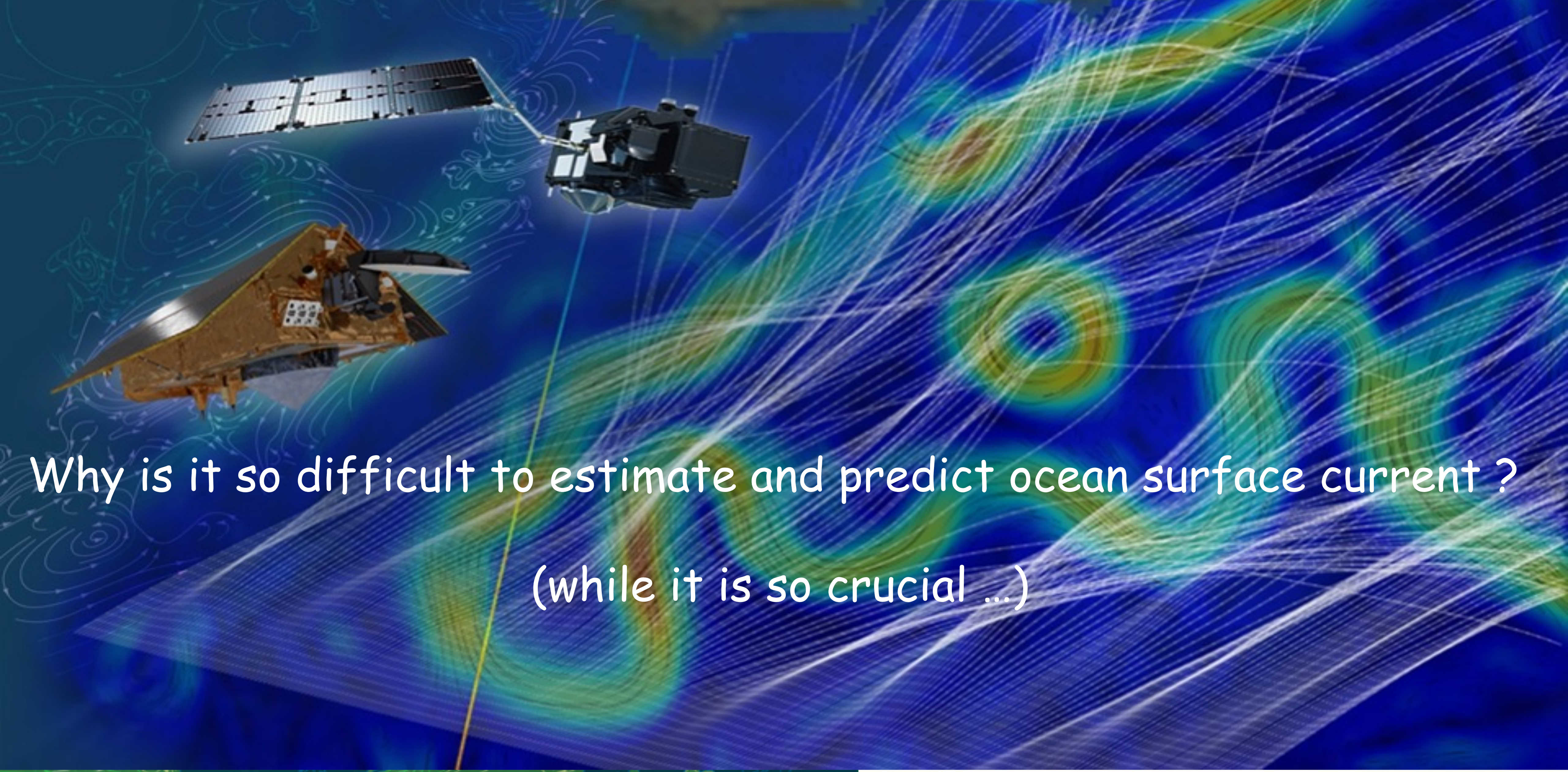

Why is it so difficult to estimate and predict ocean surface current ?

(while it is so crucial …)

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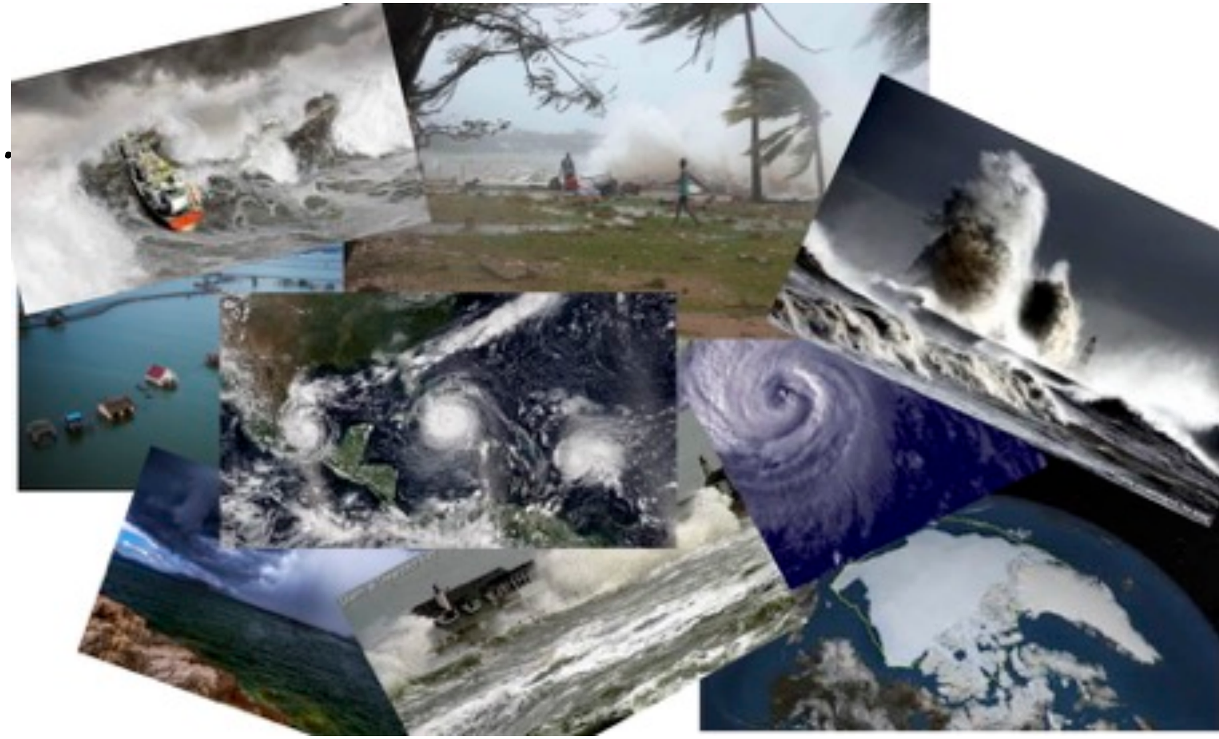
Oceans form a major constituent of the Earth's Climate System

Oceans acts as an integrator for climate processes

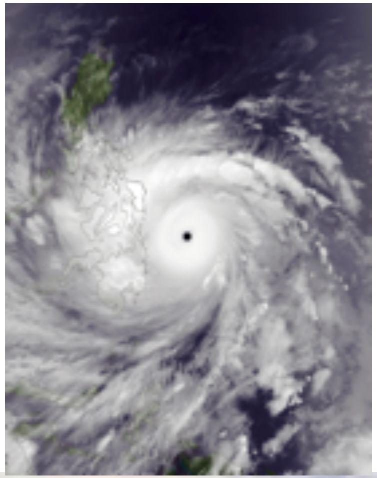
Oceans are the main heat storage on Earth…

- Top 3 m contains same heat as whole atmosphere…
- …and the oceans' mean depth > 3000m

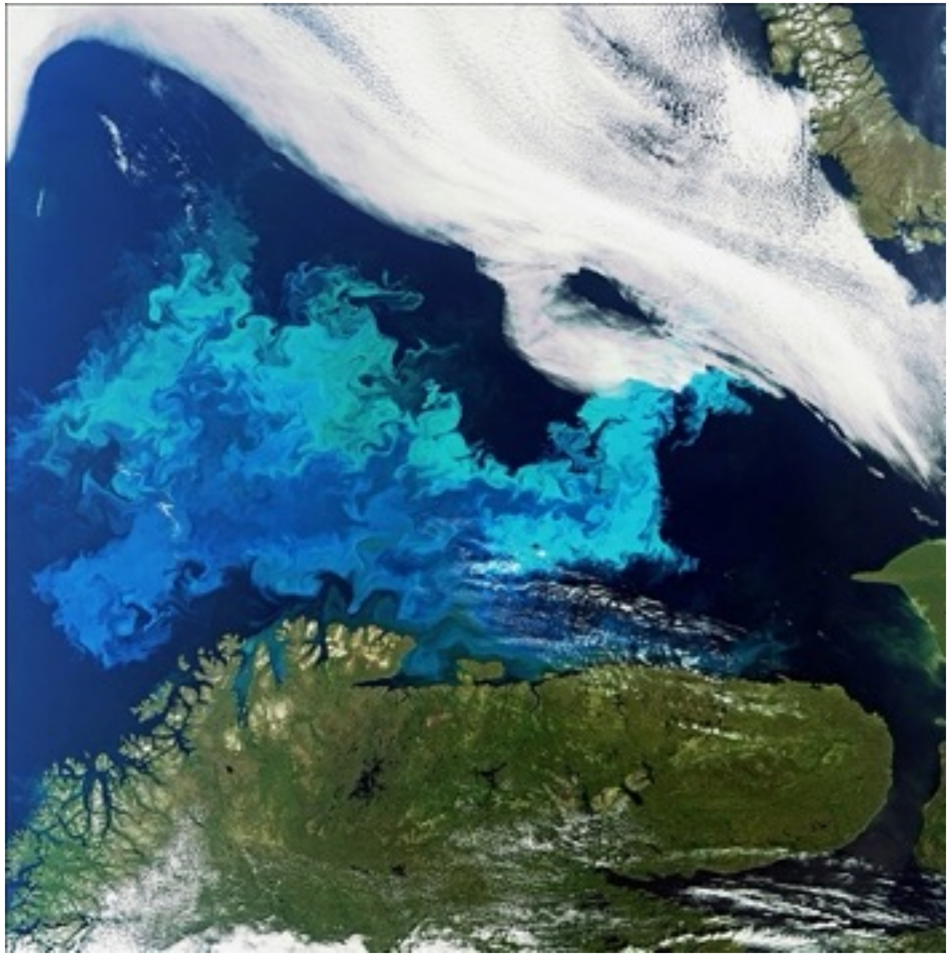
Oceans thus mitigate the worst effects of climate change



Problem: 1/1000 year events now seem to occur yearly!



Stirring and mixing : interplay and scale interactions



How does the ocean breathe? How does the ocean engine work?

Earth system approach: Hasselmann's holistic view (1990)

The reduction of ocean anoxia is key to control the influence of climate or the sea level on the rate of organic matter burial, thereby stabilizing the carbon cycle, global climate and atmospheric oxygen levels :

Oxygen accumulation in the atmosphere is ultimately a by-product of the burial of organic matter produced via oxygenic photosynthesis

<u>WCRP Strategic Plan (2020)</u>: the development of a new generation of coupled Earth system models that explicitly represent global storms, deep convection, ocean eddies and land-atmosphere interactions (1 km scale) and that provides information with reliable regional precision (horizon 2026-2028).

