Simulation de la Turbulence Méso-échelle dans l'Océan Global

Simulation of Mesoscale Turbulence in the Global Ocean

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OUTLINES

1 - Main Features of the Ocean General Circulation

- Mean Ocean Circulation
- Transient Mesoscale Eddies (Turbulence)

2 – Eddy-Resolving Ocean General Circulation Models

- Primitive equations
- Choosing the model resolution
- Realistic DRAKKAR global configurations
- Computational Issues

3 – Few model results

4 – Conclusions

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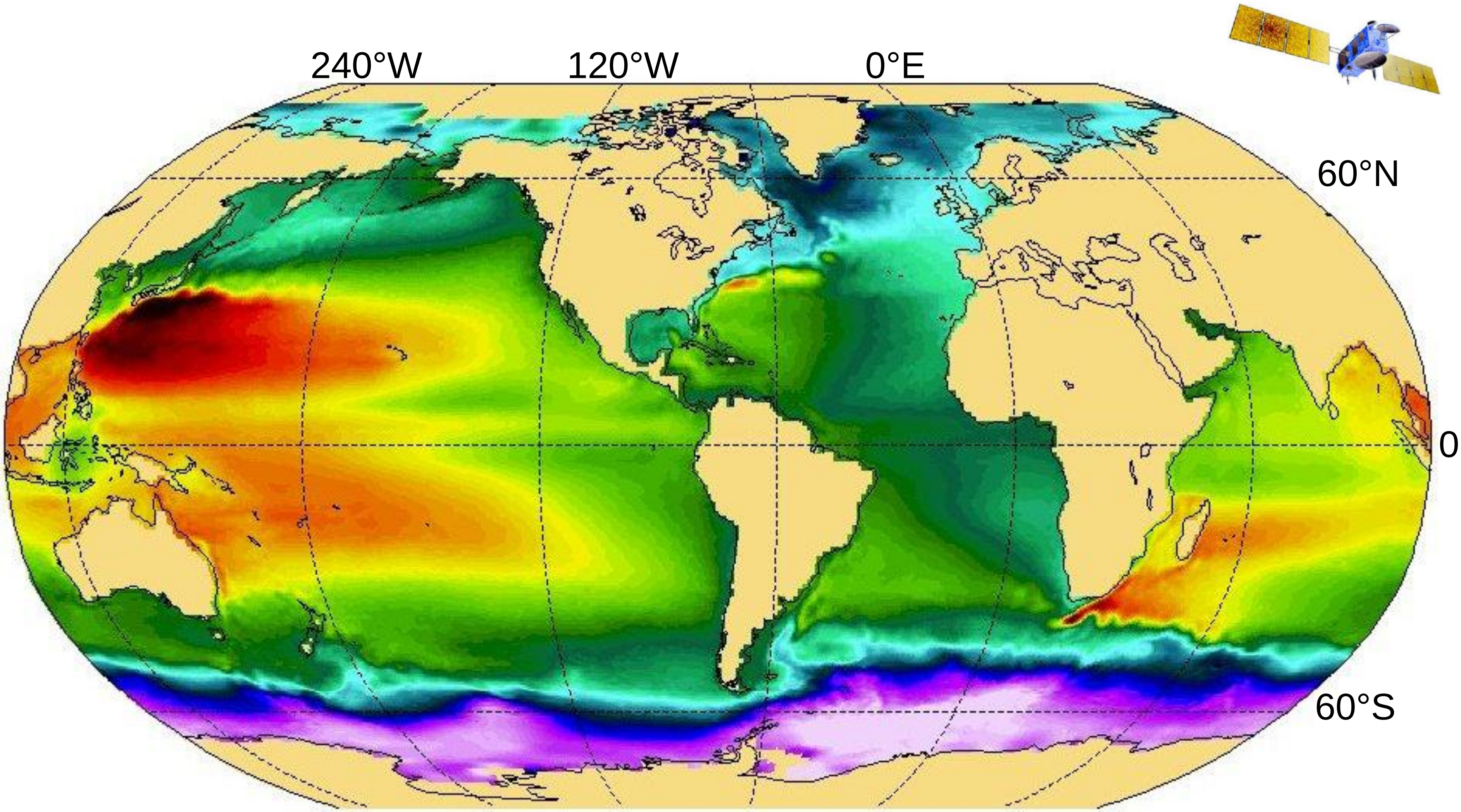
Mean sea surface height (1993-1999) from satellite altimetry (CNES/CLS2009).



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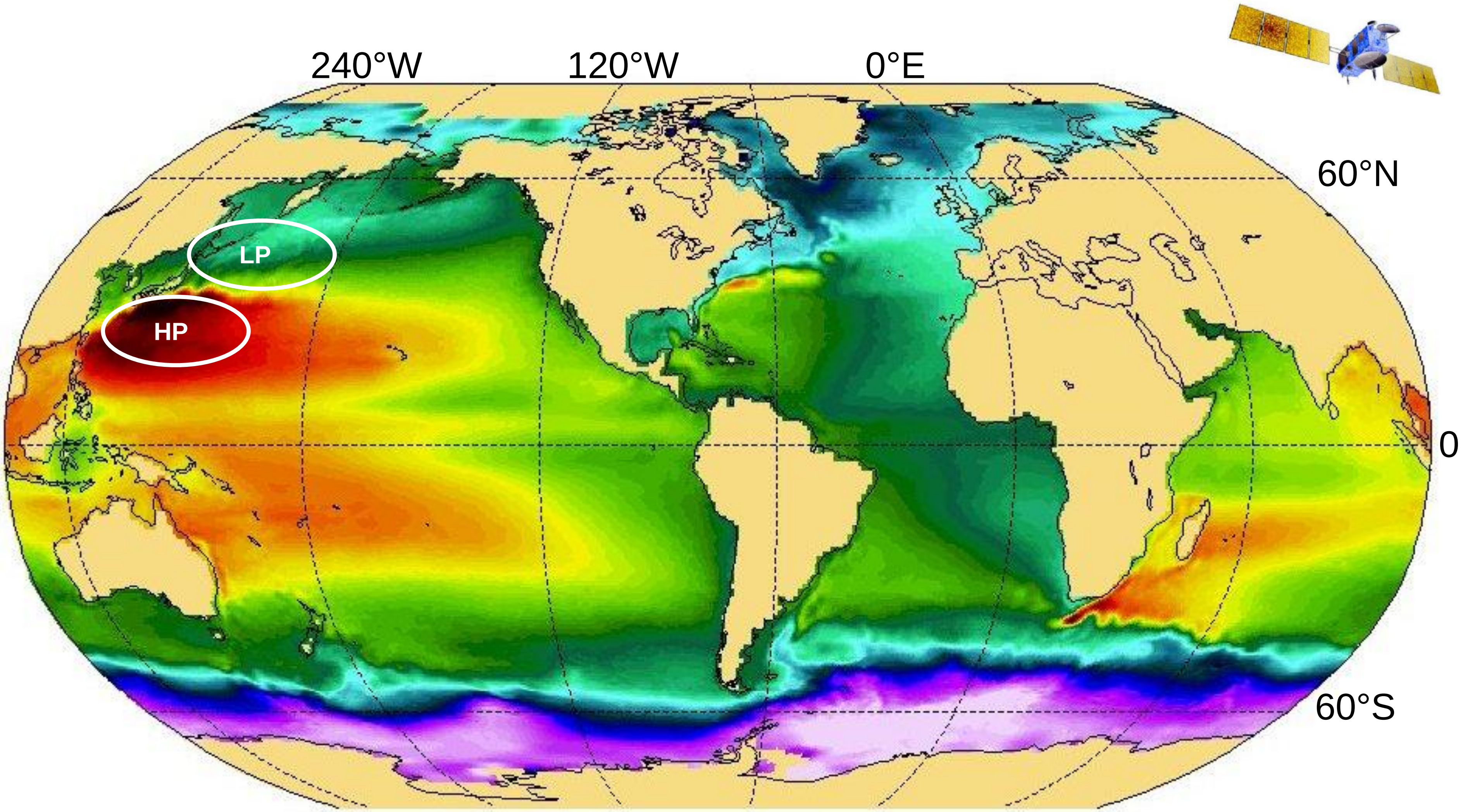

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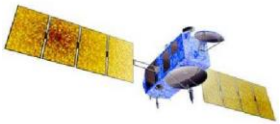
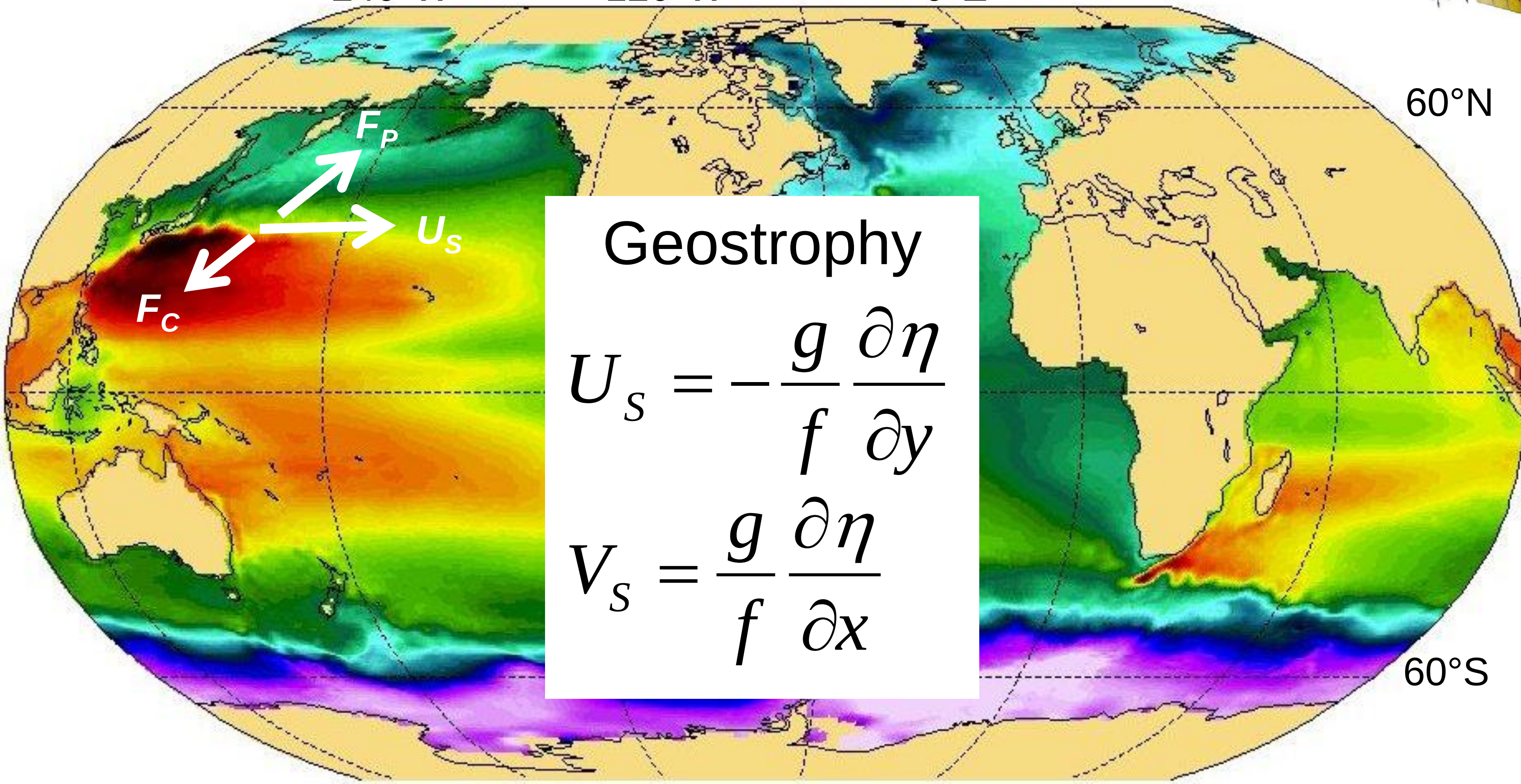


