→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Satellite Oceanography: an integrated perspective

How to contribute/accelerate new skills/discoveries to help reveal and model unknow unknowns from all available multi-modal satellite ocean remote sensing measurements ?

Some Earth Observation Challenges:

- *Upper vertical motions i.e. 3D dynamics (e.g. including time evolution) of the upper ocean,* Mesoscale and submesoscale circulation as key to control the vertical ocean pump and its impact on energy transport and biogeochemical cycles

- *Climate modelling due to these vast and diverse scales of fluid motions:* in the upper ocean, horizontal scales as big as basins and as small as cm-mm (capillary-gravity surface waves) contribute non-negligibly to air-sea exchanges and climate, and dynamics of scales of less than 30 km, is characterized by departures from the Earth's rotation constraint, i.e ageostrophic motions and strong impact of wind/wave transient forcings.

Problem: 1/100(0) year events now occur yearly!

Ocean remote sensing: a privileged view

- Spatially detailed
  - Spatial resolution from meters to Kms
  - A synoptic picture that is 100 km - 10 000 km wide
- Regularly repeated
  - Revisit intervals between 30 min. and 35 days
  - Continuously repeated over years to decades
- Global coverage
  - Satellites see the parts where ships rarely go
  - Single-sensor consistency - no intercalibration uncertainties
- Measures parameters that cannot be observed in situ
  - Surface roughness at short length scales (2-50 cm)
  - Surface slope (a few cm over 100s of kilometres)

New Era - Nanosatellites - CubeSat

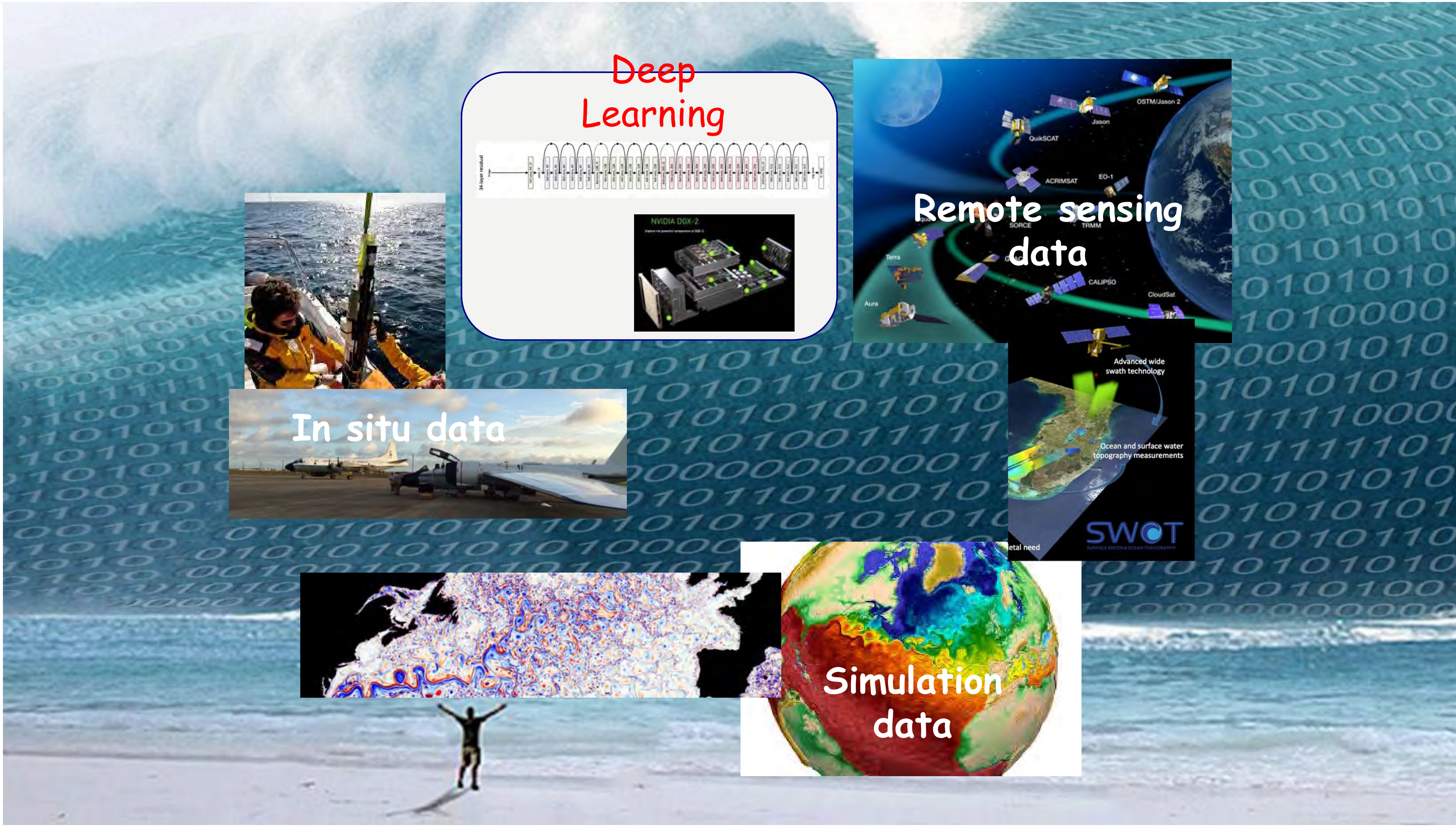
A **CubeSat** is a type of miniaturized satellite for space research that usually has a volume of exactly 10 cm cube, and mass of no more than 1.33 kilograms.

Big Data & AI/Data Science

Data

Big data infrastructure

DL/AI


Deep Learning
NVIDIA DGX-2
In situ data
Remote sensing data
OSTM/Jason 2
Jason
QuikSCAT
ACRIMSAT
EO-1
SORCE
TRMM
Terra
CALIPSO
CloudSat
Aura
Advanced wide swath technology
Ocean and surface water topography measurements
SWOT
Simulation data

Numerous questions and challenges

Some of the Living Planet Challenges to better assess the existing pressures on the marine environment (e.g. overfishing, pollution, habitat destruction, ...) potentially leading to increased risks to global food security, economic prosperity, ...

Evolution of coastal ocean systems including the interactions with land in response to natural and human-induced environmental perturbations

Mesoscale and submesoscale circulation and the role of the vertical ocean pump and its impact on energy transport and biogeochemical cycles

Response of the marine ecosystem and associated ecosystem services to natural and anthropogenic changes,

Physical and biogeochemical air/sea interaction processes on different spatio-temporal scales and their fundamental role in weather and climate

Sea level changes from global to coastal scales and from days (e.g. storm surges) to centuries (e.g. climate change)

Numerous questions and challenges

How can we map the distribution of marine plastic Debris?

Has the Agulhas current strengthened in the last 5 years?

Is the surface circulation of the Black Sea and in the Mediterranean Sea stable?

How is the Arctic Ocean changing ?

How is marine biodiversity changing, locally, regionally, globally ?

What is the extent of ocean acidification ?

Are western boundary currents changing, the Gulf Stream ?

How can ship routing be optimised ?

Why and where is regional sea level changing?

How are our coastal regions changing?

How can we map estuary systems from space?

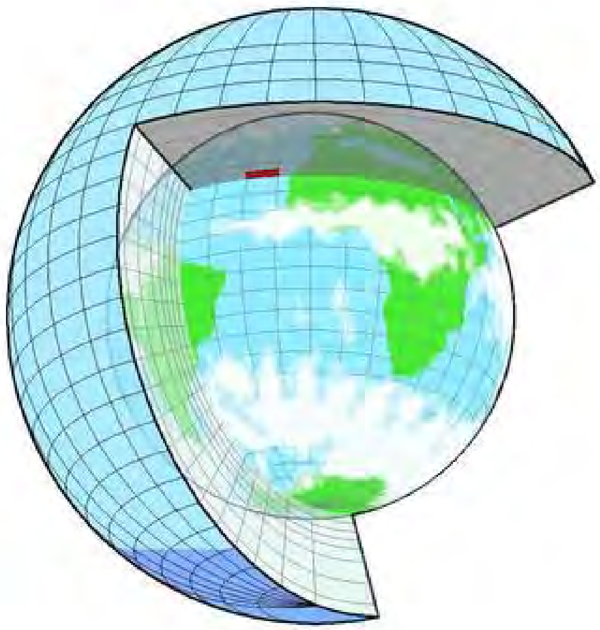
- … most observations are not yet sufficiently explored and used

Synergy between high and medium resolution observations to reveal mean states and trends, near-surface ocean-atmosphere dynamics, local and non-local interactions, convergence/divergence surface fronts and numerous roughness contrasts

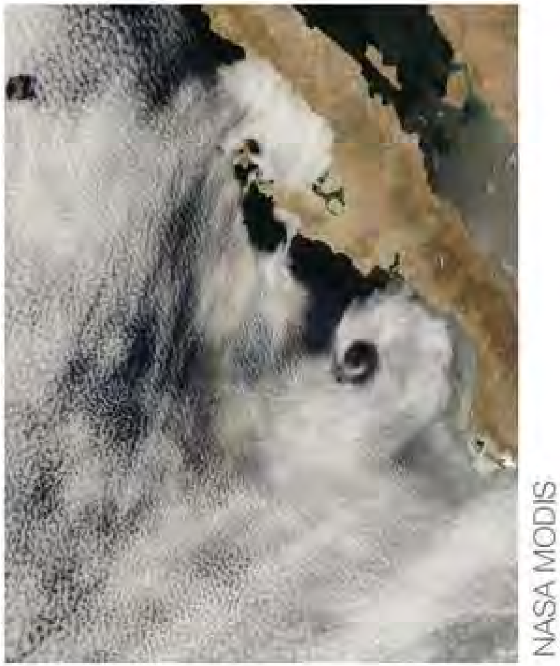
Atmospheric and Oceanic observations generally produce high quality data, but it is often too sparse (many gaps where information is missing, and/or often too local in both space and time)

How can we use observed data in combination with the physical knowledge of stochastic processes in nonlinear dynamical systems to estimate and model those effects on the variability of computationally resolvable scales of motion that are caused by the small, rapid, unresolvable scales of fluid motion that upscaling in data assimilation leaves out?

Climate models are too coarse to resolve clouds



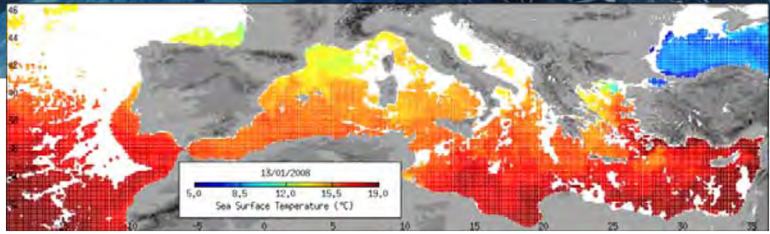
Global model:
~100 km resolution



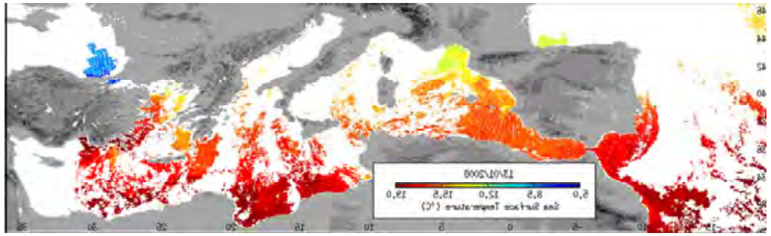
Cloud scales: ~10-100 m

SST

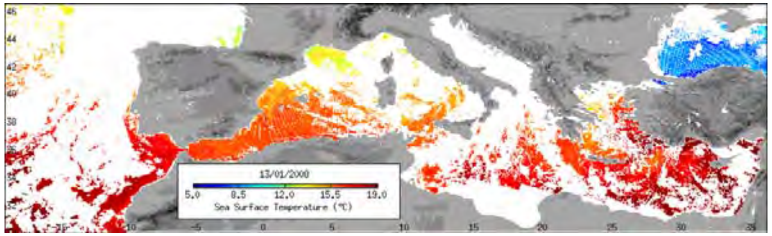
1 jour



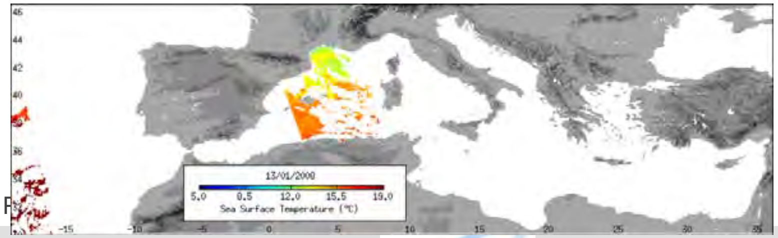
MSG/SEVIRI (10km, 3 heures)



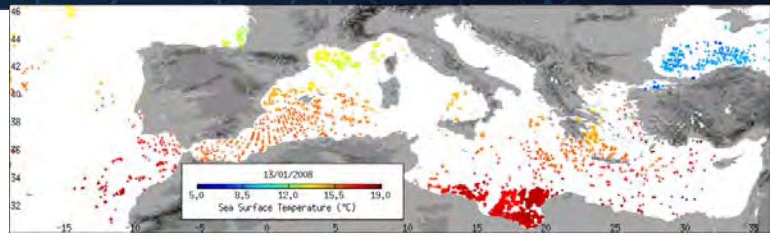
SAF O&SI NAR pour AVHRR17 (2km, 2 passes/jour)



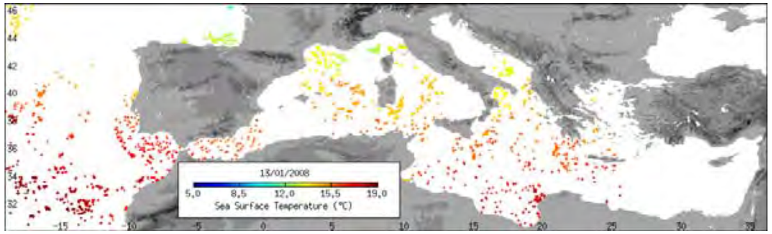
SAF O&SI NAR18 pour AVHRR17 (2km, 2 passes/jour)



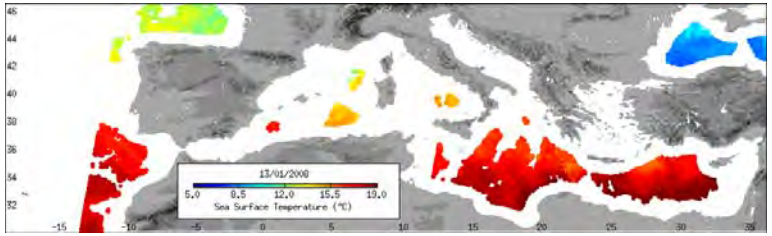
ATS



Avhrr 18



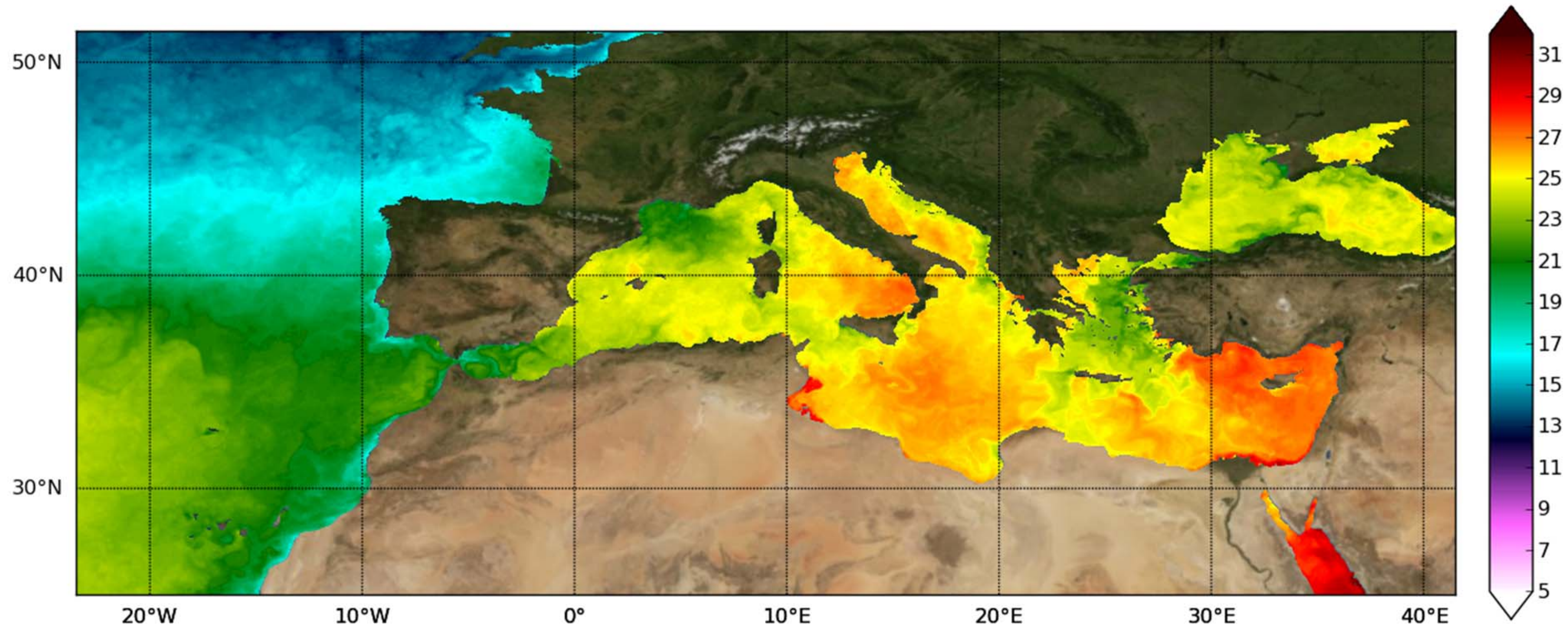
Avhrr 17



ENVISAT/AATSR (1 km, 14-15 orbites/jour)

