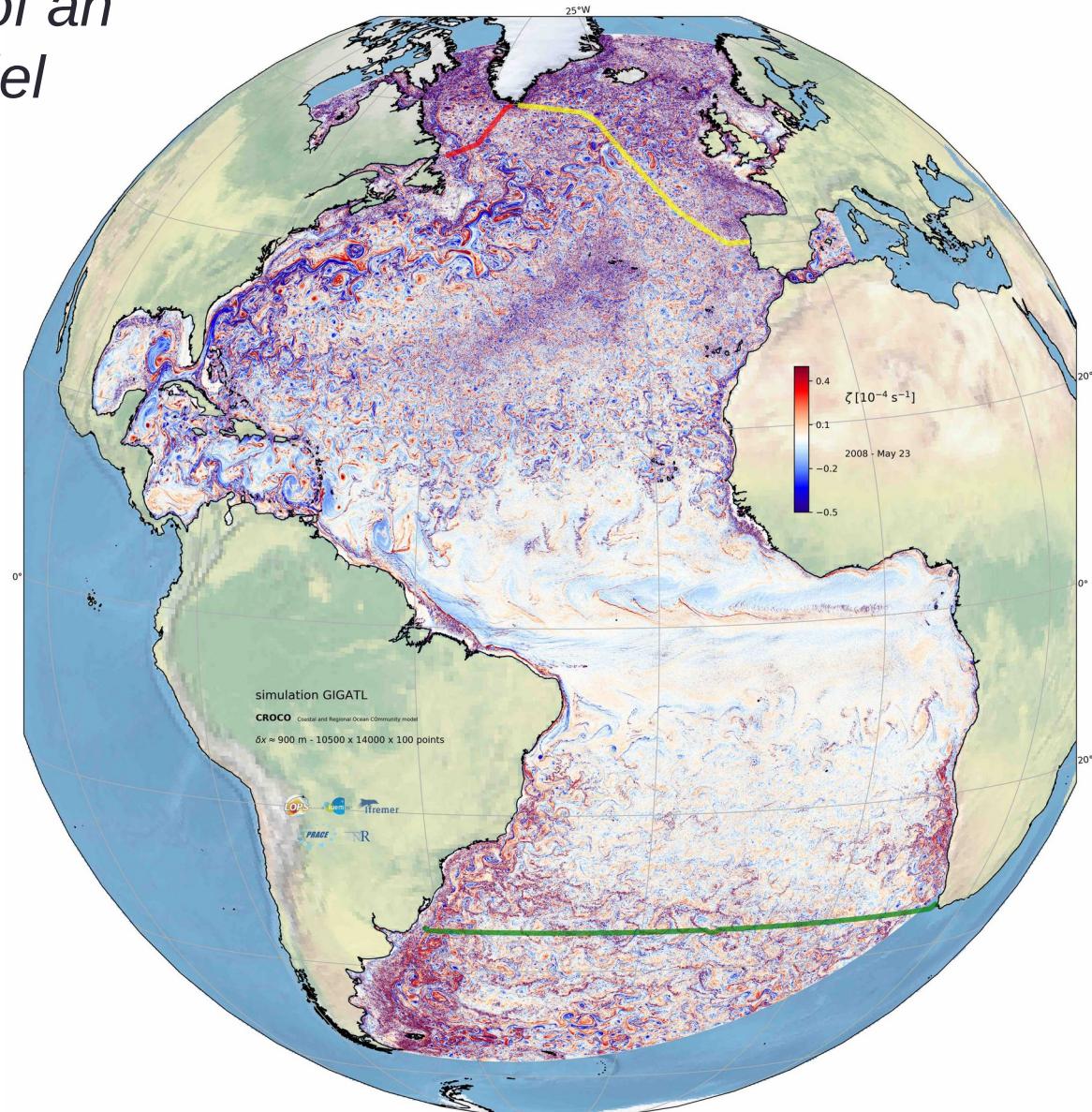


Numerical Modelling

*the anatomy of an
ocean model*

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- **Lesson 1 : [D109]**
 - Introduction
 - Equations of motions
 - *Activity 1 [run an ocean model]*
- **Lesson 2 : [B 012]**
 - Horizontal Discretization
 - *Activity 2 [Dynamics of an ocean gyre]*
- **Lesson 3 : [D109]**
 - Presentation of the model CROCO
 - Dynamics of the ocean gyre
 - *Activity 2 [Dynamics of an ocean gyre]*
- **Lesson 4 : [D109]**
 - Numerical schemes + subgrid param
 - *Activity 3 [Impacts of numerics]*
- **Lesson 5 : [D109]**
 - Vertical coordinates
 - *Activity 3 [Impact of topography]*
- **Lesson 6 : [D109]**
 - Boundary Forcings
 - *Activity 4 [Design a realistic simulation]*
- **Lesson 7 : [D109]**
 - Diagnostics and validation
 - *Activity 5 [Analyze a realistic simulation]*
- **Lesson 8 : [D109]**
 - *Work on your projet*

Presentations and material will be available at :

jgula.fr/ModNum/

**[https://github.com/quentinjamet/
Tuto/tree/main/ModNum](https://github.com/quentinjamet/Tuto/tree/main/ModNum)**

Numerical Modelling

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Evaluation

- The evaluation is based on a project, which consists in setting up a realistic configuration of the region of your choice, run the experiment and perform some analysis.
- Written Report due for (**Feb. 15**)

Useful references

Extensive courses:

- MIT:
<https://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-950-atmospheric-and-oceanic-modeling-spring-2004/lecture-notes/>
- Princeton: https://stephengriffies.github.io/assets/pdfs/GFM_lectures.pdf

Overview on ocean modelling and current challenges:

- Griffies et al., 2000, Developments in ocean climate modelling, Ocean Modelling.
<http://jgula.fr/ModNum/Griffiesetal00.pdf>
- Griffies, 2006, "Some Ocean Model Fundamentals", In "Ocean Weather Forecasting: An Integrated View of Oceanography", 2006, Springer Netherlands. http://jgula.fr/ModNum/Griffies_Chapter.pdf
- Fox-Kemper et al, 19, "Challenges and Prospects in Ocean Circulation Models"
<http://jgula.fr/ModNum/FoxKemperetal19.pdf>

ROMS/CROCO:

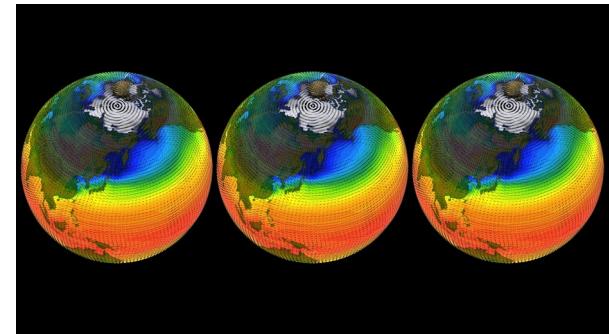
- <https://www.croc-ocean.org/documentation/>
- https://croc-ocean.gitlabpages.inria.fr/croc_doc/index.html
- Shchepetkin, A., and J. McWilliams, 2005: The Regional Oceanic Modeling System (ROMS): A split-explicit, free-surface, topography-following- coordinate ocean model. Ocean Modell.
<http://jgula.fr/ModNum/ShchepetkinMcWilliams05.pdf>

Introduction

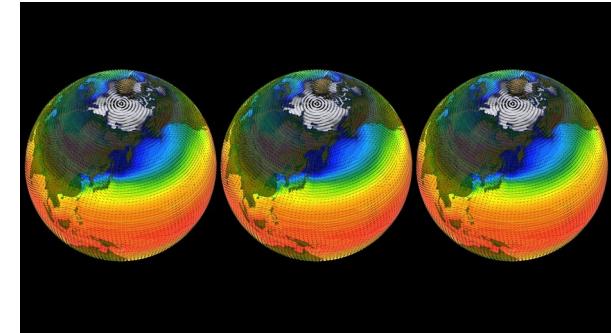
Master's degree 2nd year Marine Physics

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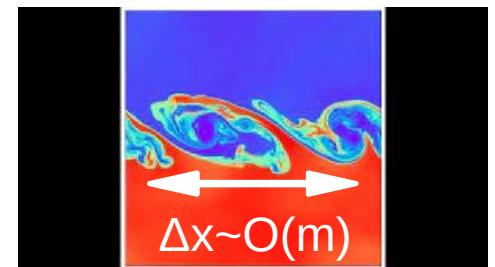
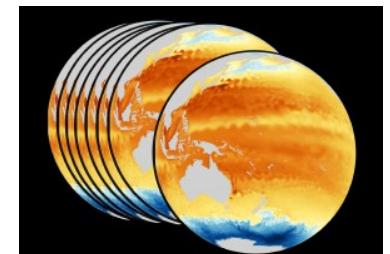
- For what ocean model are used for?



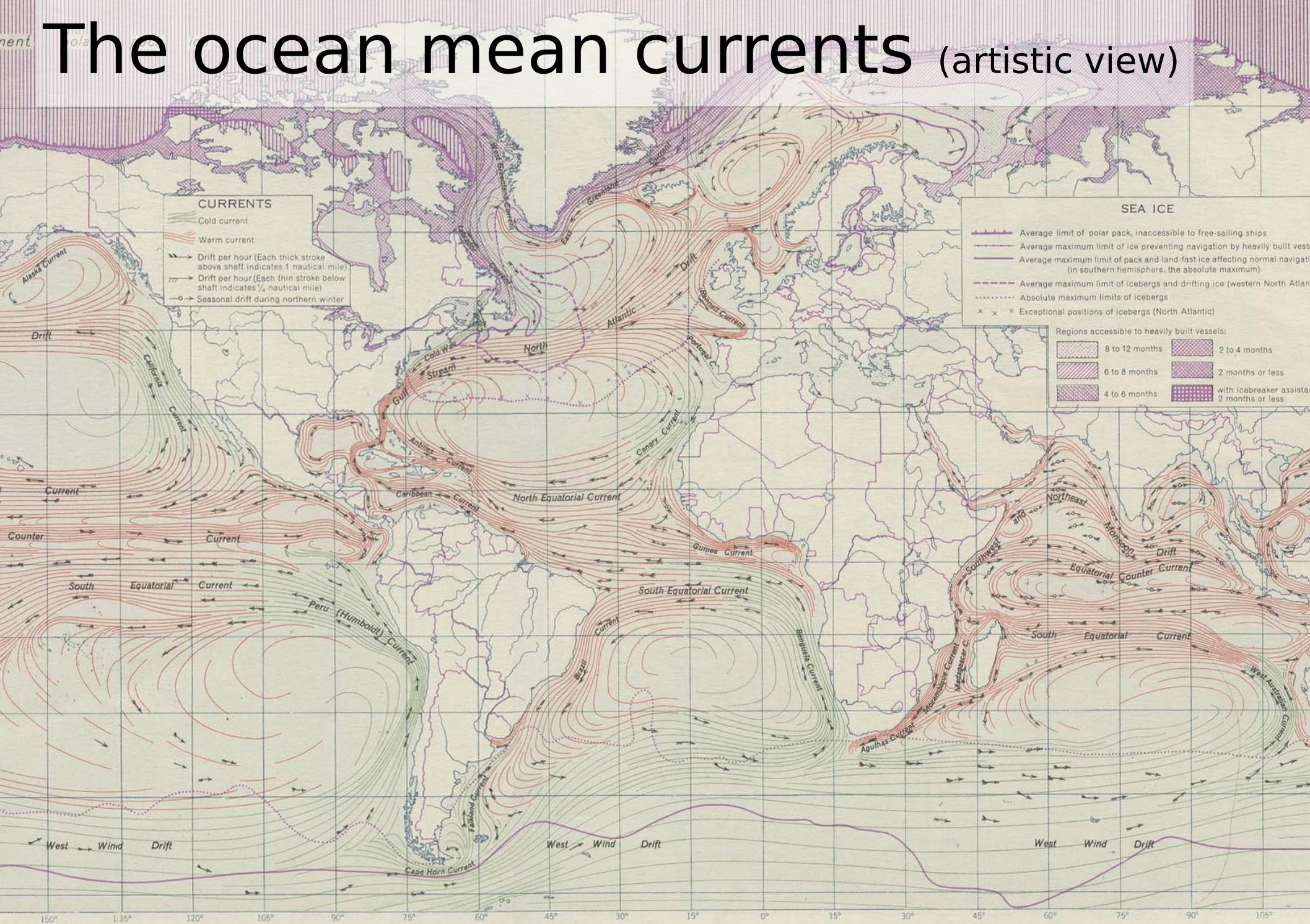
- For what ocean model are used for?



- Weather forecasts and Climate projections
- Explore different states of the ocean and earth system
- Better understand the complex dynamics of geophysical flow, from small to large scales
- Testing (idealized) mathematical models
- ...



The ocean mean currents (artistic view)



Can be understood using theory and simplified models

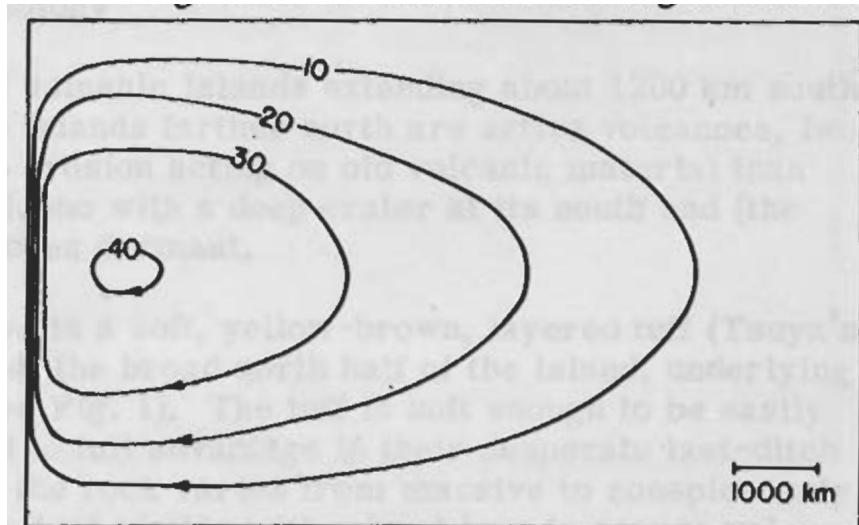
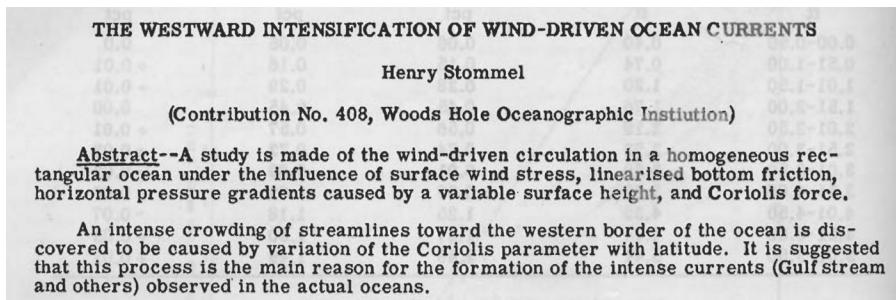


Fig. 5--Streamlines for the case where the Coriolis force is a linear function of latitude

Stommel (1948)

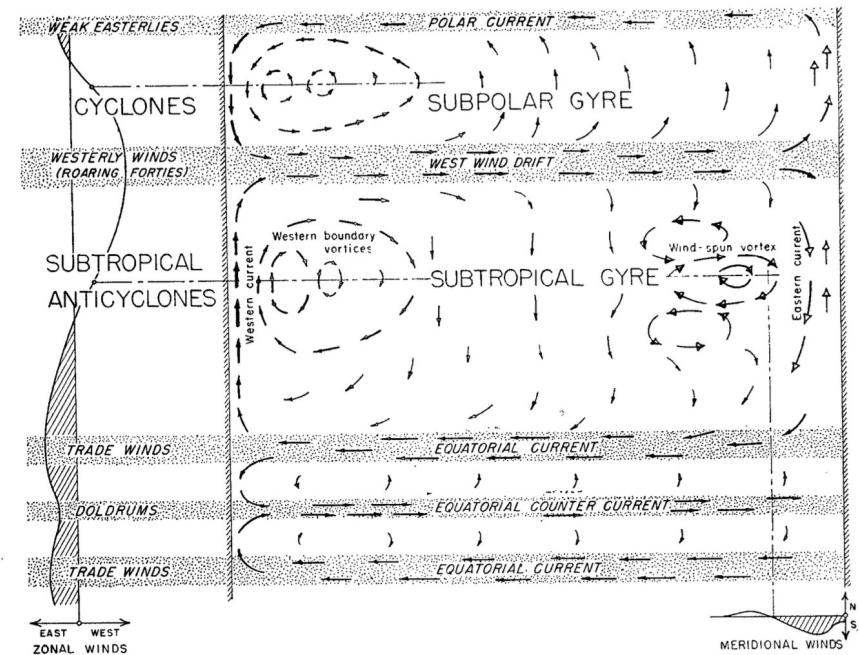
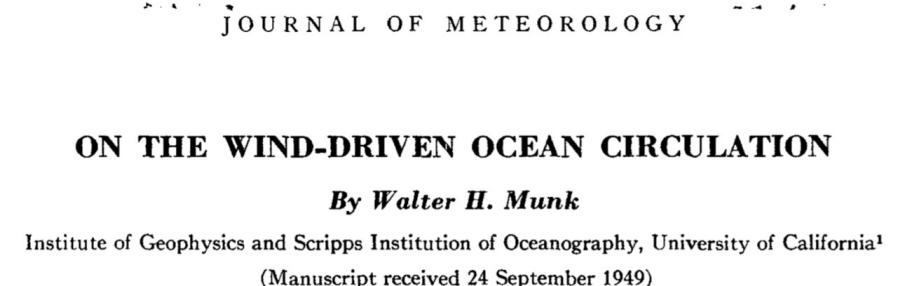
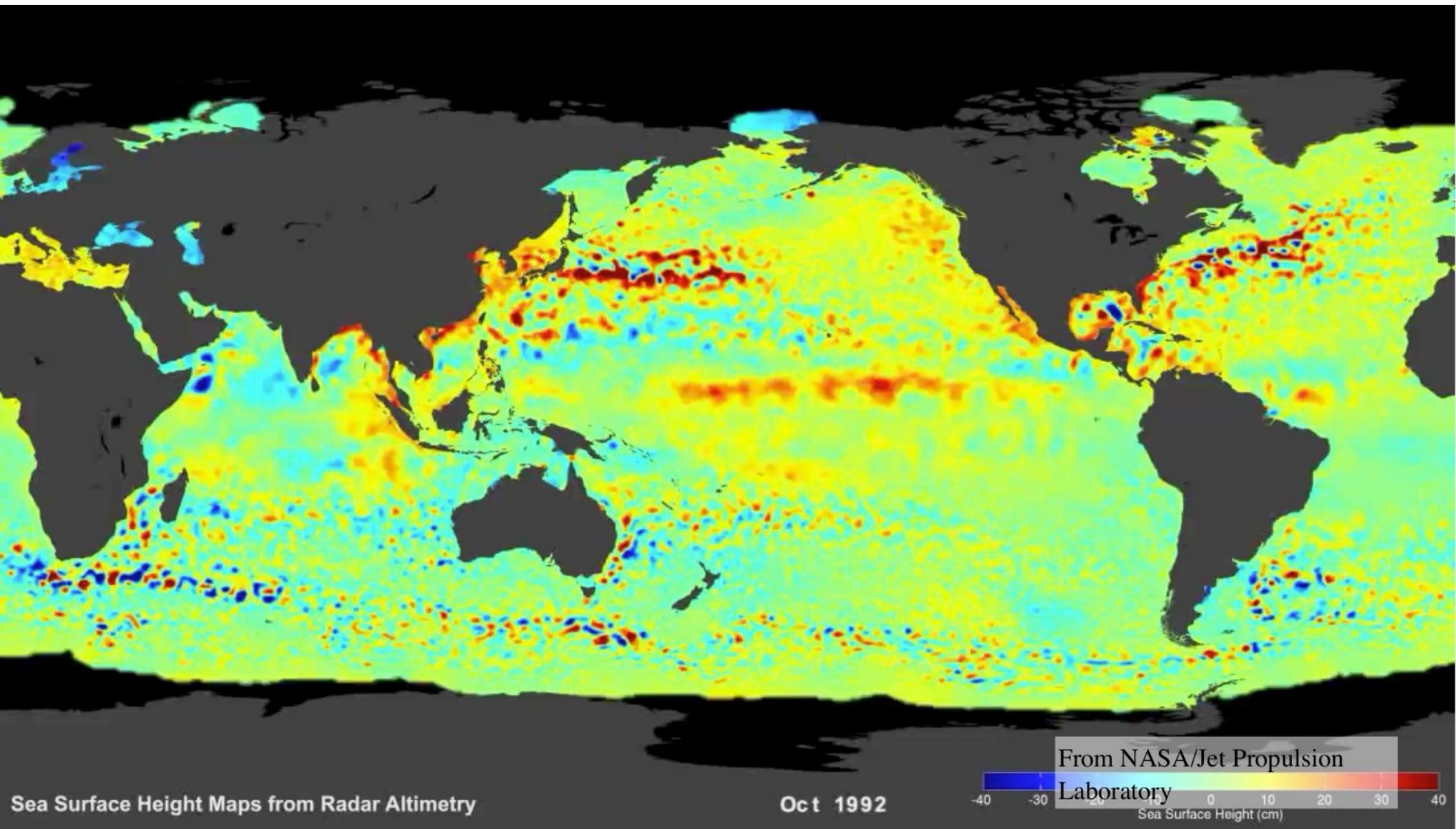


FIG. 8. Schematic presentation of circulation in a rectangular ocean resulting from zonal winds (filled arrowheads), meridional winds (open arrowheads), or both (half-filled arrowheads). The width of the arrows is an indication of the strength of the currents. The nomenclature applies to either hemisphere, but in the Southern Hemisphere the subpolar gyre is replaced largely by the Antarctic Circumpolar Current (west wind drift) flowing around the world. Geographic names of the currents in various oceans are summarized in table 3.