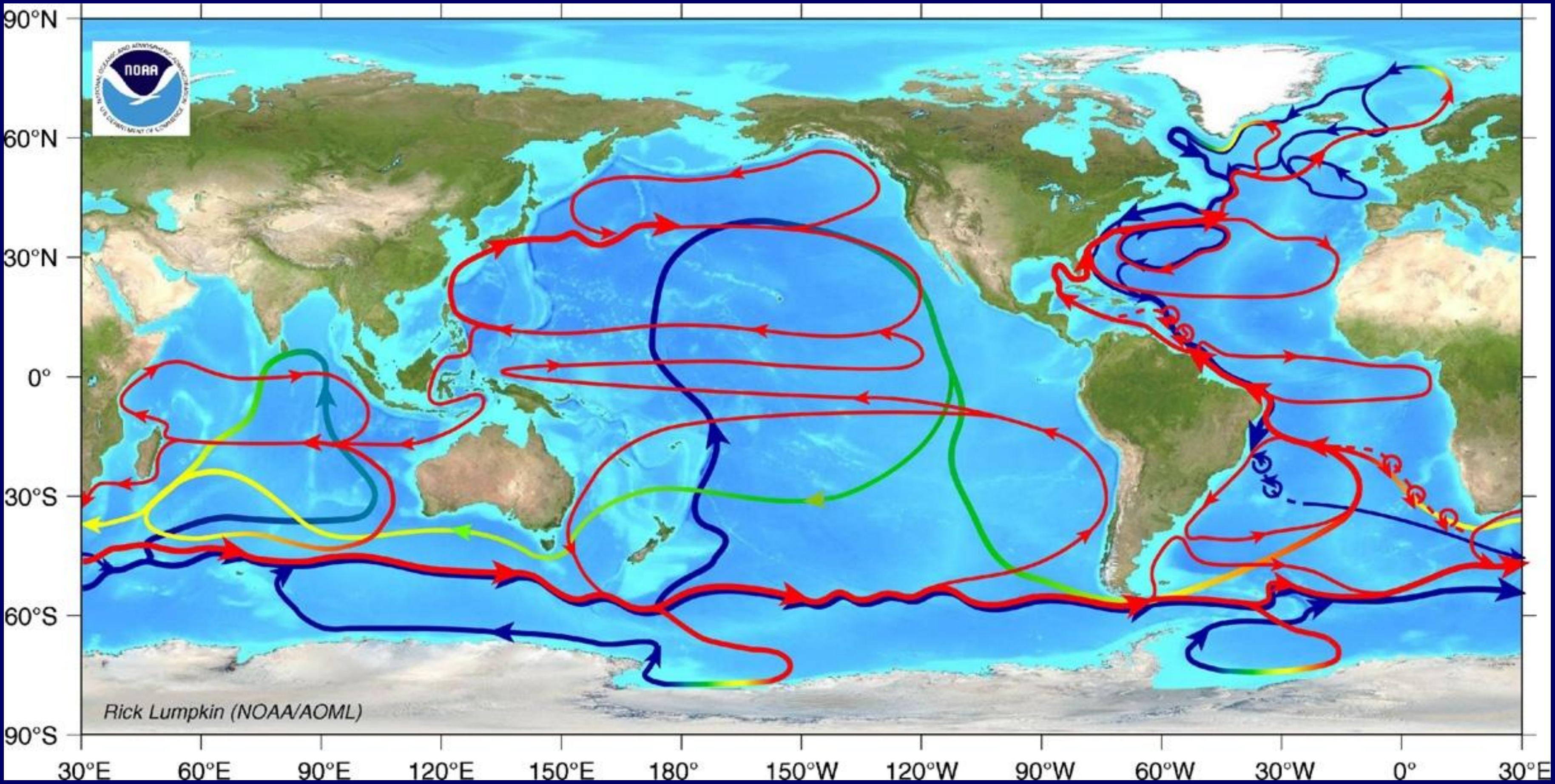


Geostrophy

$$U_s = -\frac{g}{f}\frac{\partial \eta}{\partial y}$$

$$V_s = \frac{g}{f}\frac{\partial \eta}{\partial x}$$

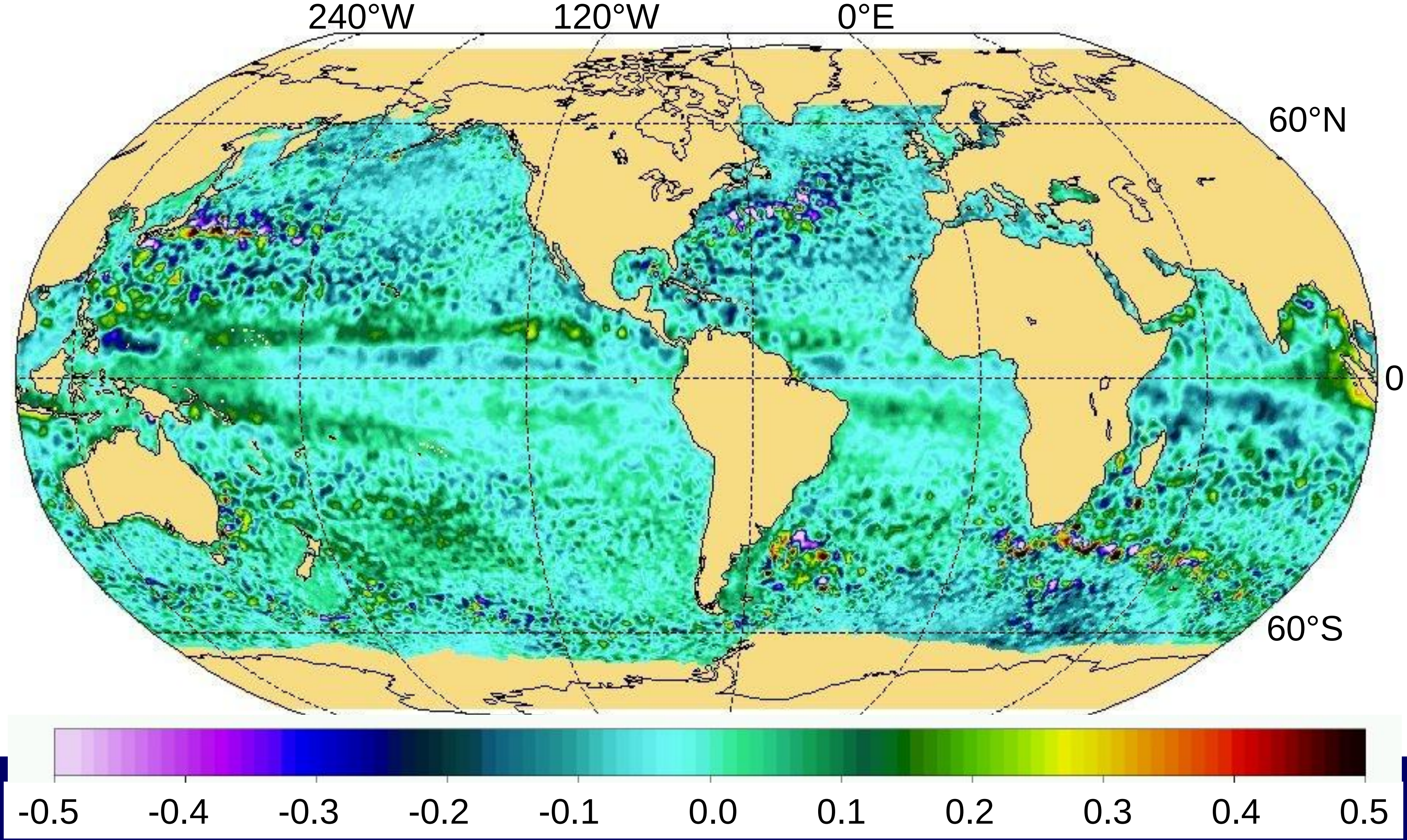
Schematic of the Ocean General Circulation



Large scale currents

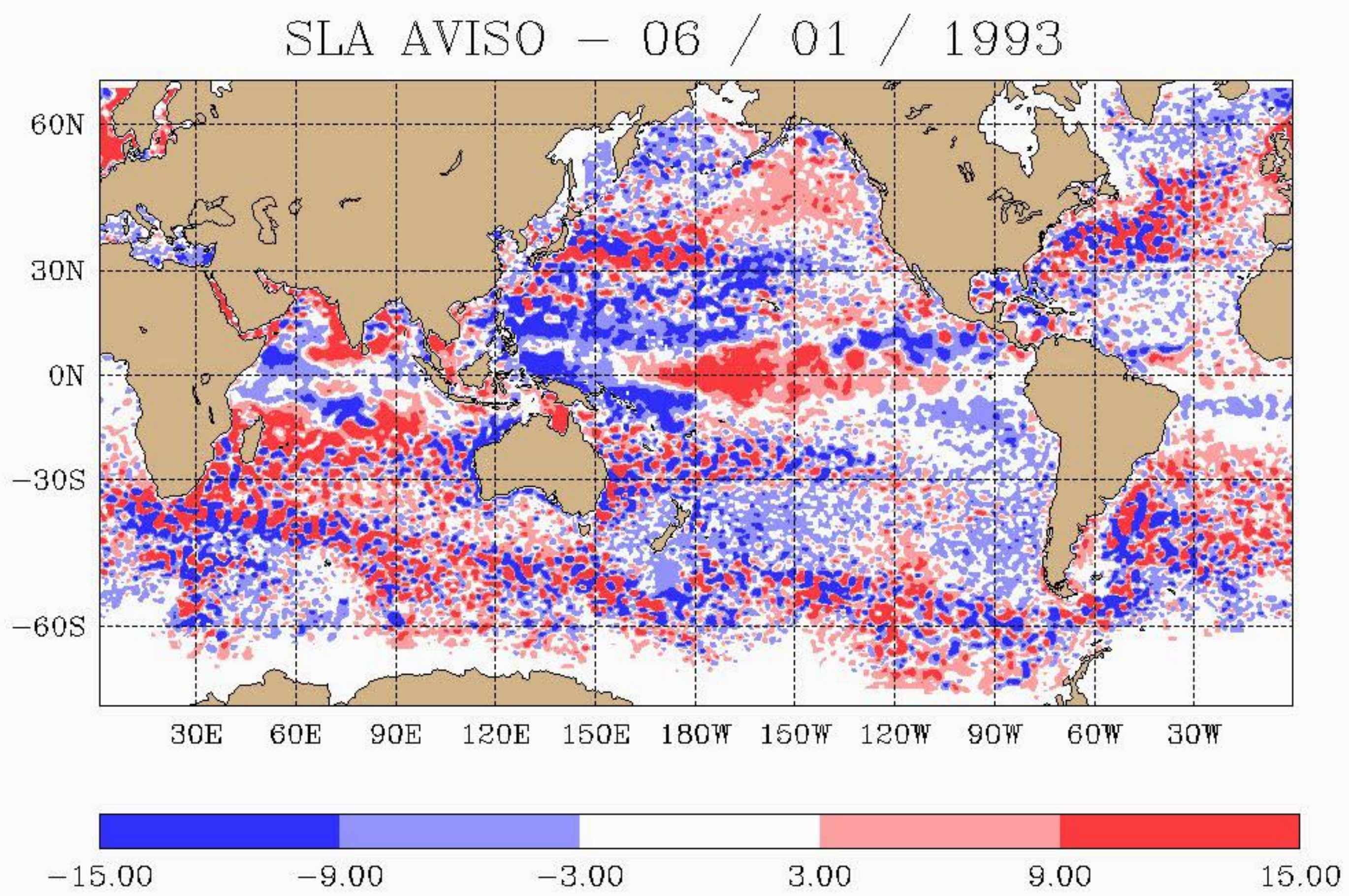
- at the surface and at depth
- western intensified

Sea Level Anomaly (19 May 2005) from satellite altimetry (T/P+ERS Aviso product)



Ubiquity of “transient features” with spatial scale of the order of a few 100 km and time scale > few weeks

Ubiquity of "transient features"



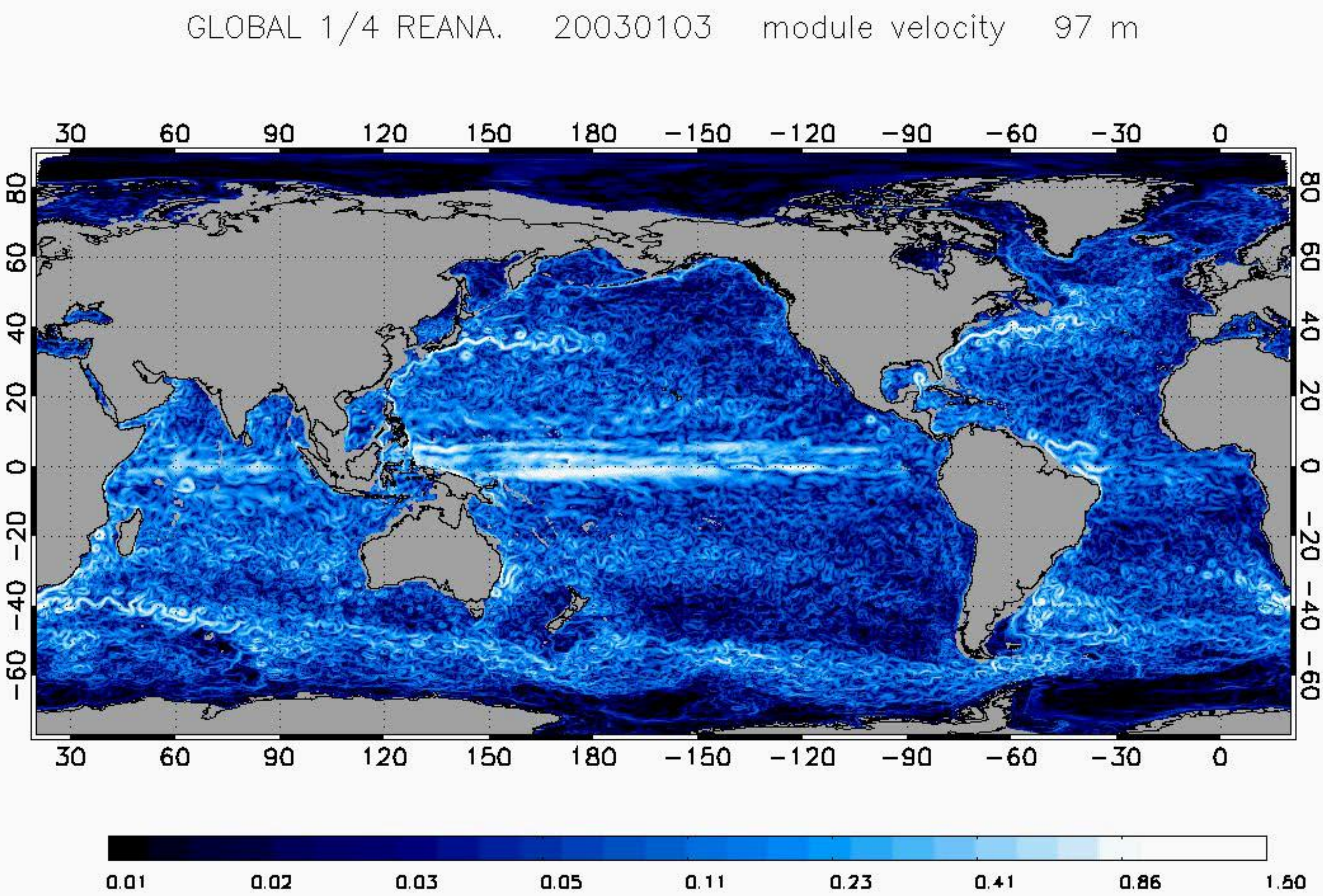
How does the Ocean General Circulation look like ?