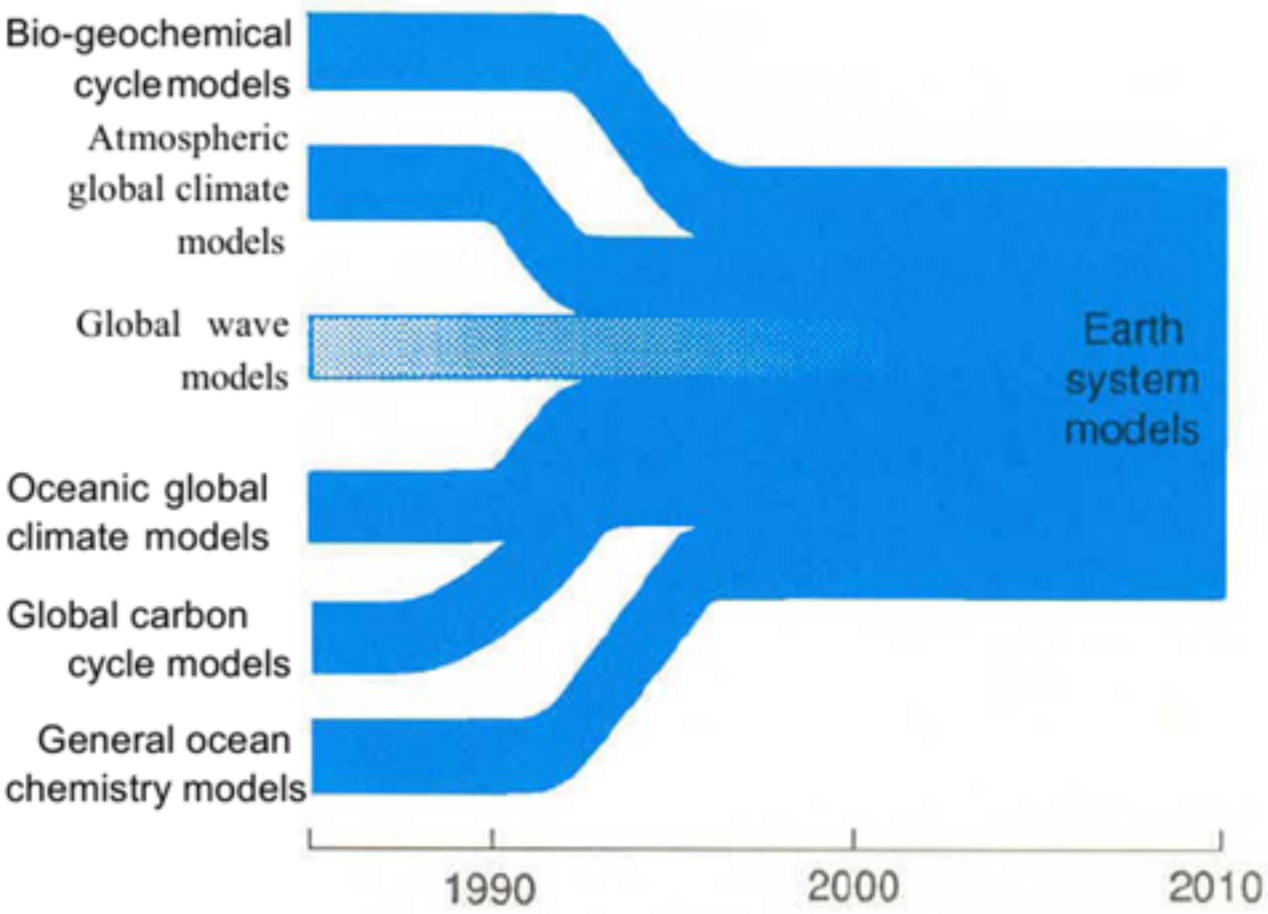
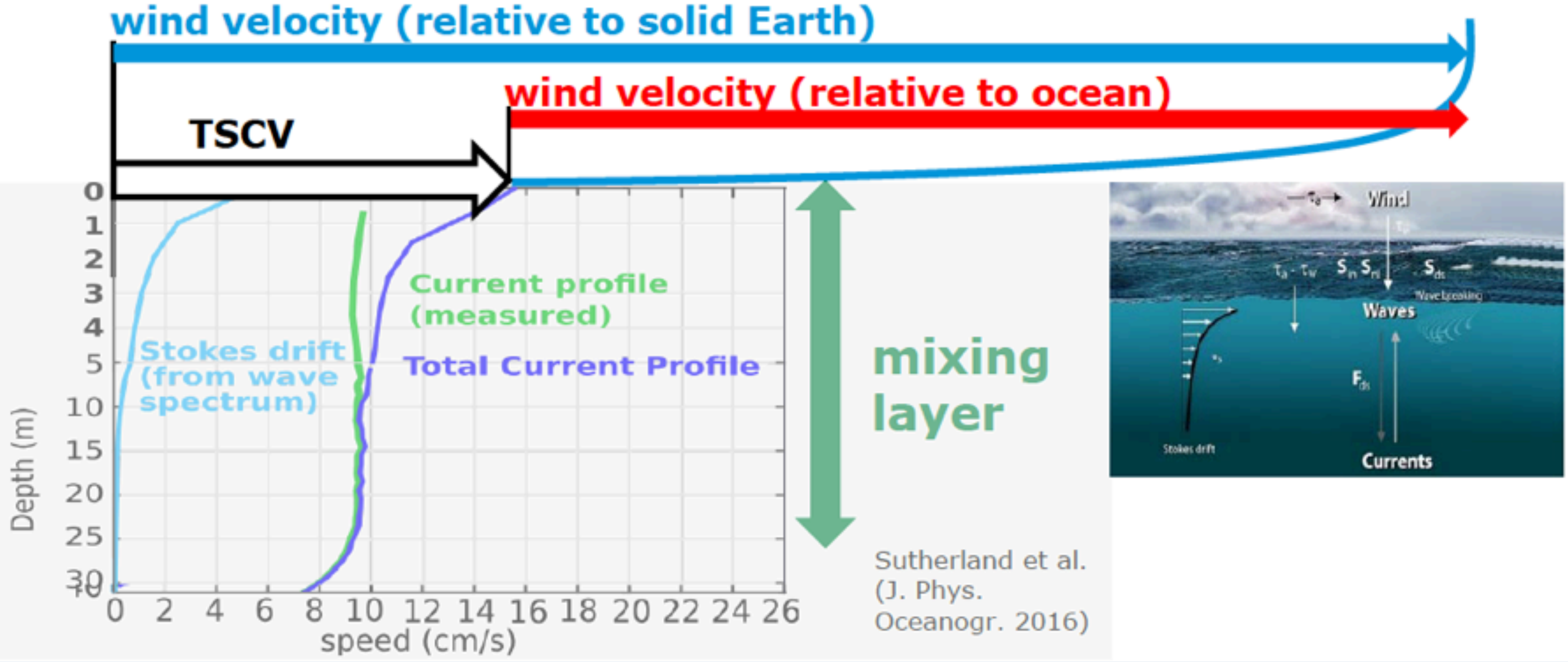


Figure 1. Future role of wave models as an essential coupling component for ocean-atmosphere-carbon-cycle modets developed in the context ot the World Climate and Global Change programs.

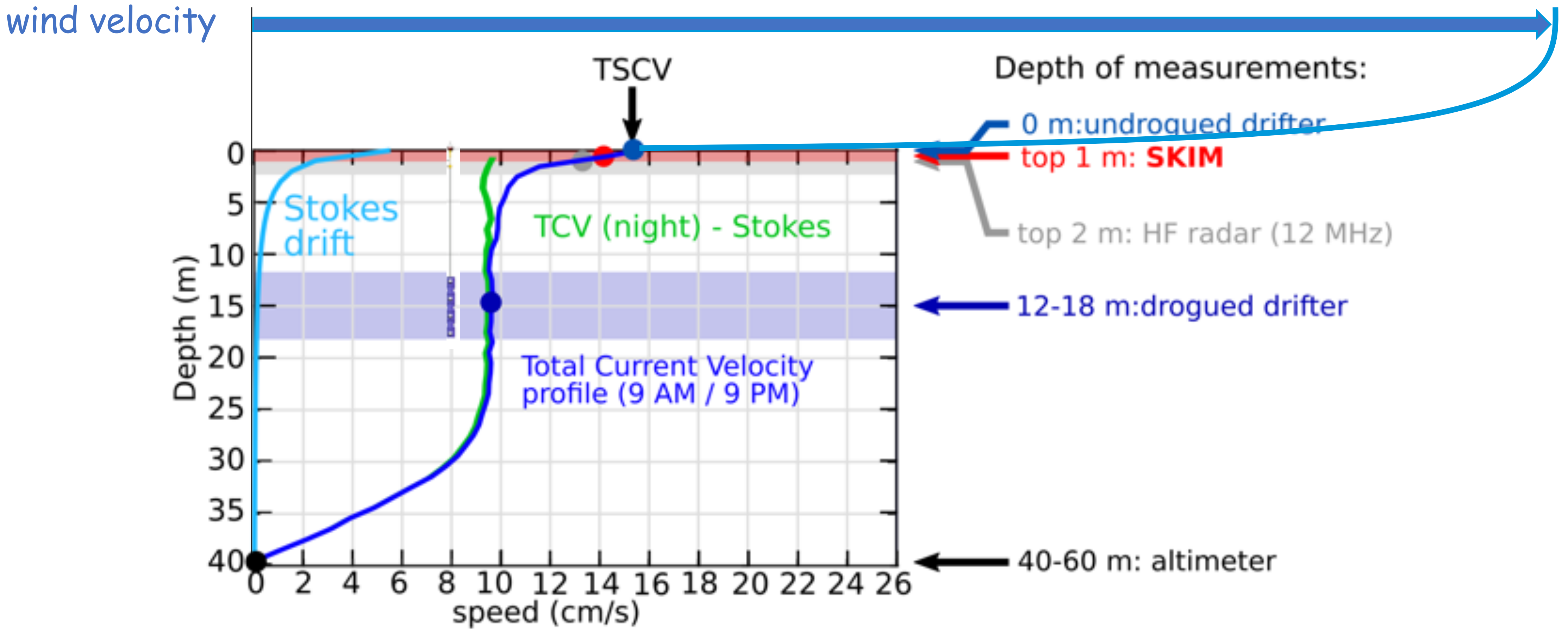
BUT … It is already very difficult to define and measure upper ocean surface currents !



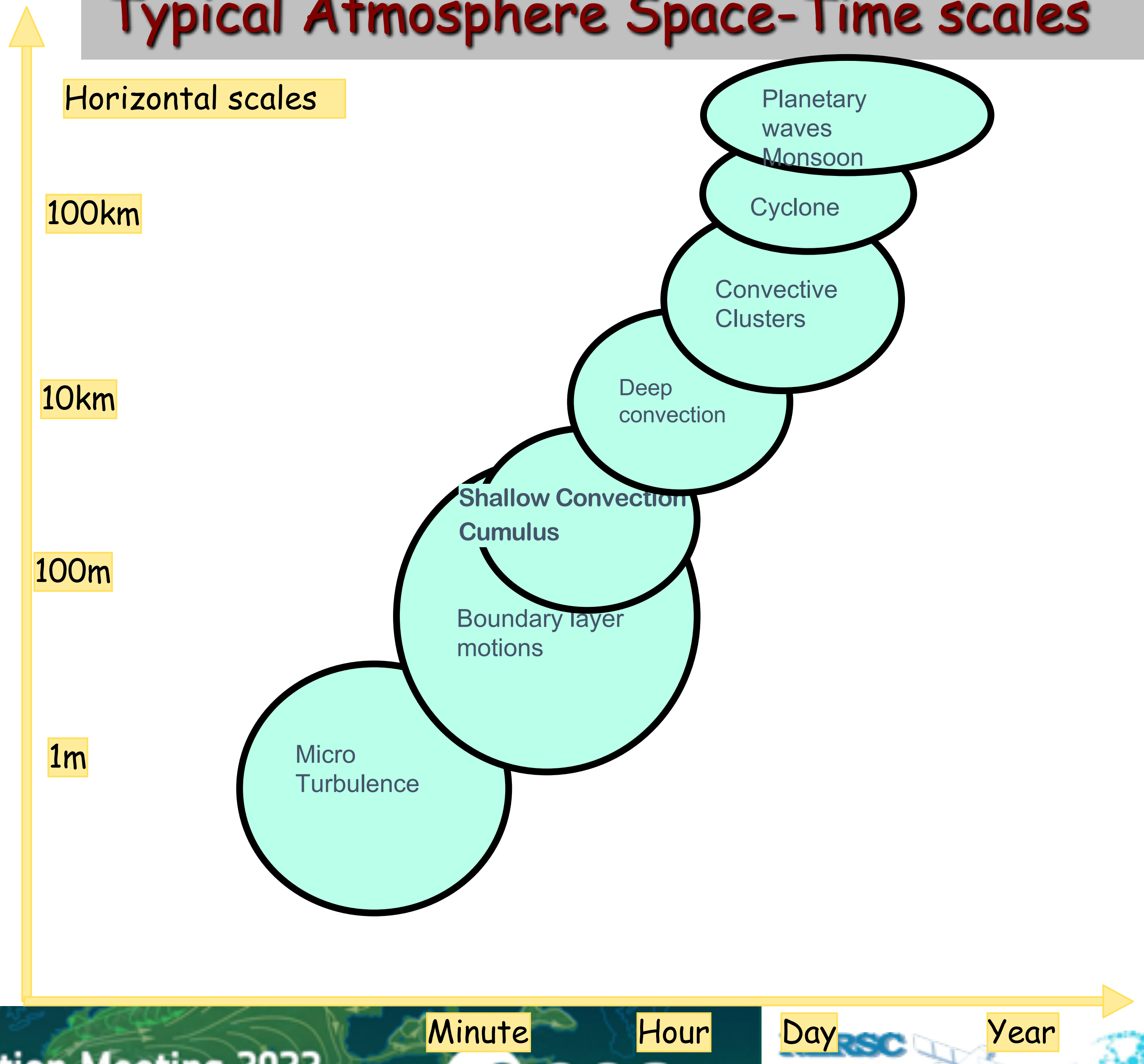
Wind and waves locally control the depth of influence of the atmosphere forcing, acting on a pre-existing ML, over a deep layer

Defining the Total Surface Current Velocity (TSCV)

