
  - **TAC** products are primarily **based on satellite and in situ observations**

Ocean products: Satellite Observations







- Satellites have the unique capability to provide **synoptic, regular and systematic mapping** of the main EOVs/ECVs at global scale
- **High accuracy and quality** of satellite data (e.g., accuracy of SST ~1/100° deg.)
- Possibility to have **Near-Real-Time (NRT)** and **Multi-Year (MY)** satellite data
  - NRT data could be available with a 1-day delay (operational use)
  - MY data are long time series, updated every 12/6 months
- **Combined** use of **satellite and in situ data** is essential (e.g., validation, subsurface obs., etc)

Observational products

What choices do I have to make?

- Spatial resolution and coverage
- Temporal resolution and coverage
- Single sensor / multisensors
- Observations (with gaps) or interpolated gap-free maps
- Near real time or multi-year

Which is the best product?

Observational products

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- Spatial resolution and coverage
- Temporal resolution and coverage
- Single sensor / multisensors
- Observations (with gaps) or interpolated gap-free maps
- Near real time or multi-year

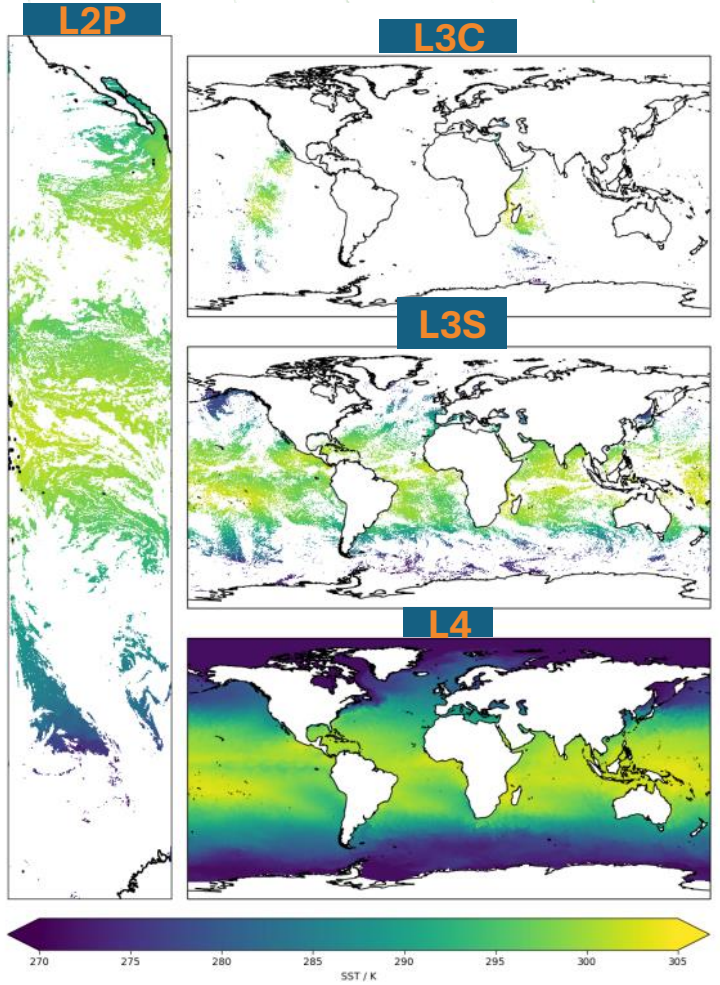
Which is the best product?

It really depends on the application!

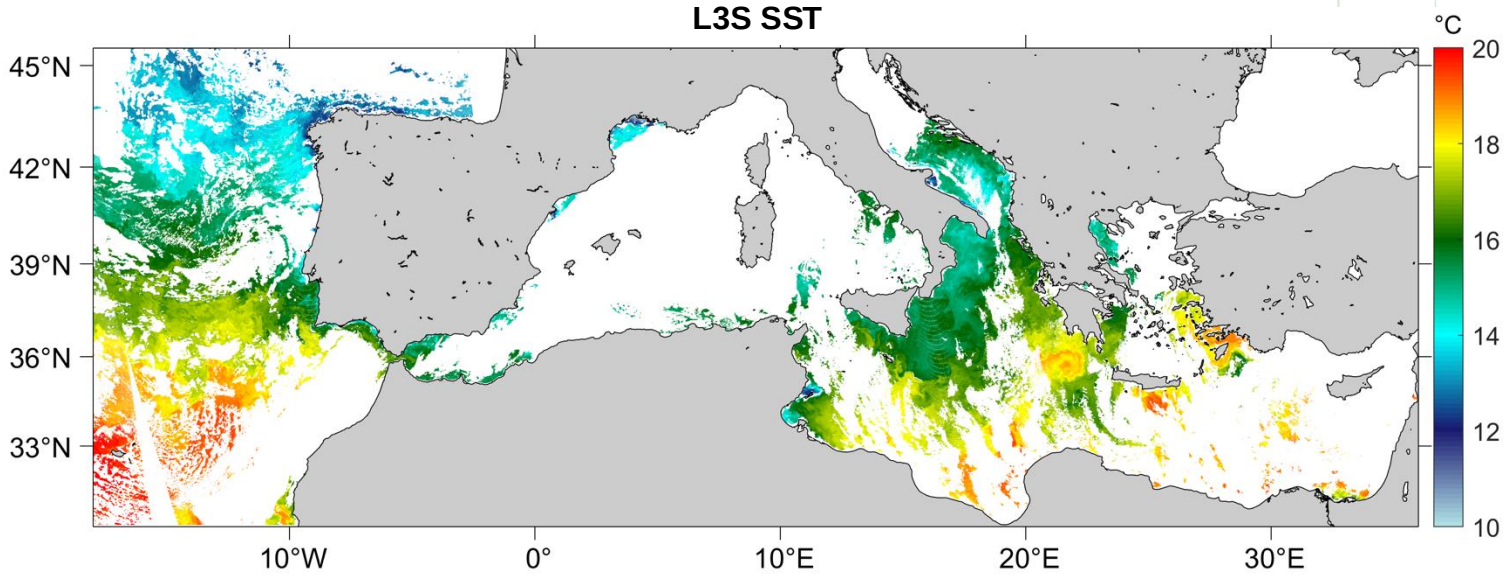
Levels of satellite derived products

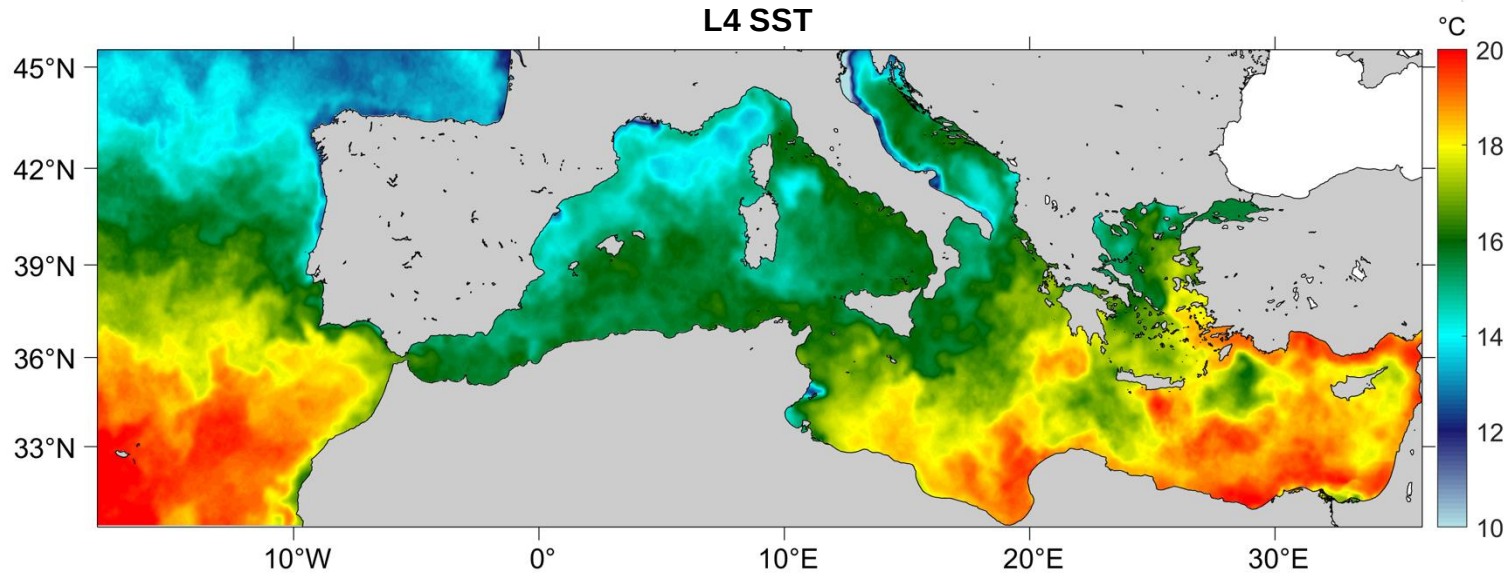
Data observations are categorized into five main levels, ranging from Level 0 to Level 4:

Processing level	Note
Level 0 (L0)	Unprocessed instrument data
Level 1 (L1)	Data processed to sensor unit
Level 2 (L2)	Data on the native satellite swath grid and derived from single-sensor measurements (typically, granules of 3-5 minutes).
Level 3 (L3)	Product generated by regridding L2 data onto a latitude-longitude grid, typically provided as daily (day and night) composite data.
Level 4 (L4)	Gap-free (no data voids) product based on data from L3 sensors.

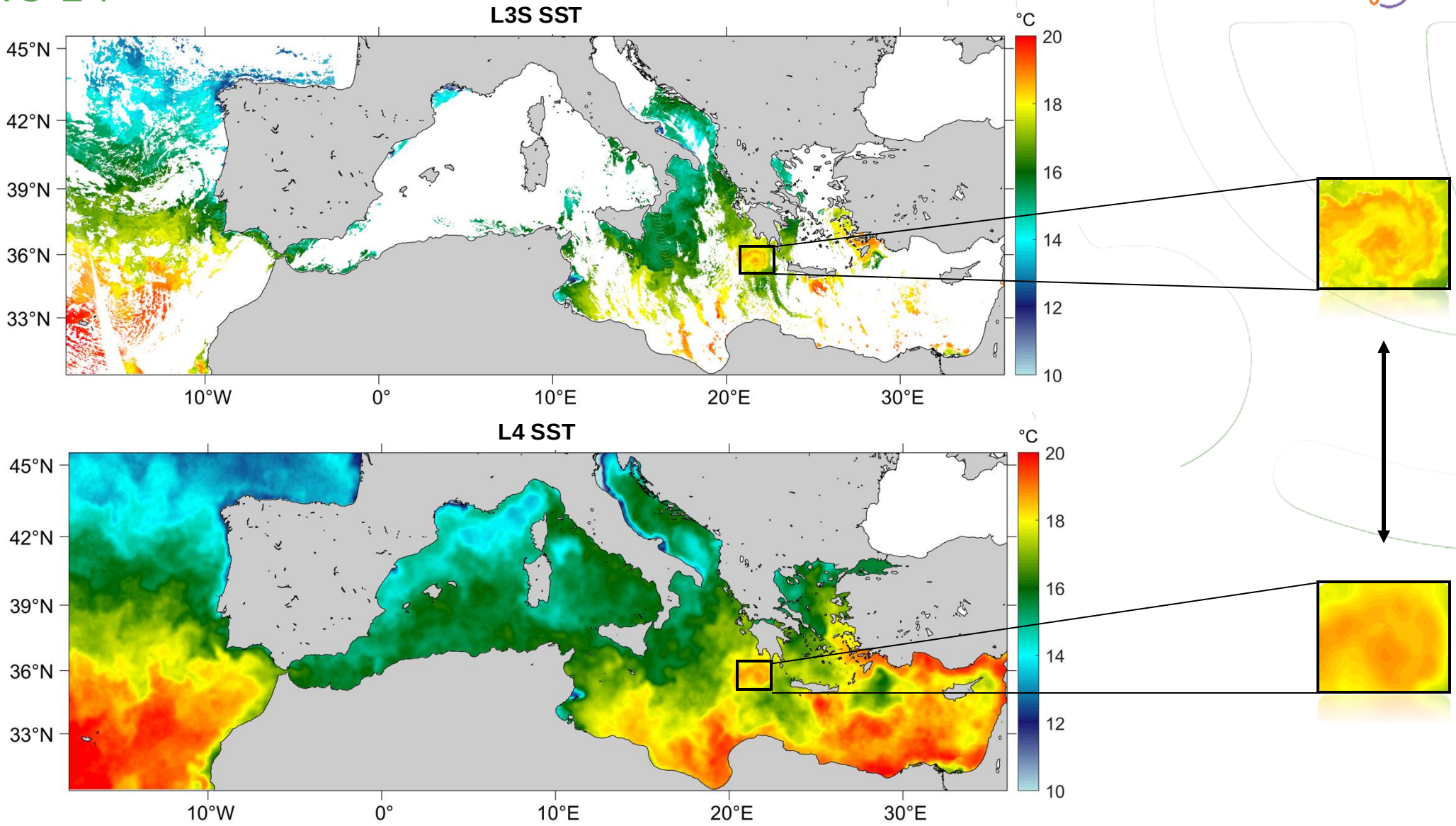


L3 vs L4


L3S SST
°C
20
18
16
14
12
10
45°N
42°N
39°N
36°N
33°N
10°W
0°
10°E
20°E
30°E


L4 SST
°C
20
18
16
14
12
10
45°N
42°N
39°N
36°N
33°N
10°W
0°
10°E
20°E
30°E

L3 vs L4


L3S SST
°C
20
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°C
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16
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12
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45°N
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39°N
36°N
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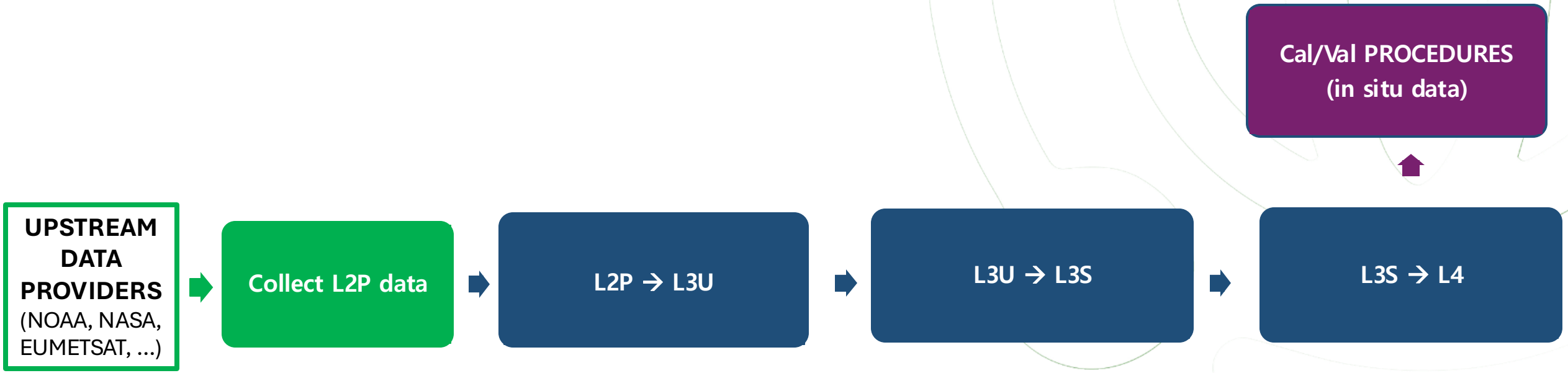
10°W
0°
10°E
20°E
30°E

General idea of L3/L4 processing



Level-2 Pre-processed (L2P):
Data on the native satellite swath grid and derived from single-sensor measurements (typically, granules of 3-5 minutes).

Level-3 Uncollated (L3U):
Product generated by regridding L2P data onto a latitude-longitude grid.

Level-3 Collated (L3C):
Single-sensor product based on collated L3U data, typically provided as daily (day and night) composite data.

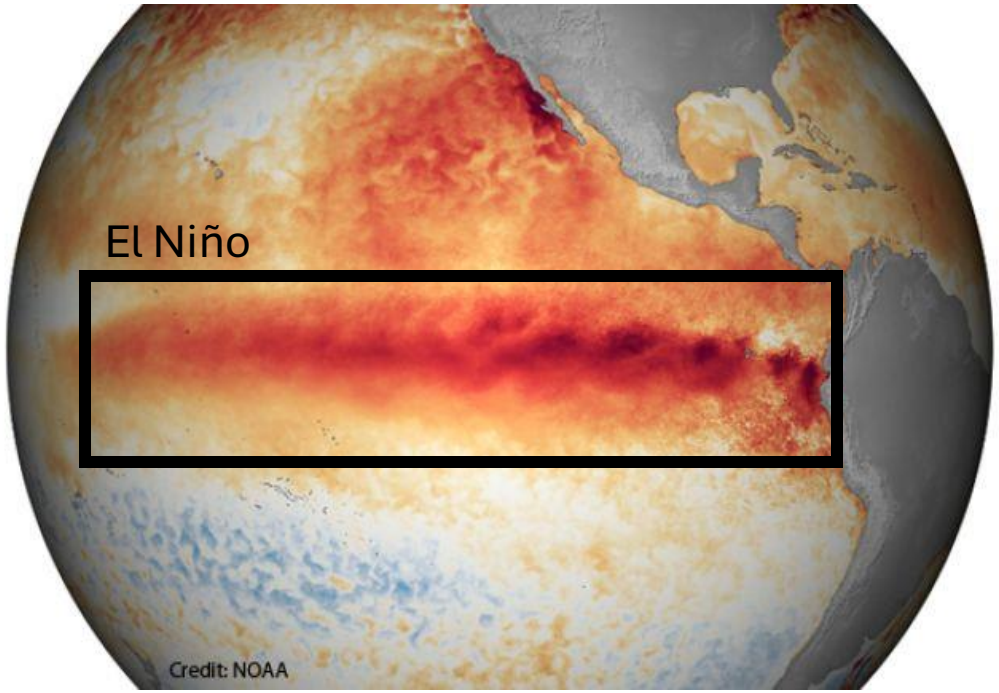
Level-3 Supercollated (L3S):
Merged multi-sensor product based on L3C products.

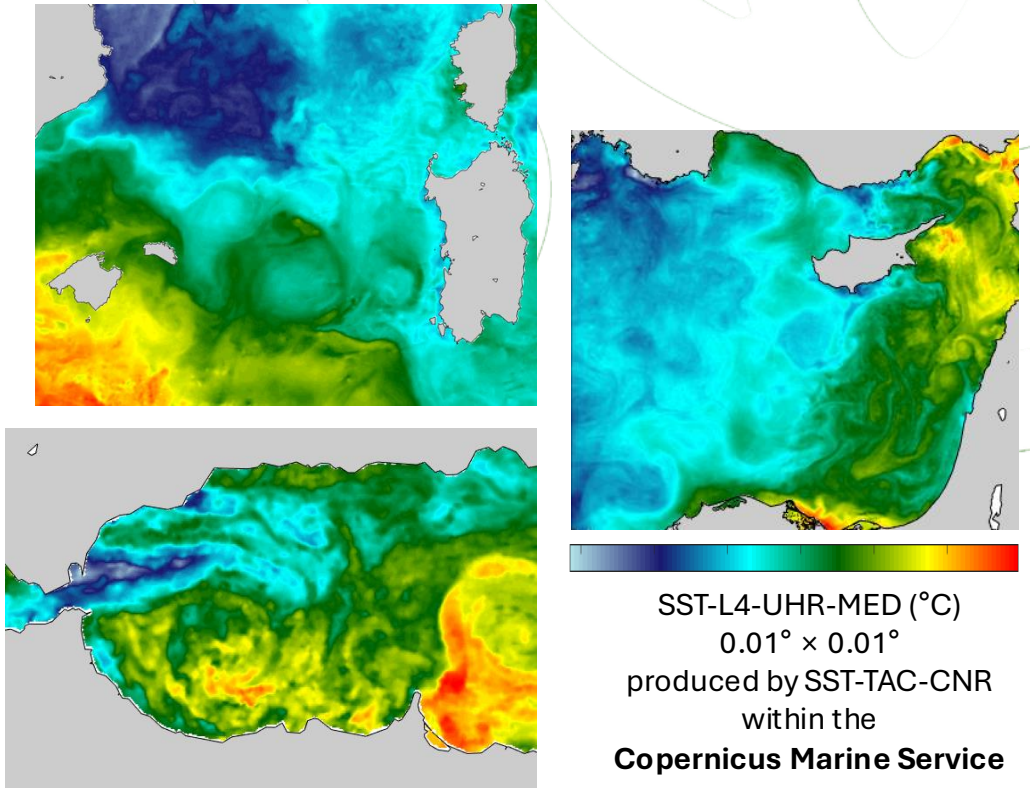
Level-4 (L4):
Gap-free (no data voids) product based on data from L3S sensors.

SEA SURFACE TEMPERATURE

Why is Sea Surface Temperature important?

SST is an essential ocean and climate variable (EOV/ECV), crucial to investigate climate variability, monitoring many biological processes and ocean dynamics

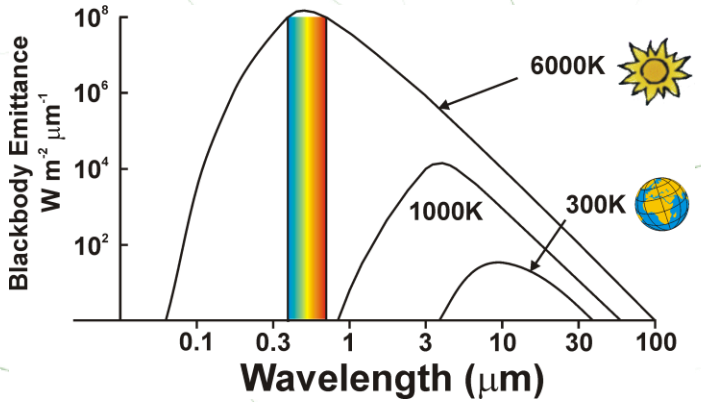




SST-L4-UHR-MED (°C)
0.01° × 0.01°
produced by SST-TAC-CNR
within the
Copernicus Marine Service

Sea Surface Temperature from space

All surfaces emit radiation, the strength of which depends on the surface temperature. The higher is the temperature, the greater is the radiant energy.



Sea Surface Temperature from space

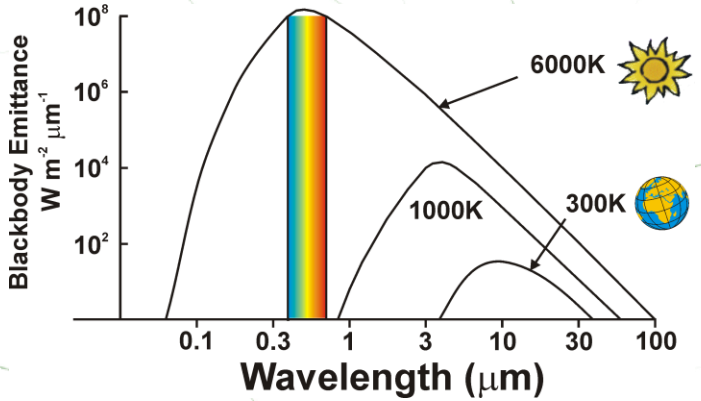
All surfaces emit radiation, the strength of which depends on the surface temperature. The higher is the temperature, the greater is the radiant energy.

Satellite infrared and microwave sensors measure the radiation emitted from the surface ocean, which well approximates the black-body radiation (Planck's) law:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1},$$

where:

ν is the frequency of the electromagnetic radiation
h is the Planck constant
c is the speed of light in vacuum
k is the Boltzmann constant

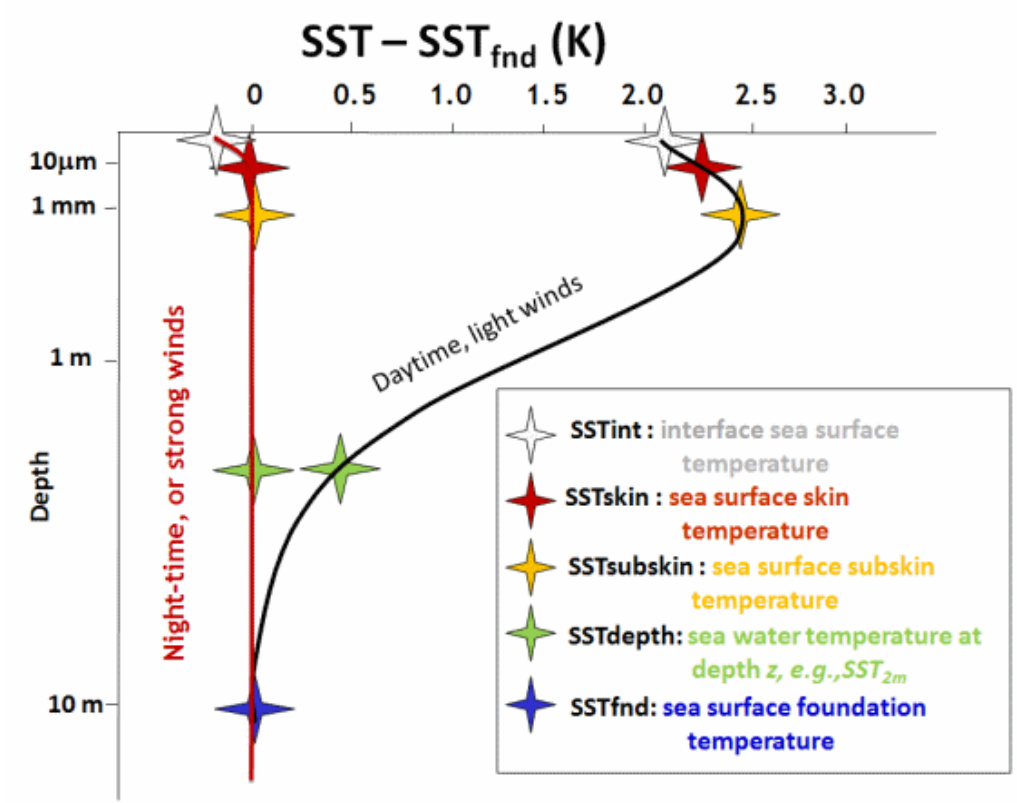


Planck's Law quantifies the amount of energy emitted per unit surface area (radiance, B_ν) as a function of the temperature (T) of a 'black' body (idealized physical body that absorbs all incident electromagnetic radiation).

The inverse of the Planck Function is used to find the "brightness temperature" (BT) of an object whose emitted radiance has been measured.

Sea Surface Temperature definitions

Definitions of SST in the upper 10 m of the ocean (related to the instruments used to measure it):

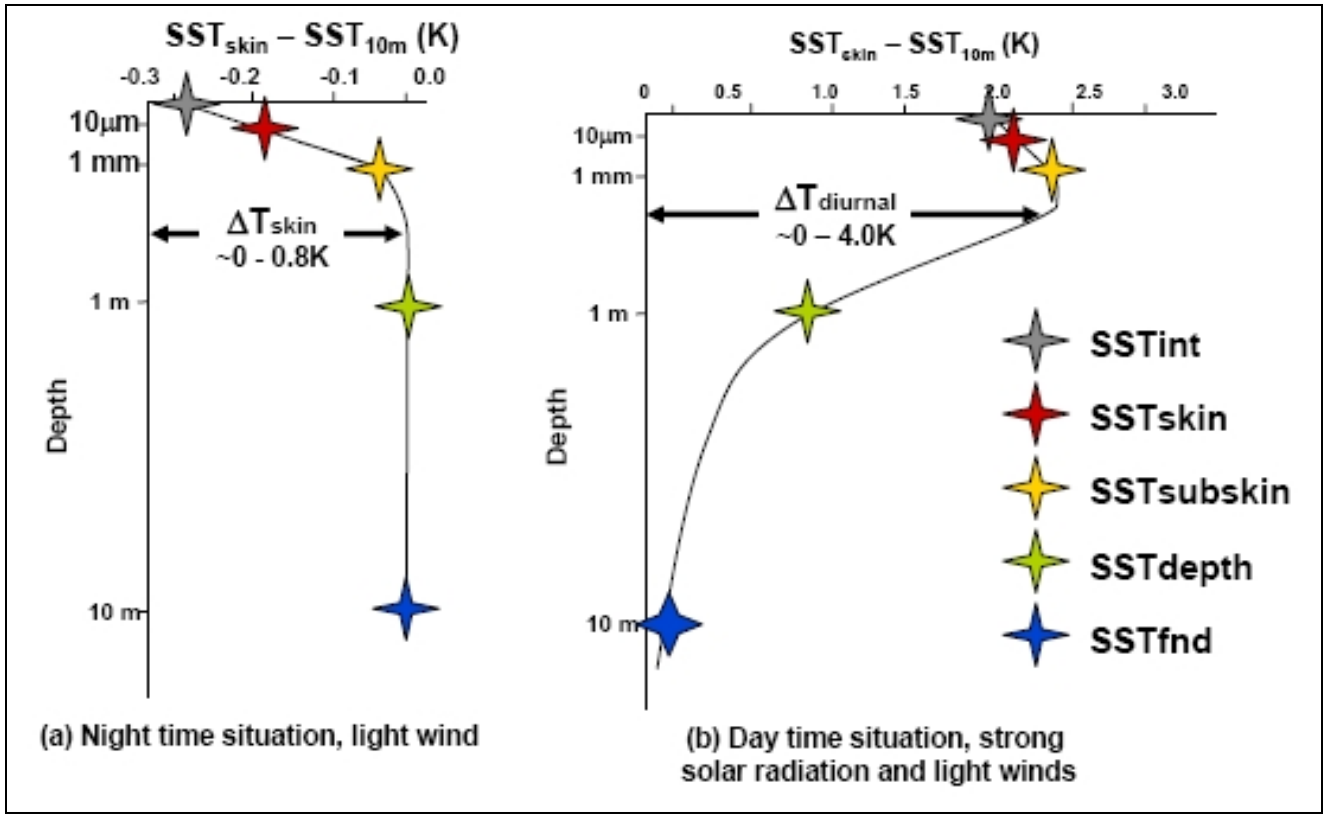


- **Skin SST**, temperature measured by **IR sensors**: 3.5-12 µm (depth: ~10-20 µm)
- **Subskin SST**, from **MW sensors**: 6-11 GHz (depth: ~1 mm)
- **Depth SST**, SST measured at a given depth (typically by in situ instruments)
- **Foundation SST**, the temperature free of diurnal warming (depth: ~10 m)

SST variables must be carefully checked/chosen depending on objectives/usage!