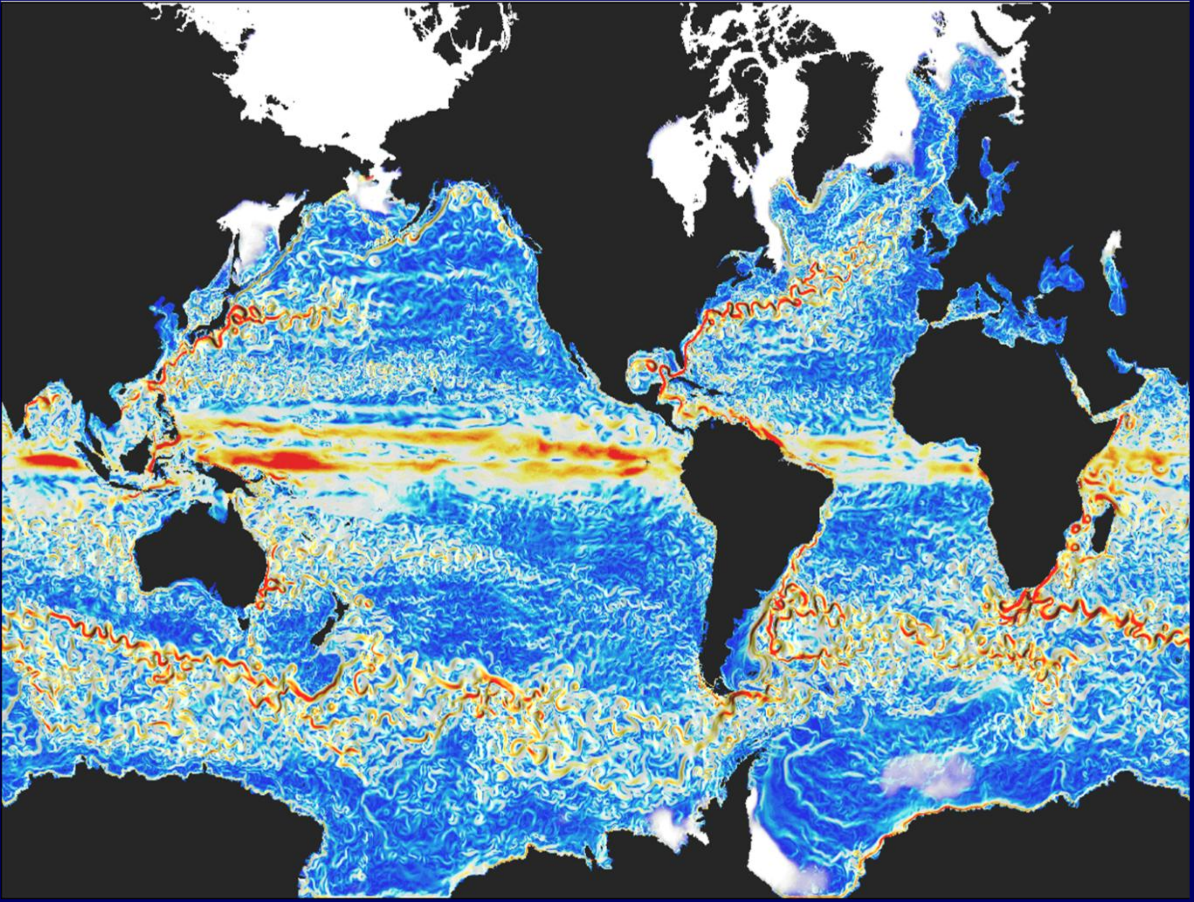
Global Ocean Reanalysis
GLORYS

combines all in-situ and satellite observations

with a Ocean General Circulation Model

GLORYS Reanalysis: Current Velocity (m/s) 2003-2009





Dominant circulation features

Great Ocean Currents:
- basin scale
- surface and deep
- western intensified

Mesoscale variability:
- More intense in the vicinity of the great currents.
- western propagation

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Ocean Mesoscale variability is often described as ...

... the "weather system" (or synoptic circulation) of the global ocean

by a dynamical analogy with the **synoptic variability in the Atmosphere**.

Dynamical properties of Ocean Mesoscale (and Atmospheric Synoptic) Eddies

- Quasi-geostrophic equilibrium — **Rossby Nb**

$$R_0 = \frac{U}{fL} << 1$$

- Characteristic velocitiy small compared to the celerity of internal gravity waves — **Froude Nb**

$$F_r = \frac{U}{\sqrt{g'H}} = \frac{U}{NH} << 1$$

- They are generated by instabilities of the large scale flow, and such, are equally influenced by stratification (vertical shear) and rotation — **Burger Nb**

$$B_u = \frac{R_0^2}{F_r^2} = \left(\frac{NH}{fL}\right)^2 = O(1)$$

- Hydrostatic equilibrium: Quasi 2D turbulence — 2D turbulence

Ocean Mesoscale variability is often described as ...

... the "weather system" (or synoptic circulation) of the global ocean

by a ... phere.

Dyna ... ric
Sync

Characteristic length scales: $L = \frac{NH}{f}$

$$N^2 = \frac{g}{H}\frac{\Delta\rho}{\rho_0}$$

N = Brunt-Vaïsala frequency

H = thermocline depth

H = troposphere height

- Qu
- Ch
com
gravity waves

Froude Nb

$$F_r = \ldots = \frac{U}{NH} << 1$$

$$\sqrt{g'H}$$

- They are generated by ins... of the large scale flow, and ... are equally influenced by stratification (vertical shear) ... rotation

$$B_u = \frac{R_0^2}{F_r^2} = \left(\frac{NH}{fL}\right)^2 = O(1)$$

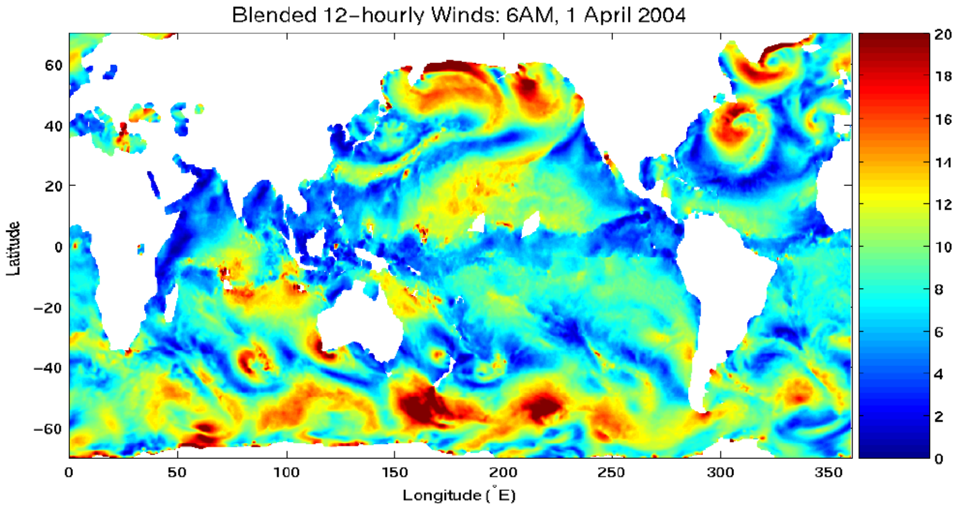
Eddy Length scale : $$L = \frac{NH}{f}$$ at mid-latitude ($f=10^{-4}\ s^{-1}$)

Atmosphere	Ocean
$N=10^{-2}\ s^{-1}$	$N=5\times10^{-3}\ s^{-1}$ and
$H=10^{4}\ m$	$H=10^{3}\ m$
$L_{atm}=1000\ km$	$L_{oce}=50\ km$

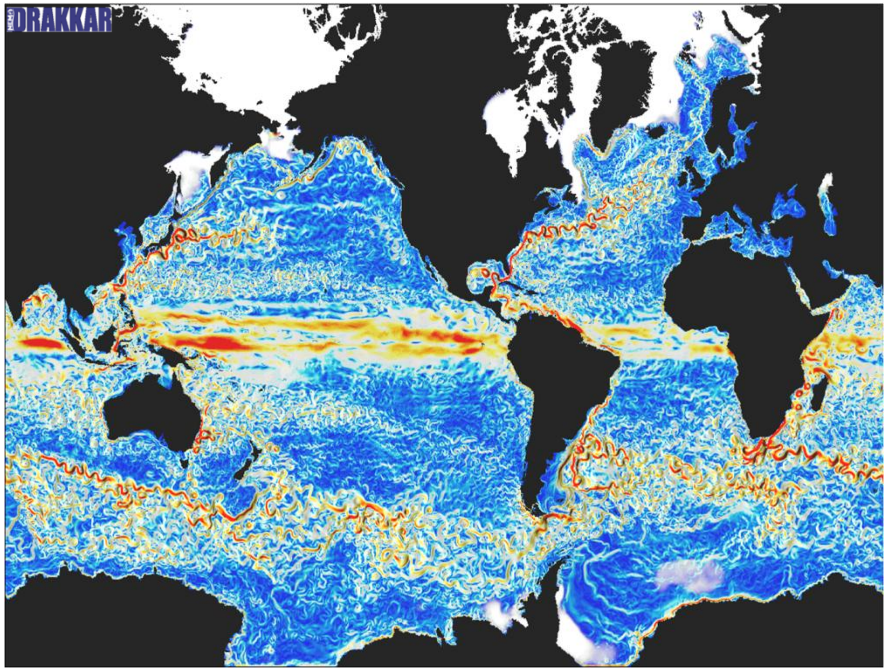
The eddy Length scale is therefore **20 times smaller** in the ocean than in the atmosphere

The difference in the eddy scale is so large that the **analogy with atmospheric synoptic scale does not simply hold** in terms of "**impact on the general circulation**".

(Zhang et al.,)



Atmospheric surface wind speed (12h)



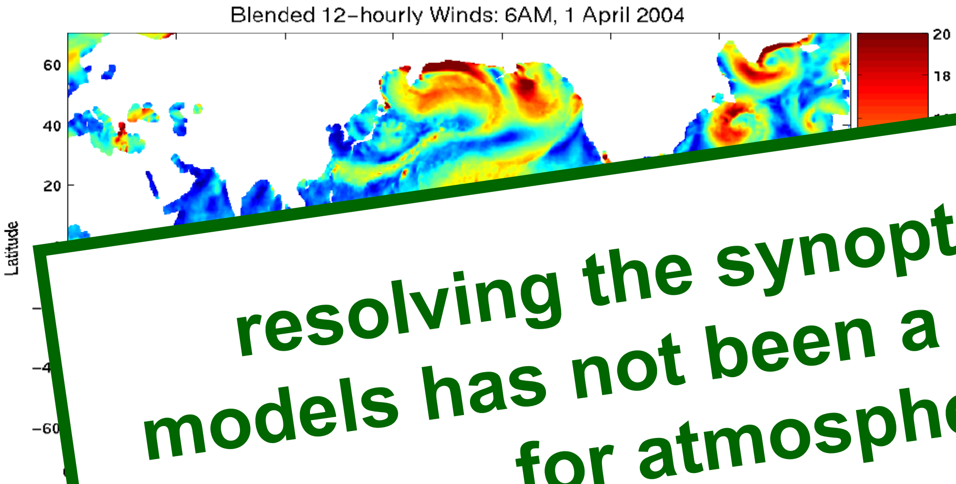
Ocean current speed (model simulation, 5 day mean)

Meridional Heat Transport (MHT) at mid latitudes

The **totality** of the MHT is done the synoptic transient features

A large part of the MHT is done by **poleward Mean Currents** flowing along continents

(Zhang et al.,)



resolving the synoptic scales in ocean models has not been a strong case as it was for atmospheric models

At present the ocean models used in earth system modelling do not resolve eddies

) at mid latitudes

Th **totality** of the MHT is done the synoptic transient features

A large part of the MHT is done by **poleward Mean Currents** flowing along continents

•Eddy processes/fluxes have many « potential » consequences for the ocean general circulation and climate (McWilliams, 2008)

- Maintenance of strong currents
- Dispersion and mixing (isopycnal)
- Energy cascade and dissipation
- Density re-stratification
- Ventilation, subduction
- Frontogenesis, rectification
- Topographic form stress
- Generation of intrinsic low frequency variability
- ...