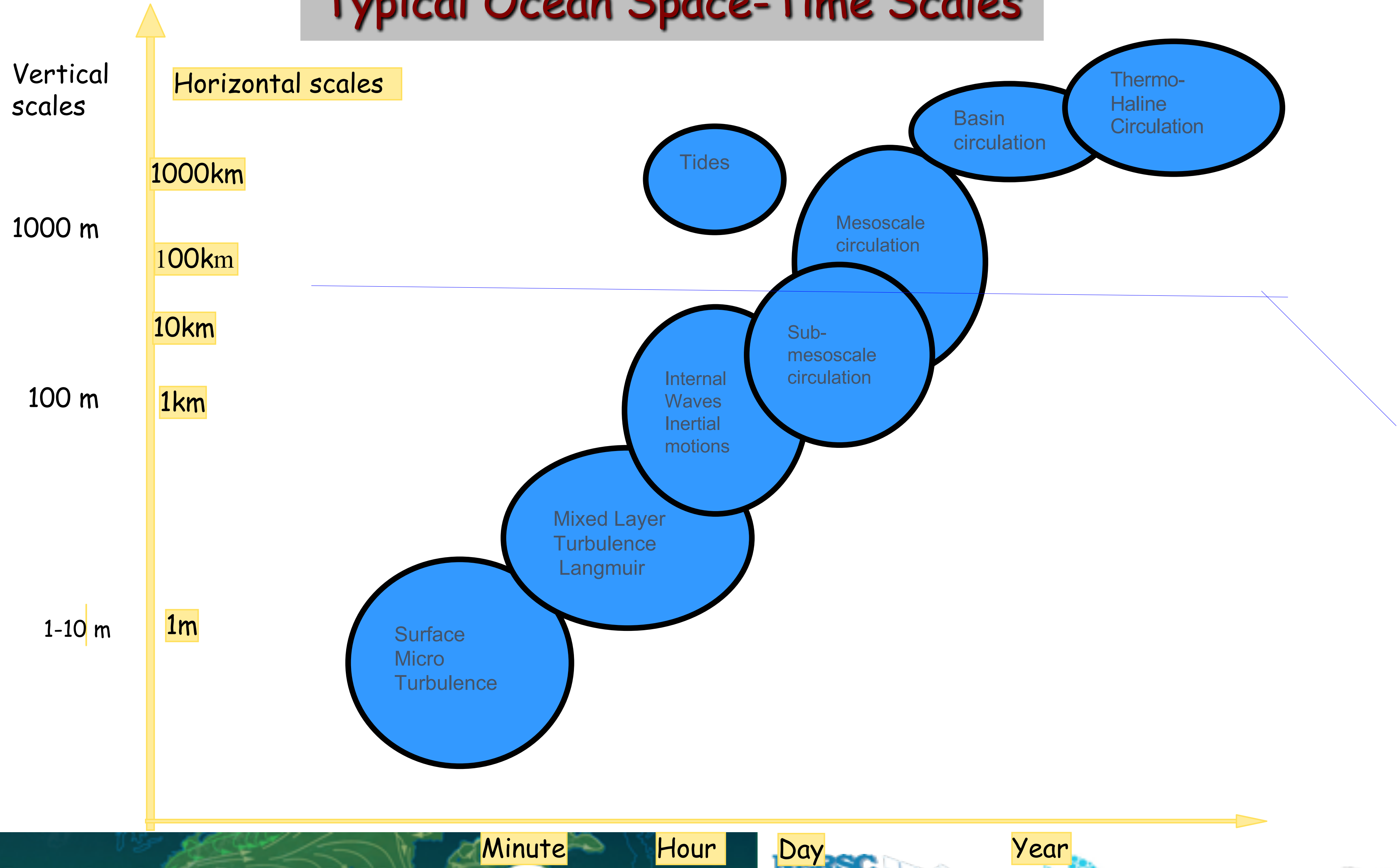
The mean velocity of surface particles in contact with the atmosphere



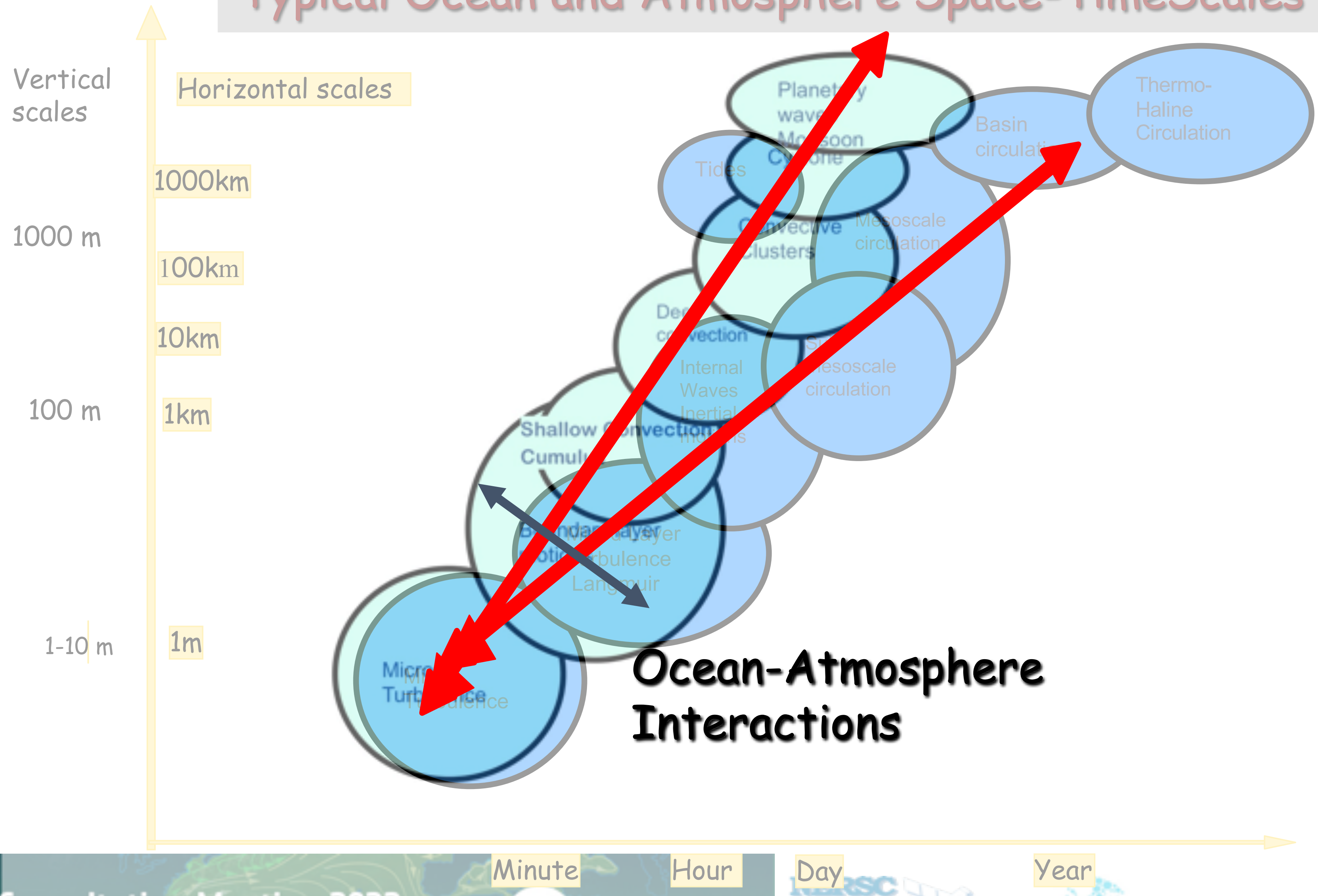
Typical Atmosphere Space-Time scales



Typical Ocean Space-Time Scales

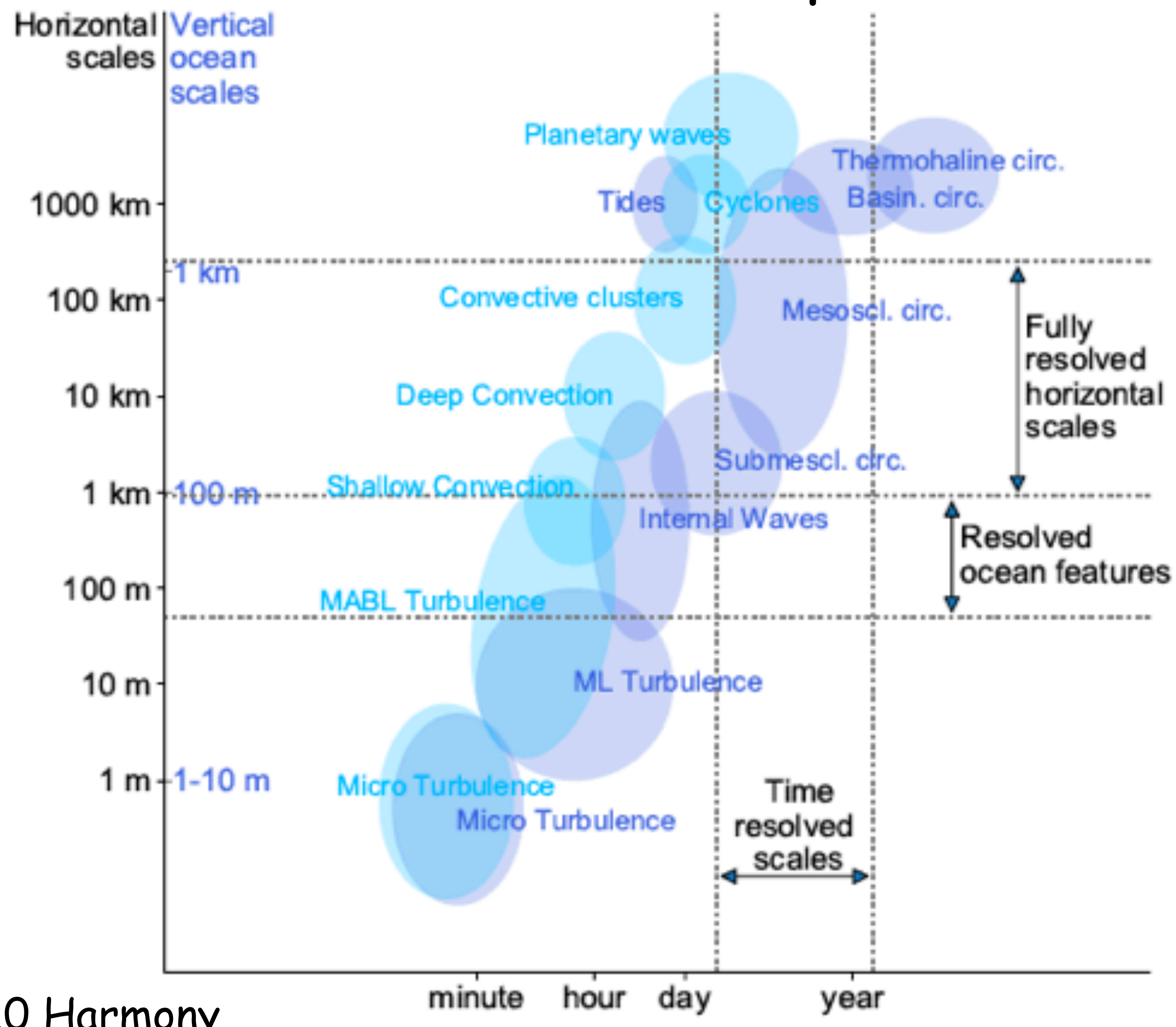


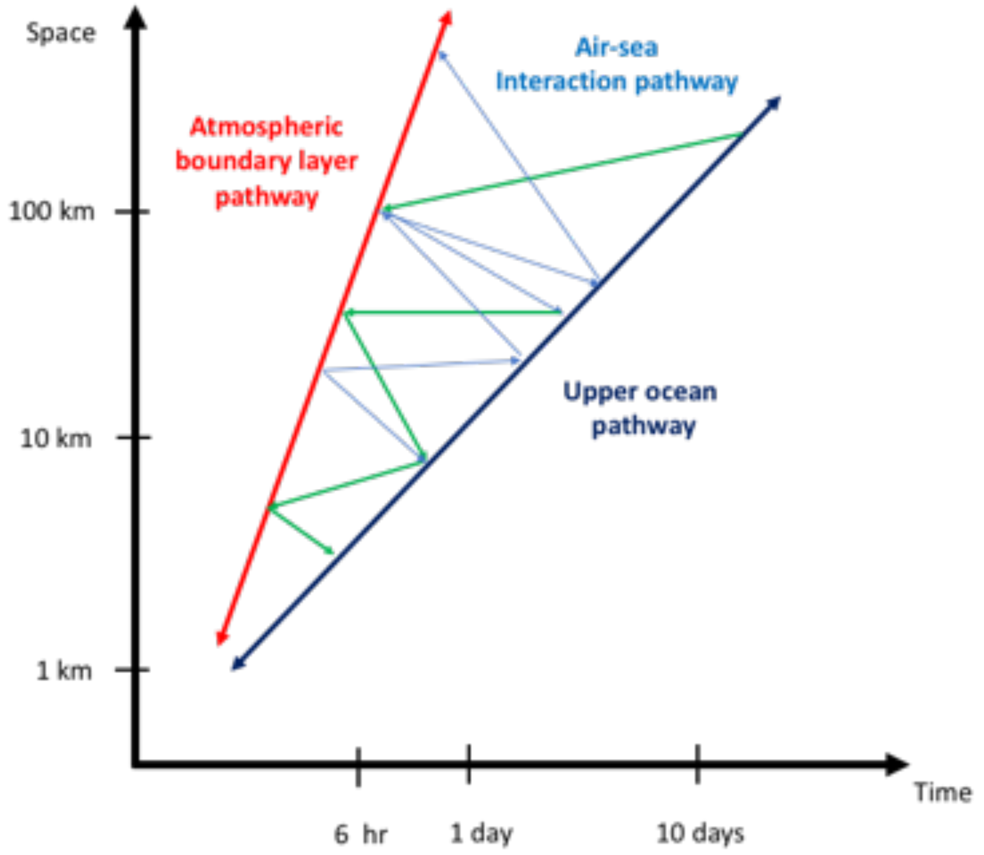
Typical Ocean and Atmosphere Space-TimeScales