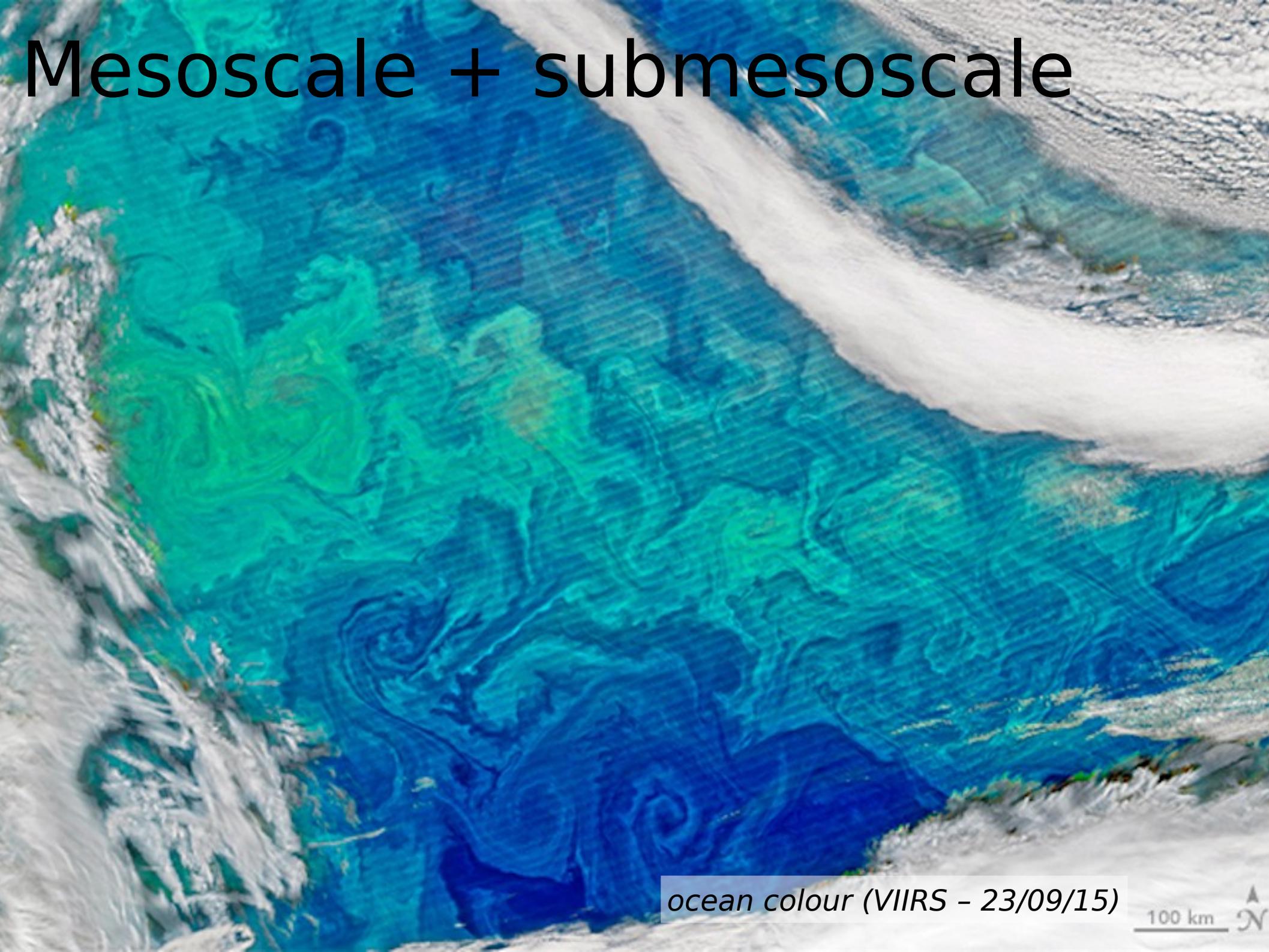
Munk (1950)

But reality is much more turbulent:



'Snapshot' of the global sea surface height (SSH)

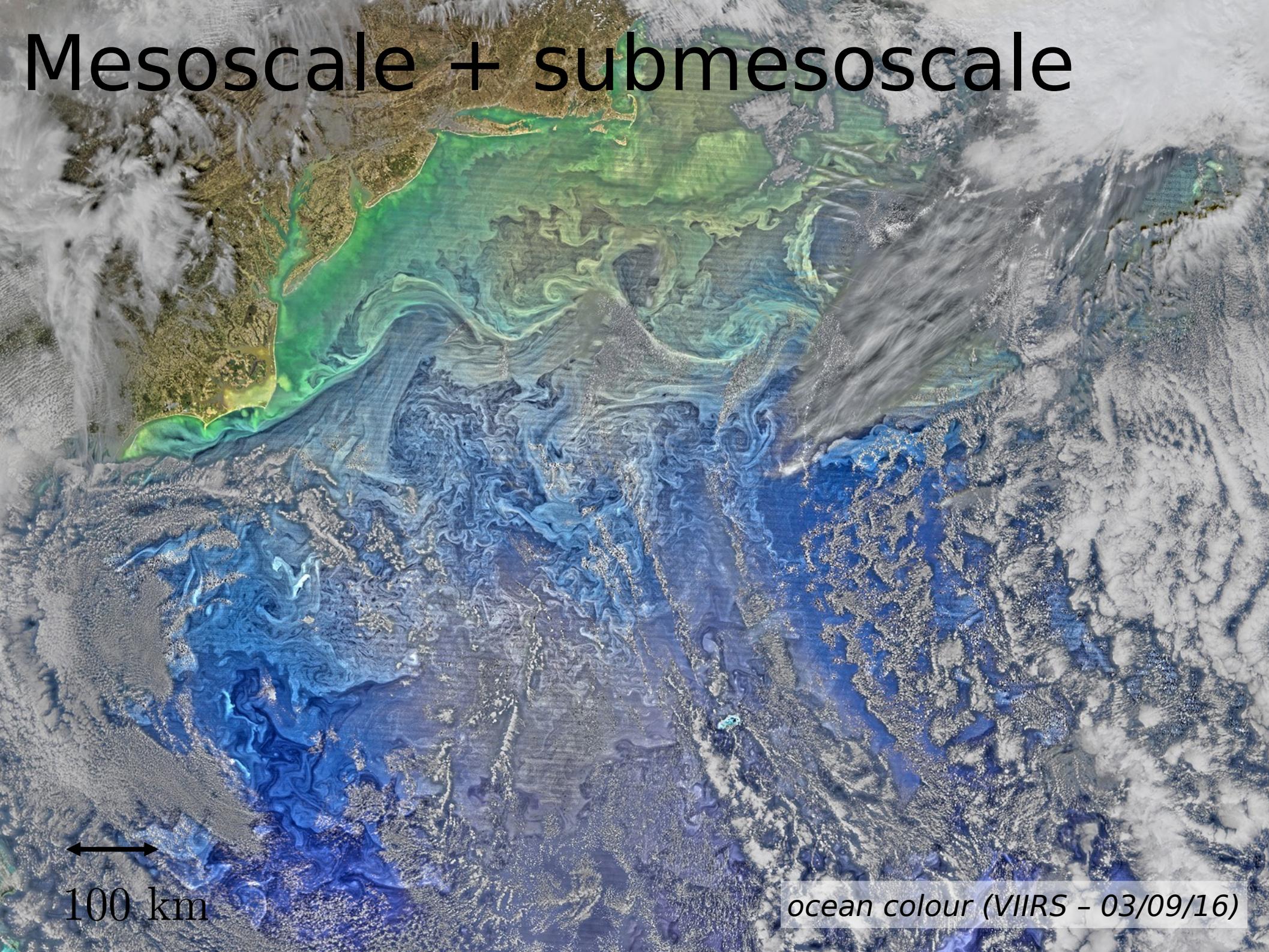
Mesoscale + submesoscale



ocean colour (VIIRS - 23/09/15)

100 km 

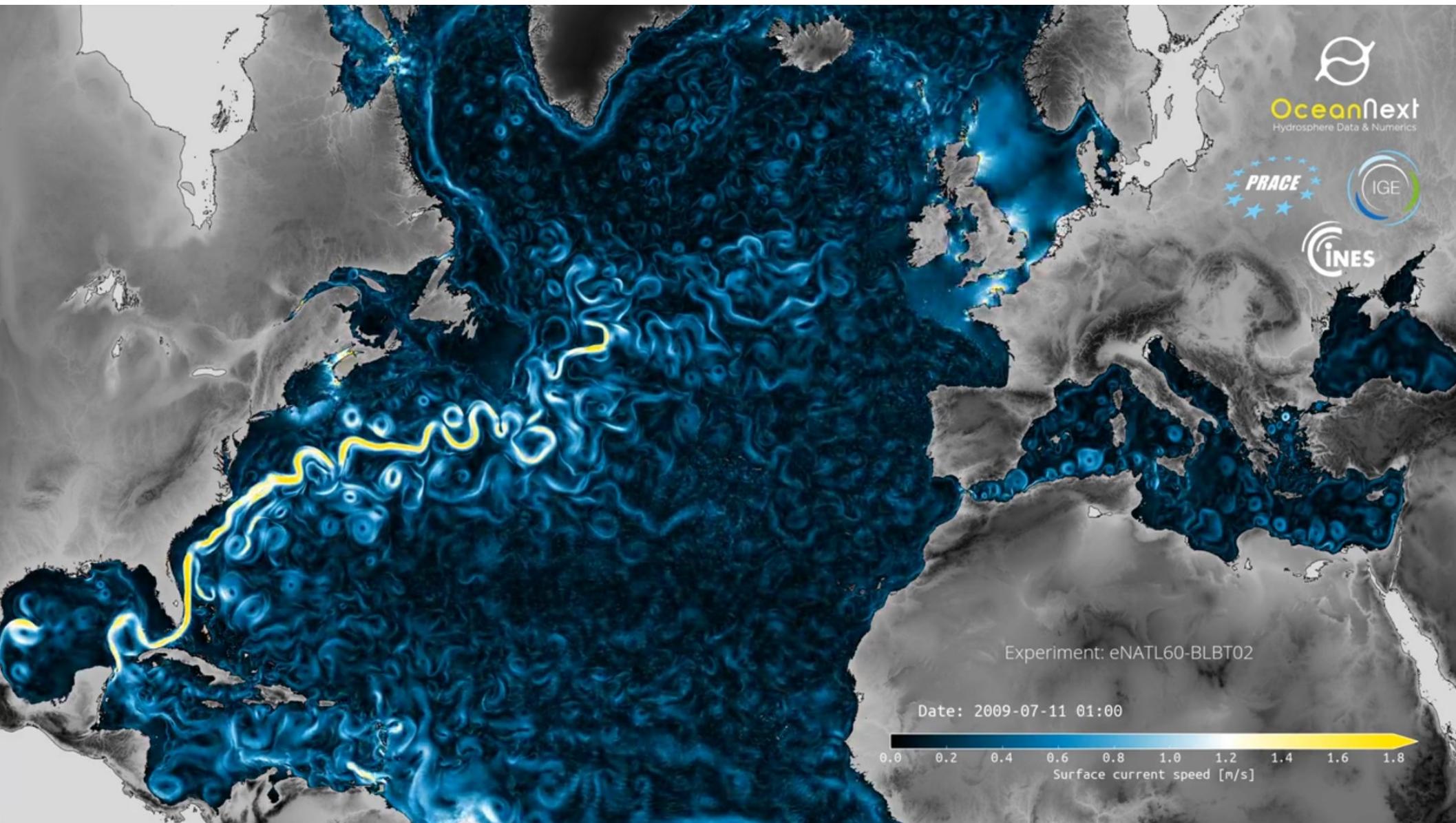
Mesoscale + submesoscale



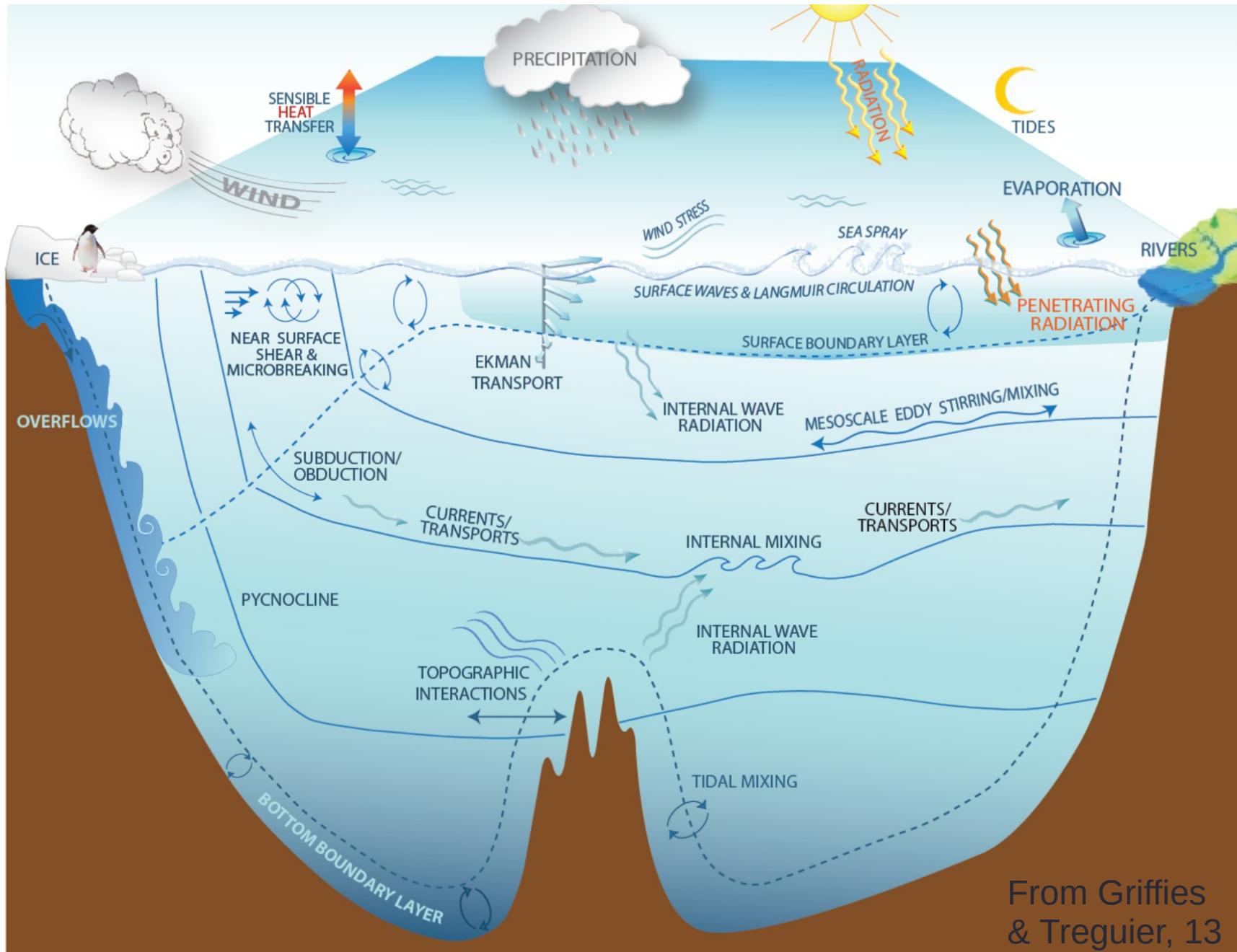
100 km

ocean colour (VIIRS - 03/09/16)

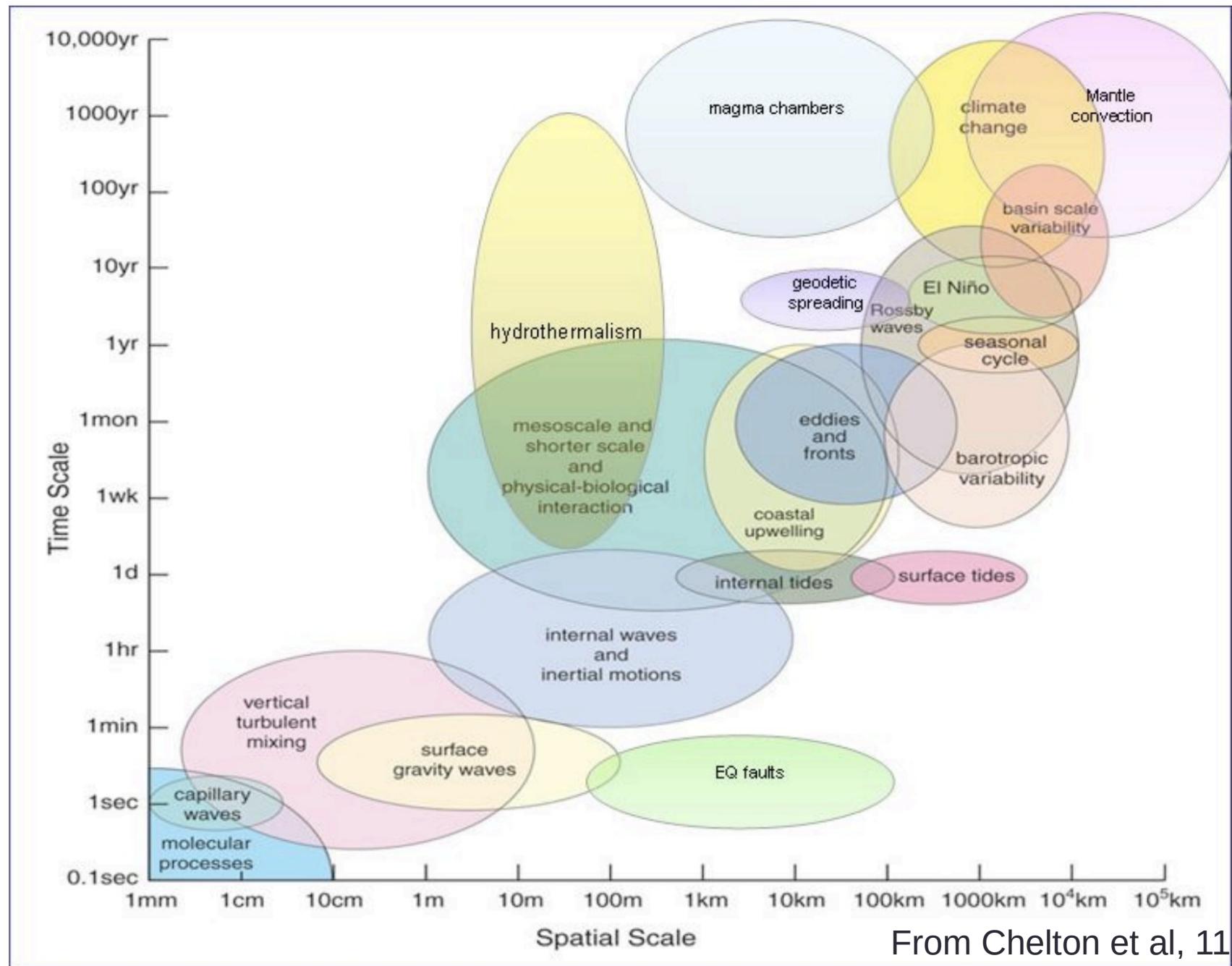
And HF motions like tides:



A zoo of processes and scales



Temporal and spatial scales in the ocean



Temporal and spatial scales in the ocean

*"We can therefore set up **seven equations** independent from each other with the **seven normally occurring variables**.*

As far as it is possible to have an overview of the problem now, we must conclude that our knowledge of the laws of atmospheric processes is sufficient to serve as a basis for a rational weather prediction. However, it must be admitted that we may have overlooked important factors due to our incomplete knowledge. The interference of unknown cosmic effects is possible.

*Furthermore, the major atmospheric phenomena are accompanied by a long list of side effects, such as those of an electrical and optical nature. The question is to what extent such side effects could have considerable effects on the development of atmospheric processes. Such effects evidently do exist. **The rainbow**, for instance, **will result in a modified distribution of incoming radiation and it is well known that electrical charges influence condensation processes**. However, evidence is still lacking on whether processes of this kind have an impact on major atmospheric processes. At any rate, the scientific method is to begin with the simplest formulation of the problem, which is the problem posed above with seven variables and seven equations."* [Bjerknes 1904]

We know the equations:

- 7 Variables:
 - U, V, W, P, ρ, T, S (*q for the atmosphere*)
- 7 equations:
 - Momentum (u,v,w): [Navier-Stokes]
$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + 2\vec{\Omega} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \vec{\mathcal{F}}$$
 - Equation of State (EOS):
$$\rho = \rho(T, S, p)$$
 - Conservation of mass: **(continuity)**
$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$
 - Conservation of heat (of internal energy):
$$\frac{DT}{Dt} = \mathcal{S}_T$$
 - Conservation of salt: (humidity)
$$\frac{DS}{Dt} = \mathcal{S}_S$$

We know the equations:

- 7 Variables:
 - U, V, W, P, ρ, T, S (*q* for the atmosphere)

- 7 equations:
 - Momentum [Navier-Stokes]

But we don't know
the solutions...

- Equations:
 - Conservation of mass: (continuity)

- Conservation of heat (of internal energy):

- Conservation of salt: (humidity)

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$

$$\frac{DT}{Dt} = \mathcal{S}_T$$

$$\frac{DS}{Dt} = \mathcal{S}_S$$

We know the equations:

Millennium Prize problems

Navier–Stokes existence and smoothness

The Clay Mathematics Institute in May 2000 made this problem one of its seven Millennium Prize problems in mathematics. It offered a US \$1,000,000 prize to the first person providing a solution for a specific statement of the problem:^[1]

Prove or give a counter-example of the following statement:

In three space dimensions and time, given an initial velocity field, there exists a vector velocity and a scalar pressure field, which are both smooth and globally defined, that solve the Navier–Stokes equations.

