Modeling the global ocean circulation at eddy-resolving resolution

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Colleagues of the Drakkar Consortium

Mercator Ocean

Special thanks to

J.-M. Molines, A. Lecointre, M. Juza

Focus of this meeting:

The needs for ocean surface current measurements from space

Ocean circulation model simulations

- are a mean to obtain ocean currents at global scale
  ocean analysis, forecast/hindcast, reanalysis

- need accurate surface current estimates for validation

Objective of this talk:

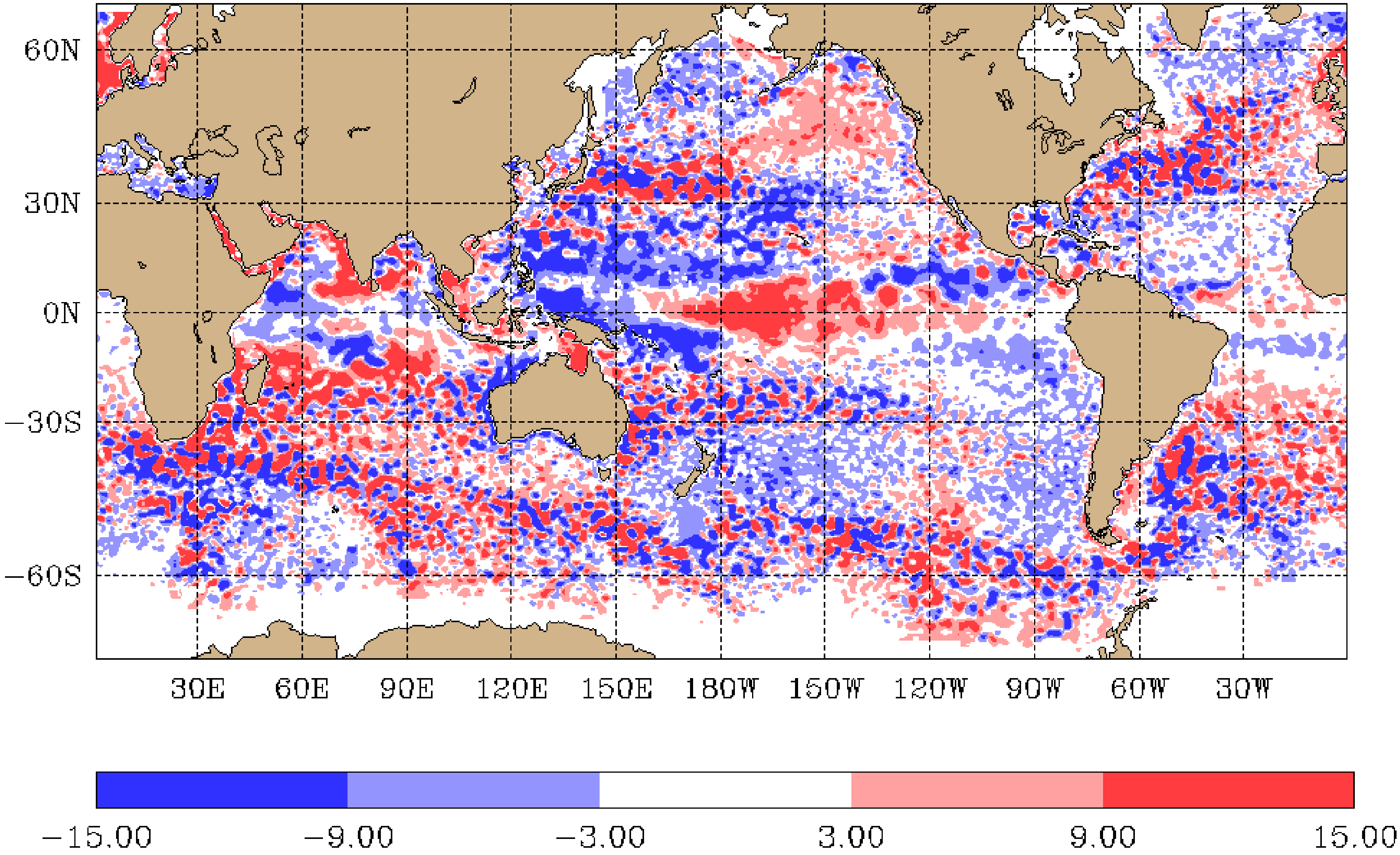
Discuss model simulations of the “ocean weather” or “synoptic scale circulation” (i.e. the large scale circulation and its associated mesoscale “eddy” field)

Outlines

- Ubiquity of oceanic “mesoscale circulation features”
- Dynamical properties of the “ocean mesoscale”
- Ocean model fundamentals
- DRAKKAR hierarchy of global ocean circulation models
- ORCA12: The 1/12° DRAKKAR model configuration
- ORCA12 sensitivity to the parameter space
- Conclusion

Ubiquity of
"mesoscale circulation features"
in the ocean
from
satellite observations
and
model simulations

Sea level anomalies from T/P+ERS (M. Juza)



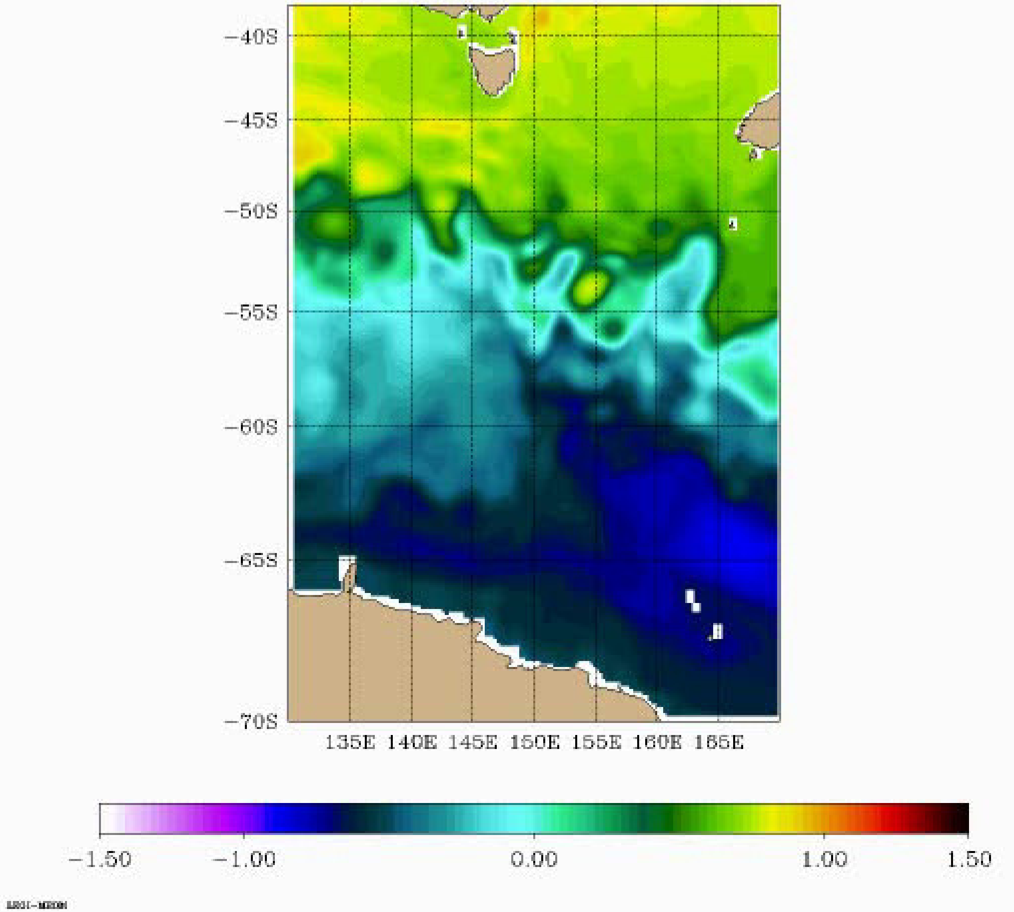
Ubiquity of eddies in the ocean from satellite observations.

"Mesoscale" is more than just "eddies"

Persistent Boundary Currents
Waves
Persistent Fronts

} have similar **time** and **space scales of variability**

SSH in Drakkar ¼° ORCA025 model simulation



Ubiquity of eddies in the ocean from satellite observations.

Eddies, fronts and meanders in ...

… all great current systems:

Gulf Stream

Kurosiho,

Brazil Current,

EastAustralian Current,

Leewin Current, …

and

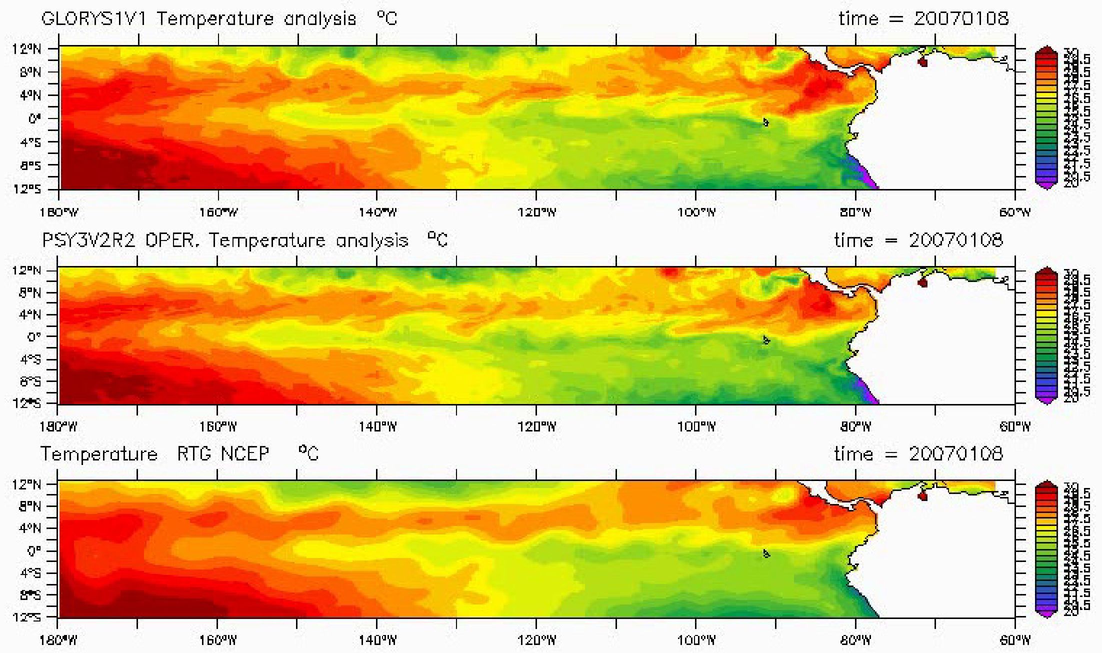
ACC

"Mesoscale" is more than just "eddies"

Persistent Boundary Currents
Waves
Persistent Fronts

have similar **time** and **space scales of variability**

… equatorial waves (TIW)



SST

GLORYS Re-analysis

MERCATOR Operational Analysis

Assimilated observation (RTGG NCEP)

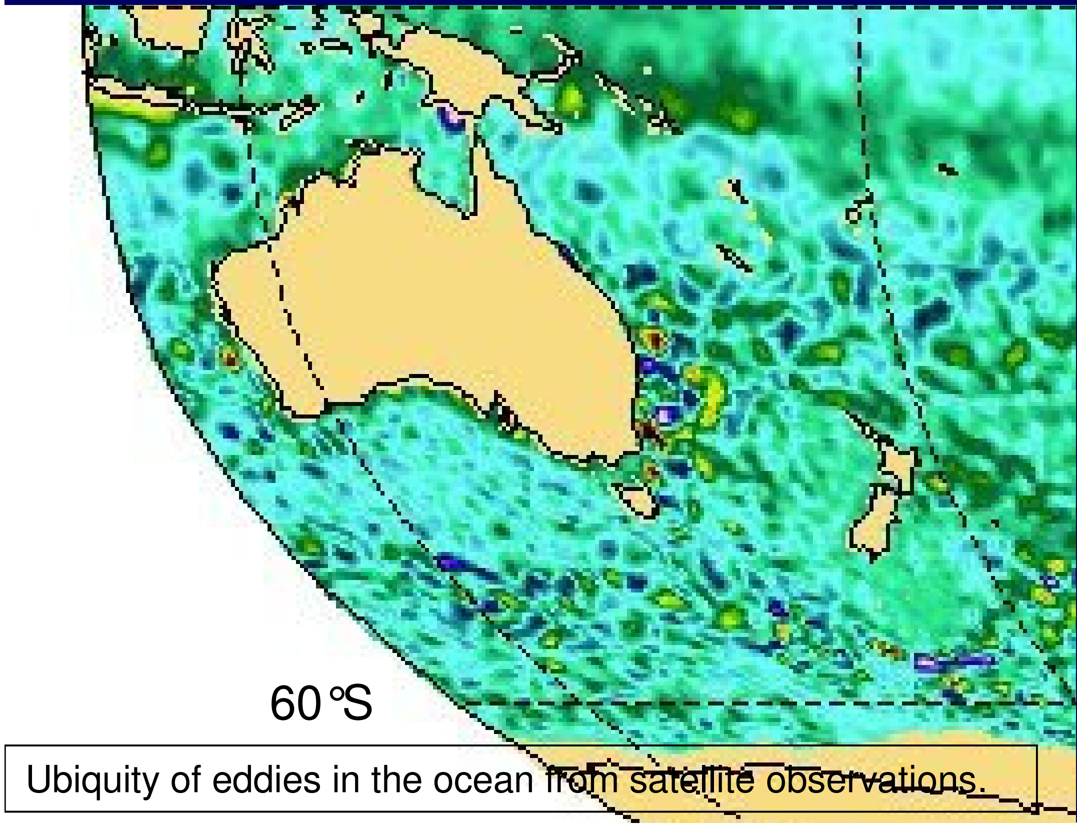
Ubiquity of eddies in the ocean from satellite observations.