Ocean-Atmosphere Interactions

The Space -Time Characteristics





EE10 Harmony

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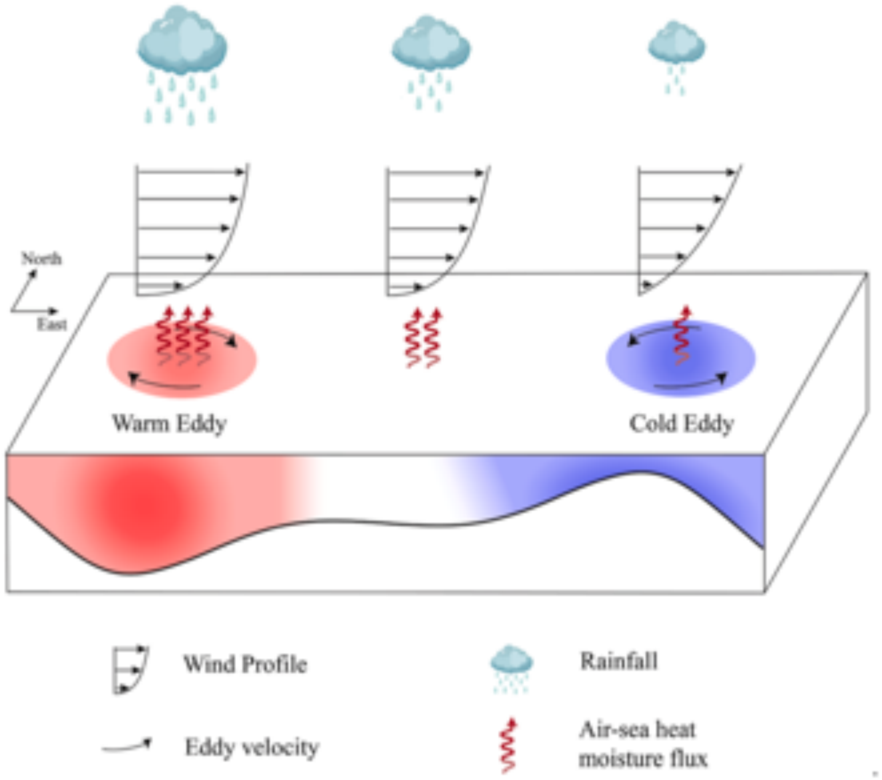
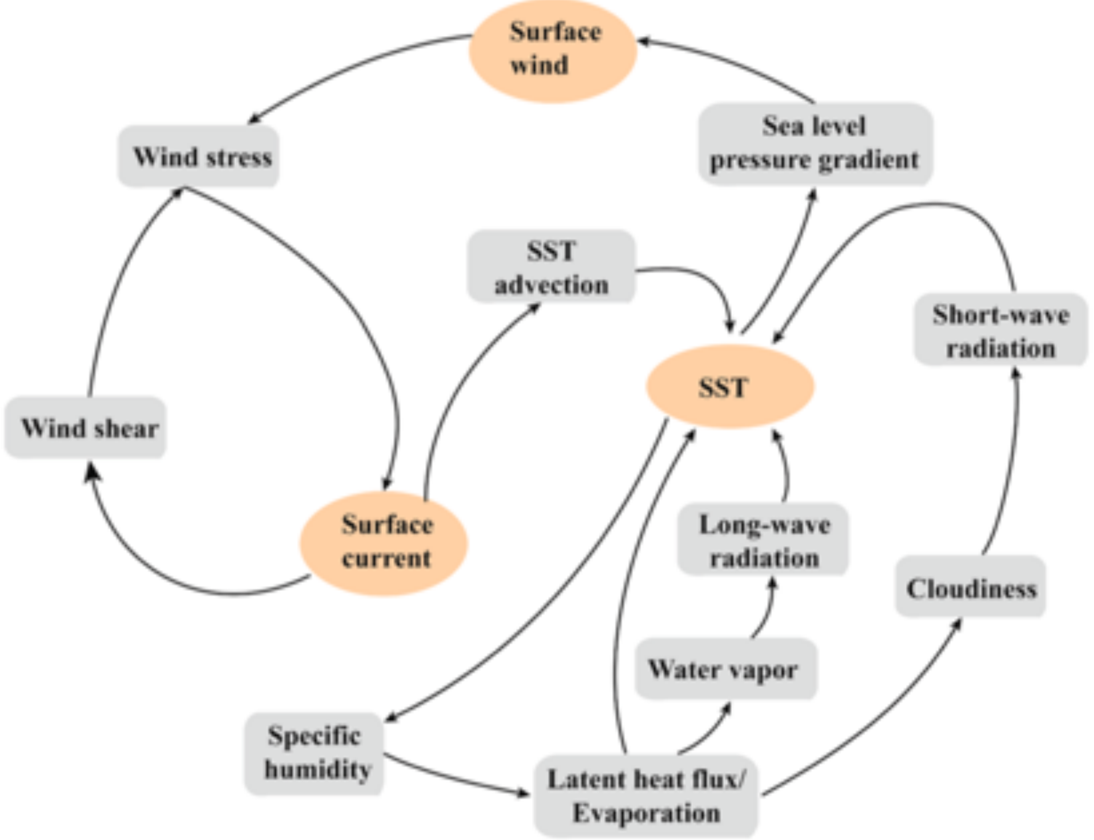
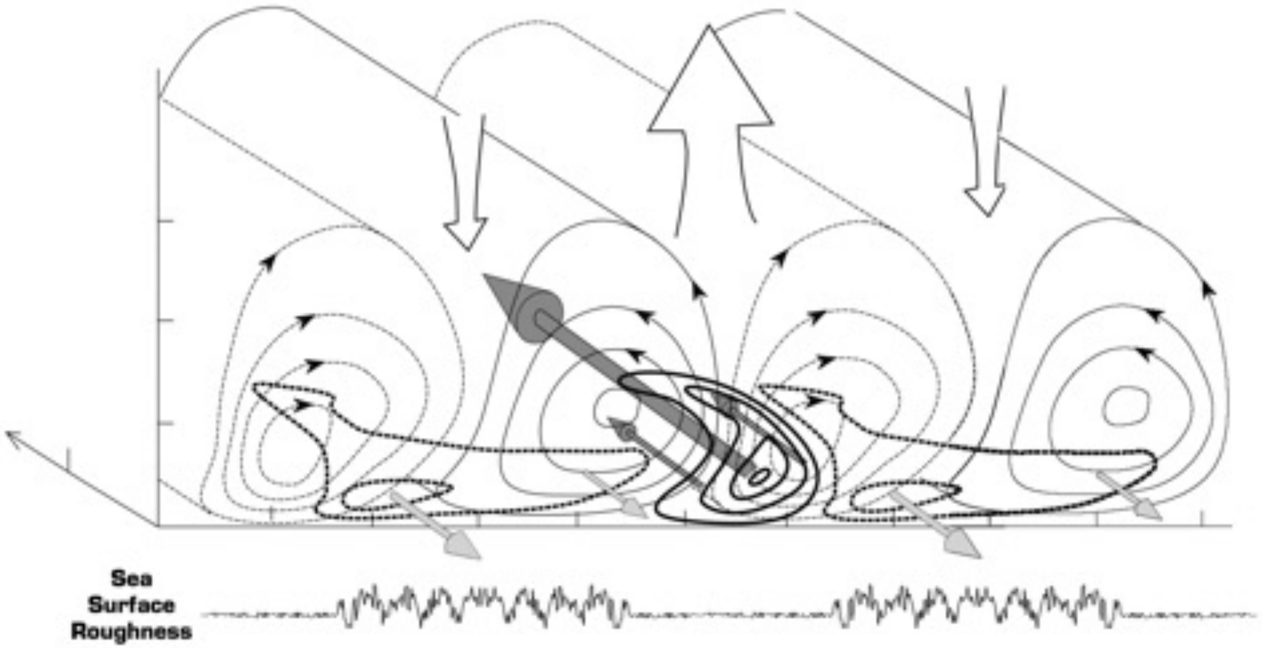
Earth system complexity: Ocean-Atmosphere, local and non-local multi-scale interactions



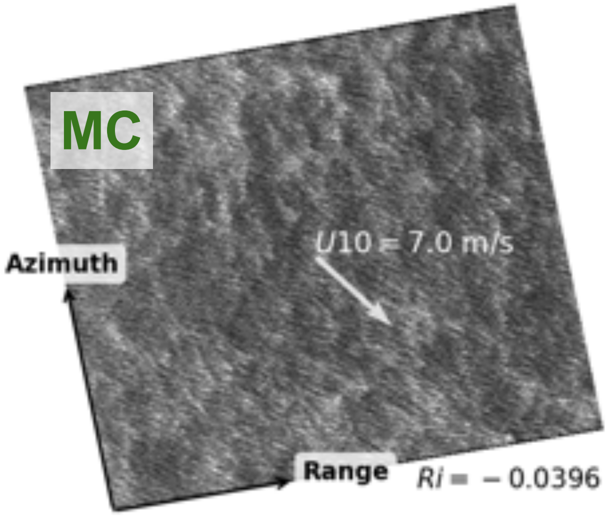


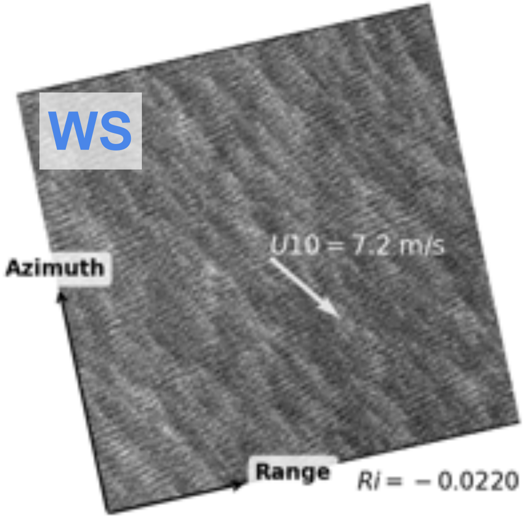
<u>Ocean</u>, mainly sea surface temperature distribution, back-scatters slow-time small-scale effects on fast time large atmospheric scales ! If the Atmosphere is a temporal-noise to the ocean, the Ocean becomes a spatial-noise to the atmosphere

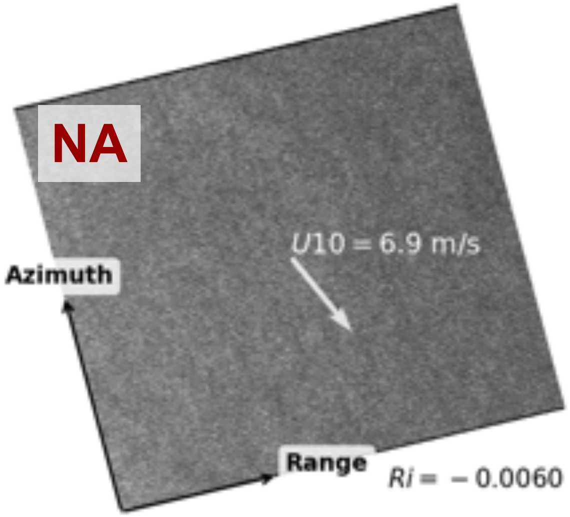


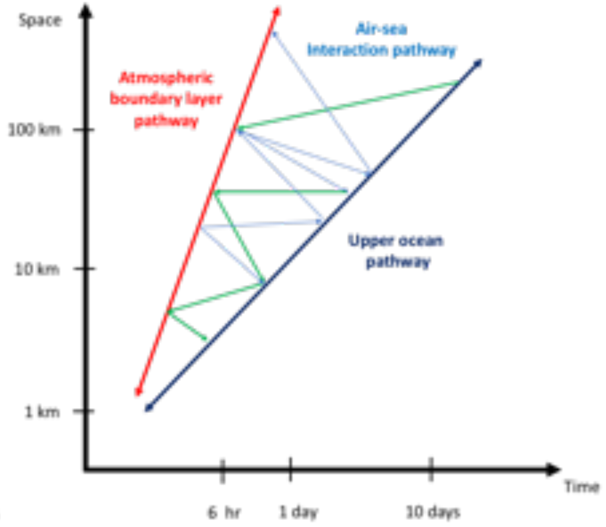
MABL rolls induce **Quasi-periodic perturbations** in wind speed
Instantaneous change in the sea surface roughness and surface stress