We know the equations:

Navier-Stokes [Momentum equations]

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + 2\vec{\Omega} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \vec{\mathcal{F}}$$

Non-linear terms = Turbulence



turbolenza by da Vinci [1507]

*Big whorls have little whorls,
which feed on their velocity;
And little whorls have lesser
whorls,
And so on to viscosity.*
L.F. Richardson [1922]

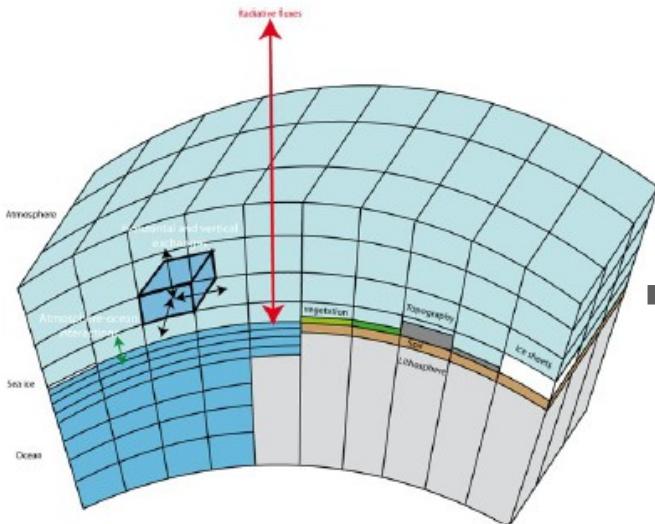


Turbulent water jet ($Re = 2300$) [Van Dyke, 82]

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + 2\vec{\Omega} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \vec{\mathcal{F}}$$



Navier-Stokes equations



Grid Discretization



Supercomputer (Curie - CEA)

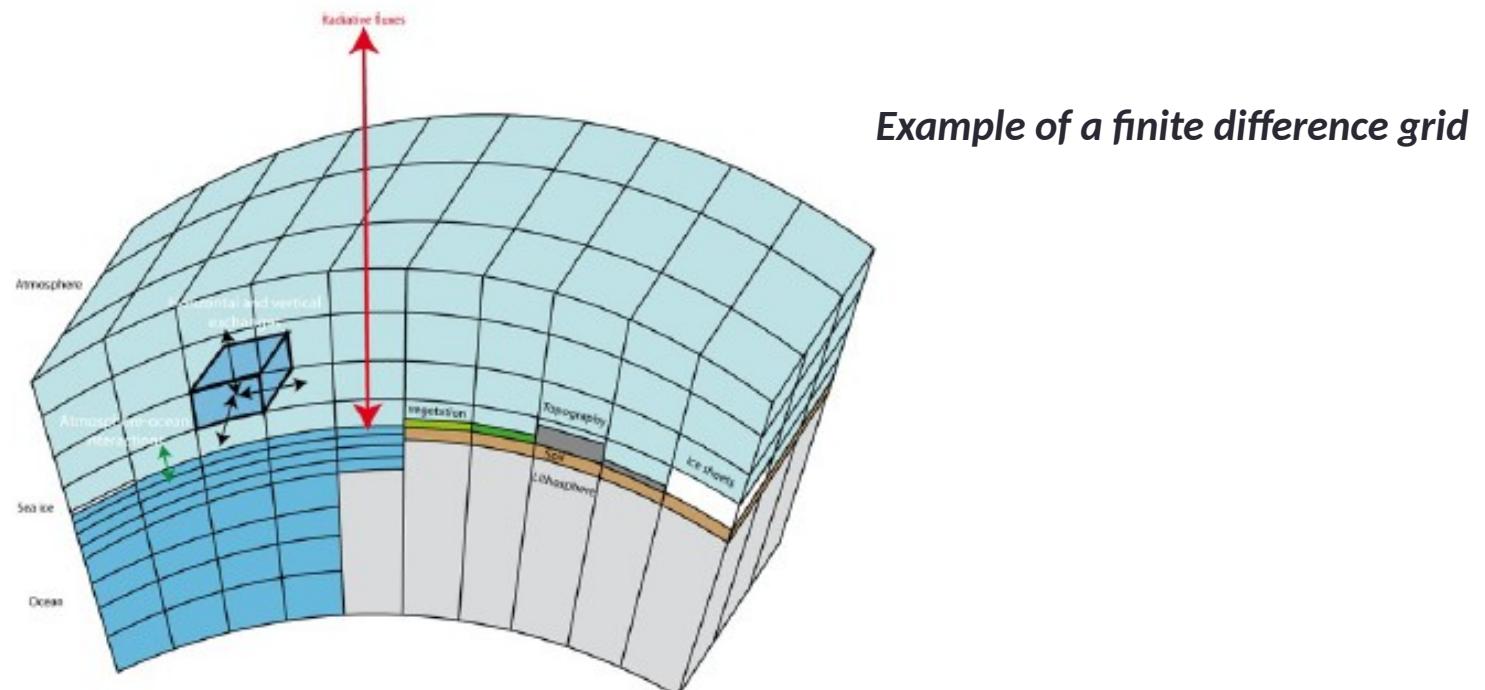
One way to solve them (approximately):
→ Numerical modelling

Ocean modeling principle

An ocean model is simplified representation of physical processes that take place in the ocean.

The ocean is divided into boxes (finite difference, finite volume) : **discretization**

The NS equations can be solved on the grid using **numerical methods**



Ocean modeling principle

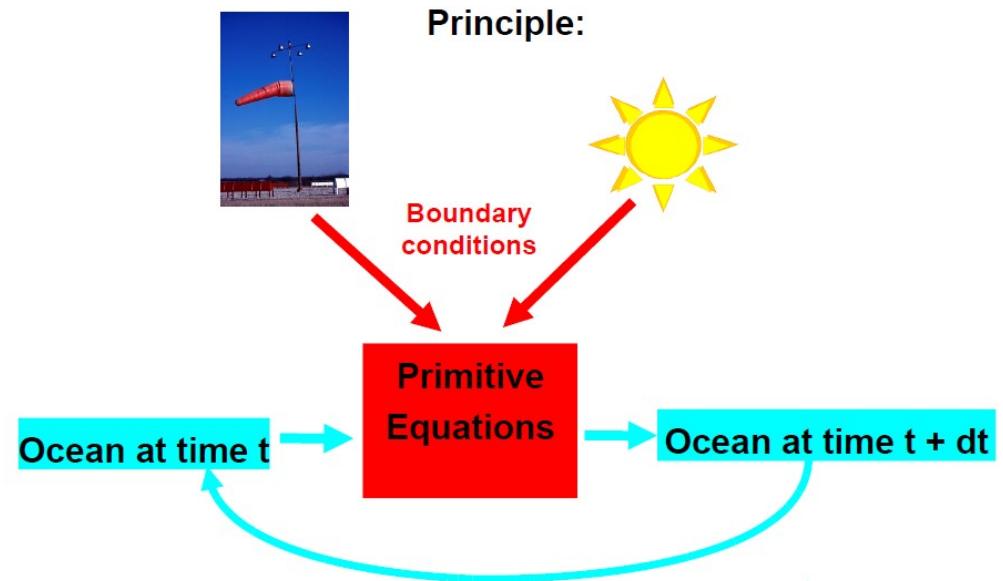
If we know:

- The **ocean state at time t** :

u, v, w, T, S, \dots

- **Boundary conditions** :

surface, bottom, lateral sides



→ We can compute an estimated state of the ocean at time $t+dt$ using numerical approximations of fluid dynamics equations

Ocean modeling principle

One major Problem:

Setting the model's grid scale to the Kolmogorov length
(to resolve diffusive processes)

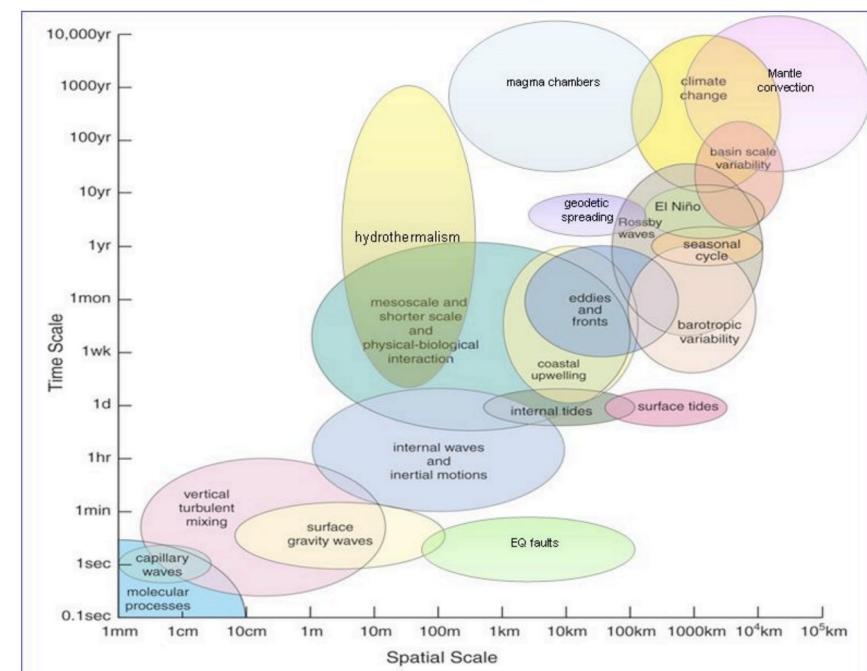
$\Delta = 10^{-3}\text{m}$ over a global ocean domain of volume $1.3 \times 10^{18} \text{ m}^3$ requires 1.3×10^{27} discrete grid cells.

And Direct Numerical Simulation (DNS) of the global ocean climate requires 3×10^{10} time steps of one second (1000 years).

So we will be dust long before DNS of global ocean climate is possible:

In the meantime, we must use
subgrid scale parameterizations
to simulate the ocean.

→ (See Lesson 4)



Ocean Circulation Models

- ROMS → CROCO <https://www.croco-ocean.org/>
- NEMO <http://www.nemo-ocean.eu/>
- MITgcm <http://mitgcm.org/>
- HYCOM <http://hycom.org/>
- POP <http://www.cesm.ucar.edu/models/cesm1.0/pop2/>
- OFES <http://www.jamstec.go.jp/esc/ofes/eng/>
- MOM <http://www.gfdl.noaa.gov/ocean-model>
- POM <http://www.ccpo.odu.edu/POMWEB/>
- etc

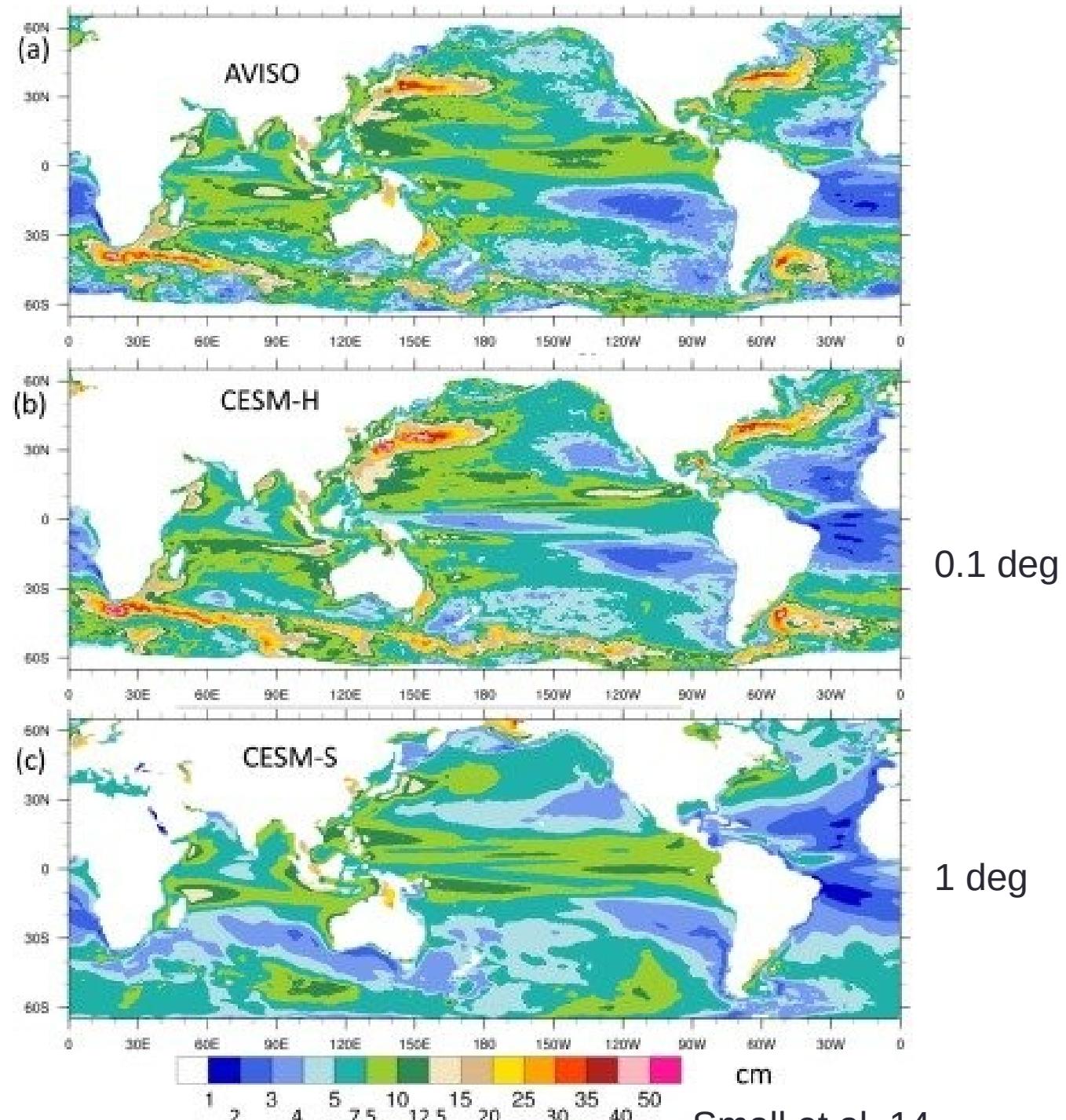
Ocean Circulation Models

- Mechanistic studies of ocean and climate processes:
 - Process studies using fine resolution (≤ 1 km) simulations (**MITgcm**, **SUNTANS**, **CROCO-NH**)
 - Mechanisms for coastal and shelf processes (≤ 10 km) (**ROMS/CROCO**, **MARS3D**, **HYCOM**)
 - Mechanisms for climate variability (basin to global) (**MOM6**, **NEMO**)
- Operational predictions and state estimation
 - Coastal forecasting India **INCOIS**
 - Coastal forecasting USA **NCEP**
 - Ocean state estimation **ECCO**
- Projections for future climate change
 - IPCC-class simulations with anthropogenic forcing (e.g. **CMIP**)

Ocean Modelling example:

IPCC global run

*Typical length =
100 - 1000
years*



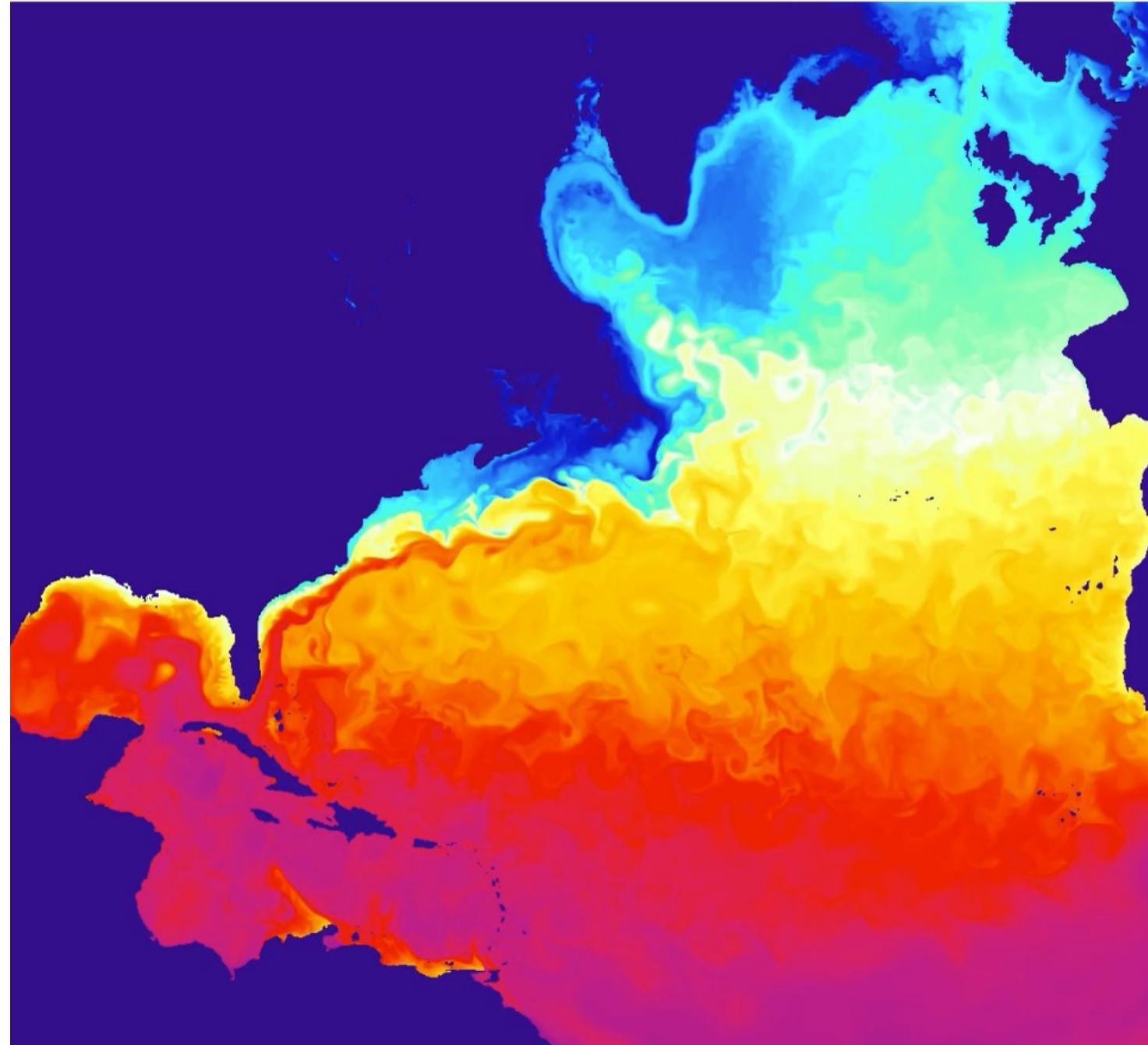
Ocean Modelling example:

*Mesoscale-
resolving basin-
scale simulation*

*Typical length =
10 - 100 years*

North-Atlantic
coupled
simulations:

- oceanic model (6 km)
- atmospheric model (18 km)



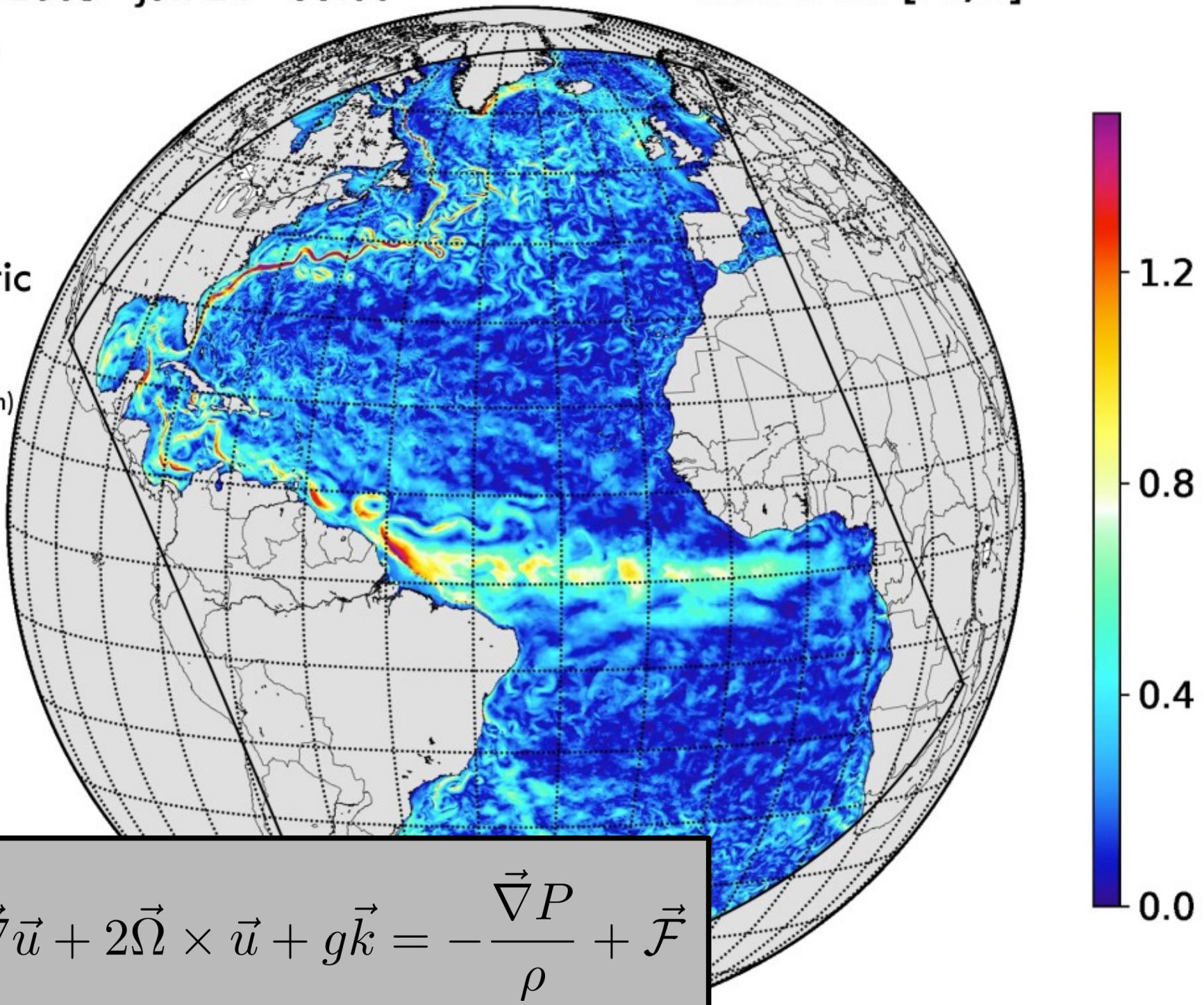
Realistic 2005 - Jan 14 - 00:00

currents [m/s]