To conclude :

Mesoscale variability is ubiquitous in all oceans and at all latitudes

It consists in very energetic features such as eddies, waves, meandering of strong currents and fronts

T/P+ERS Aviso product: SLA on 19 May 2004



Ubiquity of eddies in the ocean from satellite observations.

Mesoscale (from observations):

Length scale ($L \approx Rd$) :

from a few 10km

to a few 100km

Time scale :

few weeks

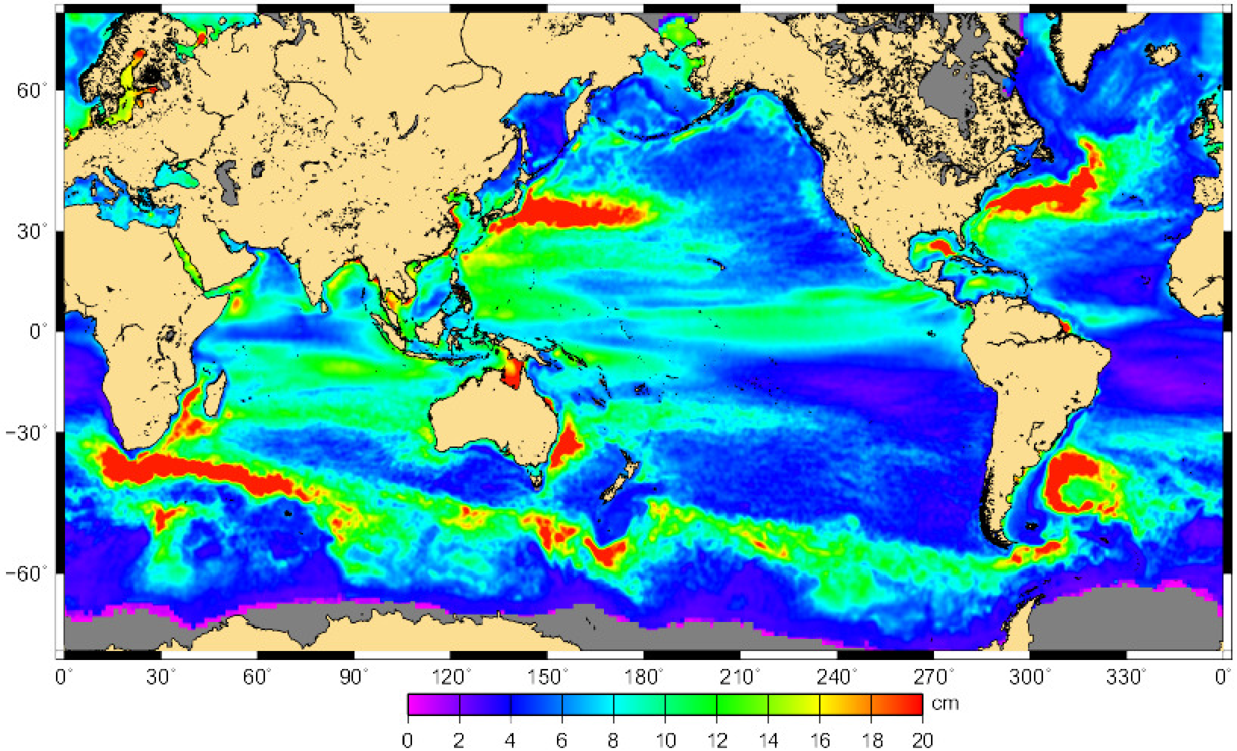
to few months

Dynamical properties of the "ocean mesoscale"

"Ocean Weather"

"Ocean Synoptic Circulation Features"

SSH Variability (rms) estimated from 15 years of satellite altimetry (CLS).



Mesoscale variability is concentrated in the vicinity of the great ocean currents.

Mesoscale eddies are generated by the instability of the large scale flows:

- Baroclinic instability (vertical shear) which is ubiquitous in the ocean (1st baroclinic mode)
- Barotropic instability (hz shear) in strong currents.

Mesoscale eddies are strongly coupled to the general circulation,

weakly coupled to surface forcing, inertia gravity waves, tides.

Characteristic scales of the mesoscale variability are those of these instabilities

Ocean Mesoscale variability are 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 (Atmopheric Synoptic) Eddies

McWilliams, 2008

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

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

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

N = Brunt-Vaïsala frequency

H = thermocline depth

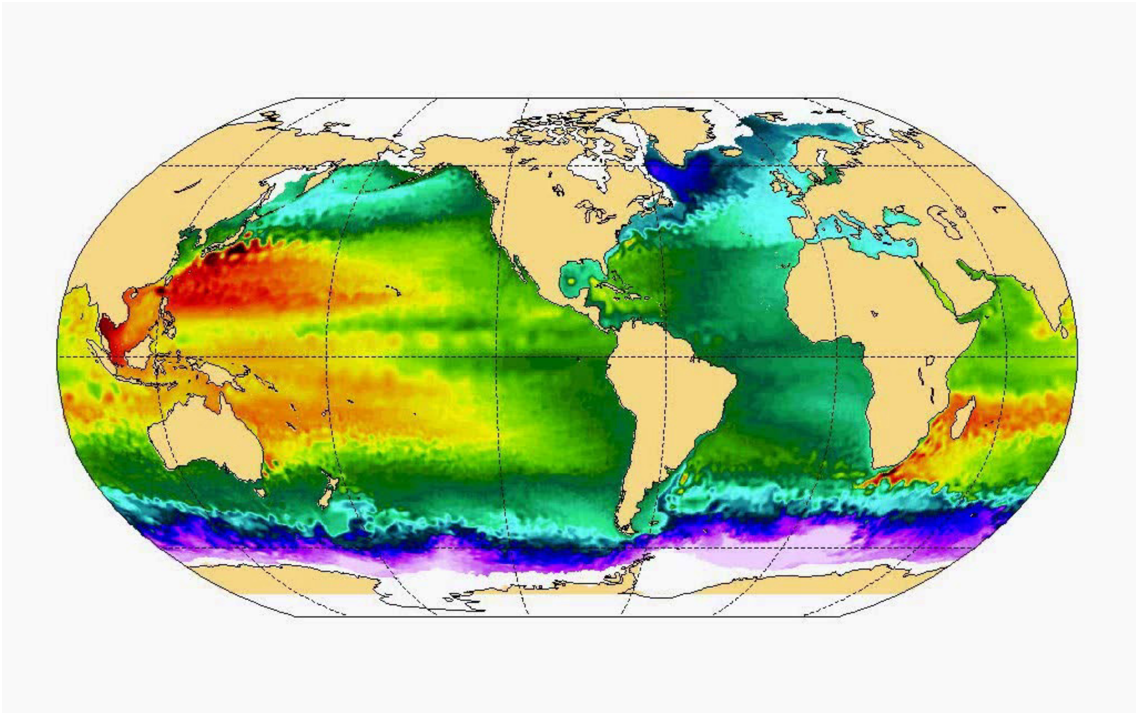
H = troposphere height

Eddy Length scale : $L = \dfrac{NH}{f}$ 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

Meridional Heat Transport (MHT) at mid latitudes



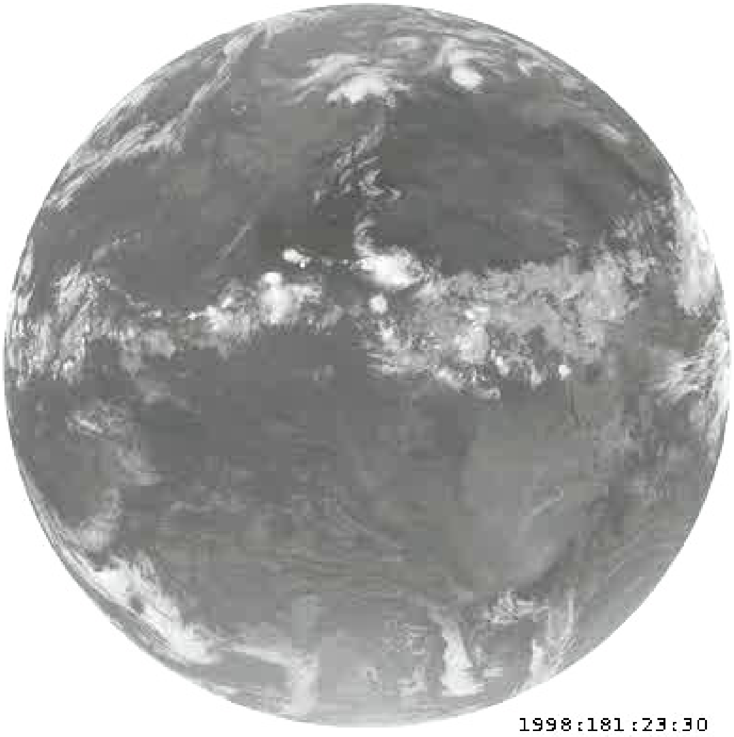
Atmosphere:

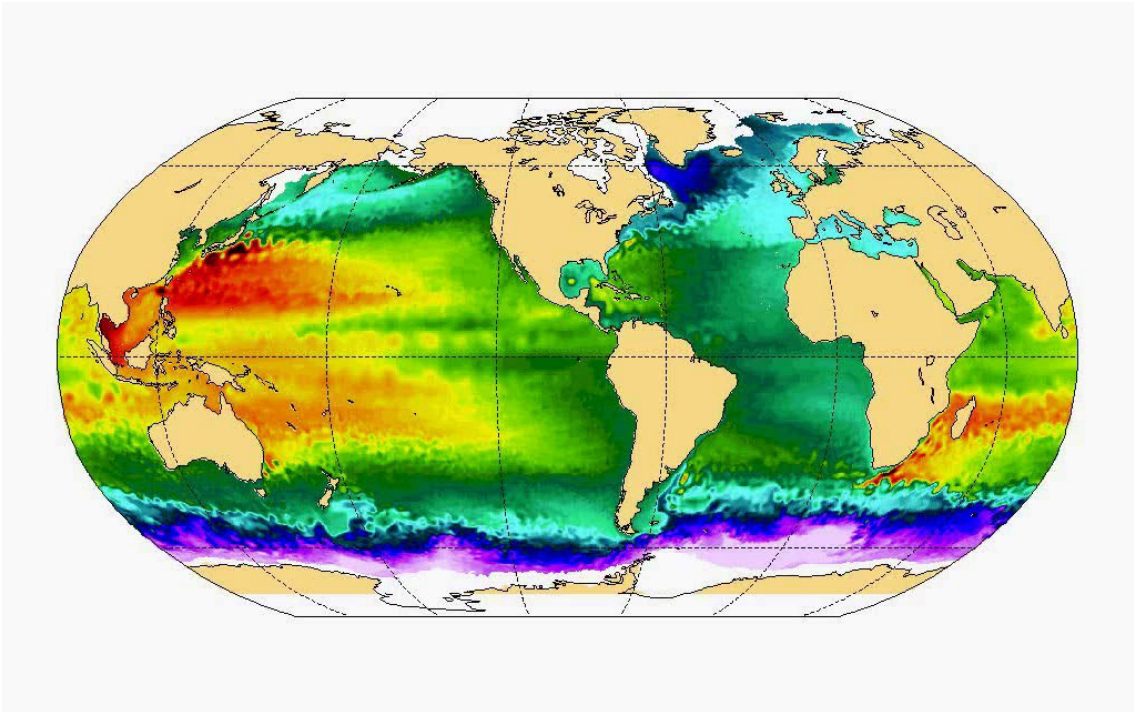
The totality of the MHT is done the synoptic transient features

Ocean:

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

Meridional Heat Transport (MHT) at mid latitudes





Atmosphere:

Ocean:

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".

Except may be in the ACC where eddies are suspected to play a peculiar role?

Ocean model fundamentals

----

resolved and unresolved scales of motion

The Primitive Equations … (written in a more generic forms as in Treguier, 2008)

$$\frac{\partial Y}{\partial t} + \vec{u} \cdot \vec{\nabla} Y + F(Y) = 0$$

$Y = (\vec{u}, T, S)$ State vector

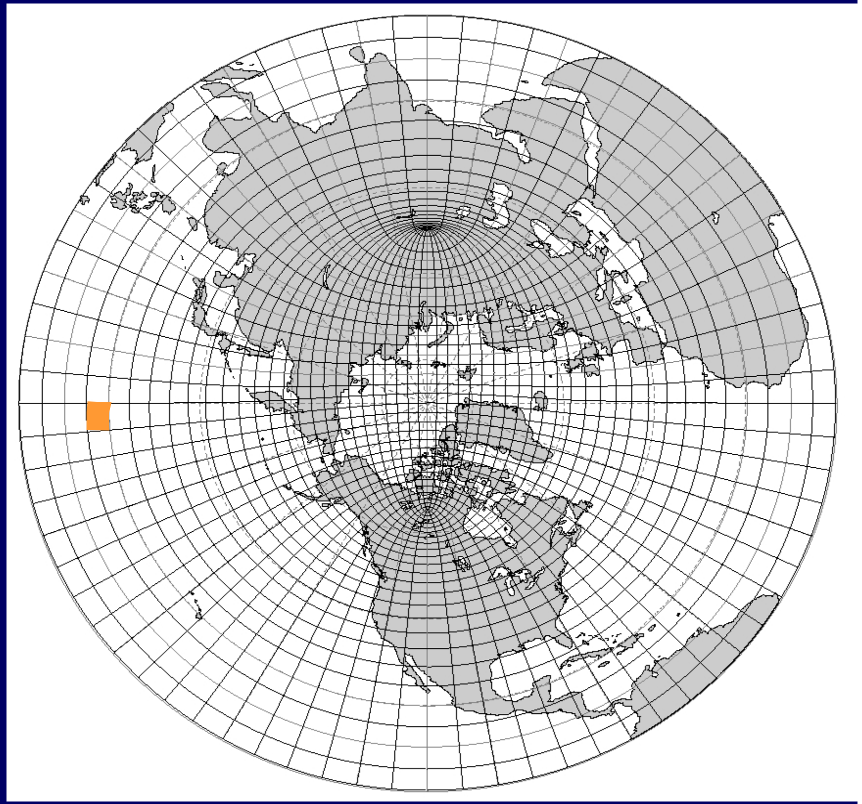
F(Y) includes all other terms of the PEs, including coriolis force, pressure gradient, external forcing , ...