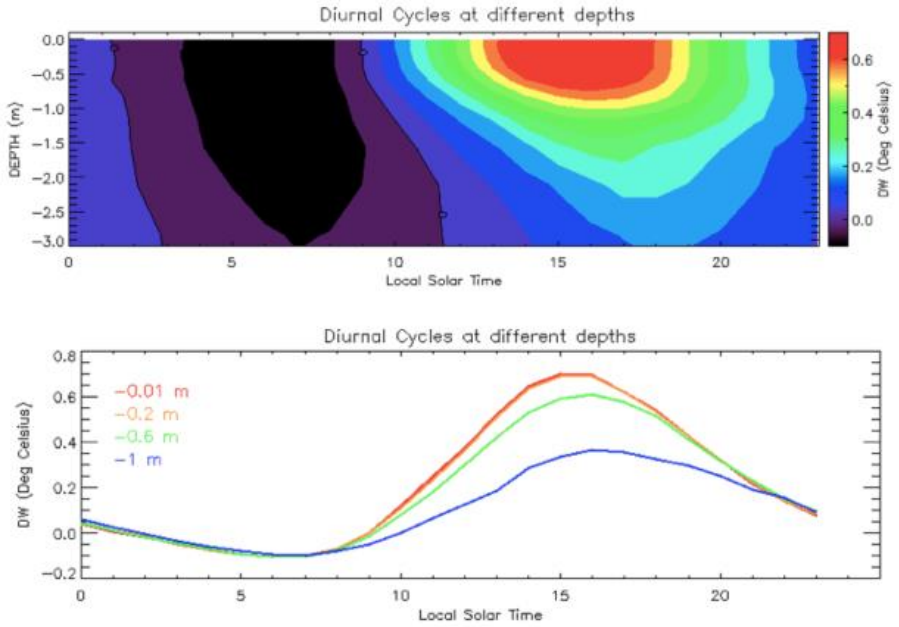
GHRSST GROUP FOR HIGH RESOLUTION SEA SURFACE TEMPERATURE
www.ghrsst.org

Sea Surface Temperature: Diurnal warming



GHRSST
GROUP FOR HIGH RESOLUTION SEA SURFACE TEMPERATURE
www.ghrsst.org

Diurnal warming in the Mediterranean Sea

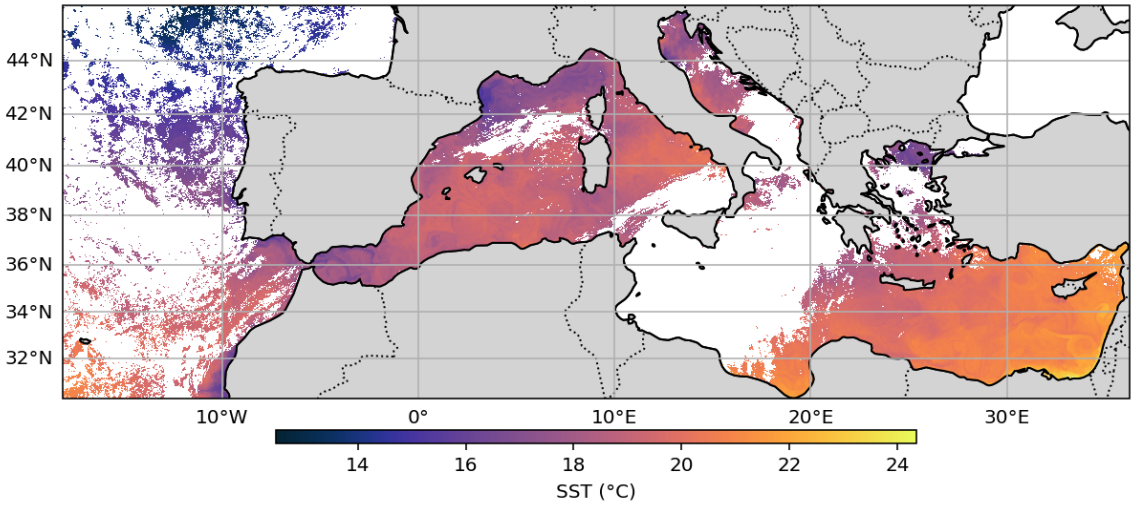


Credits to D. Ciani (CNR-ISMAR)

Sea Surface Temperature: IR vs MW

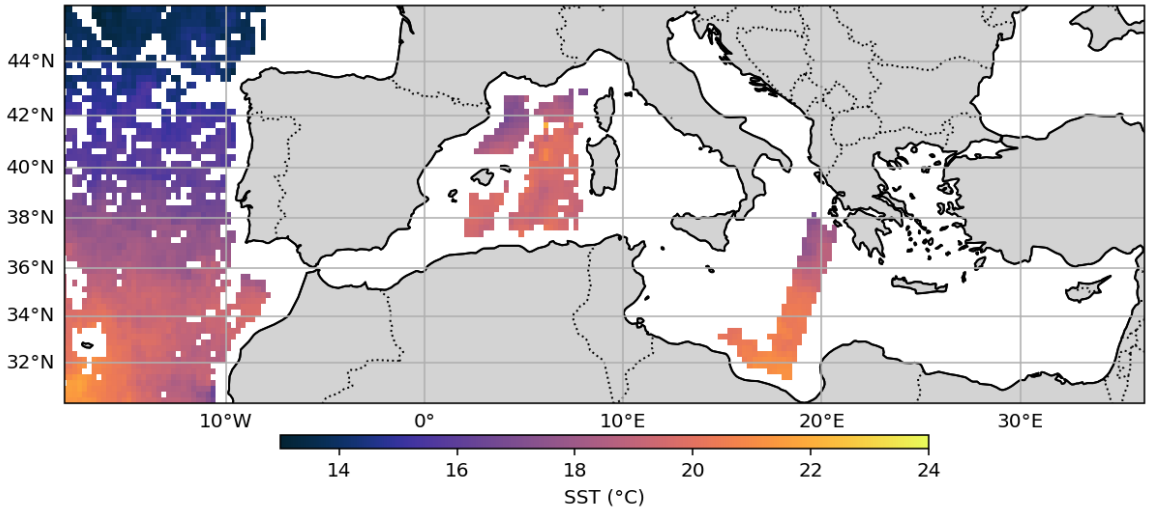
SST on 17/05/2024

SST_MED_SST_L3S_NRT_OBSERVATIONS_010_012



Merged multi-sensors (all **IR** based)

RSS_AMSR2_ocean_L3_daily



Descending (nighttime) **MW** measures

The Copernicus SST TAC Catalogue

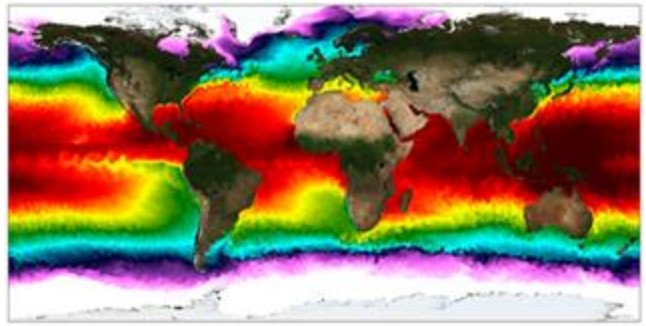
Global & Reg. SST Product

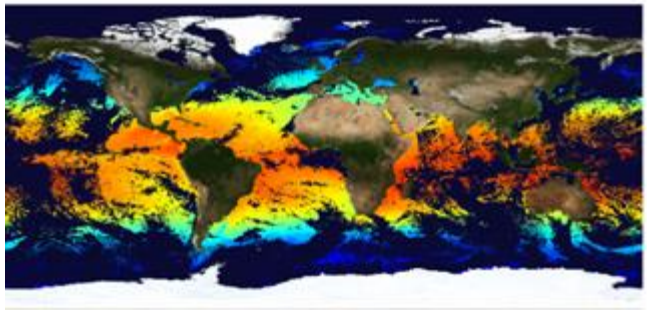
- **Near-Real-Time (NRT)** (last 2 years → 1 day before RT)
  - L4
  - L3S
- **Multy-Year/REP (MY)** (1982 → 1 month before RT)
  - L4
  - L3S

Operational applications

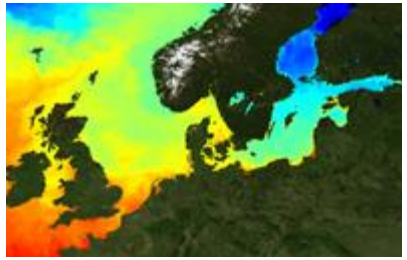
Climate applications

Global (GLO)

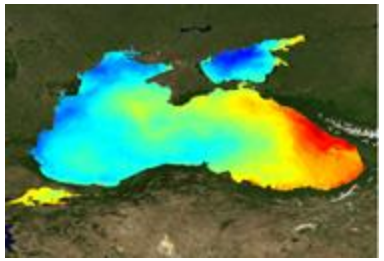




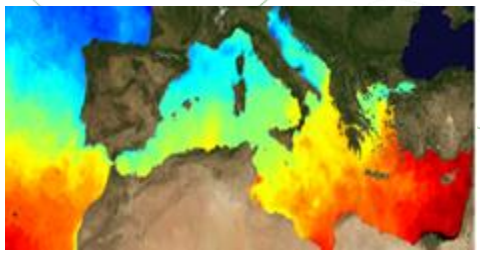
Baltic Sea (BAL)



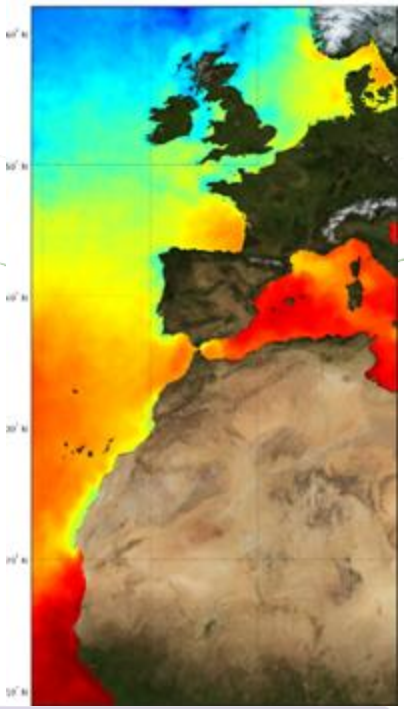
Black Sea (BS)



Mediterranean Sea (MED)



ATL (IBI+NWS)



- Overall, each SST product provides a **daily mean map of foundation SST** at a given spatial res.
- More recently, daily **hourly mean maps of skin/subskin SST** (MED/BS/BAL) are also available

The Copernicus SST TAC Catalogue

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  - L4
  - L3S
  - *Operational applications*
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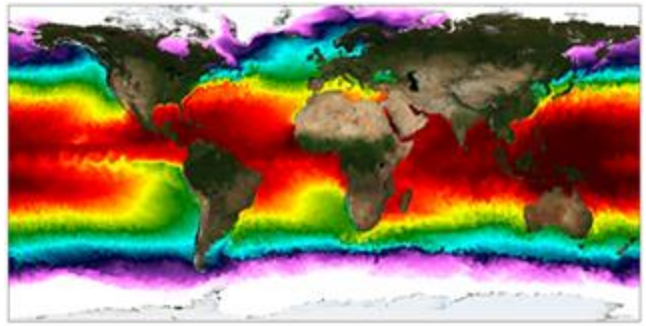
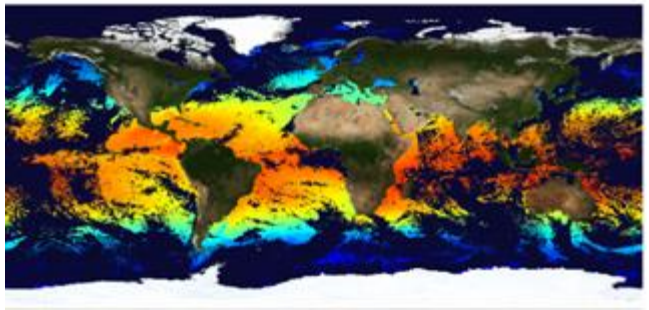
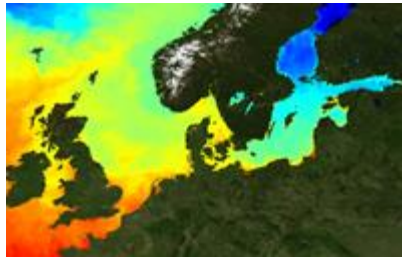
  - L3S
  - *Climate applications*

Global (GLO)

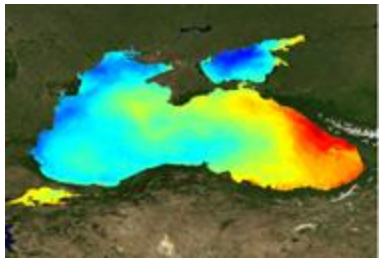




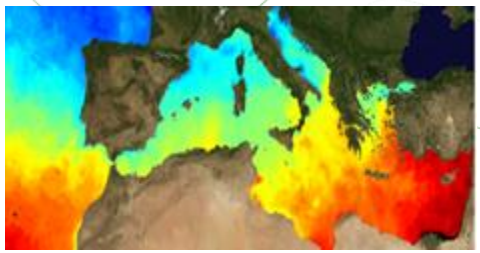
Baltic Sea (BAL)



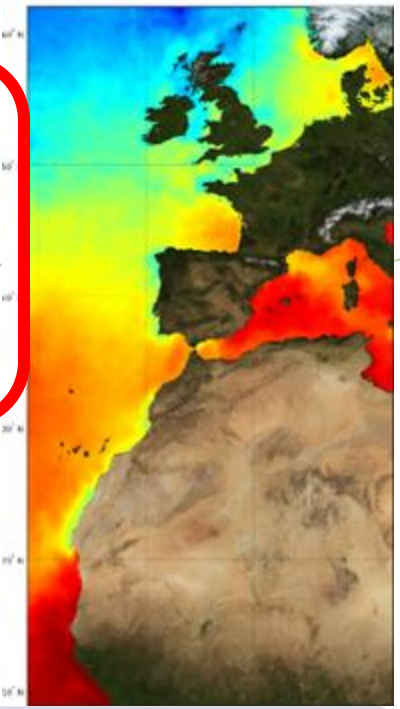
Black Sea (BS)



Mediterranean Sea (MED)



ATL (IBI+NWS)

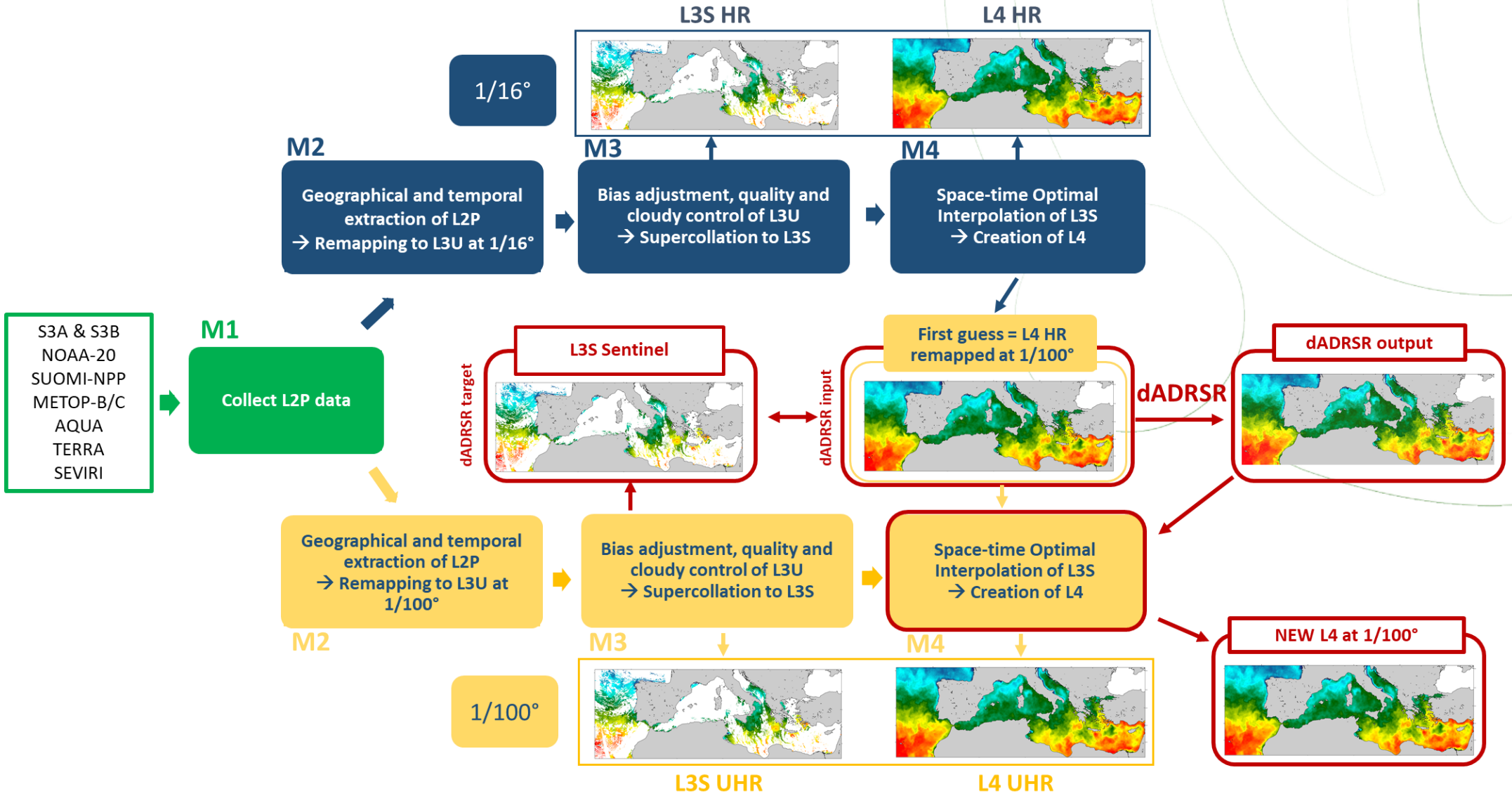


- Overall, each SST product provides a **daily mean map of foundation SST** at a given spatial res.
- More recently, daily **hourly mean maps of skin/subskin SST** (MED/BS/BAL) are also available

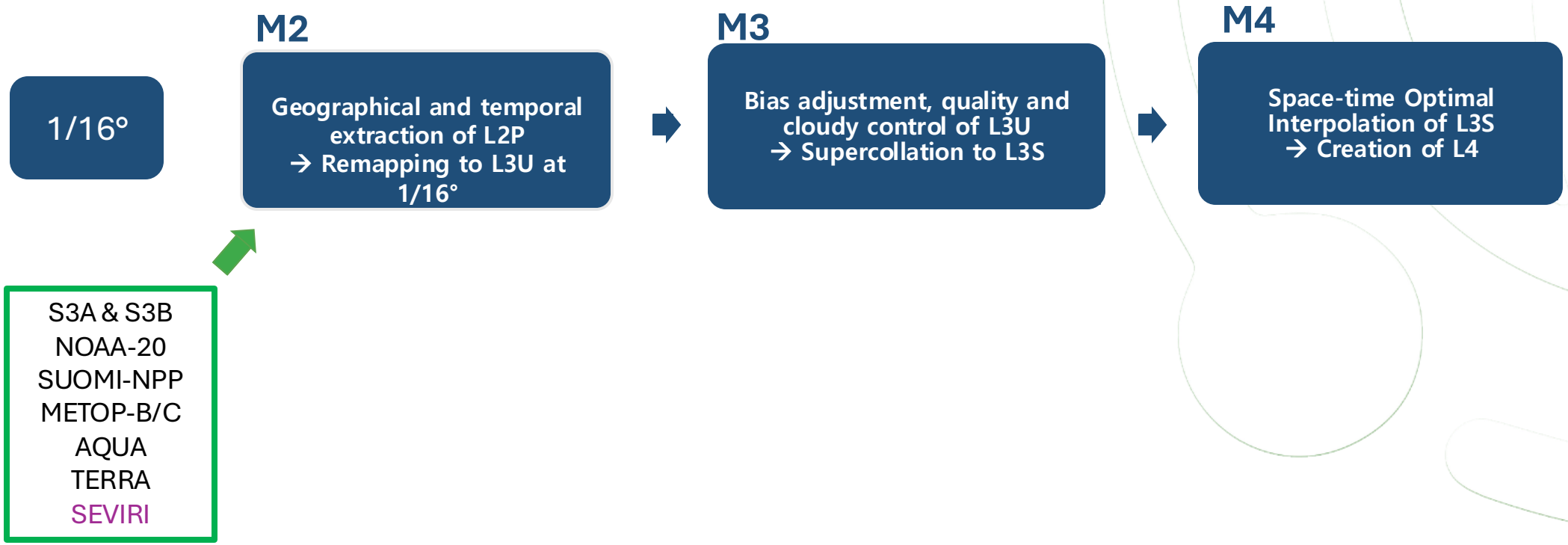
The Copernicus SST TAC Catalogue

Black Sea – High Resolution and Ultra High Resolution L3S Sea Surface Temperature	SST_BS_SST_L3S_NRT_OBSERVATIONS_010_013
Black Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis	SST_BS_SST_L4_NRT_OBSERVATIONS_010_006
Black Sea – High Resolution L4 Sea Surface Temperature Reprocessed	SST_BS_SST_L4_REP_OBSERVATIONS_010_022
Mediterranean Sea – High Resolution and Ultra High Resolution L3S Sea Surface Temperature	SST_MED_SST_L3S_NRT_OBSERVATIONS_010_012
Mediterranean Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis	SST_MED_SST_L4_NRT_OBSERVATIONS_010_004
Mediterranean Sea – High Resolution L4 Sea Surface Temperature Reprocessed	SST_MED_SST_L4_REP_OBSERVATIONS_010_021
Baltic Sea- Sea Surface Temperature Analysis	SST_BAL_SST_L4_NRT_OBSERVATIONS_010_007_b
Baltic Sea- Sea Surface Temperature Reprocessed	SST_BAL_SST_L4_REP_OBSERVATIONS_010_016
North Sea/Baltic Sea - Sea Surface Temperature analysis L3S	SST_BAL_SST_L3S_NRT_OBSERVATIONS_010_032
Global Ocean Sea Surface Temperature L3 Observations	SST_GLO_SST_L3S_NRT_OBSERVATIONS_010_010
Atlantic European North West Shelf Ocean – ODYSSEA Sea Surface Temperature Analysis	SST_NWS_SST_L4_NRT_OBSERVATIONS_010_025
Atlantic European North West Shelf Seas – High Resolution L4 Sea Surface Temperature Reprocessed (1982-2012)	SST_NWS_SST_L4_REP_OBSERVATIONS_010_026
Global Ocean OSTIA Sea Surface Temperature and Sea Ice Analysis	SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001
Global Ocean Sea Surface Temperature Multi Product Ensemble (GMPE)	SST_GLO_SST_L4_NRT_OBSERVATIONS_010_005
Global Ocean OSTIA Diurnal Skin Sea Surface Temperature	SST_GLO_SST_L4_NRT_OBSERVATIONS_010_014
Global Ocean OSTIA Sea Surface Temperature and Sea Ice Reprocessed	SST_GLO_SST_L4_REP_OBSERVATIONS_010_011
ESA SST CCI reprocessed sea surface temperature analyses	SST_GLO_SST_L4_REP_OBSERVATIONS_010_024

SST L3/L4 NRT MED CNR processing chains



SST L3/L4 NRT MED CNR processing chains: HR



SST L3/L4 NRT MED CNR processing chains: HR

M2

1/16°

Geographical and temporal extraction of L2P → Remapping to L3U at 1/16°

M3

Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

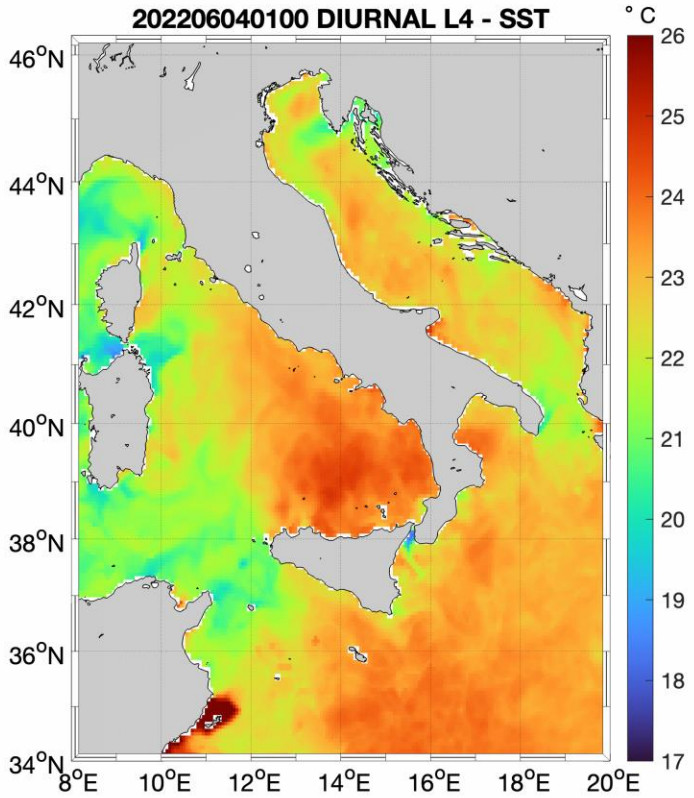
M4

Space-time Optimal Interpolation of L3S → Creation of L4

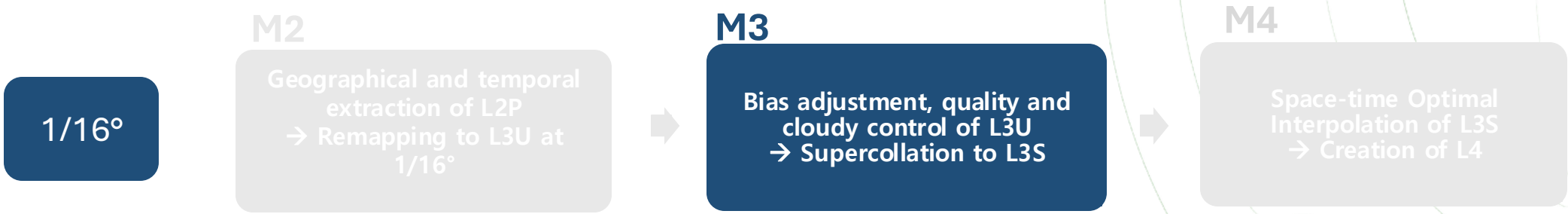
S3A & S3B
NOAA-20
SUOMI-NPP
METOP-B/C
AQUA
TERRA
SEVIRI

- **Temporal extraction**:
  Diurnal effect → selection of data only from 6 pm to 6 am. This product is representative of night-time SST values (centred at 00:00 UTC).

- **Geographical extraction and remapping**:
  Original L2P are often at different spatial resolution



SST L3/L4 NRT MED CNR processing chains: HR



- **Cloud detection is an essential step to provide "high quality" SST fields for data assimilation:**
  It requires a compromise between maximization of coverage and minimization of cloud contaminated pixels.

- **Cloud detection is performed at various steps:**

  - On original images (before the composite is performed) applying selection criteria on L2P confidence flag, rejection flag, proximity confidence, etc.

  - Before selecting SST data in the optimal interpolation algorithm: comparison to the nearest analysis available (if interpolation error is lower than a fixed value)

SST L3/L4 NRT MED CNR processing chains: HR

1/16°

M2

Geographical and temporal extraction of L2P
→ Remapping to L3U at 1/16°

M3

Bias adjustment, quality and cloudy control of L3U
→ Supercollation to L3S

M4

Space-time Optimal Interpolation of L3S
→ Creation of L4

Hierarchy	L2P Code
1.	SLSTR-3A D3
2.	VIIRS
3.	METOP B
4.	MODIS A
5.	MODIS T
6.	SLSTR-3A N3
7.	SLSTR-3B D3
8.	SLSTR-3B N3
9.	SEVIRI

- **Bias adjustment:**

  Merging procedure selects valid pixels using a predefined **sensor hierarchy**. The first sensor in the hierarchy list (in our case Sentinel 3A) is used as reference sensor (for which no correction is needed) while all the others are bias-adjusted with respect to the reference.