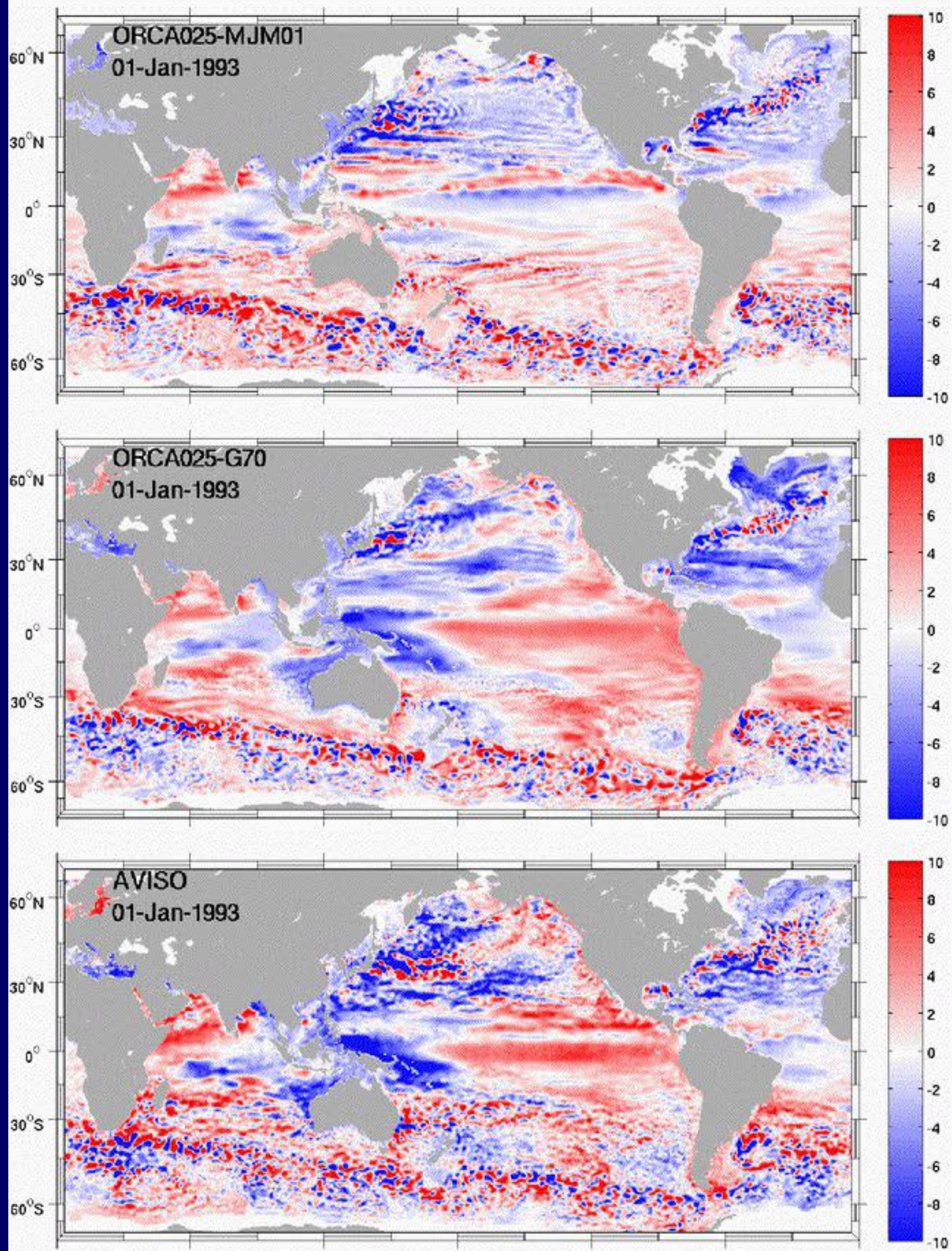
•Eddies are essential for Operational Oceanography applications

Low Frequency (> 18 months)
SSH anomalies

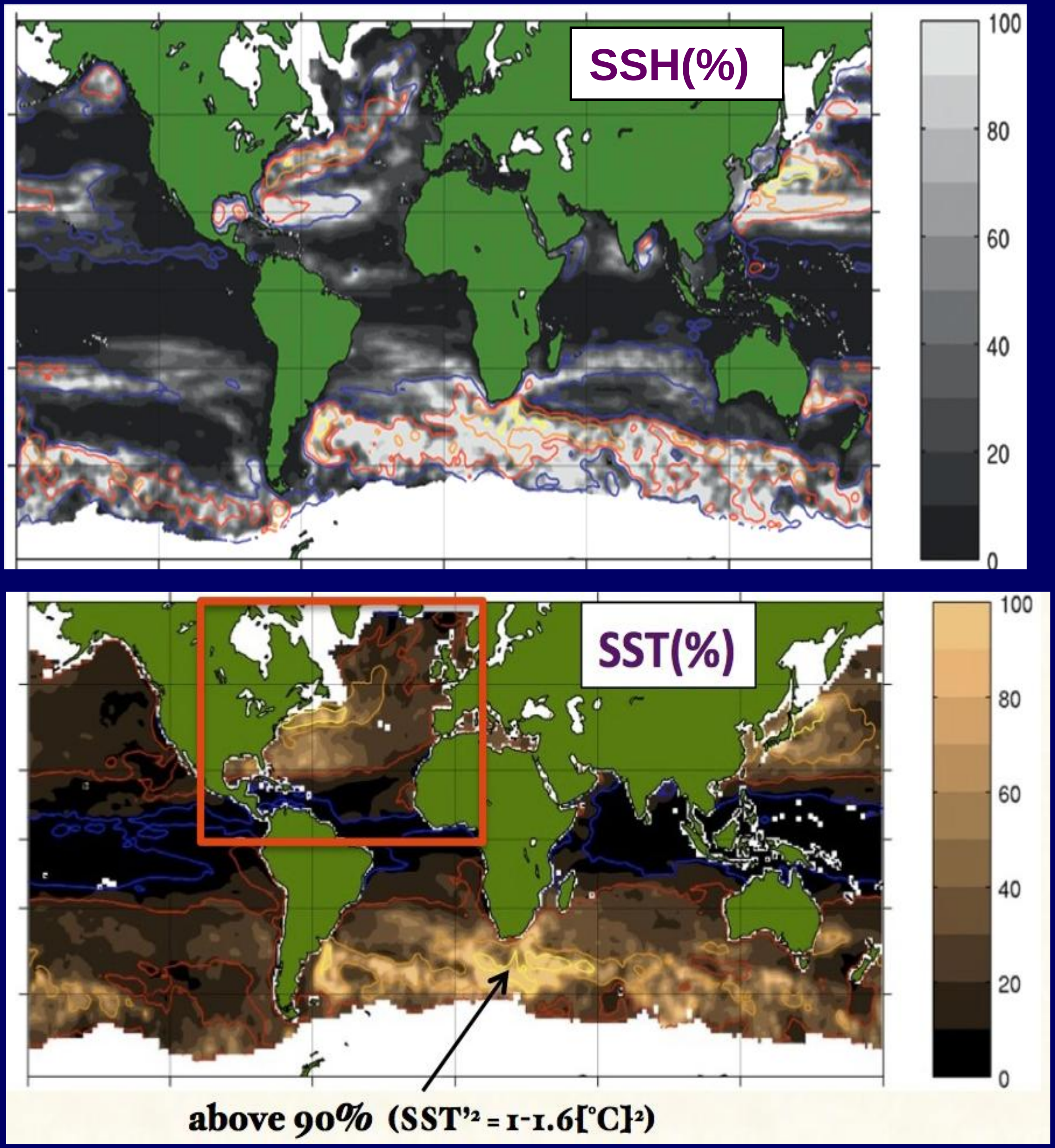
No interannual forcing

Full interannual forcing

Observations (altimetry)



% of intrinsic low-frequency variability (Penduff et al., 2011)



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Eddy-Resolving Ocean General Circulation Models are numerical systems that provides a representation of:

- the ocean "state" variables

Temperature, Salinity, Currents, Pressure, Sea Surface Height, sea-ice, *Biogeochemistry*...

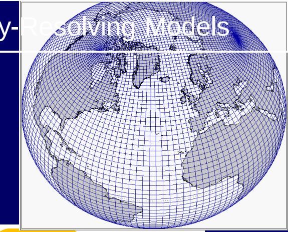
- **their evolution and interactions at the relevant space and time scales (i.e. large and eddy scales)**

Resolve the sources of "mesoscale" instabilities

Allow the growth of "mesoscale" instabilities

Allow the propagation of mesoscale features and their interactions with their environment (large scale mean flow, topography, eddies, ...)

Properly represents the effects of the "unresolved" (subgrid) scales



The Primitive Equations of an OGCM (NEMO code, (Madec, 2008)

Approximations (rotation ➡ 2D turbulence):

- Shallow water
- Boussinesq
- Hydrostatic

$$\frac{\partial u}{\partial t} + (\vec{u}\cdot\vec{\nabla})u - fv = -\frac{1}{\rho}\frac{\partial P}{\partial x} + D_u$$

$$\frac{\partial v}{\partial t} + (\vec{u}\cdot\vec{\nabla})v + fu = -\frac{1}{\rho}\frac{\partial P}{\partial y} + D_v$$

$$\frac{\partial P}{\partial z} = -\rho g$$

$$no\ \frac{\partial w}{\partial t}\ term$$

$$\vec{\nabla}\cdot\vec{u} = 0$$

$$\rho = \rho(T,S,P)$$

$$\vec{u} = (u,v,w)$$

$$\frac{\partial T}{\partial t} + \vec{u}\cdot\vec{\nabla}T = D_T + F_T$$

$$\left.\frac{\partial T}{\partial t}\right]_z = \frac{1}{\Delta z}F_{SOL}(z)$$

$$\frac{\partial S}{\partial t} + \vec{u}\cdot\vec{\nabla}S = D_S + F_S$$

Surface boundary conditions

Kinematics

$$\frac{\partial \eta}{\partial t} + \vec{u}\cdot\vec{\nabla}\eta = w\big]_{surf} + P + R - E$$