Modelling:

Forced Atlantic
simulations:

- oceanic model (3 km)

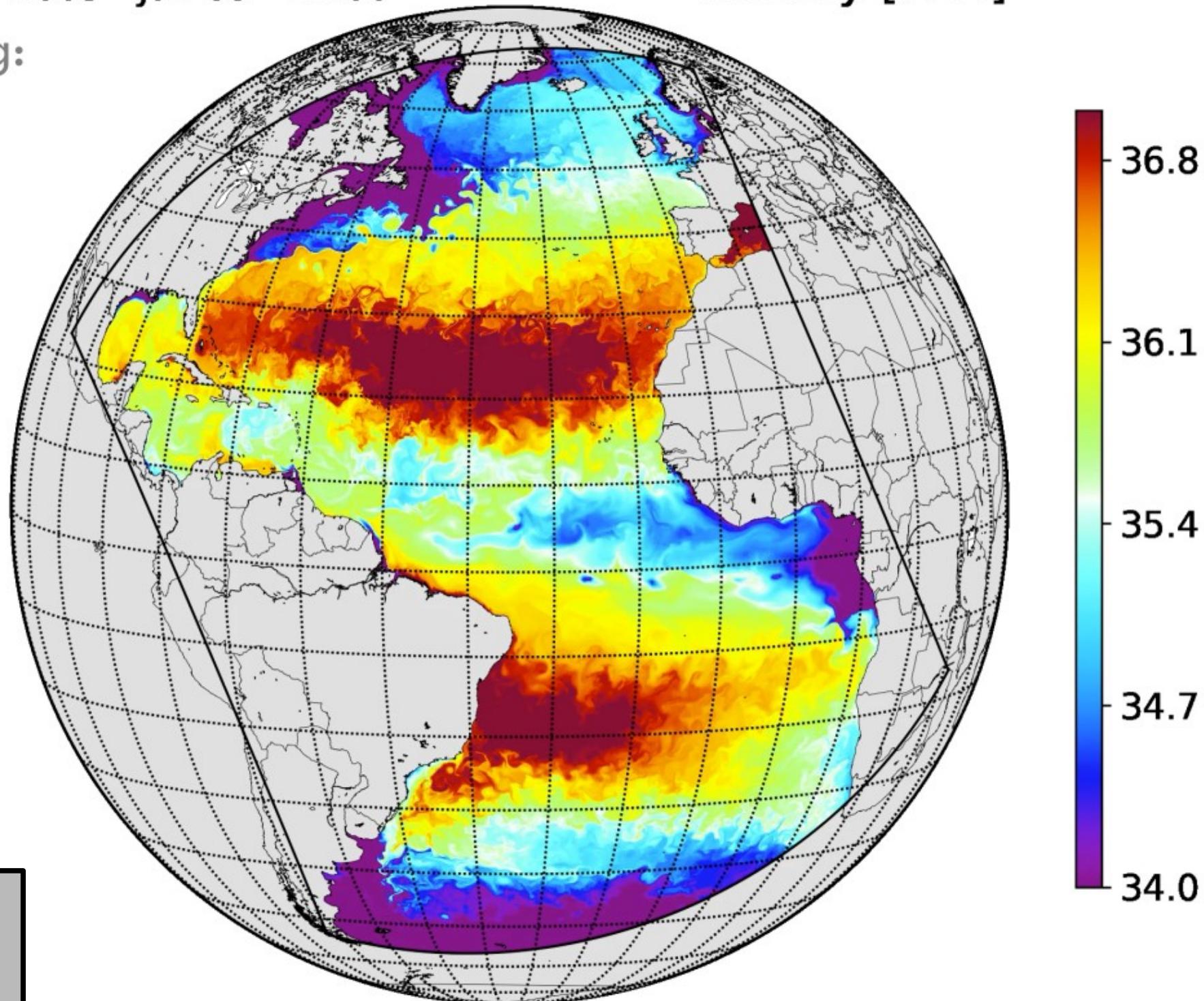


$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + 2\vec{\Omega} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \vec{F}$$

Realistic 2005 - Jan 09 - 11:00

salinity [PSU]

Modelling:



$$\frac{DS}{Dt} = \mathcal{S}_S$$

Realistic 2005 - Jan 15 - 03:00

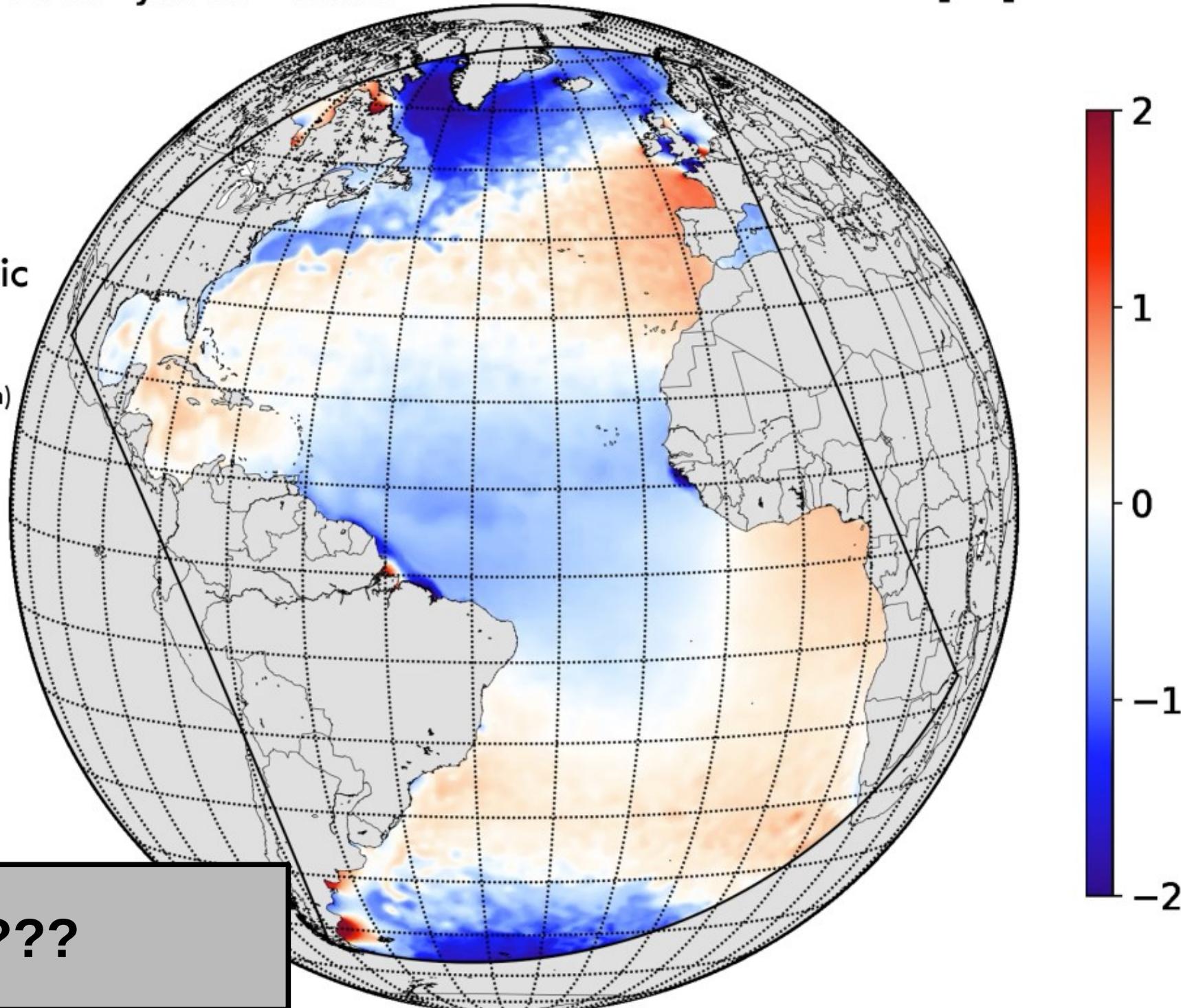
SSH [m]

Modelling:

Forced Atlantic
simulations:

- oceanic model (3 km)

???



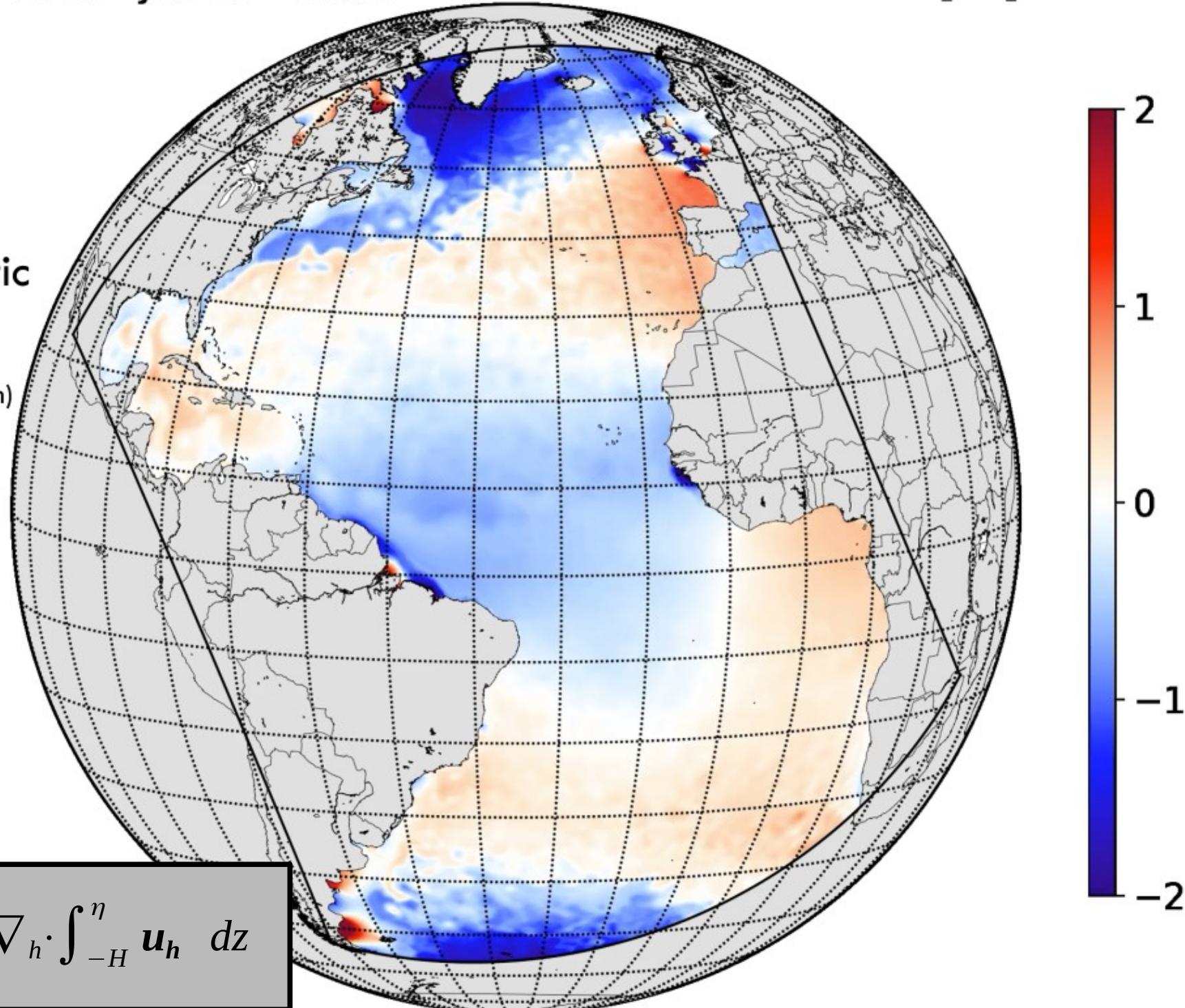
Realistic 2005 - Jan 15 - 03:00

SSH [m]

Modelling:

Forced Atlantic
simulations:

- oceanic model (3 km)



$$\partial_t \eta = -\nabla_h \cdot \int_{-H}^{\eta} u_h \ dz$$

Basin-scale configuration GIGATL

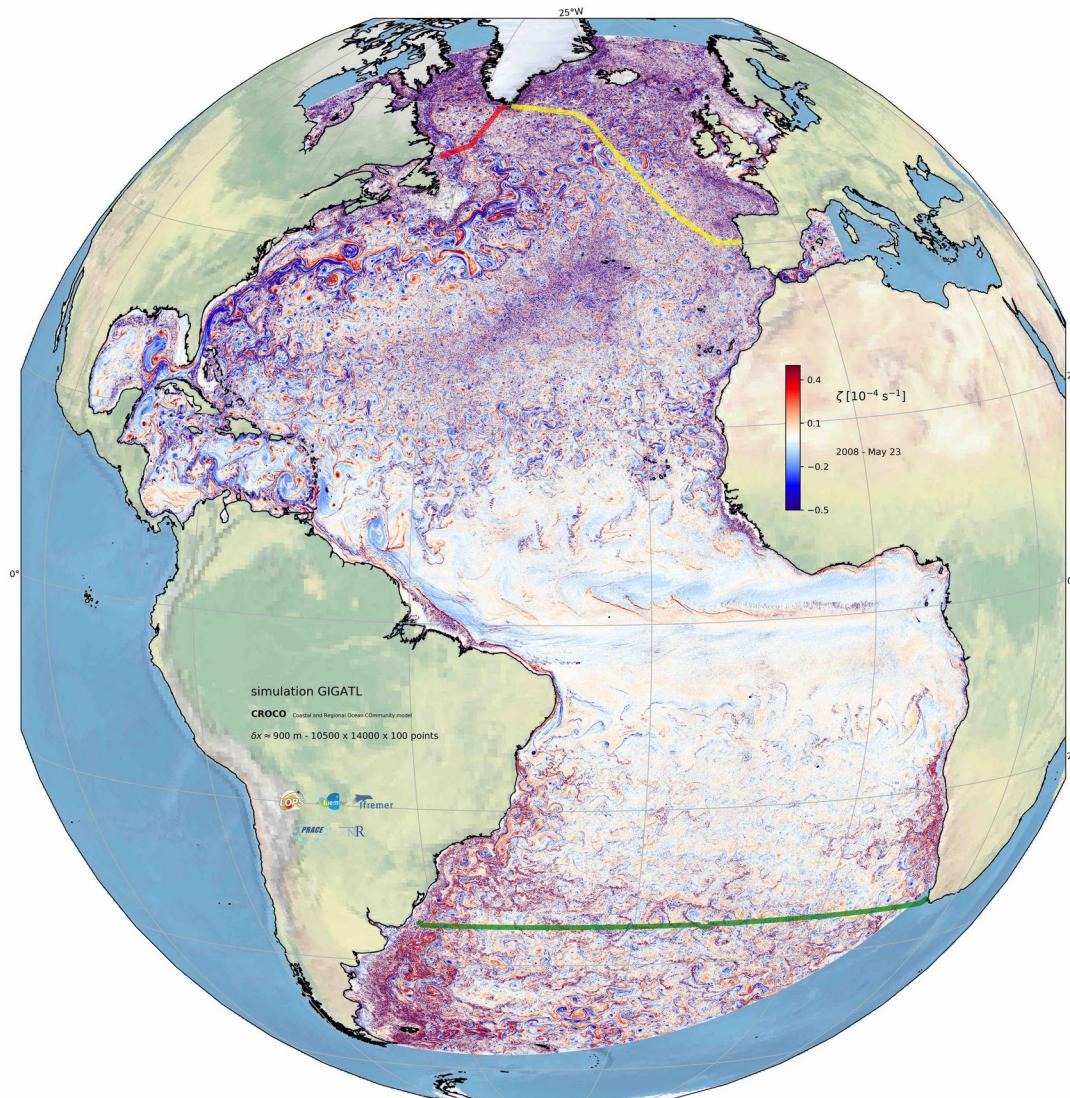
*Submesoscale-permitting
basin-scale simulation*

Typical length = 1 year

Horizontal resolutions up to **0.75 - 1 km** with 100 topography following levels (refined at the bottom)
 $= 10500 \times 14000 \times 100$ points

including **hourly surface forcings and tides**.

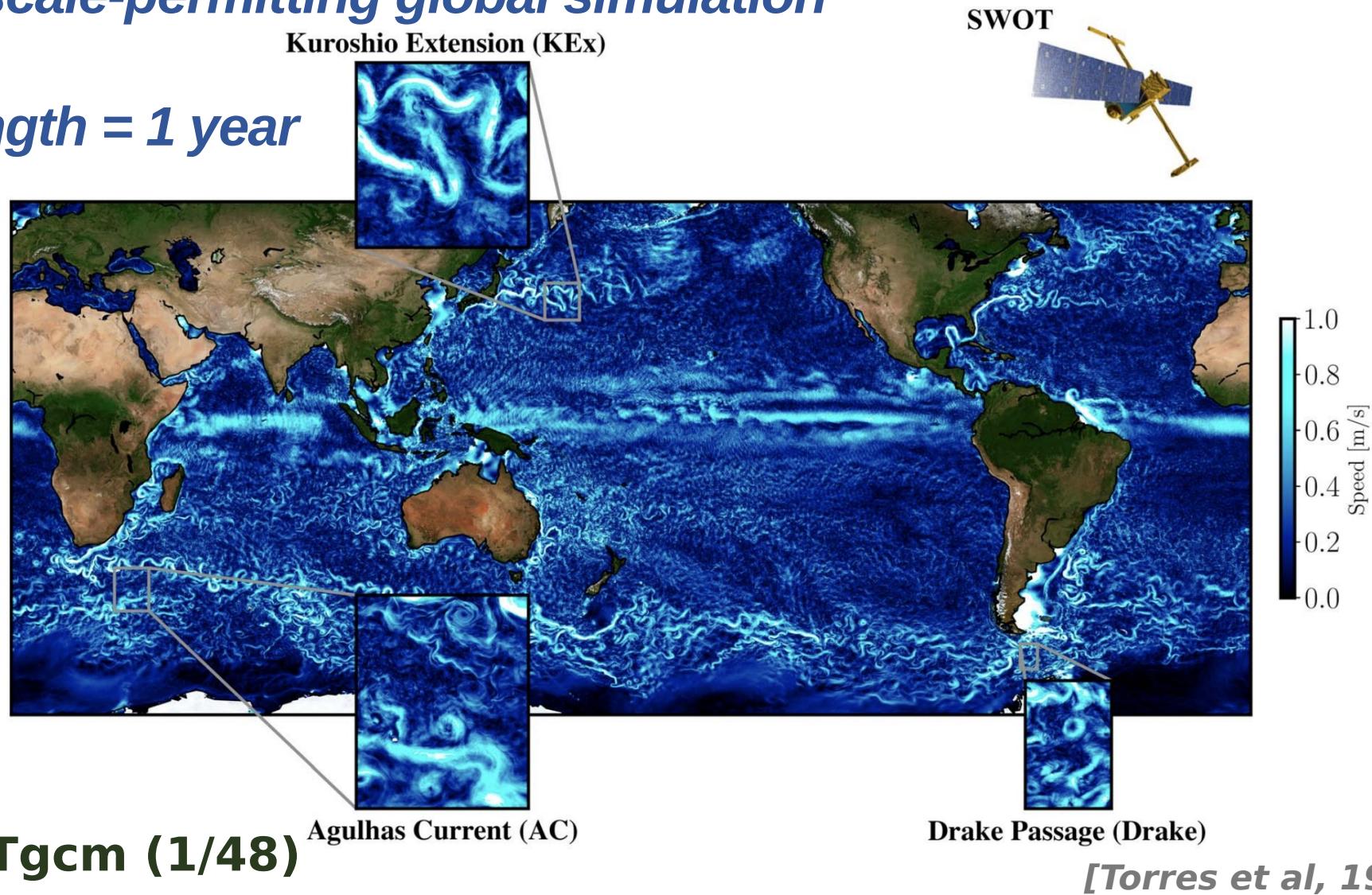
Run on 10000 processors - 40M cpu-hours - About 4PB of data



Global configuration LLC4320

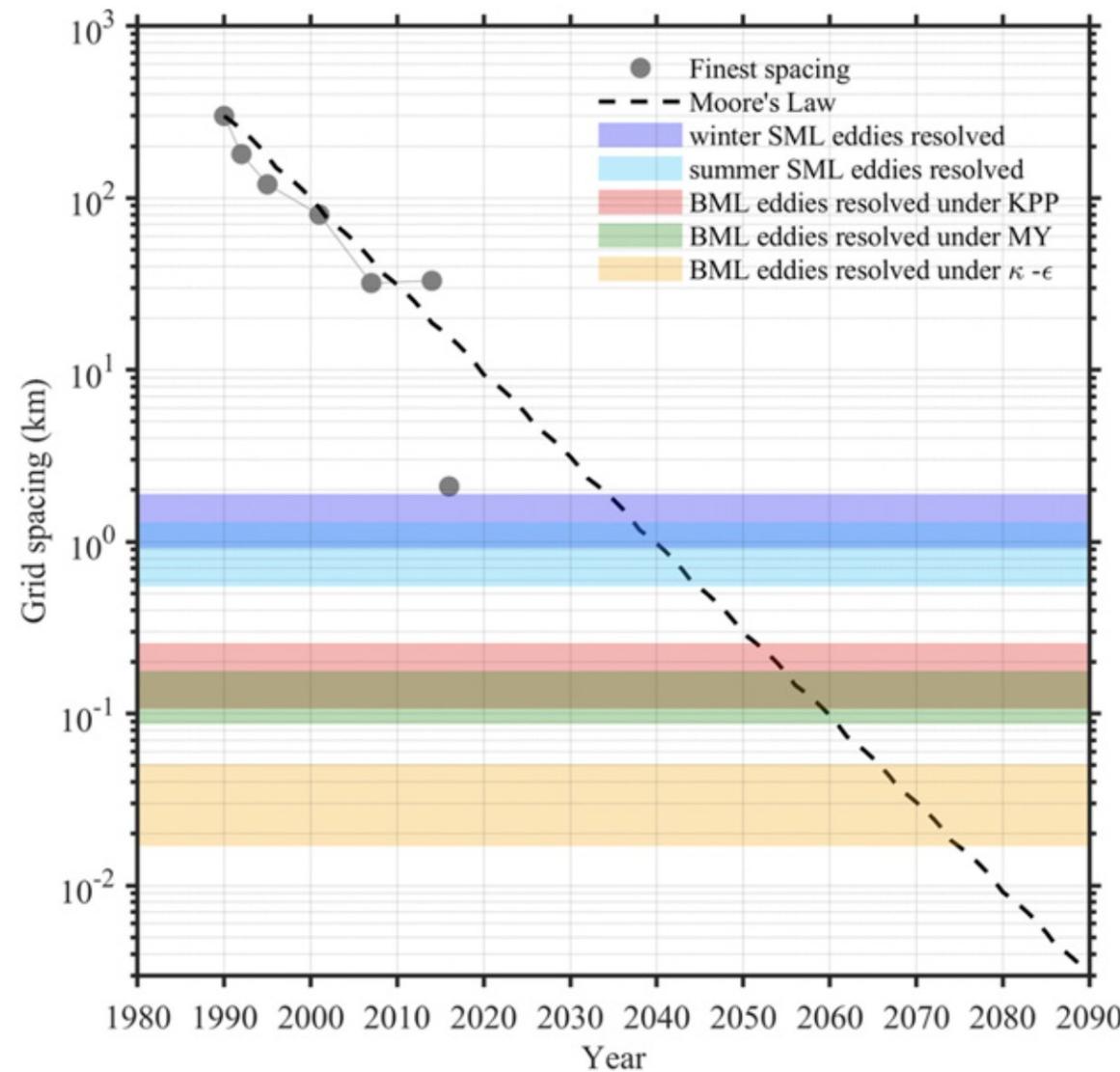
Submesoscale-permitting global simulation

Typical length = 1 year



Estimate of horizontal grid spacings of the IPCC ocean models

- The gray dots denote the finest grid spacings reported by the IPCC reports by year of publication, except the latest one from the ECCO MITgcm LLC4320 simulation.
- The black line denotes the estimate predicted by Moore's Law, while the shaded regions denote the grid spacing intervals resolving 50% and 90% of surface mixed-layer eddies globally based on the observations and bottom mixed-layer eddies based on simulations.