SST L3/L4 NRT MED CNR processing chains: HR

1/16°

M2

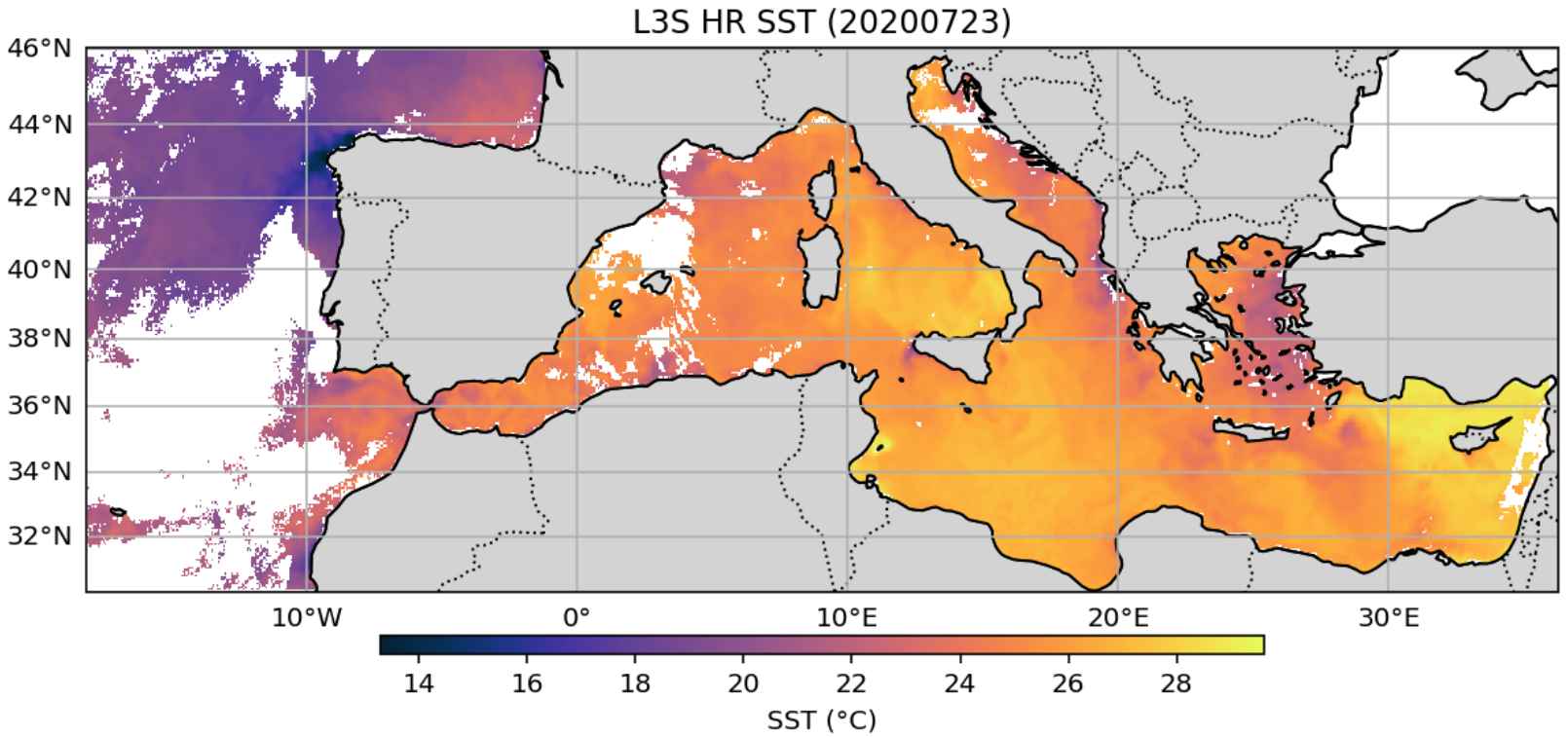
Geographical and temporal extraction of L2P
→ Remapping to L3U at 1/16°

M3

Bias adjustment, quality and cloudy control of L3U
→ Supercollation to L3S

M4

Space-time Optimal Interpolation of L3S
→ Creation of L4



SST L3/L4 NRT MED CNR processing chains: HR

1/16°

M2

Geographical and temporal extraction of L2P
→ Remapping to L3U at 1/16°

M3

Bias adjustment, quality and cloudy control of L3U
→ Supercollation to L3S

M4

Space-time Optimal Interpolation of L3S
→ Creation of L4

OPTIMAL INTERPOLATION

- Estimates the anomaly field with respect to a **first guess**, assuming statistical characteristics of the variability are known (background error covariance and observation error covariance).

- Linear combination of the observations, weighted directly with their correlation to the interpolation point and inversely with their cross-correlation:

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{B}(\mathbf{R}+\mathbf{B})^{-1}(\mathbf{y}_o - \mathbf{x}_b)$$

However, different processes at different scales contribute to the variability of the SST
→ OI acts as a low-pass filter for the scales smaller than those dominating the background error covariance

SST L3/L4 NRT MED CNR processing chains: HR

1/16°

M2

Geographical and temporal extraction of L2P
→ Remapping to L3U at 1/16°

M3

Bias adjustment, quality and cloudy control of L3U
→ Supercollation to L3S

M4

Space-time Optimal Interpolation of L3S
→ Creation of L4

OPTIMAL INTERPOLATION

MED HR L4 near-real-time processing algorithm based on:

- Spatially variable covariance function model → $C(\Delta r, \Delta t) = C(\Delta r)C(\Delta t)$
- Pentad climatological background field

SST L3/L4 NRT MED CNR processing chains: HR

1/16°

M2

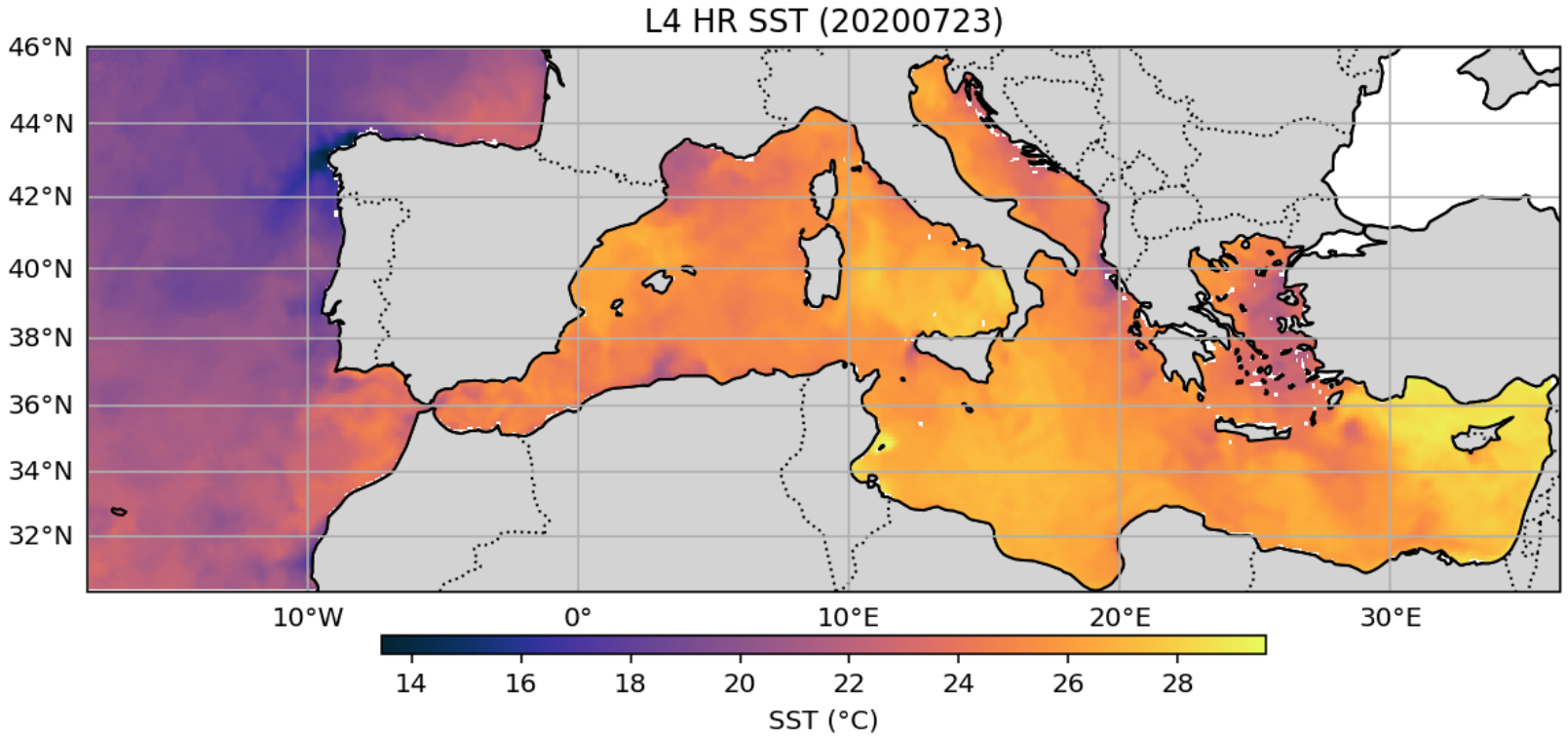
Geographical and temporal extraction of L2P
→ Remapping to L3U at 1/16°

M3

Bias adjustment, quality and cloudy control of L3U
→ Supercollation to L3S

M4

Space-time Optimal Interpolation of L3S
→ Creation of L4



SST L3/L4 NRT MED CNR processing chains: UHR

S3A & S3B
NOAA-20
SUOMI-NPP
METOP-B/C
AQUA
TERRA

1/100°

Geographical and temporal extraction of L2P → Remapping to L3U at 1/100°

M2

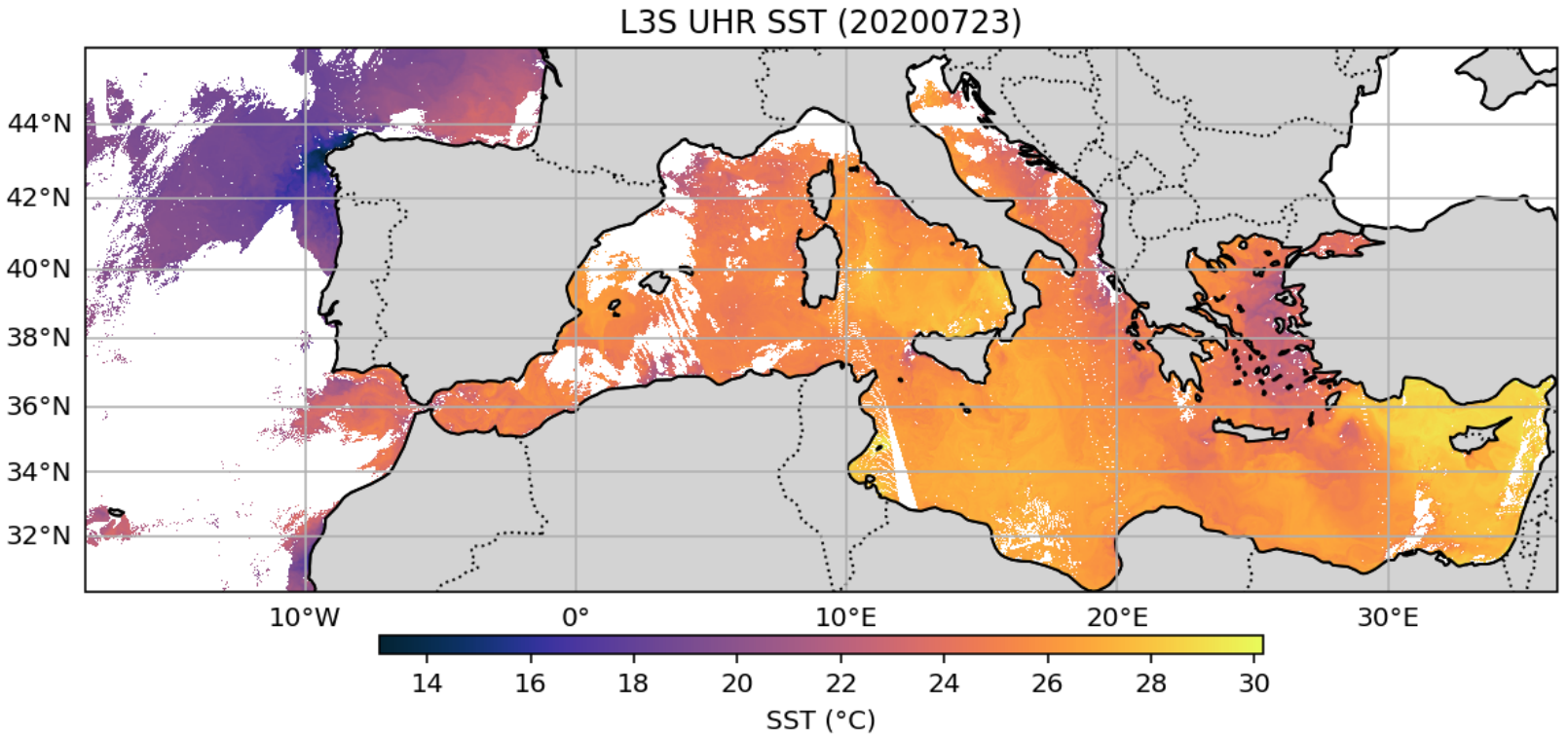
Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

M3

Space-time Optimal Interpolation of L3S → Creation of L4

M4

SST L3/L4 NRT MED CNR processing chains: UHR



S3A & S3B
NOAA-20
SUOMI-NPP
METOP-B/C
AQUA
TERRA

SAME AS HR

1/100°

Geographical and temporal extraction of L2P → Remapping to L3U at 1/100°

M2

Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

M3

Space-time Optimal Interpolation of L3S → Creation of L4

M4

SST L3/L4 NRT MED CNR processing chains: UHR

OPTIMAL INTERPOLATION

MED UHR L4 near-real-time processing algorithm based on:

- Spatially variable covariance function model → $C(\Delta r, \Delta t) = e^{-\Delta t/\tau}\, e^{-r/L}$
  Present configuration: $\tau = 1$ day, $L = 7$ km
- First guess is the **AI super resolved HR SST field**

1/100°

Geographical and temporal extraction of L2P → Remapping to L3U at 1/100°

M2

Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

M3

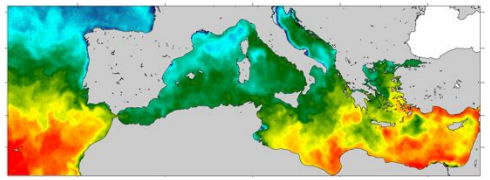
Space-time Optimal Interpolation of L3S → Creation of L4

M4

SST L3/L4 NRT MED CNR processing chains: UHR

AI super resolved HR SST field as background field

Old First guess = L4 HR remapped at 1/100°



1/100°

Geographical and temporal extraction of L2P → Remapping to L3U at 1/100°

M2

Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

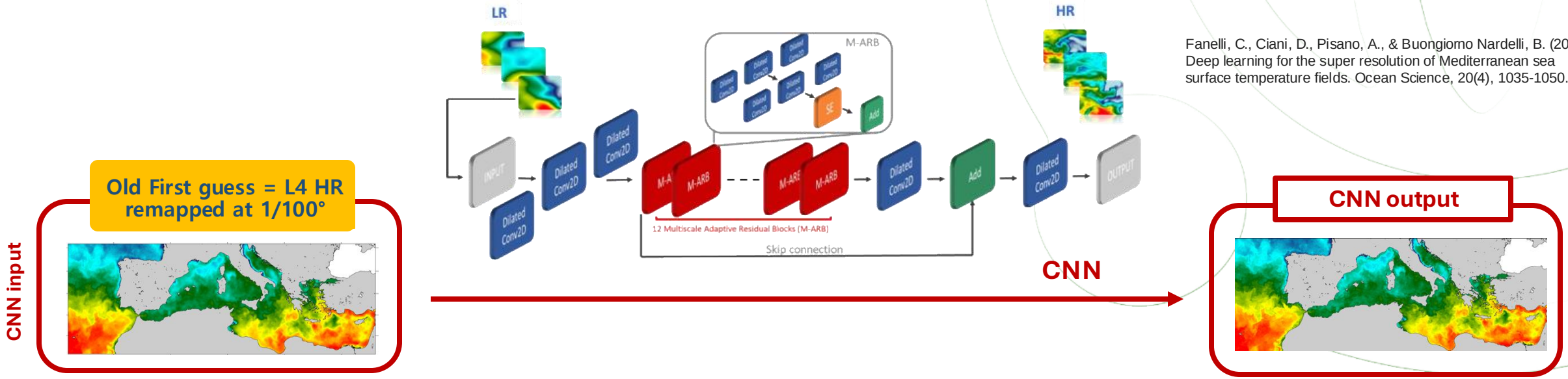
M3

Space-time Optimal Interpolation of L3S → Creation of L4

M4

SST L3/L4 NRT MED CNR processing chains: UHR

AI super resolved HR SST field as background field



Fanelli, C., Ciani, D., Pisano, A., & Buongiorno Nardelli, B. (2024). Deep learning for the super resolution of Mediterranean sea surface temperature fields. Ocean Science, 20(4), 1035-1050.

First guess Super Resolved

1/100°

M2 Geographical and temporal extraction of L2P → Remapping to L3U at 1/100°

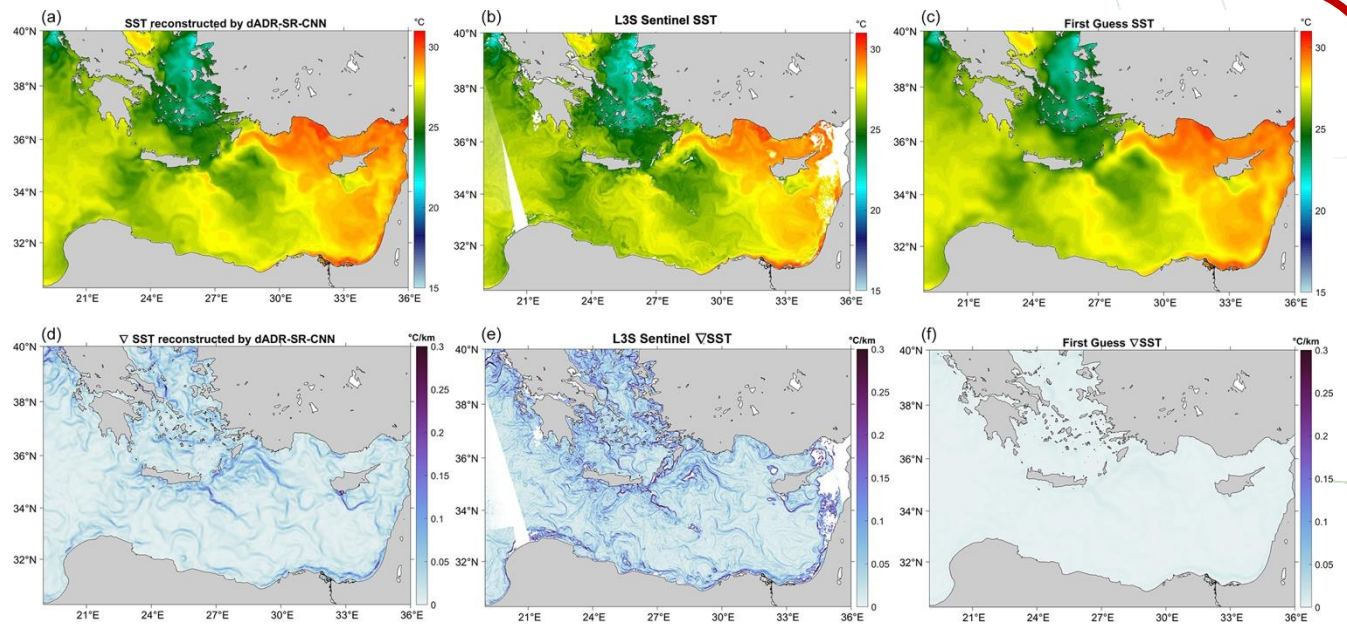
M3 Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

M4 Space-time Optimal Interpolation of L3S → Creation of L4

SST L3/L4 NRT MED CNR processing chains: UHR

AI super resolved HR SST field as background field

CNN qualitative results



Fanelli, C., Ciani, D., Pisano, A., & Buongiorno Nardelli, B. (2024). Deep learning for the super resolution of Mediterranean sea surface temperature fields. Ocean Science, 20(4), 1035-1050.

1/100°

Geographical and temporal extraction of L2P → Remapping to L3U at 1/100°

M2

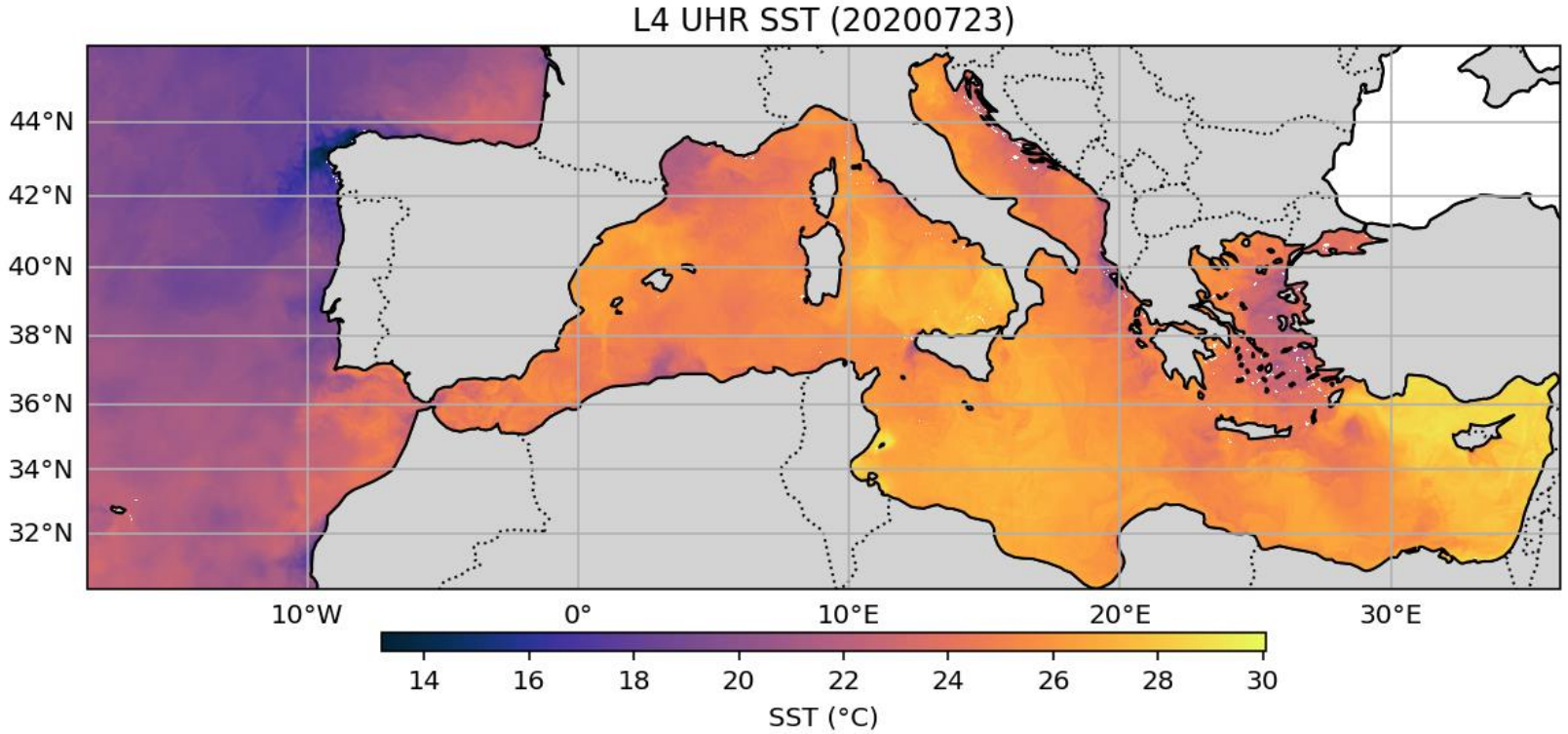
Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

M3

Space-time Optimal Interpolation of L3S → Creation of L4

M4

SST L3/L4 NRT MED CNR processing chains: UHR



1/100°

Geographical and temporal extraction of L2P → Remapping to L3U at 1/100°

M2

Bias adjustment, quality and cloudy control of L3U → Supercollation to L3S

M3

Space-time Optimal Interpolation of L3S → Creation of L4

M4

SST L3/L4 NRT MED CNR processing chains

Routine validation statistics → online statistics

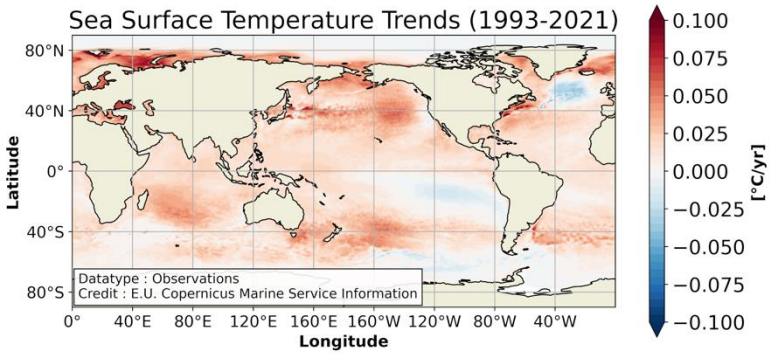
Comparison with SST in situ data:
from drifting buoys
from Argo profilers
from moorings

Cal/Val PROCEDURES (in situ data)

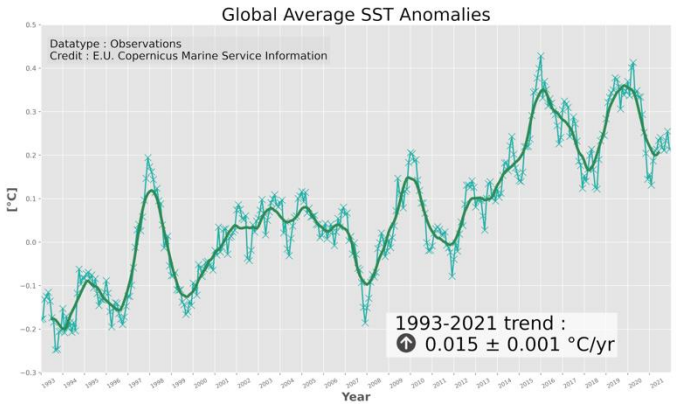
Product Name	Mean bias (°C)	RMSD (°C)	Samples
SST_MED_SST_L4_NRT_OBSERVATIONS_010_004_a_V2 (HR)	-0.106 ± 0.006	0.423 ± 0.006	19004
SST_MED_SST_L3S_NRT_OBSERVATIONS_010_012_a (HR)	-0.142 ± 0.007	0.443 ± 0.008	13151
SST_MED_SST_L4_NRT_OBSERVATIONS_010_004_c_V2 (UHR)	-0.078 ± 0.003	0.408 ± 0.003	60014
SST_MED_SST_L3S_NRT_OBSERVATIONS_010_012_b (UHR)	-0.089 ± 0.008	0.420 ± 0.008	10462

Some applications

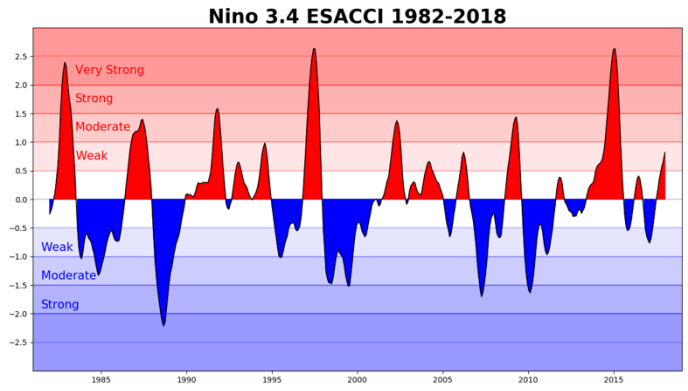
Climate & Variability



SST_GLO_SST_L4_REP_OBSERVATIONS_010_011



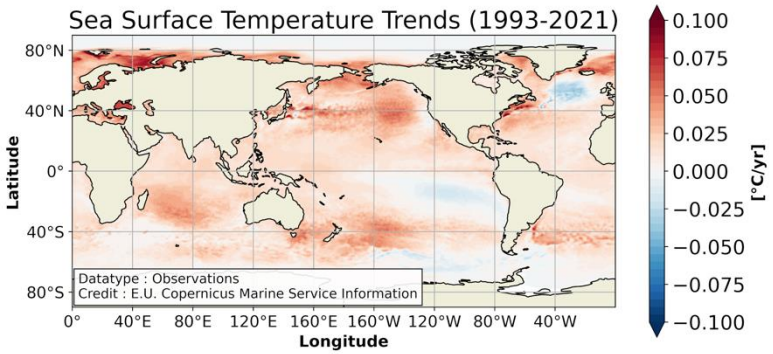
SST_GLO_SST_L4_REP_OBSERVATIONS_010_011



SST_GLO_SST_L4_REP_OBSERVATIONS_010_024

Some applications

Climate & Variability



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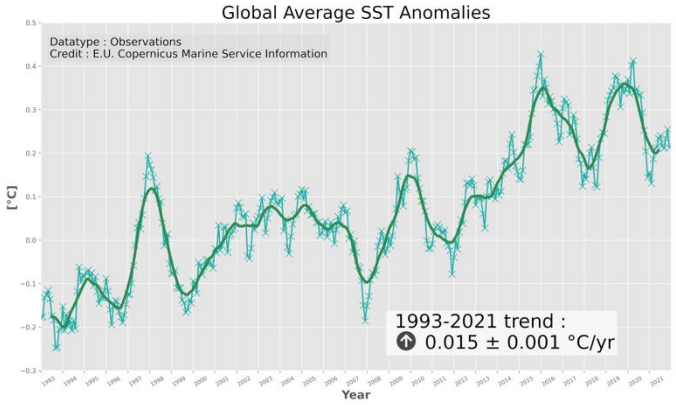
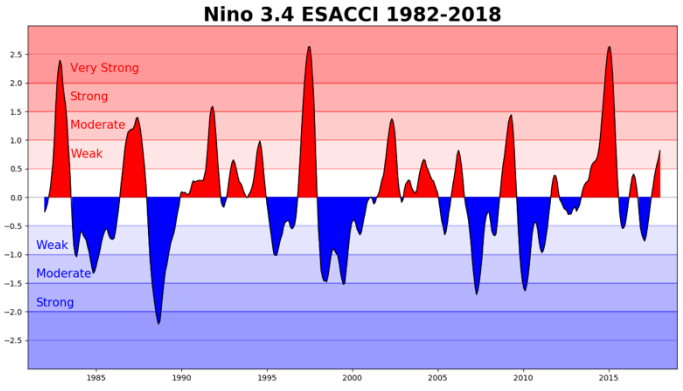
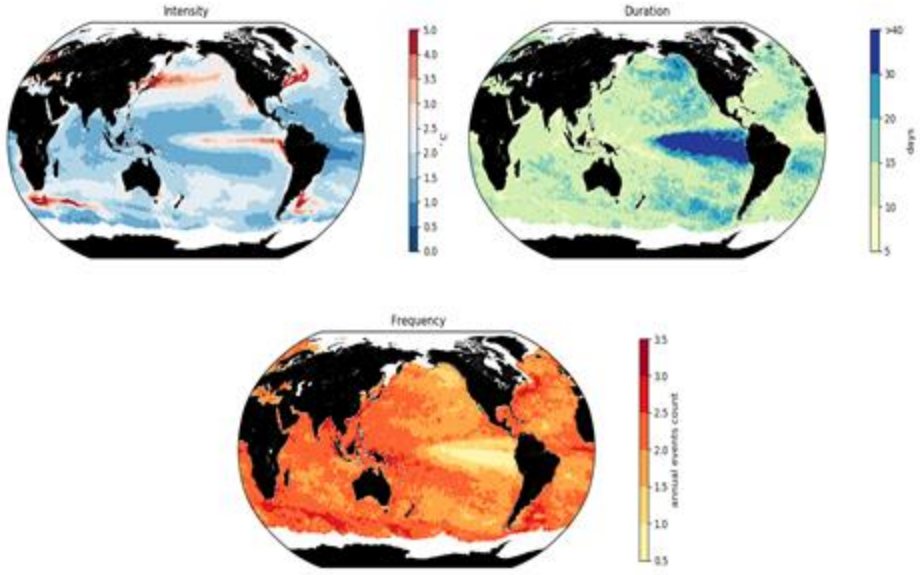