… are solved numerically

PEs are discretized

- on a mesh of grid points

- using finite difference formulas



Solving the PEs is applying a "numeric resolution operator $(\text{-})_R$" to the state vector *Y*

Resolved/unresolved scales of motion

The Primitive Equations

$$\frac{\partial Y}{\partial t} + \vec{u}\cdot\vec{\nabla}Y + F(Y) = 0 \xrightarrow{(-)_R} \frac{\partial Y_R}{\partial t} + \left(\vec{u}\cdot\vec{\nabla}Y\right)_R + \left(F(Y)\right)_R = 0$$

$$\frac{\partial Y_R}{\partial t} + \vec{u}_R\cdot\vec{\nabla}Y_R + F_R(Y_R) = -\left(\left(\vec{u}\cdot\vec{\nabla}Y\right)_R - \vec{u}_R\cdot\vec{\nabla}Y_R\right) - \left(\left(F(Y)\right)_R - F_R(Y_R)\right)$$

Evolution of the resolved state of the ocean

Numerical errors

Effects of the unresolved scaled must be accounted for

Parameterisation errors

For Ocean Currents

$$\frac{\partial u}{\partial t} + (\vec{u}\cdot\vec{\nabla})u - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} - \vec{\nabla}\cdot(\overline{u'\vec{u}'}) + D_u + F_u$$

For Ocean Currents

$$\frac{\partial u}{\partial t} + \boxed{(\vec{u}\cdot\vec{\nabla})u} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} - \boxed{\vec{\nabla}\cdot(\overline{u'\vec{u}'})} + D_u + F_u$$

Fine grid Eddy-Resolving models (ocean weather)

Coarse grid ocean models (ocean climate)

$$(\vec{u}\cdot\vec{\nabla})u$$

Fine grid (eddy-resolving):

- Larger current velocities
- Sharper velocity gradients

This term will be large →

- Greater sensitivity to numerical scheme

Coarse grid:

- Smaller current velocities
- Smoother velocity gradients

← This term will be small

- Lower sensitivity to numerical schemes

$$\vec{\nabla}\cdot(\overline{u'\vec{u}'})$$

Fine grid (eddy-resolving):

This term will be "smaller"

- Lower sensitivity to the parameterisation used

Coarse grid:

This term will be important

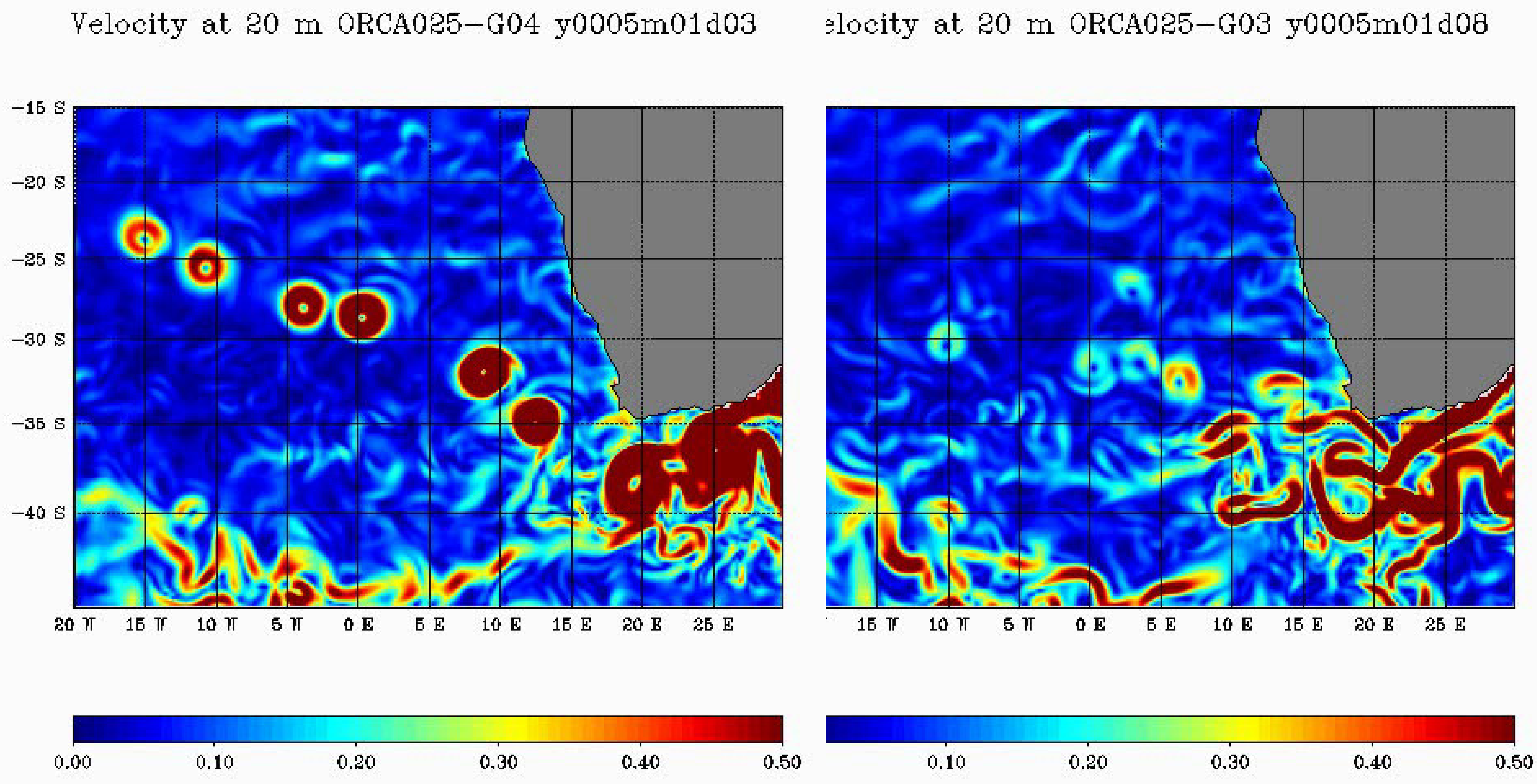
- Greater sensitivity to the parameterisation used

Agulhas Rings (Barnier et al., Oc. Dyn., 2006)

Sensitivity to the numerics In the momentum advection scheme

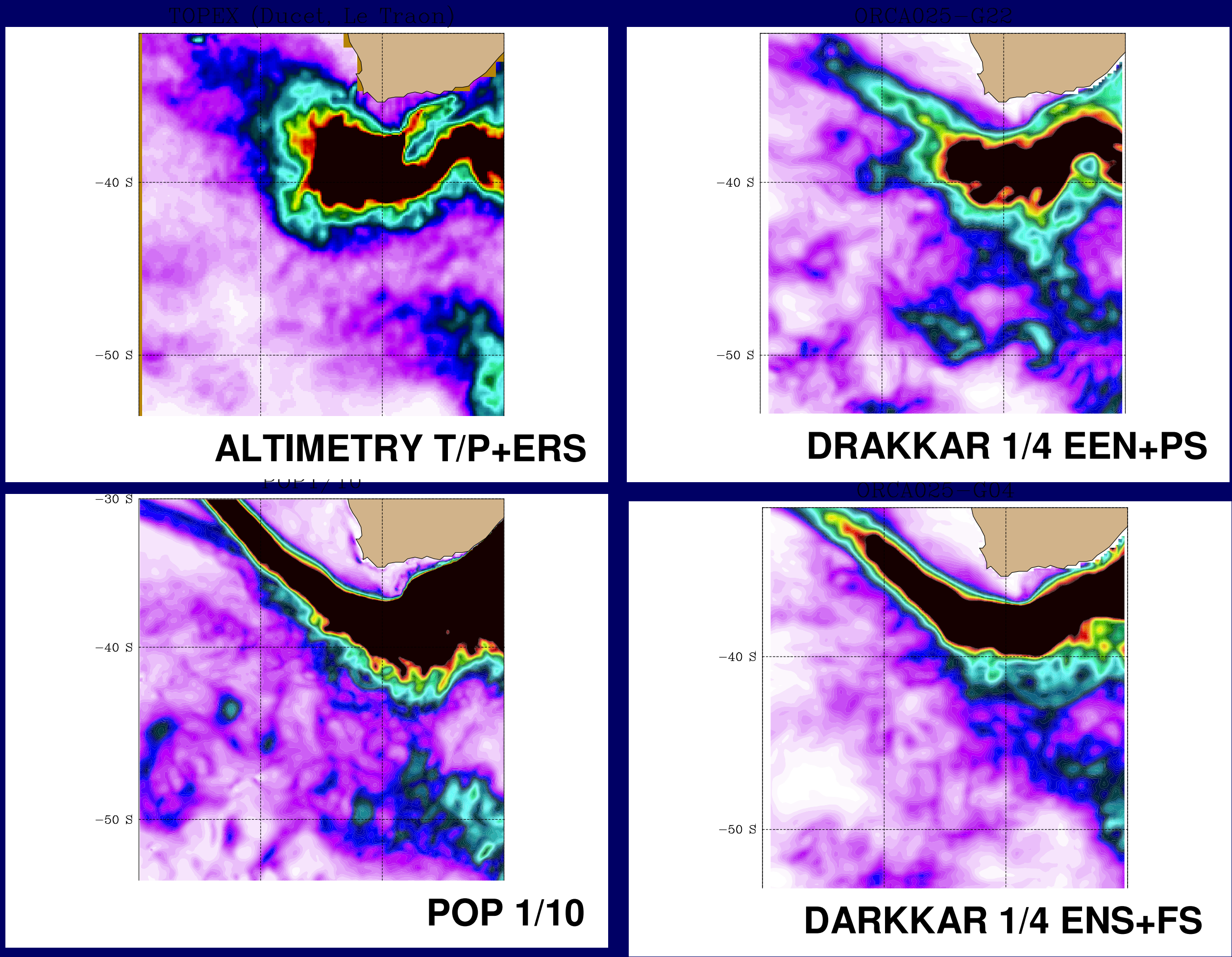
ENS $(\vec{u} \cdot \vec{\nabla})u$ EEN

Current velocity at 20 m



Agulhas Rings (Barnier et al., Oc. Dyn., 2006)

Sensitivity to the numerics In the momentum advection scheme



Surface

Eddy Kinetic Energy

The EEN scheme was found to reduce the noise in vertical velocity field near the bottom cells. (Le Sommer et al., Oc. Mod. 2009)

DRAKKAR hierarchy of global ocean circulation models

DRAKKAR

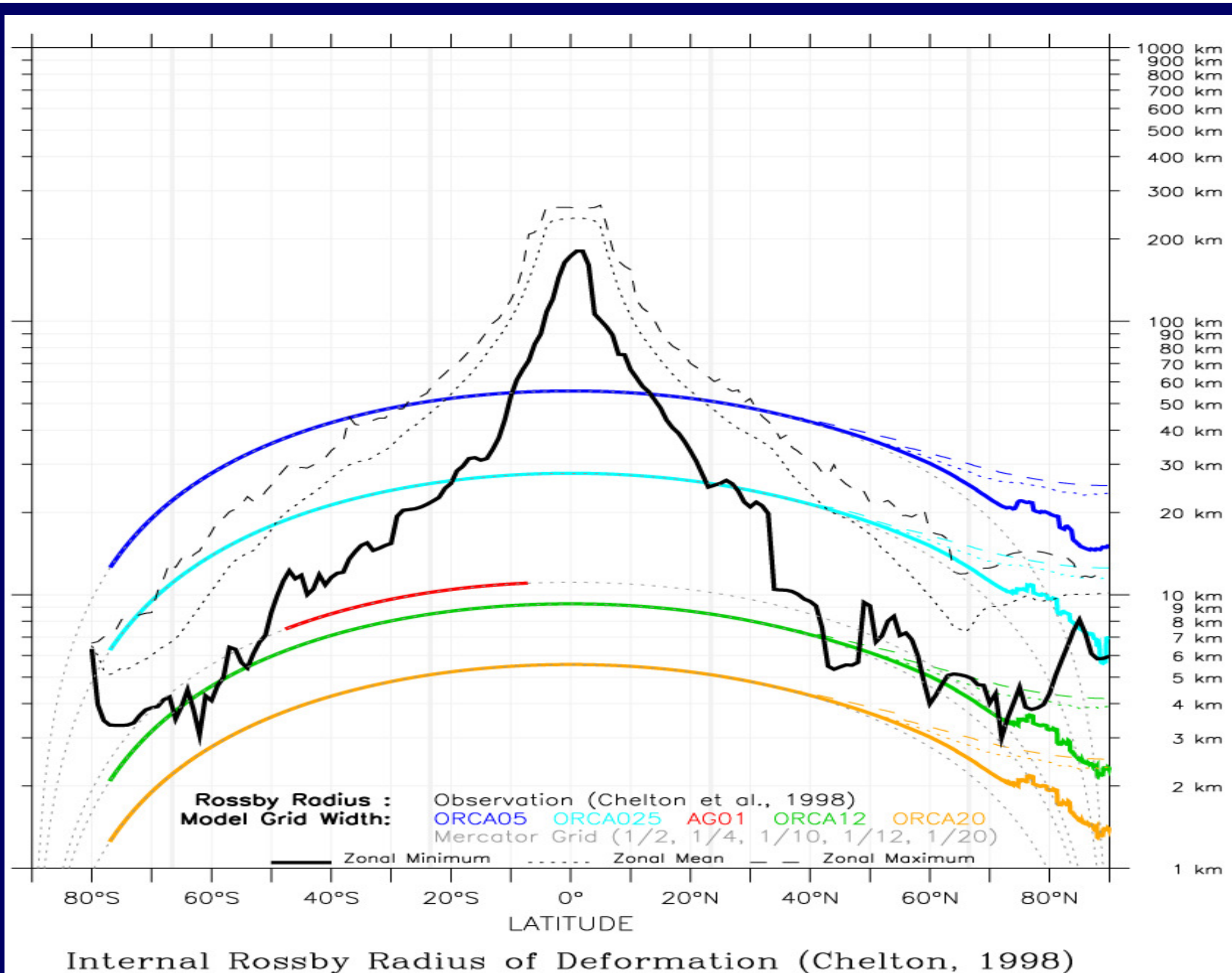
LEGI – Grenoble
LPO – Brest
LOCEAN – Paris
MERCATOR-Ocean – Toulouse
GEOMAR – Kiel
NOC – Southampton
U. Reading – Reading
U. Alberta – Canada
(DFO – Canada, UKMO, KNMI, SIO, …)