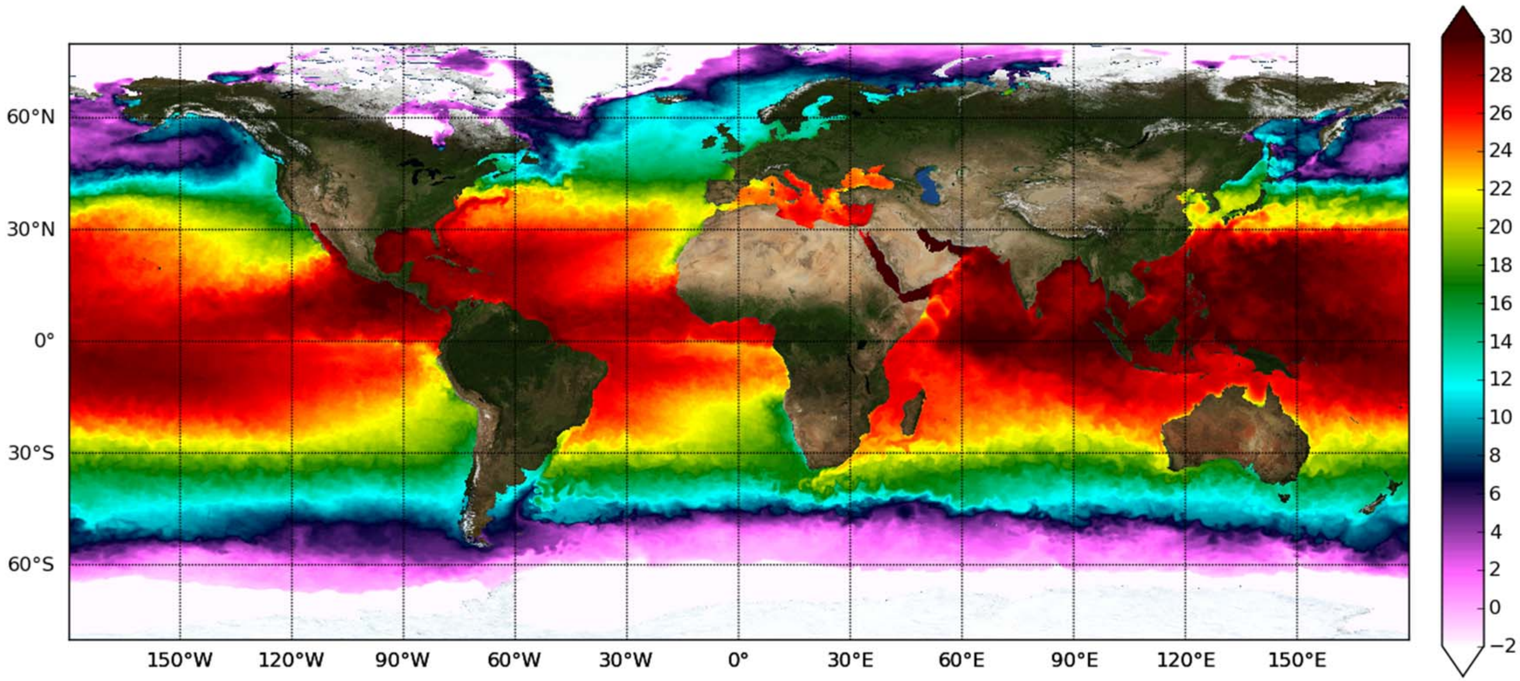
⇒ Multi-satellite product

Sea surface temperature



projet ESA Medspiration

Global SST


60°N
30°N
0°
30°S
60°S
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
30
28
26
24
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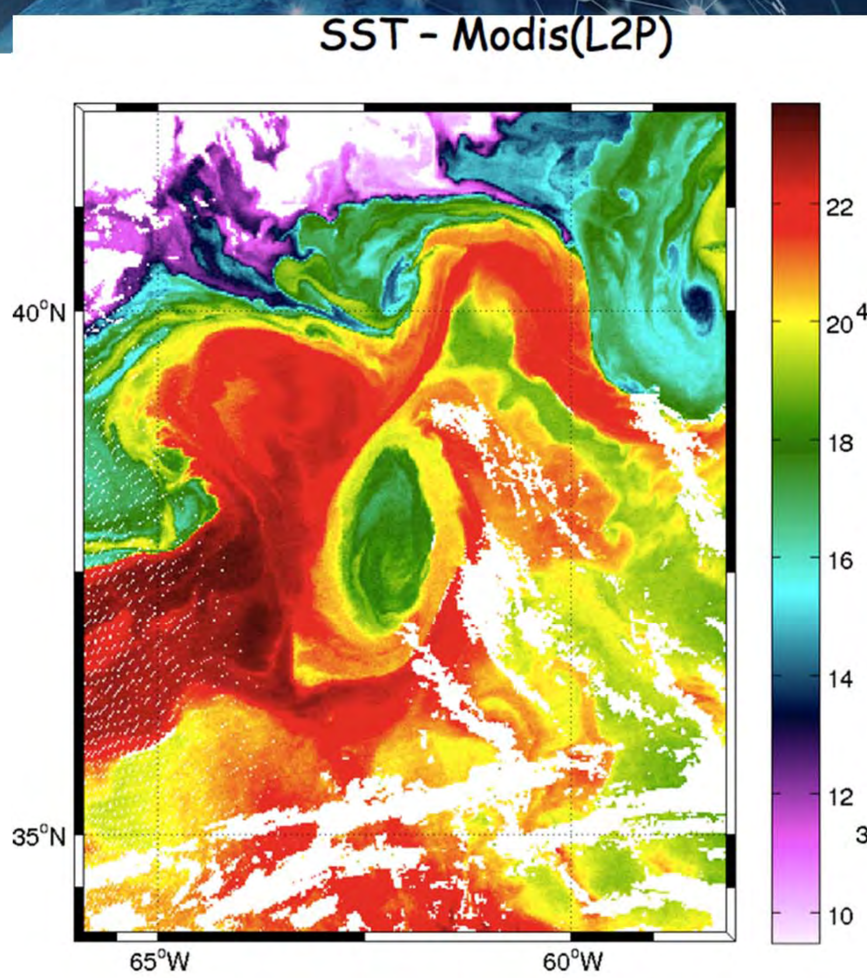
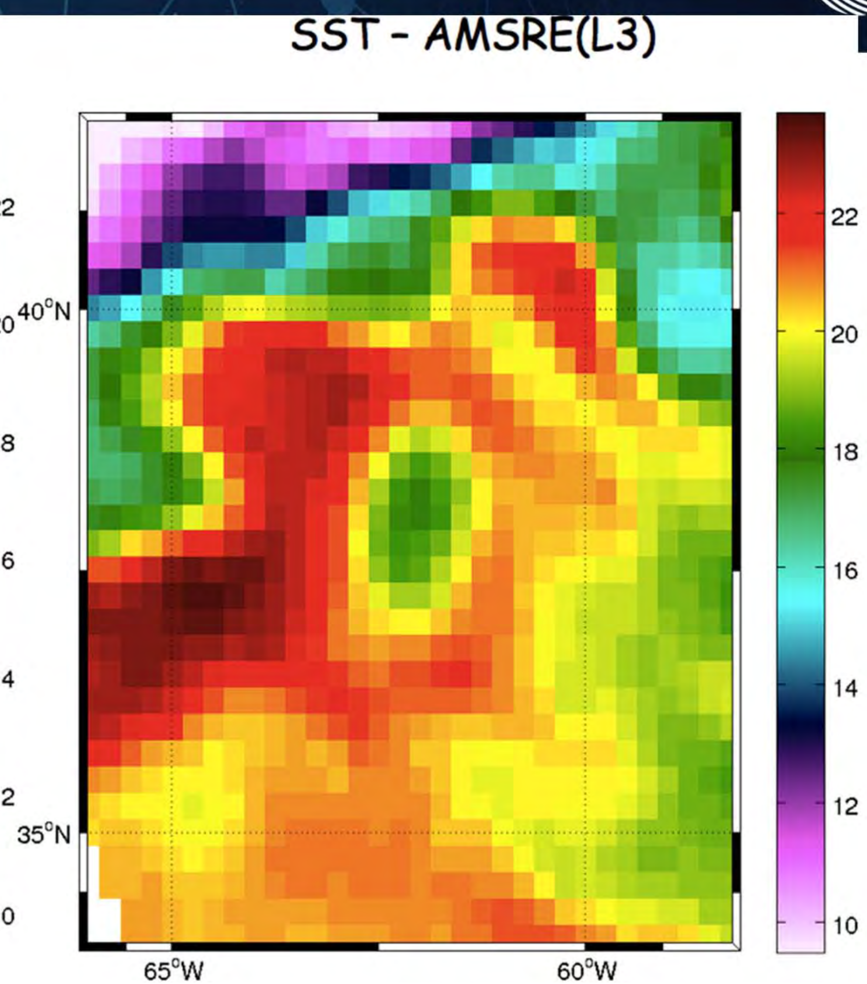
14
12
10
8
6
4
2
0
−2

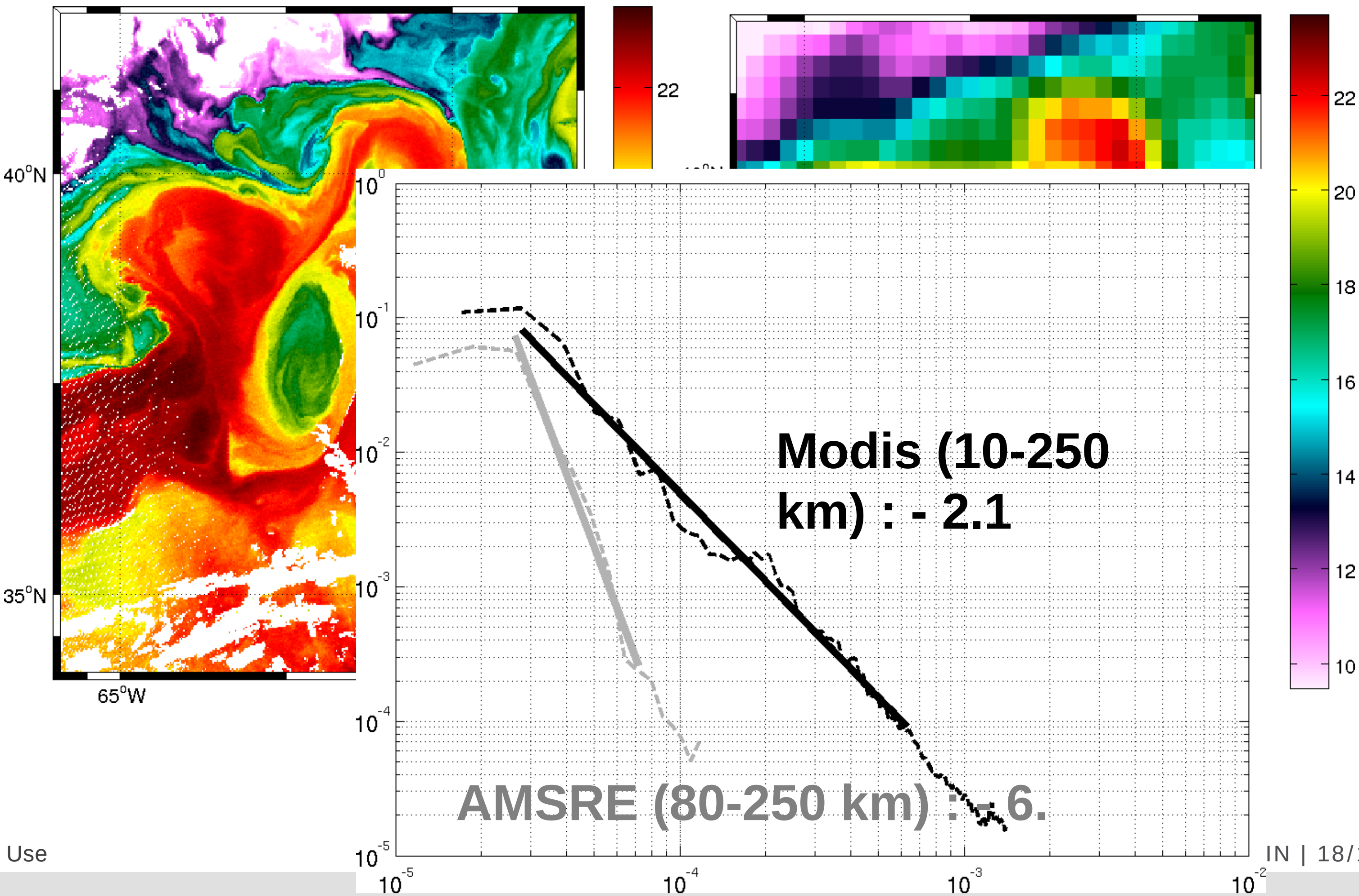
Small scales / mesoscale

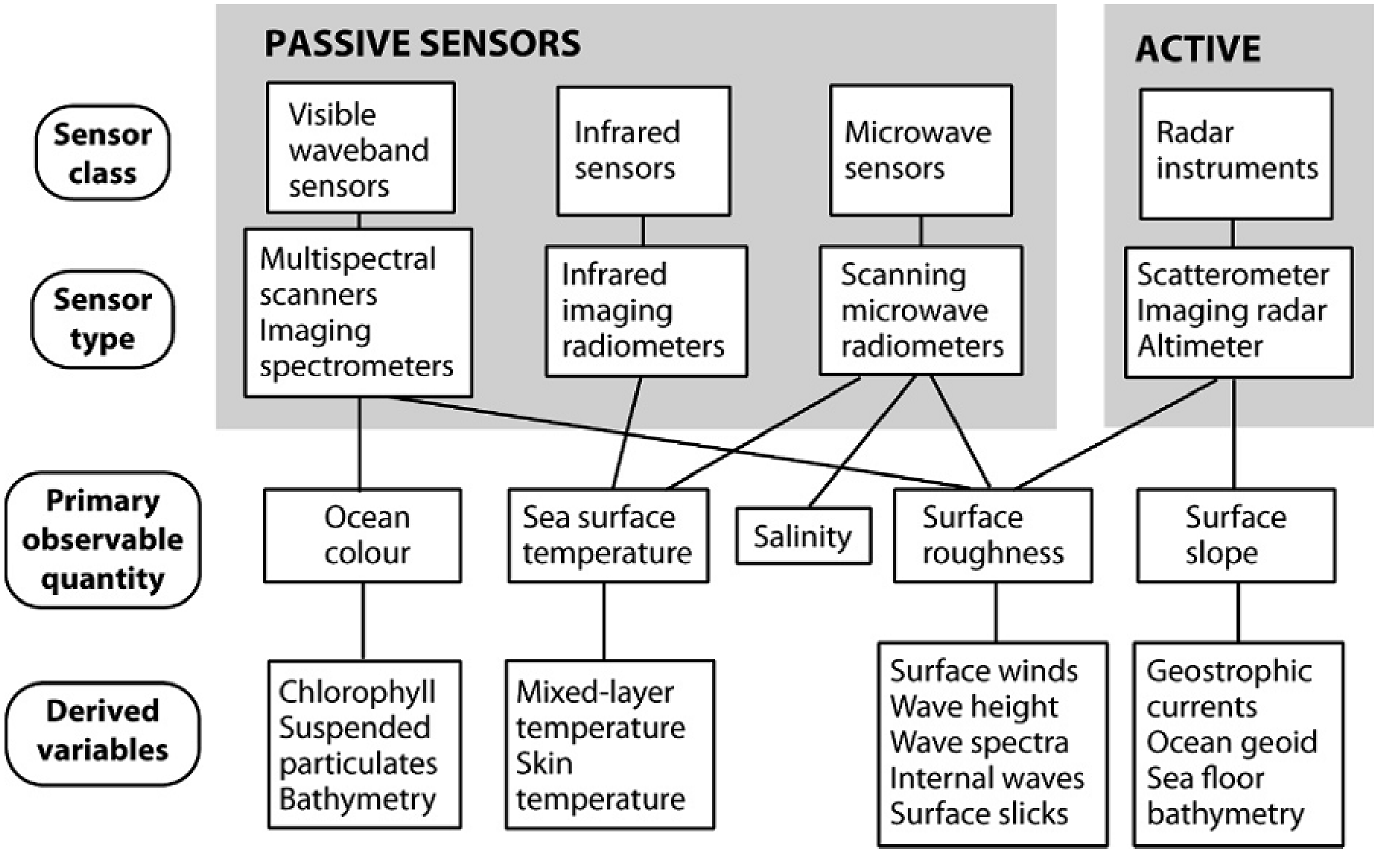




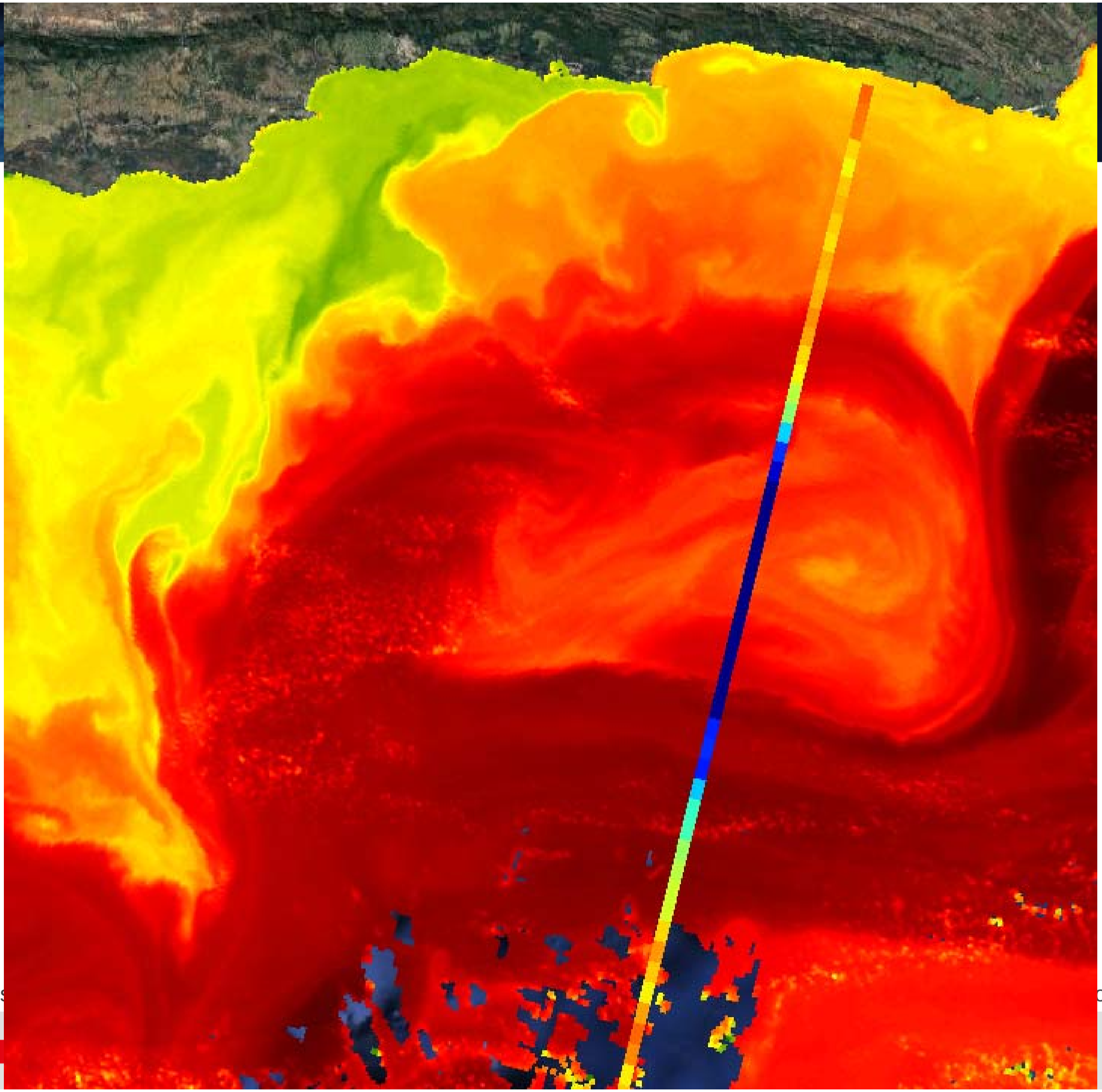
Characterizing the submesoscale - Spectral approach