Flux

$$K_v\left.\frac{\partial T}{\partial z}\right]_{surf} = -\rho C_p Q_{NSOL}$$

$$K_v\left.\frac{\partial S}{\partial z}\right]_{surf} = 0$$

$$A_v\left.\frac{\partial u}{\partial z}\right]_{z=0} = \frac{1}{\rho_0}\tau_x$$

$$A_v\left.\frac{\partial v}{\partial z}\right]_{z=0} = \frac{1}{\rho_0}\tau_y$$

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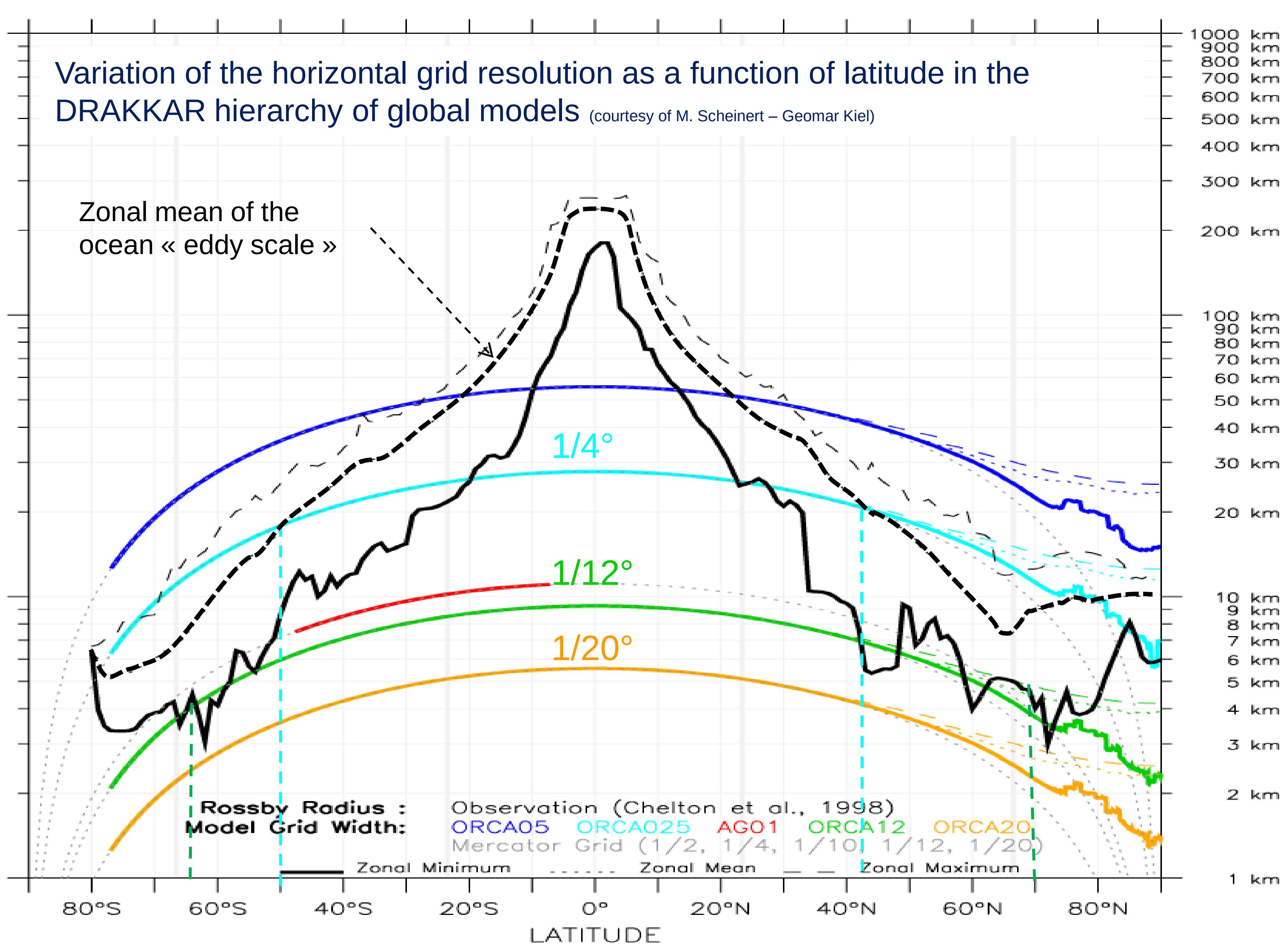
Choosing the model resolution (i.e. the resolved scales)



Internal Rossby Radius of Deformation (Chelton, 1998)

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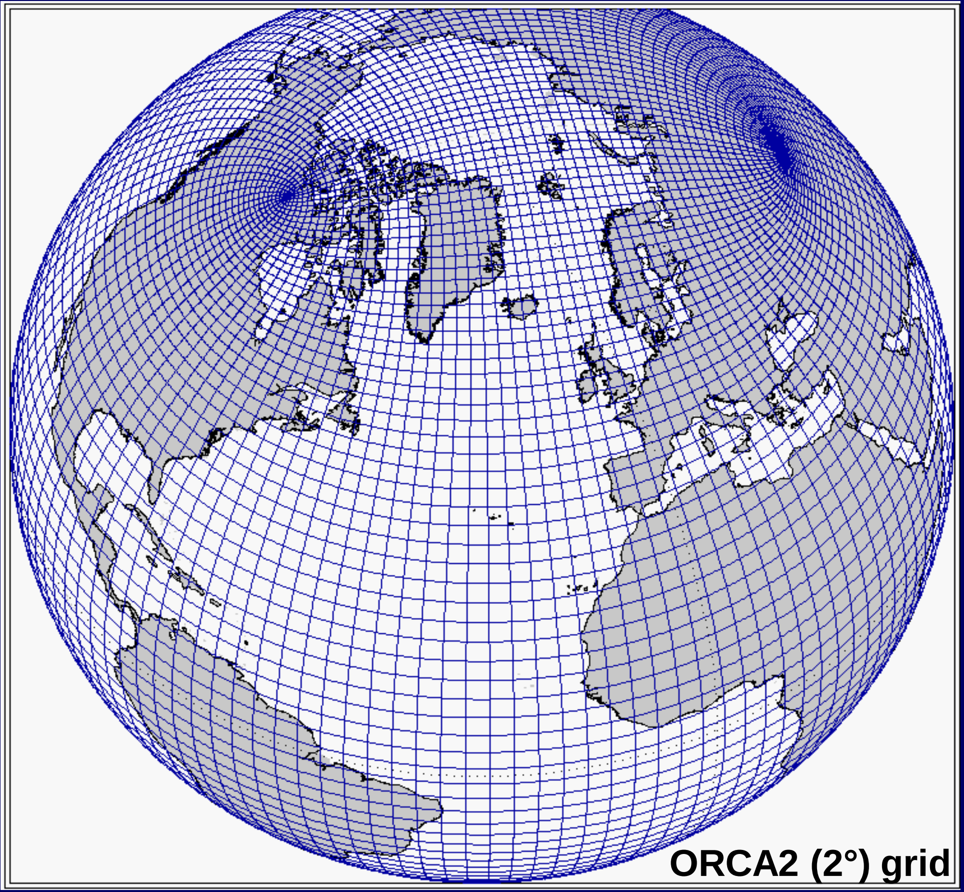
DRAKKAR hierarchy of global configurations

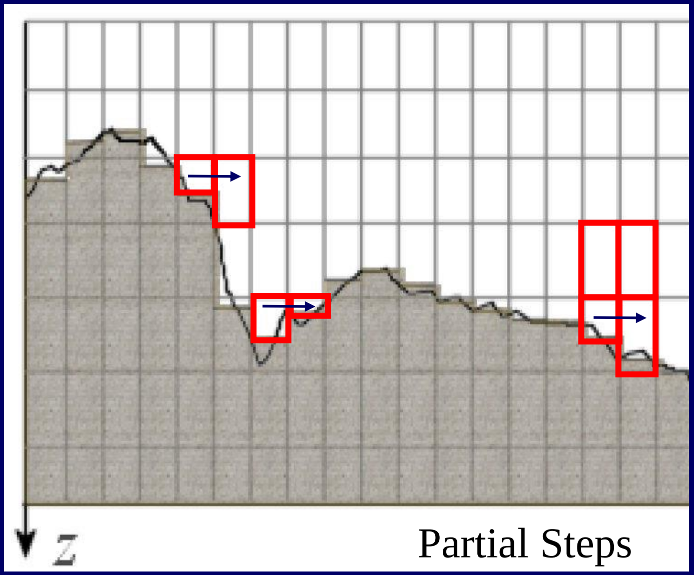
Numerical Code: NEMO (OGCM + LIM Sea-Ice mode, LOCEAN)

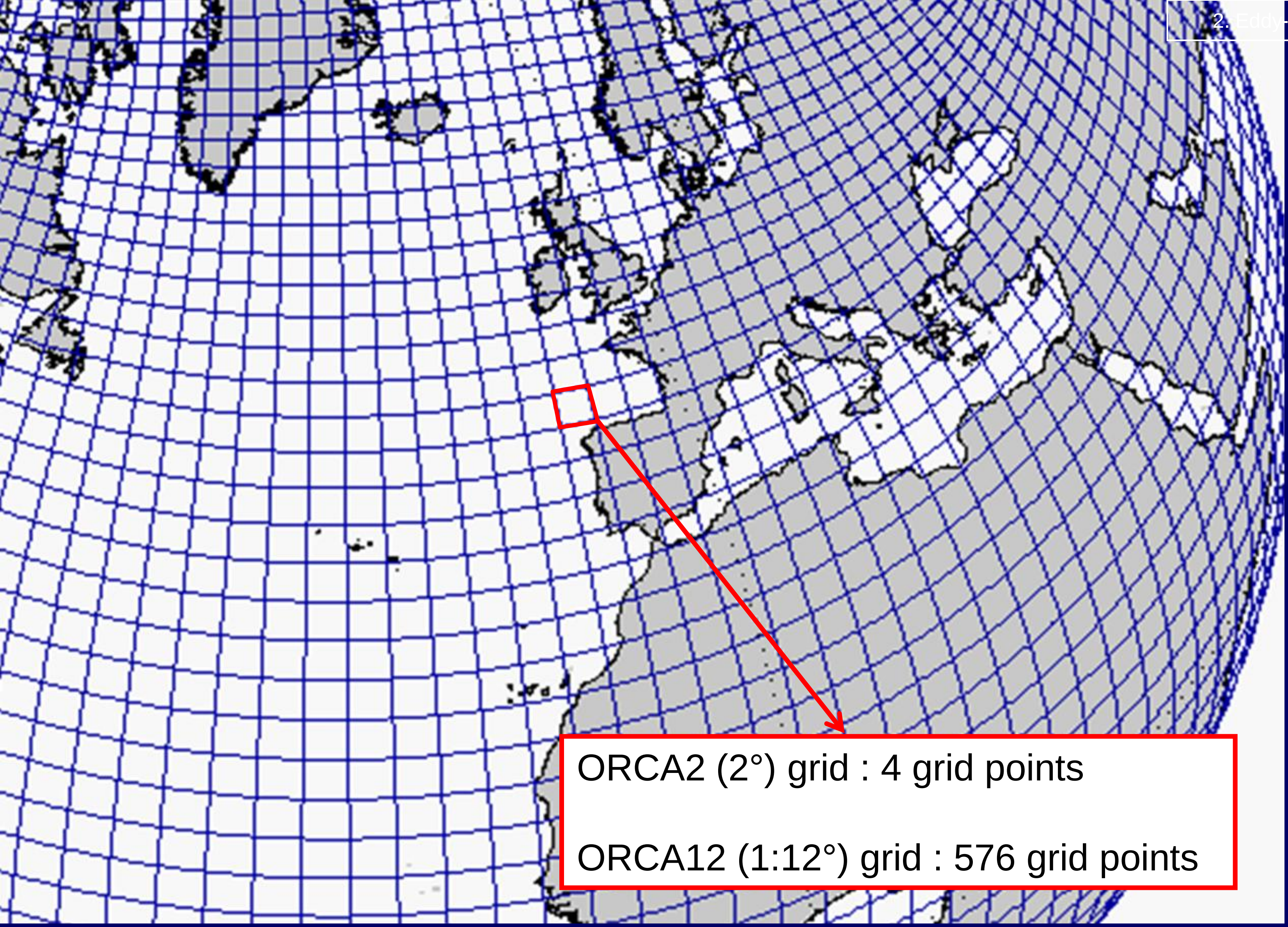
Horizontal Grid: Tri-Polar ORCA grid at resolutions of:
1° 1/2° 1/4° 1/12°


ORCA2 (2°) grid

Vertical grid:

46 to 75 levels refined at surface (1m to 250 m)
Partial step topography




ORCA2 (2°) grid : 4 grid points
ORCA12 (1:12°) grid : 576 grid points

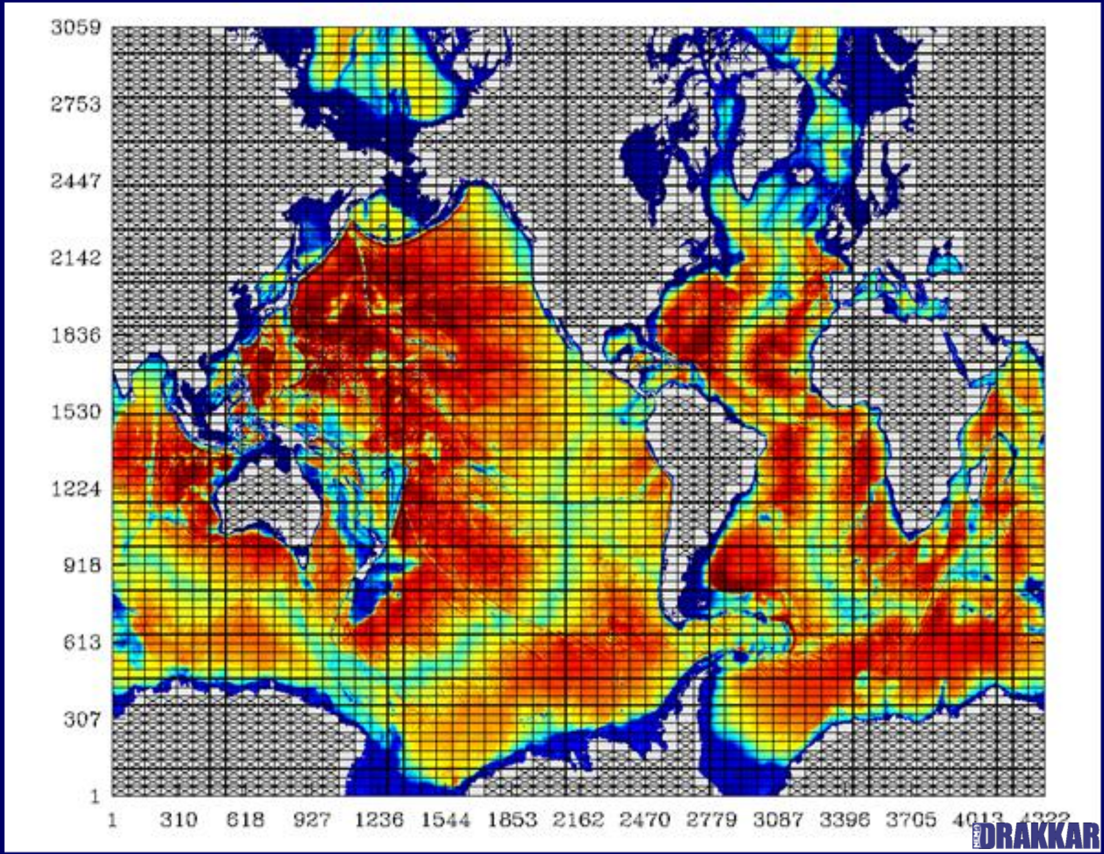
ORCA12 numerical model

The highest resolution global ocean circulation model used in Europe for both operational (GMES/MyOcean) and research (DRAKKAR consortium) purposes.