Scientific and technical coordination the purpose of which is to

- implement high-resolution global ocean/sea-ice model configurations based on the NEMO OGCM and the tri-polar ORCA grid

- design, realize, assess and distribute eddy resolving numerical simulations

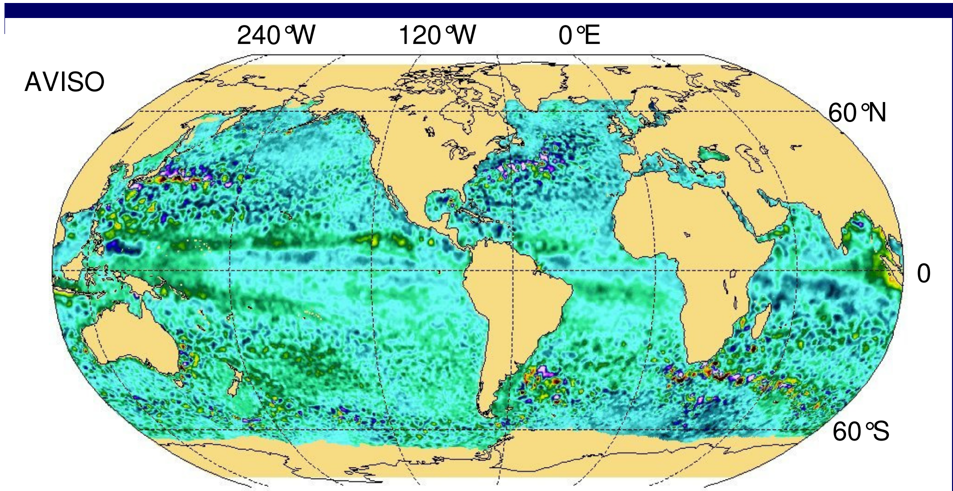
Resolutions of 2°, 1°, 1/2°, 1/4°, **1/12°**

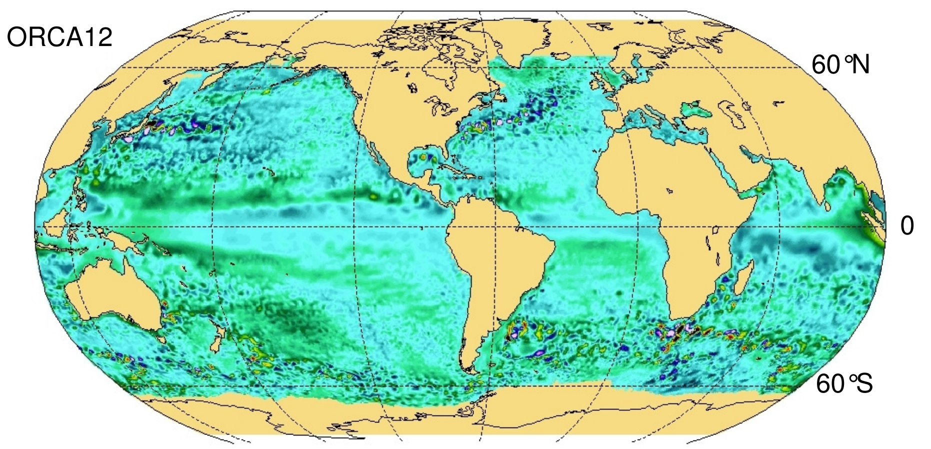


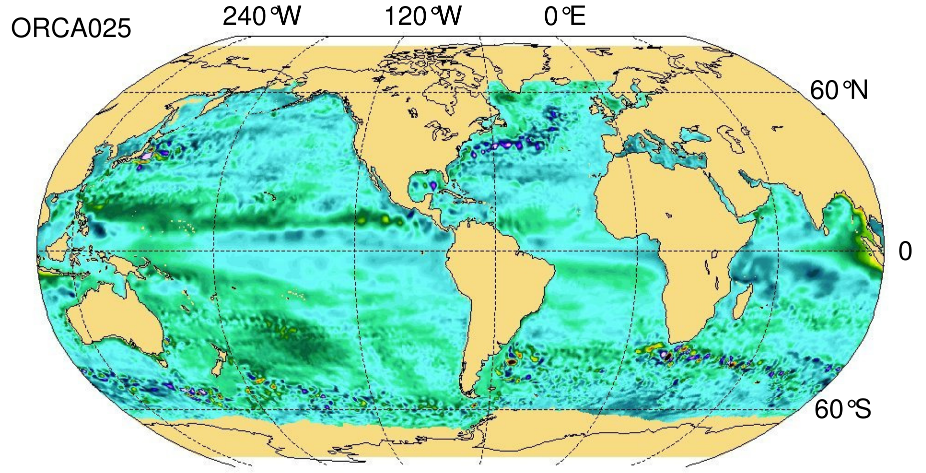
ORCA12: 1/12° resolution DRAKKAR configuration is the closest to eddy-resolving

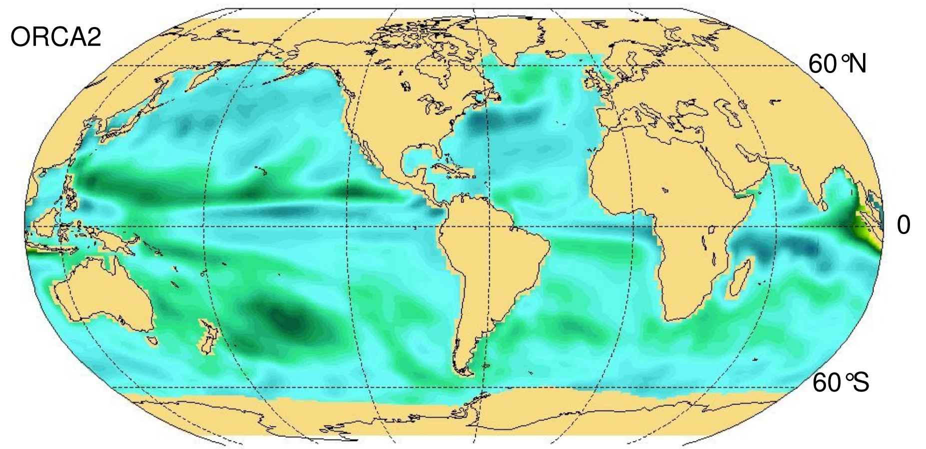
Sea Level Anomaly on 19 May 2005

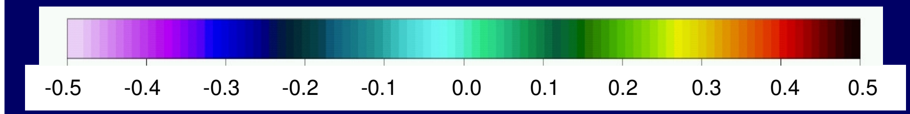
Model outputs are co-localized with the AVISO product











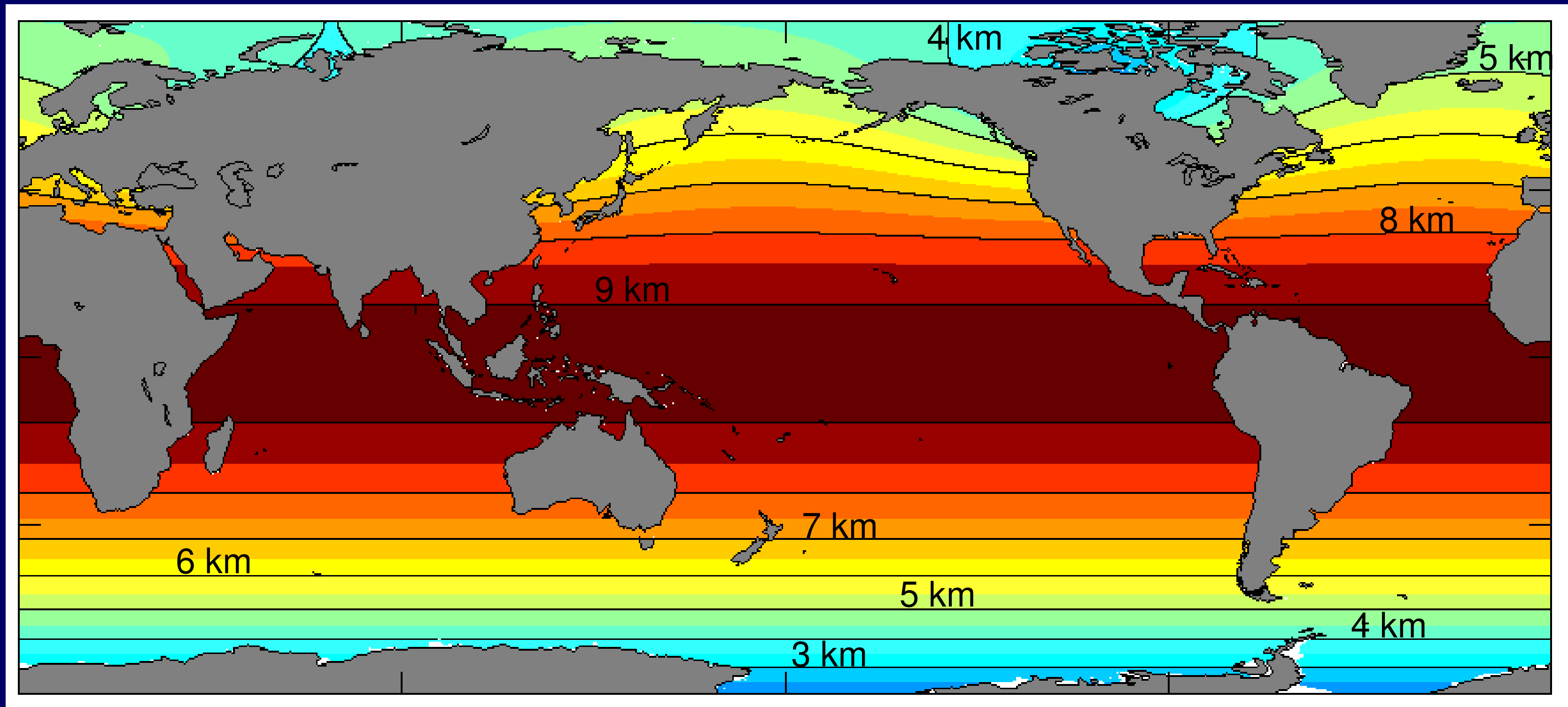
ORCA12

The community 1/12° DRAKKAR model configuration based on the NEMO OGCM

ORCA12: the grid

Nb of grid points	: 4326x3061
Nb of vertical levels	: 46, 50 or 75
Time step	: 360 sec.