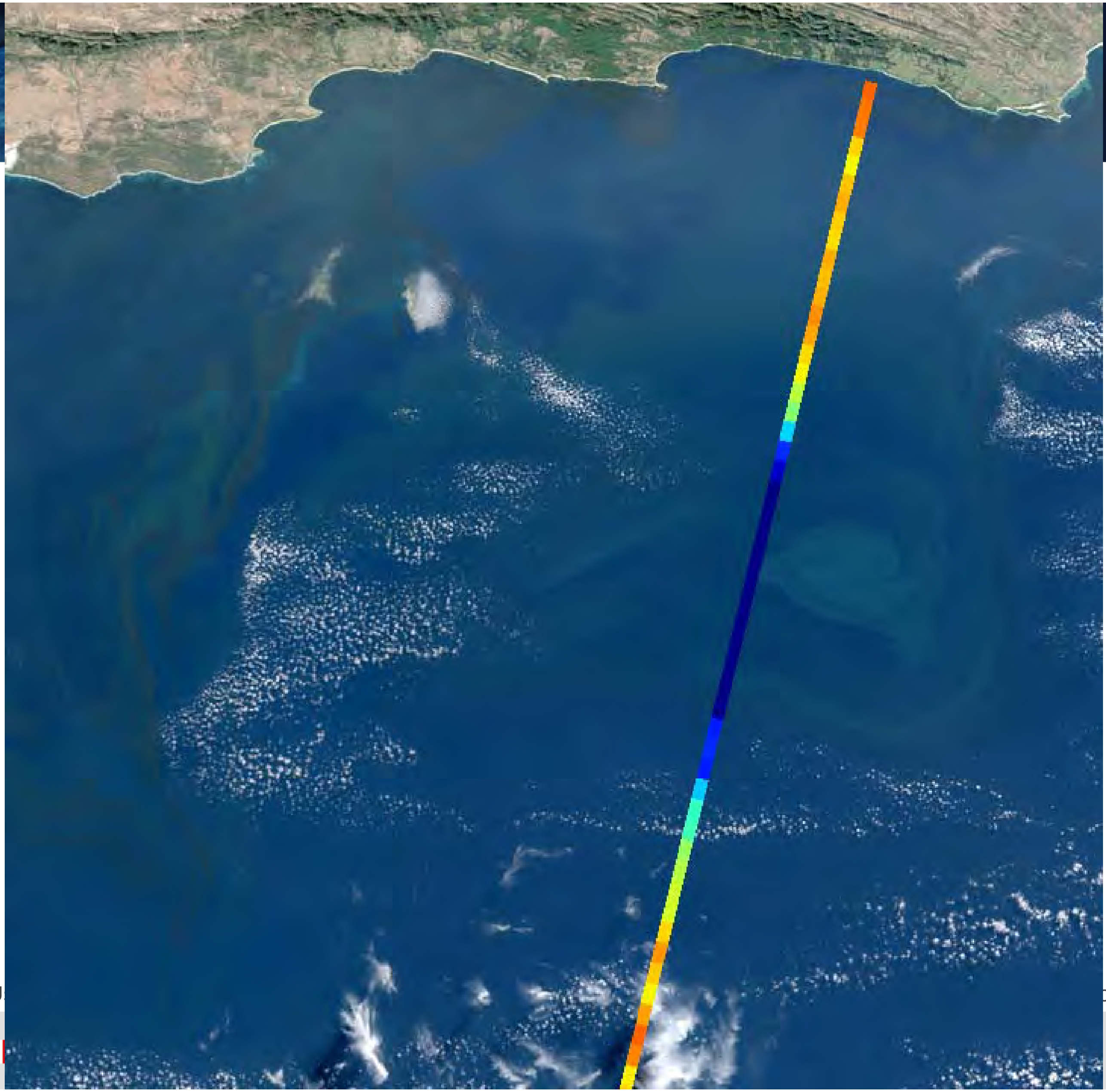
SST Modis(L2P) SST AMSRE(L3)





Schematic illustrating the different remote-sensing methods and classes of sensors used in satellite oceanography, along with their applications (from Robinson, 2004).

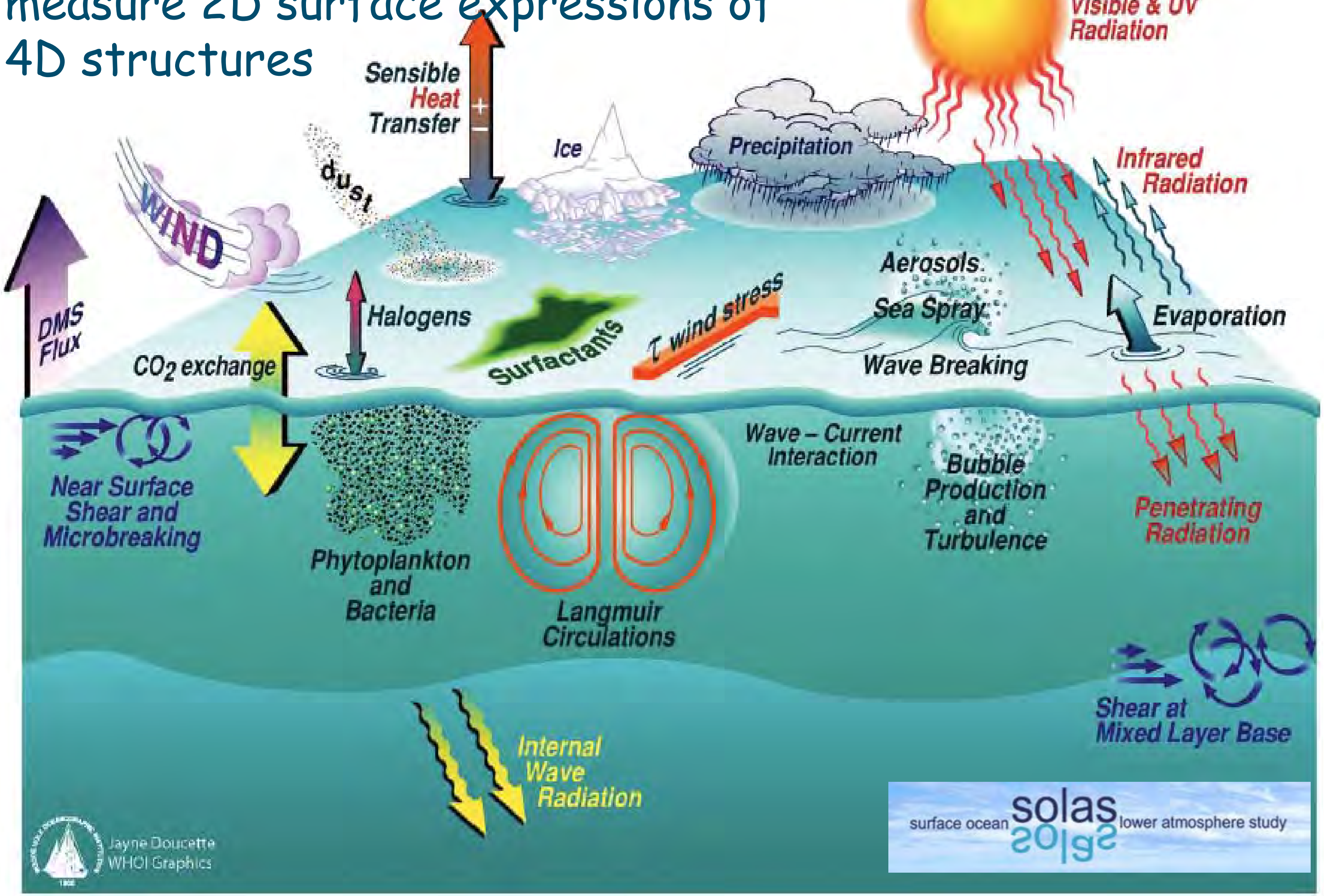




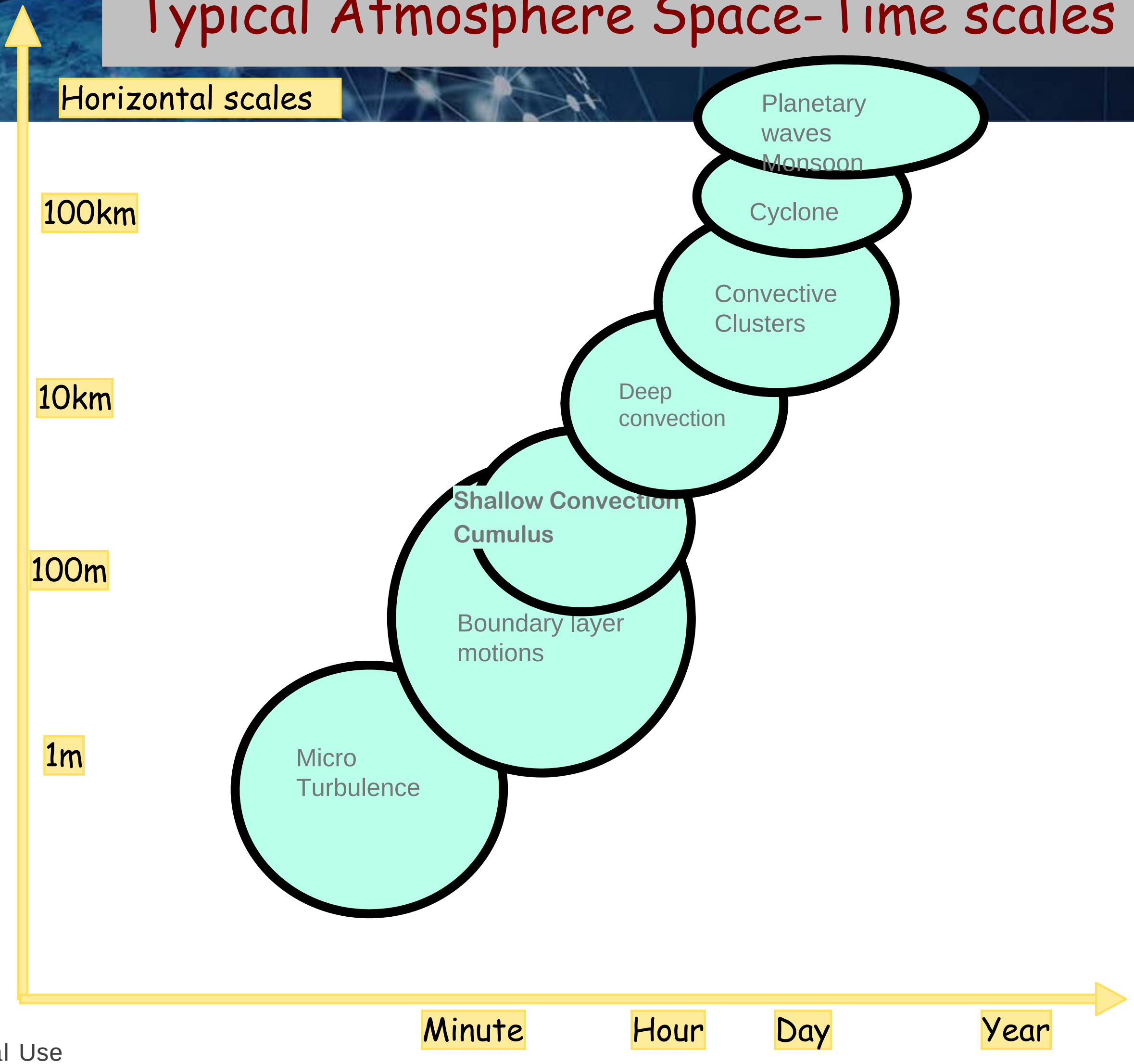
Main message (to be repeated) …

- Today ideal instrument … (wide-swath, high-resolution, topography, roughness, Doppler, emissivity, reflectance, …) = the combined use of observations, including in situ measurements
- Very (too) large number of spatio-temporal scales under local and non-local interactions
- Improved technologies (instruments, resolution, computer capabilities, storage, dissemination) all contribute to improved combined analysis
- Theoretical frameworks and numerical simulations can be used to assess the causes and contexts of the different observations (including sensor physics, observability conditions and instrument capabilities), to refine dynamical/statistical gap filling methods
- New challenges, new altimeter instruments (SARAL, Sentinel-3, SWOT, …, CubeSat opportunities), possible new high-resolution microwave instruments (10-20 km), Doppler measurements to infer sea surface currents (SAR and/or RAR-SKIM or DopplerScat), and combined roughness contrasts as local quantitative proxies to trace strong surface gradient areas

Satellite instruments generally measure 2D surface expressions of 4D structures



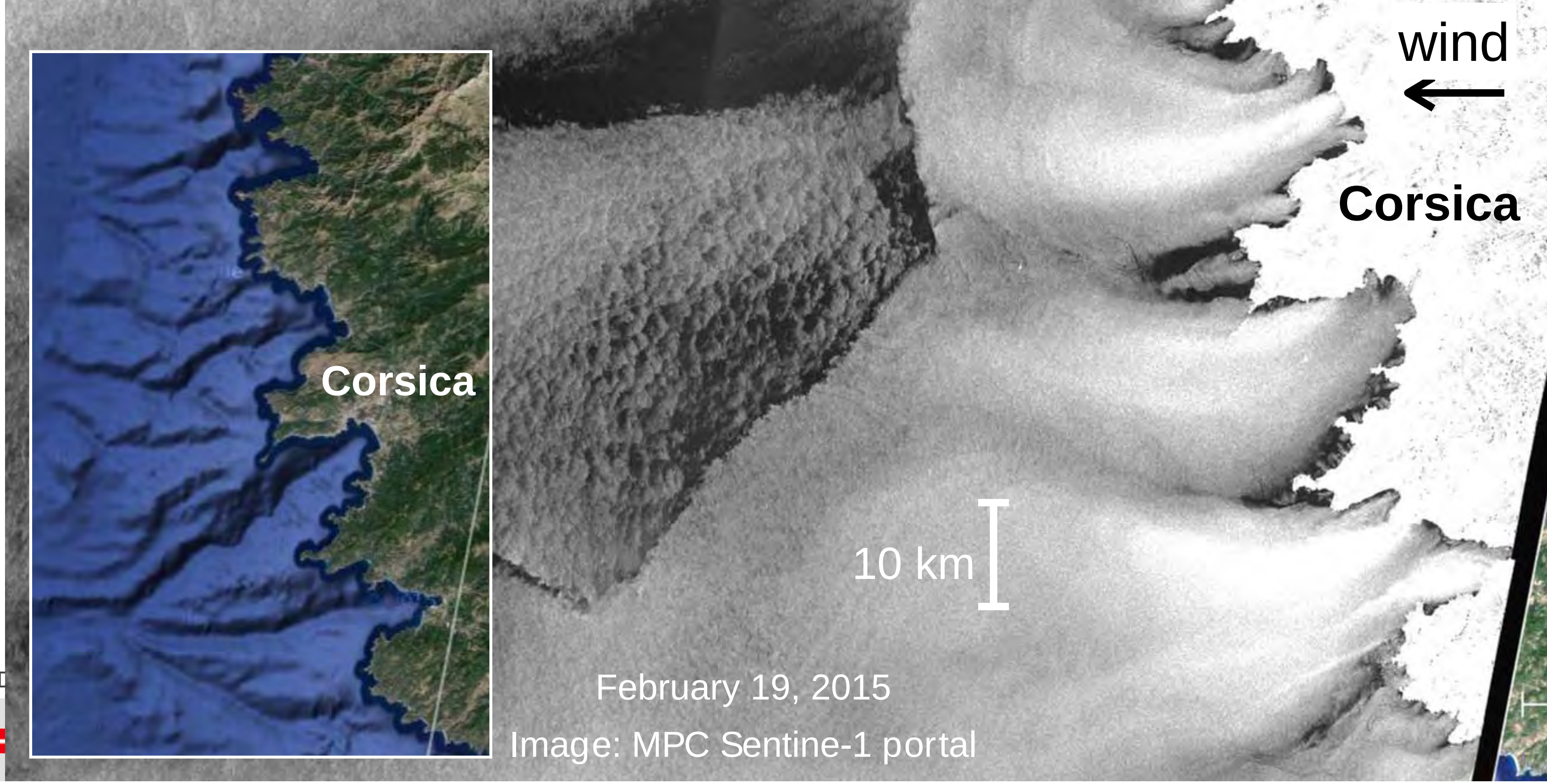
Typical Atmosphere Space-Time scales



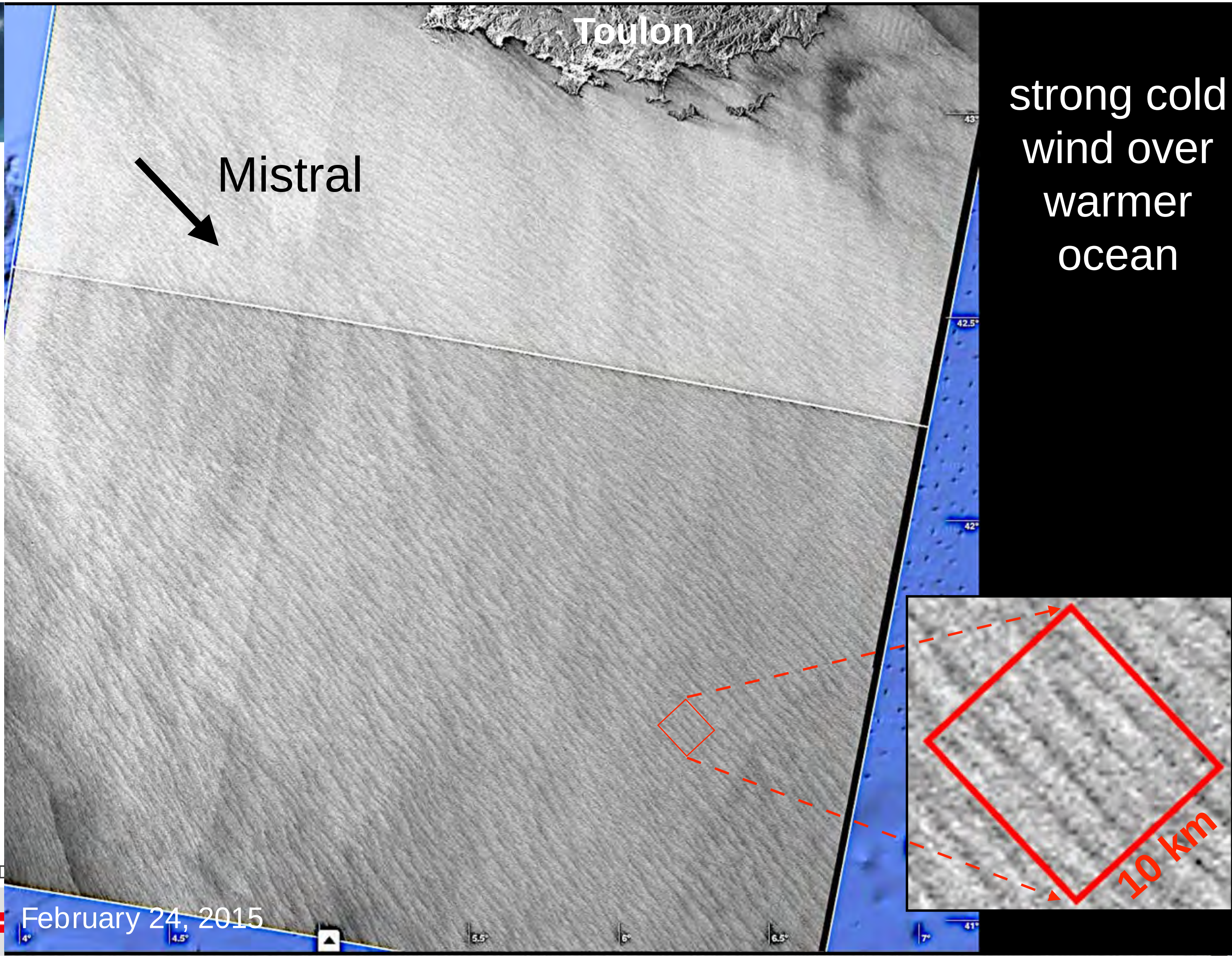
Satellite synthetic aperture radar (SAR)

light = more short waves
- ~ stronger wind forcing
- ~ air-sea heat, KE, momentum, gas exchange