SST_GLO_SST_L4_REP_OBSERVATIONS_010_011



SST_GLO_SST_L4_REP_OBSERVATIONS_010_024

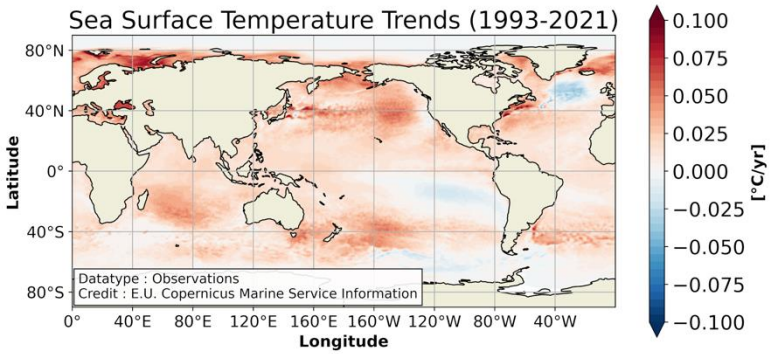
Extremes



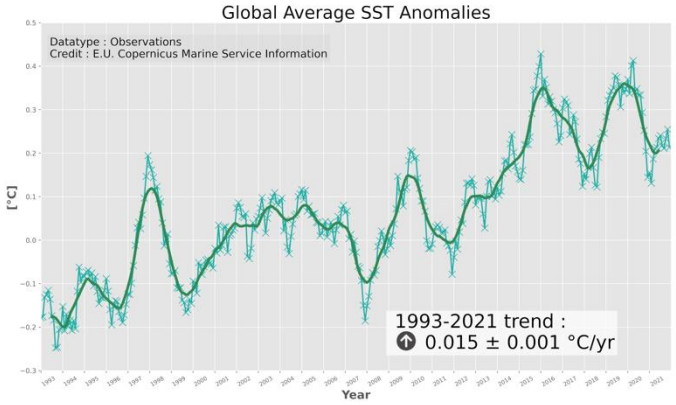
SST_GLO_SST_L4_REP_OBSERVATIONS_010_024

Some applications

Climate & Variability



SST_GLO_SST_L4_REP_OBSERVATIONS_010_011



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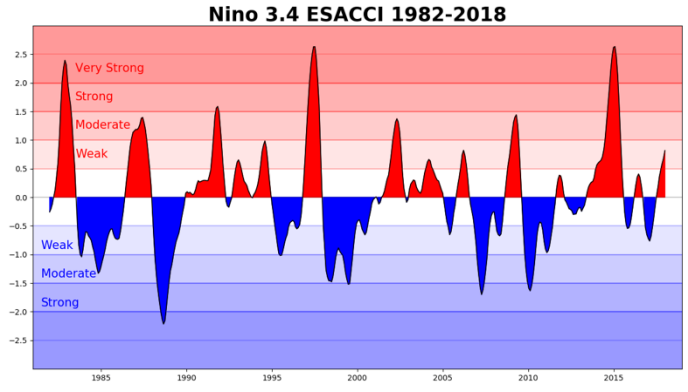
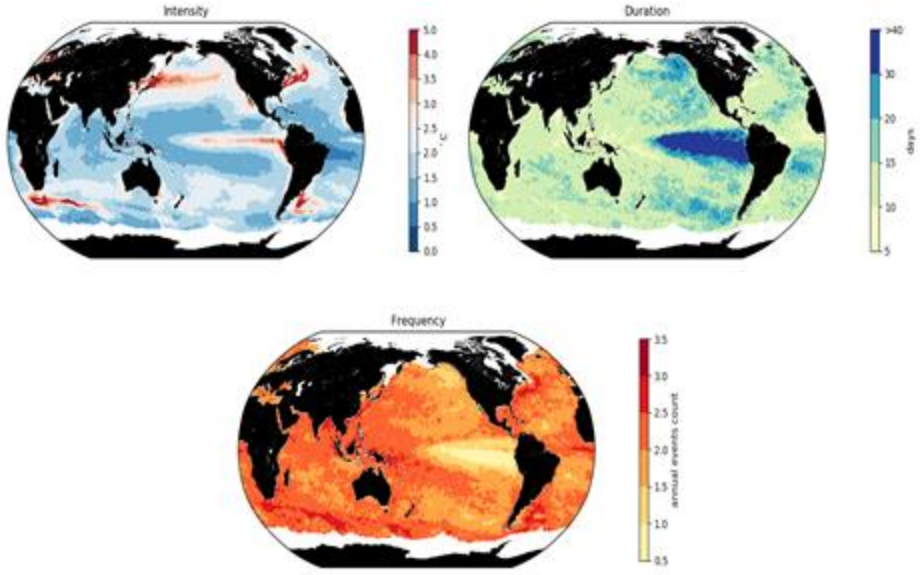


SST_GLO_SST_L4_REP_OBSERVATIONS_010_024

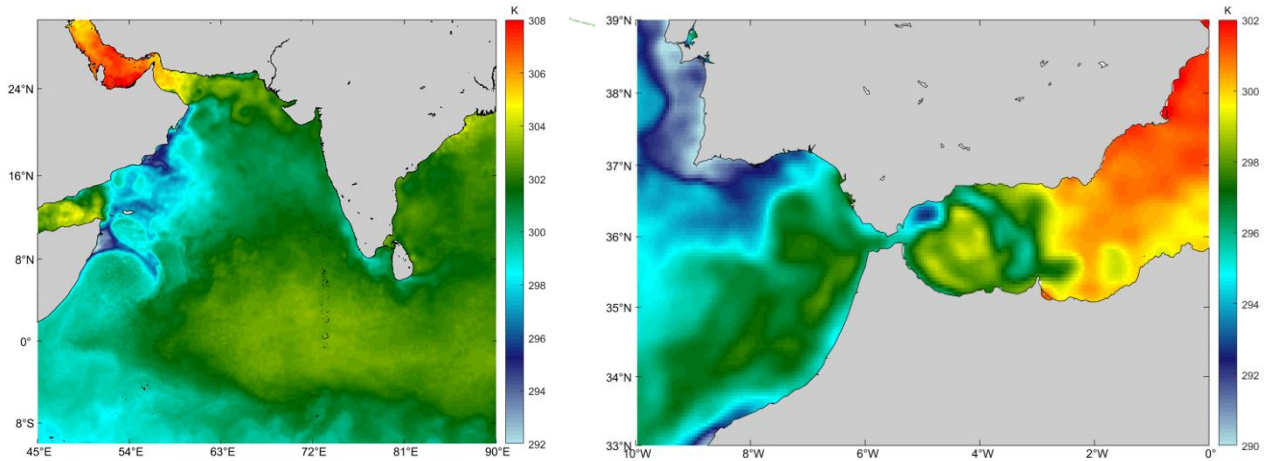
Extremes



SST_GLO_SST_L4_REP_OBSERVATIONS_010_024

Thermal Fronts & Upwelling

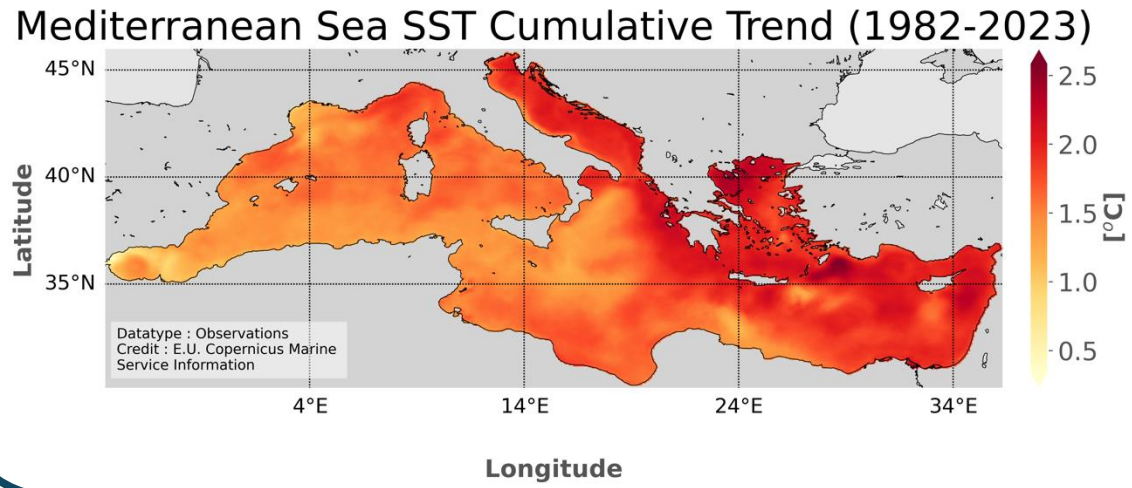
23 July 2023

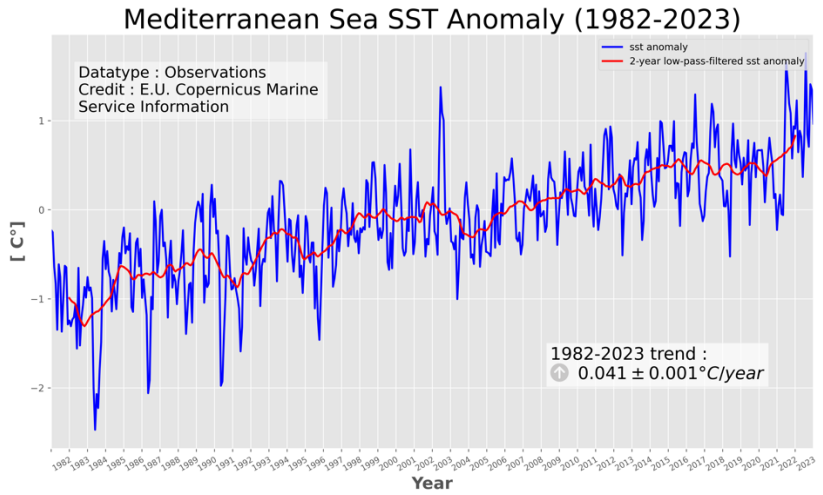


SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001

Climate & Variability

Ocean Monitoring Indicators (Copernicus Marine Service)



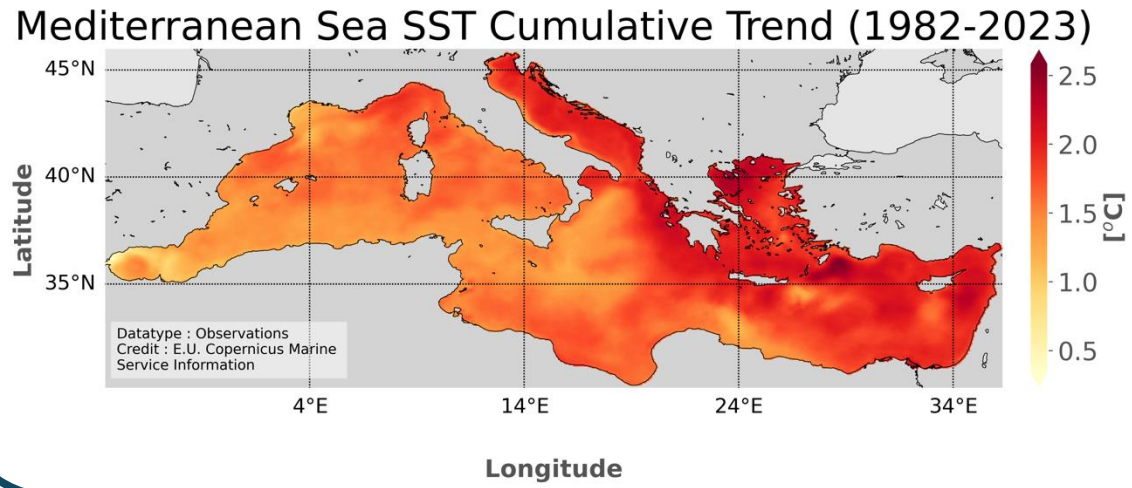


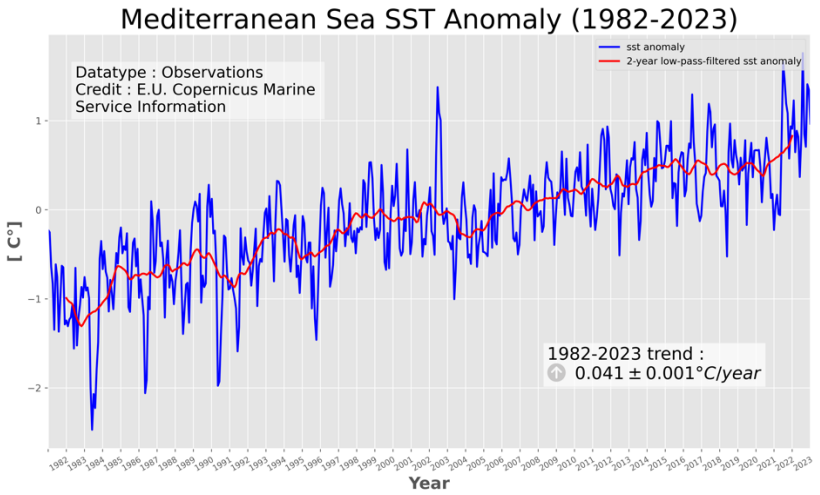
The Mediterranean Sea is burning!

- Biodiversity and habitat loss
- Marine Heat Waves (MHWs)
- Extreme weather events (medicanes, floods,...)

Climate & Variability

Ocean Monitoring Indicators (Copernicus Marine Service)





The Mediterranean Sea is burning!

- Biodiversity and habitat loss
- Marine Heat Waves (MHWs)
- Extreme weather events (medicanes, floods,...)

BUT...

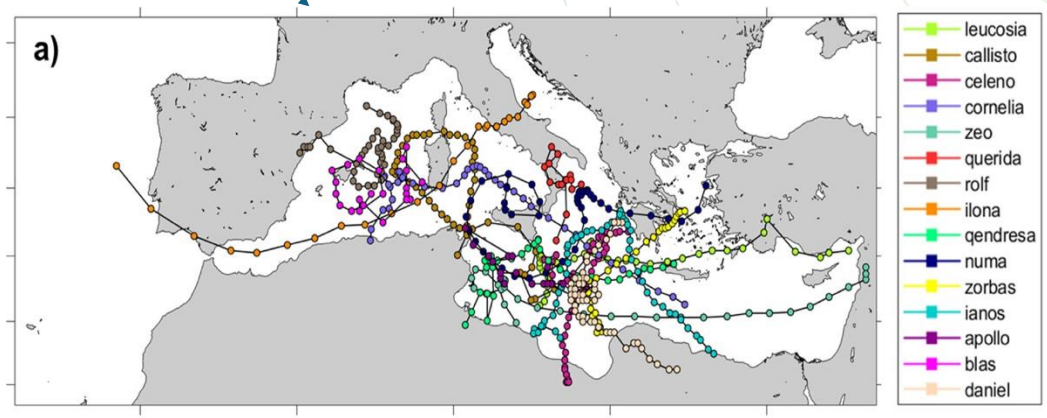
Extremes events (air/sea interaction)

The Mediterranean area is particularly prone to severe weather events, which are likely to become more common and more severe in the future (IPCC).

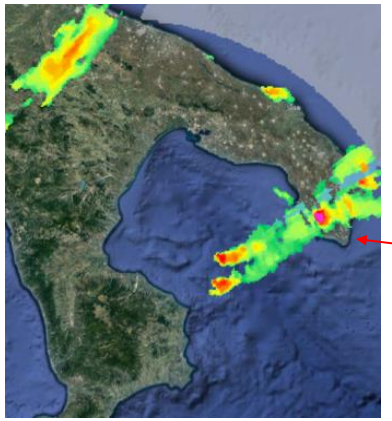
medicanes (MEDIterranean hurriCANES)

Medicane Ianos (September 2020) - Copernicus Sentinel-3 / ESA

15 most important medicanes in the last 40 years



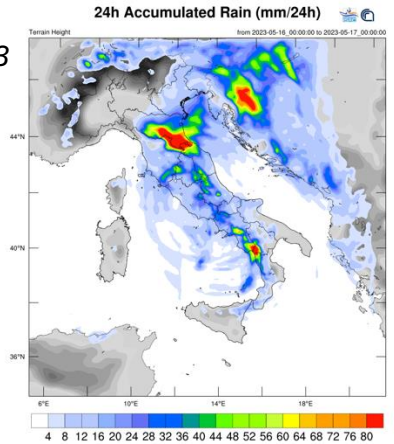
tornado



Tornadic cells (OBS RADAR) on Ionian Sea (november 2018) and tornado affecting Apulia

Emilia-Romagna Flood, May 2023

floods



Credits to E. Avolio (CNR-ISAC)

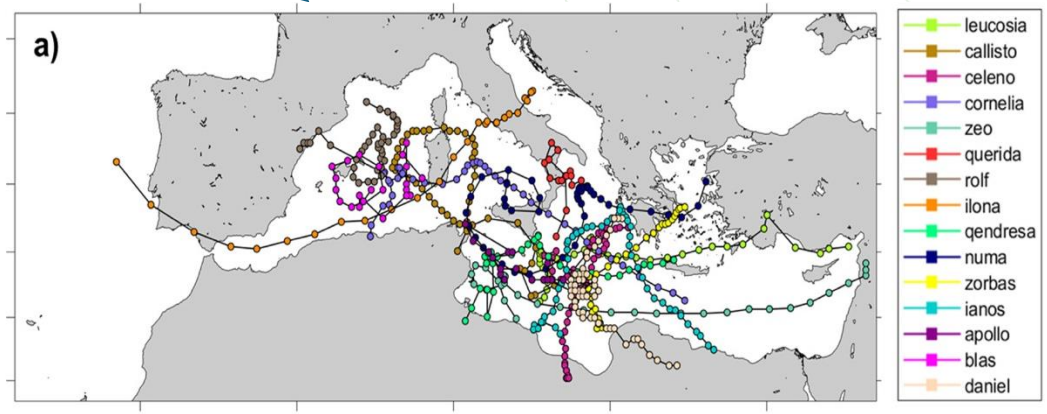
Extremes events (air/sea interaction)

The Mediterranean area is particularly prone to severe weather events, which are likely to become more common and more severe in the future (IPCC).

medicanes (MEDIterranean hurriCANES)

Medicane Ianos (September 2020) - Copernicus Sentinel-3 / ESA

15 most important medicanes in the last 40 years



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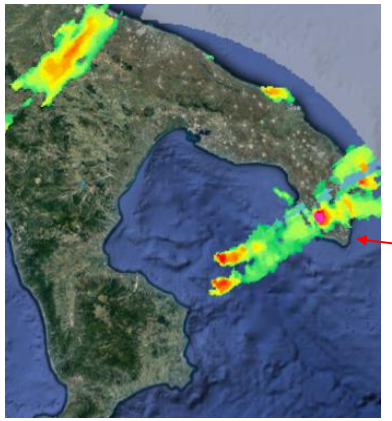

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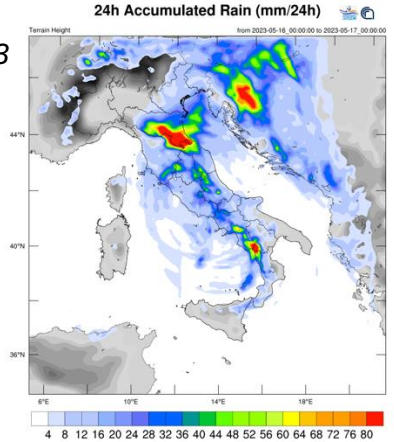

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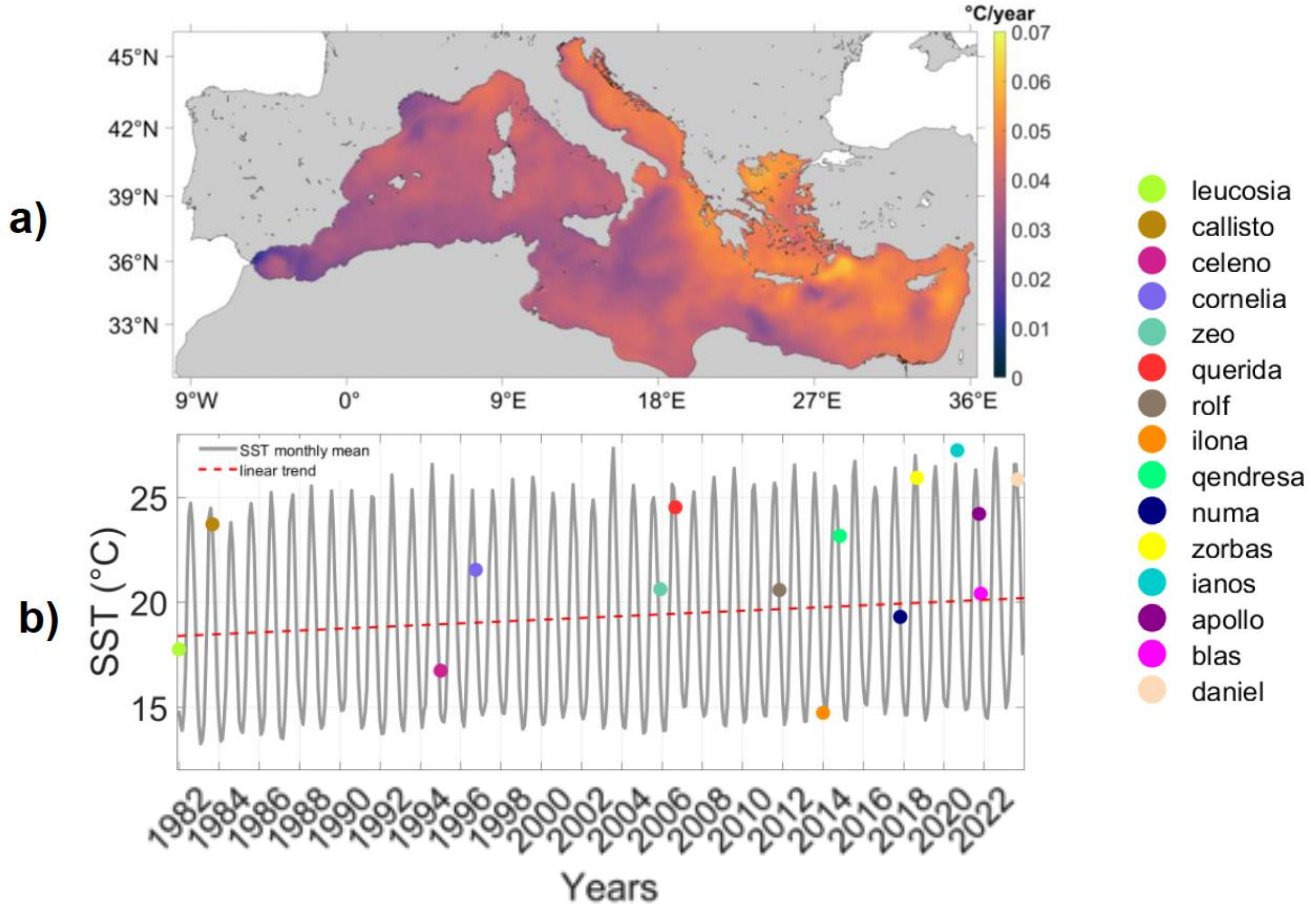
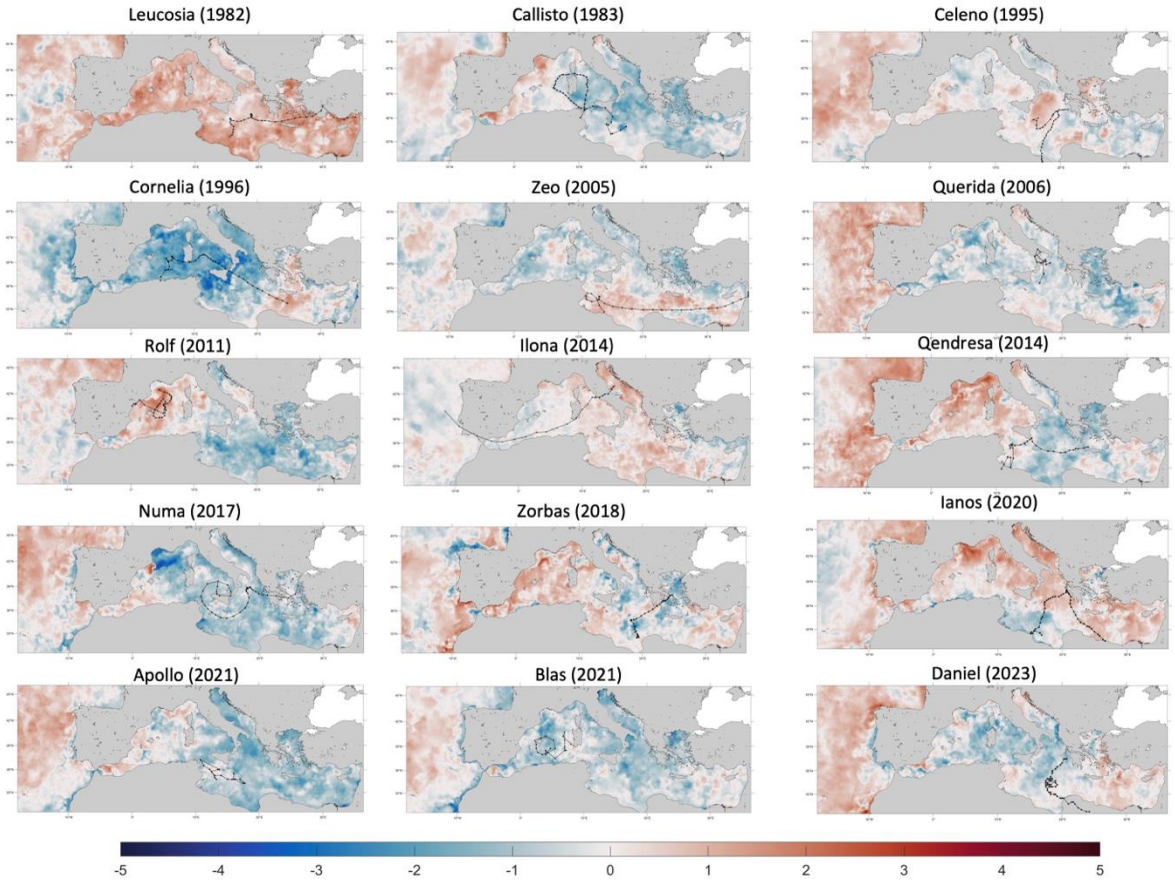


Avolio, E., Fanelli, C., Pisano, A., & Miglietta, M. M. (2024). Unveiling the relationship between Mediterranean tropical-like cyclones and rising Sea Surface Temperature. *Geophysical Research Letters*, *51*(20), e2024GL109921.