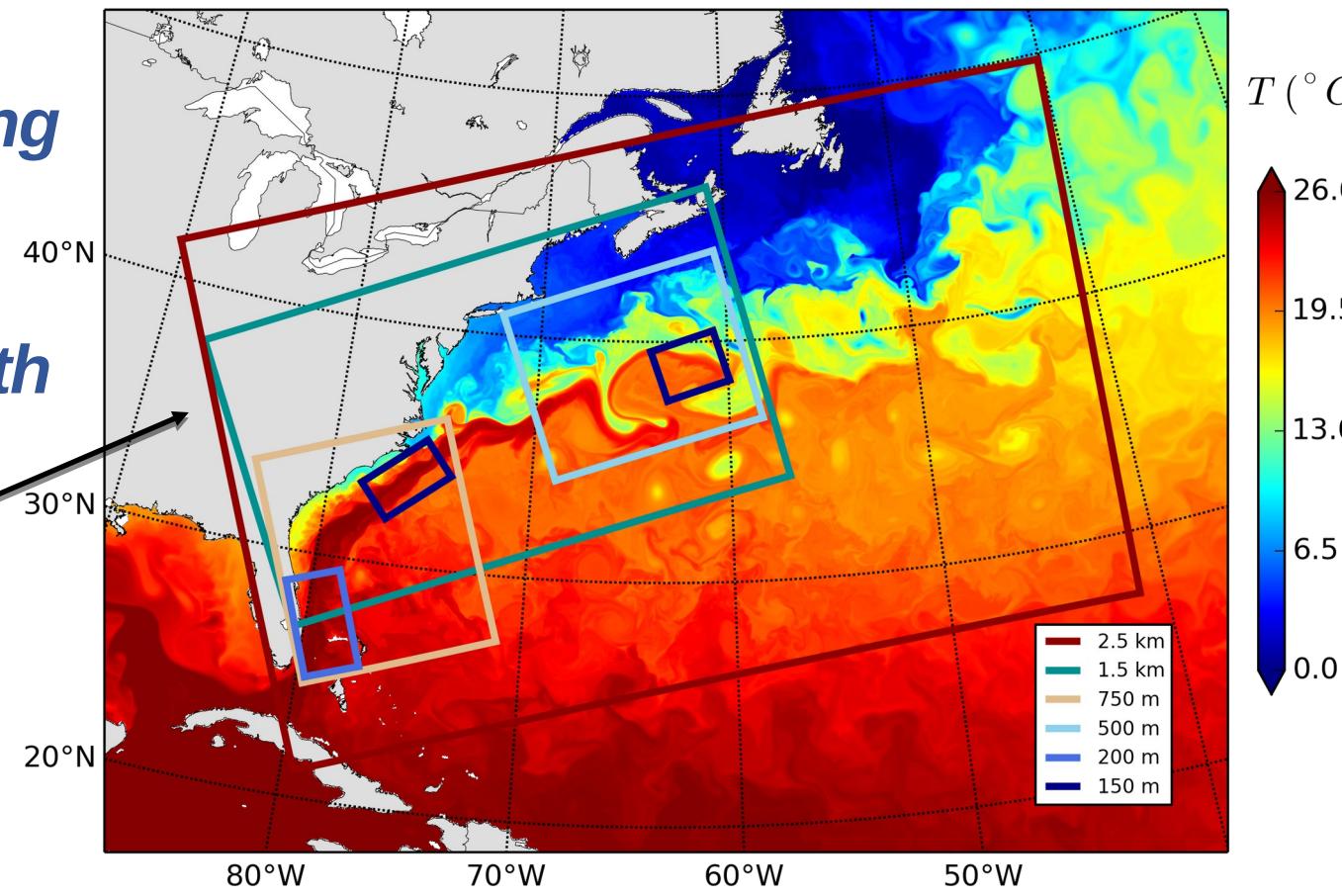
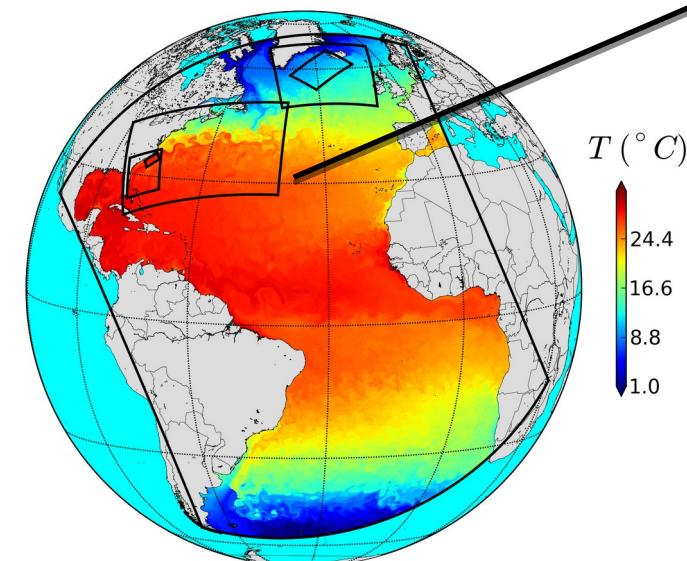


Ocean Modelling examples:

$$\Delta x = 6 \rightarrow 0.15 \text{ km}$$

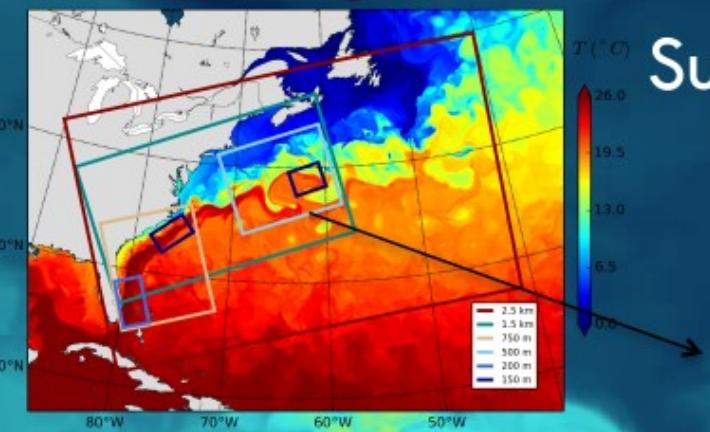
***Submesoscale-resolving
regional simulation***

***Typical length = 1 month
10 years***

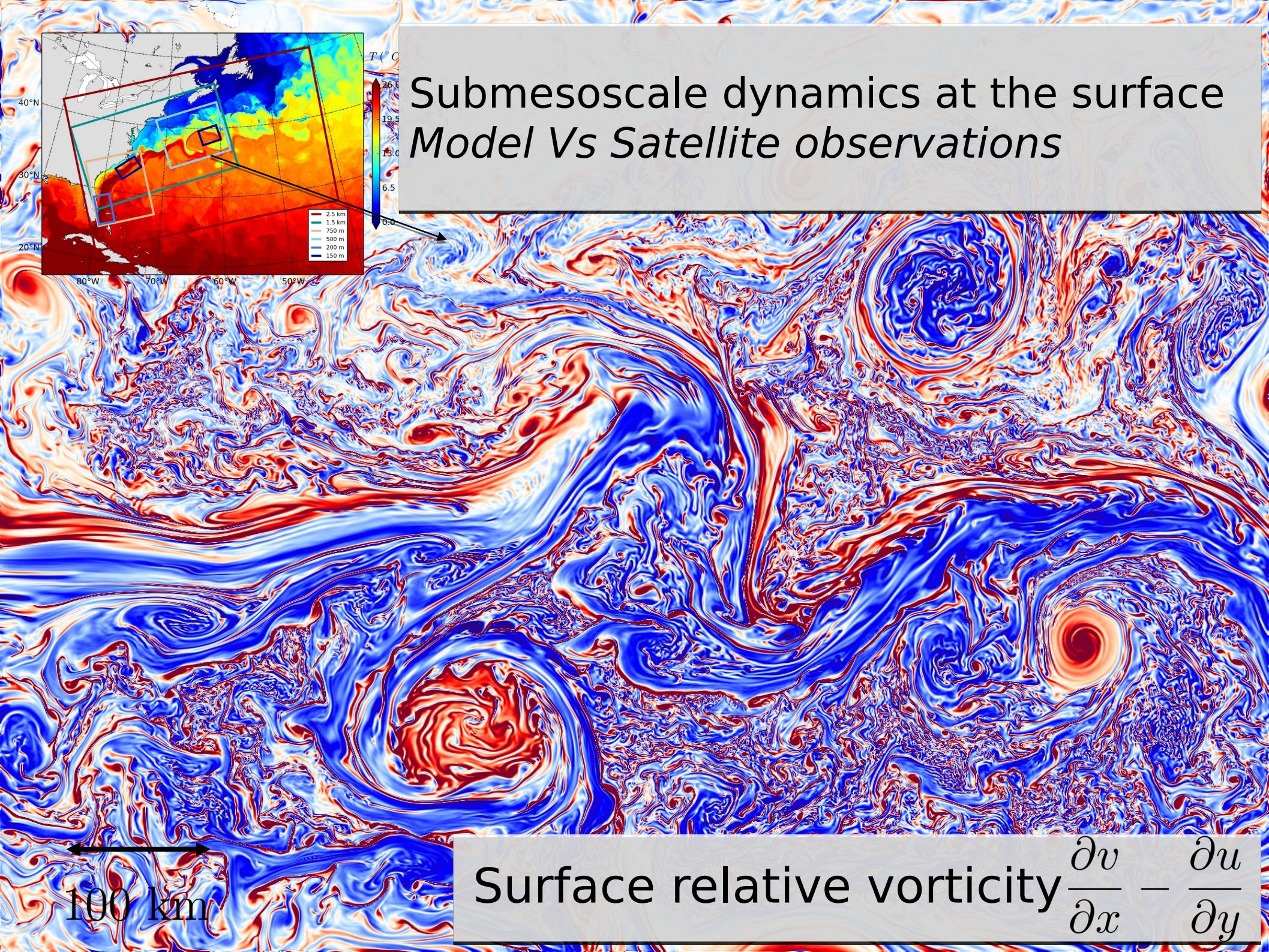


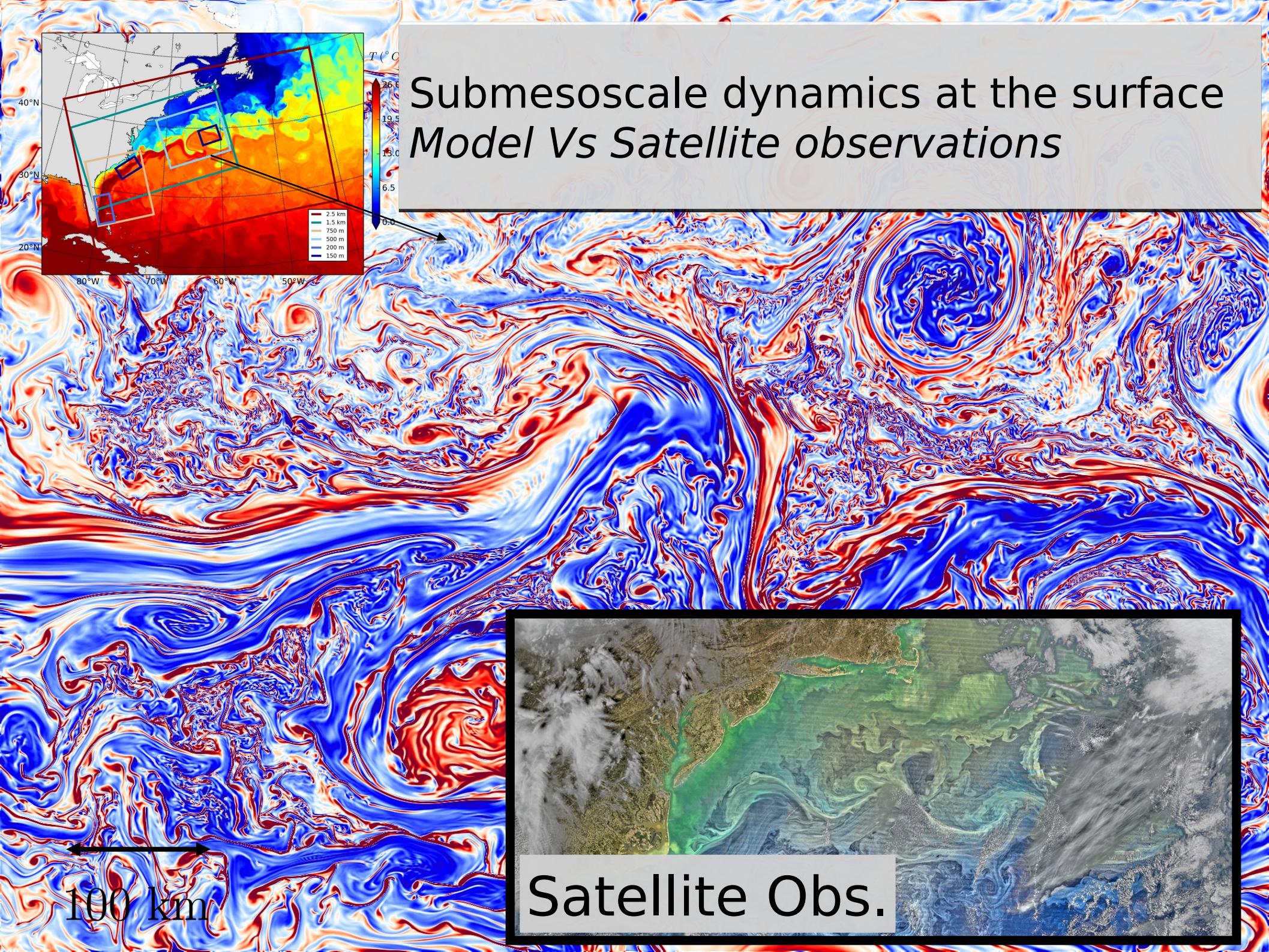
A portion of the Atlantic domain
showing mean SST and several (1-way)
nested grids:

Submesoscale dynamics at the surface



ROMS ($\Delta x = 500$ m)

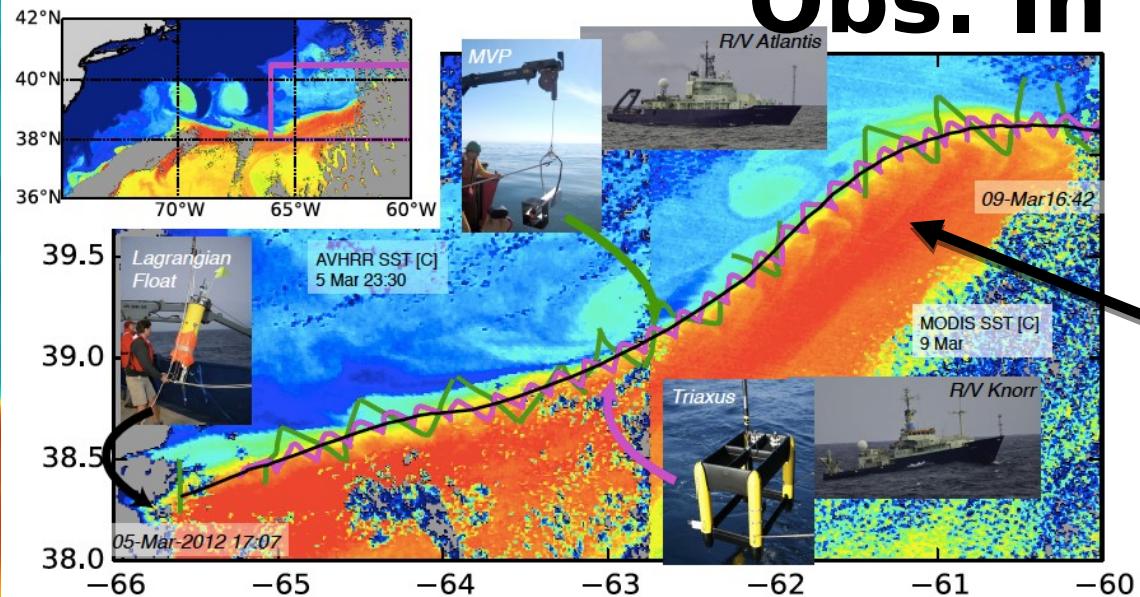




Submesoscale dynamics at the surface

Model Vs Satellite observations

Obs. In situ

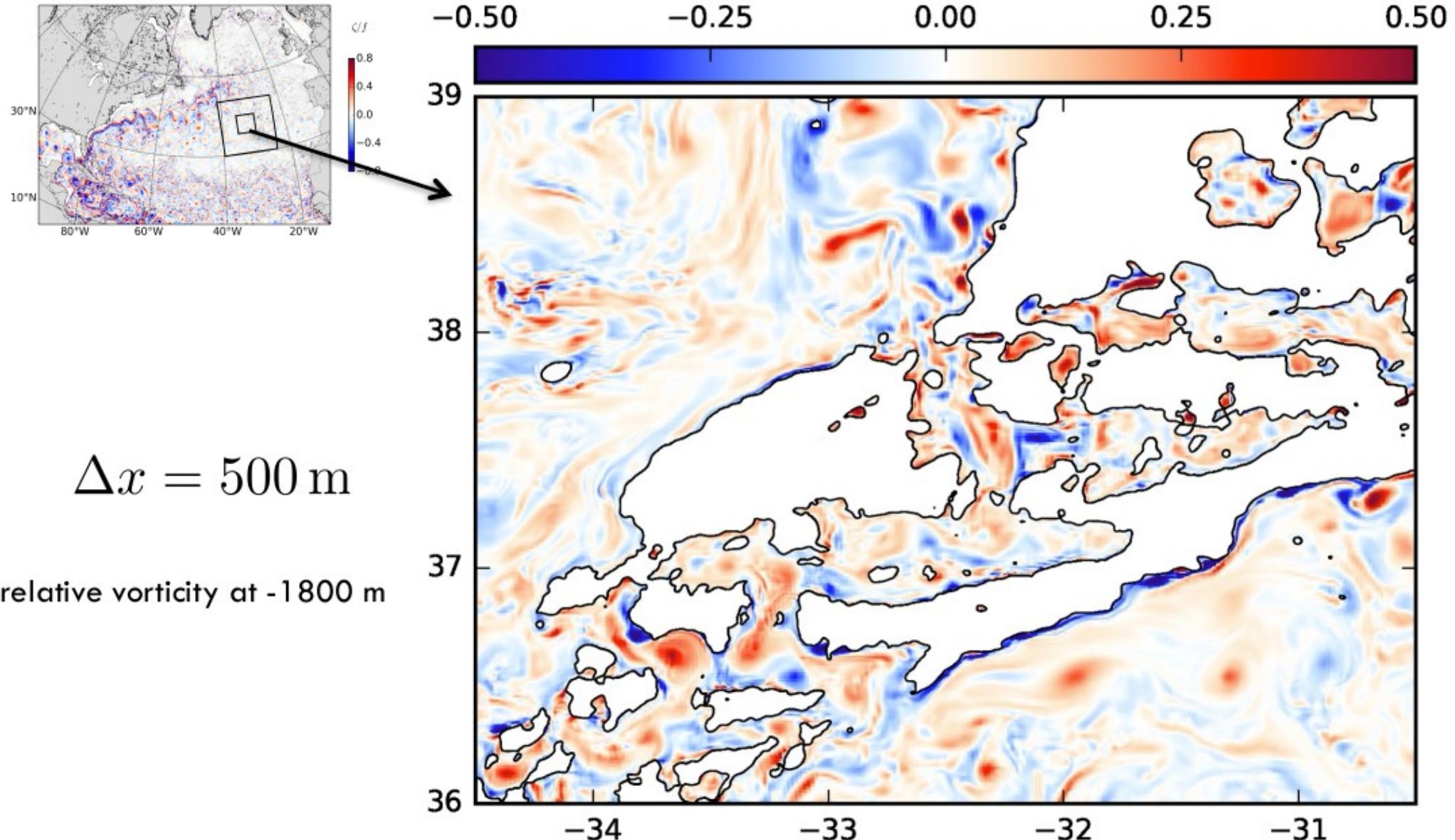


LATMIX 2012 Campaign

(Scalable Lateral Mixing and Coherent Turbulence)

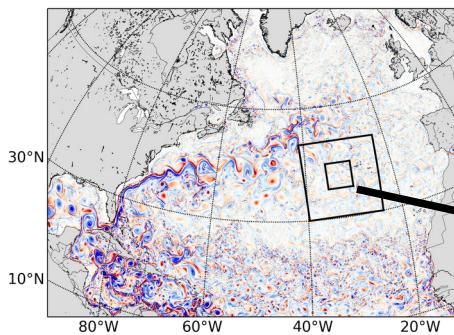
Model

Submesoscale dynamics in the Abyss!