Model grid size in km

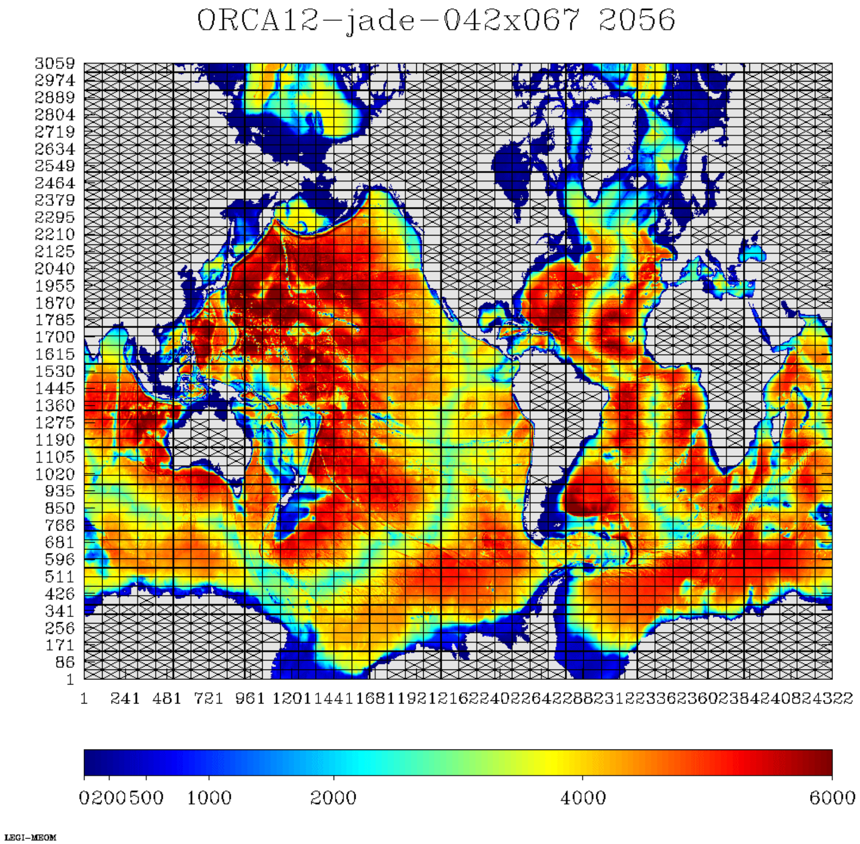


ORCA12: the cost

1 year simulation	Nb of Procs	Elapsed Time	CPU cost	Storage	
				Restart	5days
ORCA12.L75					
JADE2(LEGI)	2056	40h	82,000 h	300 GB	2800 GB
CRAY XE6 (NOCS)	1784	170h	300,000 h		

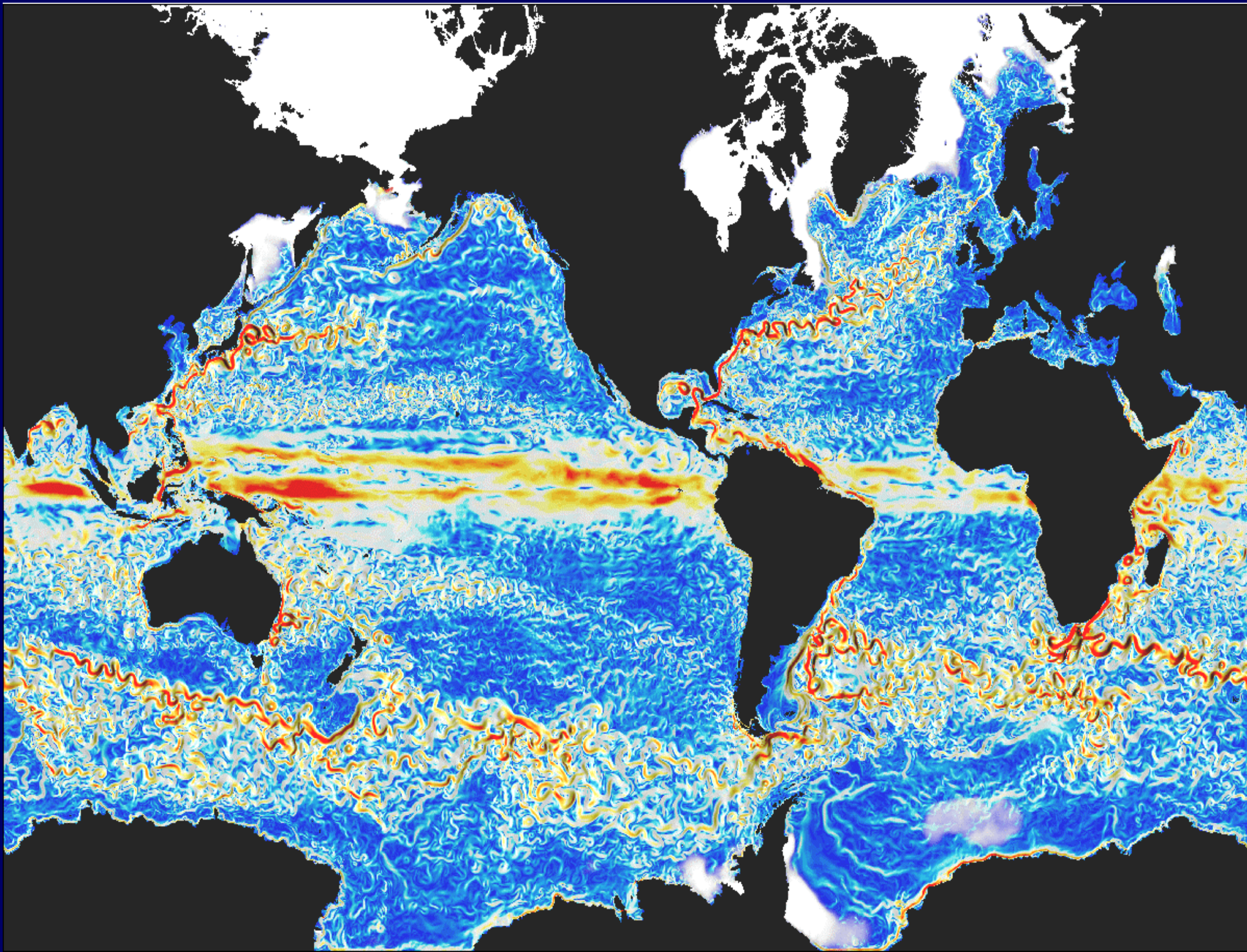
JADE2 (tier 1) 50 years of simulation:

- 2 months full time
- 2 750 000 hcpu
- 170 TB

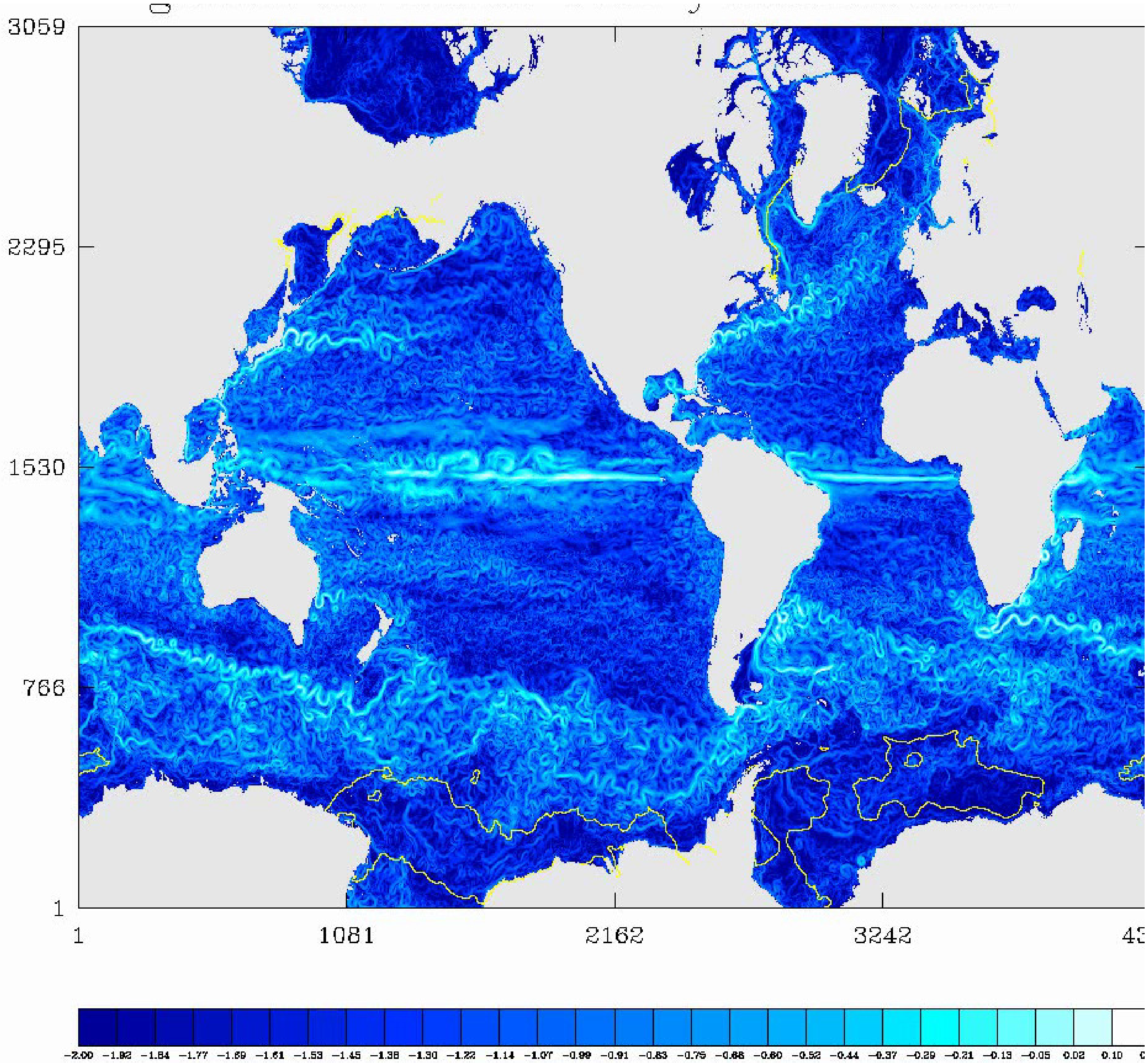


ORCA12: the surface currents

Markus Scheinert (GEOMAR)



ORCA12



3059
2295
1530
766
1
1
1081
2162
3242
-2.00 -1.92 -1.84 -1.77 -1.69 -1.61 -1.53 -1.45 -1.38 -1.30 -1.22 -1.14 -1.07 -0.99 -0.91 -0.83 -0.76 -0.68 -0.60 -0.52 -0.44 -0.37 -0.29 -0.21 -0.13 -0.05 0.02 0.10

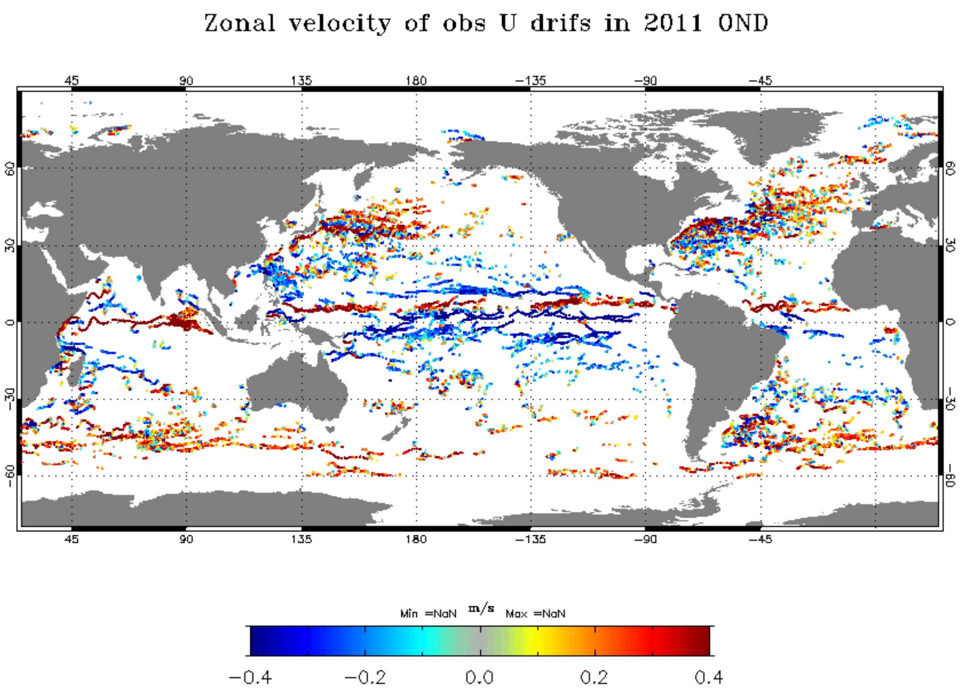
ORCA12: how model surface currents compare to observations?

Lack of ocean surface currents for validation

Validation is difficult because of :

- the nature of available observations
  - Drifter velocities
  - Local current meter mooring
  - Ship ADCPs
- the turbulent nature of the flow

ORCA12: how model surface currents compare to observations?



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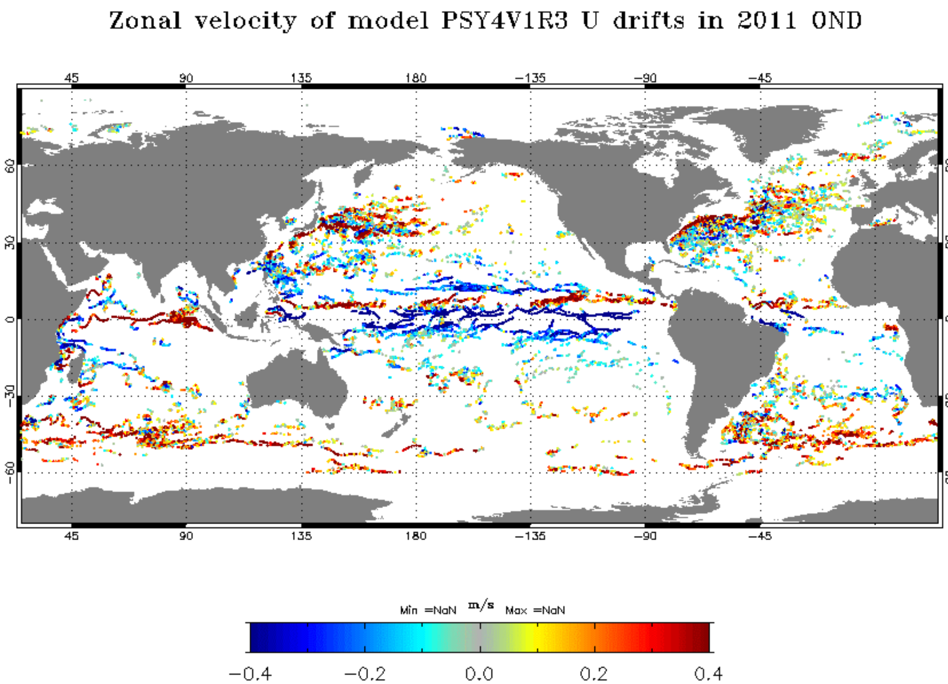


We compare ORCA12 analyses performed at MERCATOR with AOML currents derived from surface drifter trajectories.