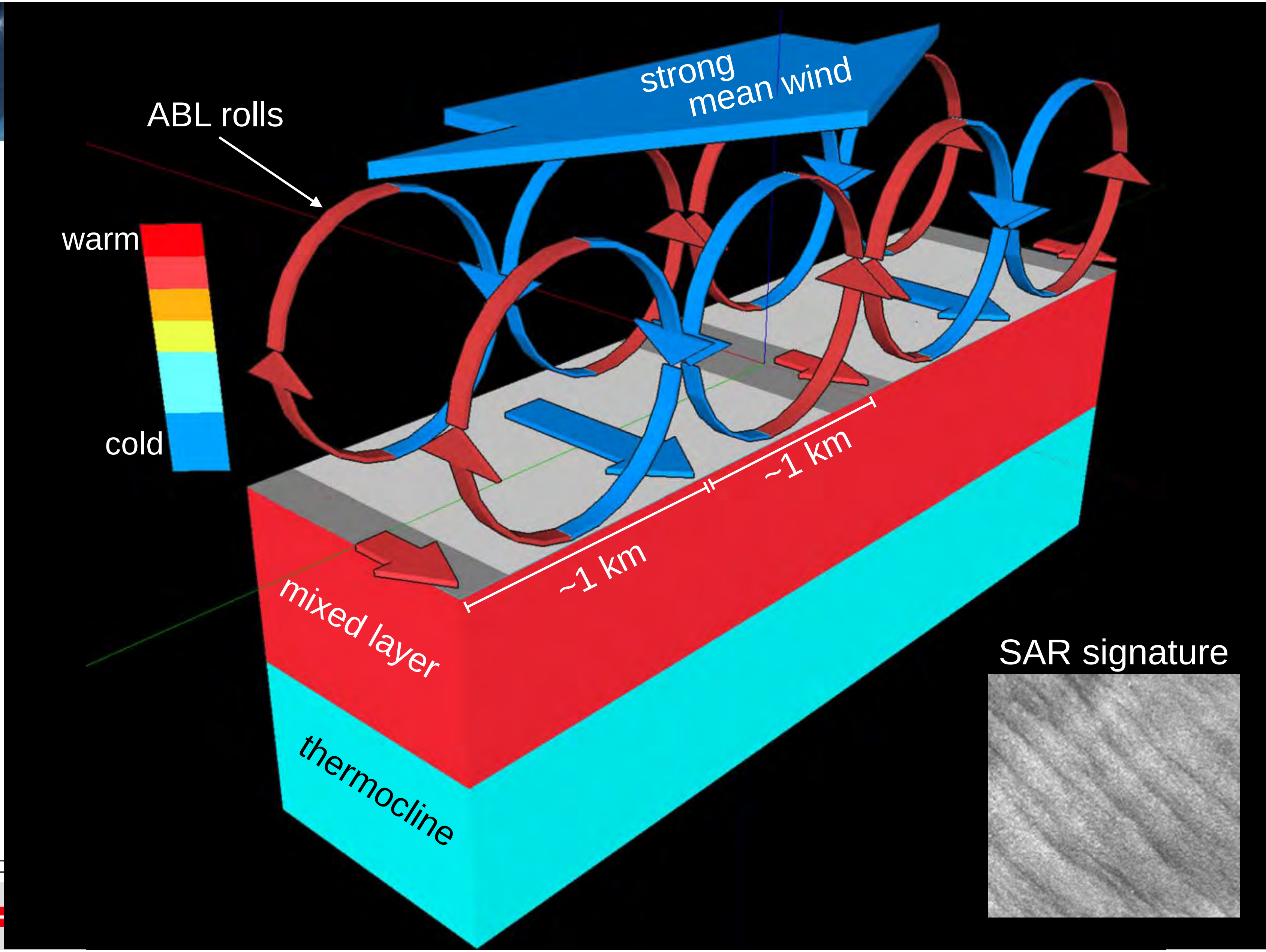
dark = weak wind or surfactant

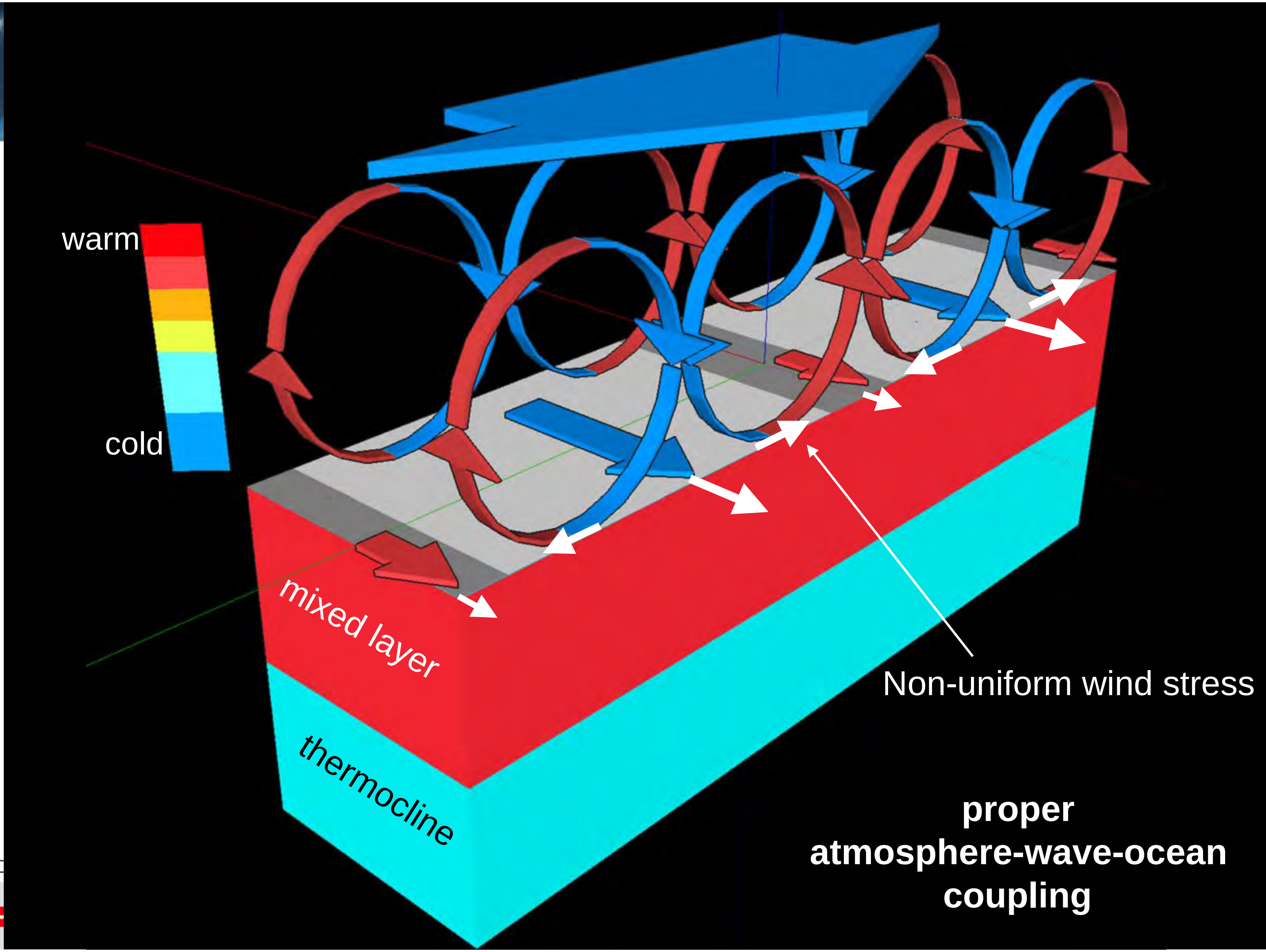


February 19, 2015
Image: MPC Sentine-1 portal



strong cold wind over warmer ocean


strong
mean wind
ABL rolls
warm
cold
~1 km
~1 km
mixed layer
thermocline
SAR signature


warm
cold
mixed layer
thermocline
Non-uniform wind stress
proper
atmosphere-wave-ocean
coupling

We can illustrate this partitioning using the expression for the total momentum flux at the

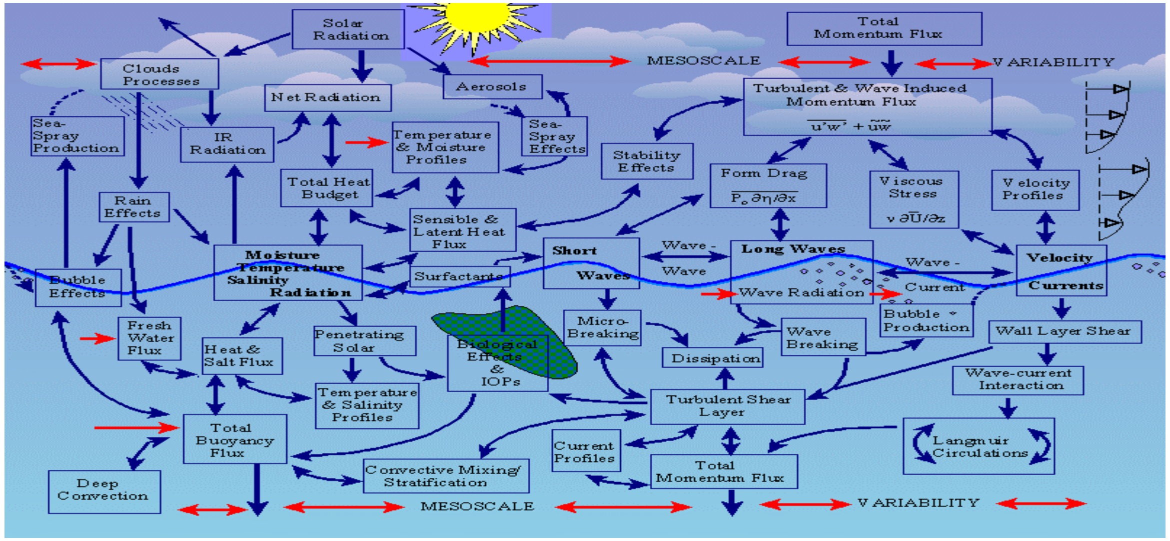


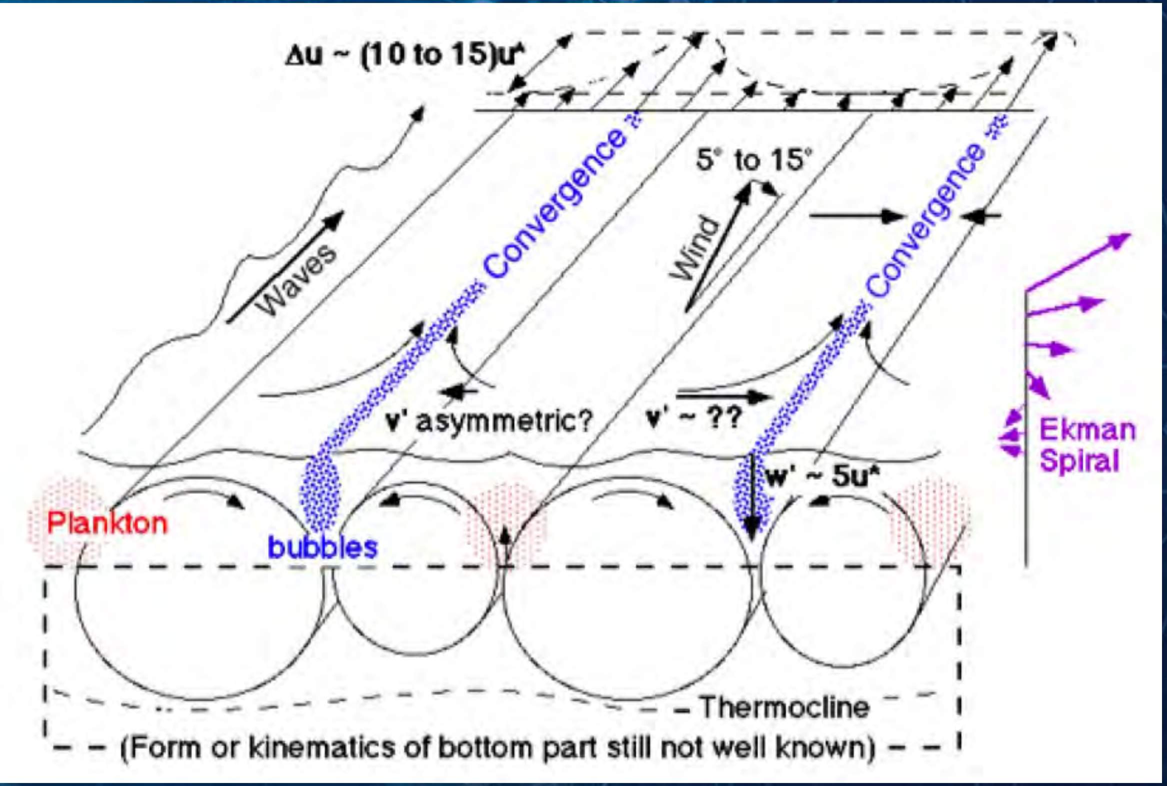
Figure 2. Some of the processes that govern the transfer of heat, mass, and momentum within the coupled boundary layers.

ocean surface (i.e., where the turbulent component becomes negligible) derived by Deardorff (1967). Deardorff (1967) derived this expression by evaluating the integrated horizontal momentum equation at the ocean surface to obtain

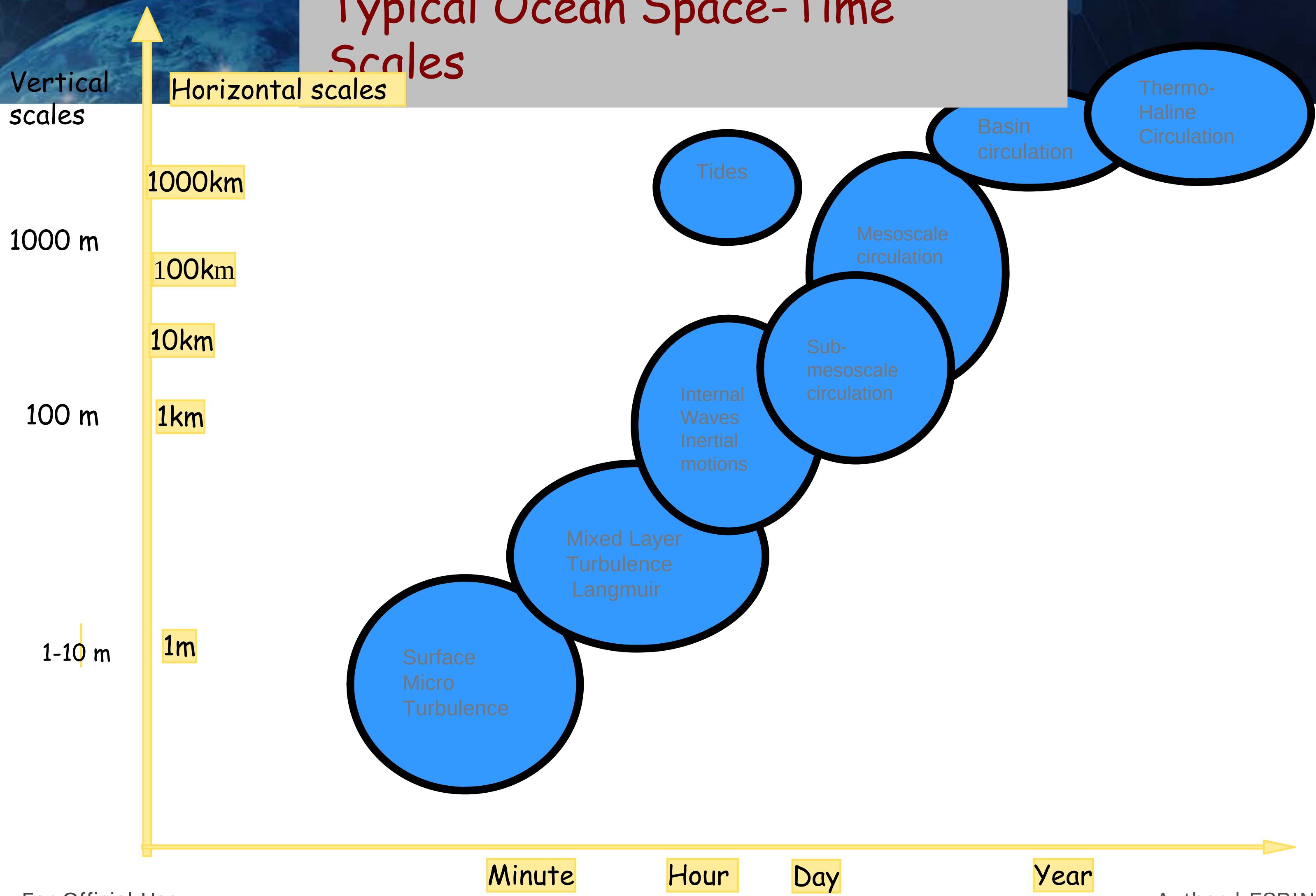
$$\tau_a = \rho_a \left[-\overline{\tilde{u}\tilde{w}} + \nu \frac{\partial U}{\partial z} \right]_\eta \approx \overline{p_\eta \frac{\partial \eta}{\partial x}} + \rho_a \nu \frac{\partial U}{\partial z} \Big|_\eta = \tau_{aw} + \tau_{ao} \qquad \textbf{(15)}$$