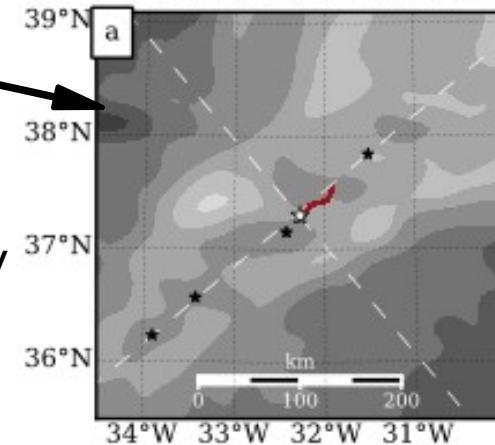
[Vic et al., 2018]

Dispersion of larvae by abyssal turbulence

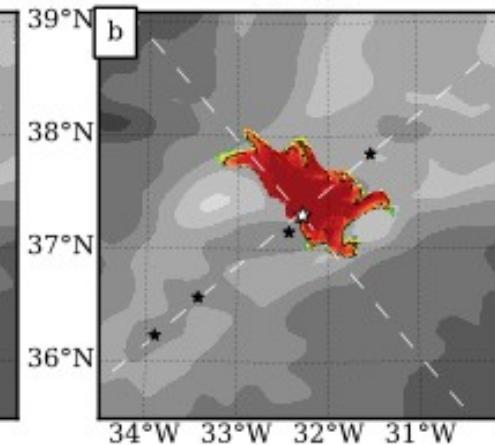


Mean
currents only

ROMS6 - mean currents



ROMS6

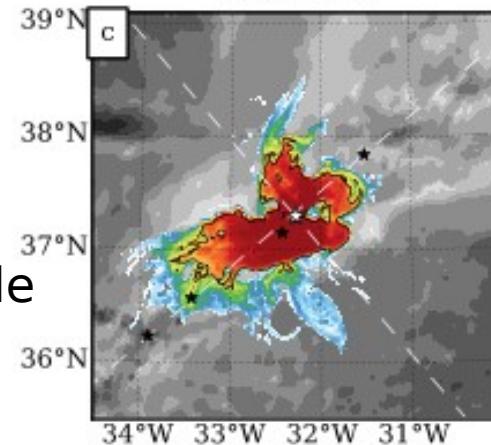


Mesoscale

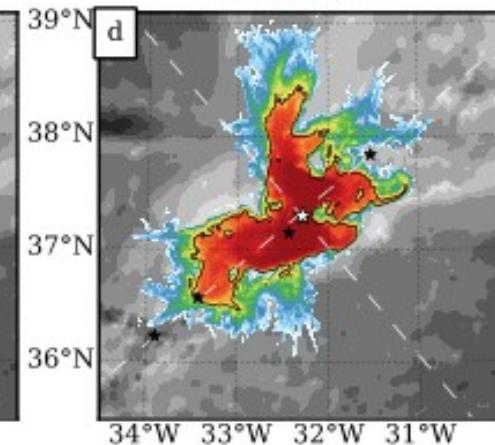
Larvae dispersion
from the Lucky Strike
vent after 30 days.

Mesoscale +
submesoscale

ROMS0.75



ROMS0.75T



Mesoscale +
submesoscale
+ tides

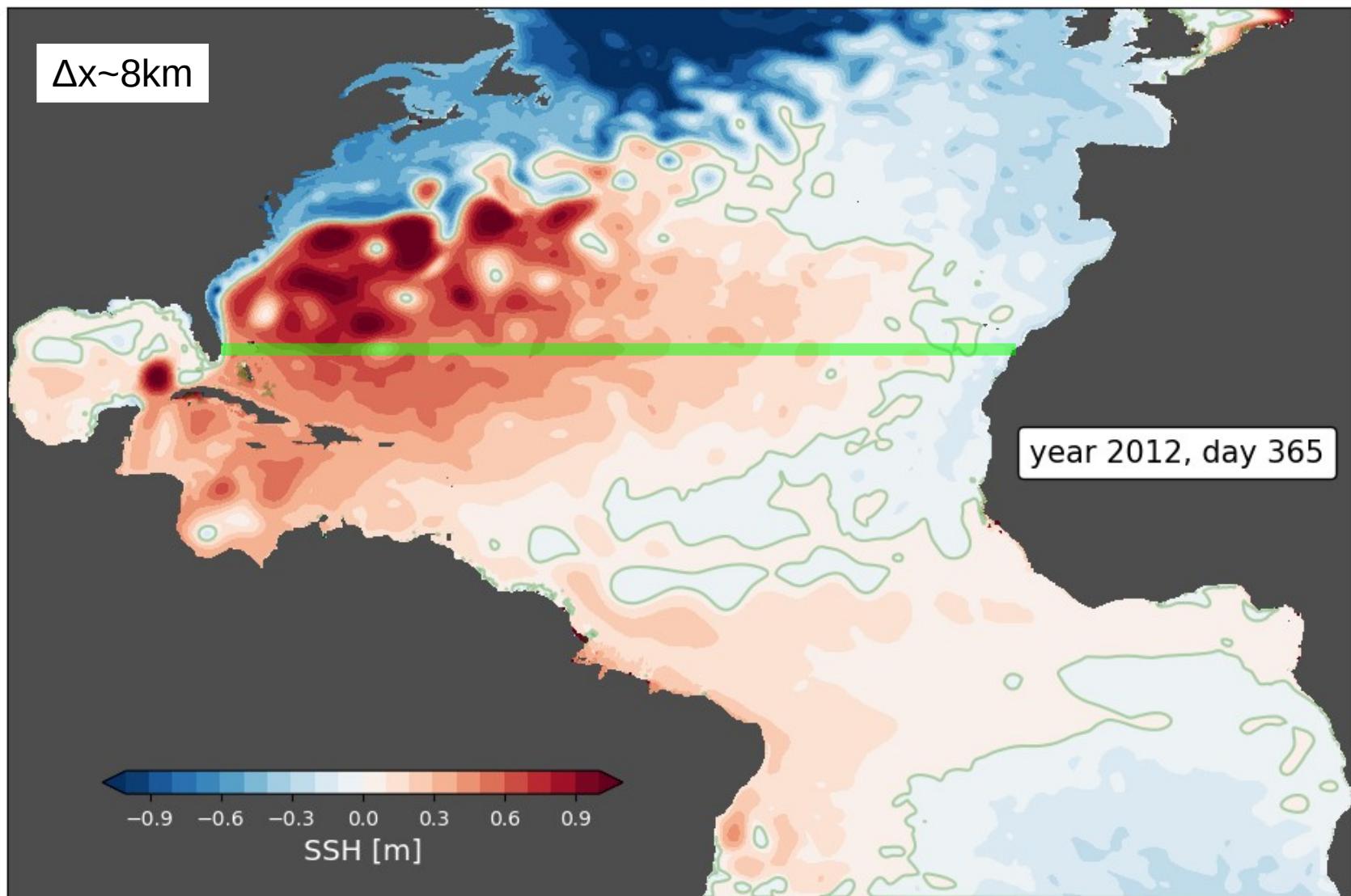
Probability density [km^{-2}]



[Vic et al., 2018]

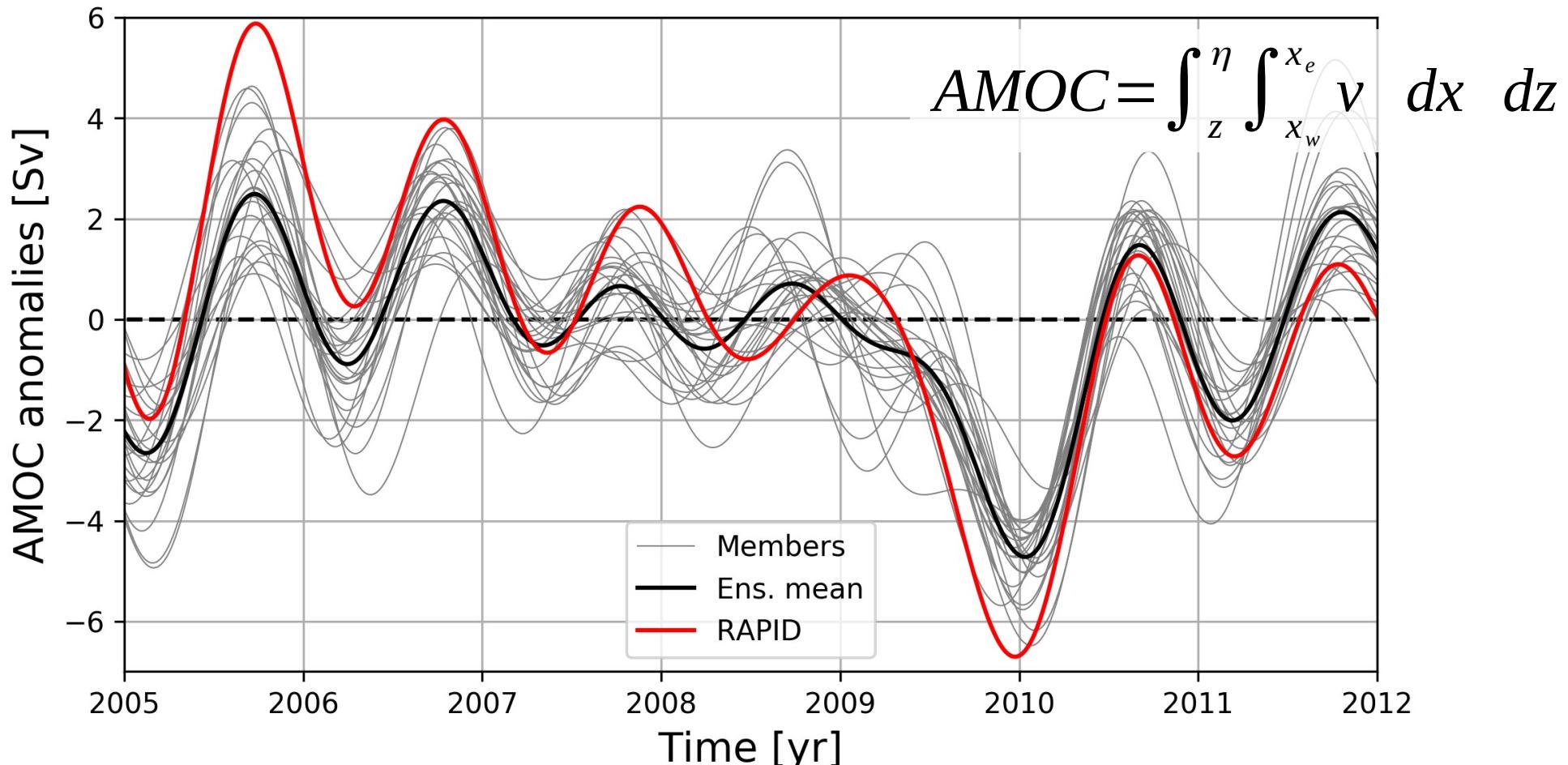
Model vs. Observations

→ The ocean is a chaotic system



Model vs. Observations

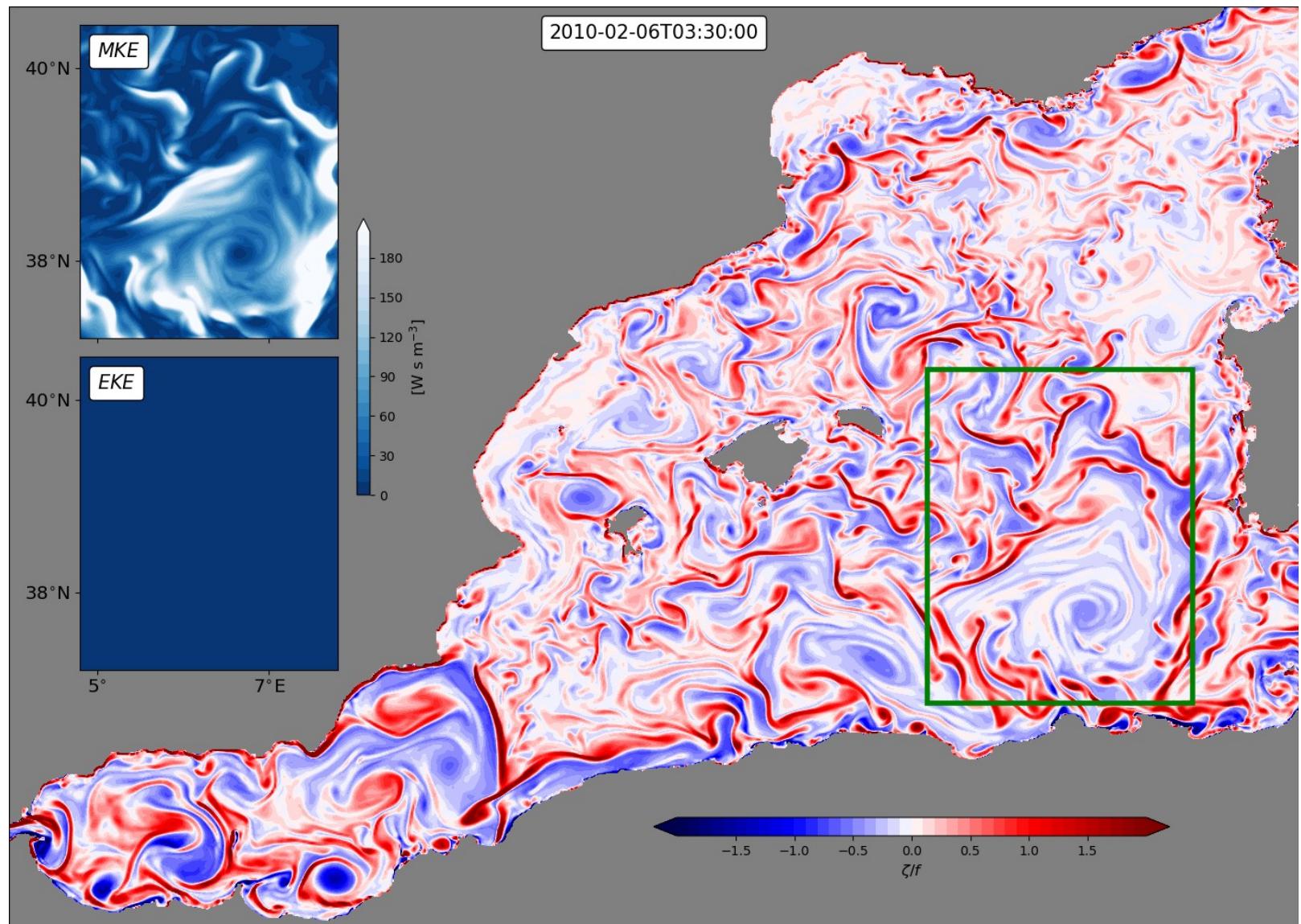
→ The ocean is a chaotic system



24 equi-valid model reproductions of AMOC time series @ 26.5°N.