(QuoVadis, M. Drevillon, Feb 2012)

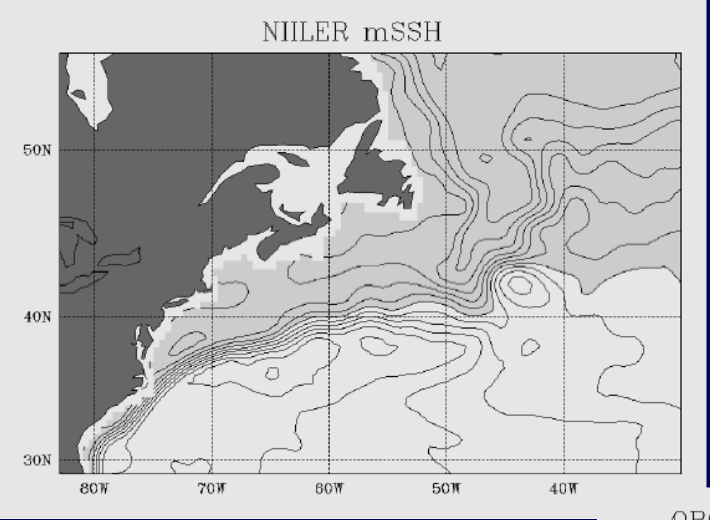
ORCA12 sensitivity to the parameter space

ORCA12 sensitivity to the parameter space

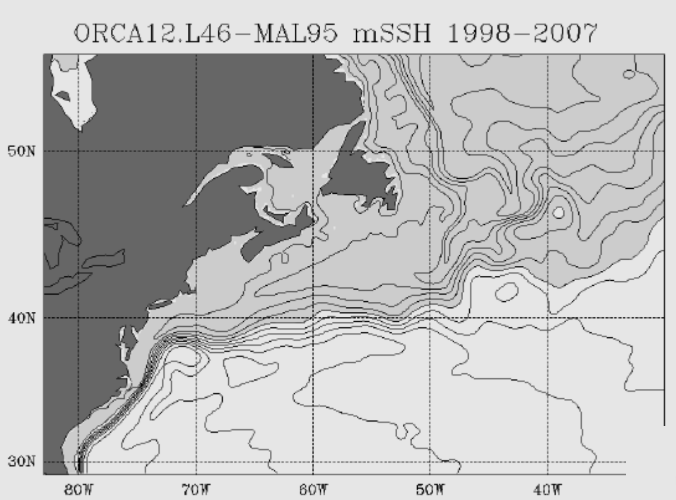
- Lateral friction at the wall
- Momentum advection scheme
- Surface forcing (absolute versus relative wind)

Lateral friction at the wall

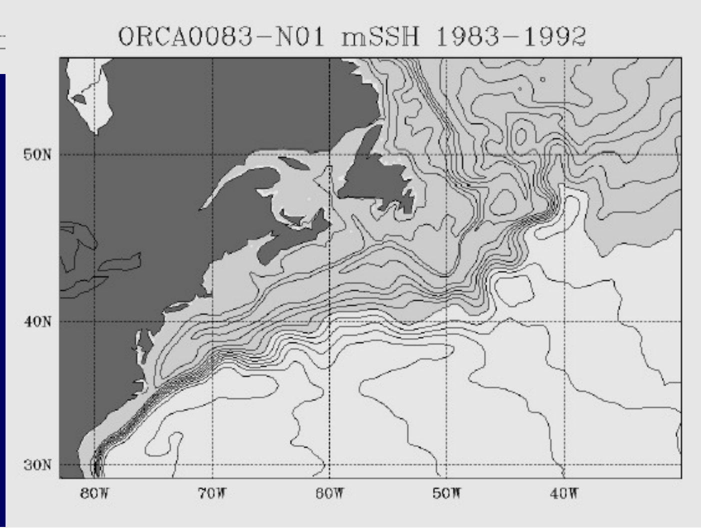
Effect on mean currents - (mean SSH)



Observation (Niiler)



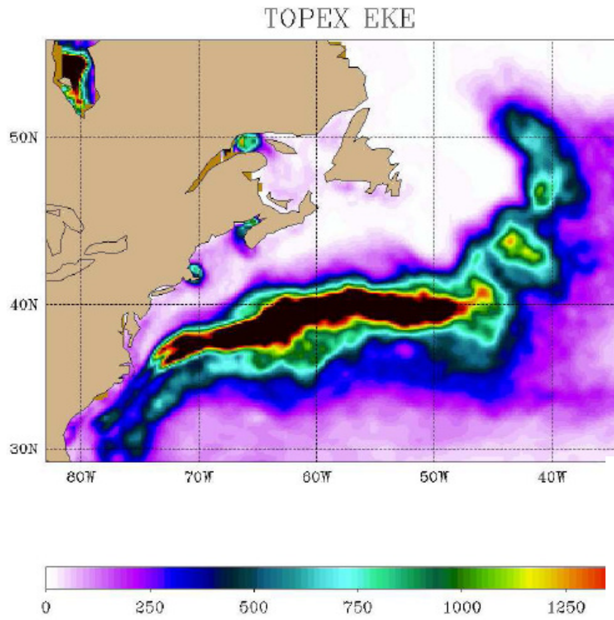
ORCA12 - partial slip B.C.



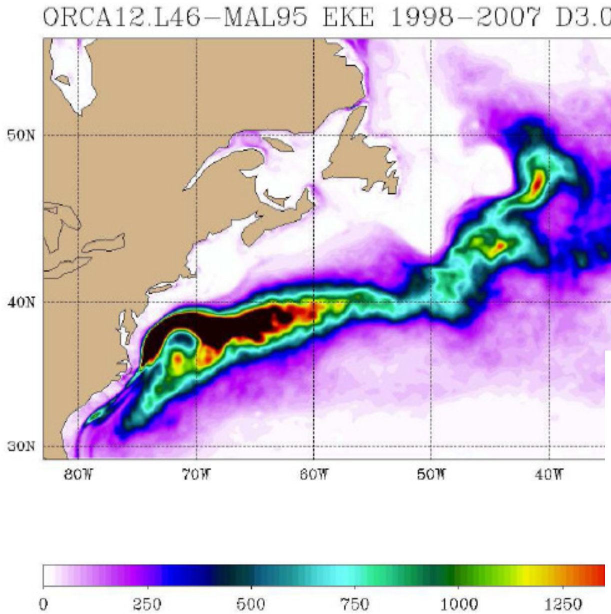
ORCA12 - free slip B.C.

Lateral friction at the wall

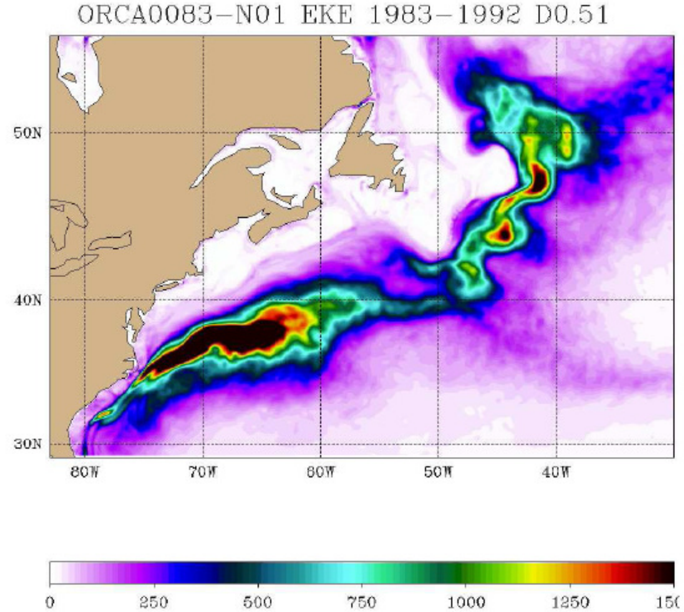
Effect on eddy kinetic energy



Observation (T/P)

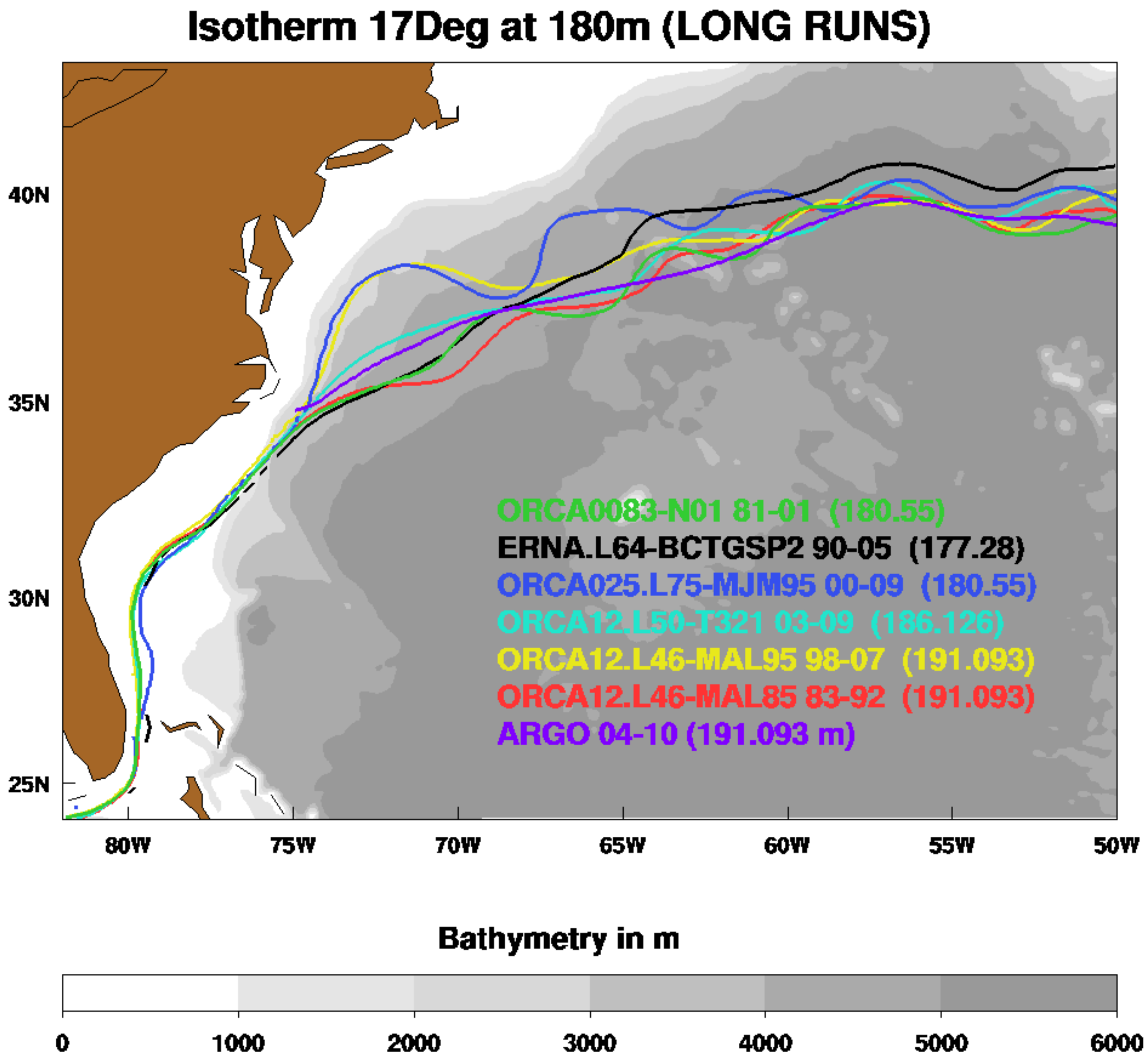


ORCA12 - partial slip B.C.



ORCA12 - free slip B.C.