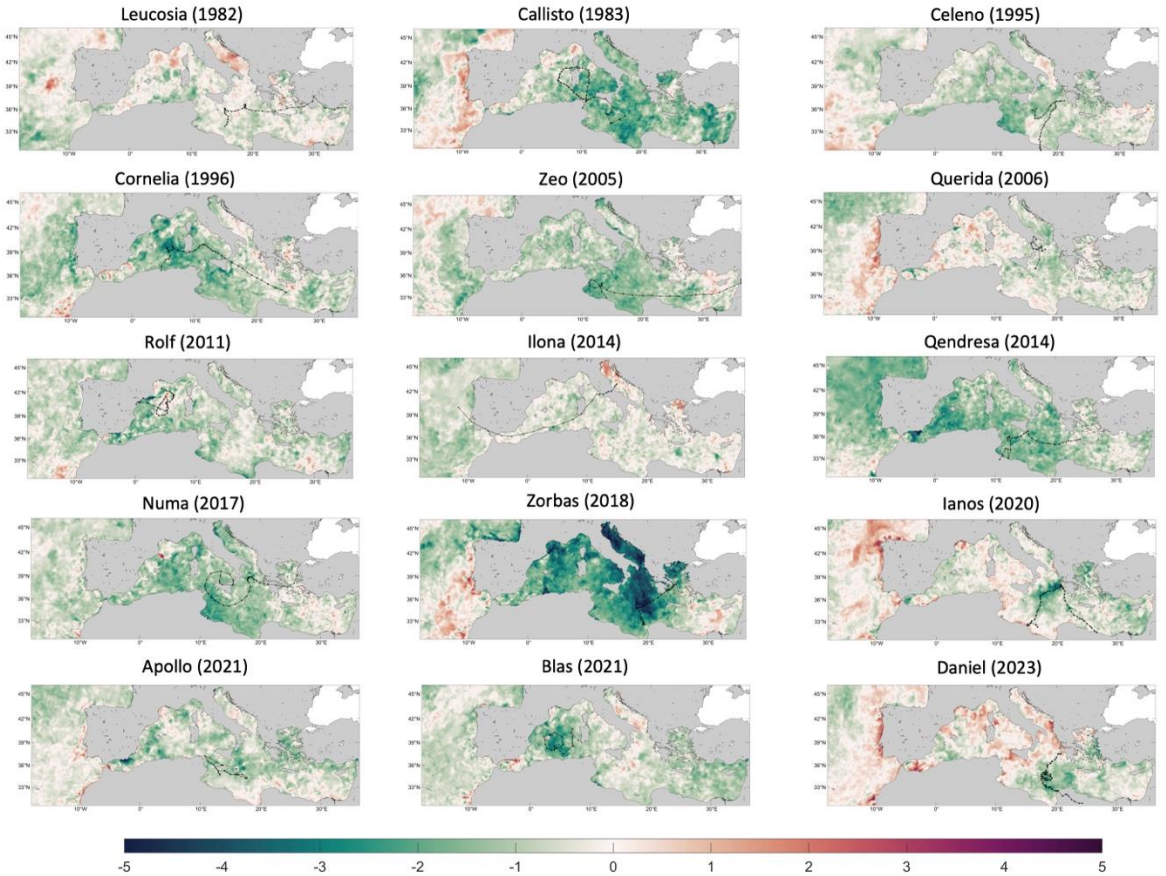
Extremes events (air/sea interaction)

medicanes (MEDIterranean hurriCANES)

SST anomaly at early stages



SST differences after medicanes



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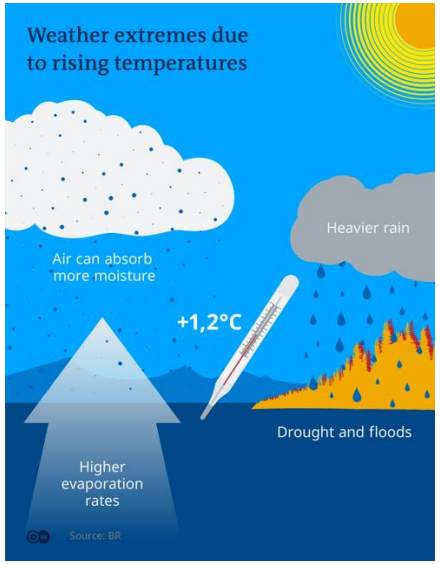
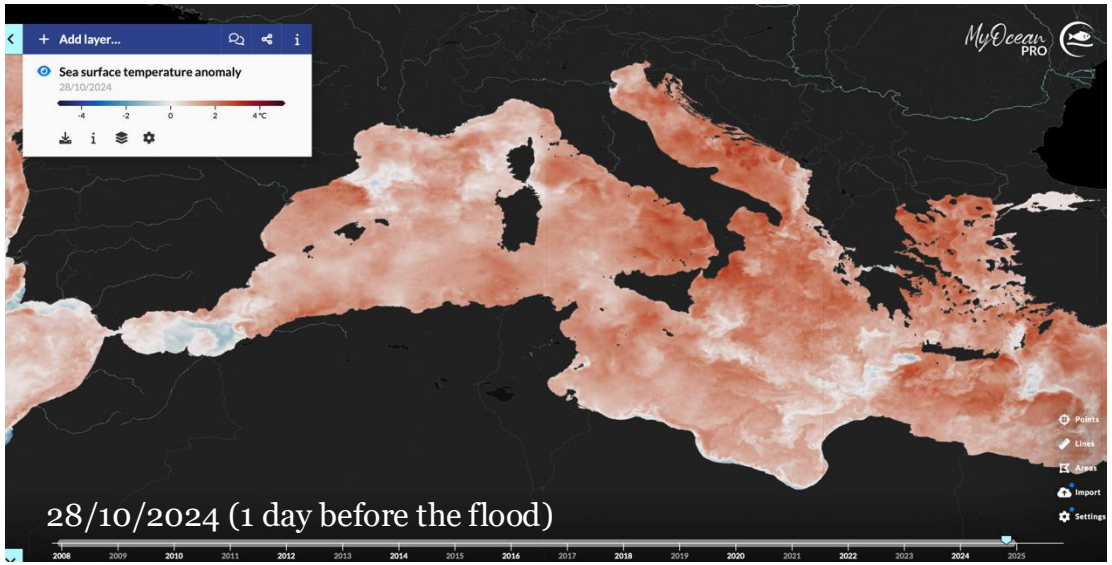
Extreme events (air/sea interaction)

On 29/10/2024 extreme rainfall resulting from a specific persistent baric configuration brought over a year's worth of precipitation to several areas in eastern Spain.





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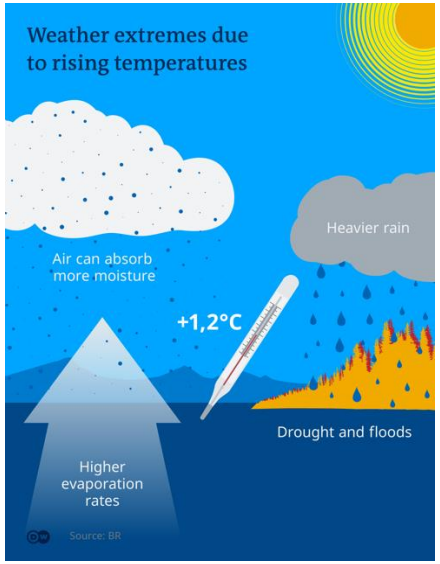


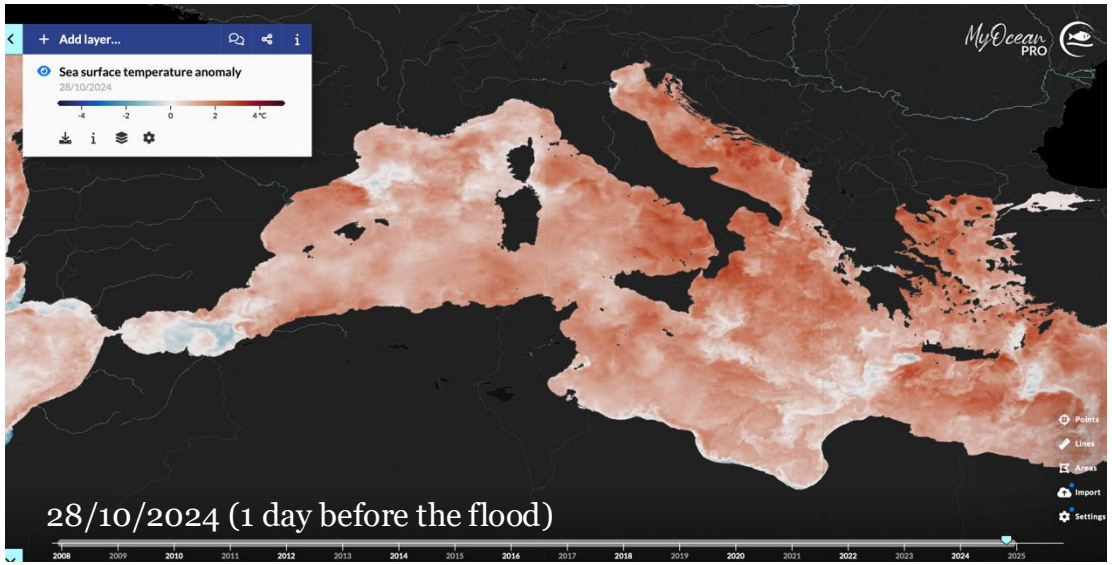
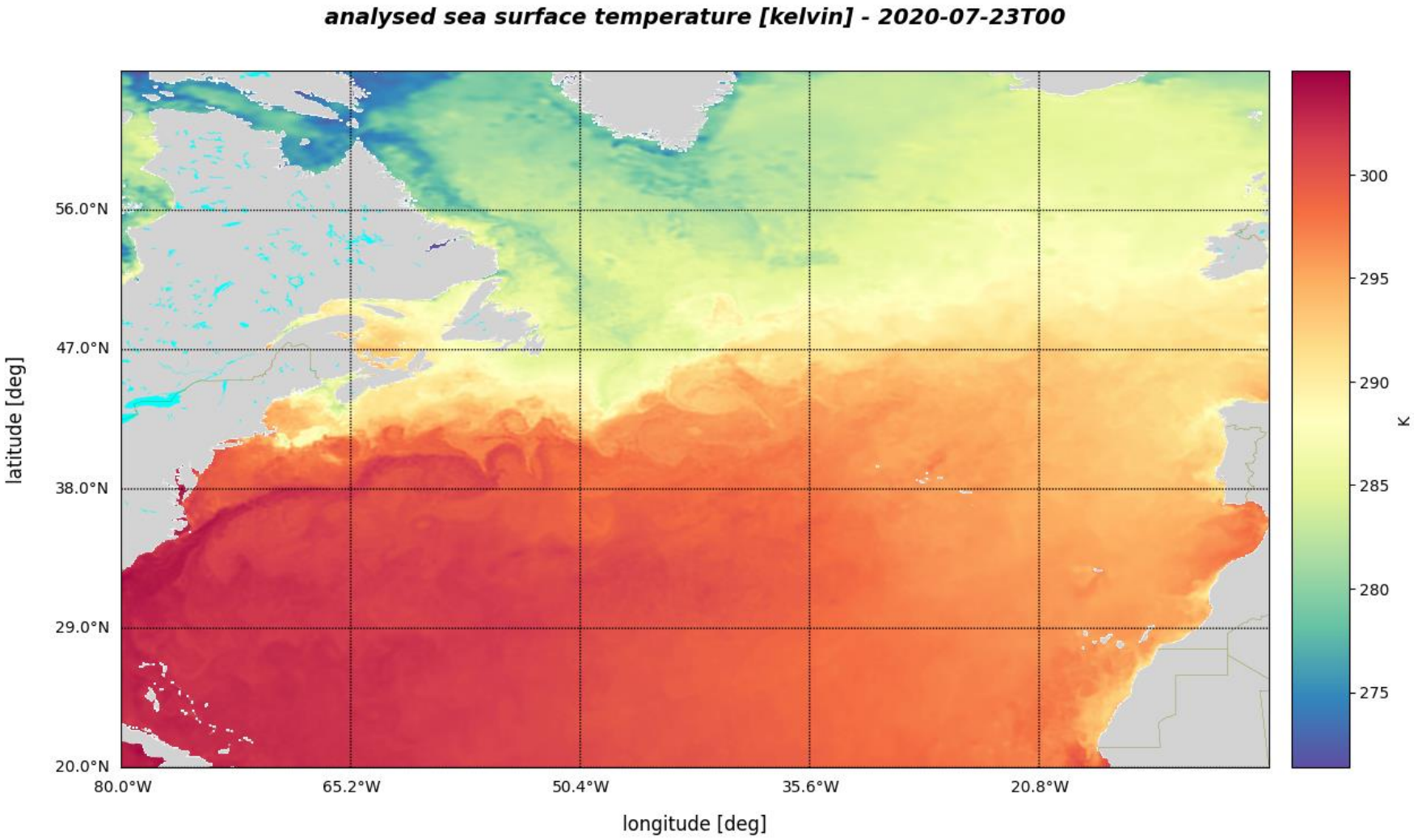


Foto scattata il 29 ottobre 2024 a Llombai, Valencia (Spagna). EUROPA PRESS NEWS/GETTY IMAGES

Thermal Fronts & Upwelling

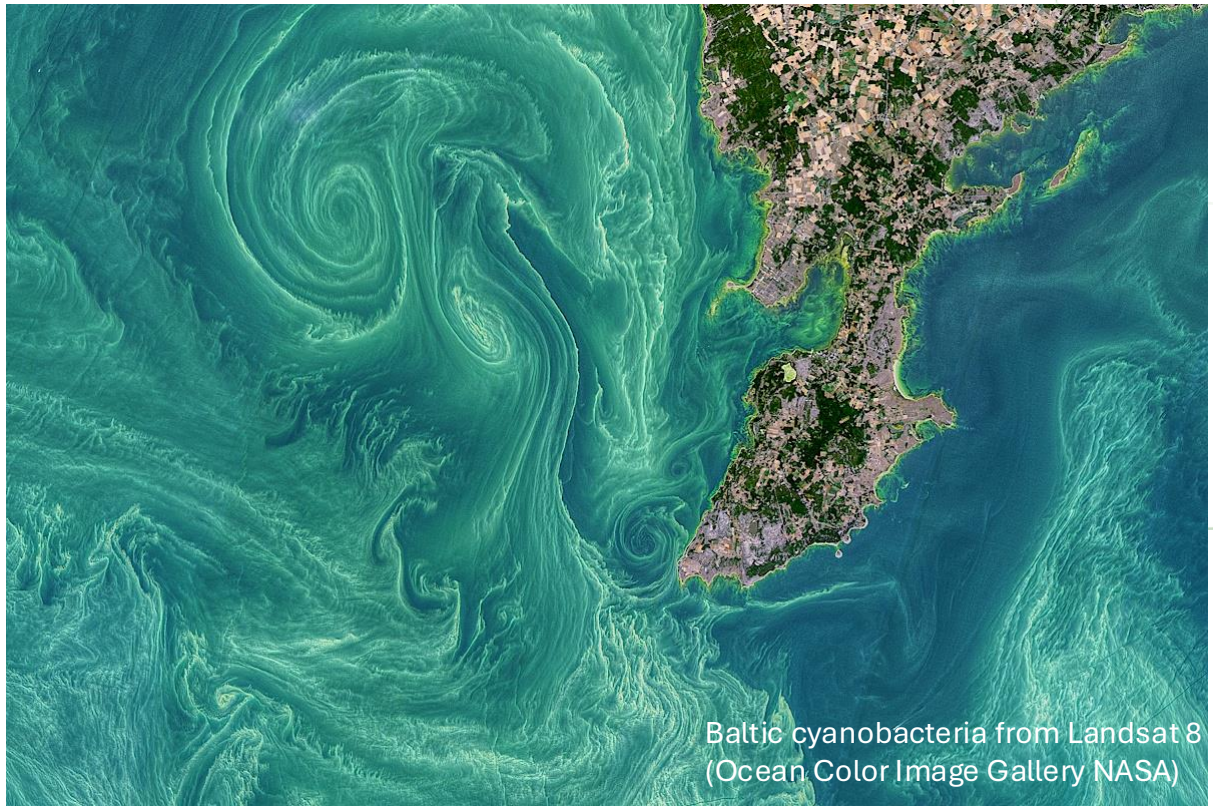


...you will have a closer look at this later!

OCEAN COLOUR

What is Ocean Colour?

Ocean colour (OC) is one of the essential ocean and climate variables (EOV/ECVs) listed by the World Meteorological Organization.



Baltic cyanobacteria from Landsat 8
(Ocean Color Image Gallery NASA)

Ocean colour is the visible hue of water resulting from backscattered sunlight interacting with the water and its microscopic components.

These interactions cause photons to be absorbed or scattered at various wavelengths, creating the ocean's characteristic colors.

Why is Ocean Colour important?

OC data are utilized to assess the health of aquatic ecosystems and water quality. They also support sustainable marine resource management, such as fisheries and aquaculture, as well as coastal management, including erosion control and sedimentation monitoring.

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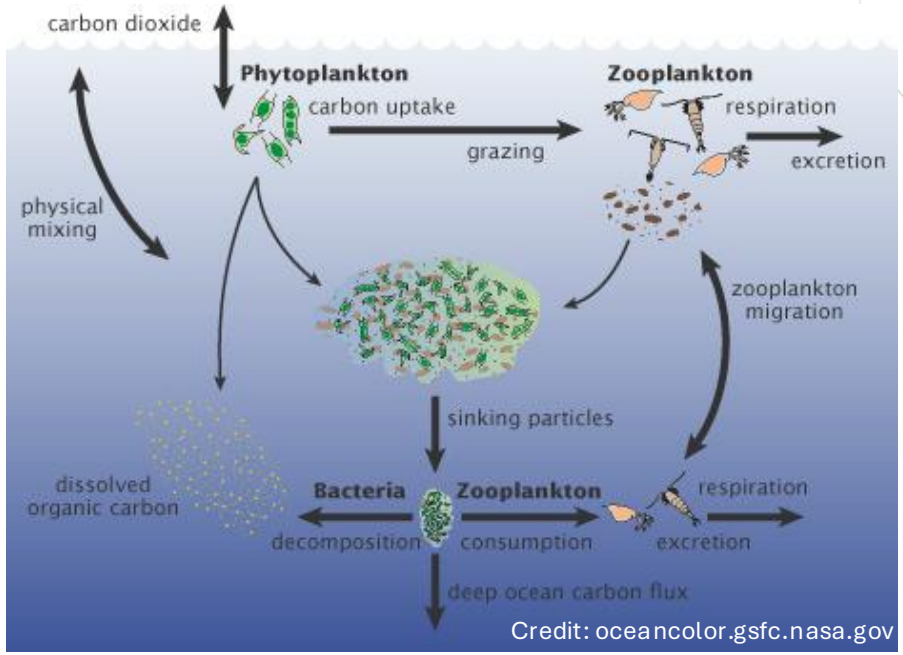
Marine ecosystems absorb a comparable amount of atmospheric CO_2 as terrestrial ecosystems, primarily due to phytoplankton capturing carbon dioxide (CO_2) through photosynthesis, making them vital carbon sinks. A carbon sink absorbs more carbon from the atmosphere than it releases. Ocean color data help track the annual global CO_2 uptake by phytoplankton and improve the accuracy of these estimates.

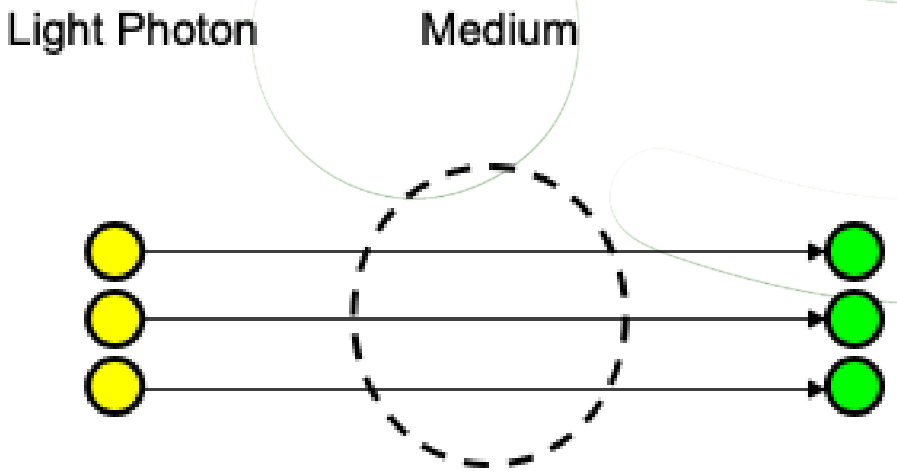


Radiative processes

Ocean colour depends on the interaction between sun light and whatever is in the water

Light through a medium (air or water) can:

- be transmitted without interaction (glass)

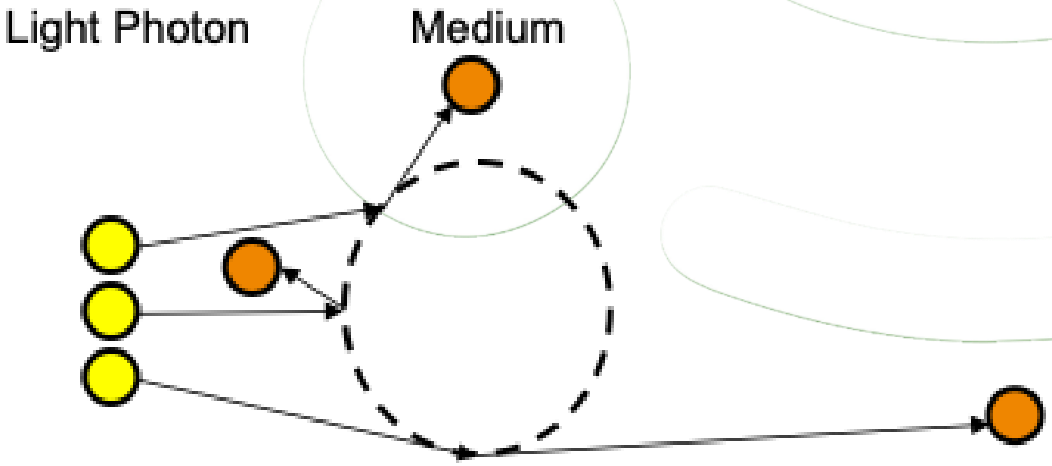


Radiative processes

Ocean colour depends on the interaction between sun light and whatever is in the water

Light through a medium (air or water) can:

- be transmitted without interaction (glass)
- collide with molecules of the medium and change direction (e.g., being scattered)

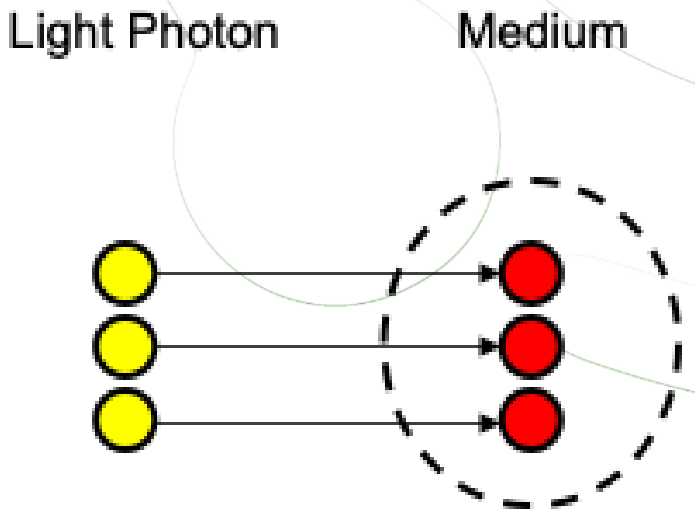


Radiative processes

Ocean colour depends on the interaction between sun light and whatever is in the water

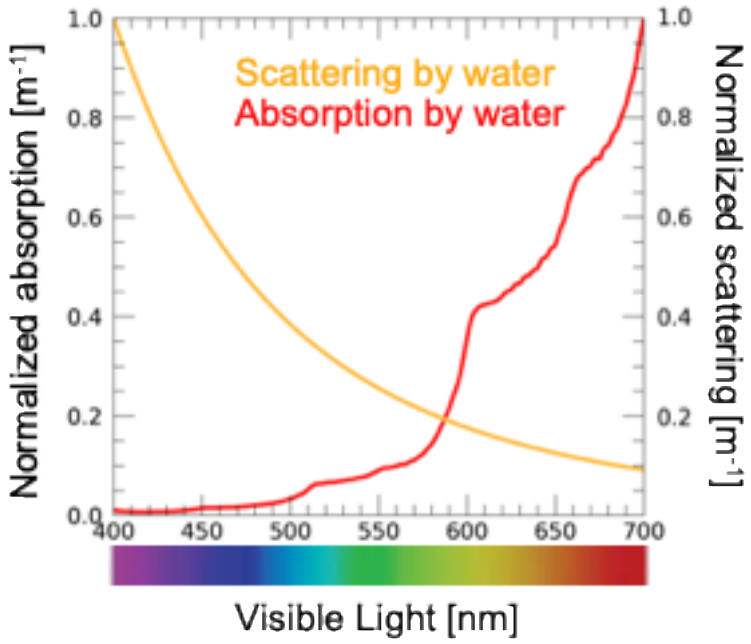
Light through a medium (air or water) can:

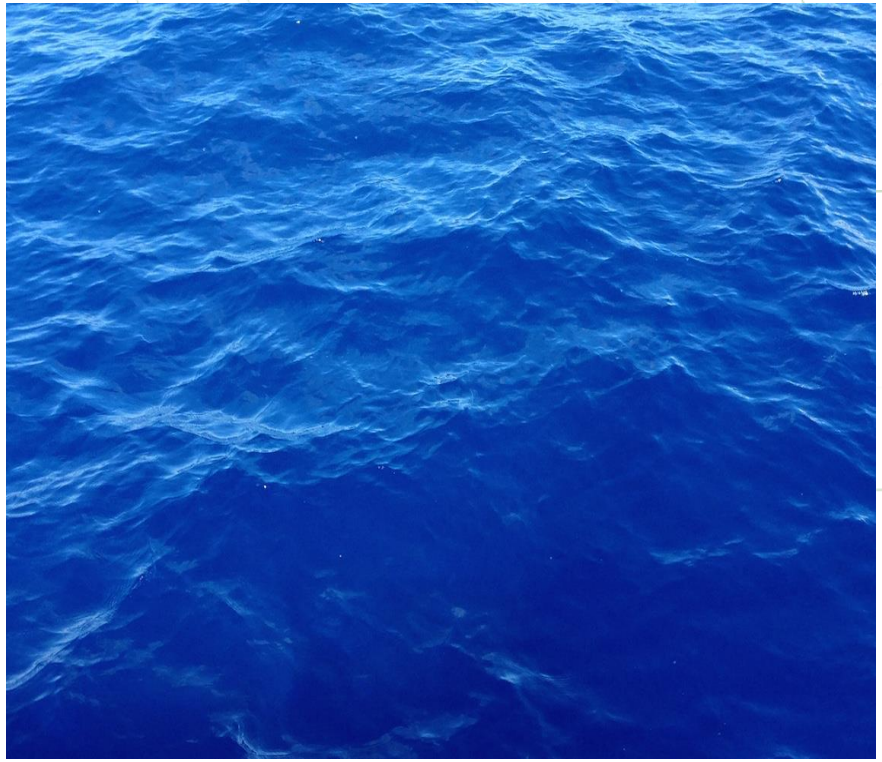
- be transmitted without interaction (glass)
- collide with molecules of the medium and change direction (e.g., being scattered)
- transfer its energy to the medium (e.g., being absorbed)



Radiative processes

Water molecules alone absorb almost all sunlight except for the blue part of the spectrum, which is reflected back out





That is why open ocean regions appear as deep blue!

Radiative processes

Any particles/organisms in the ocean absorb or reflect different wavelengths of light, depending on their individual properties

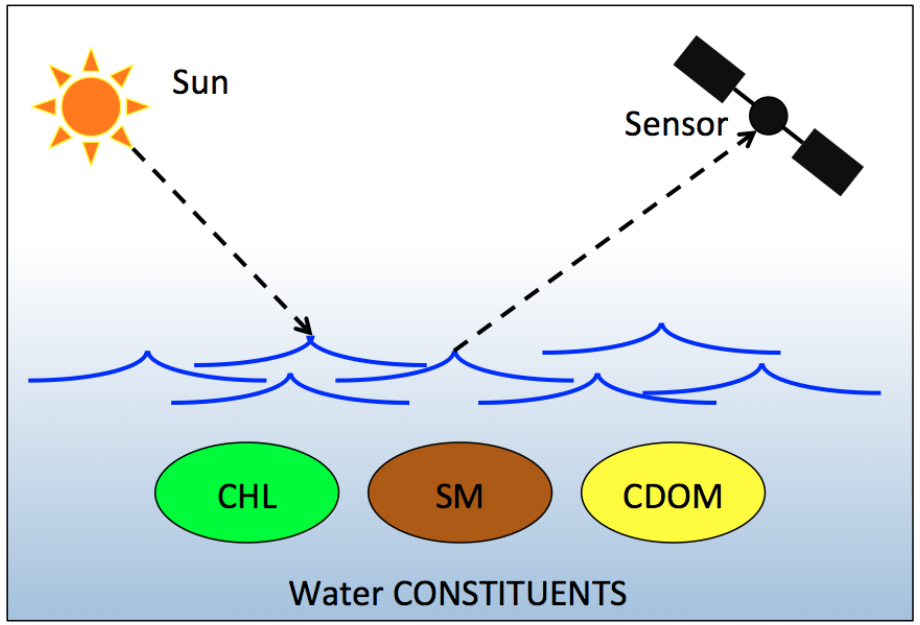
sediment

Phytoplankton

Congo River from Landsat 8
(Ocean Color Image Gallery NASA)

Satellite Ocean Colour

Light emitted from the sun INTERACTS with the SEAWATER and its CONSTITUENTS before being captured by the remote sensor



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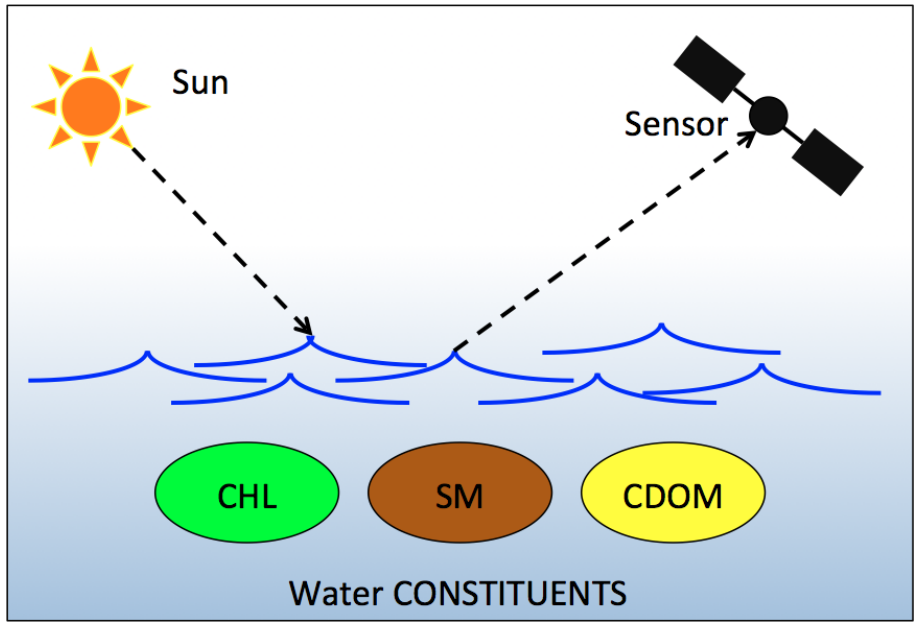
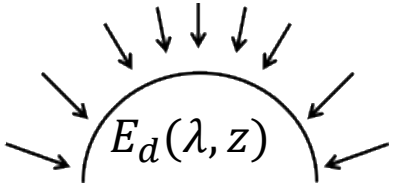


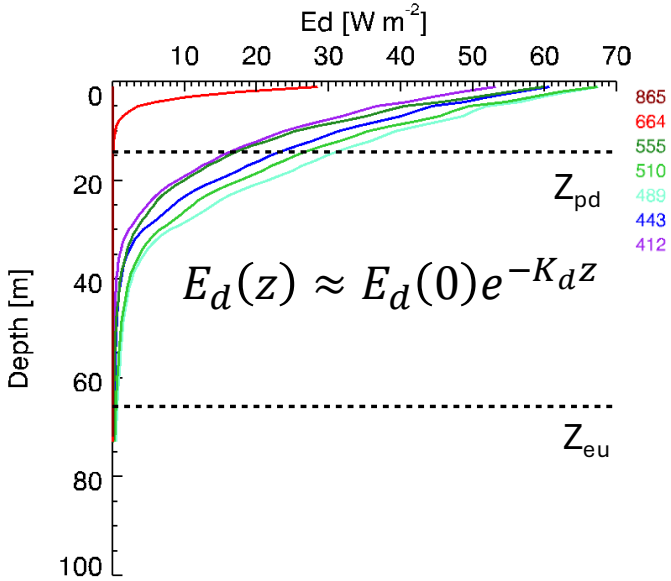
Ocean Colour is the description of the optical properties of the medium through which the light propagates.