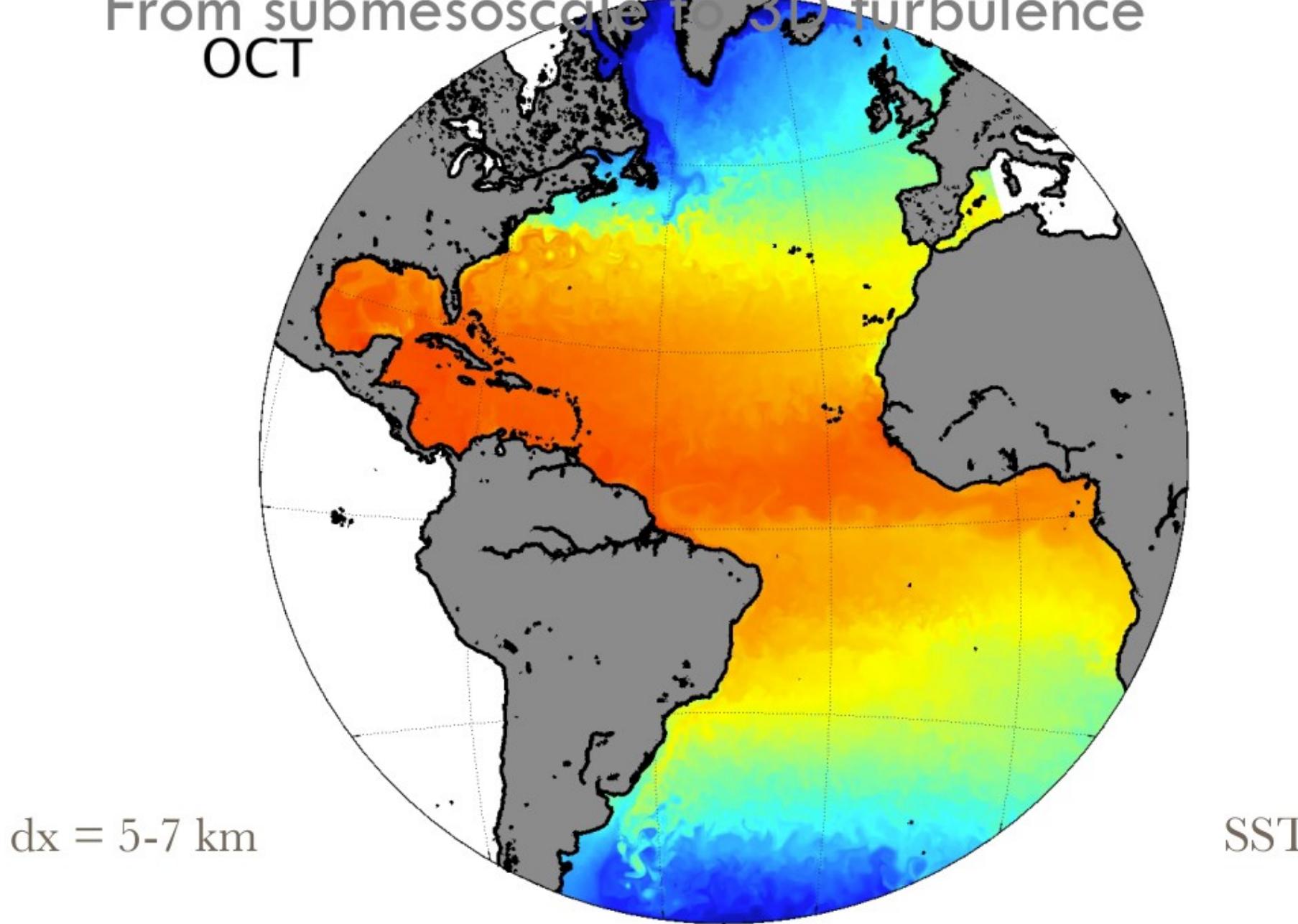
Model vs. Observations

→ The ocean is a chaotic system



From submesoscale to 3D turbulence

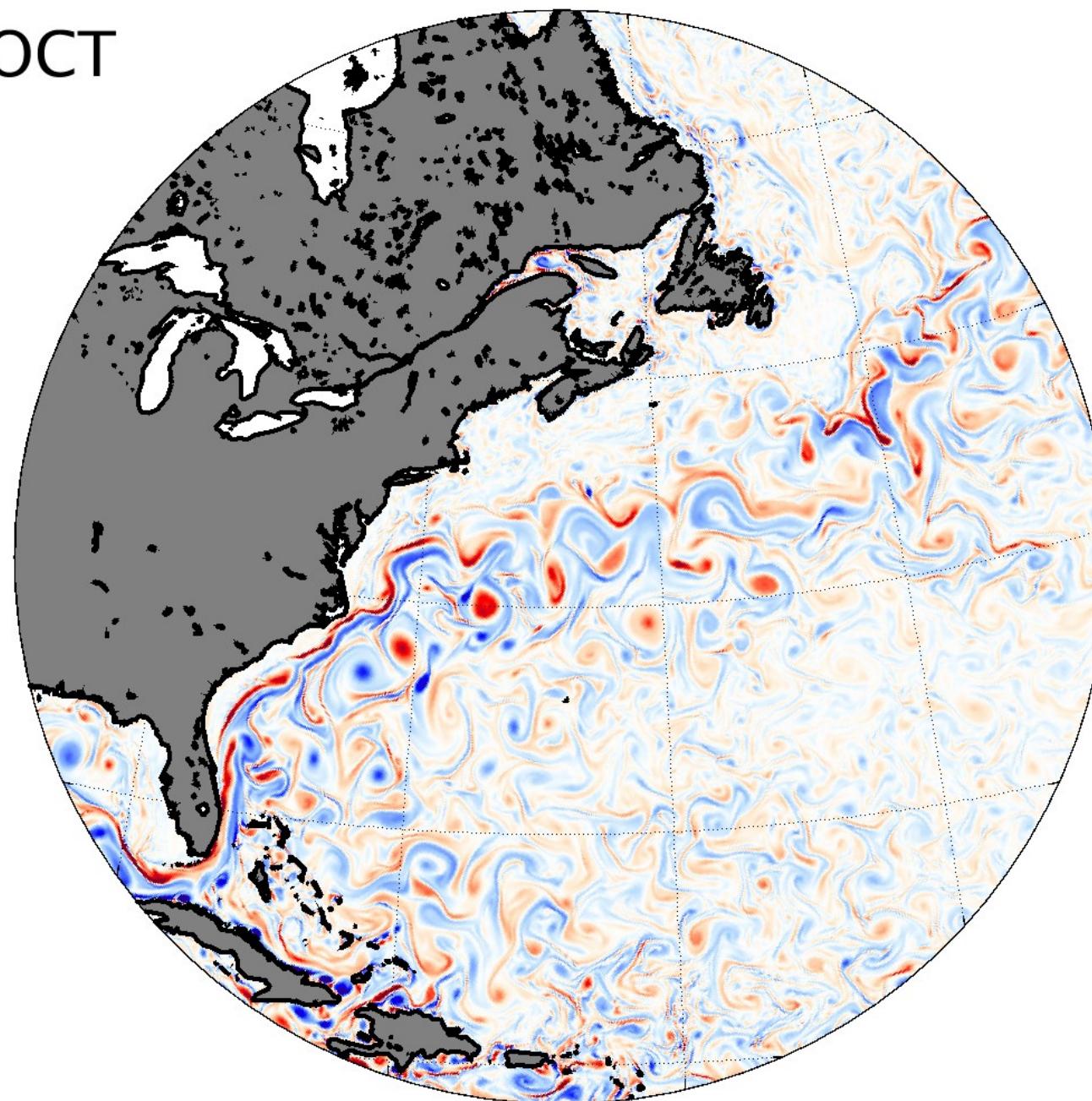
OCT



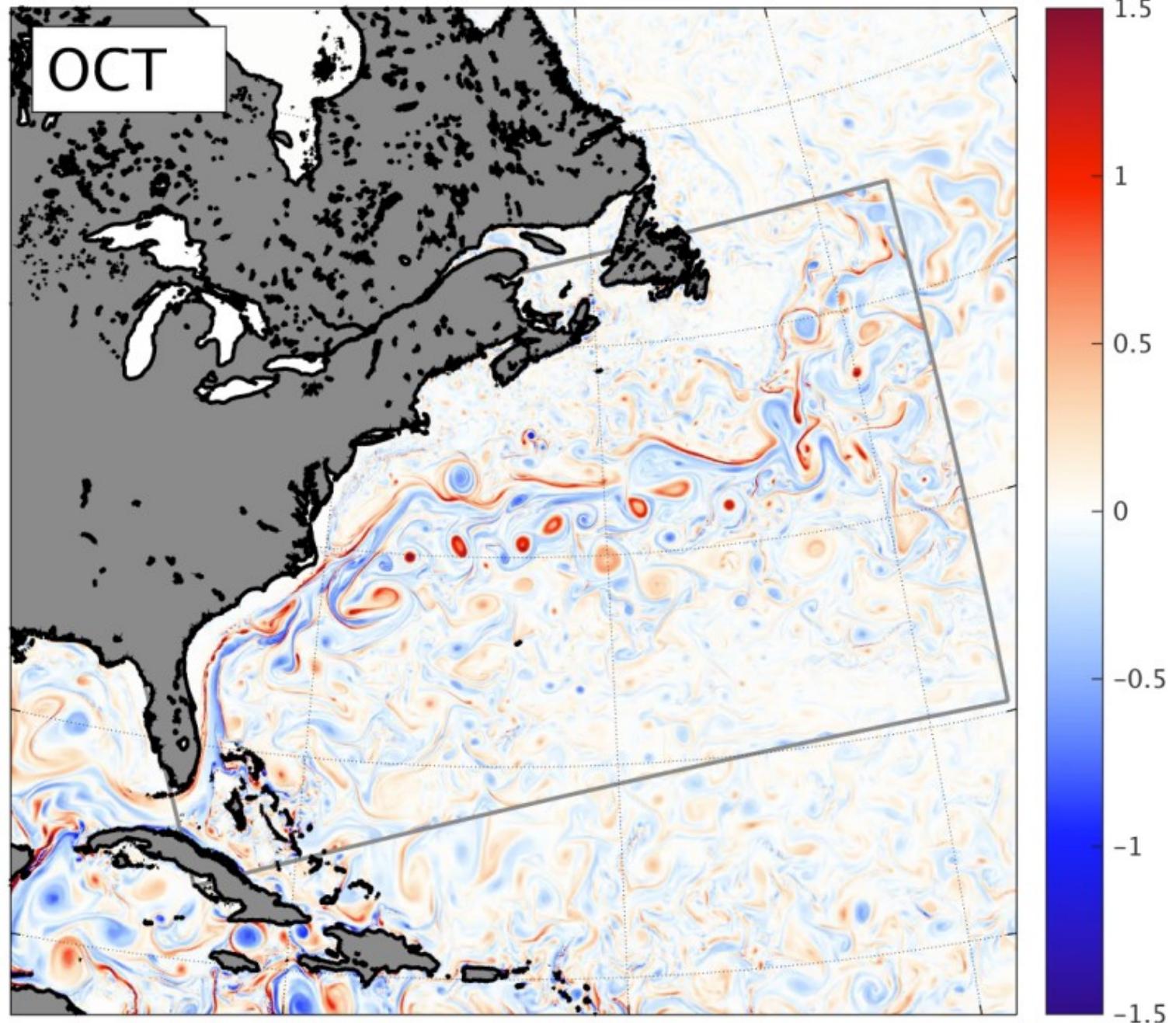
Simulations using ROMS: Regional is a relative concept