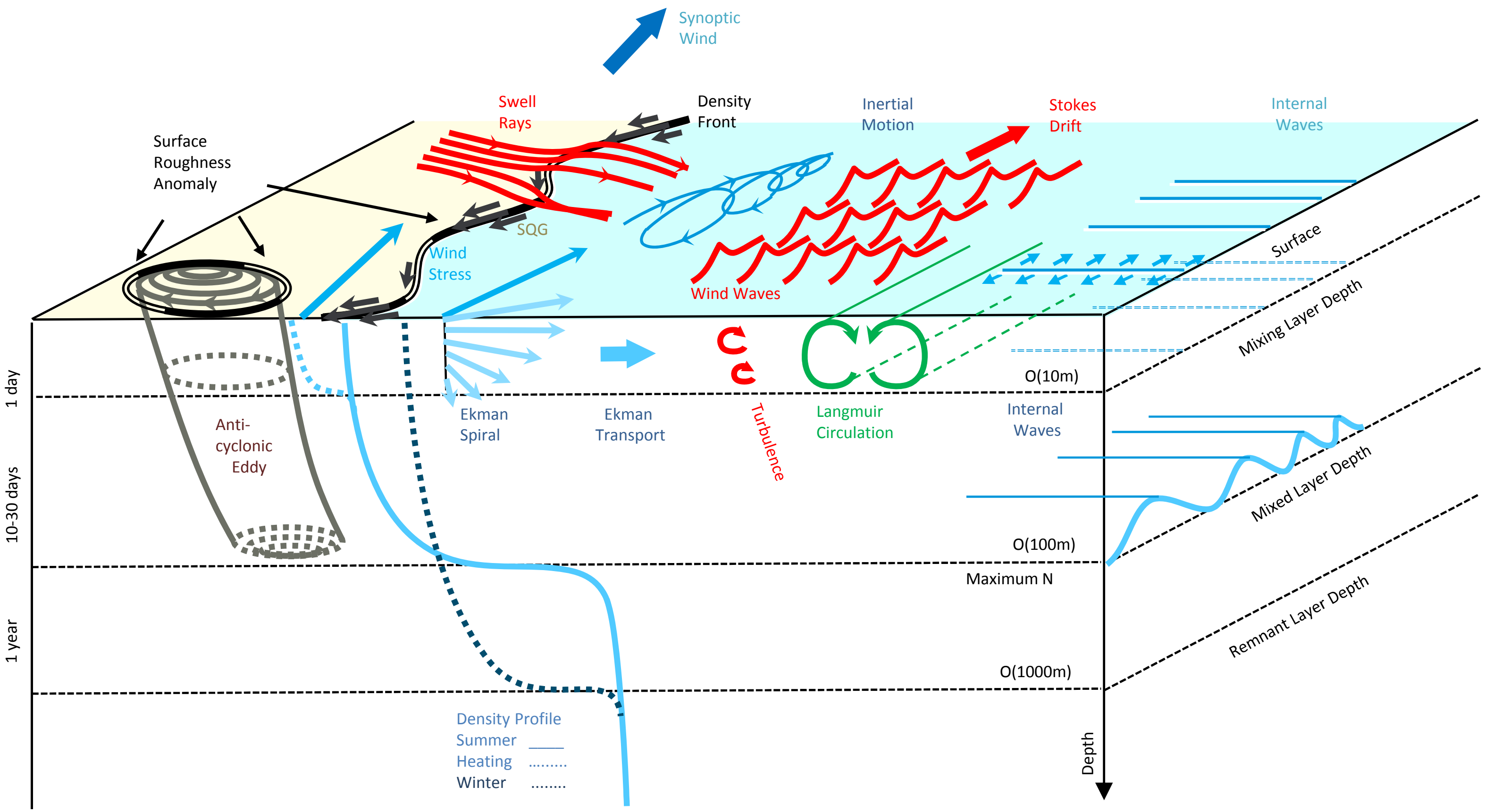
where η is the wave height, p_η is the surface pressure, and the small component of the viscous stress associated with inclinations of the interface has been neglected. The stresses given on the RHS on based on the nomenclature given in Lionello et al. (1996, 1998), where τ_{aw} represents the momentum transfer from the wind to the waves (i.e., the wave-induced flux), while τ_{ao} represents the direct momentum transfer from the wind to the ocean (i.e., **viscous stress**). This

Schematic illustration of the Langmuir circulation (first described by Langmuir, 1938). The separation scale of the convergence zones are typically 10-100 m

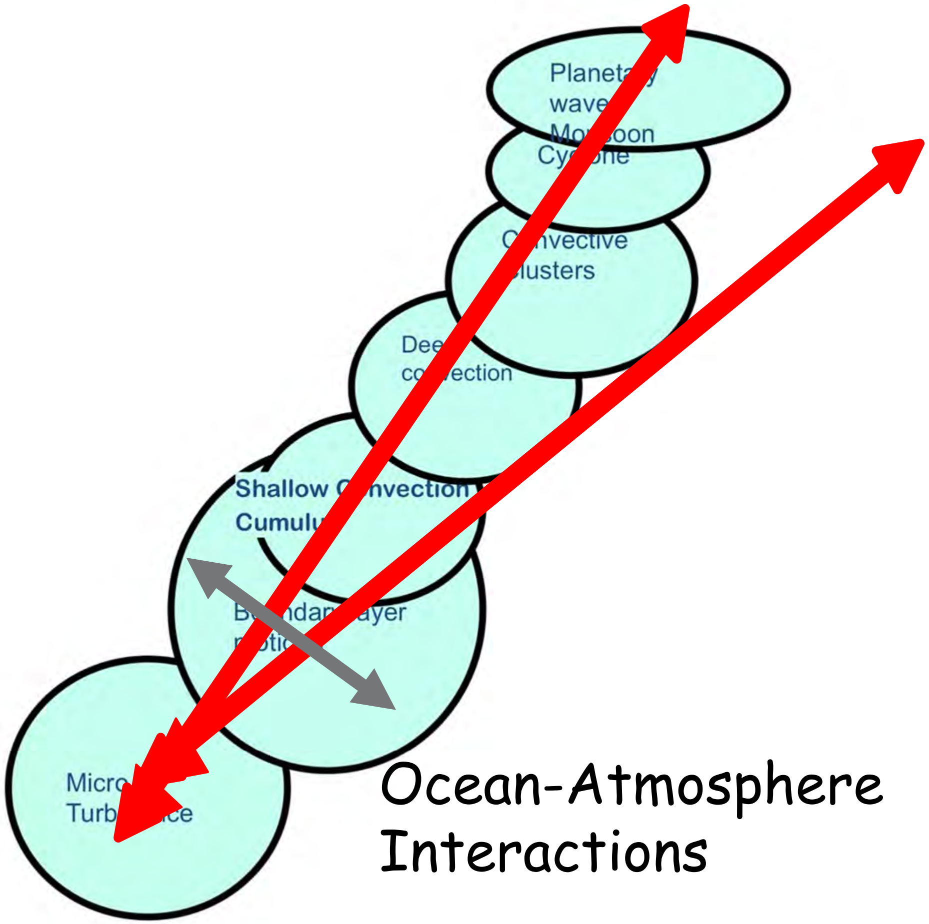


Typical Ocean Space-Time Scales





Synoptic Wind
Swell Rays
Density Front
Inertial Motion
Stokes Drift
Internal Waves
Surface Roughness Anomaly
SQG
Wind Stress
Wind Waves
Surface
Mixing Layer Depth
1 day
10-30 days
1 year
Anti-cyclonic Eddy
Ekman Spiral
Ekman Transport
Turbulence
Langmuir Circulation
Internal Waves
O(10m)
Mixed Layer Depth
O(100m)
Maximum N
Remnant Layer Depth
O(1000m)
Density Profile
Summer
Heating
Winter
Depth



Ocean-Atmosphere
Interactions

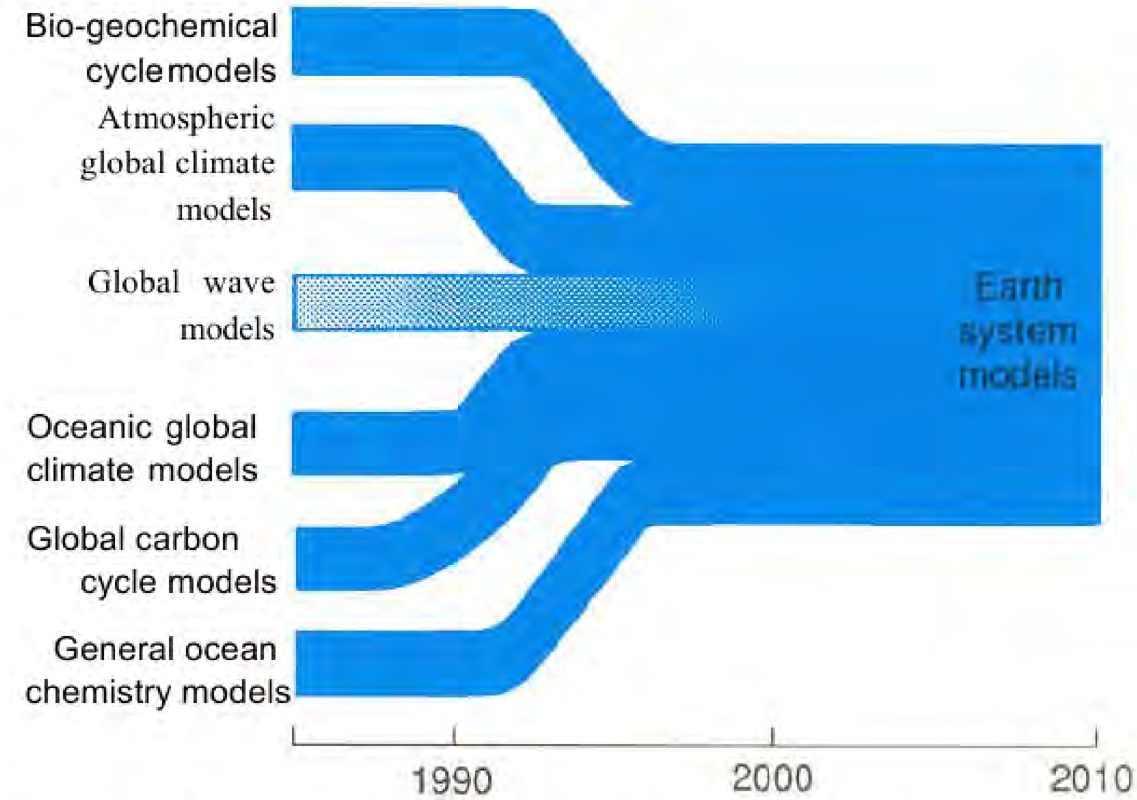
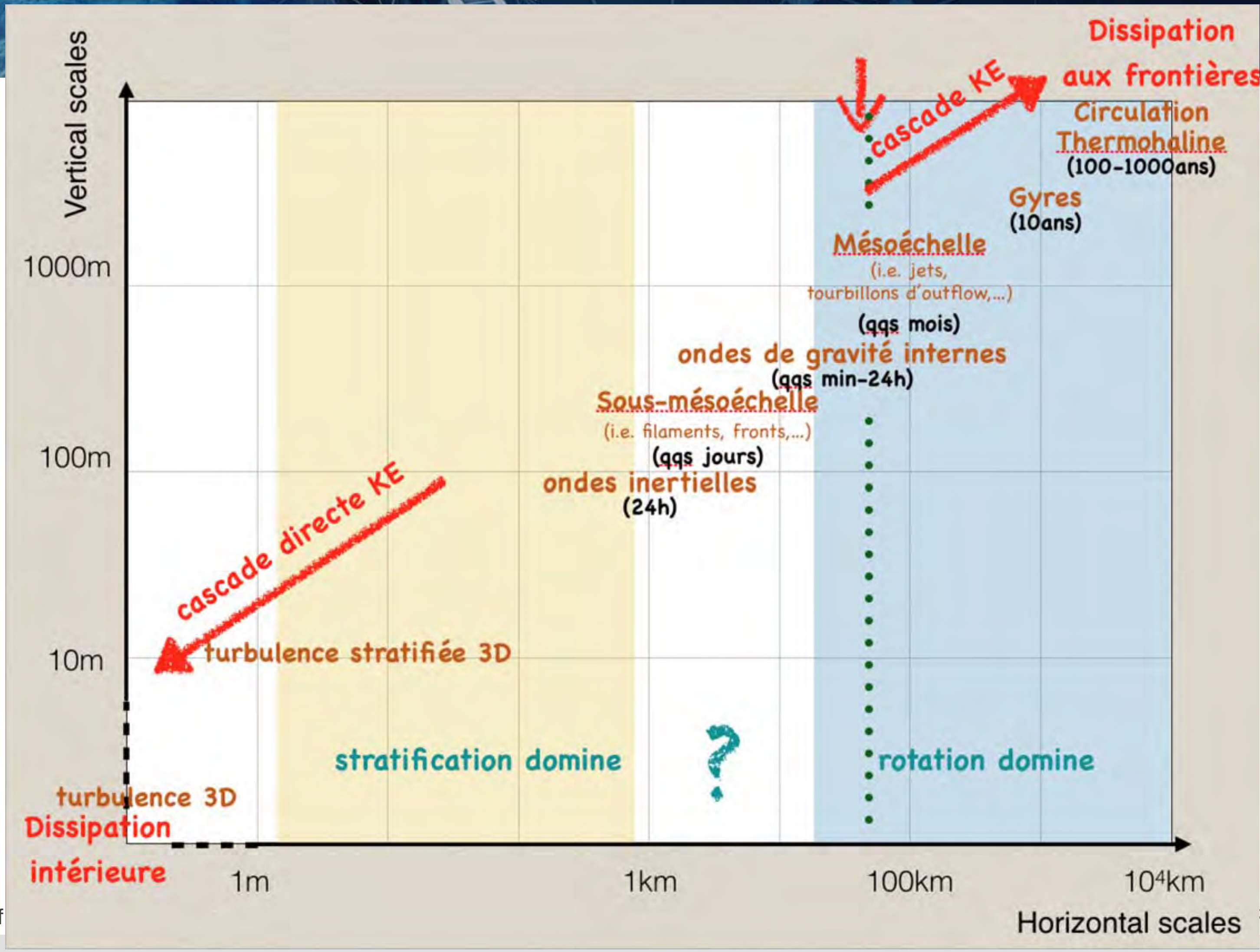


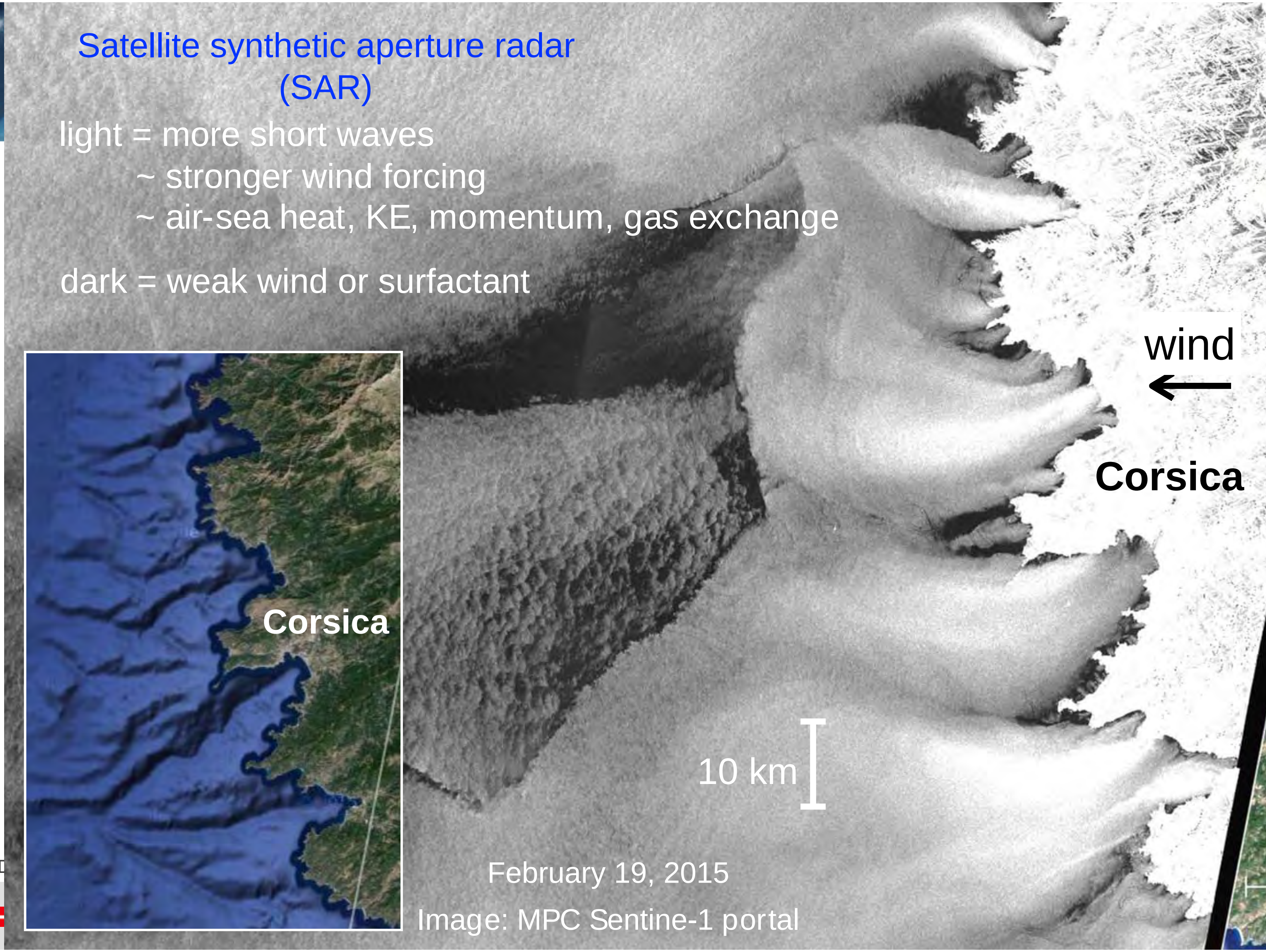
Figure 1. Future role of wave models as an essential coupling component for ocean-atmosphere-carbon-cycle modets developed in the context ot the World Climate and Global Change programs.