Resolution	: 1/12° (9km to 3 km)
Nb of hz grid points	: 4322x3059
Nb of vertical levels	: 46, 50 or 75
Time step	: 360 sec.

(In total 600 to 1000 million grid points)

Decomposition in 3584 domains on ADA



<u>Domain decomposition</u>

JADE : 2056 (257x8) cœurs
in production mode

ADA : (112x32) 3584 cœurs
in Grand Challenge mode

Pure MPI version

<u>DRAKKAR consortium:</u>
France, Germany, UK
to coordinate Eddy Resolving Modelling in Europe

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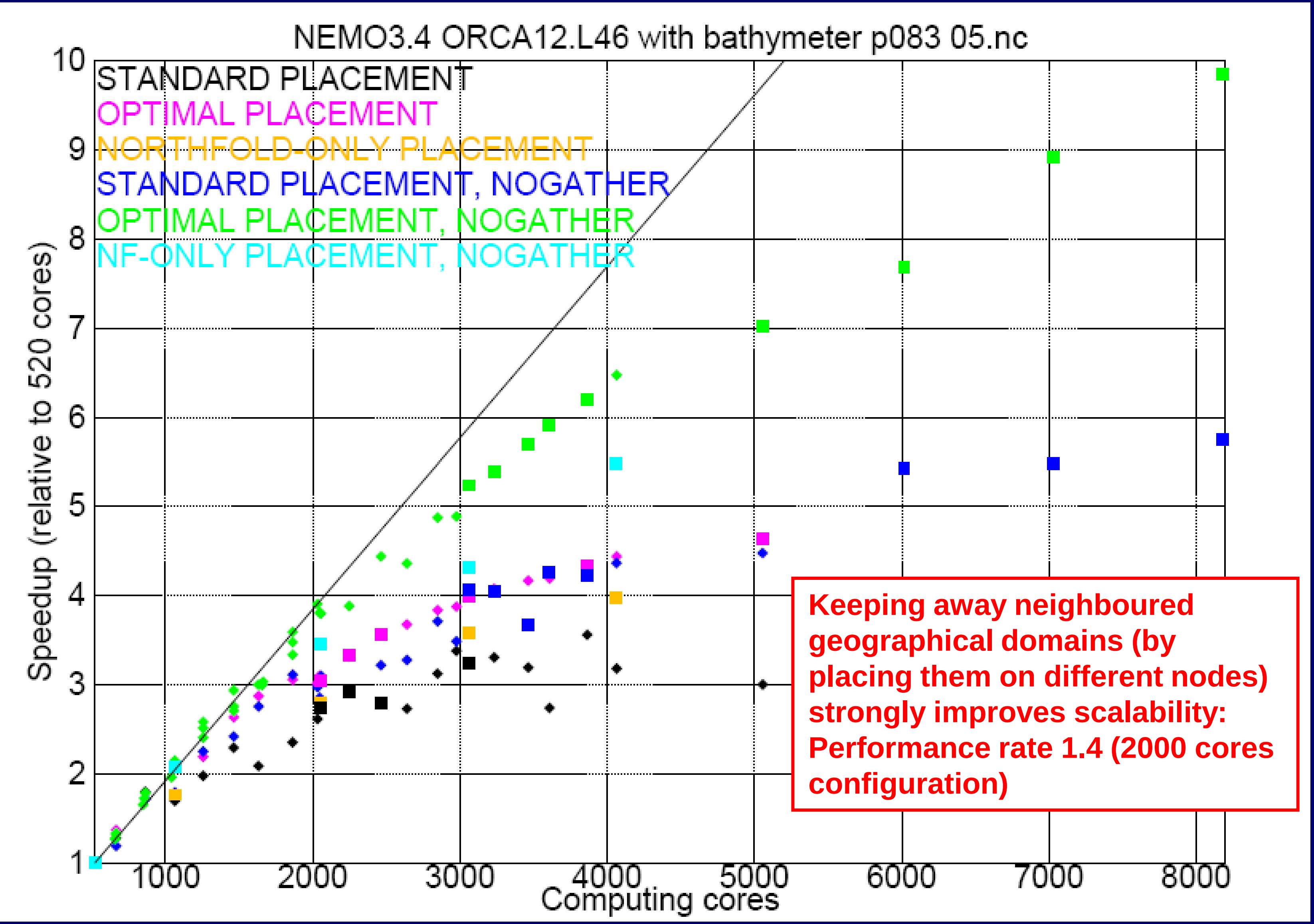
Scalability (JADE2) requires professional help



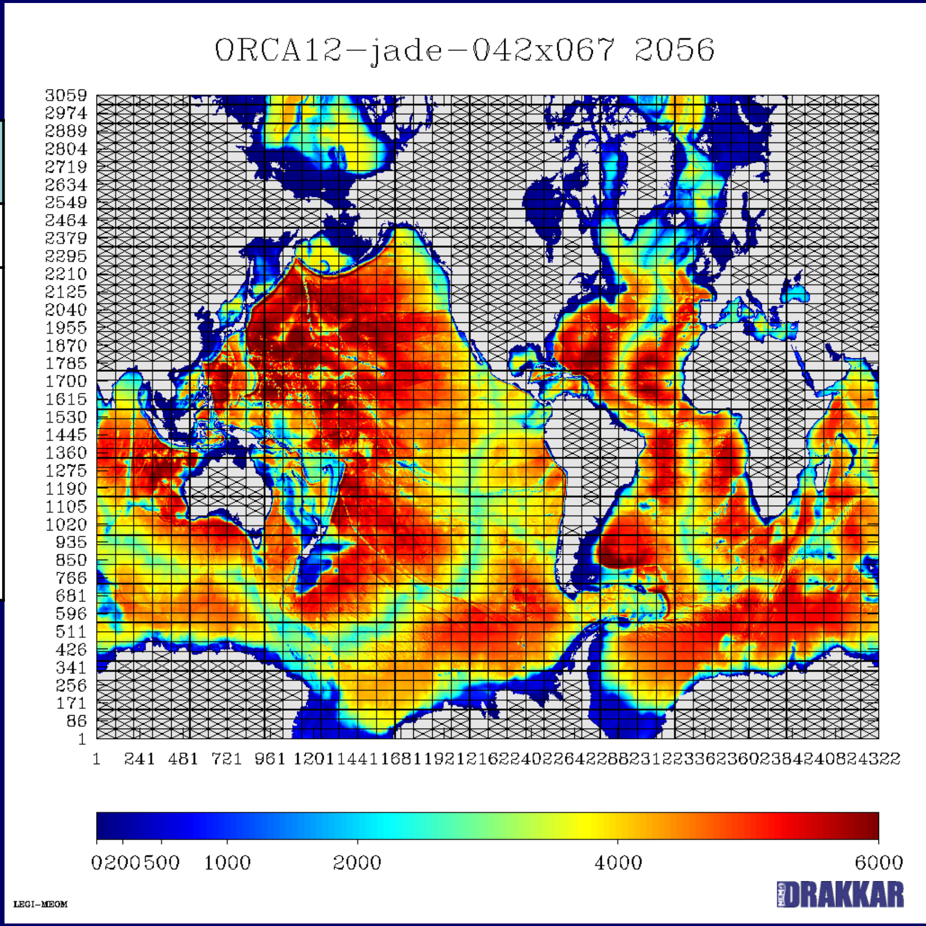
Keeping away neighboured geographical domains (by placing them on different nodes) strongly improves scalability: Performance rate 1.4 (2000 cores configuration)

A. Lecointre (CNRS) et N. Audiffren (CINES)

The ORCA12 numerical model

Resolution : 1/12° (9km to 3 km)
Nb of grid points : 4322x3059x46
Nb of vertical levels : 46, 50 or 75
Time step : 360 sec.

1 noeud nehalem : 90 Gigaflops
2056 coeurs = 257 noeuds = 23 Teraflops



1 year simulation	Nb of Procs	Elapsed Time	CPU cost	Storage (5 days)
ORCA12.L46				
JADE2 (CINES) (thin nodes)	**2056**	**27h**	**55,000 h**	**2100 GB**
IBM Power 6 (DKRZ)	**512**	**78h**	**40,000 h**	**-------**
CRAY (NERSC)	**1784**	**104 h**	**184,000 h**	**--------**

Typical 60 years of simulation at CINES (JADE2) 1958-2012

2 months full time 2,750,000 hcpu

Storage: The whole simulation is needed at 5 day interval
105 TB and a stable file system is necessary