Satellite ocean colour radiometry involves detecting variations in spectrally-resolved water-leaving radiances.

Satellite Ocean Colour

The spectral downwelling Irradiance (E_d) is the total amount of light reaching a surface area element, from all the upward directions.

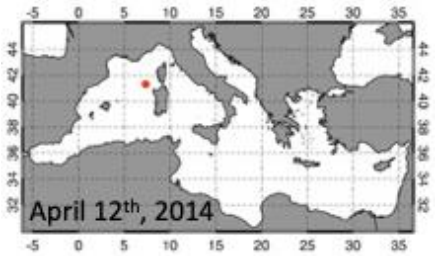




K_d = **attenuation coefficient** (m^{-1})

Penetration Depth is roughly 20% of the euphotic depth

Euphotic Depth = 1% Ed(0)



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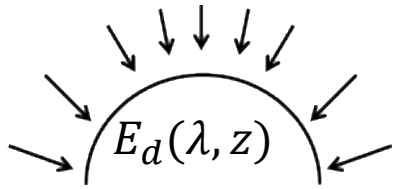
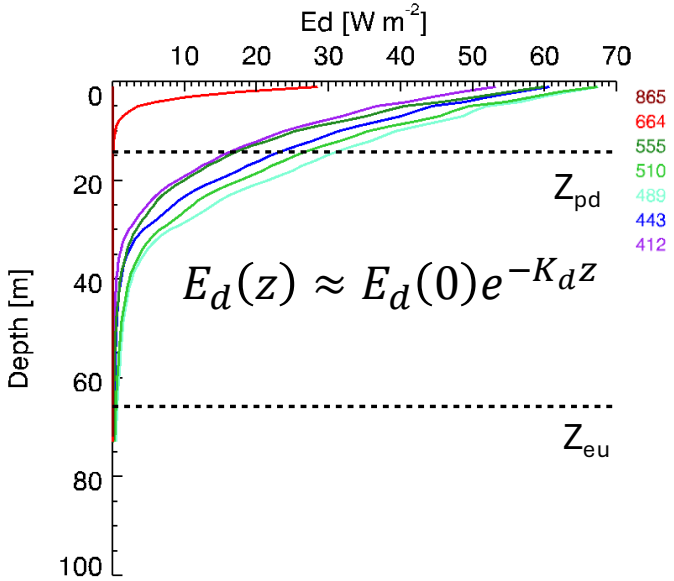
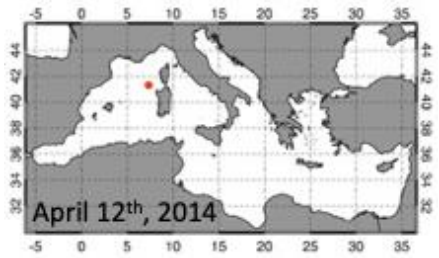






K_d = attenuation coefficient (m^{-1})

is the vertical attenuation coefficient for downward irradiance and describes the rate of change of E_d with depth

smaller K_d values

↓

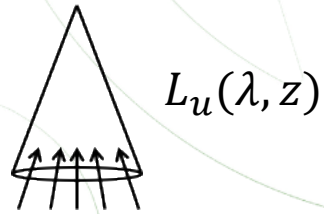
less attenuation

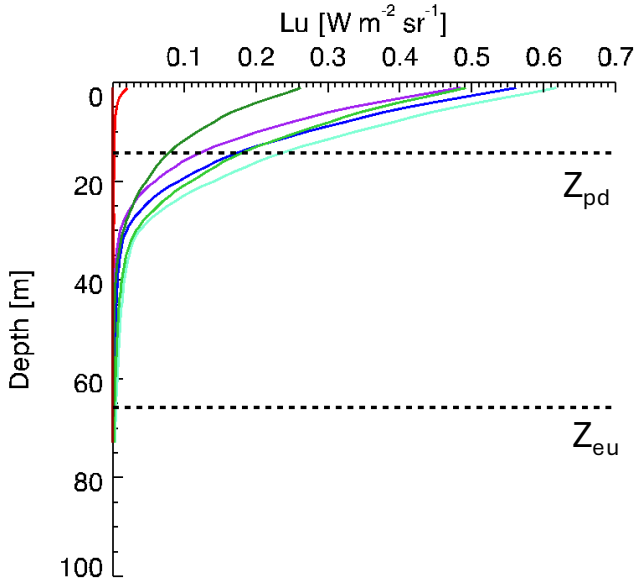
↓

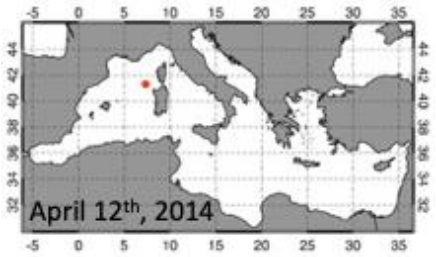
greater water transparency

Satellite Ocean Colour

The spectral upwelling Radiance (L_u) is the amount of light reaching a surface area element, through one solid angle.







Z_{pd} = Penetration depth
Z_{eu} = Euphotic zone

Satellite Ocean Colour

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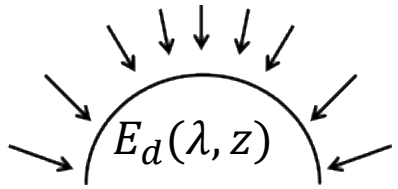

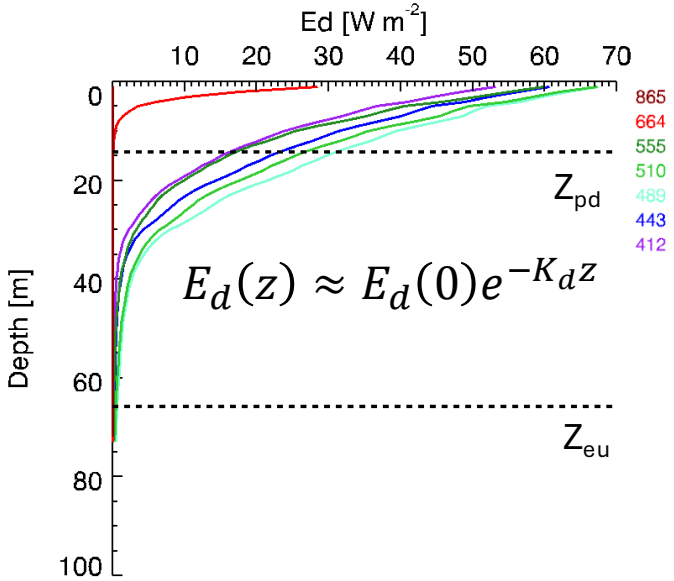

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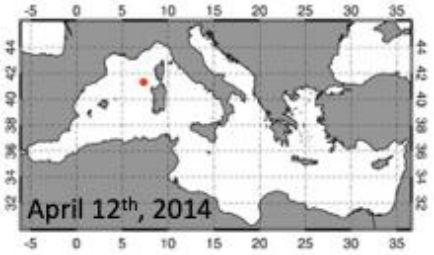

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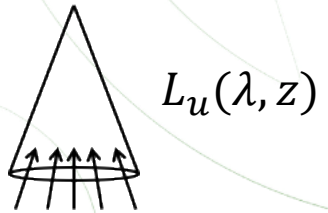

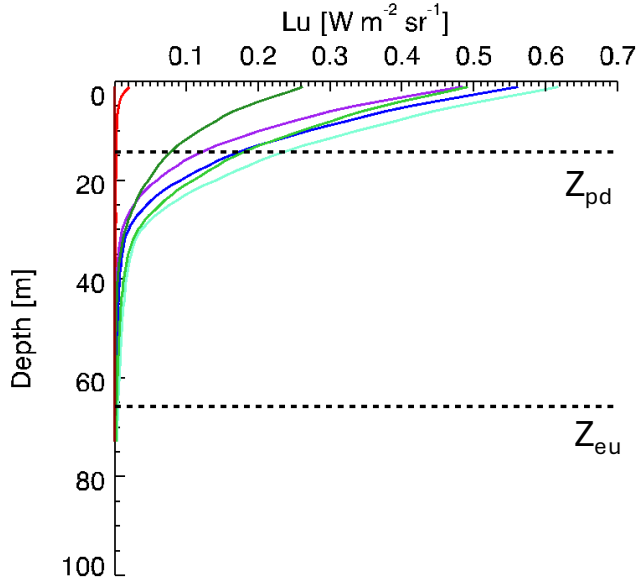

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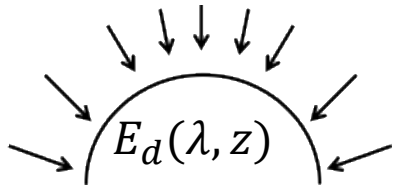

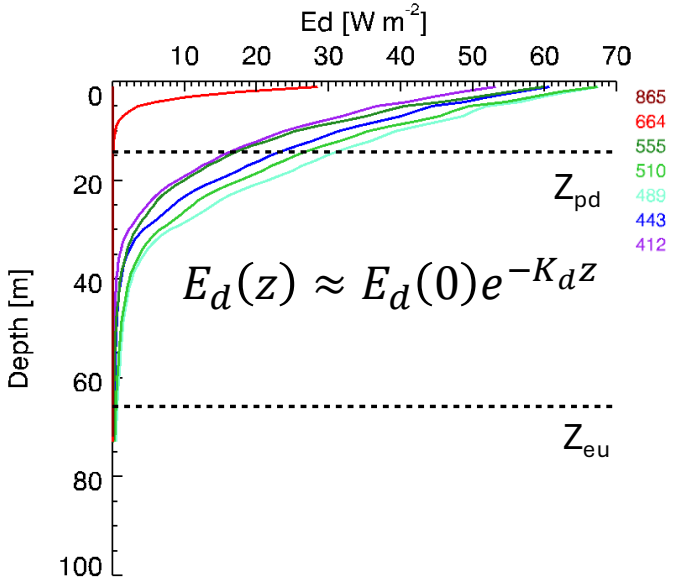

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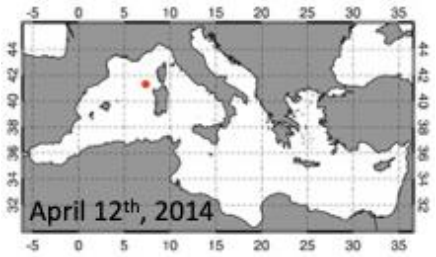
Remote sensing Reflectance

$$R_{rs}(\lambda, 0^+) \sim \frac{L_u}{E_d}$$



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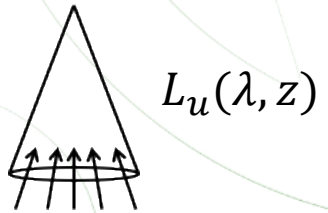

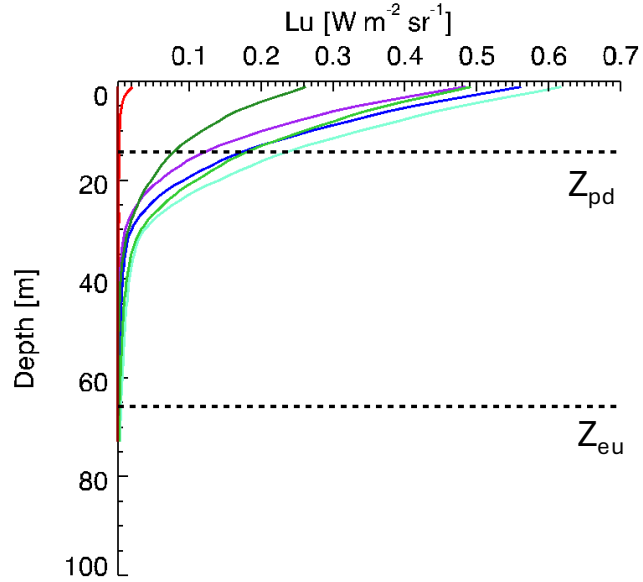

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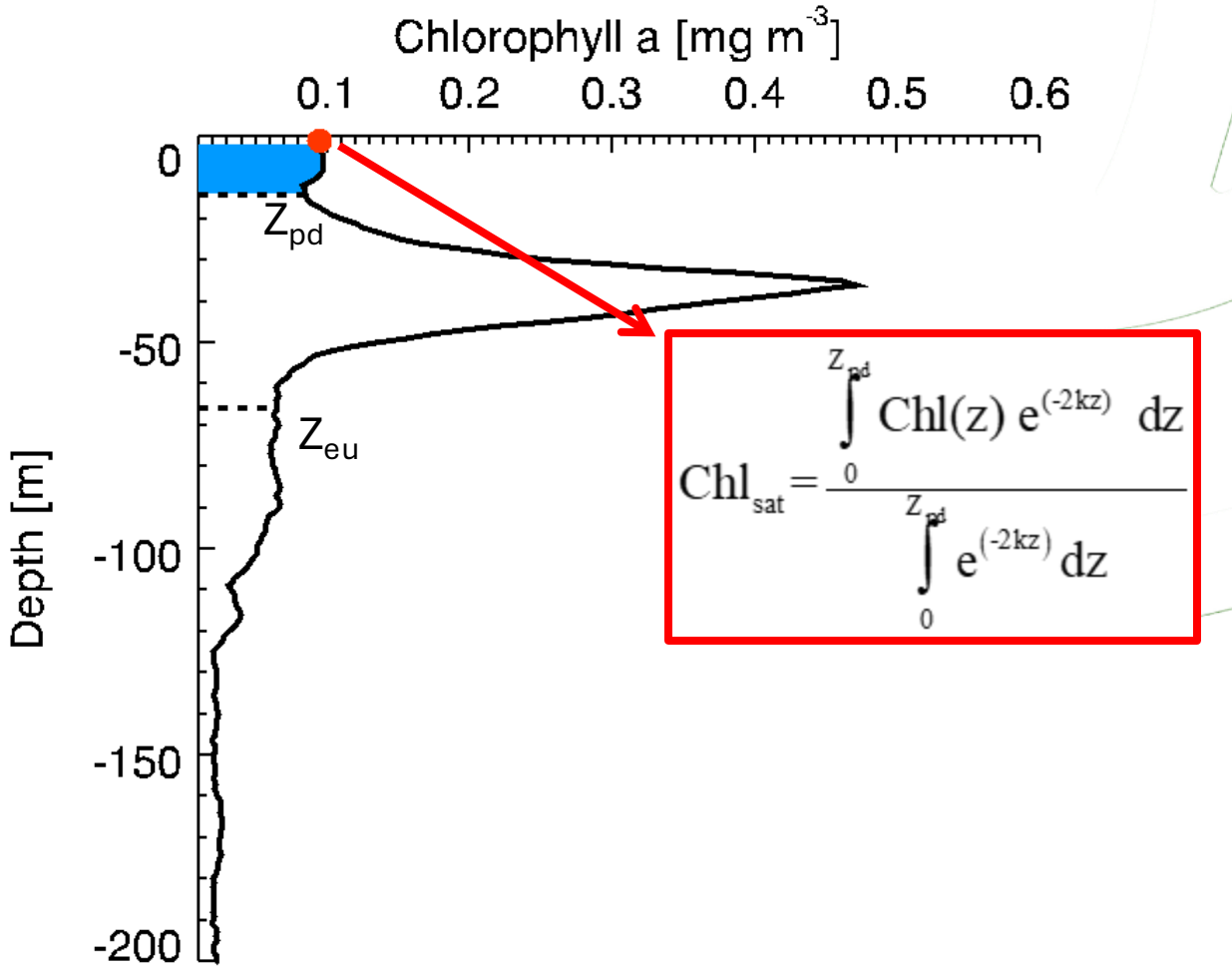
Satellite Ocean Colour

OC gives information about the surface ocean:

most of the signal captured by a remote sensor is the result of the light interaction with particles within the penetretion depth



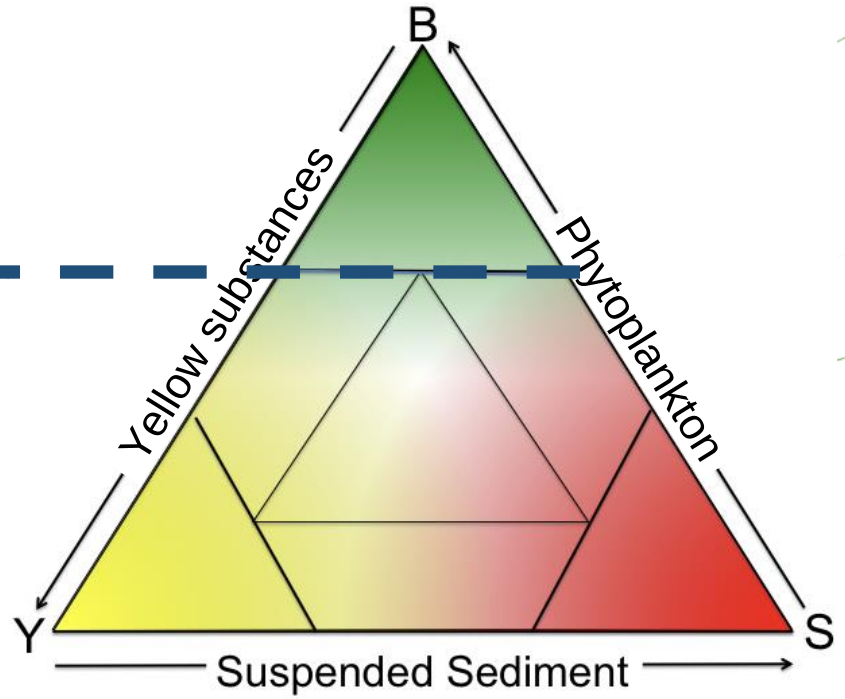
Satellite Ocean Colour

Case I waters

- Optical signal variability is WELL explained by the variability in phytoplankton biomass (i.e., Chlorophyll)
- Open ocean

Case II waters

- Optical signal variability is ONLY PARTIALLY explained by the variability in phytoplankton biomass
- CDOM & TSM can play a significant role
- Coastal waters



The Copernicus OC TAC Catalogue

For each ocean region (Global Ocean, Mediterranean and Black Sea, North Atlantic, Baltic and Arctic seas), OC TAC delivers two sets of products, CHL and OPTICS:

- **Ocean Optics**

  The OPTICS product includes all other variables retrieved from ocean colour sensors: Inherent Optical Properties (IOPs), such as absorption and scattering, the diffuse attenuation coefficient of light at 490 nm (K_d490), Secchi depth (transparency of water), spectral Remote Sensing Reflectance ($R_{rs}(\lambda)$), photosynthetically available radiation (PAR), Coloured Dissolved Organic Matter (CDOM), and the Suspended Particulate Matter (SPM).

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- **Ocean Chlorophyll**

  CHL is the phytoplankton chlorophyll concentration. For the global and each of the regional seas, OC TAC selected the state-of-the-art product algorithm on the basis of optical characteristics of the basin and round robin procedure. For the regional seas, daily chlorophyll fields are produced by applying two different algorithms for open ocean (Case I) and coastal waters (Case II). The data are then merged into a single chlorophyll field providing a regional product with an improved accuracy of estimates in coastal waters.

The Copernicus OC TAC Catalogue

OCTAC products are provided at global scale and at the regional scales of European seas across four resolutions:

- Multi-sensor 1km (Regions) , 4km (GLO, ARC)
- Sentinel-3 OLCI B+C 300m
- Sentinel-2 MSI A+B 100m

Each product contains up to five datasets:

1. Plankton – with the phytoplankton chlorophyll concentration (CHL), Phytoplankton Size Classes (PSC) and Phytoplankton Functional Types (PFT);
2. Primary Production – integrated productivity within the euphotic zone (PP);
3. Reflectance – with the spectral Remote Sensing Reflectance (Rrs);
4. Transparency – with diffuse attenuation coefficient of light at 490 nm (Kd490), Secchi depth (ZSD - an indicator of water transparency), and the Suspended Particulate Matter (SPM); and
5. Optics – including the Inherent Optical Properties (IOPs), such as absorption and scattering by particulate and dissolved matter.

The Copernicus OC TAC Catalogue

Global & Reg. SST Product

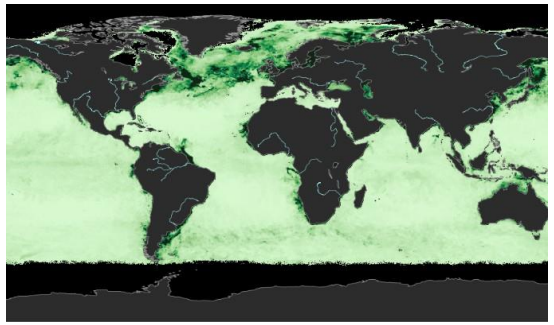
Near-Real-Time (NRT)
(last 2 years → 1 day before RT)
- L4
- L3S

Operational applications

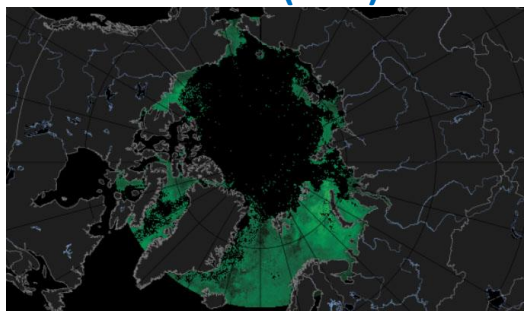
Multy-Year/REP (MY)
(1998 → 1 month before RT)
- L4
- L3S

Climate applications

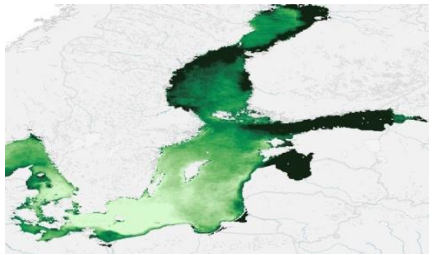
Global (GLO)



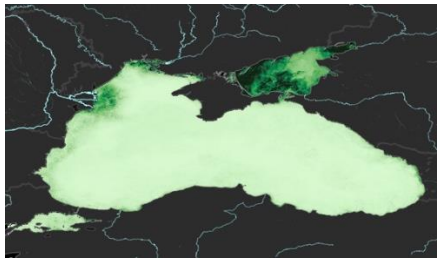
Arctic (ARC)



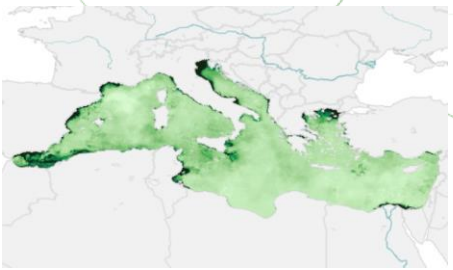
Baltic Sea (BAL)



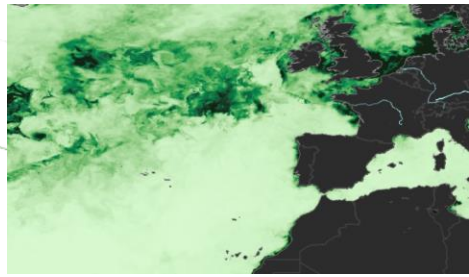
Black Sea (BLK)



Mediterranean Sea (MED)

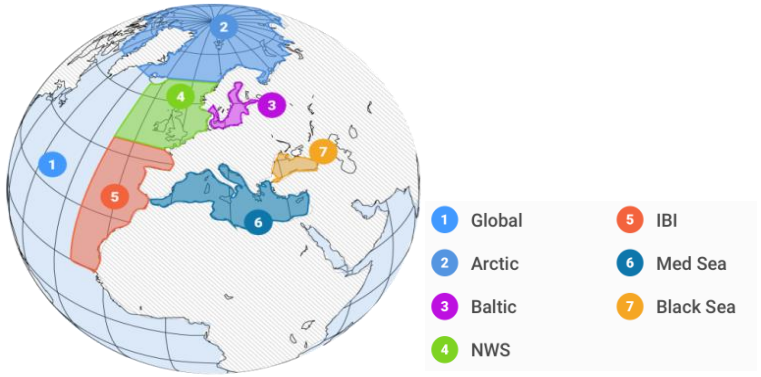


ATL (IBI+NWS)



- Regional products provide higher accuracy as they take into account the bio-optical characteristics of each regional sea
- Detailed information of each product are reported in the **PUM and QUID**

The Copernicus OC TAC Catalogue



Global & Reg. SST Product

- **Near-Real-Time (NRT)** (last 2 years → 1 day before RT)
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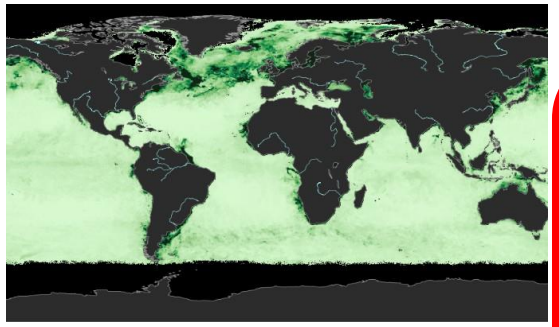

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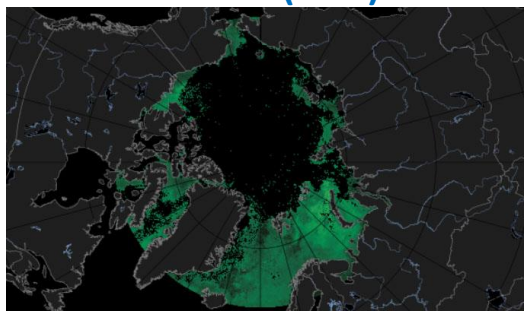

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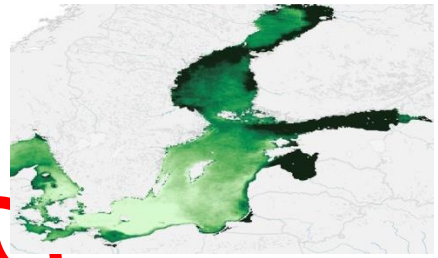

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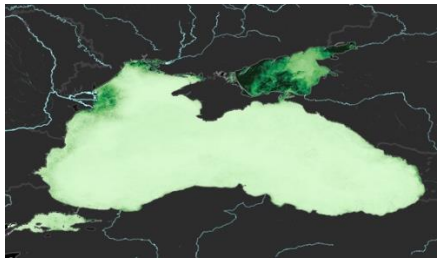
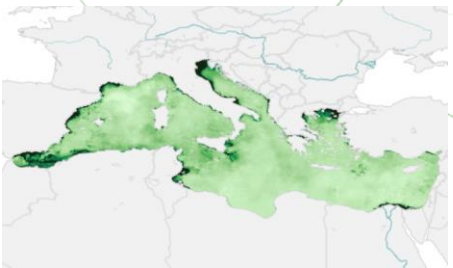


Mediterranean Sea (MED)



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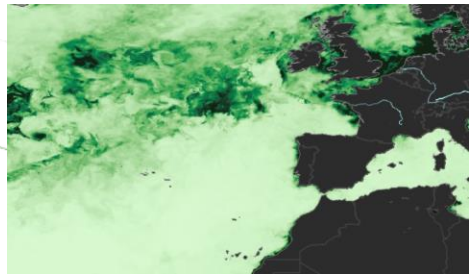