Vertical scales
1000m
100m
10m
1m
1km
100km
10^4km
Horizontal scales
Dissipation aux frontières
cascade KE
Circulation Thermohaline
(100-1000ans)
Gyres
(10ans)
Mésoéchelle
(i.e. jets, tourbillons d'outflow,...)
(qqs mois)
ondes de gravité internes
(qqs min-24h)
Sous-mésoéchelle
(i.e. filaments, fronts,...)
(qqs jours)
ondes inertielles
(24h)
cascade directe KE
turbulence stratifiée 3D
stratification domine
?
rotation domine
turbulence 3D
Dissipation intérieure

Satellite synthetic aperture radar (SAR)

light = more short waves
~ stronger wind forcing
~ air-sea heat, KE, momentum, gas exchange

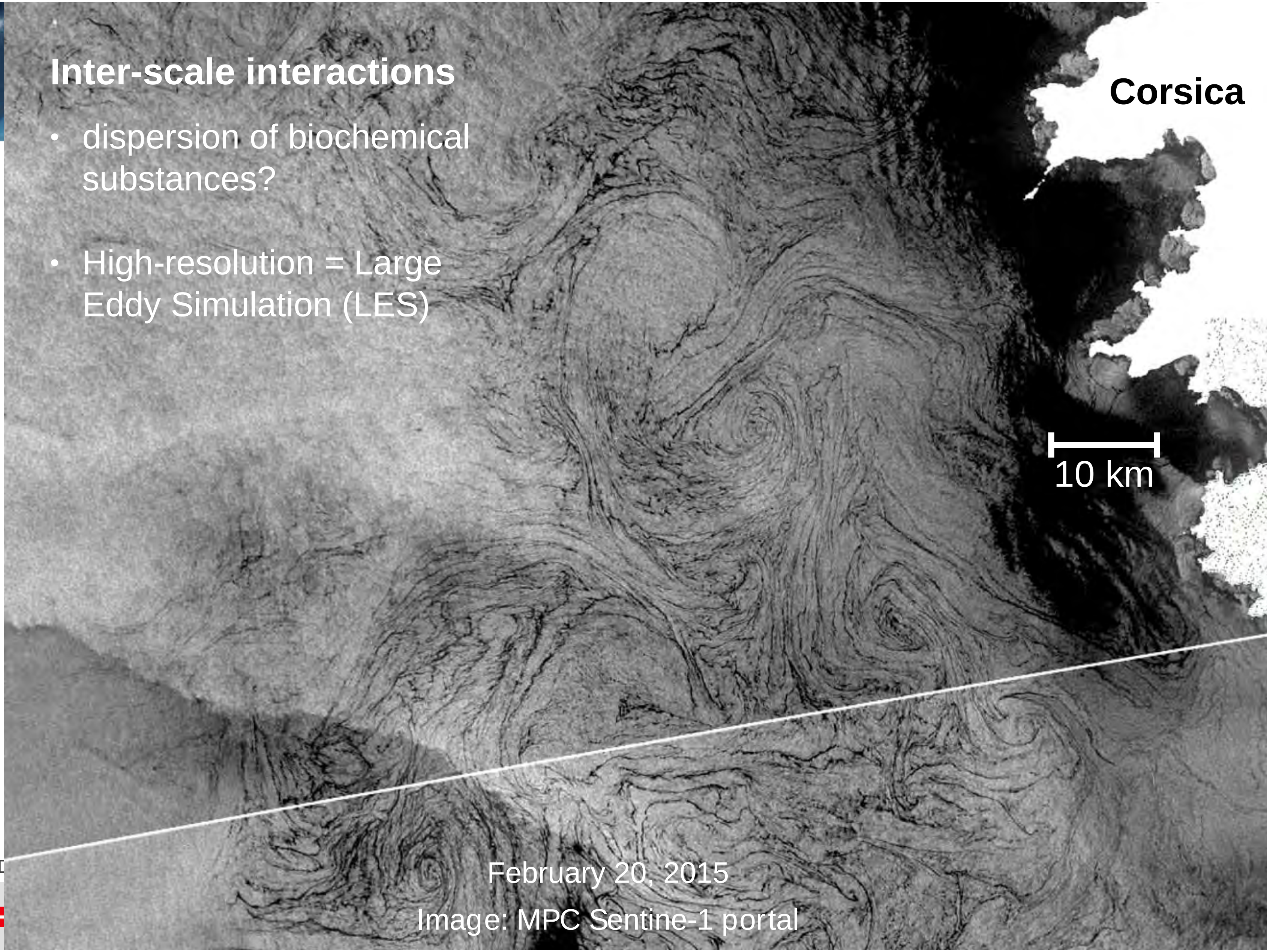
dark = weak wind or surfactant



February 19, 2015
Image: MPC Sentine-1 portal

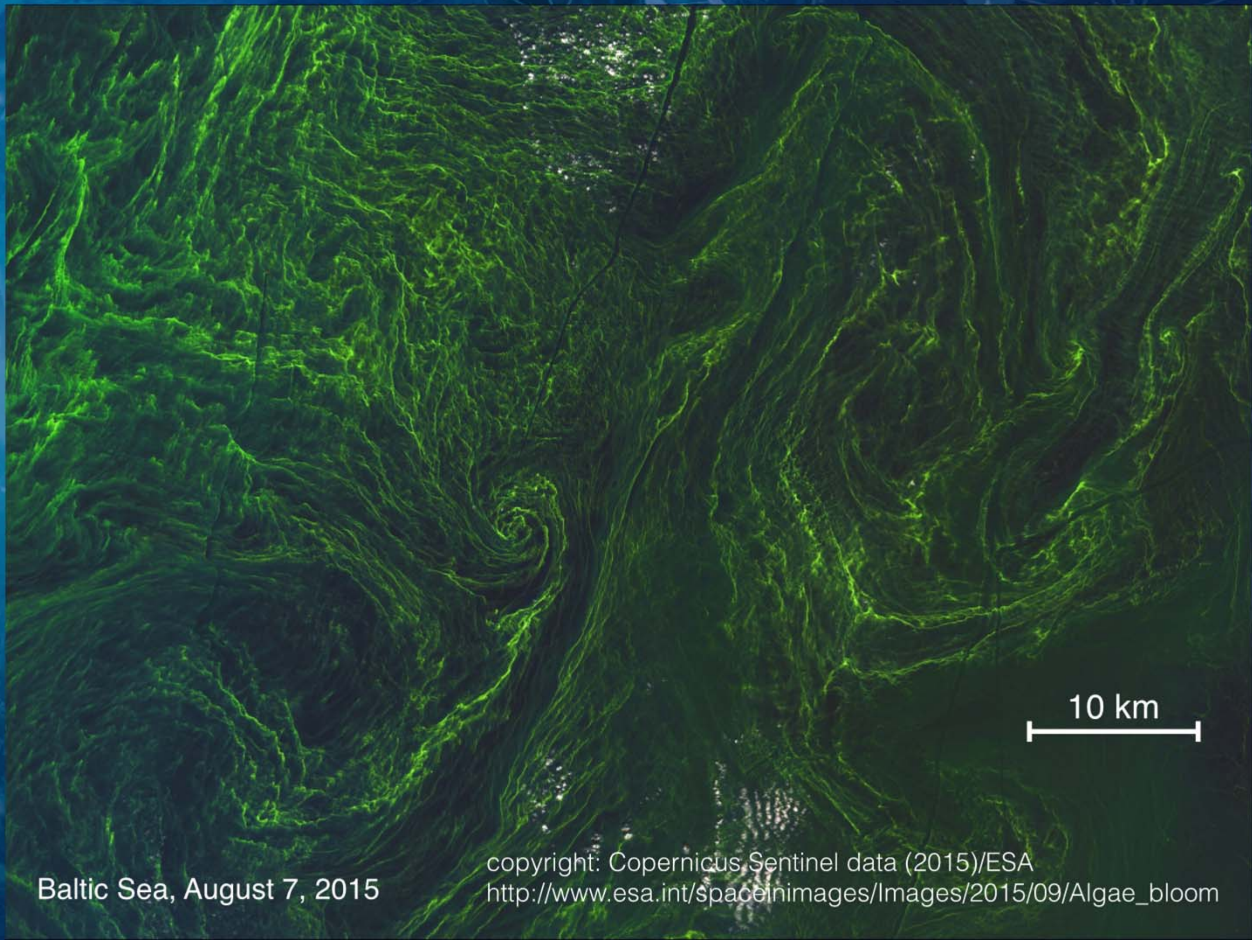
Inter-scale interactions

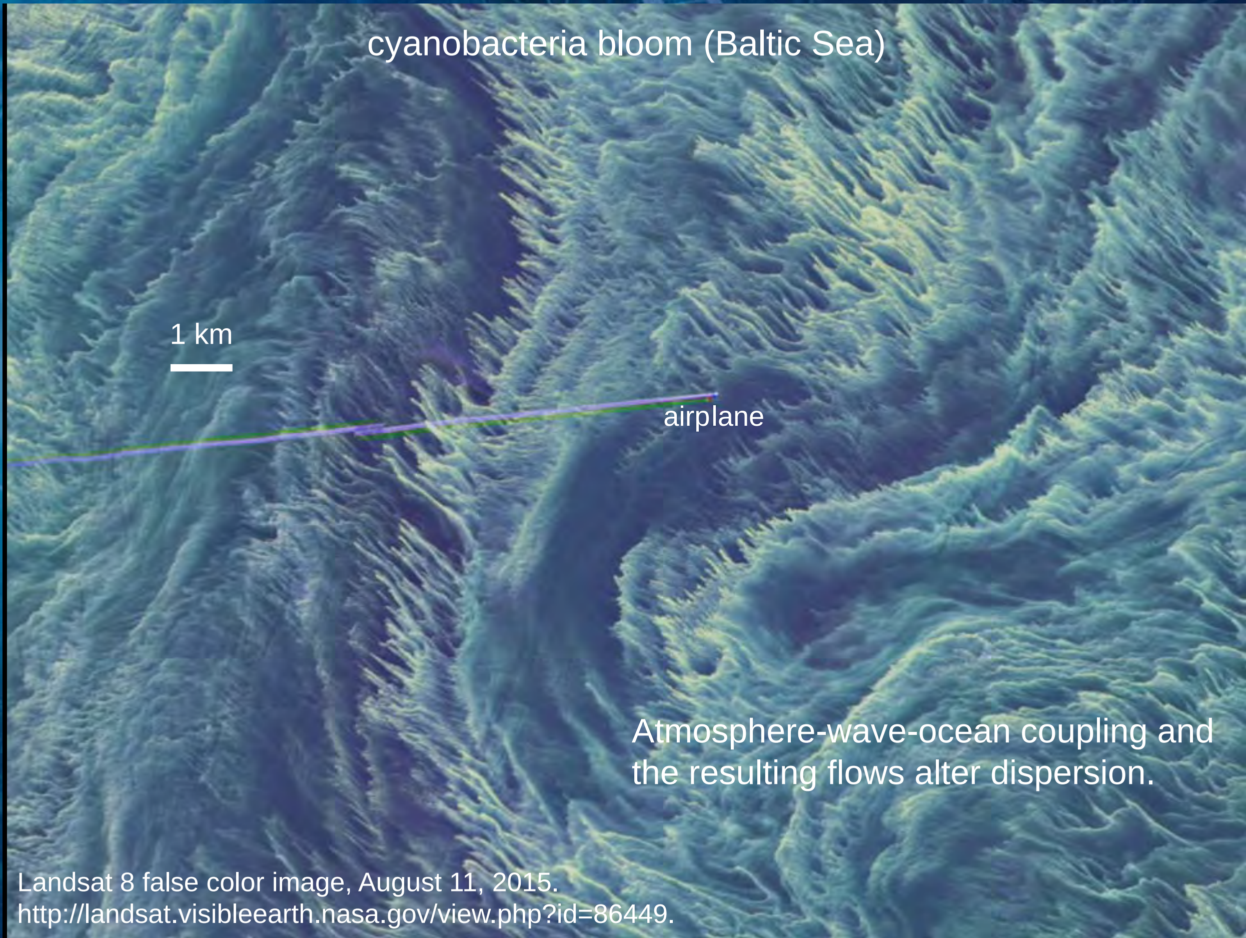
- dispersion of biochemical substances?
- High-resolution = Large Eddy Simulation (LES)



February 20, 2015
Image: MPC Sentine-1 portal

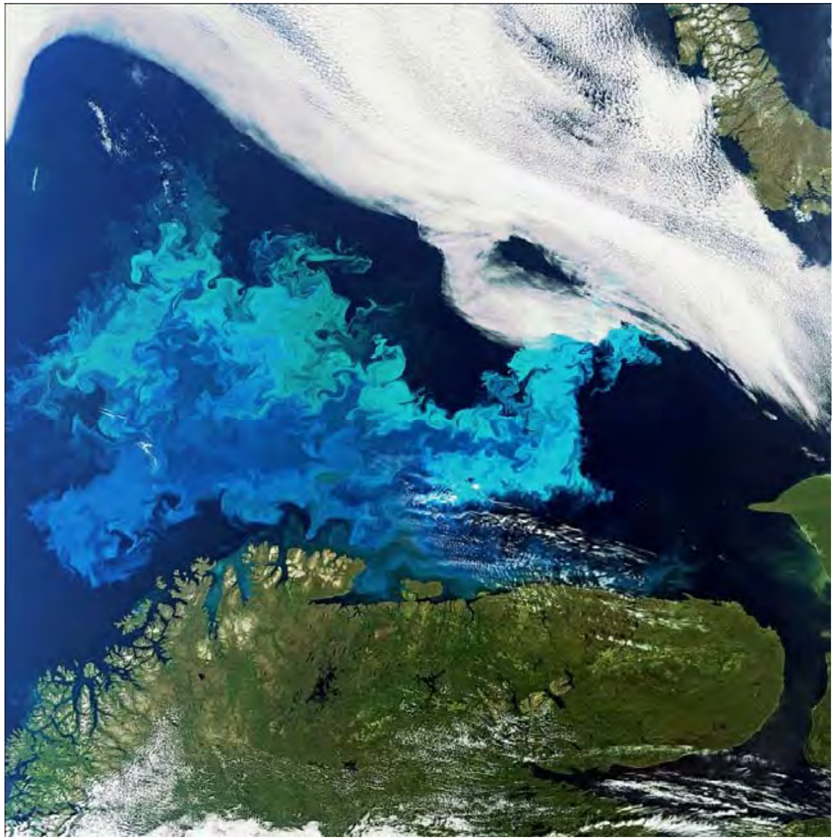

©ESA 2009
0 6 12 km

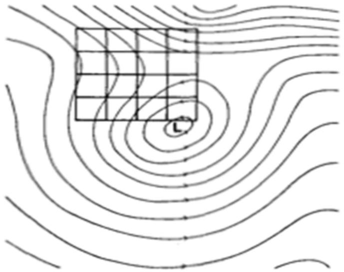

10 km
Baltic Sea, August 7, 2015
copyright: Copernicus Sentinel data (2015)/ESA
http://www.esa.int/spaceinimages/Images/2015/09/Algae_bloom

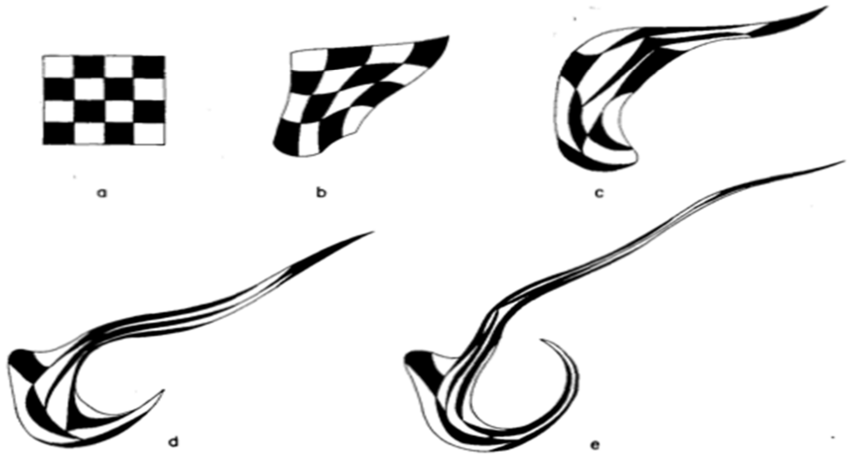


Landsat 8 false color image, August 11, 2015.
http://landsat.visibleearth.nasa.gov/view.php?id=86449.

Stirring and mixing : interplay and scale








April 20


r Horizon
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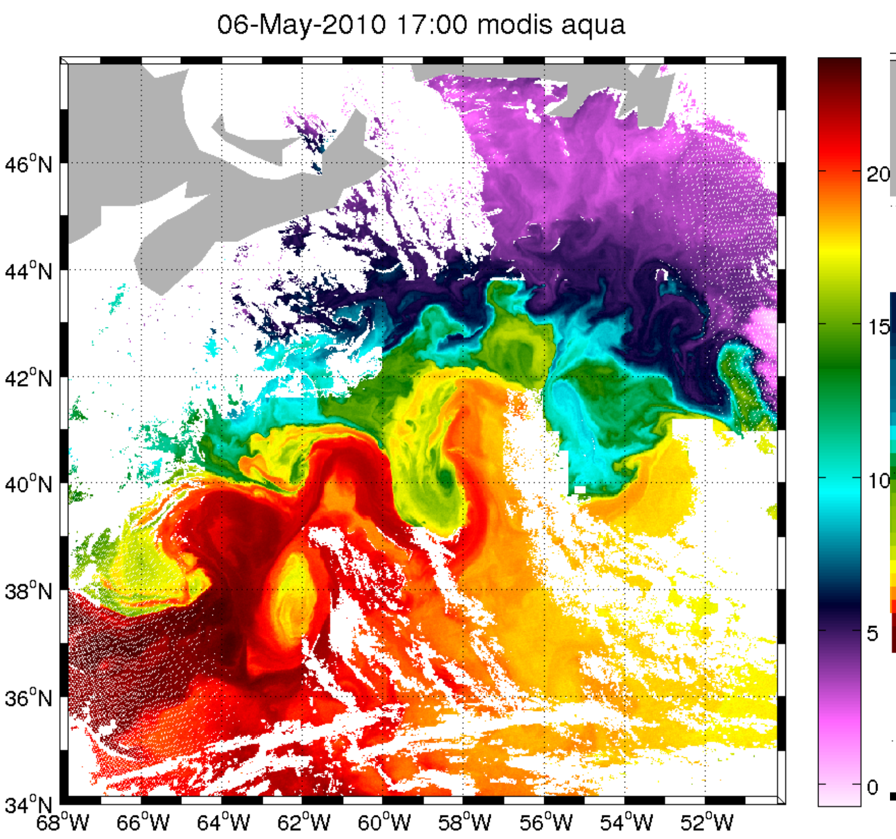
DIS