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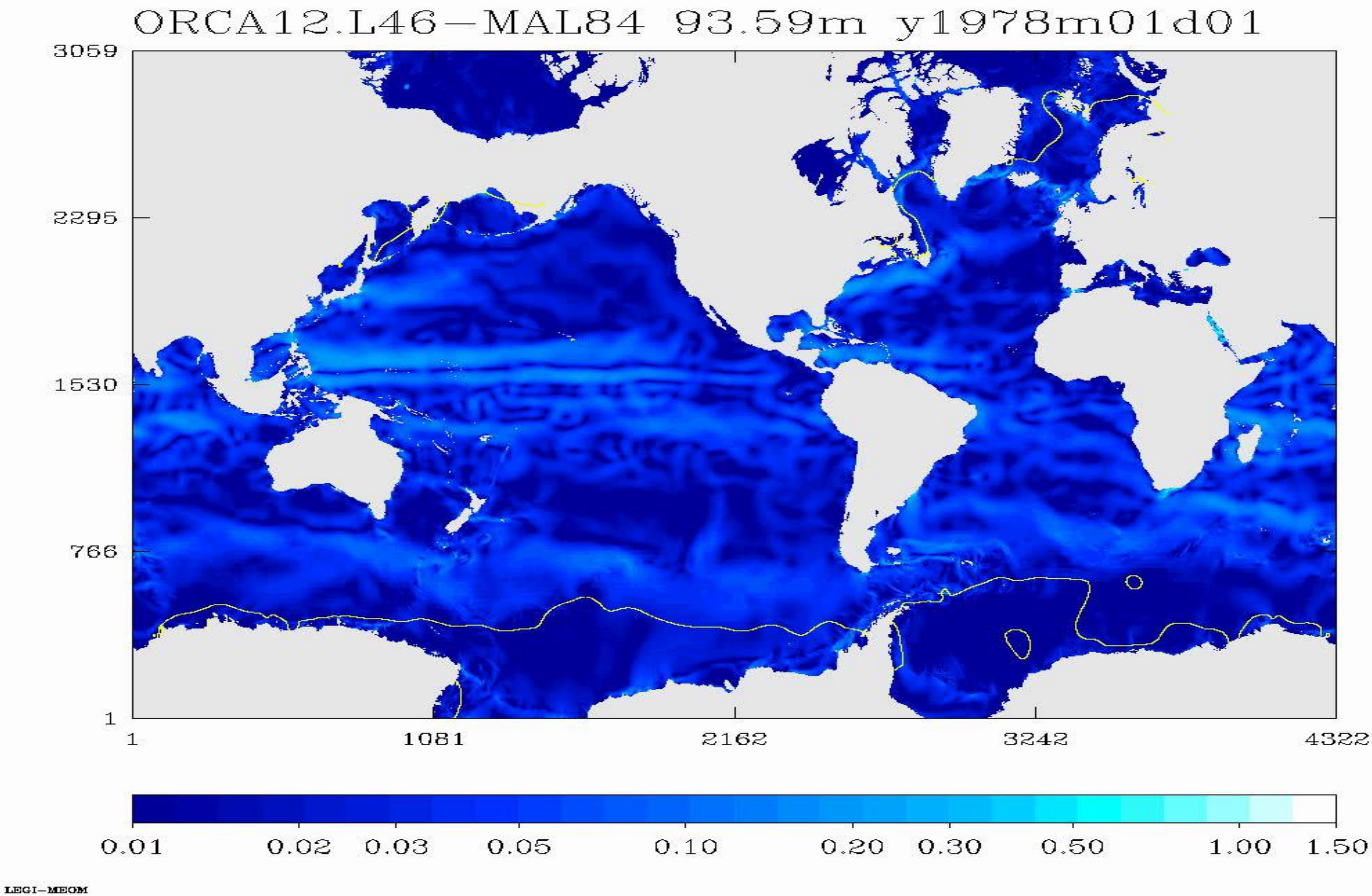
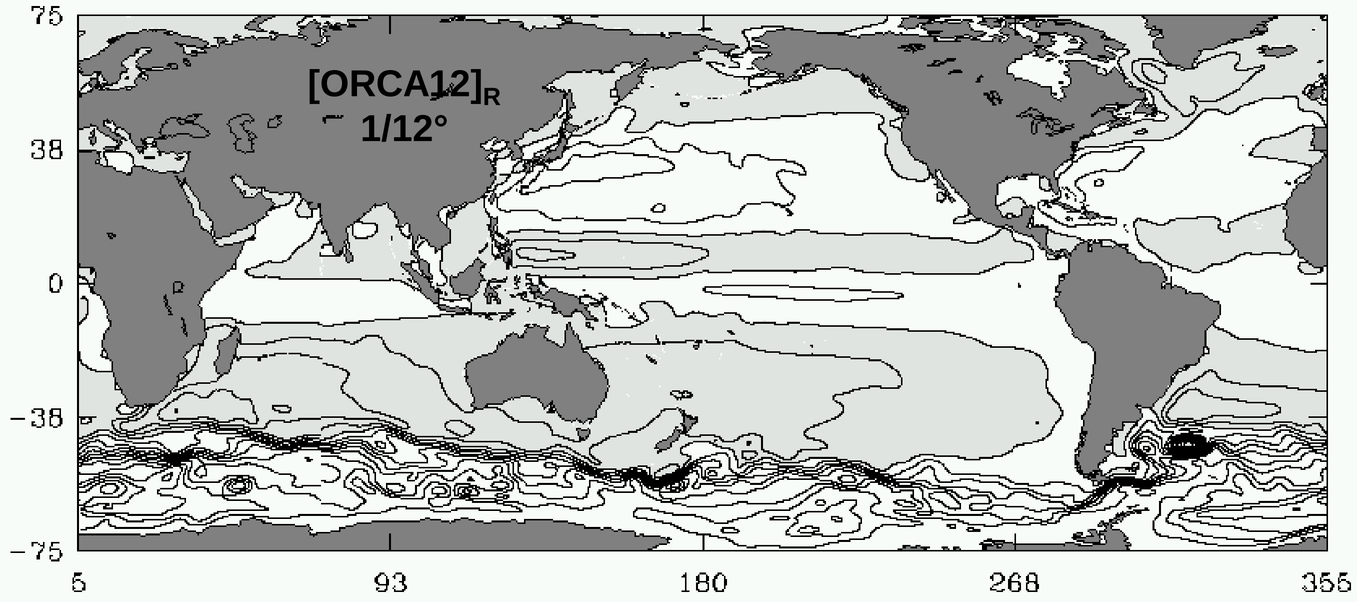
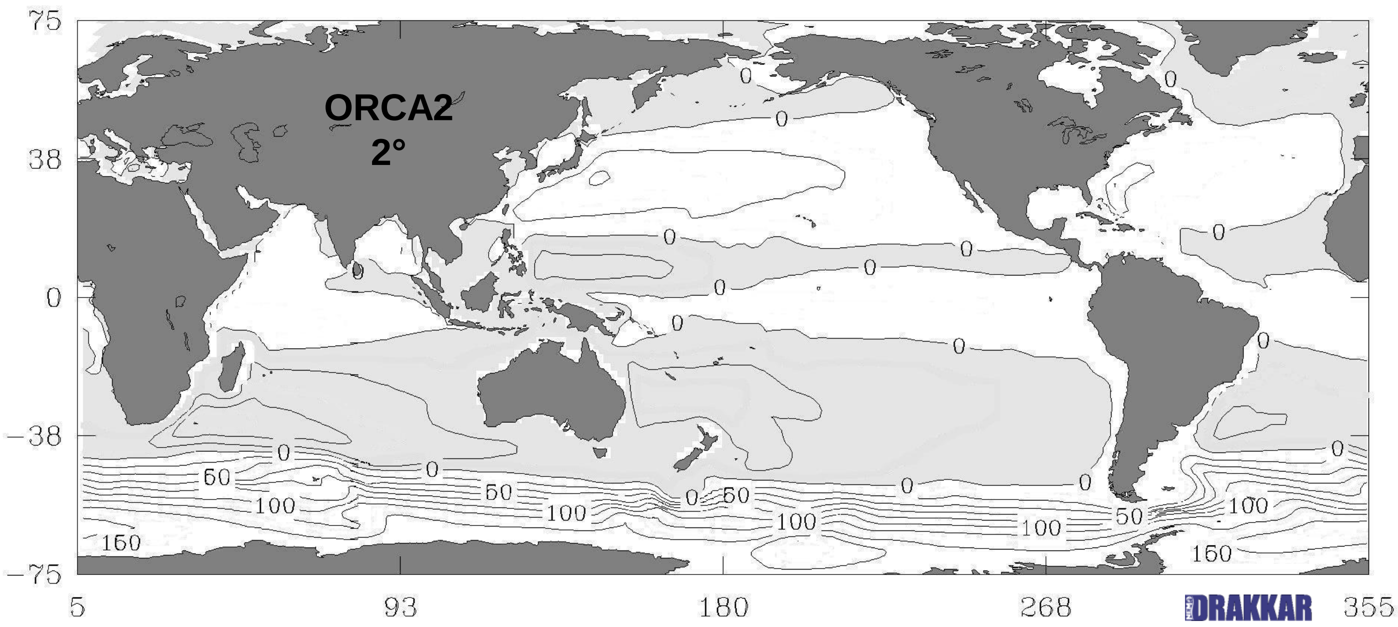
DRAKKAR 1/12° model simulations (model initialised with observations, forced at the surface by atmospheric reanalysis data) 1978 -1992 (5 day snapshots)



Large scale flow patterns



CI: 20 SV

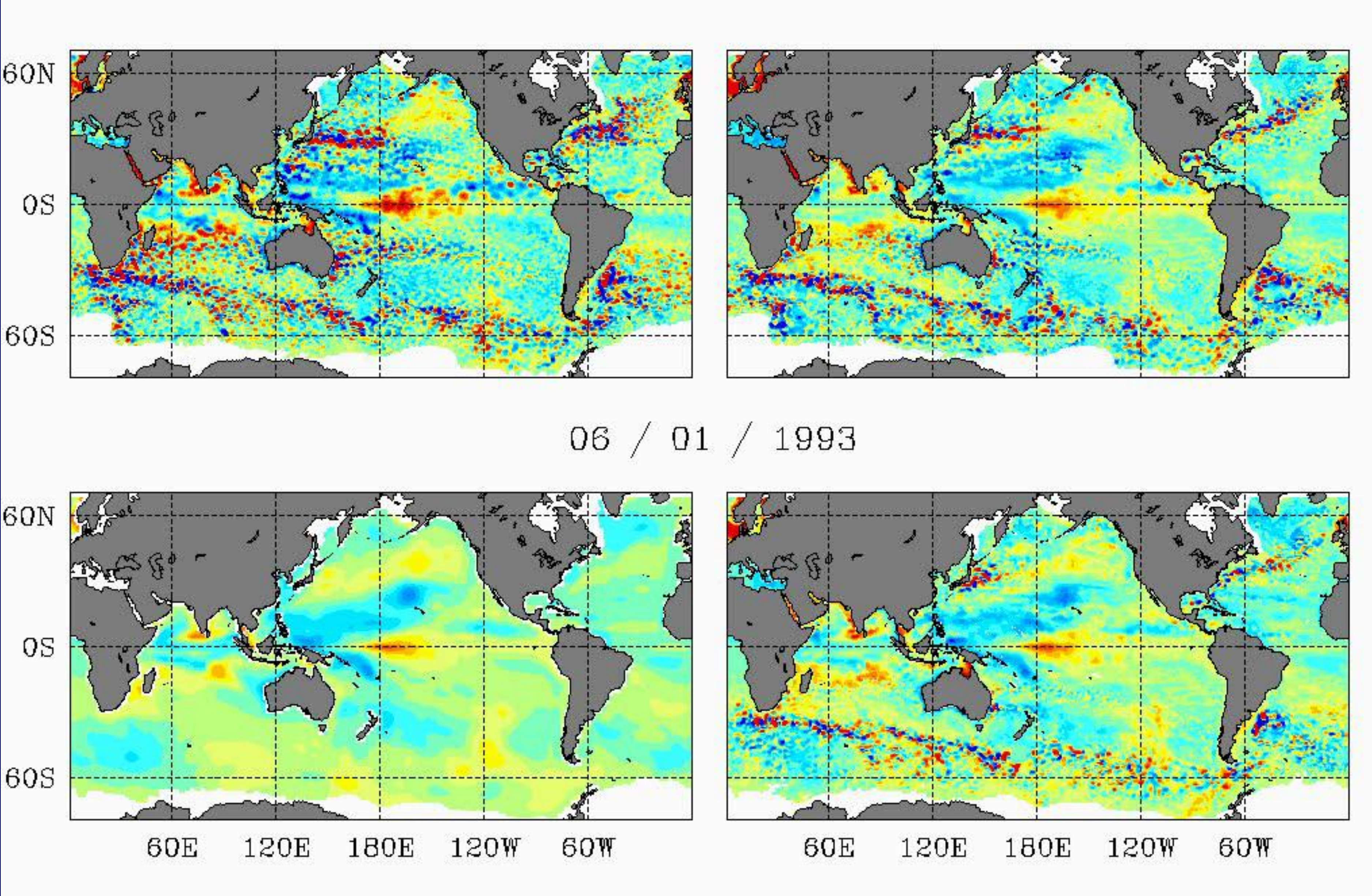


CI: 20 SV

Sea Level Anomalies

Observation (altimetry)

ORCA12 (1/12°, operational forecasting)



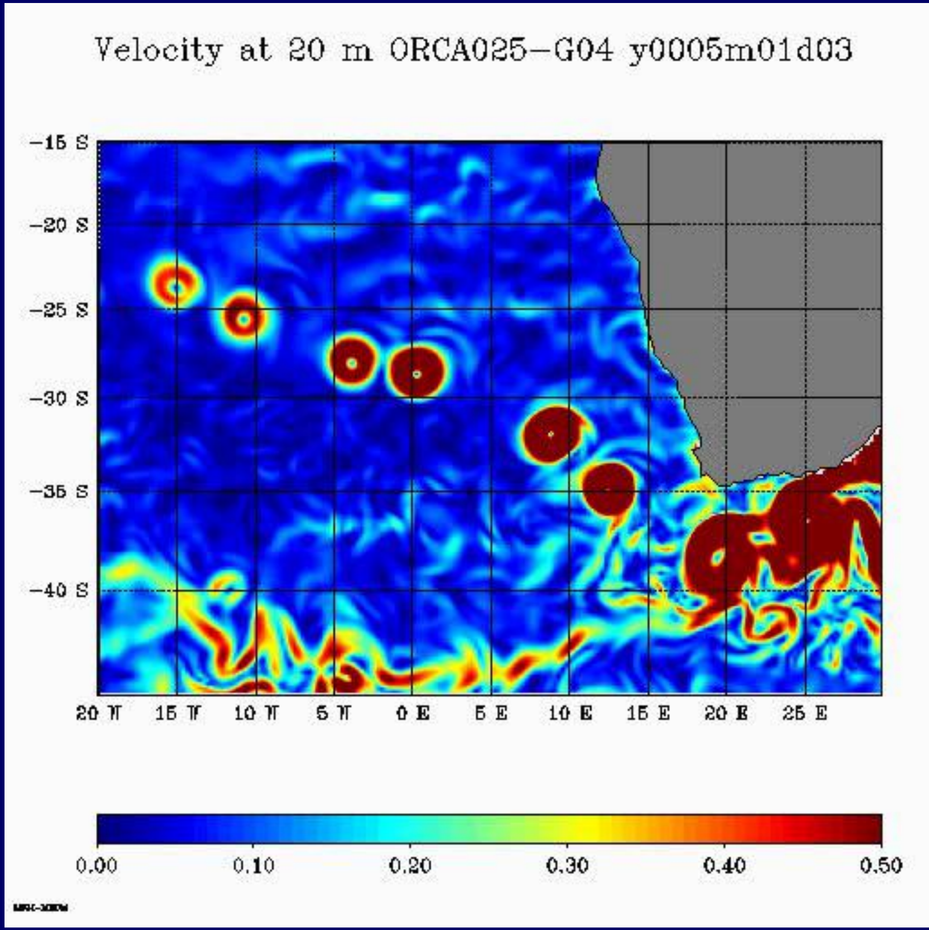
ORCA2 (2°, IPCC like resolution)