Lateral friction at the wall

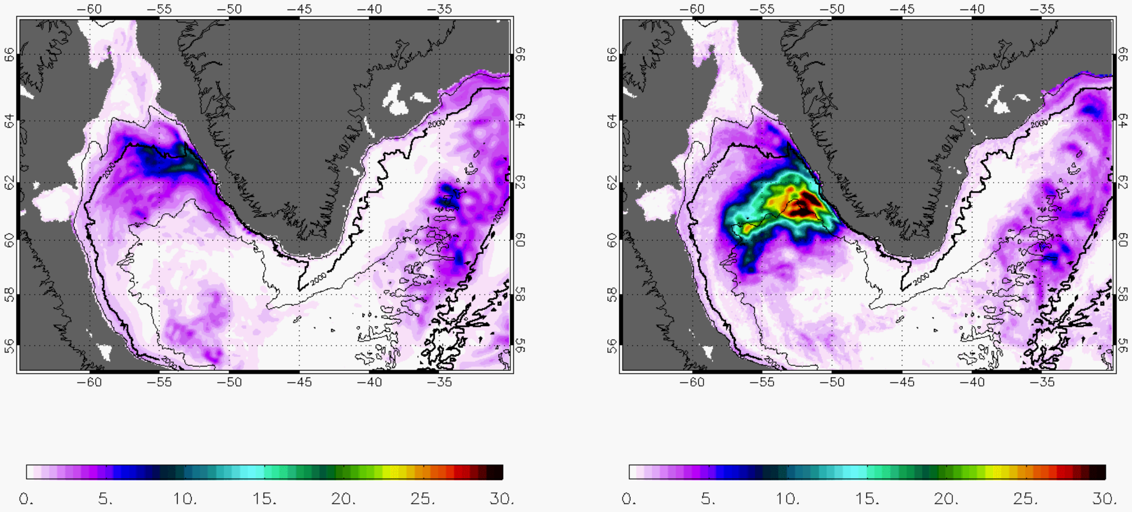


Effect on Gulf Stream separation

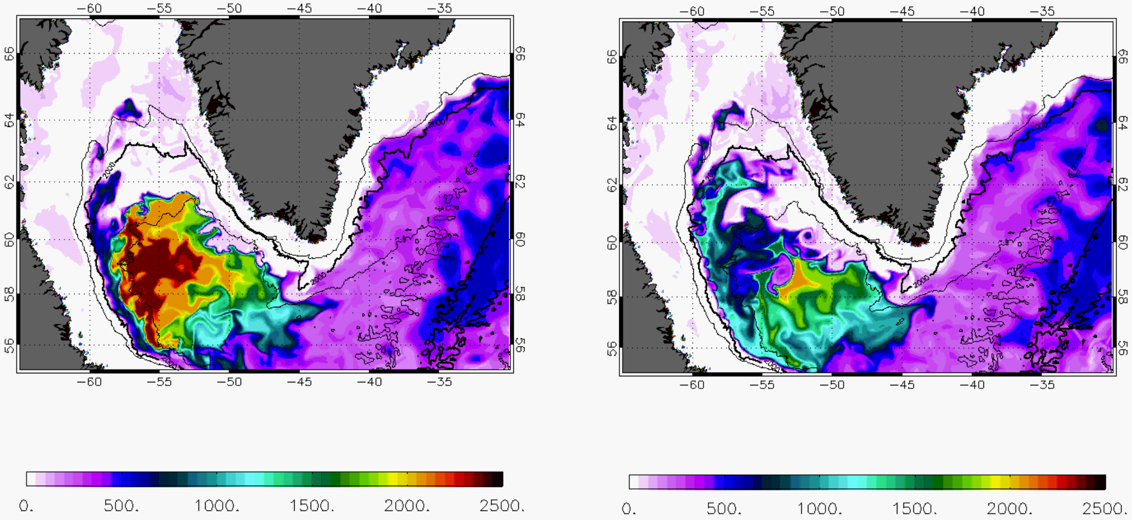
Lateral friction at the wall

Free slip — Variable slip

EKE at 540m y2004

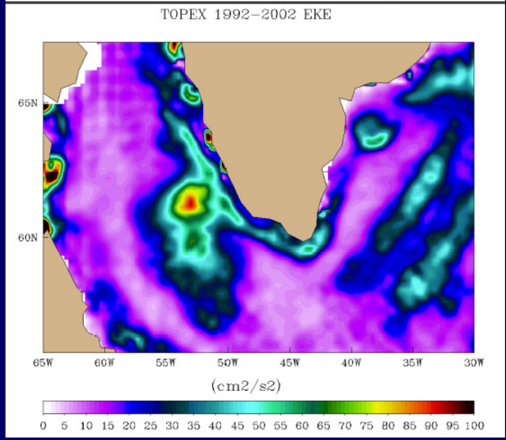


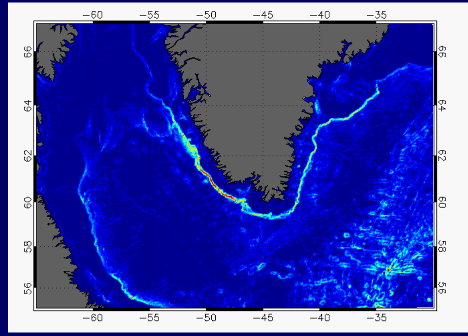
MLD Y2004 m03d28



Local effect

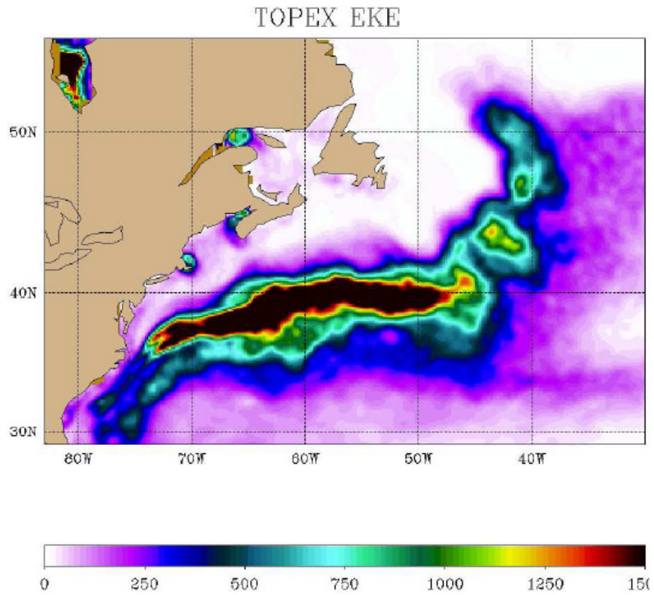
TOPEX (92-02)



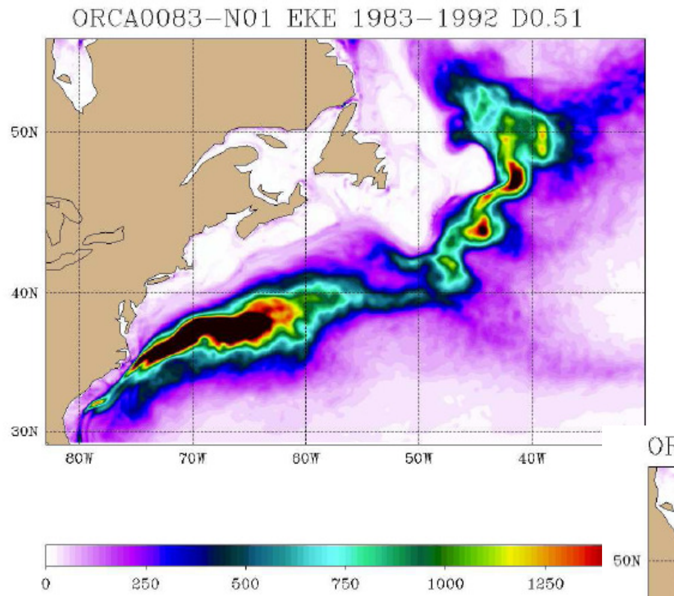


Momentum advection scheme

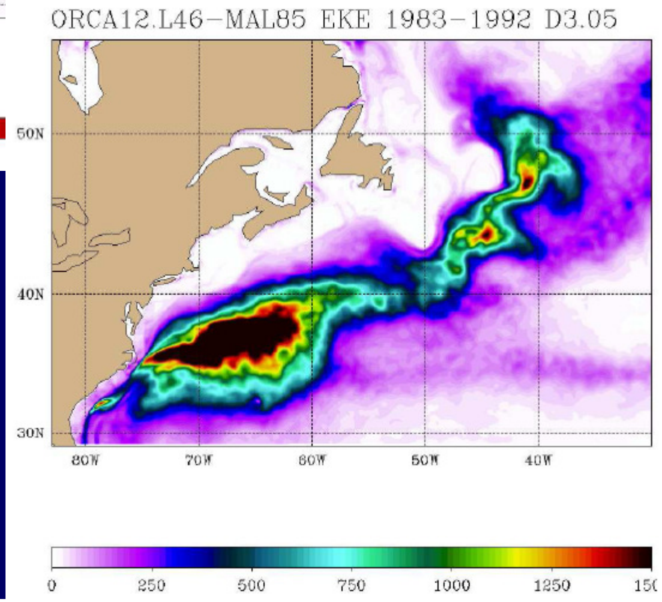
Effect on eddy kinetic energy



Observation (T/P)



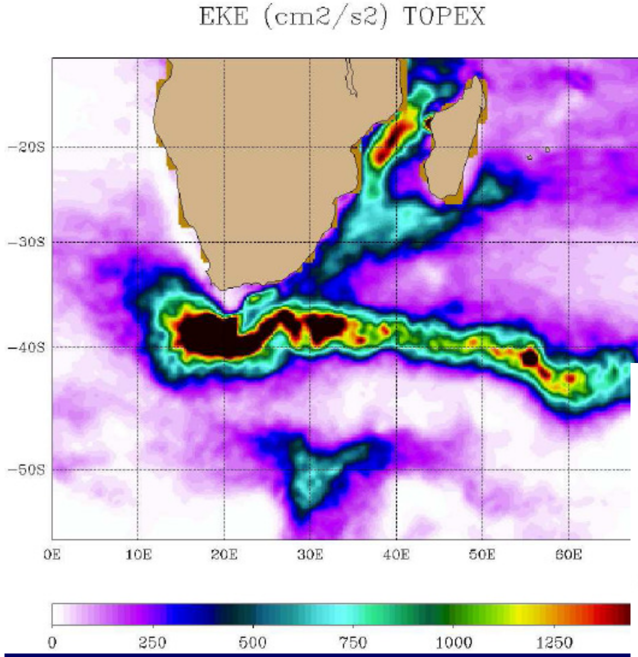
ORCA12 – EEN scheme



ORCA12 – FLX scheme.

Momentum advection scheme

Effect on eddy kinetic energy



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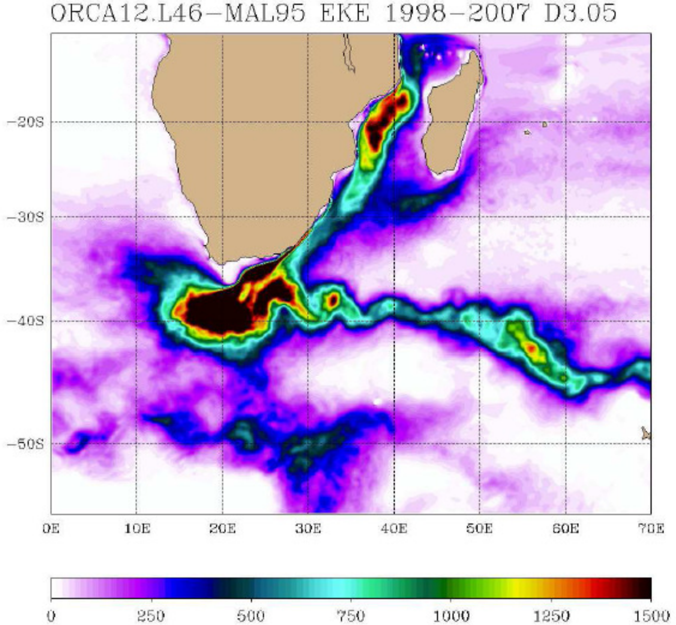
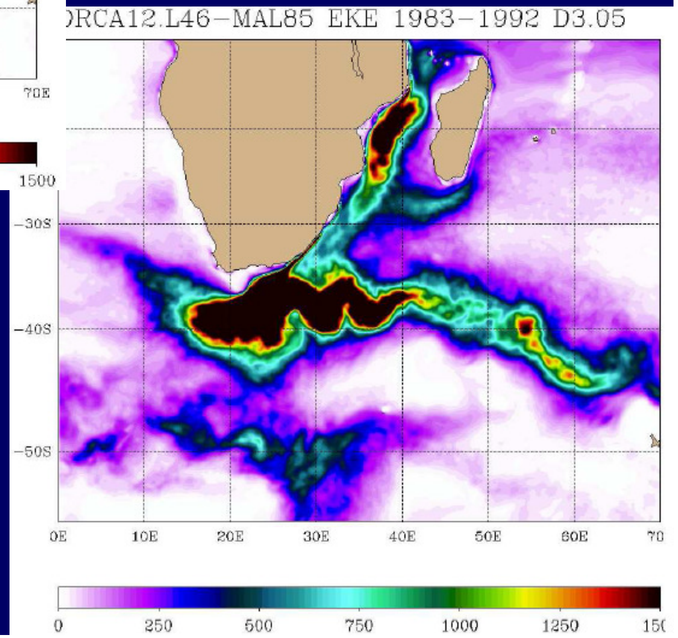


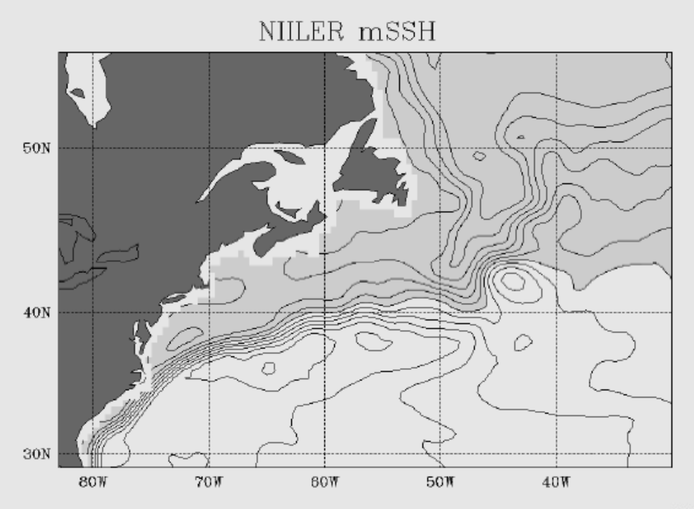
ORCA12 – EEN scheme



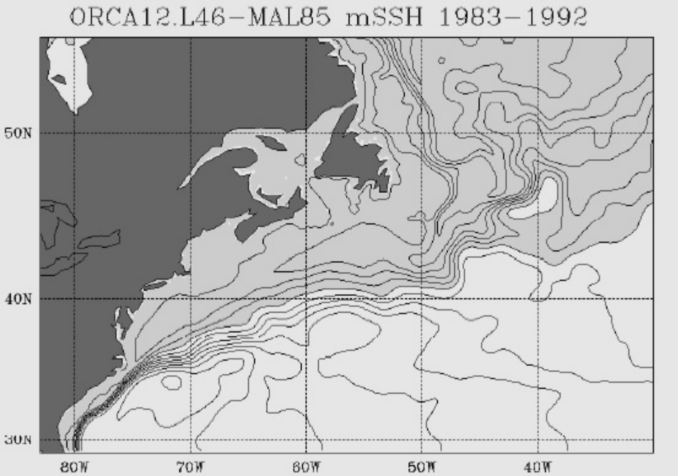
ORCA12 – FLX scheme.