06-May-2010 17:00 modis aqua
46°N
44°N
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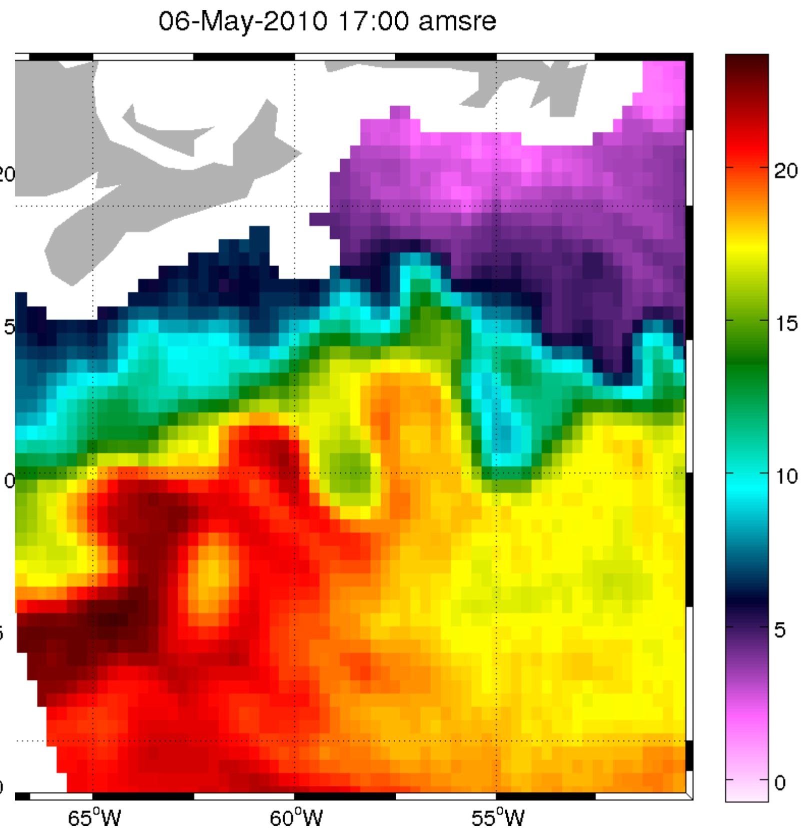
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65°W
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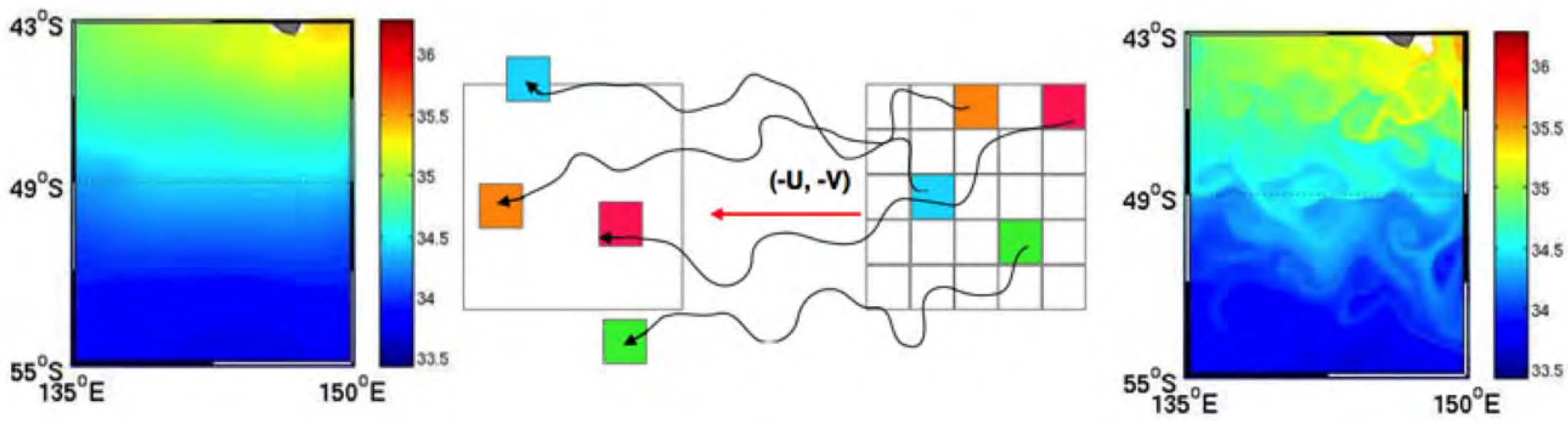
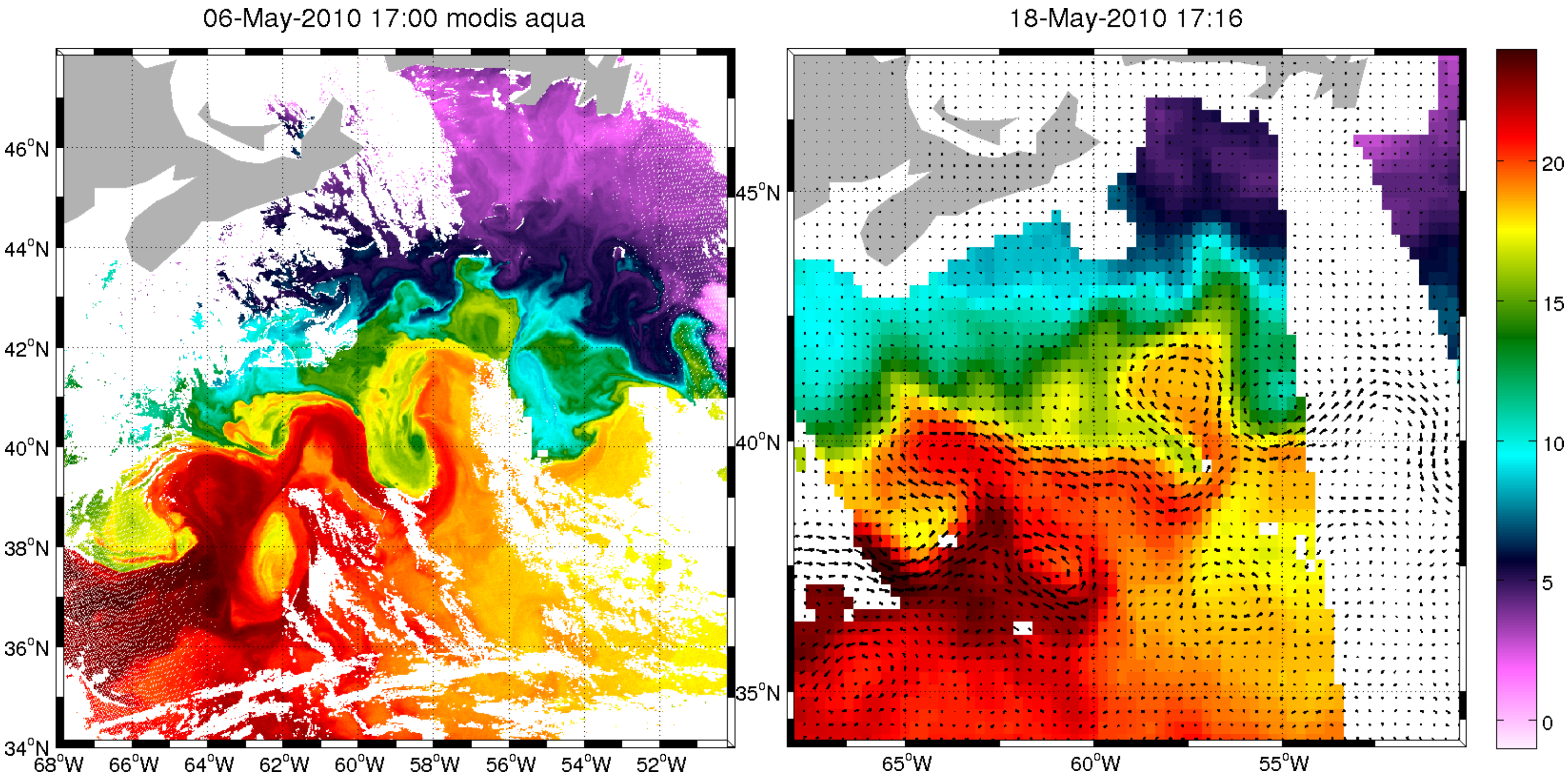
Lagrangian advection to dynamically interpolate large-scale tracer (sea surface temperature field, left) onto a high-resolution product (right). Particle trajectories computed using altimetry-derived velocities (AVISO, weekly 1/3°) with 3 hours time steps

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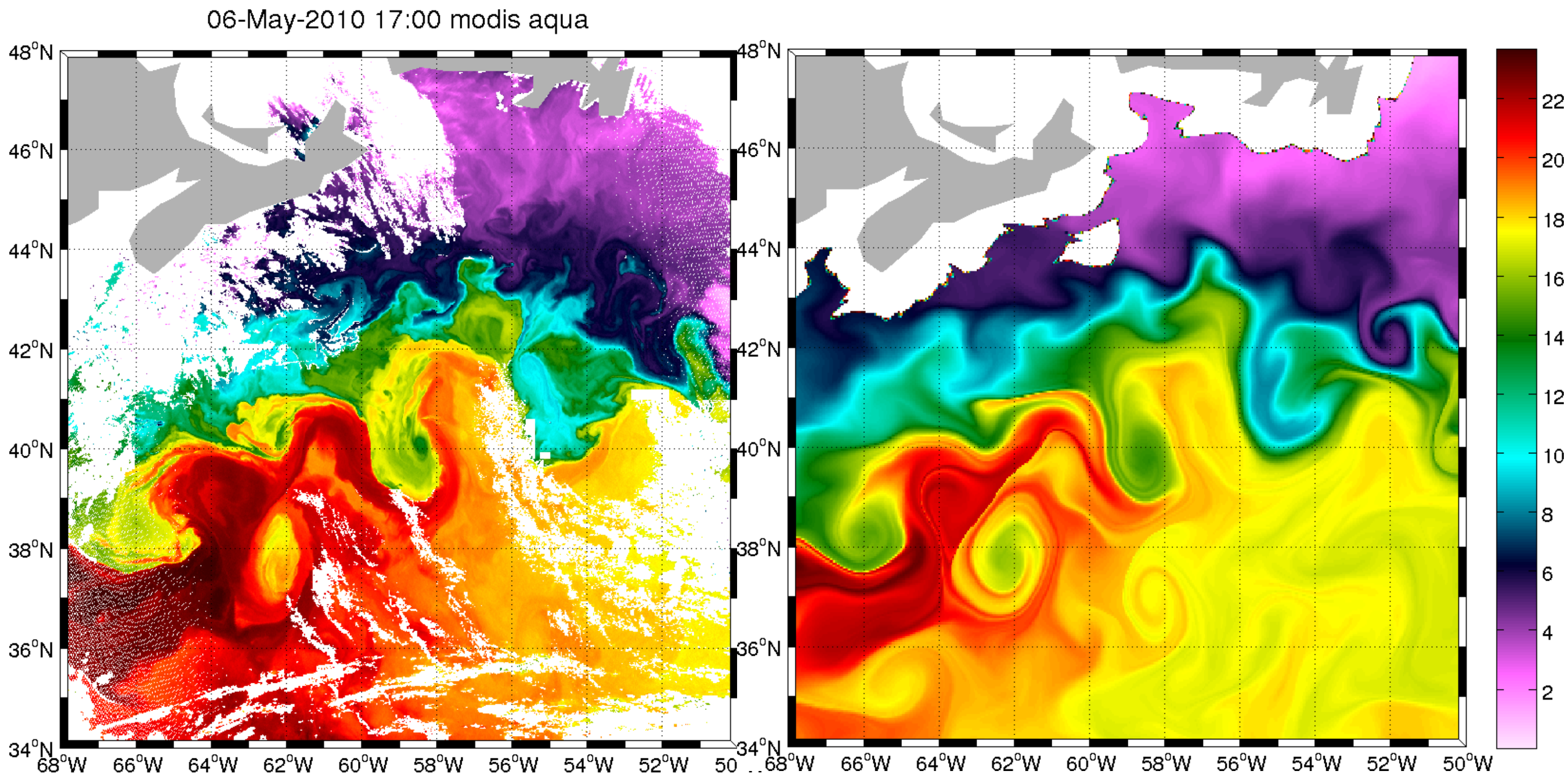
06-May-2010 17:00 modis aqua
48°N
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44°N
42°N
40°N
38°N
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68°W 66°W 64°W 62°W 60°W 58°W 56°W 54°W 52°W 50°W
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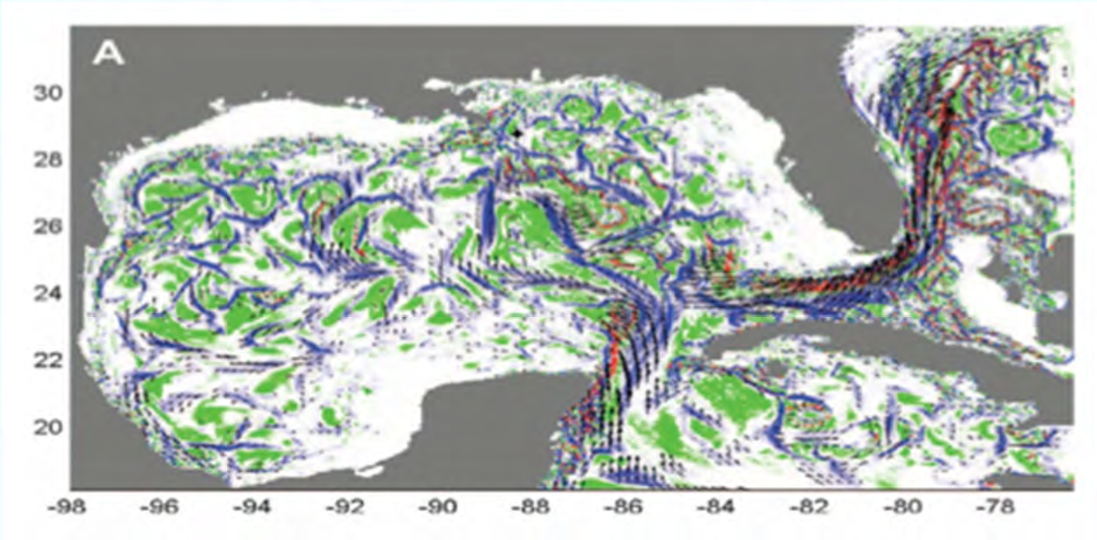
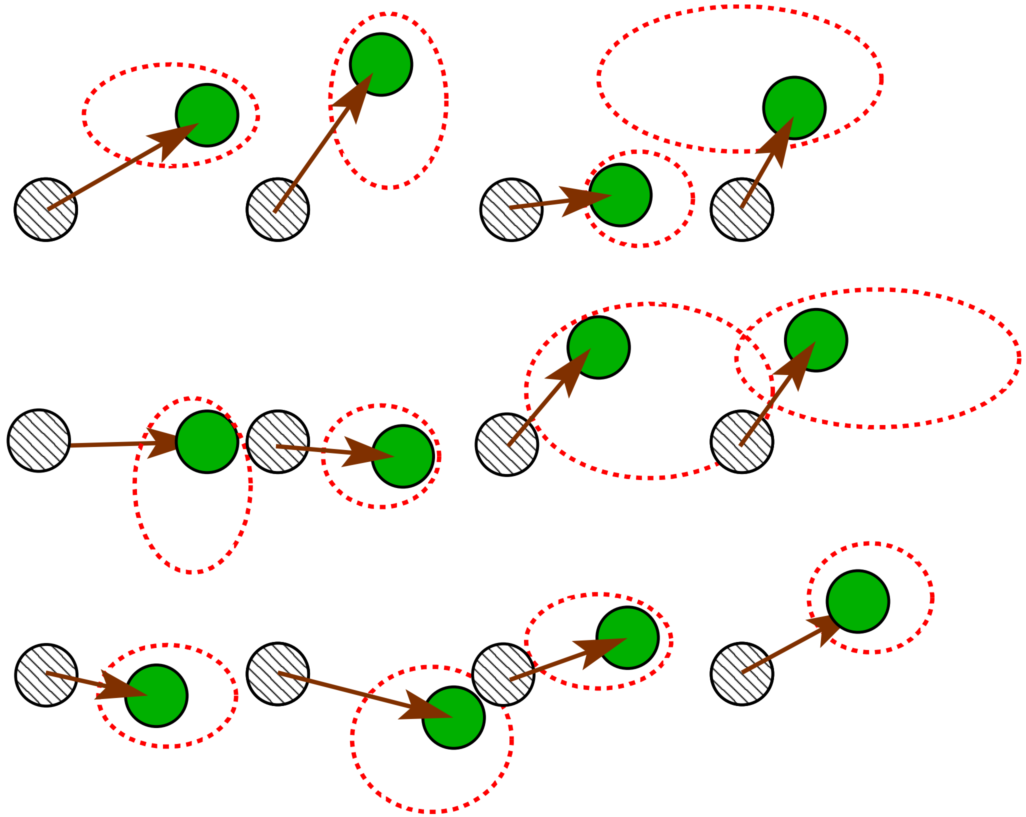
The blended satellite products allow to estimate the impact of surface currents on the biogeochemical transport, on the dispersion of pollutants and oil spills



Forecast of oil spill dispersion in the Gulf of Mexico on 25 june 2010: red and blue show regions of strong oil dispersion within 3 days. This diagnosis, based on altimetric data, compared well with what was observed (Mezic et al, Science, 2010).

However these satellite datasets (altimetric and microwave data) cannot capture ocean dynamics at scales smaller than 100 km because of the resolution (or/and noise level).

Observed data in combination with the physical knowledge of stochastic processes in nonlinear dynamical systems



LU :Adding random velocity

Large scales:

$\boldsymbol{w}$

Small scales:

$\boldsymbol{\sigma \dot{B}}$

Variance tensor:

$$\boldsymbol{a} = \boldsymbol{a}(\boldsymbol{x}, \boldsymbol{x}) = \frac{\mathbb{E}\{\boldsymbol{\sigma} d\boldsymbol{B} \, (\boldsymbol{\sigma} d\boldsymbol{B})^T\}}{dt}$$

Resolved large scales

White-in-time small scales

$$\boldsymbol{v} = \boldsymbol{w} + \boldsymbol{\sigma} \dot{\boldsymbol{B}}$$

References :

Mikulevicius and Rozovskii, 2004
Flandoli, 2011

Memin, 2014
Resseguier et al. 2017 a, b, c
Chapron et al. 2017
Cai et al. 2017

Holm, 2015
Holm and Tyranowski, 2016
Arnaudon et al., 2017

Cotter and al 2017
Crisan et al., 2017
Gay-Balmaz & Holm 2017
Cotter and al 2018 a, b

Advection of tracer Θ

Large scales:

$\boldsymbol{w}$

Small scales:

$\boldsymbol{\sigma}\dot{\boldsymbol{B}}$

Variance tensor:

$$\boldsymbol{a} = \boldsymbol{a}(\boldsymbol{x},\boldsymbol{x}) = \frac{\mathbb{E}\{\boldsymbol{\sigma} d\boldsymbol{B}\,(\boldsymbol{\sigma} d\boldsymbol{B})^T\}}{dt}$$