CNR ISMAR ISTITUTO DI SCIENZE MARINE

- Regional products provide higher accuracy as they take into account the bio-optical characteristics of each regional sea
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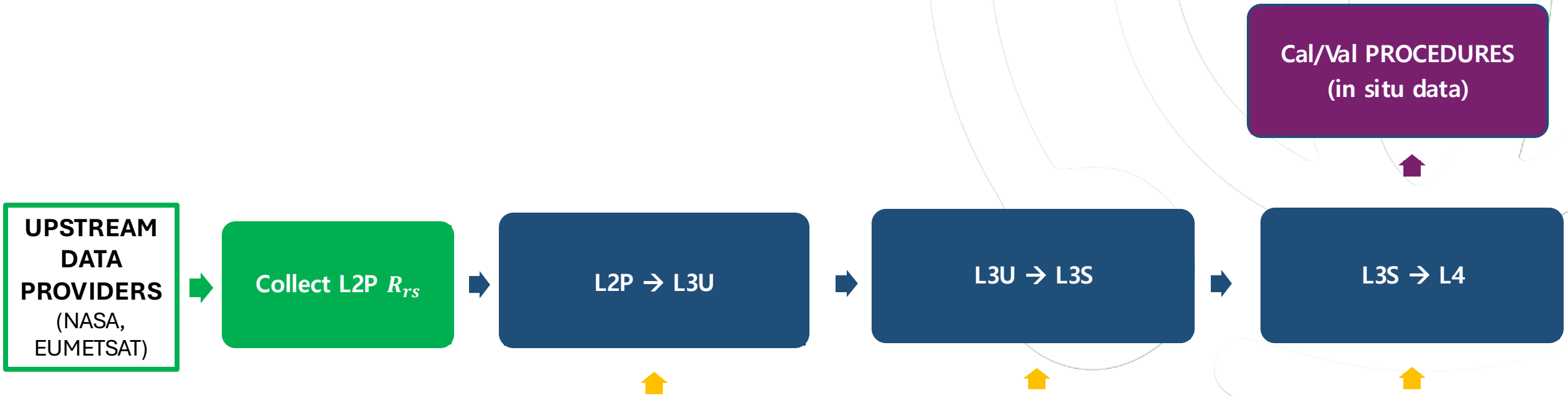
OC L3/L4 MED CNR processing chains



OC L3/L4 MED CNR processing chains

Destriping - Bowtie Removal - Flagging and Mosaicking - Band shifting

OC L3/L4 MED CNR processing chains

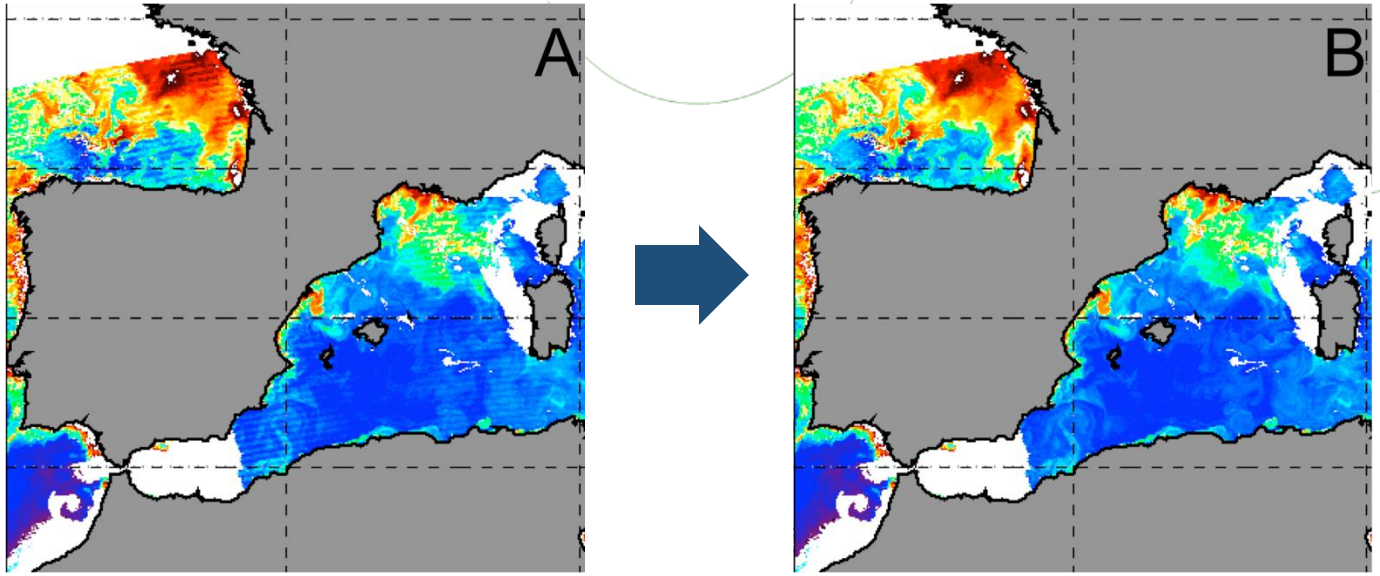
L2P → L3U → L3U → L3S → L3S → L4

Destriping - Bowtie Removal - Flagging and Mosaicking - Band shifting

Both **AQUA** and **VIIRS** scan the Earth surface via a rotating mirror system which reflect the surface radiance to band detectors

Two hardware problems

- the two sides of the **mirror** are not exactly identical
- the band **detector degradation** is not homogeneous



Mikelsons et al. (2014) Opt. Express, 22, 28058-28070.

OC L3/L4 MED CNR processing chains

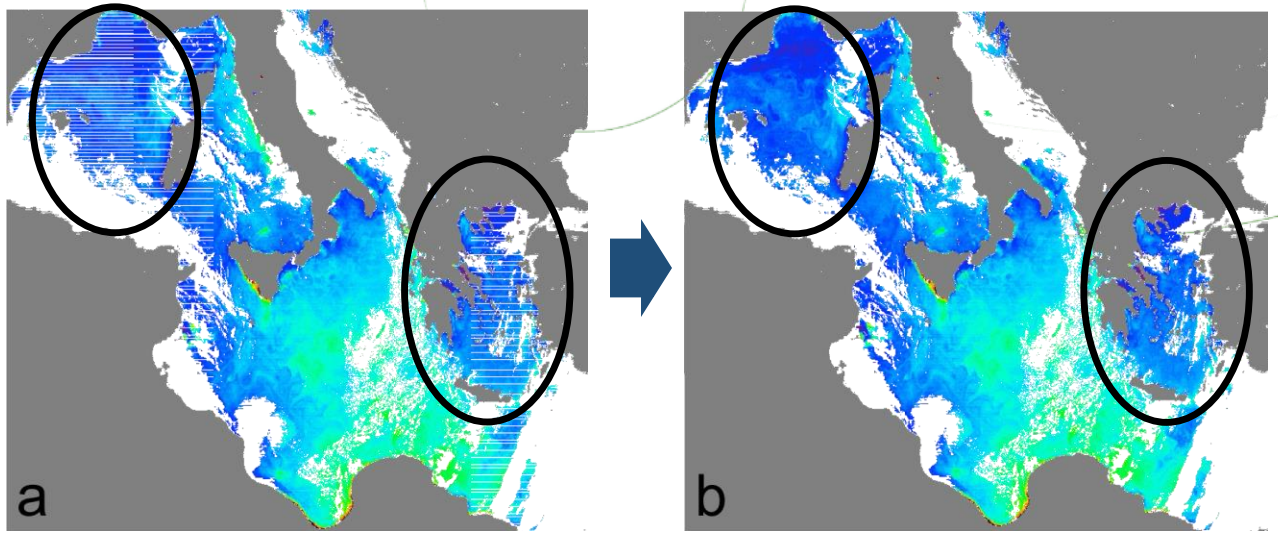
L2P → L3U → L3U → L3S → L3S → L4

Destriping - Bowtie Removal - Flagging and Mosaicking - Band shifting

VIIRS data suffer of the bowtie effect

Sensor detectors have constant angular resolution so that the sampled Earth area increases with the scan angle. This results in consecutive scans to overlap away from nadir: the entire scan has the shape of a bowtie.

The processing performed by space agencies generally removes this effect in each VIIRS granule through a combination of aggregation and deletion of overlapping pixels, resulting in a series of rows of missing values at the edge of each L2 granule.



These missing values are filled in by linear interpolation.

OC L3/L4 MED CNR processing chains

Destriping - Bowtie Removal - Flagging and Mosaicking - Band shifting

Each L2 granule is quality checked via the application of the L2 flags provided by Space Agencies

All isolated pixels are removed

All isolated missing pixels are filled in using the near-neighbourhood approach

All available granules for each day are remapped on a regular grid covering the Mediterranean Sea

All regridded granules from the same sensor and from the same day are mosaicked together into a single file containing the Remote Sensing Reflectance at nominal sensors' wavelengths.

OC L3/L4 MED CNR processing chains

Destriping - Bowtie Removal - Flagging and Mosaicking - Band shifting

	Sensor						
Wavelength (nm)	VIIRS	MODIS	MERIS	OLCI	SeaWiFS	REP	In situ
410	•						
412		•			•	•	•
413			•	•			
443	•	•	•	•	•	•	•
486	•						
488		•					
490			•	•	•	•	•
510			•	•	•	•	•
531		•					
547		•					
551	•						
555					•	•	•
560			•	•			
665			•	•			•
667		•					
670					•	•	
671	•						

The motivation behind the band-shifting is to merge single-sensor Rrs spectra into a single spectrum.

Bands can differ from a few nanometres to a significant amount

Band shifting consists in the application of the **Quasi Analytical Algorithm** (QAA, Lee et al., 2002) in forward and backward modes (Melin and Sclep, 2015)

OC L3/L4 MED CNR processing chains

Merging procedure

Three possible conditions can happen:

i) the pixel is in no clear sky condition or masked out because of any of the operational L2 flags

ii) the pixel is observed from more than one sensor

iii) the pixel is observed from one sensor only

OC L3/L4 MED CNR processing chains

Merging procedure

Three possible conditions can happen:

i) the pixel is in no clear sky condition or masked out because of any of the operational L2 flags

ii) the pixel is observed from more than one sensor

iii) the pixel is observed from one sensor only

→ i) The pixel is assigned the missing value.

→ ii) & iii) There is a high probability of introducing artefacts or spatial gradients, which in reality do not exist and are only given by the merging procedure

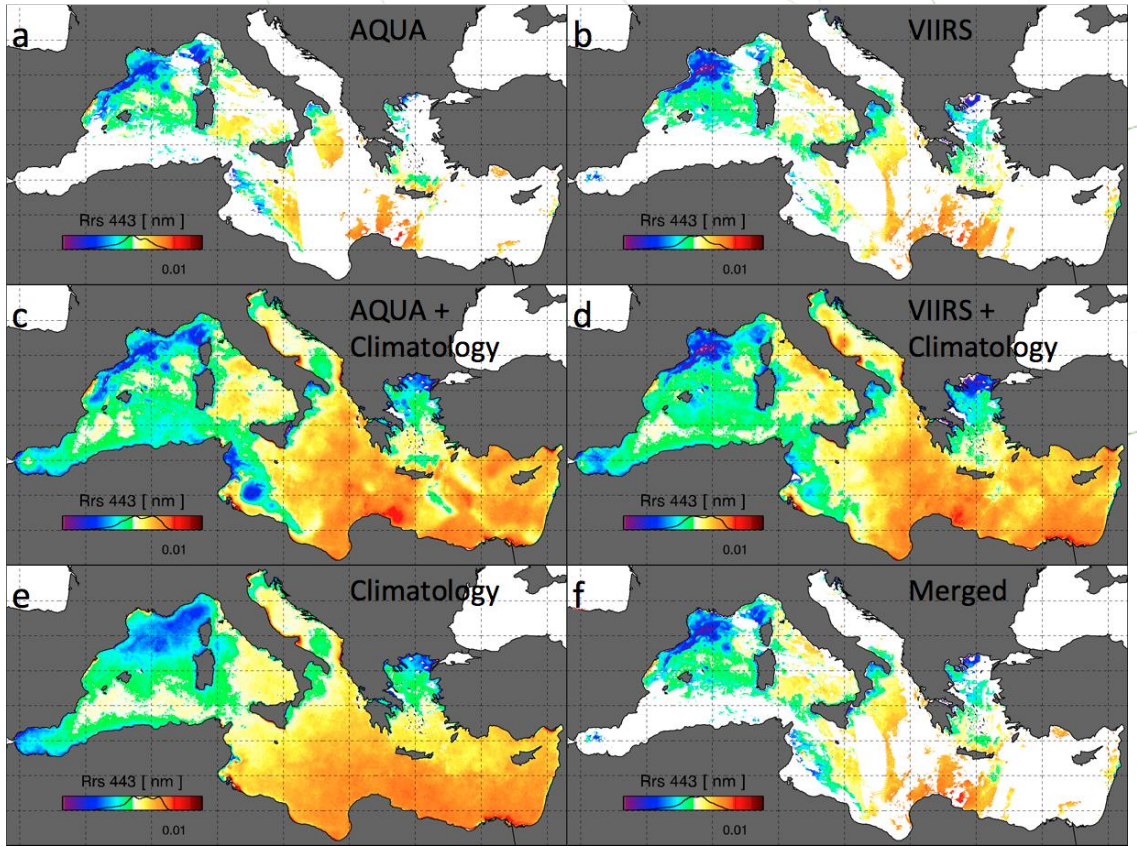
OC L3/L4 MED CNR processing chains

L2P → L3U | **L3U → L3S** | L3S → L4

Merging procedure

The field from each sensor is filled with the same relevant daily climatology. This enables the average of these two (or more) fields to be easily computed.

All the non-observed pixels are then set to the missing value



OC L3/L4 MED CNR processing chains

L3S geophysical products

2 water CHL Algorithm :

- Case I → MedOC4 (Volpe et al., 2007)
- Case II → AD4 (Berthon & Zibordi, 2004)

On a pixel-by-pixel basis, the satellite Rrs spectrum is compared with the distributions of two *in situ* datasets, representative of **Case I** and **Case II** conditions, respectively.

OC L3/L4 MED CNR processing chains

L3S geophysical products

2 water CHL Algorithm :

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- Case II → AD4 (Berthon & Zibordi, 2004)

On a pixel-by-pixel basis, the satellite Rrs spectrum is compared with the distributions of two *in situ* datasets, representative of **Case I** and **Case II** conditions, respectively.

The Mahalanobis distance parameter is used for quantifying the distance of the i^{th} satellite pixel spectrum, **x**, from the reference *in* situ datasets, **μ**:

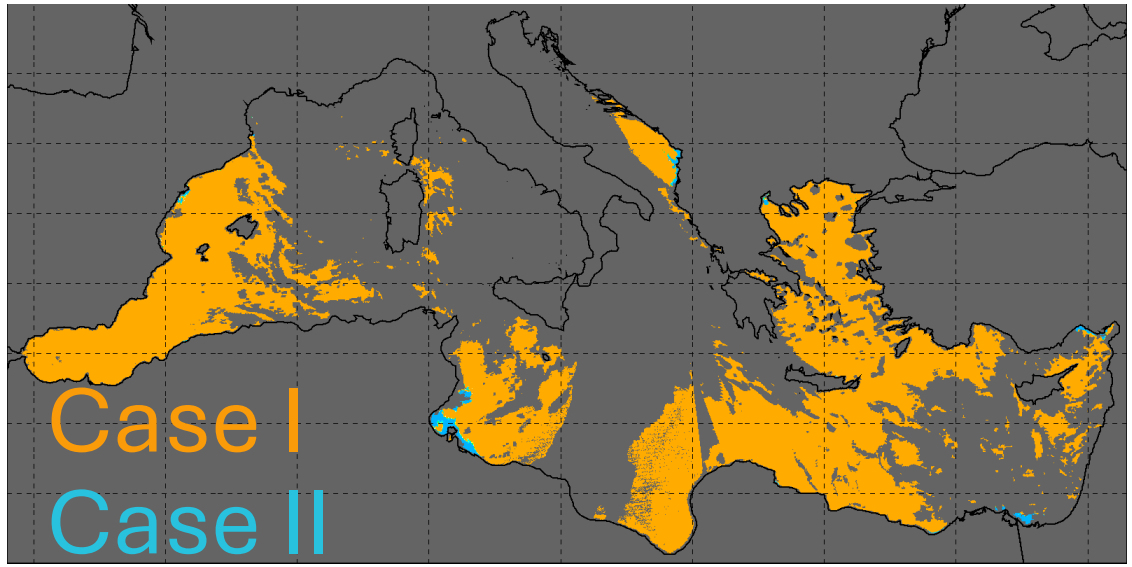
$$\Delta^2 = (x - \mu)^T \Sigma^{-1} (x - \mu)$$

$$Chl_{Merged} = \frac{Chl_{CaseI}\Delta^2_{CaseI} + Chl_{CaseII}\Delta^2_{CaseII}}{\Delta^2_{CaseI} + \Delta^2_{CaseII}}$$

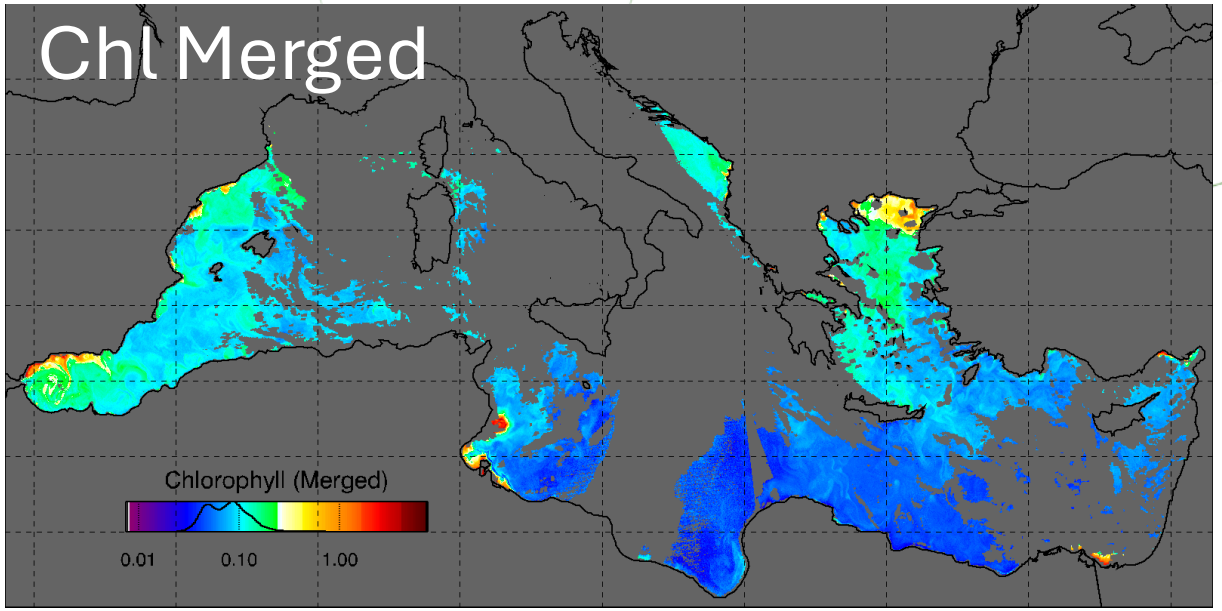
D'Alimonte *et al*. [2003]

OC L3/L4 MED CNR processing chains

L2P → L3U → **L3U → L3S** → L3S → L4



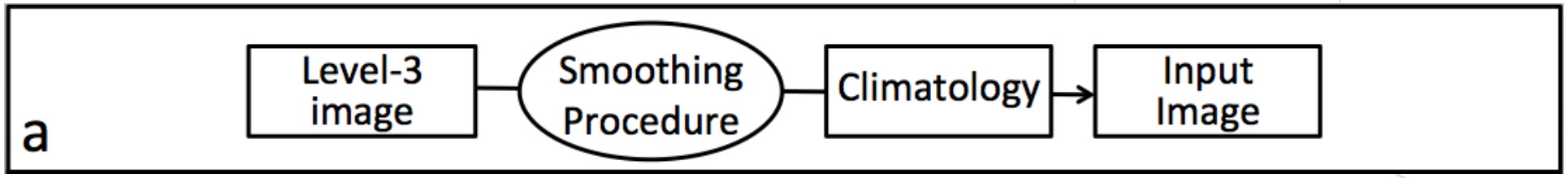
Multi-sensor Chlorophyll April 2nd, 2017



OC L3/L4 MED CNR processing chains

L2P → L3U → L3U → L3S → L3S → L4

Filling gaps to obtain L4 data

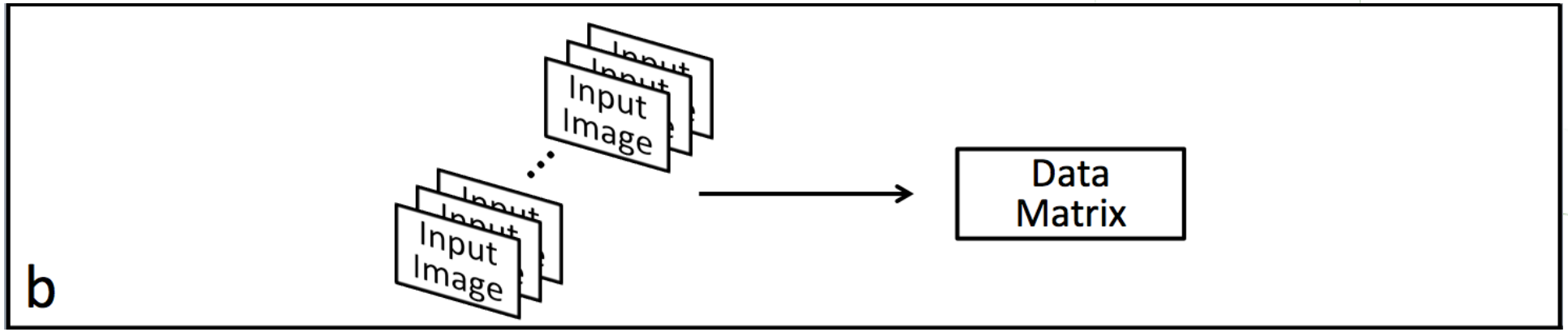


a. Original Level-3 image is merged with the climatology to obtain the input image

OC L3/L4 MED CNR processing chains

L2P → L3U → L3U → L3S → L3S → L4

Filling gaps to obtain L4 data



a. Original Level-3 image is merged with the climatology to obtain the input image
b. A time series of input image is used to build the data matrix, input to the Level-4 processor

OC L3/L4 MED CNR processing chains

Filling gaps to obtain L4 data

NRT

T0
T-1
T-2
T-3
T-4
T-5
T-6
T-7
T-8
T-9
T-10

DT

T+4	T+3	T+2	T+1	T0
T+3	T+2	T+1	T0	T-1
T+2	T+1	T0	T-1	T-2
T+1	T0	T-1	T-2	T-3
T0	T-1	T-2	T-3	T-4
T-1	T-2	T-3	T-4	T-5
T-2	T-3	T-4	T-5	T-6
T-3	T-4	T-5	T-6	T-7
T-4	T-5	T-6	T-7	T-8
T-5	T-6	T-7	T-8	T-9
T-6	T-7	T-8	T-9	T-10

REP

T+10	T+9	T+8	T+7	T+6	T+5	T+4	T+3	T+2	T+1	T0
T+9	T+8	T+7	T+6	T+5	T+4	T+3	T+2	T+1	T0	T-1
T+8	T+7	T+6	T+5	T+4	T+3	T+2	T+1	T0	T-1	T-2
T+7	T+6	T+5	T+4	T+3	T+2	T+1	T0	T-1	T-2	T-3
T+6	T+5	T+4	T+3	T+2	T+1	T0	T-1	T-2	T-3	T-4
T+5	T+4	T+3	T+2	T+1	T0	T-1	T-2	T-3	T-4	T-5
T+4	T+3	T+2	T+1	T0	T-1	T-2	T-3	T-4	T-5	T-6
T+3	T+2	T+1	T0	T-1	T-2	T-3	T-4	T-5	T-6	T-7
T+2	T+1	T0	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8
T+1	T0	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9
T0	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10

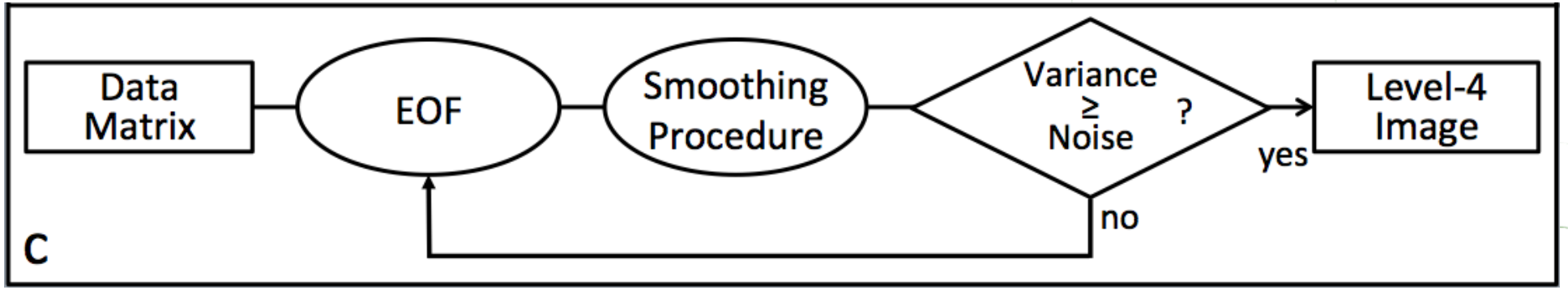
The structure of the input data matrix varies among the three processing modes.

This configuration enables the **temporal variability** to be taken into account when computing the EOF modes.