Momentum advection scheme

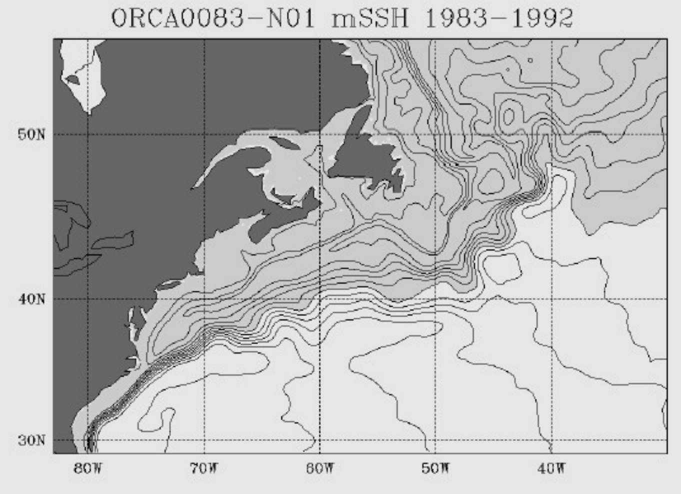
Effect on mean currents - (mean SSH)



Observation (T/P)



ORCA12 – EEN scheme

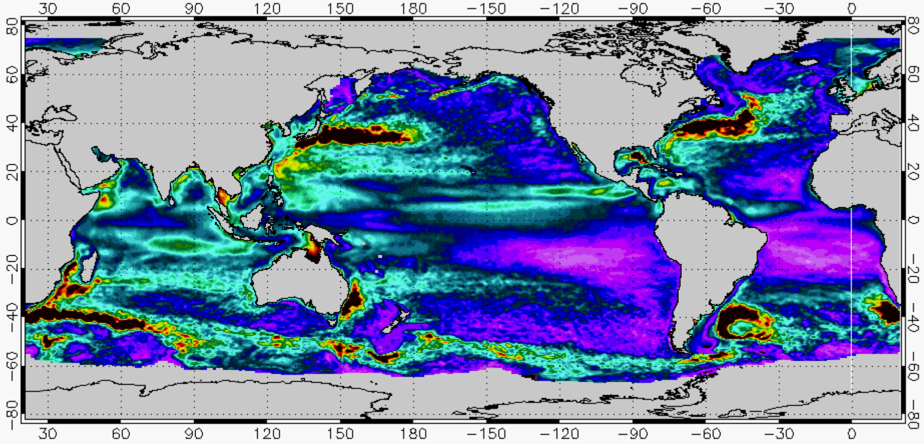


ORCA12 – FLX scheme.

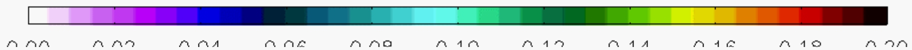
Wind forcing
Absolute wind vs Relative wind

$$\vec{\tau} = \rho_a C_d \left\| \vec{U}_{10} - \vec{U}_{ocean} \right\| \cdot (\vec{U}_{10} - \vec{U}_{ocean})$$

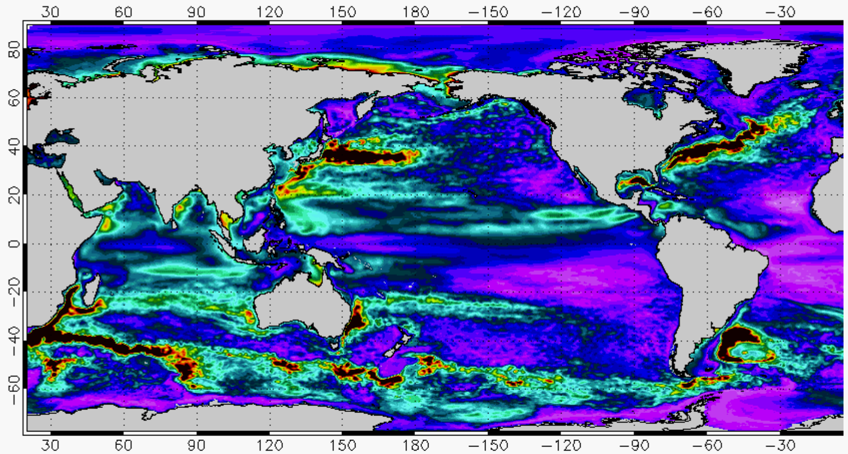
SSH rms



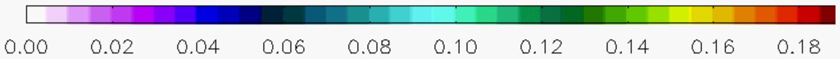
AVISO



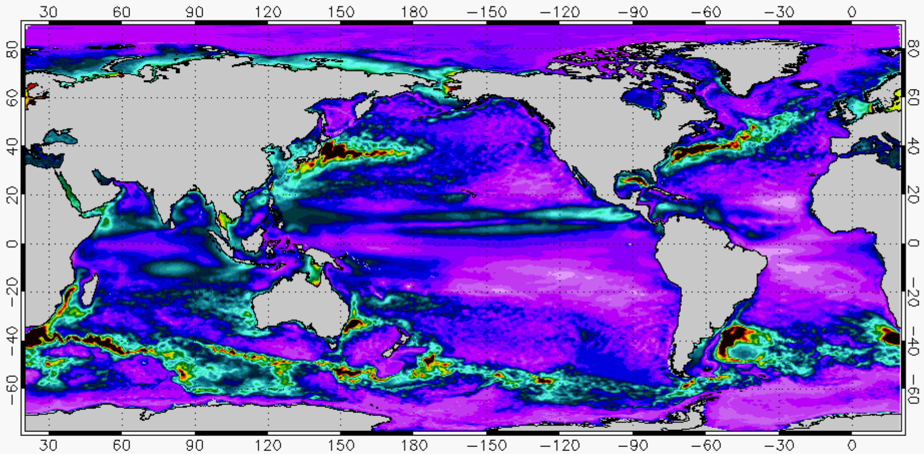
ORCA12_LIM−T321 2003−2007 SSH rms



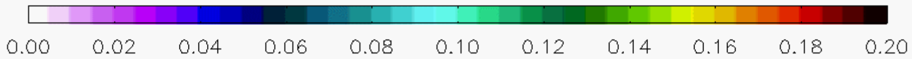
ORCA12.L50



ORCA12.L46−MAL95 2003−2007 SSH rms



ORCA12.L46

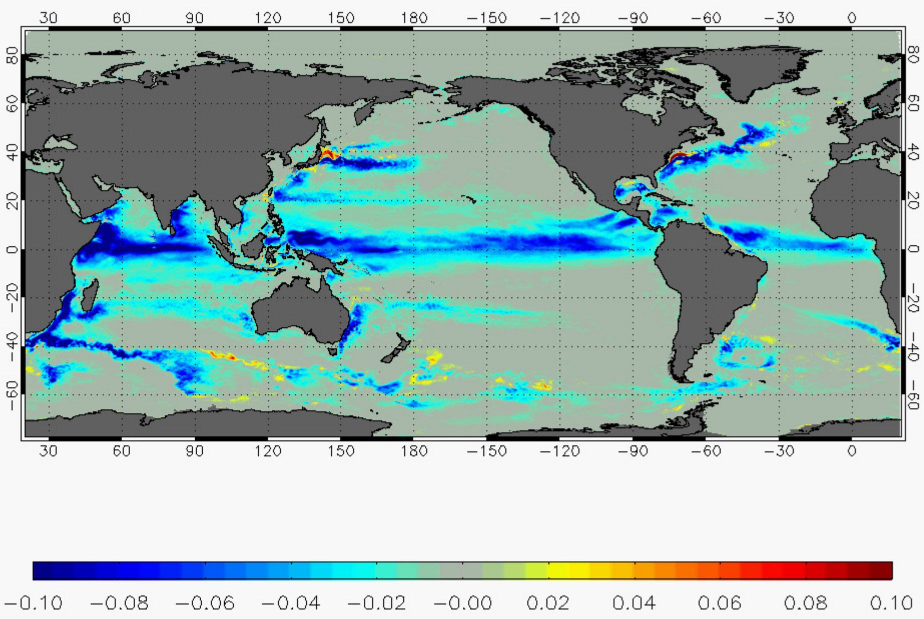


Wind forcing
Absolute wind vs Relative wind

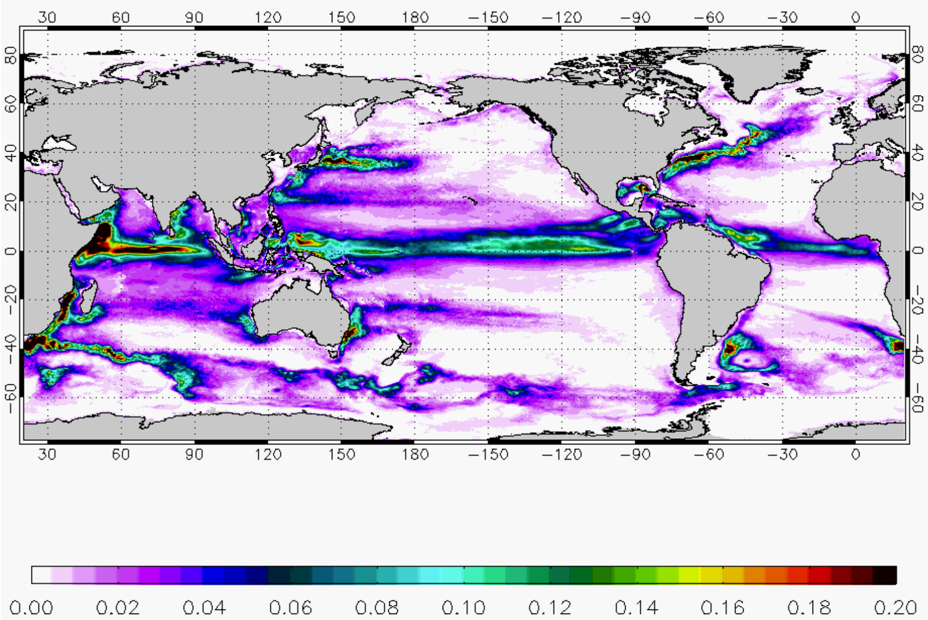
$$\vec{\tau} = \rho_a C_d \left\| \vec{U}_{10} - \vec{U}_{ocean} \right\| \cdot (\vec{U}_{10} - \vec{U}_{ocean})$$

EKE

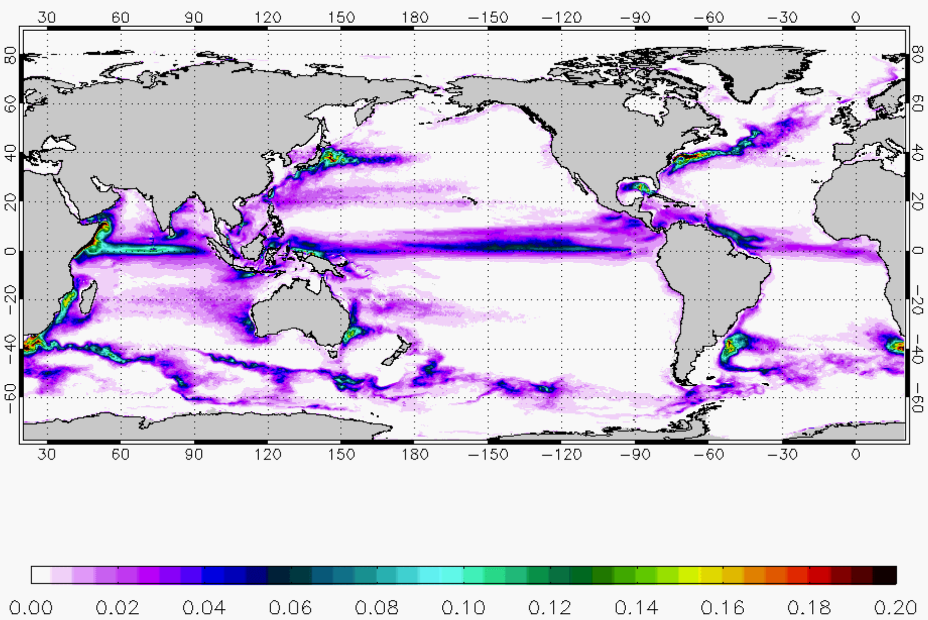
ORCA12.L46–MAL95 – ORCA12_LIM–T321 2003–2007 EKE



ORCA12.L50 ORCA12_LIM–T321 2003–2007 EKE



ORCA12.L46 ORCA12.L46–MAL95 2003–2007 EKE



CONCLUSION

Although we know and understand a lot on ocean mesoscale features, modelling the ocean circulation at synoptic scales is just at its beginning

Sensitivity to model parameters is poorly known at those high resolutions, and its exploration will be very costly (Drakkar objective), but model cost (cpu and storage) is already very high...

Resolution of 1/12° still not high enough, and ocean currents are still generally underestimated.

There is a need to improve the sampling of the synoptic scales of motion (Jason and ARGO do not do it adequately). Wide Swath Altimeter?

Lack of “adequate” ocean current observations for validation of highly turbulent models (drifters, local moorings, ...).

Observational network is not dense enough to constrain surface currents (which still present significant biases in the analysis).