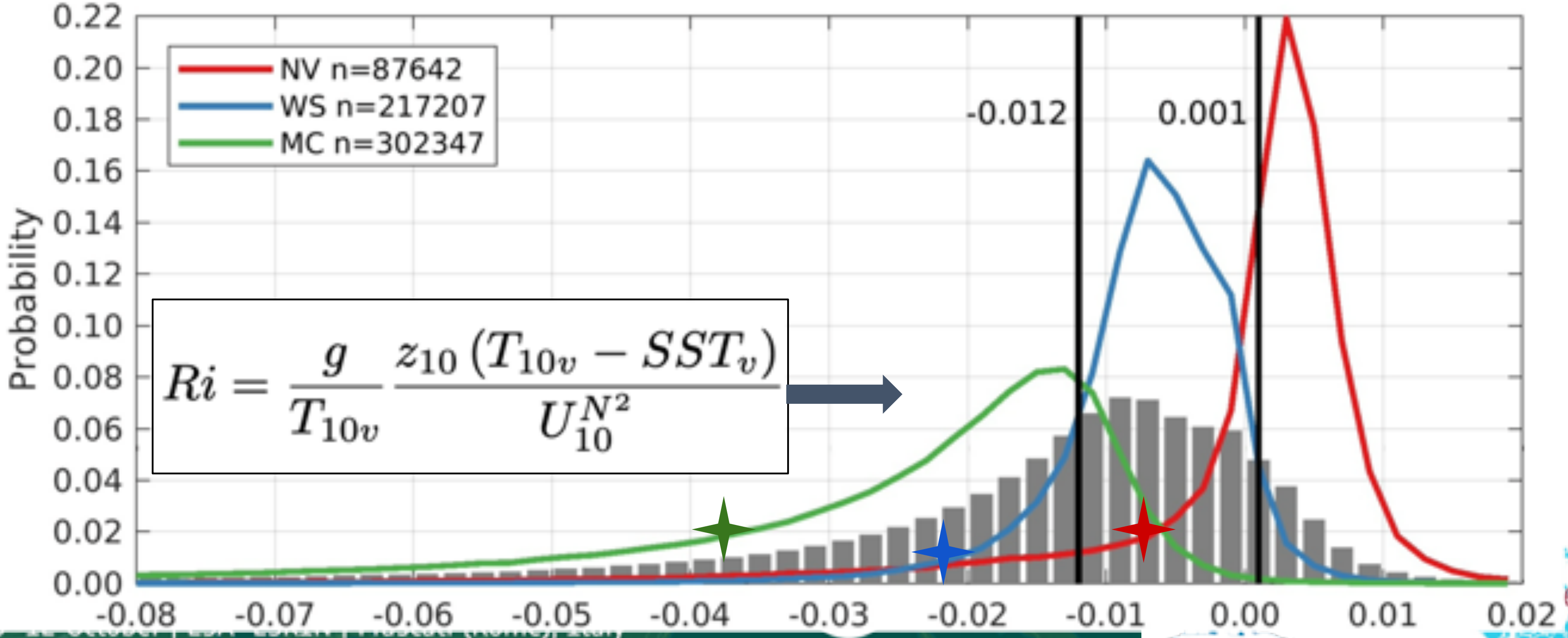












$$Ri = \frac{g}{T_{10v}} \frac{z_{10}\left(T_{10v} - SST_v\right)}{U_{10}^{N^2}}$$

Unstable

- more negative Ri
- favorable for MC

Near-neutral

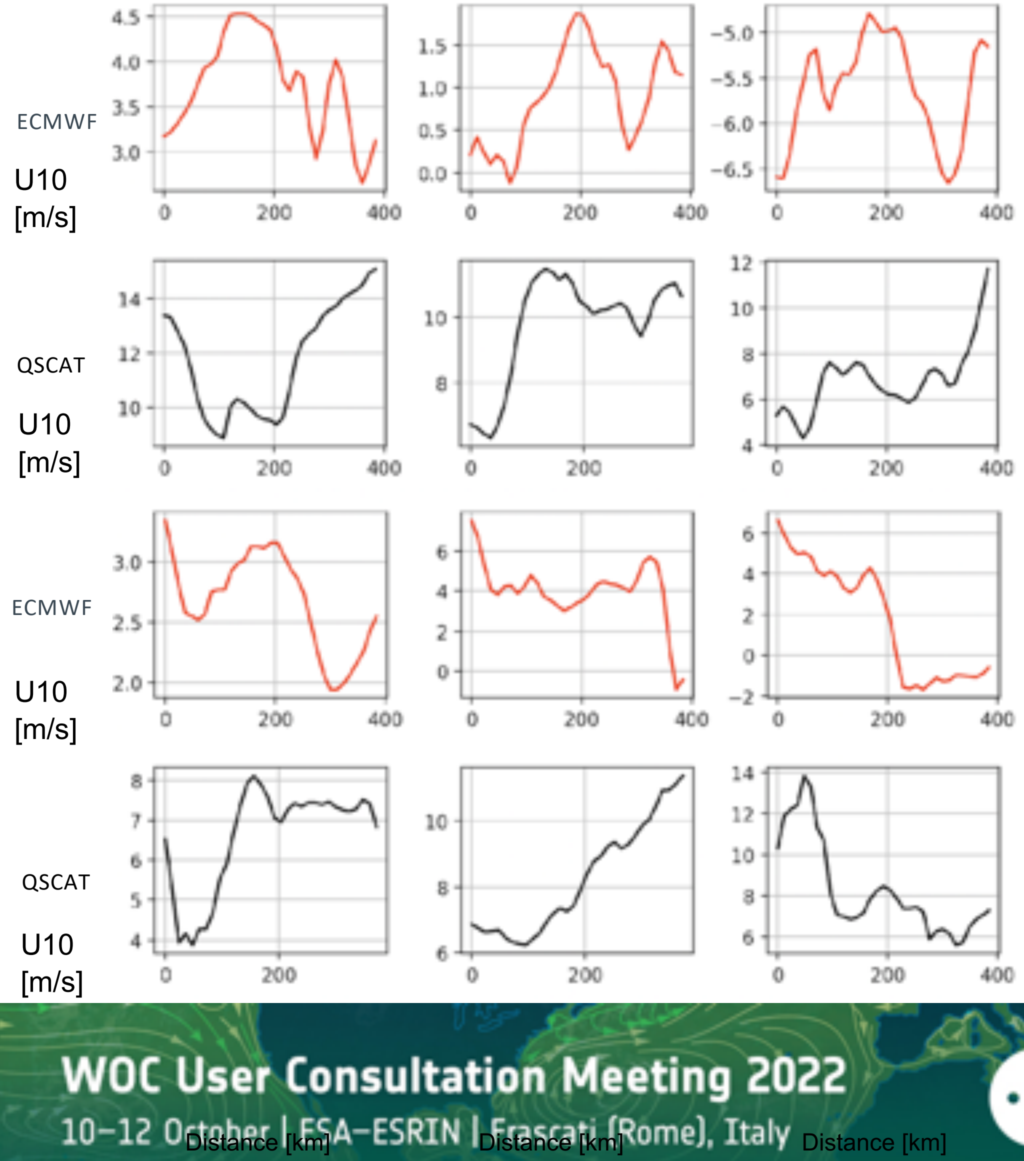
- weakly negative Ri
- favorable for WS

Stable

- positive Ri
- only turbulence left

Statistical Characterisation of Observed vs Modelled Wind Properties

Random Samples



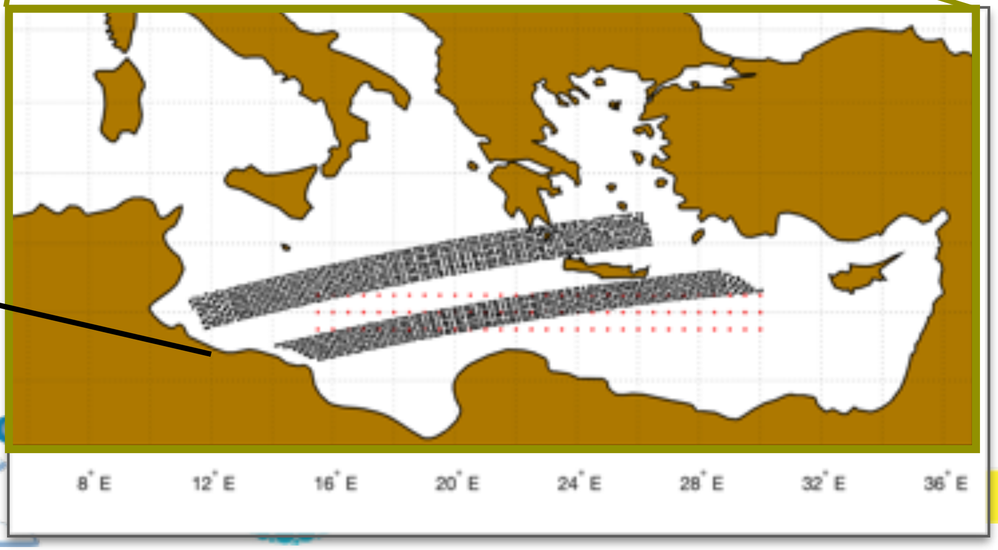
GRIDDED MODELING PRODUCT
(i.e., model analysis and forecast)
02-02-2005
6:00HR

SATELLITE ESTIMATES
(HARMONY-like SVW measurements)
02-02-2005
6:00/9:00HR

- Surface winds statistics from ECMWF analysis with various satellite estimates along “long” lines in Mediterranean Sea

Example of sampled lines

QSCAT vs ECMWF



Statistical Characterisation of Observed vs Modelled Wind distributed spatial Properties : ocean-noise back-scattering effects, captured by scatterometer measurements, are missing in NWP