Animation from J. Molemaker

OCT

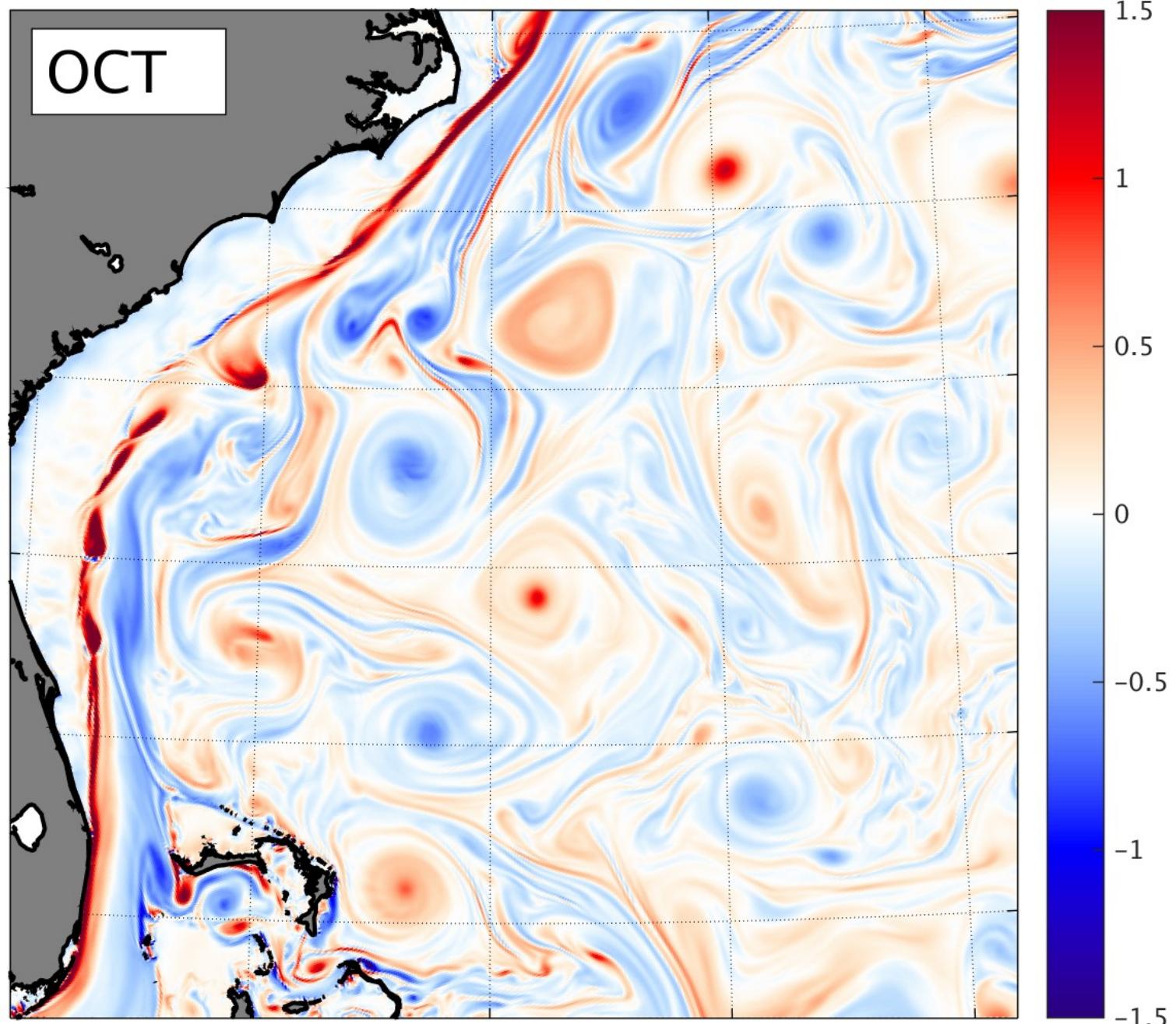


Normalized relative vorticity, or $Ro = \zeta / f$

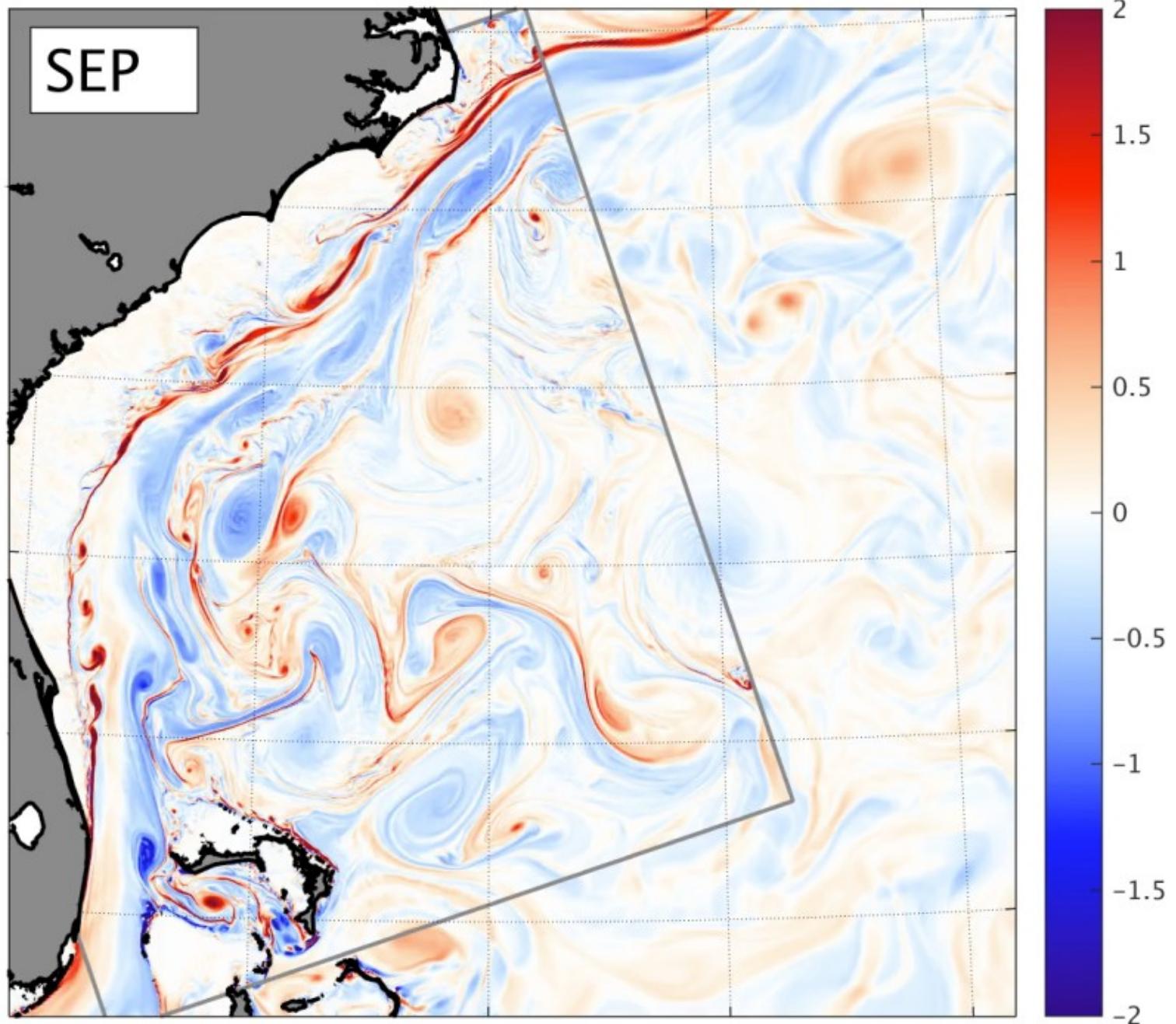
ζ / f 

Nested domain with open boundaries with $dx = 2.5 \text{ km}$

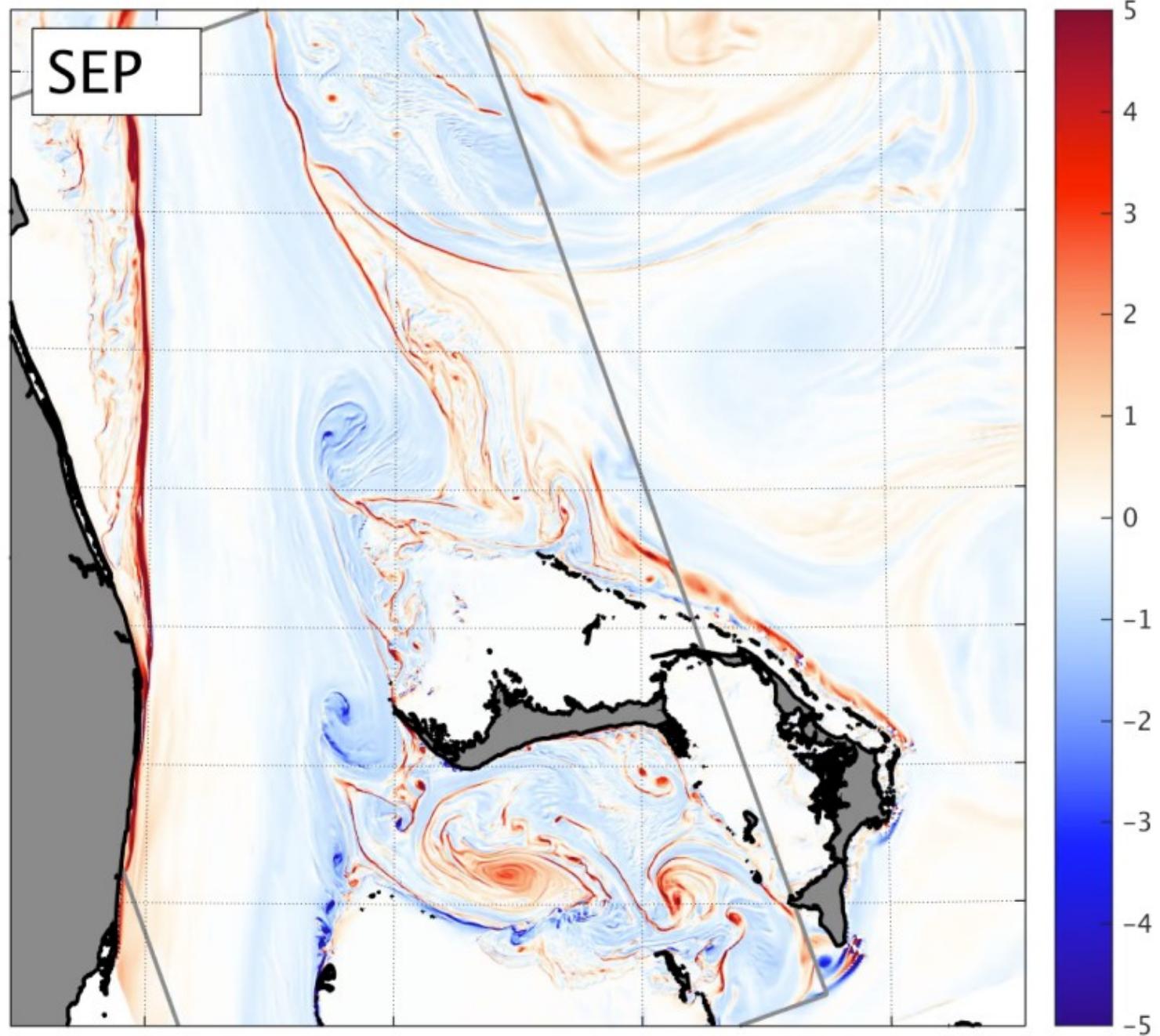
ζ / f

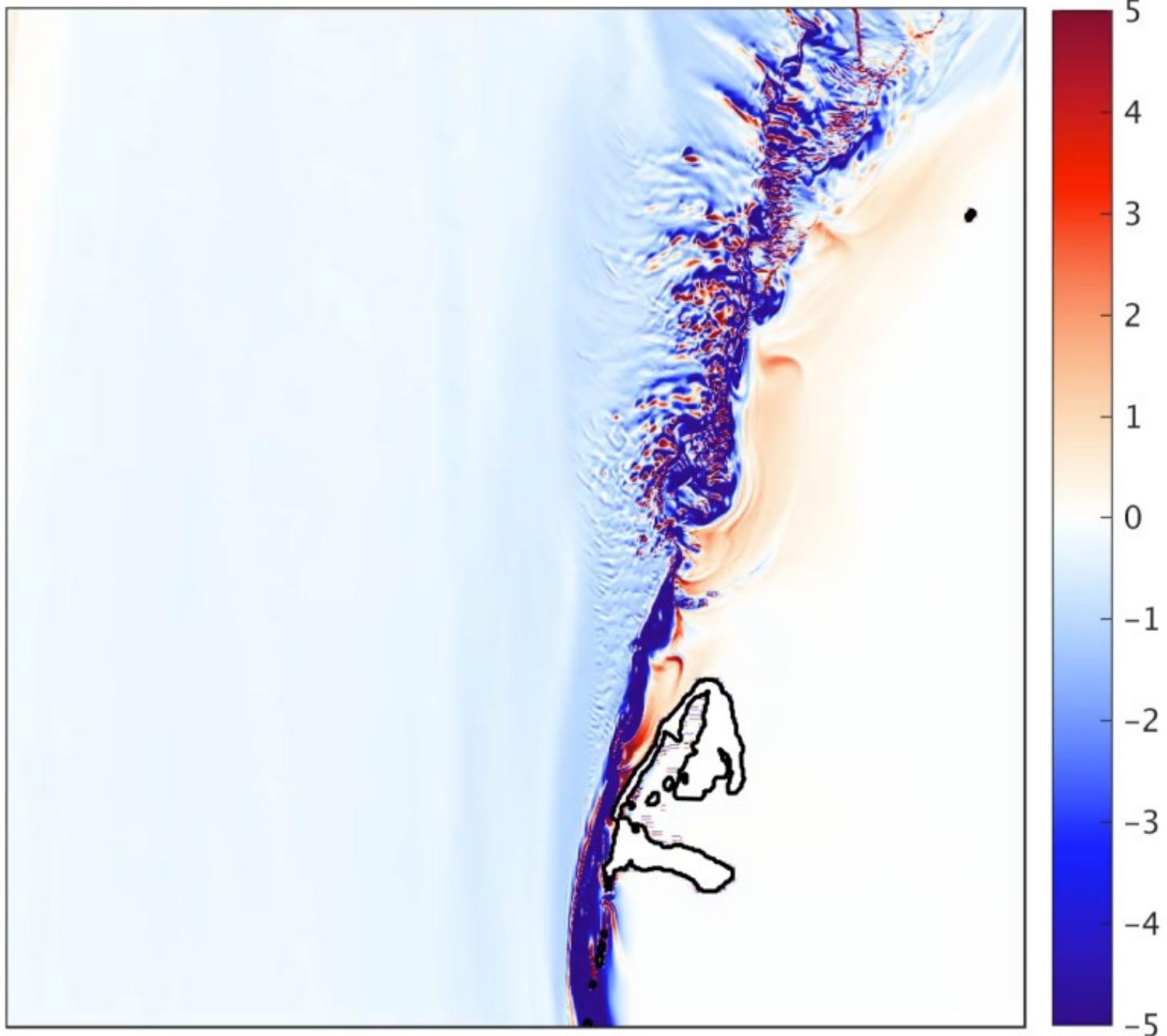


$dx = 2.5 \text{ km}$

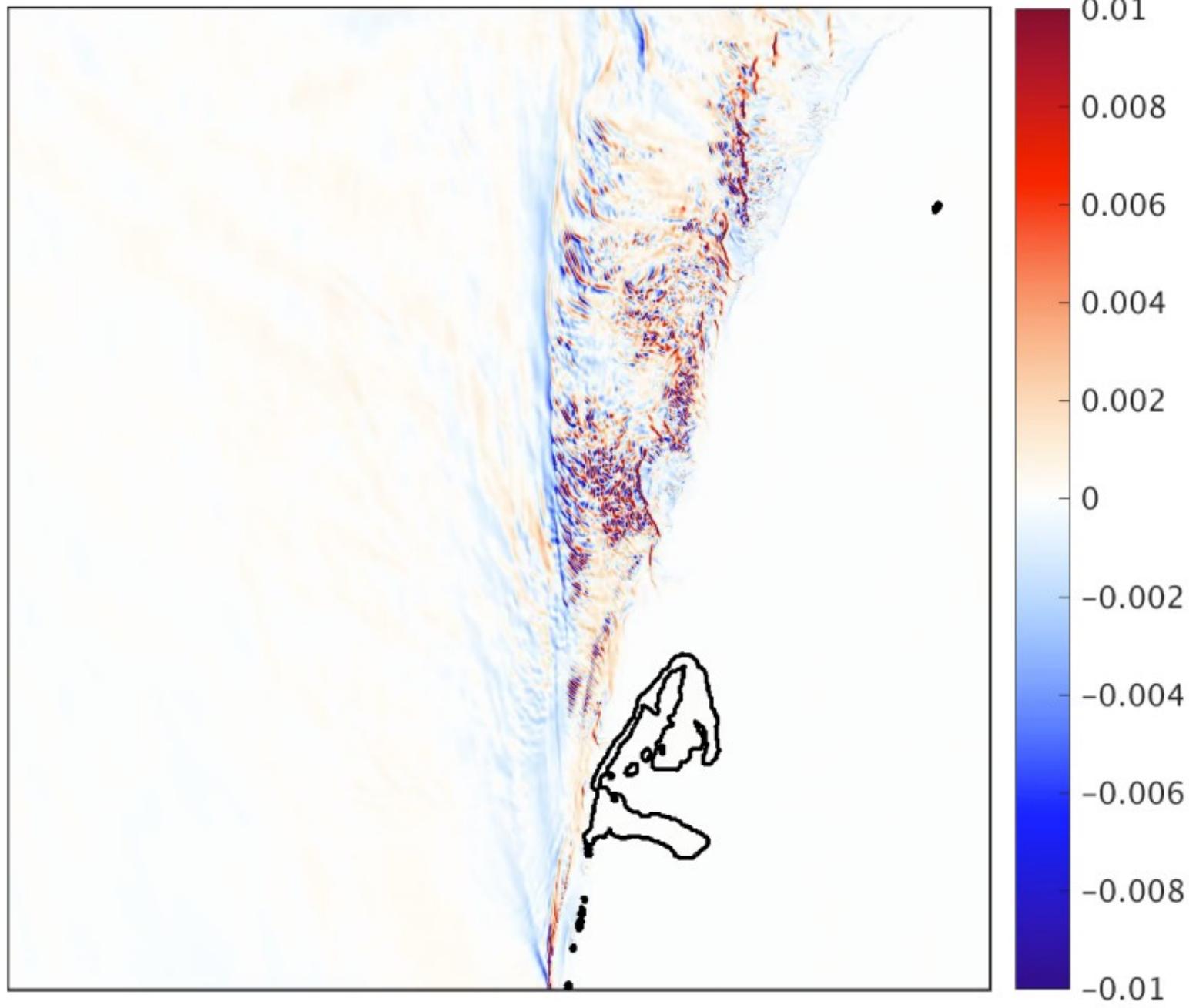


$\text{dx} = 700 \text{ m}$



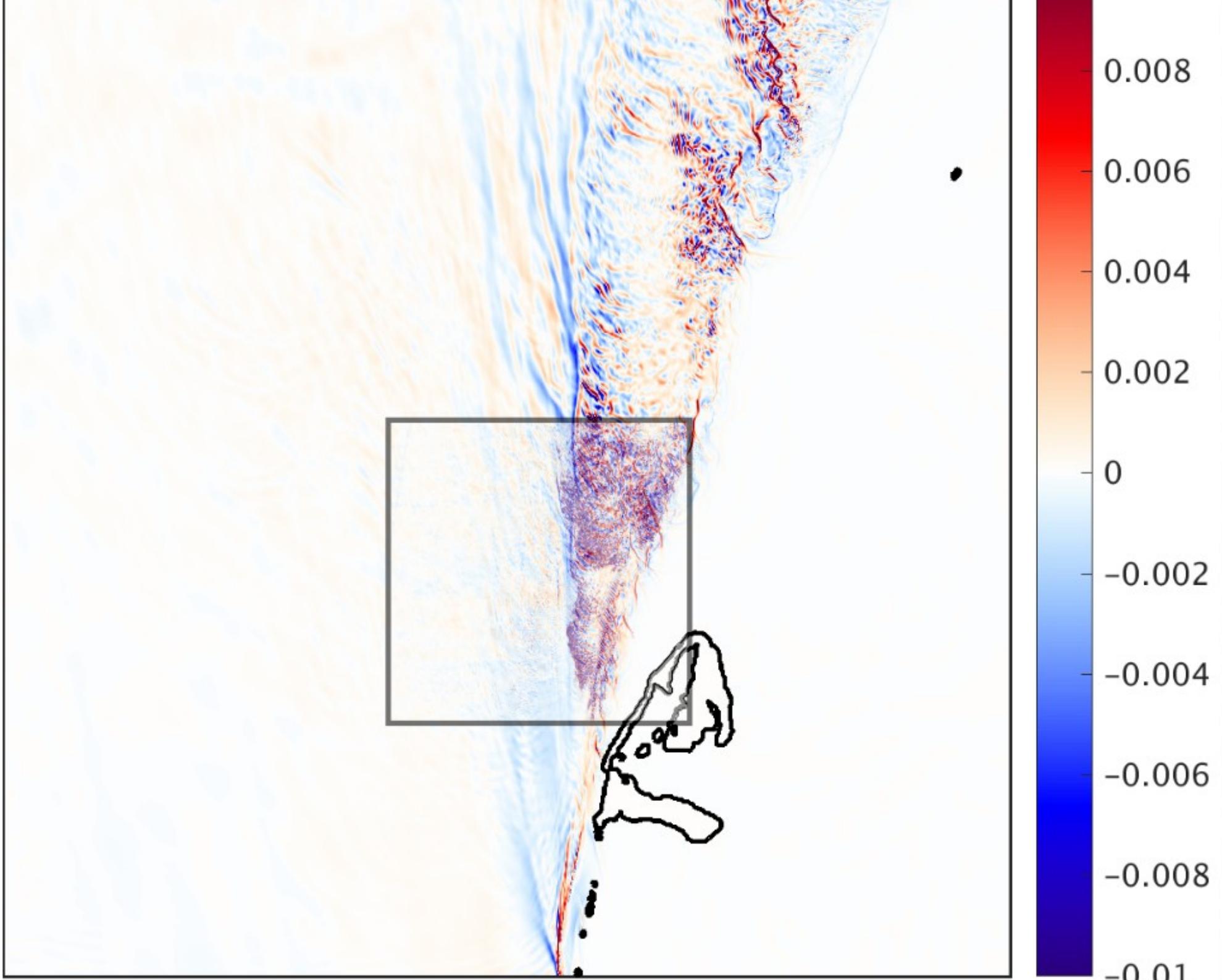


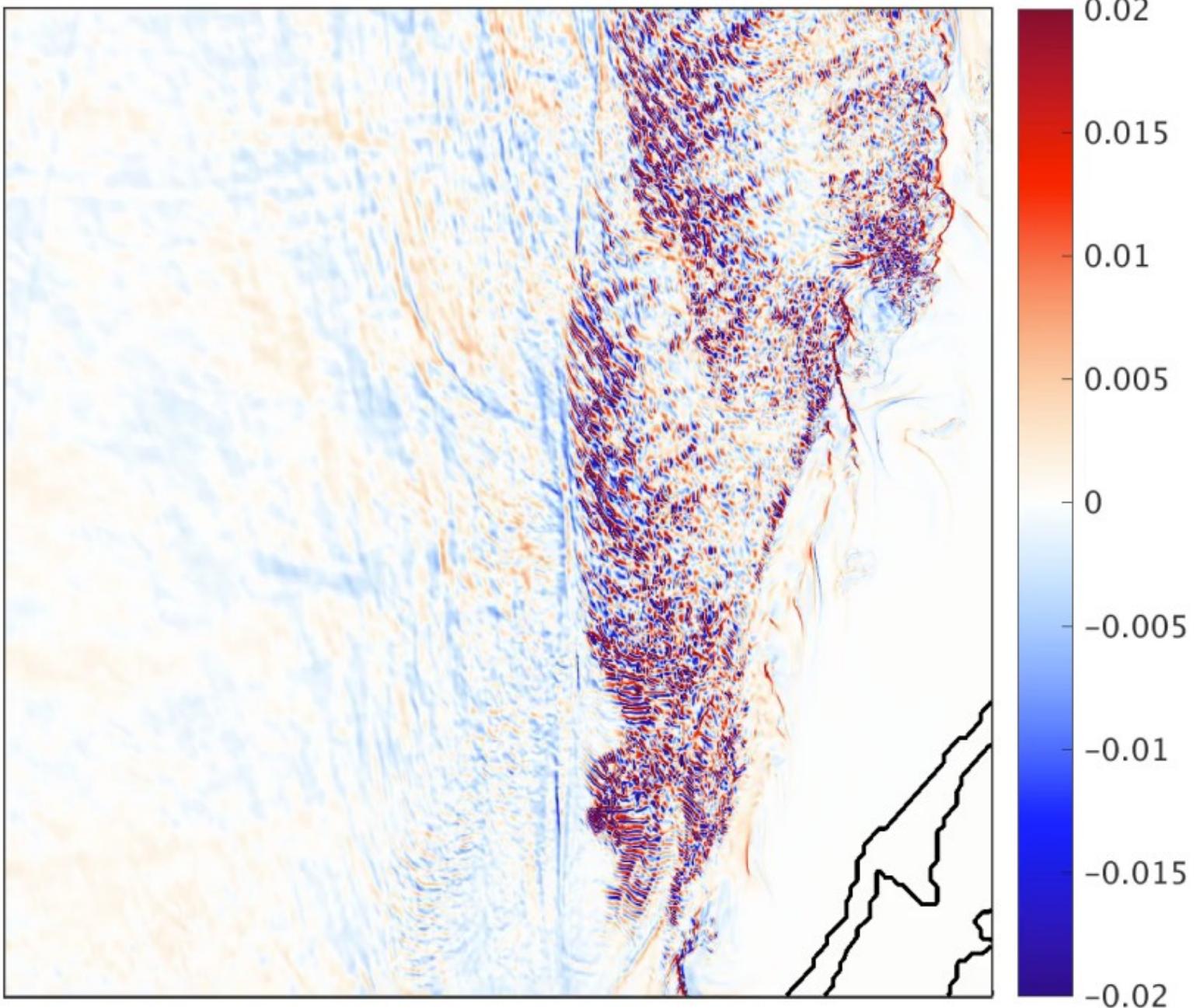
$\Delta x = 50\text{m}$, non-hydrostatic



$\text{dx} = 50\text{m}$, **non-hydrostatic**

Surface layer vertical velocity





$dx = 15 \text{ m}$ (NH)

Surface layer vertical velocity

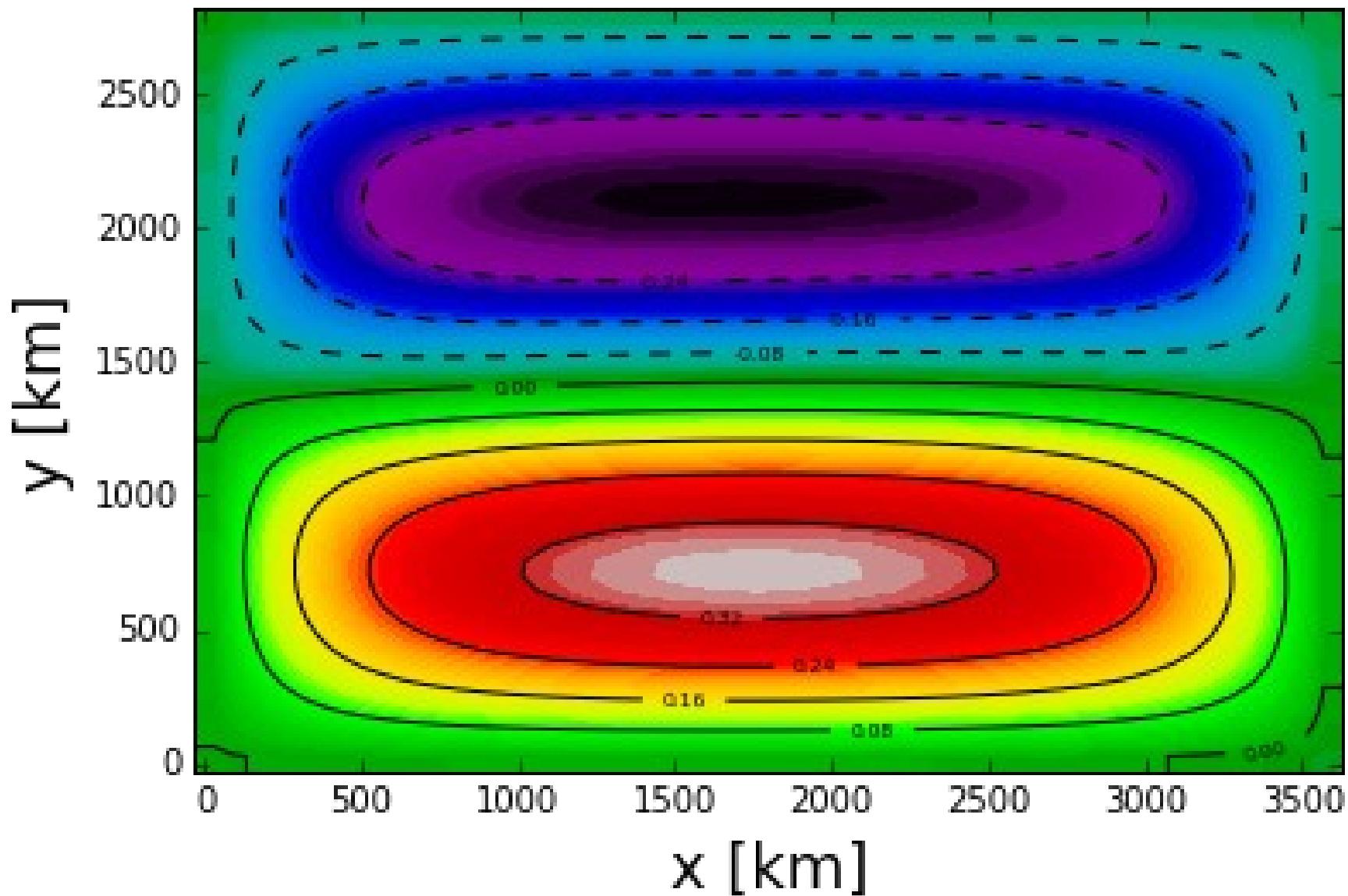


Visible light, (credit NASA)

Activity 1 – Run an idealized ocean basin

Activity 1 - Run an idealized ocean basin

SSH



Activity 1 – Run an idealized ocean basin

- **Jobcomp** (compilation)
- **cppdefs.h** (Numerical/physical options)
- **param.h** (gris size/ parallelisation)
- **croco.in** (choice of variables, parameter values, etc.)

Activity 1 – Run an idealized ocean basin

<https://github.com/quentinjamet/Tuto>

1) Preparing and compiling the model

For that use the jobcomp bash file

`./jobcomp`

1. Set library path
2. Automatic selection of option accordingly the platform used
3. Use of makefile
 - C-preprocessing step : .F → .f using the CPP keys definitions (in cppdefs.h file, customization of the code)
 - Compilation step : .f → .o (object) using Fortran compiler
 - Linking step : link all the .o file and the library (Netcdf, MPI, AGRIF)
--
▪ --> produce the executable **croco**

1) Preparing and compiling the model

Edit the param.h and cppdefs.h file to set-up the model

param.h defines the size of the arrays in ROMS:

```
...
#elif defined REGIONAL
# if defined BENGUELA
  parameter(LLm0=23, MMm0=31, N=32) <---- Southern Benguela test Model
# else
  parameter (LLm0=??, MMm0=??, N=??)
# endif
...
```

Given by running make_grid

Southern Benguela test Model

Defined in romstools_param.m

cppdefs.h:

- Basic options
- More advanced options

- Define CPP keys used by the C-preprocessor when compiling the model.
- Reduce the code to its minimal size: fast compilation.
- Avoid FORTRAN logical statements: efficient coding.

1) Preparing and compiling the model

View
cppdef.h
file



```
!-----  
!      BASIC OPTIONS  
!  
*/  
/*          Configuration Name */  
# define BENGUELA  
/*          Parallelization */  
# undef OPENMP  
# undef MPI  
/*          Embedding */  
# undef AGRIF  
/*          Open Boundary Conditions */  
# undef TIDES  
# define OBC_EAST  
# undef OBC_WEST  
# define OBC_NORTH  
# define OBC_SOUTH  
/*          Embedding conditions */  
# ifdef AGRIF  
# undef AGRIF_OBC_EAST  
# define AGRIF_OBC_WEST  
# define AGRIF_OBC_NORTH  
# define AGRIF_OBC_SOUTH  
# endif  
/*          Applications */  
# undef BIOLOGY  
# undef FLOATS  
# undef STATIONS  
# undef PASSIVE_TRACER  
# undef SEDIMENTS  
# undef BBL
```

```
!-----  
!      MORE ADVANCED OPTIONS  
!  
*/  
/*          Model dynamics */  
# define SOLVE3D  
# define UV_COR  
# define UV_ADV  
# ifdef TIDES  
# define SSH_TIDES  
# define UV_TIDES  
# define TIDERAMP  
# endif  
/*          Grid configuration */  
# define CURVGRID  
# define SPHERICAL  
# define MASKING  
/*          Input/Output & Diagnostics */  
# define AVERAGES  
# define AVERAGES_K  
# define DIAGNOSTICS_TS  
# define DIAGNOSTICS_UV  
/*          Equation of State */ ...  
/*          Surface Forcing */ ...  
/*          Lateral Forcing */ ...  
/*          Input/Output & Diagnostics */ ...  
/*          Bottom Forcing */ ...  
/*          Point Sources - Rivers */ ...  
/*          Lateral Mixing */ ...  
/*          Vertical Mixing */ ...  
/*          Open Boundary Conditions */ ...  
/*          Embedding conditions */ ...
```

2) Running the model

The namelist roms.in

roms.in provides the run time parameters for ROMS:

```
title: Southern Benguela
time_stepping: NTIMES dt[sec] NDTFAST NINFO
        480    5400   60   1
S-coord: THETA_S, THETA_B, Hc (m)
        6.0d0  0.0d0  10.0d0
grid: filename
        ROMS_FILES/roms_grd.nc
forcing: filename
        ROMS_FILES/roms_frc.nc
bulk_forcing: filename
        ROMS_FILES/roms_blk.nc
climatology: filename
        ROMS_FILES/roms_clm.nc
boundary: filename
        ROMS_FILES/roms_bry.nc
initial: NRREC filename
        1
        ROMS_FILES/roms_ini.nc
restart: NRST, NRPFRST / filename
        480 -1
        ROMS_FILES/roms_RST.nc
```

Warning ! These
should be identical to
the ones in
romstools_param.m

```
history: LDEFHIS, NWRT, NRPFHIS / filename
        T 480 0
        ROMS_FILES/roms_his.nc
averages: NTSAVG, NAVG, NRPFAVG / filename
        1 48 0
        ROMS_FILES/roms_avg.nc
primary_history_fields: zeta UBAR VBAR U V wrtT(1:NT)
        T F F F F 10*T
auxiliary_history_fields: rho Omega W Akv Akt Aks HBL Bostr
        F F F F F F F F
primary_averages: zeta UBAR VBAR U V wrtT(1:NT)
        T T T T T 10*T
auxiliary_averages: rho Omega W Akv Akt Aks HBL Bostr
        F T T F T F T T
rho0:
        1025.d0
lateral_visc: VISC2, VISC4 [m^2/sec for all]
        0. 0.
tracer_diff2: TNU2(1:NT) [m^2/sec for all]
        10*0.d0
bottom_drag: RDRG [m/s], RDRG2, Zob [m], Cdb_min, Cdb_max
        0.0d-04 0.d-3 1.d-2 1.d-4 1.d-1
gamma2:
        1.d0
sponge: X_SPONGE [m], V_SPONGE [m^2/sec]
        100.e3     800.
nudg_cof: TauT_in, TauT_out, TauM_in, TauM_out [days for all]
        1. 360. 10. 360.
```

Activity 1 - Run an idealized ocean basin

- **param.h**

```
parameter (LLm0=60, MMm0=50, N=10)
```

- **cppdefs.h**

```
# define UV_COR  
# define UV_VIS2  
# define TS_DIF2
```

```
# define ANA_GRID  
# define ANA_INITIAL
```

- **ana_grid.F**

```
f0=1.E-4  
beta=0.
```

- **croco.in**

```
bottom_drag: RDRG(m/s), RDRG2, Zob [m], Cdb_min, Cdb_max  
            3.e-4          0.      0.      0.      0.  
gamma2: 1.  
linEOS_cff: R0 [kg/m3], T0 [Celsius], S0 [PSU], TCOEF [1/Celsius], SCOEF [1/PSU]  
           30.      0.      0.      0.28      0.  
lateral_visc: VIS2 [m^2/sec] 1000. 0.  
tracer_diff2: TNU2 [m^2/sec] 1000. 0.
```

Homework

- For next time:
 - Read <https://www.jgula.fr/ModNum/Stommel48.pdf>
 - Read <https://www.jgula.fr/ModNum/Munk50.pdf>