OC L3/L4 MED CNR processing chains

L2P → L3U → L3U → L3S → L3S → L4

Filling gaps to obtain L4 data

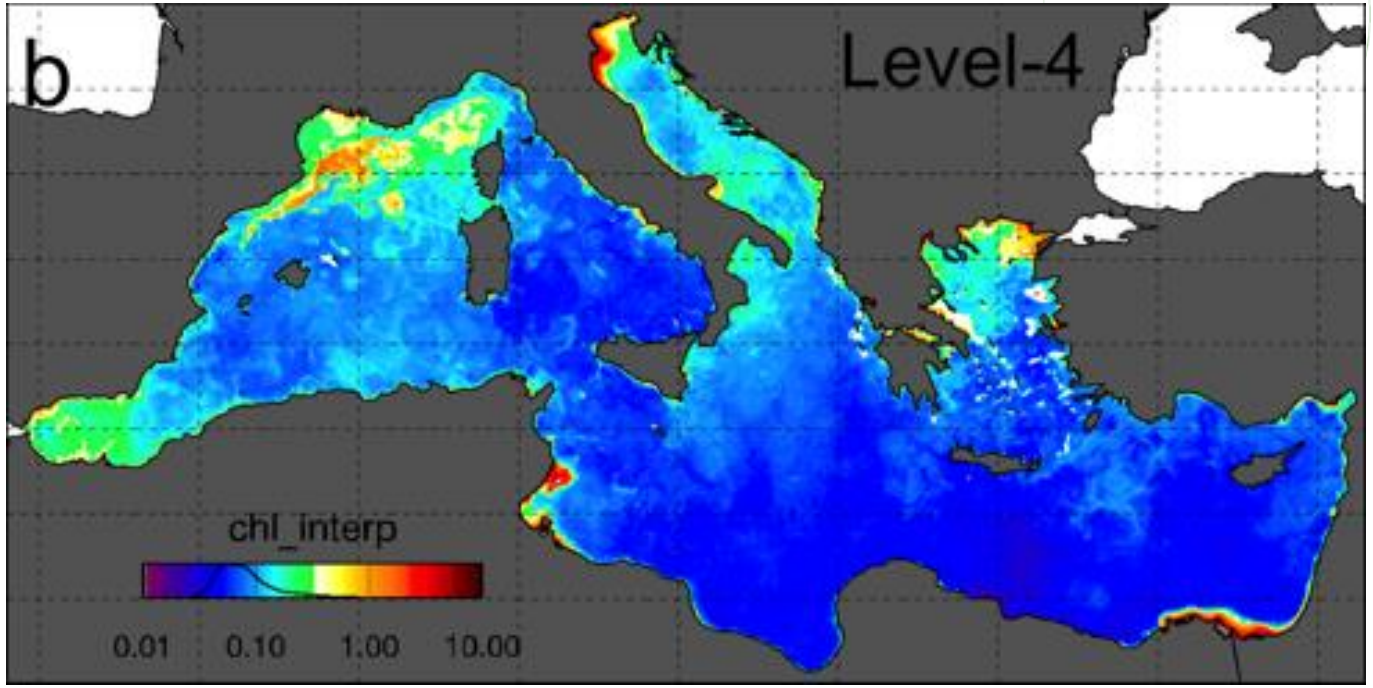


a. Original Level-3 image is merged with the climatology to obtain the input image
b. A time series of input image is used to build the data matrix, input to the Level-4 processor
c. The data matrix enters the iterative EOF calculation. At each iteration EOF patterns are used to fill gaps in the original data until the explained variance reaches the level of the noise

OC L3/L4 MED CNR processing chains

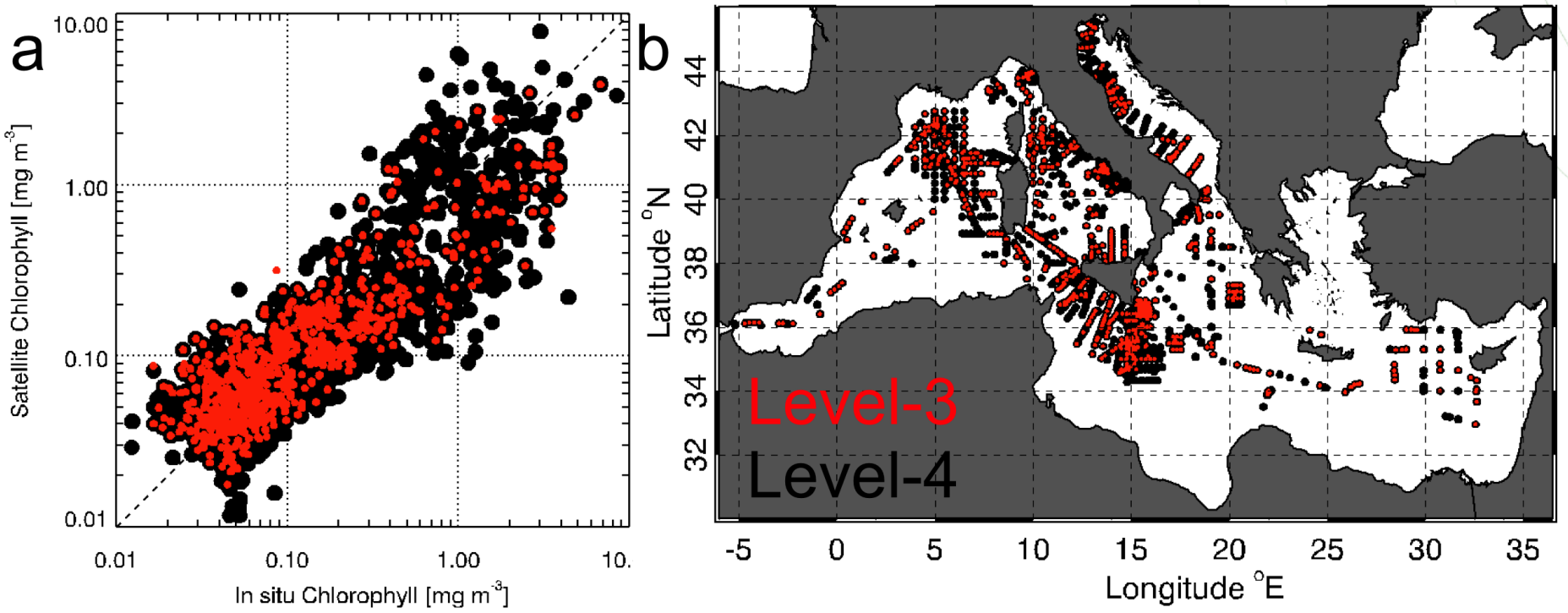
L2P → L3U → L3U → L3S → **L3S → L4**

Filling gaps to obtain L4 data



OC L3/L4 MED CNR processing chains

Cal/Val PROCEDURES (in situ data)



Processing Level	r^2	RMS	Bias	RPD	APD	N
Level-3	0.74	0.252	-0.035	8.7	47.3	797
Level-4	0.73	0.275	-0.063	3.8	48.3	2023

Some applications

Impact of the Covid-19 pandemic over marine coastal environment

On March 9, 2020, Italy entered the lockdown phase due to Sars-Covid19 pandemic

This radical choice began an unplanned experiment of drastic reduction of anthropic pressure on the environment, including the marine-coastal system

The aim of RACE-SOON was to exploit the sentinel-3 full resolution to produce synthetic water quality indicators

Some applications

Impact of the Covid-19 pandemic over marine coastal environment

F. Braga et al. / Science of the Total Environment 736 (2020) 139612

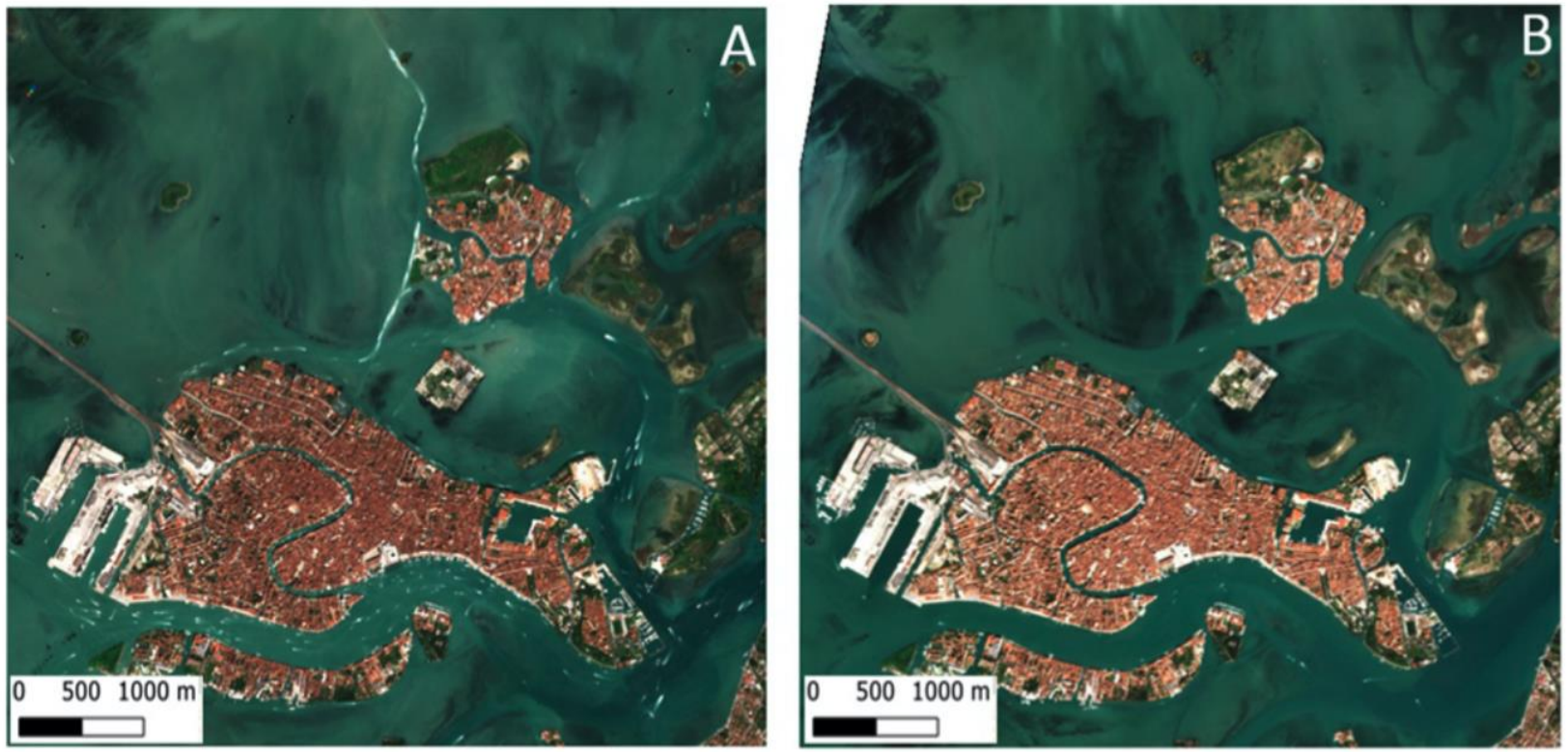
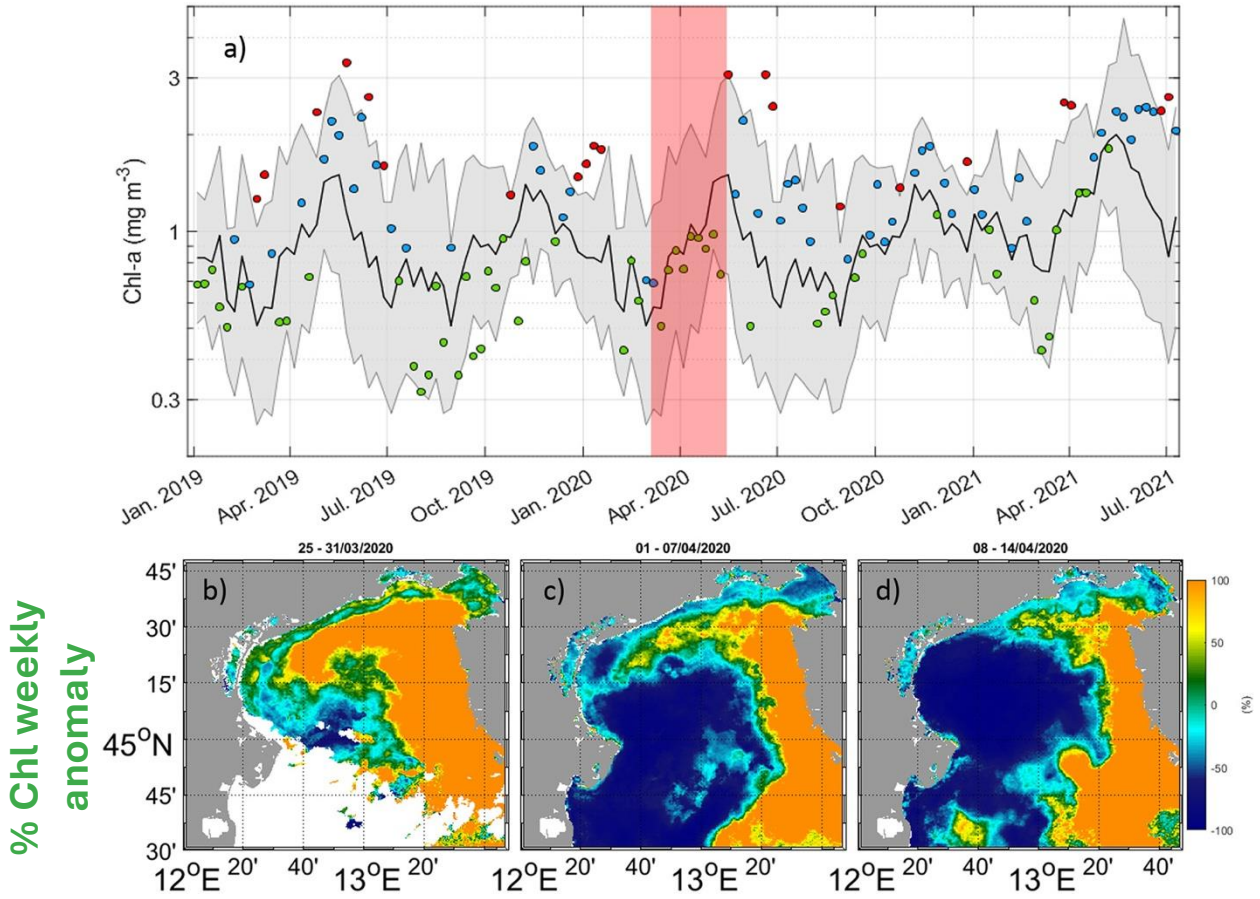


Fig. 4. S2 true-colour images in the lagoon of Venice on Good Fridays of 2019 and 2020: A) April 19th 2019; B) April 10th 2020 (during lockdown).

Important marine traffic reduction allowed to focus on natural processes and the residual stress from human activities that continued throughout the lockdown.

Some applications

Impact of the Covid-19 pandemic over marine coastal environment



The analysis indicates a favourable interplay of environmental variability that resulted in negative anomalies of Chlorophyll-a concentration, with respect to the climatologic values.

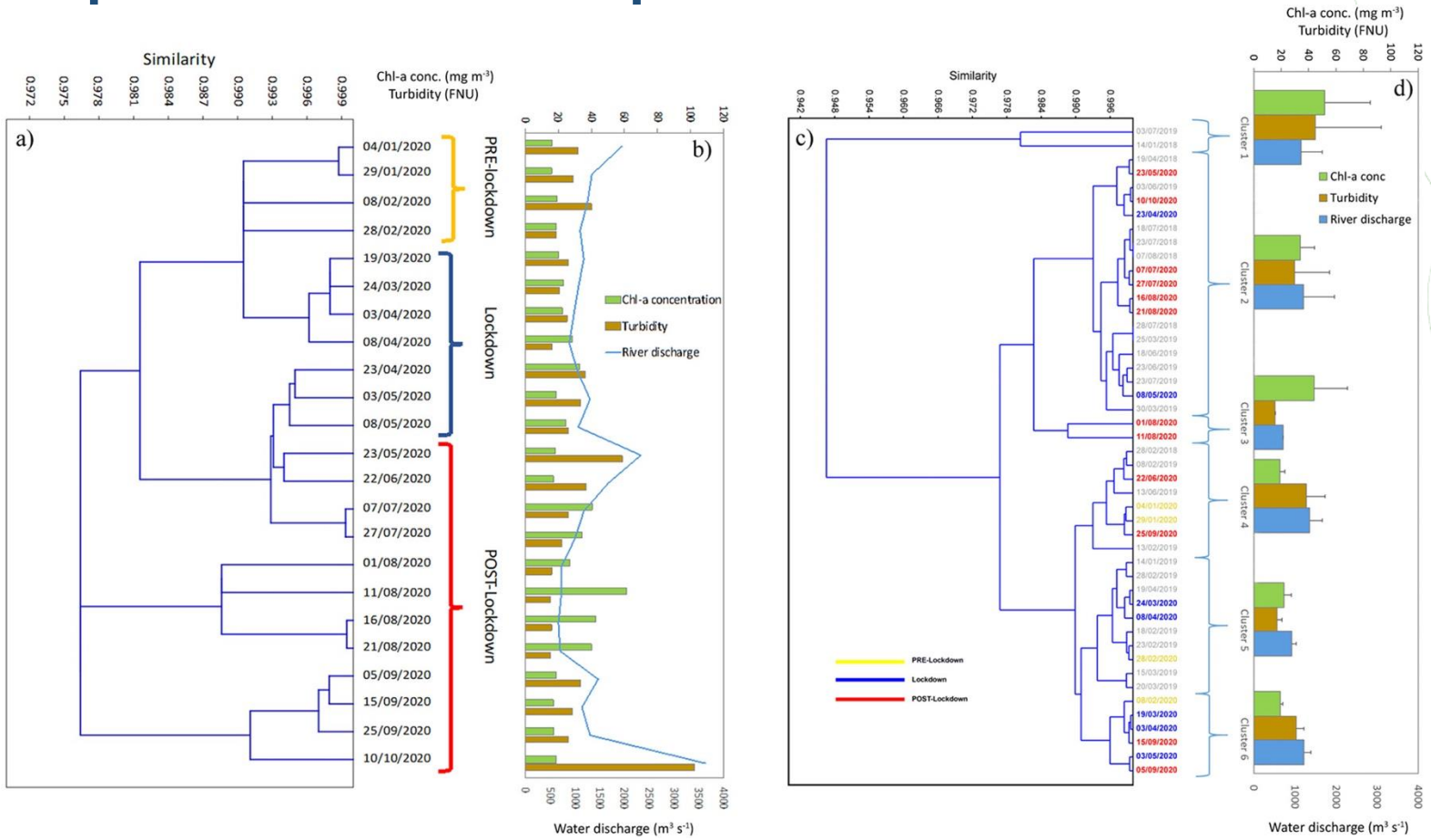
... **HOWEVER** on a wider perspective:

- Italian lockdown did not occur during high touristic season
- Exceptionally dry winter season

Braga, F., Ciani, D., Colella, S., Organelli, E., Pitarch, J., Brando, V. E., ... & Falcini, F. (2022). COVID-19 lockdown effects on a coastal marine environment: Disentangling perception versus reality. Science of the Total Environment, 817, 153002.

Some applications

Impact of the Covid-19 pandemic over marine coastal environment



The cluster analysis highlights the possibility of a **second-order,** anthropogenic effect that, superimposed to the (**first-order**) environmental natural causes, may have enhanced water quality during the lockdown.

Braga, F., Ciani, D., Colella, S., Organelli, E., Pitarch, J., Brando, V. E., ... & Falcini, F. (2022). COVID-19 lockdown effects on a coastal marine environment: Disentangling perception versus reality. Science of the Total Environment, 817, 153002.

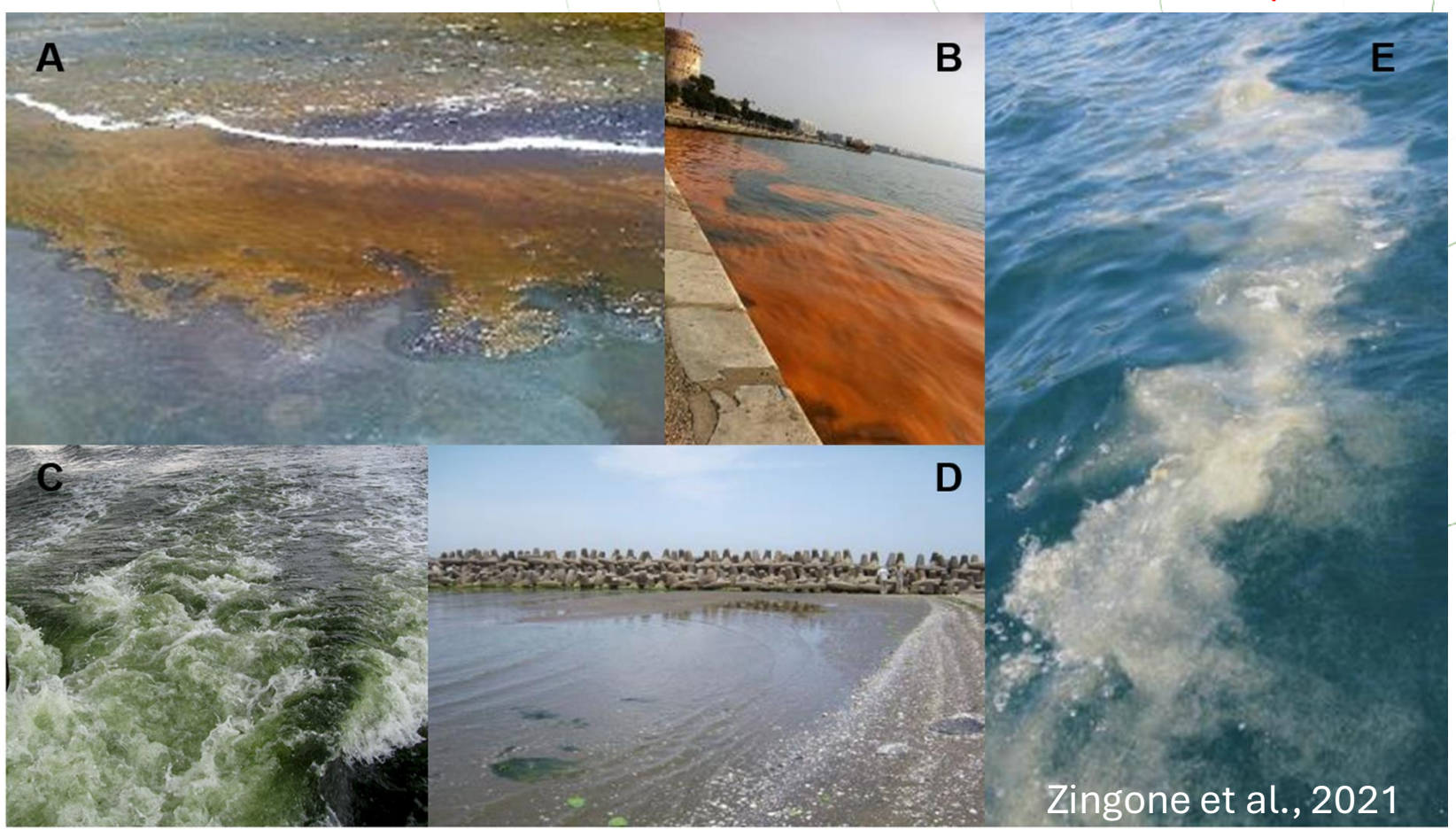
Some applications

Detection of Harmful Algal Blooms (HABs)

Gulf of Naples!

Harmful algal blooms (HABs) occur when colonies of algae grow uncontrollably in water, producing toxins that can harm marine life, ecosystems, and human health.

These blooms are often triggered by excess nutrients (such as nitrogen and phosphorus from agricultural runoff), warm temperatures, and stagnant water. HABs can lead to oxygen depletion, fish kills, and contamination of drinking water, posing serious environmental and economic risks.



Their forecast/monitoring is extremely important.

Some applications

Detection of Harmful Algal Blooms (HABs)

HABs can affect ecosystem and human healt:

- Oxygen depletion in the environment → hypoxia (death of animals and aquatic vegetation)
- Different types of shellfish poisoning (and consequent poisoning of toxic shellfish consumers)
- Drinking water threat (caused mostly by cyanobacteria groups)

Some applications

Detection of Harmful Algal Blooms (HABs)

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- Oxygen depletion in the environment → hypoxia (death of animals and aquatic vegetation)
- Different types of shellfish poisoning (and consequent poisoning of toxic shellfish consumers)
- Drinking water threat (caused mostly by cyanobacteria groups)

In situ monitoring is essential to establish species and toxins levels,

BUT

Remote sensing imagery is a powerful tool to monitor and predict HAB events,
helping to assess their impact on ecosystems and human health.

Some applications

Detection of Harmful Algal Blooms (HABs)

Remote sensing data useful in HABs detection:

- Chlorophyll
- Chlorophyll-a anomaly
- Inherent optical properties (IOPs) to discriminate algae types
- Coupled remote sensing observation and environmental condition modeling

Some applications

Detection of Harmful Algal Blooms (HABs)

Case Study – *Karenia brevis* on the West Florida Shelf:

The anomaly indicates areas where the daily chlorophyll concentration deviates from the 60-day average, calculated up to two weeks before the sample date.

Karenia brevis is a relatively large dinoflagellate that produces a low backscattering signal. This distinct backscattering pattern gives mono-specific blooms a unique remote sensing reflectance spectrum.

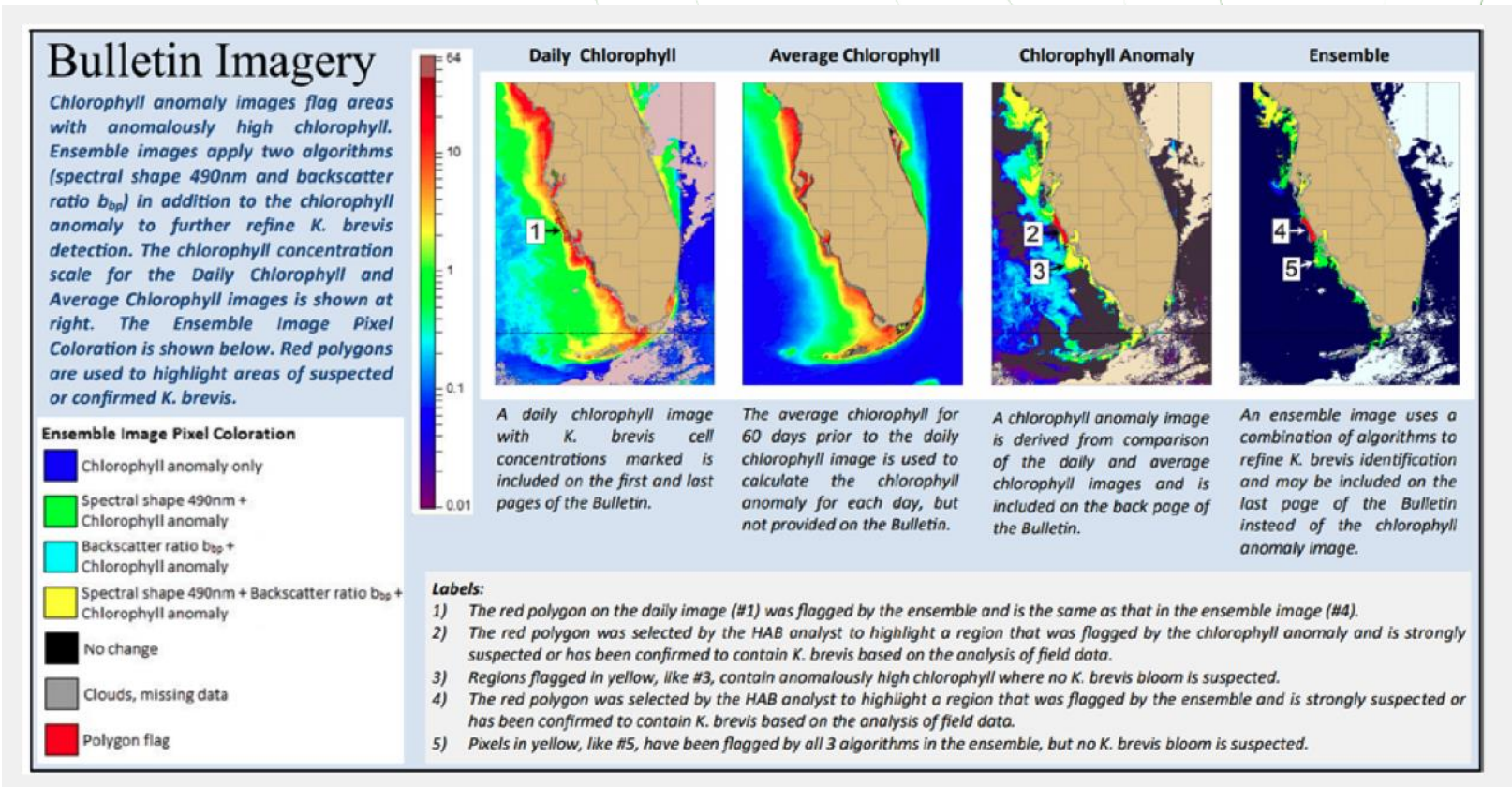

Image credits:
https://tidesandcurrents.noaa.gov/hab/hab_publication/habfs_bulletin_guide.pdf

Some applications

Detection of Harmful Algal Blooms (HABs)

Case Study – *Karenia brevis* on the West Florida Shelf:

Remote sensing observations help water resource managers target their sampling efforts to confirm the presence of a HAB, enabling adaptive sampling.

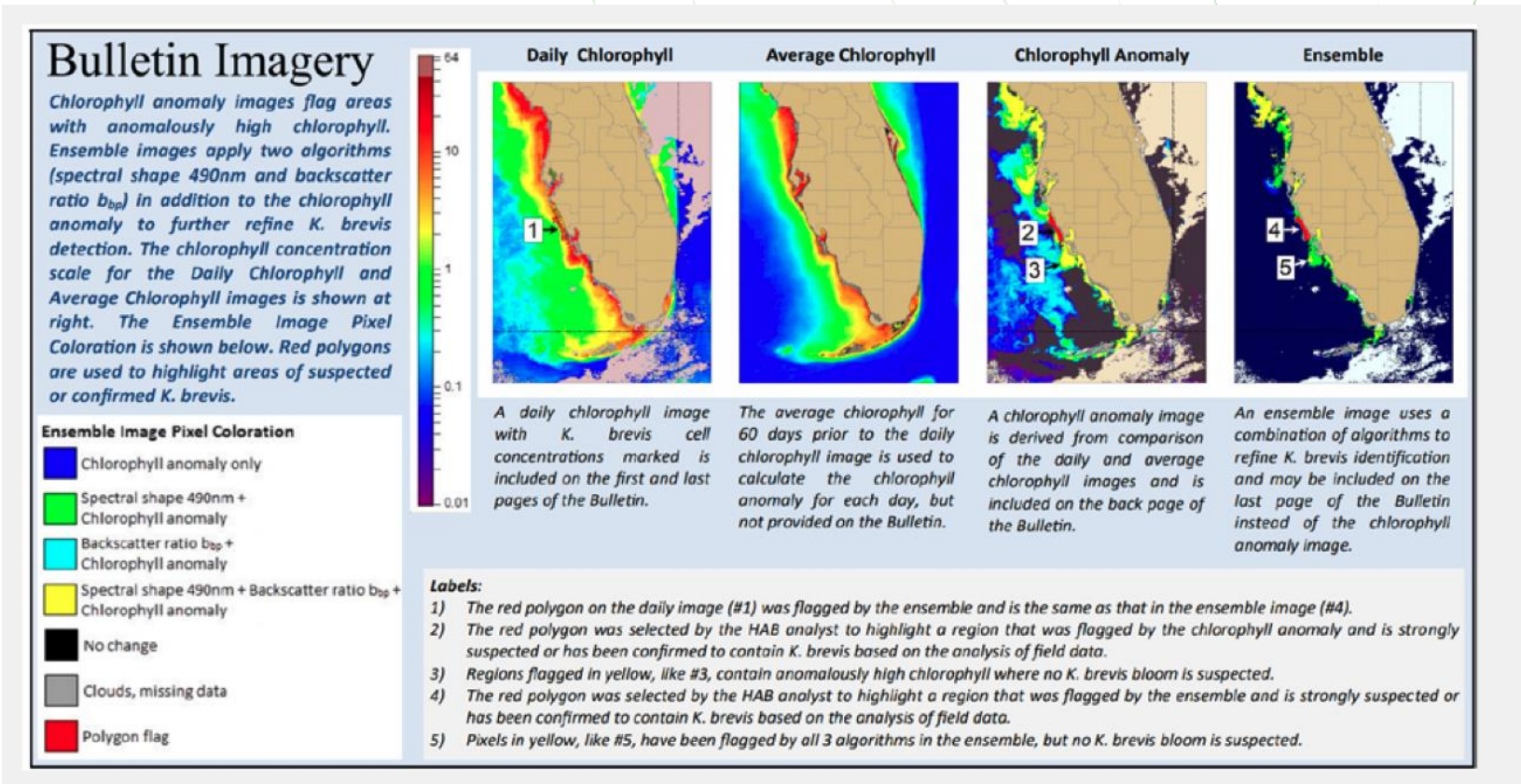

Image credits:
https://tidesandcurrents.noaa.gov/hab/hab_publication/habfs_bulletin_guide.pdf

Jupiter Notebook

Jupiter Notebook

- Go to → https://colab.research.google.com/
- Sign in with your google account
- Upload the file → ITINERIS_CopernicusTraining.ipynb

THANKS!

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