ECMWF analysis, Mediterranean Sea

ASCAT (METOP-A), 2013, Mediterranean Sea

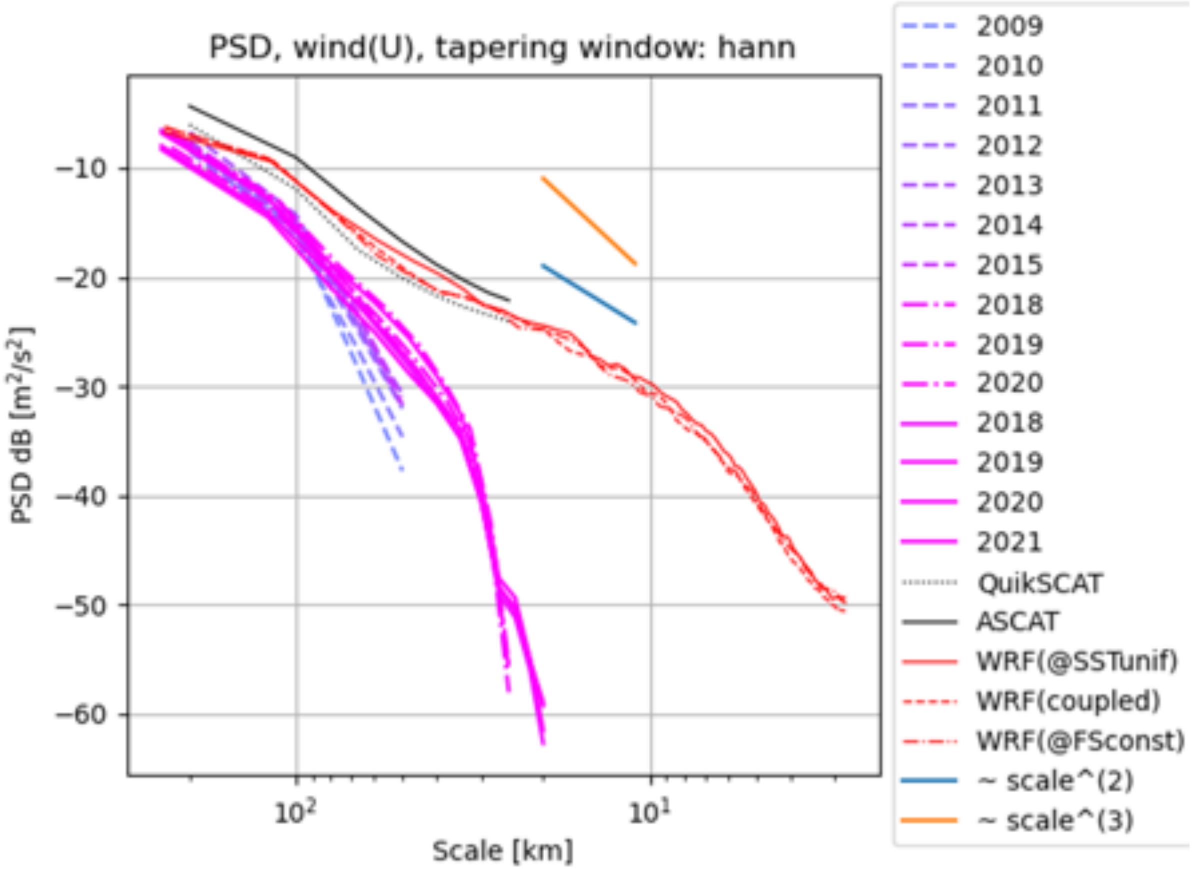
QuikScat, 2005, Mediterranean Sea

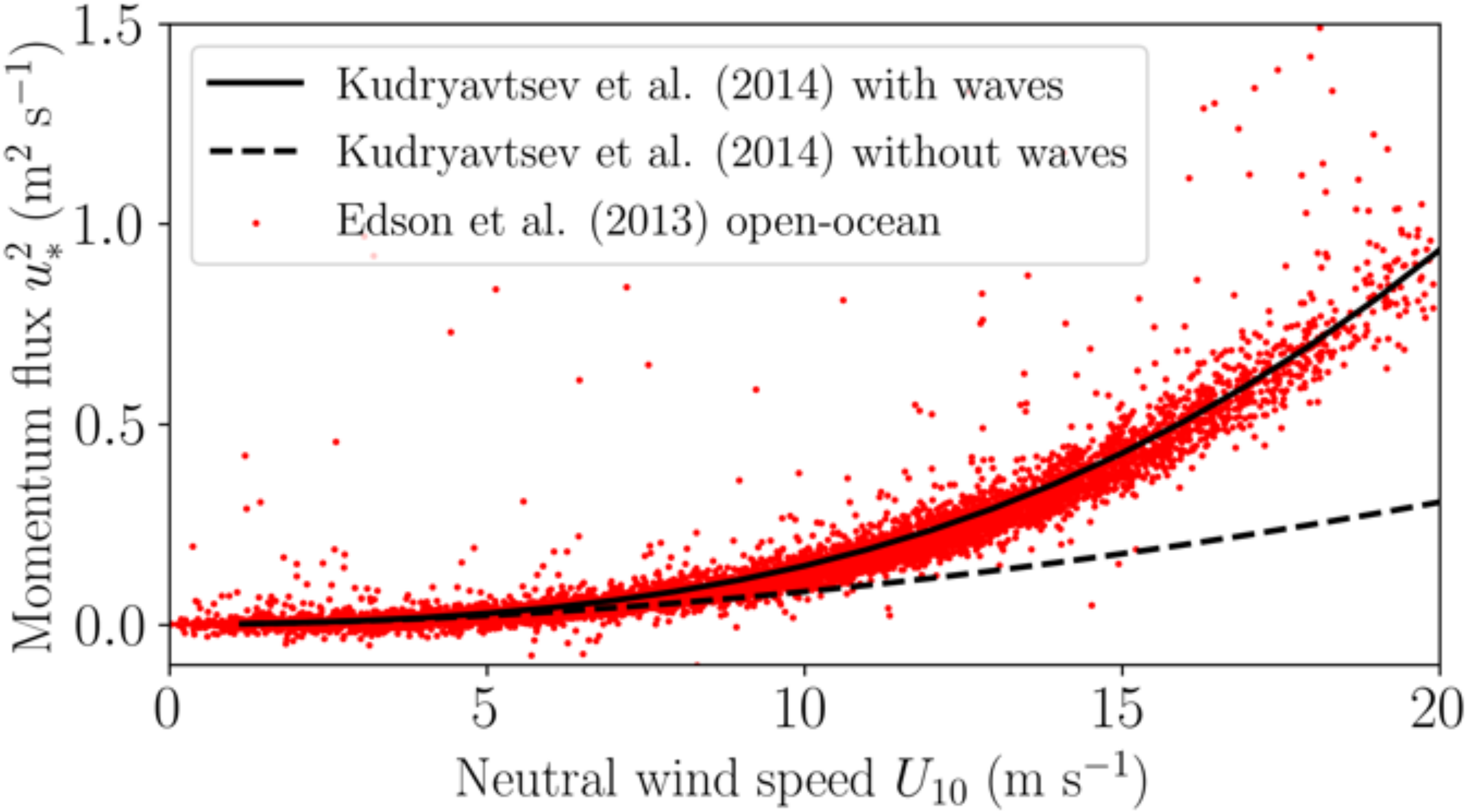
Med Sea, averages of PSD computed over 240 km line

WRF Winds Time window: 2014-10-06 to 2014-10-10.

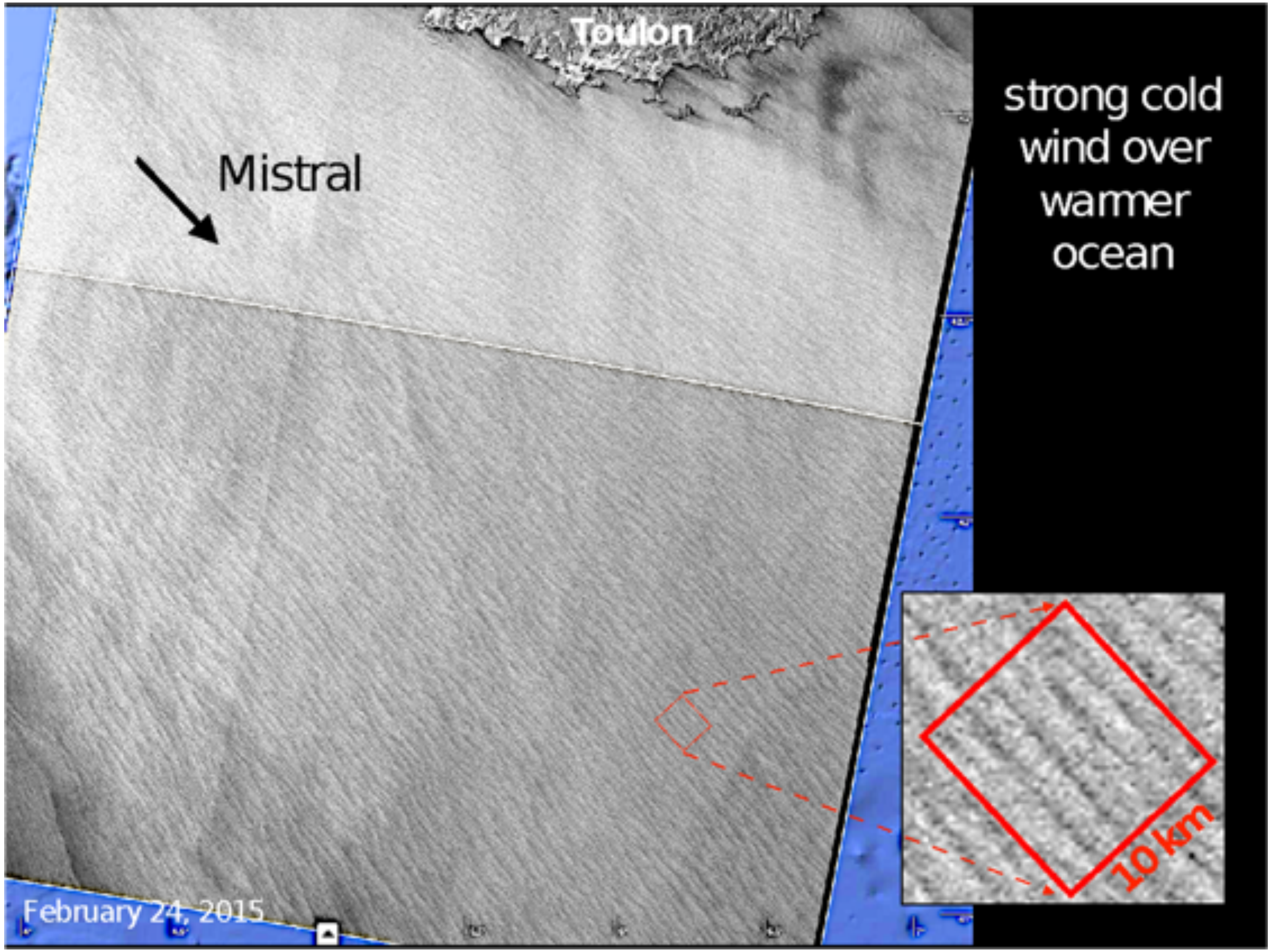
Region of interest: Ligurian Sea (domain-03).

Grid resolution: 1.4 km.




Kudryavtsev et al. (2014) with waves
Kudryavtsev et al. (2014) without waves
Edson et al. (2013) open-ocean
Momentum flux u_*^2 (m^2 s^{-1})
Neutral wind speed U_{10} (m s^{-1})
0.0
0.5
1.0
1.5
0
5
10
15
20

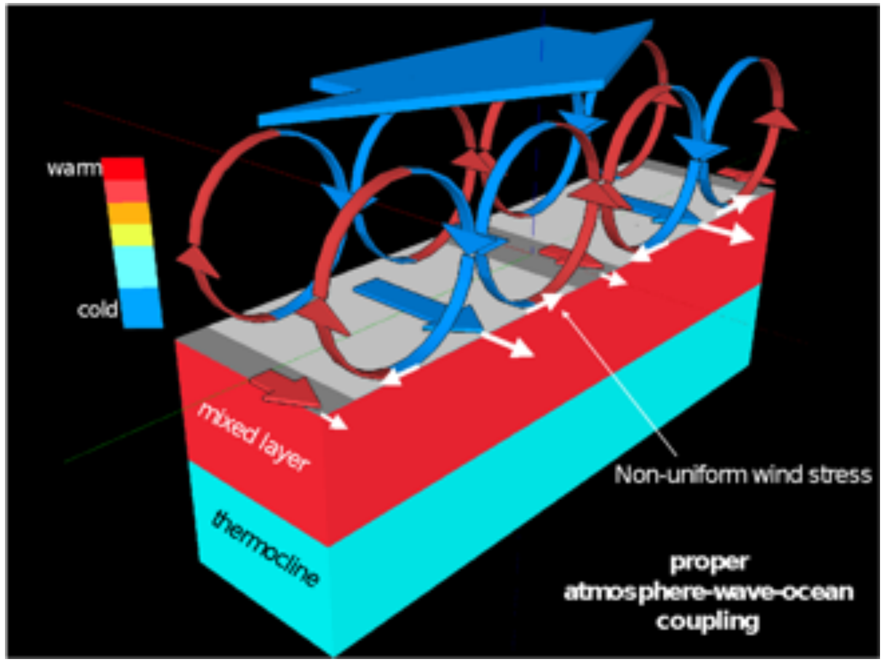
And about the waves ?



The Stokes-Ekman equation

$$\frac{\partial U}{\partial t} + ifU - \frac{\partial}{\partial z}\left(\nu_e(z,t)\frac{\partial U}{\partial z}\right) = -i\,f\,U_s(z,t)$$

The wave-induced current possibly stronger than the wind stress



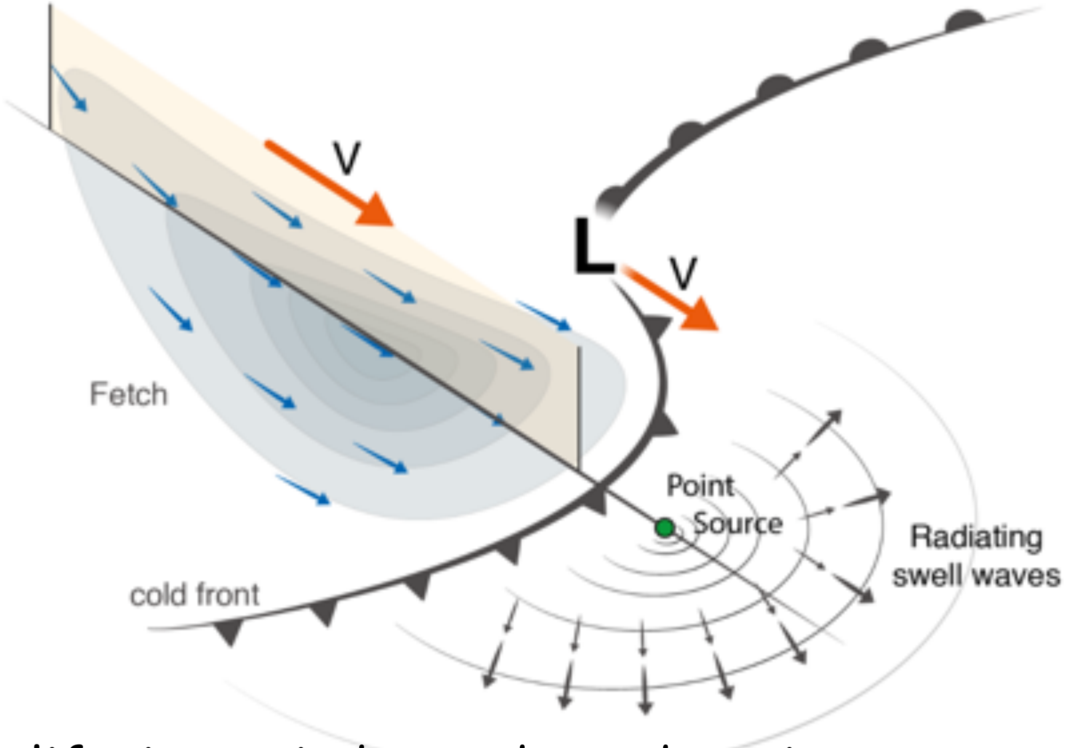
And about the waves ?