Multiplicative random forcing

Balanced energy exchanges

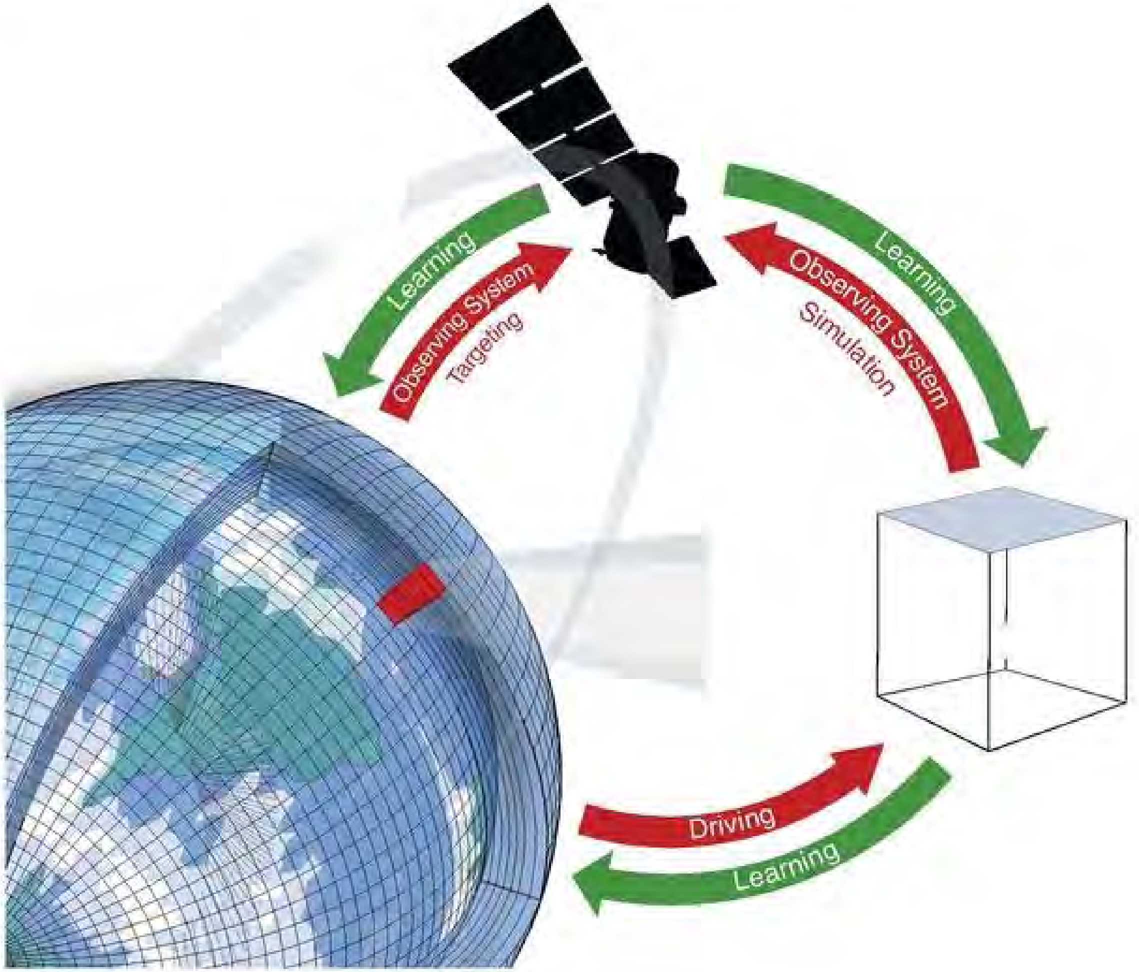
Advection

Diffusion

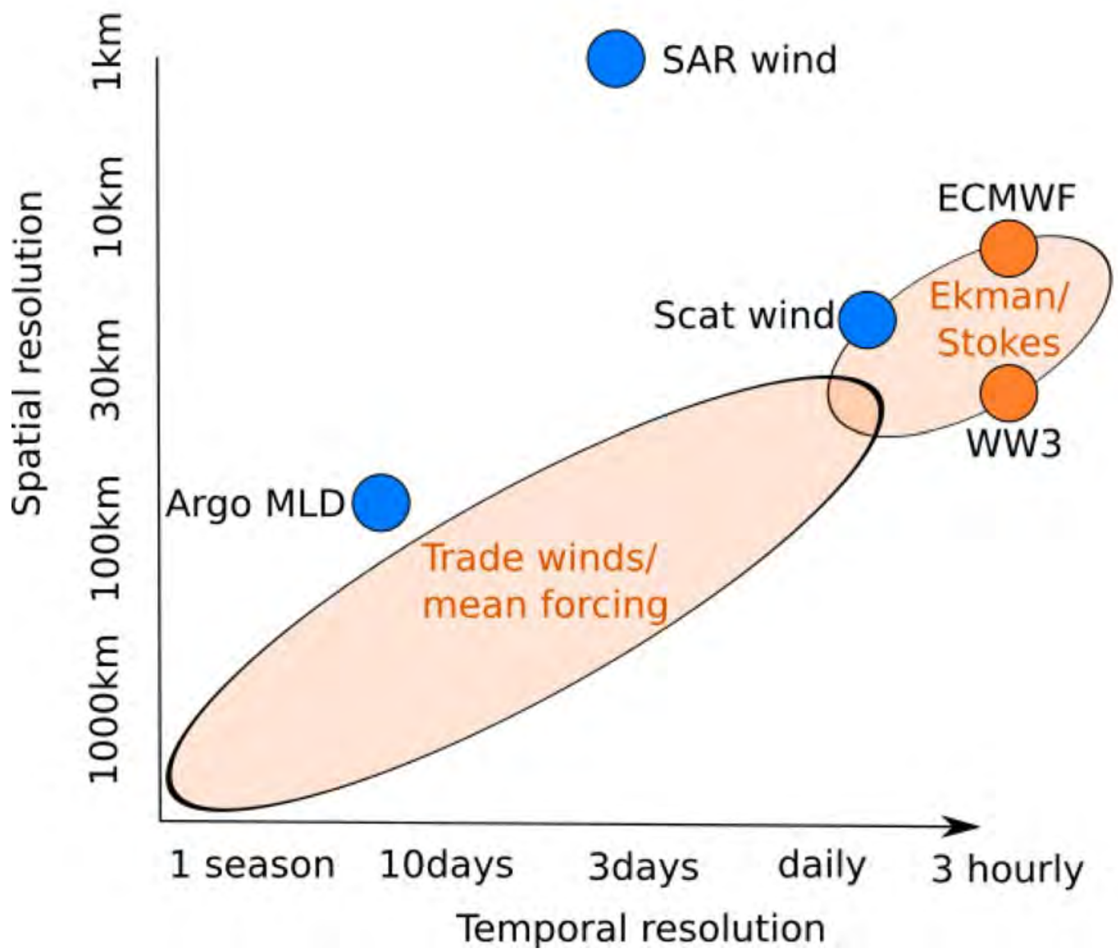
$$\partial_t \Theta + \boldsymbol{w}^{\star} \cdot \boldsymbol{\nabla}\Theta + \boldsymbol{\sigma}\dot{\boldsymbol{B}} \cdot \boldsymbol{\nabla}\Theta = \boldsymbol{\nabla} \cdot \left(\frac{1}{2}\boldsymbol{a}\boldsymbol{\nabla}\Theta\right)$$

Drift correction

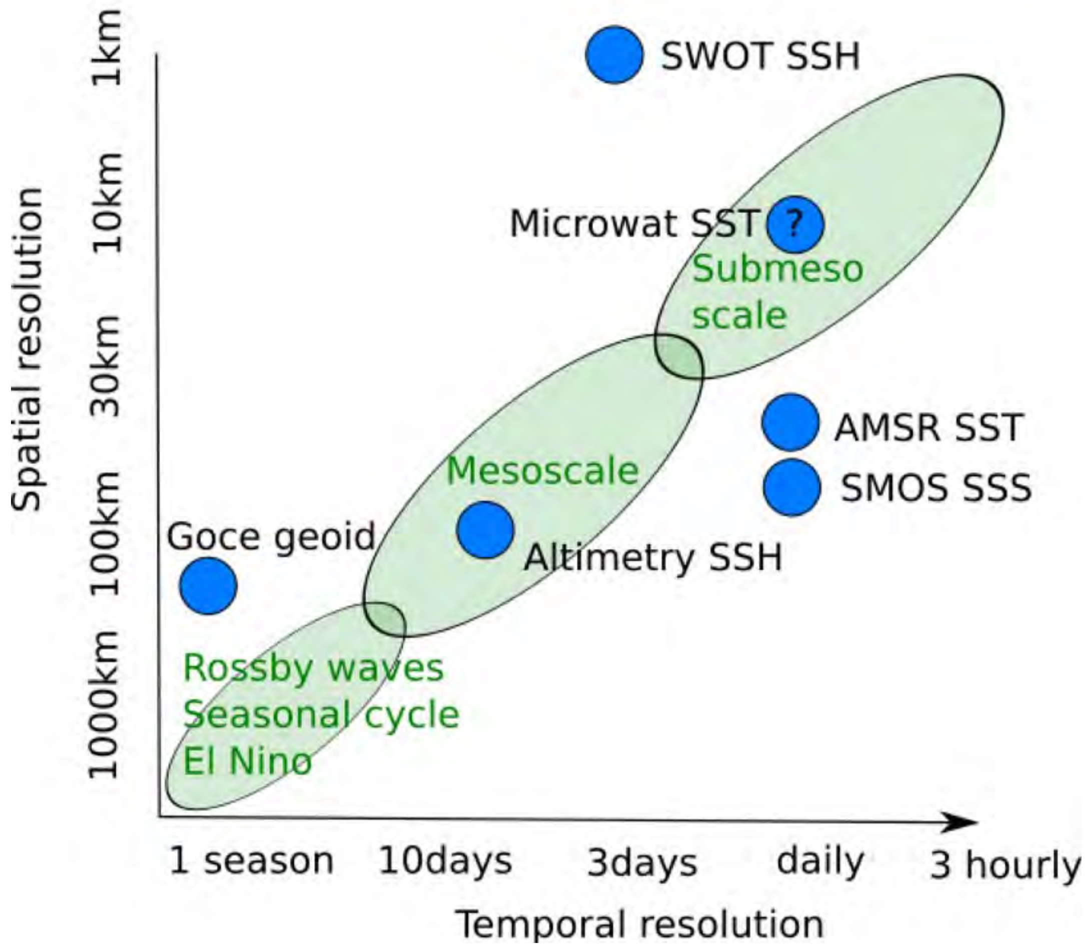
Goal is a hierarchical system that integrates data and models (and can also be used to design observing systems)

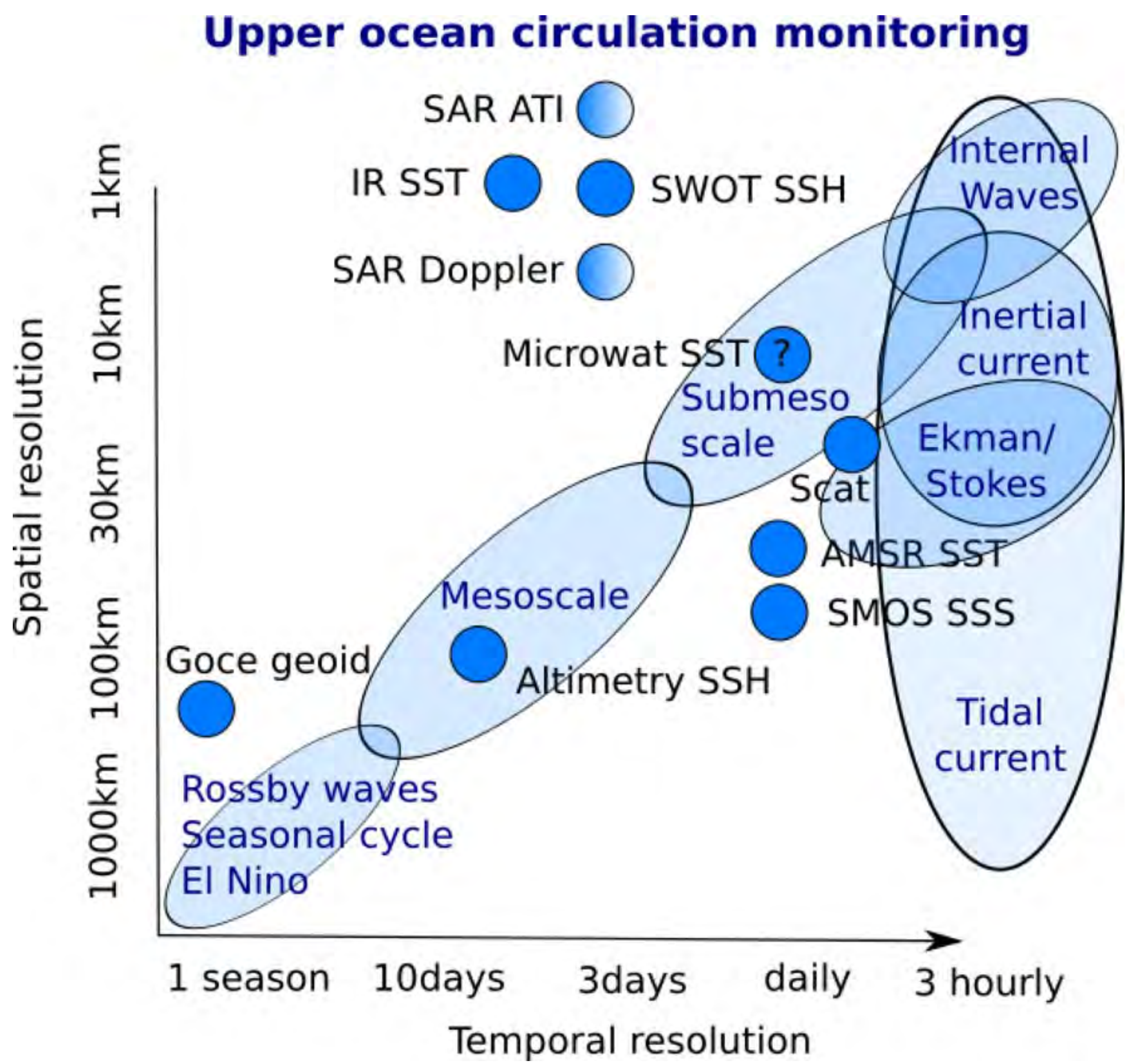


Upper ocean atmospheric forcing monitoring

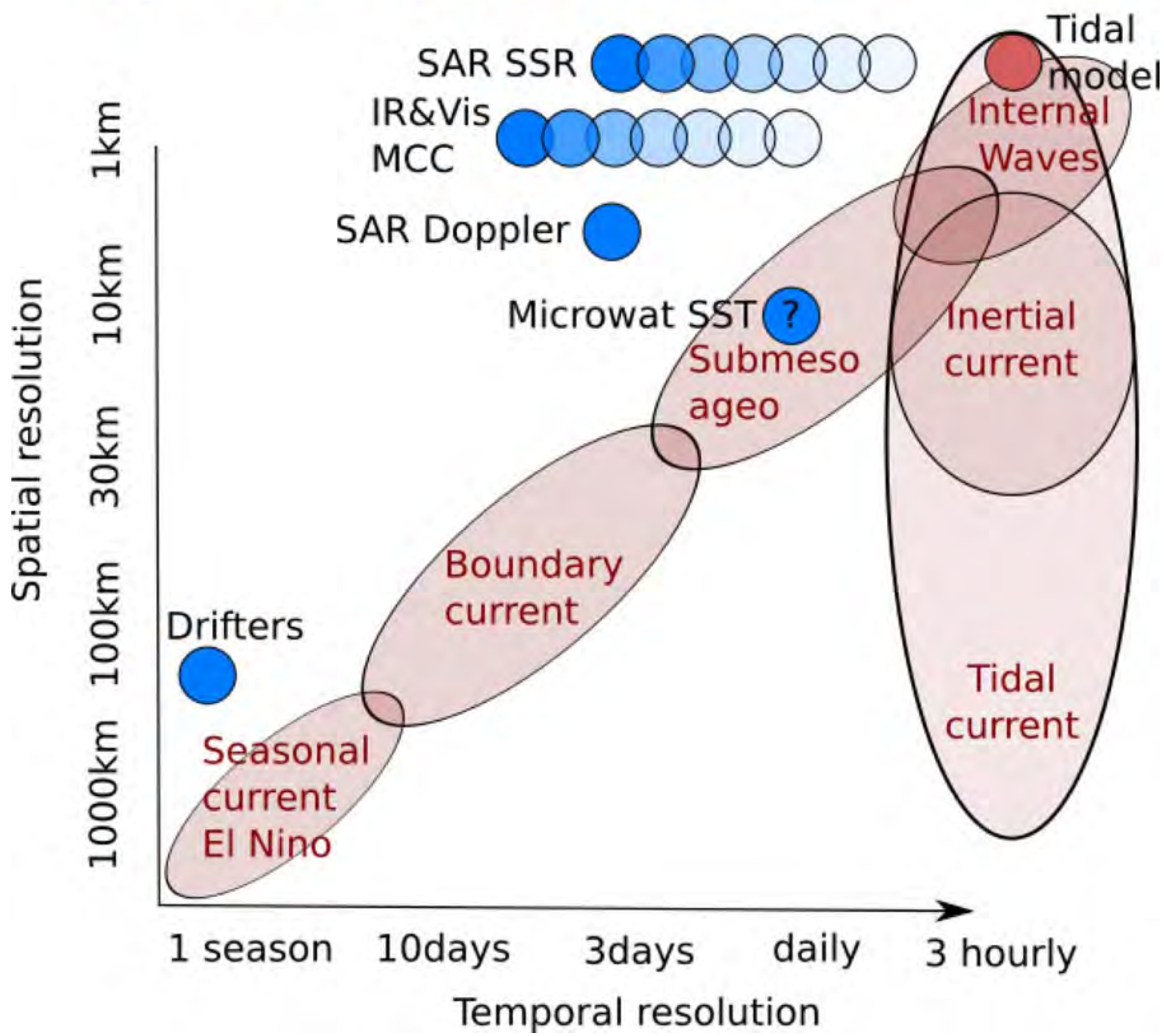


Upper ocean geostrophy monitoring

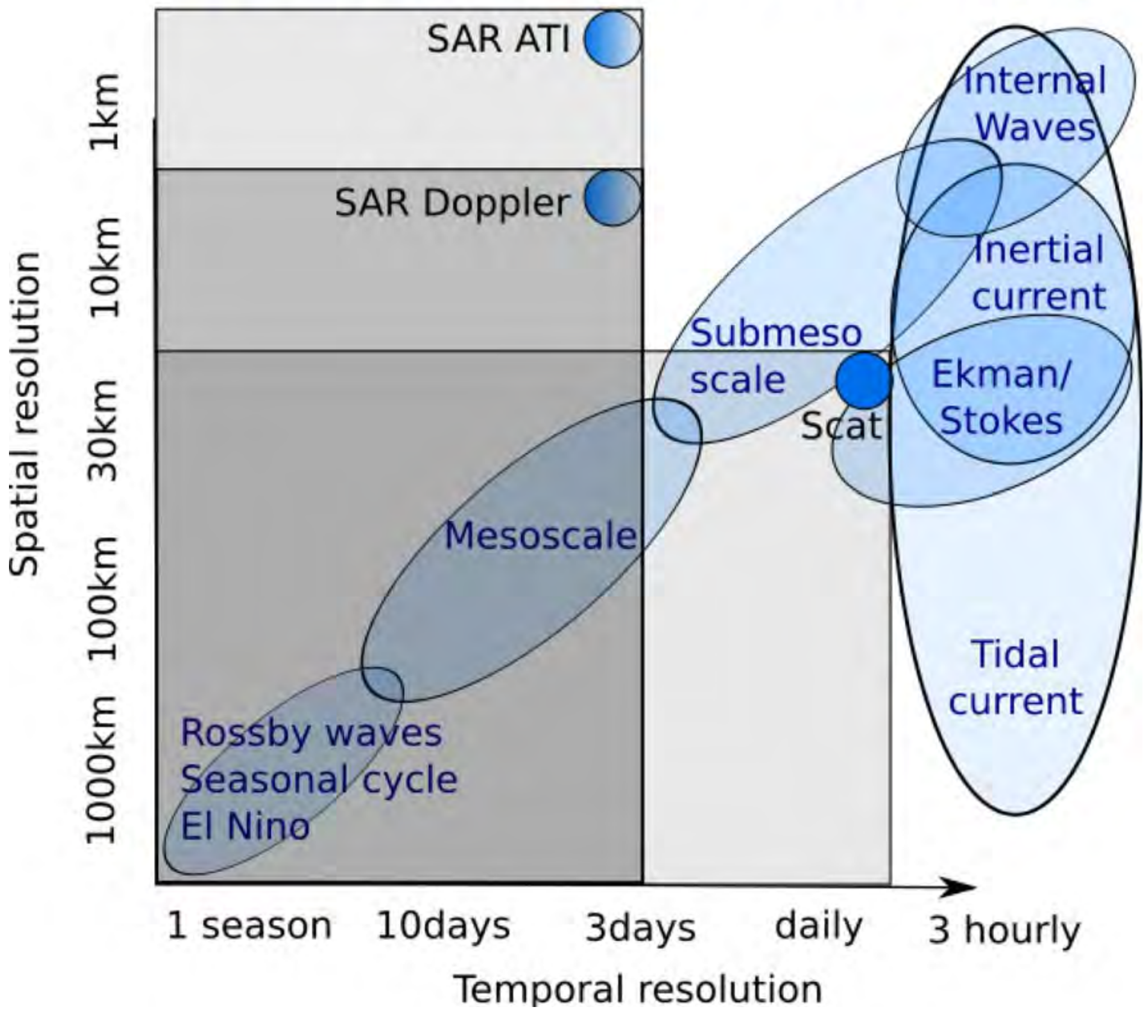



Upper ocean circulation monitoring
SAR ATI
IR SST
SWOT SSH
SAR Doppler
Microwat SST
?
Submeso scale
Scat
AMSR SST
SMOS SSS
Mesoscale
Goce geoid
Altimetry SSH
Rossby waves
Seasonal cycle
El Nino
Internal Waves
Inertial current
Ekman/ Stokes
Tidal current
Spatial resolution
1km
10km
30km
100km
1000km
1 season
10days
3days
daily
3 hourly
Temporal resolution

Upper ocean ageostrophic current monitoring



Total ocean surface current monitoring



- … most observations are not yet sufficiently explored and used

Synergy between high and medium resolution observations to reveal mean states and trends, near-surface ocean-atmosphere dynamics, local and non-local interactions, convergence/divergence surface fronts and numerous roughness contrasts

Atmospheric and Oceanic observations generally produce high quality data, but it is often too sparse (many gaps where information is missing, and/or often too local in both space and time)

How can we use observed data in combination with the physical knowledge of stochastic processes in nonlinear dynamical systems to estimate and model those effects on the variability of computationally resolvable scales of motion that are caused by the small, rapid, unresolvable scales of fluid motion that upscaling in data assimilation leaves out?