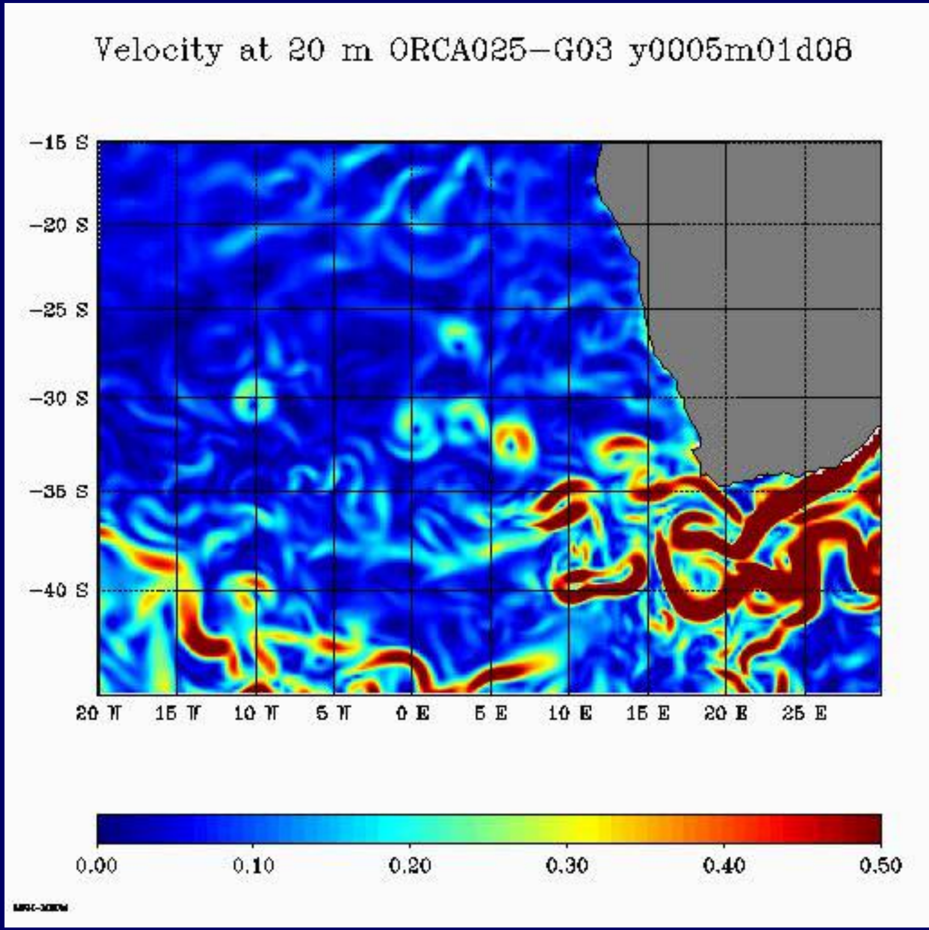
ORCA025 (1/4°, next IPCC resolution)

Agulhas Rings

Sensitivity to mentum advection scheme

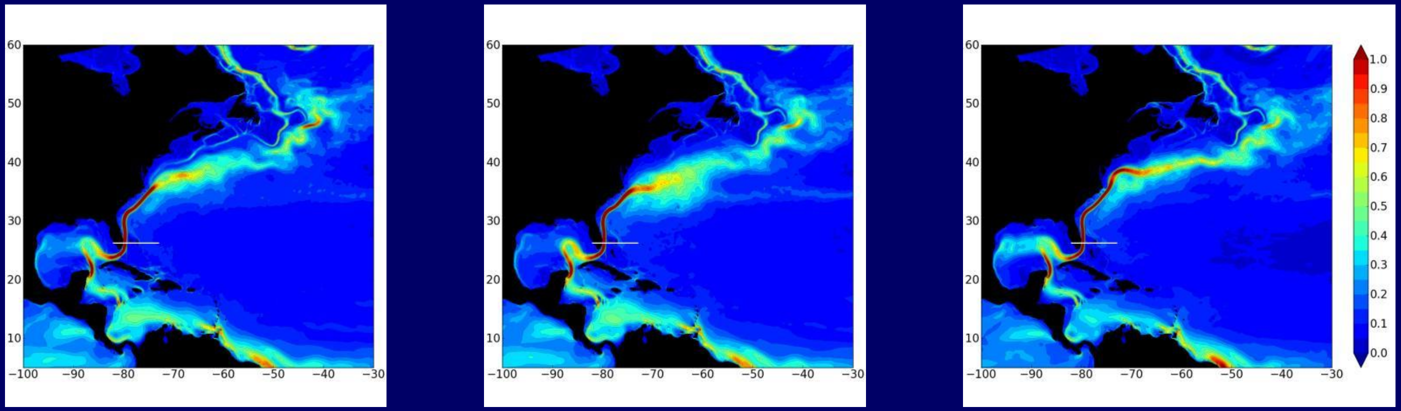
ENS Current velocity at 20 m **EEN**

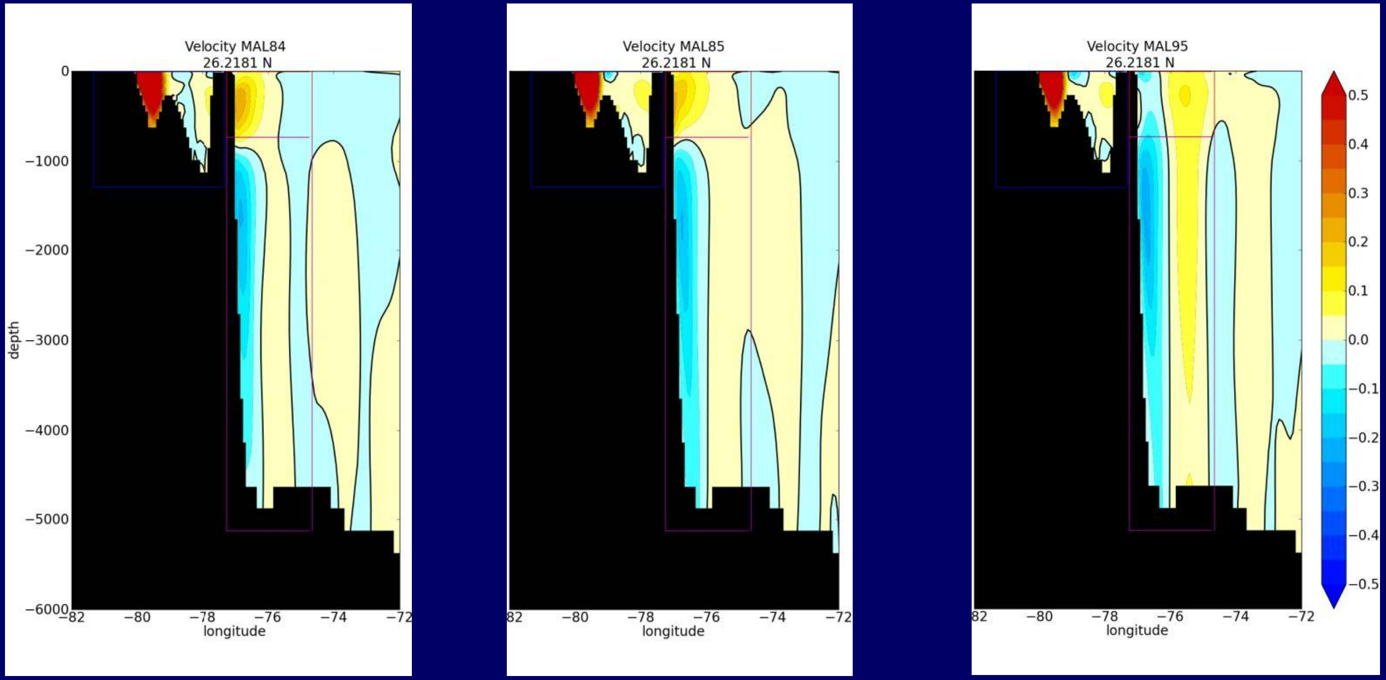




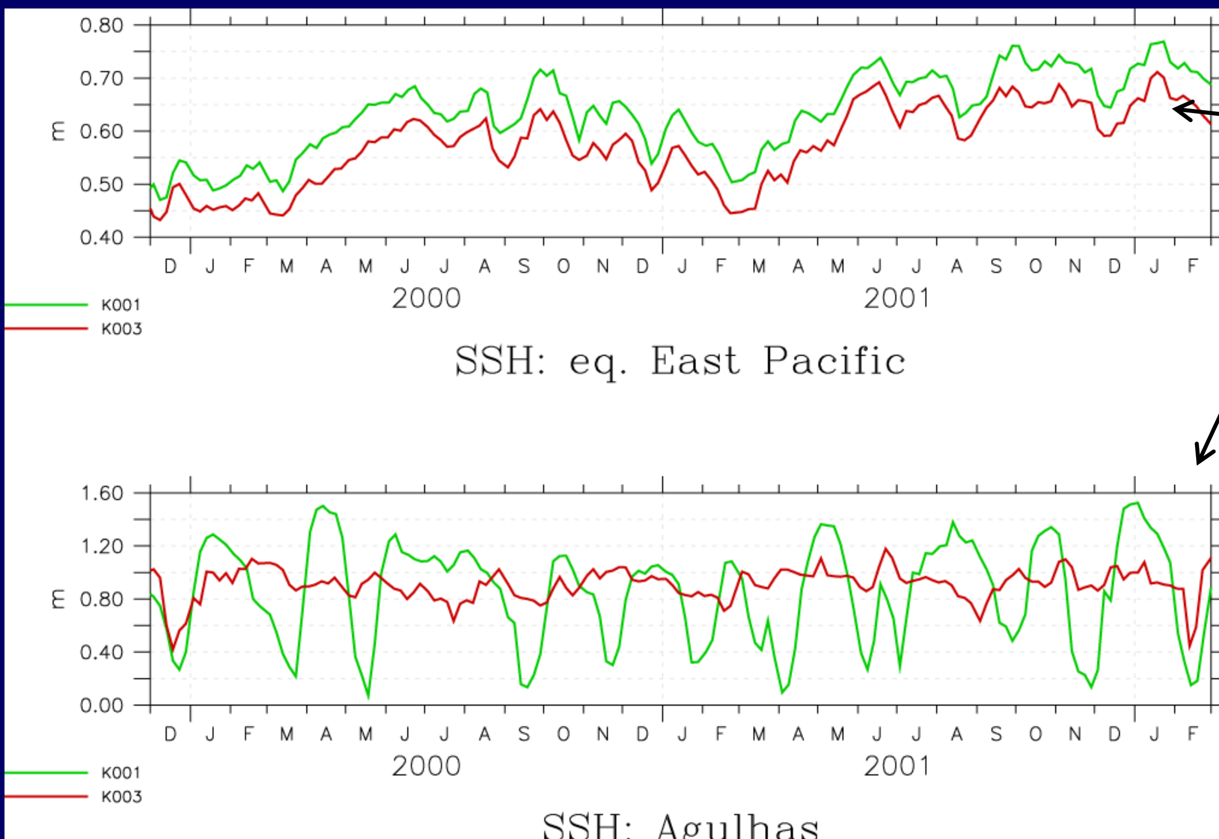
Current Speed

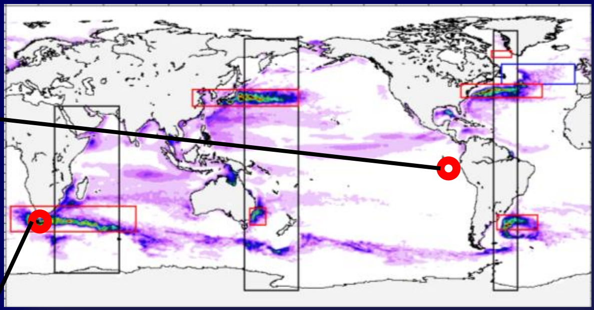
Side wall friction:	Free slip	Free slip	Partial Slip
Advection scheme:	EEN	FLX	EEN





Sensitivity to hyper viscosity





K001 : 1.25x10^{10} m^{4}s^{-1}

K003 : 0.50x10^{10} m^{4}s^{-1}

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Eddy scale models

- can be validated by direct comparison to observation

- still show great sensitivity to numerical schemes and sub-griscale parameterisation

- improvements should be searched simultaneously through

  - ➢ resolution increase
  - ➢ improved numerical schemes
  - ➢ Appropriate parameterisations

The cost of ocean models is still an issue

ORCA2 (2° - No eddy) can be run intensively

A few 1000s of years of simulation can be run each year (IPCC)

ORCA025 (1/4° - Eddy permitting) can now be used "routinely" :

several sensitivity experiments

or long runs (few 100 years)

can be run each year – Being included in most recent earth system models

ORCA12 (1/12° - Eddy resolving)

Eddy resolving models are still in an exploratory phase - Operational model

ADA grand challenge: 3584 coeurs – 60 jours – 5 000 000 hcpu – 85 years

Eddy-resolving resolution at global scale is still in a exploratory phase

- 1/12° is not fully eddy-resolving beyond 50°N-50°S
- sensitivity of eddy resolving models is not known
- parameterisation of unresolved scales (submesoscale) is not yet converged
- Model cost and storage still very high (for present super-computers)

Storage must not be overlooked

- Volume
- I/O overhead
- stability of file system

From eddy-permitting to fully resolving is the challenge of the next 10 years (objective 1/36° - 3 km à 1.5 km).