The Stokes-Ekman equation

$$\frac{\partial \boldsymbol{U}}{\partial t} + if\boldsymbol{U} - \frac{\partial}{\partial z}\left(\nu_e(z,t)\frac{\partial \boldsymbol{U}}{\partial z}\right) = -i\,f\,\boldsymbol{U}_s(z,t)$$

$$\boldsymbol{U}_s(z,t) = \frac{1}{2}\int_0^{\omega_c}\int_0^{2\pi} \omega\boldsymbol{k}(\omega,\theta)E(\omega,\theta,t)e^{-2|\boldsymbol{k}|z}d\omega d\theta.$$

A perspective in a Lagrangian frame of reference



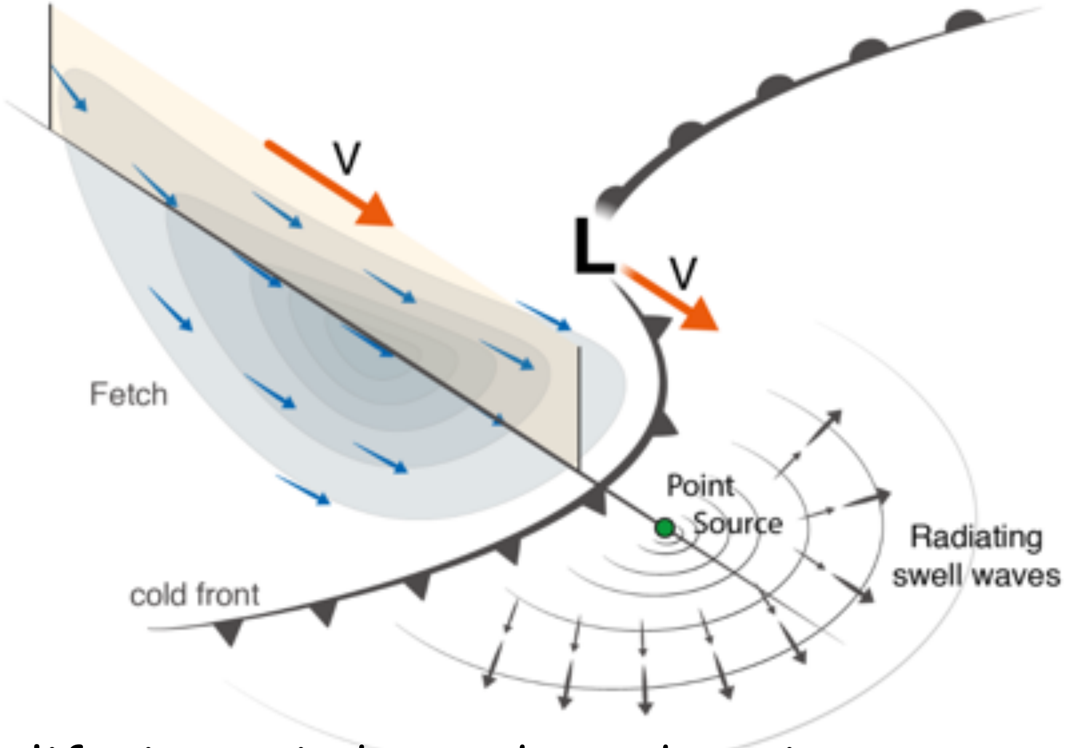
Strong and long energetic waves are not necessarily synchronized with storm maximum winds in both space and time

Lagrangian Stokes drift distributed over the horizontal and vertical scales, depends on the sea state degree of development, and possibly (likely), further interacting with interior ocean currents !

Storm size, lifetime, wind speeds, and motions compress the wave energy to a small area, and control the amplitude and period of swell events.

And about the waves ?

A perspective in a Lagrangian frame of reference



The Stokes-Ekman equation

$$\frac{\partial \boldsymbol{U}}{\partial t} + if\boldsymbol{U} - \frac{\partial}{\partial z}\left(\nu_e(z,t)\frac{\partial \boldsymbol{U}}{\partial z}\right) = -i\,f\,\boldsymbol{U}_s(z,t)$$

$$\boldsymbol{U}_s(z,t) = \frac{1}{2}\int_0^{\omega_c}\int_0^{2\pi} \omega \boldsymbol{k}(\omega,\theta)E(\omega,\theta,t)e^{-2|\boldsymbol{k}|z}d\omega d\theta.$$

Strong and long energetic waves are not necessarily synchronized with storm maximum winds in both space and time

An evolving wave field produces decaying inertial oscillations and a non-oscillating current

The current deflection is no longer pi/4 and the Ekman flux is not orthogonal to the wind !

Storm size, lifetime, wind speeds, and motions compress the wave energy to a small area, and control the amplitude and period of swell events.

About the rapid wind-wave interactions with the slowly evolving background?

Consider a simplified steady-state model: $\boldsymbol{f}\times\boldsymbol{u} - \frac{a_H}{2}\Delta\boldsymbol{u} = \frac{1}{\rho_b}\nabla\boldsymbol{p}$

where $\boldsymbol{u}$ is the slow-evolving horizontal velocity, a_H, an horizontal diffusion coefficient associated to the variance of rapidly-evolving upper ocean fluctuations, $\nabla\boldsymbol{p}$, the slow-evolving component of the pressure, possibly including the additional large-scale wind-stress forcing, and ρ_b, the mean density (to possibly include local buoyancy gradient effects). Helmholtz-Hodges decomposition:

$$\boldsymbol{u} = \nabla^{\perp}\psi + \nabla\widetilde{\psi},$$

with (Fourier space)

$$\hat{\psi} = \left(1 + \left\|{}^{\boldsymbol{k}}/_{k_c}\right\|^4\right)^{-1}\frac{\hat{\boldsymbol{p}}}{\rho_b f}$$

where $k_c = \sqrt{2f/a_H}$, corresponds to a spatial cutoff wavenumber : <u>it is possibly evolving on fast short scales</u>

The ageostrophic component of the velocity, $\nabla\widetilde{\psi}$,

$$\tilde{\psi} = \frac{1}{k_c^2}\Delta\psi$$

this contribution will act to dilate the anticyclones, maximum of pressure and negative vorticity, and to shrink the cyclones, minimum of pressure and positive vorticity, at small scales

Upper Ocean Dynamics: Sensor-Model synergies for stochastic descriptions
Digital replica and DTO strategies : blending theoretical/analytical models and data analysis

- Numerous Remote sensing measurements
  - Very high resolution (100 m – 1 km) SST, Ocean Colour, radar and optical roughness images
  - Low resolution Altimetry (50 km)
  - Mesoscale Ocean Wind Vector Scatterometry and Microwave SST and SSS (25 km), Directional wave propagation (20 km - 5000 km)

- Increased In Situ measurements
  - Fixed networks
  - AIS ship opportunities
  - ARGO floats
  - Drifters

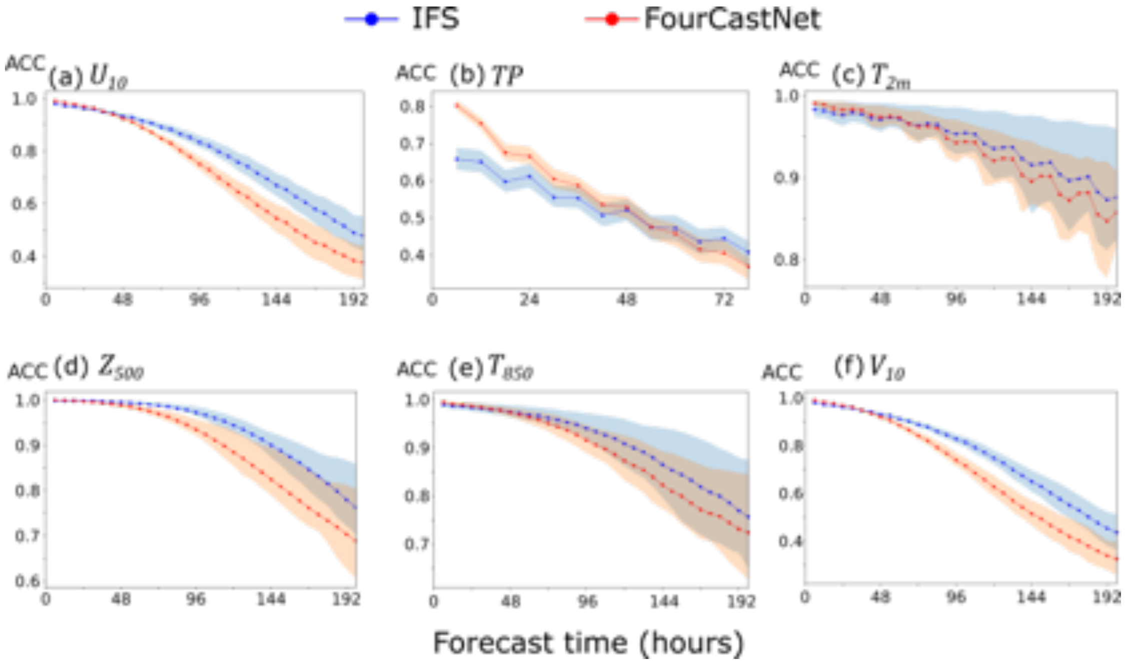
- Dynamical frameworks
  - Assimilation constrained Operational models (and resulting NN emulators)
  - Quasi-geostrophy, Surface Quasi-geostropy, Ekman, …
  - Model-Driven Data-Constrained (MDDC),Data-Driven Physics-Constrained (DDPC)

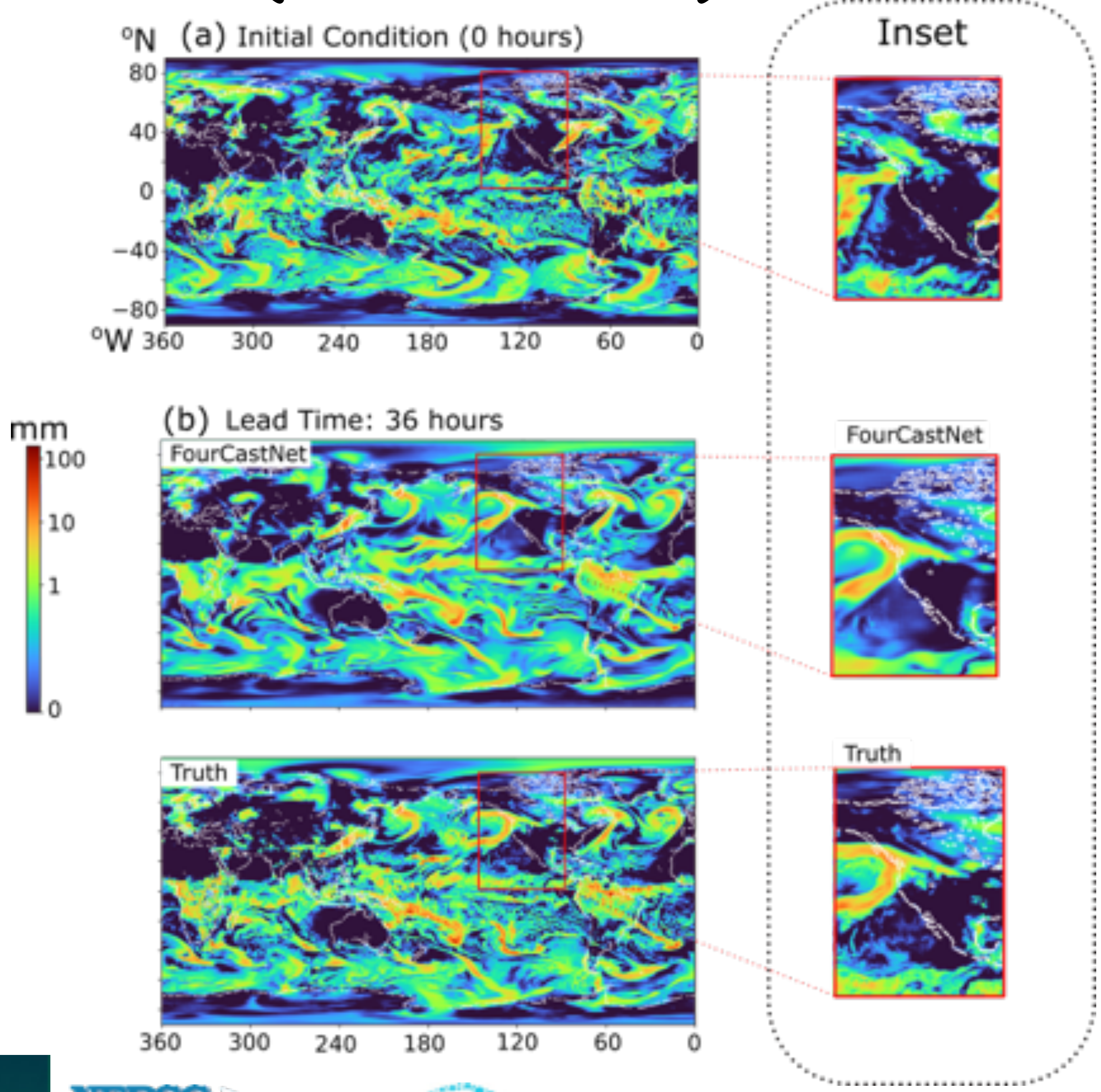
Model-tree of knowledge

$$
\begin{cases}
\mathbf{x}(k) = \mathscr{M}_k\left(\mathbf{x}(k-1)\right) + \boldsymbol{\eta}(k), \\
\mathbf{y}(k) = \mathscr{H}_k\left(\mathbf{x}(k)\right) + \boldsymbol{\epsilon}(k),
\end{cases}
$$

Forecasting Results – General (NVIDIA)

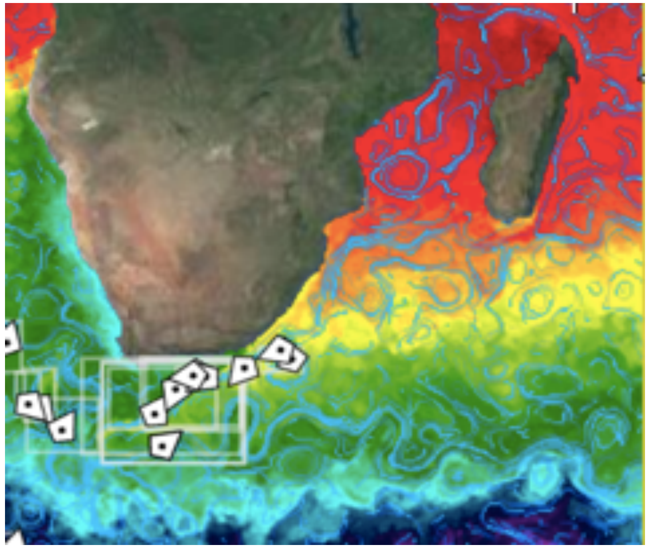
- FourCastNet reproduces structures
- Prediction Skill (ACC) close to IFS up to 8 days into the future

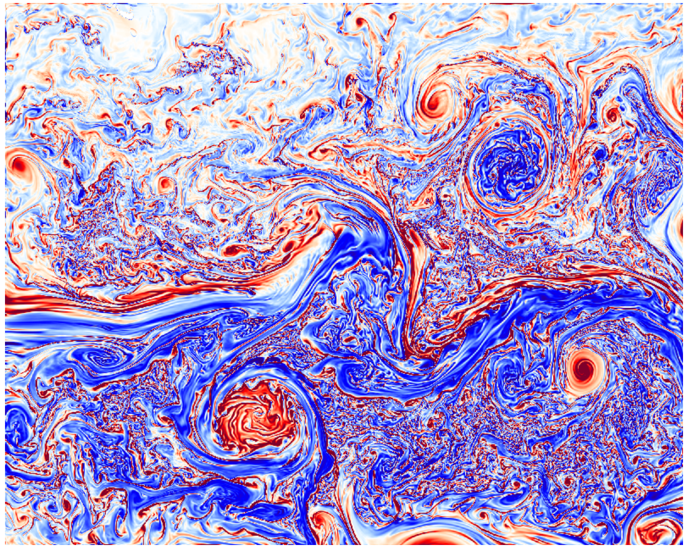


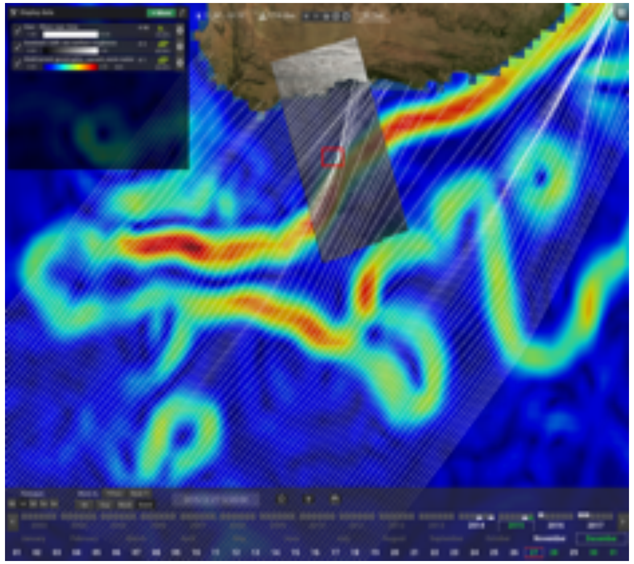


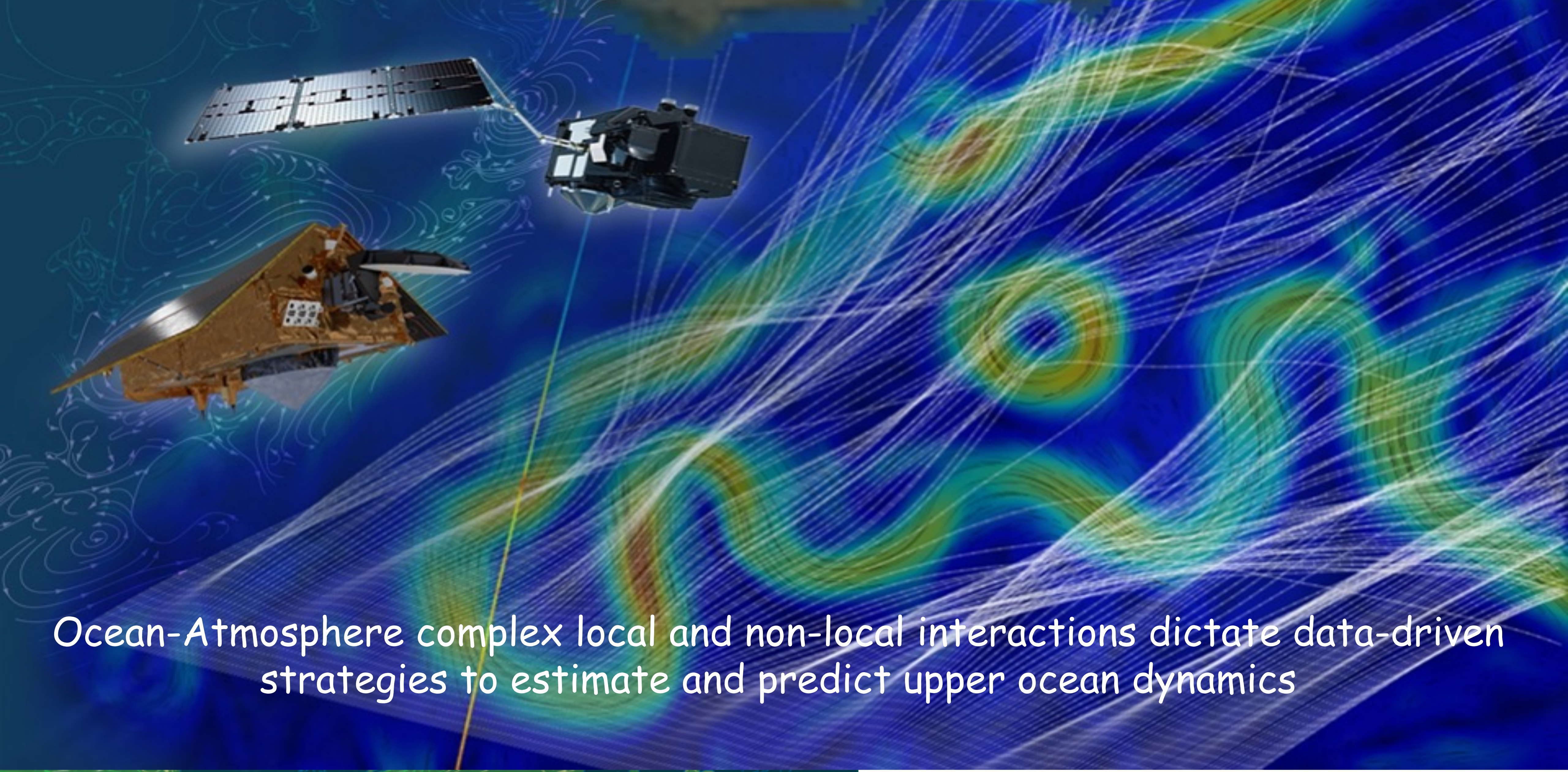
DTO-WOC perspectives: Observations bear the full probabilistic signatures of all O-A complex interactions and effects

- Infer spatio-temporal statistical properties from data : Catalogues of millions of co-located observations (learning multi-scale interactions and energy distributions, analogs and DL techniques, joint SSH-SST-SSS-Colour analysis, high-low SST-Colour analysis, Lagrangian diagnostics, Eulerian diagnostics)
- Diagnose upper ocean dynamics (dimension reduction): Data-bank of knowledge vs Model-tree of knowledge
- Linking spatio-temporal properties with consistently-derived rigorous theoretical models and/or data analysis and Machine Learning methods : Calibrate model subgrid parametrizations
- Quantify upscale effects of unresolved sub-mesoscales processes on the large-scale circulation









Ocean-Atmosphere complex local and non-local interactions dictate data-driven strategies to estimate and predict upper ocean dynamics

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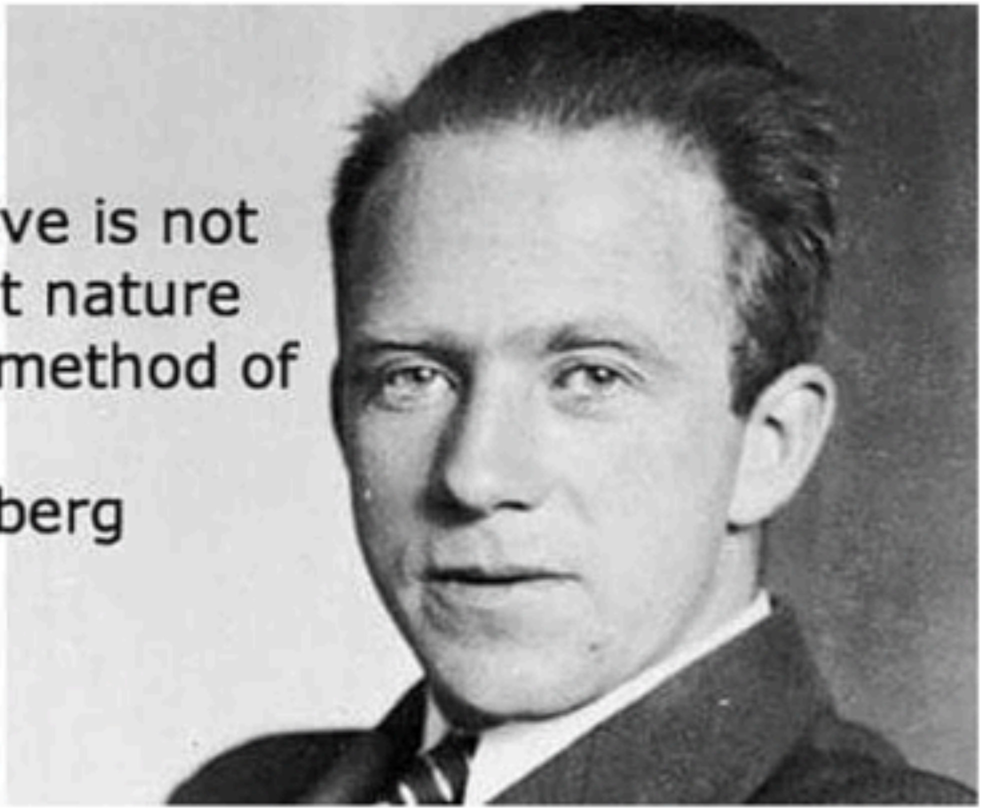
"What we observe is not nature itself, but nature exposed to our method of questioning."
-Werner Heisenberg



$$\begin{cases} \mathbf{x}(k) = \mathscr{M}_k\left(\mathbf{x}(k-1)\right) + \boldsymbol{\eta}(k), \\ \mathbf{y}(k) = \mathscr{H}_k\left(\mathbf{x}(k)\right) + \boldsymbol{\epsilon}(k), \end{cases}$$

Ocean-Atmosphere complex local and non-local interactions dictate data-driven strategies to estimate and predict upper ocean dynamics: <u>let's discuss our plans and next steps this week</u> !