Space altimetry

SCALE INTERACTIONS IN THE GLOBAL OCEAN: SYNERGIES BETWEEN ALTIMETRY, MODELLING, AND DYNAMICAL THEORIES

Thierry Penduff, CNRS
Equipe MEOM (Modélisation des Ecoulements Océaniques à Multi-échelle)
Laboratoire de Glaciologie et Géophysique de l’Environnement, Grenoble

Thanks to
Mélanie Juza, Guillaume Sérazin, Sandy Grégorio
Bernard Barnier, Jean-Marc Molines, and DRAKKAR colleagues

Context

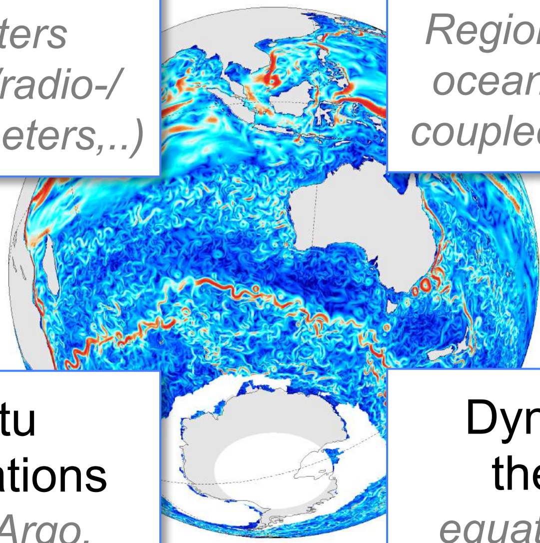
- Physical oceanography: studying the motions and physical properties of ocean waters
- Main sources of oceanographic information today :

Various quantities
Global weekly
(altimetry)
***But** mostly surface*

Satellite observations
Altimeters
(& gravi-/radio-/
scattero-meters,..)

« Realistic » simulations
Regional/global,
ocean+sea-ice/
coupled to atm,…

Comparable to real
observations
***But** very complex*
+ numerical biases



REAL OCEAN

VIRTUAL OCEAN

Various quantities
(x,y,z,t) fields
Vertical dimension
***But** uneven,*
irregular coverage

In-situ observations
CTD's, Argo,
moorings, gliders,
tidegauges, …

Dynamical theories
equations, lab.
experiments,
idealized simul.

Rigorous maths
→ Processes
***But** highly idealized*

Context

- Physical oceanography: studying the motions and physical properties of ocean waters
- Main sources of oceanographic information today :

Satellite observations
Altimeters
(& gravi-/radio-/ scaterro-meters,..)

« Realistic » simulations
Regional/global, ocean+sea-ice/ coupled to atm,…

Understanding the *REAL OCEAN*

Example: impact of small-scale dynamics on the ocean variability at large spatiotemporal scales

In-situ observations
CTD's, Argo, moorings, gliders, tidegauges, …

Dynamical theories
equations, lab. experiments, idealized simul.

Outline

① Altimetry — Sea-level — Surface circulation

② Models — Resolution and processes

③ Variability — [2° vs 1/4°] models vs AVISO

④ North Atlantic scale interactions — Intrinsic variability

⑤ Conclusion — Perspectives

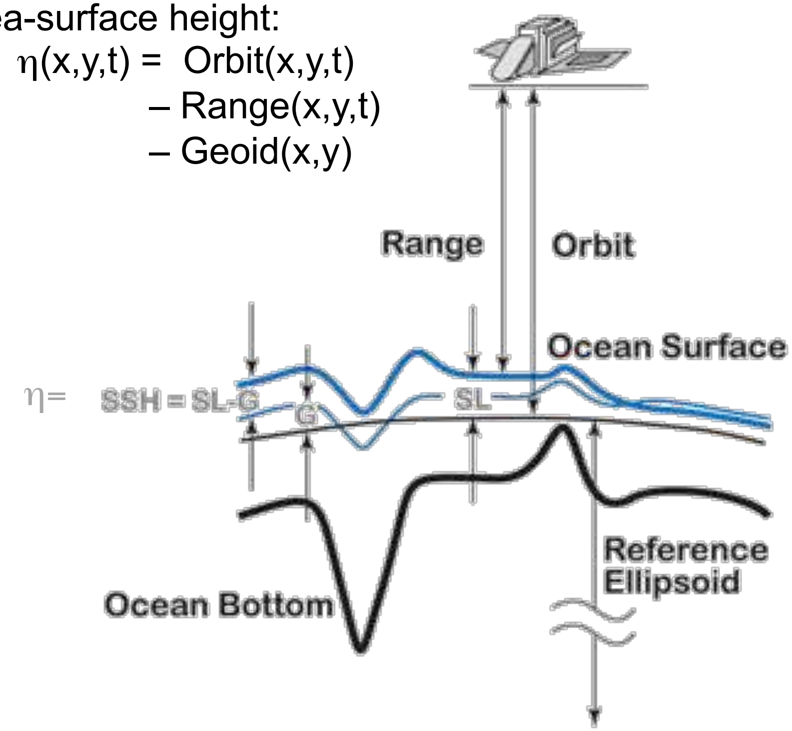
① Altimetry : Sea-level, geostrophic currents

Time delays → SSH

http://www.oc.nps.edu/nom/day1/parta.html

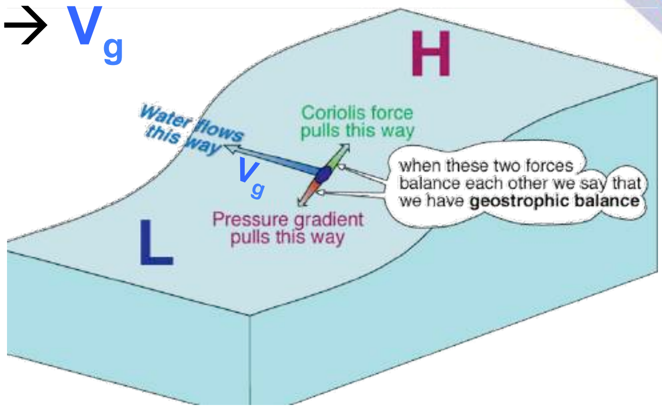
Sea-surface height:

$\eta(x,y,t) =$ Orbit(x,y,t)
– Range(x,y,t)
– Geoid(x,y)

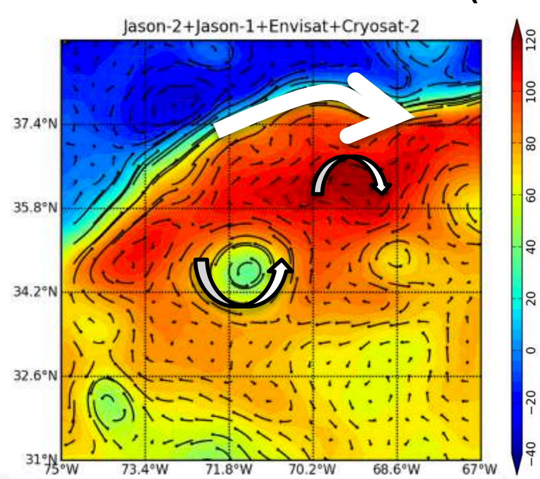


$SLA(x,y,t) = SSH(x,y,t) - \overline{SSH}(x,y)$ is provided (AVISO)
it is associated with the variable part of the geostrophic circulation : geostrophic velocity *anomalies* $\boldsymbol{V_g'}$ are // to SLA contours.

SSH → V_g

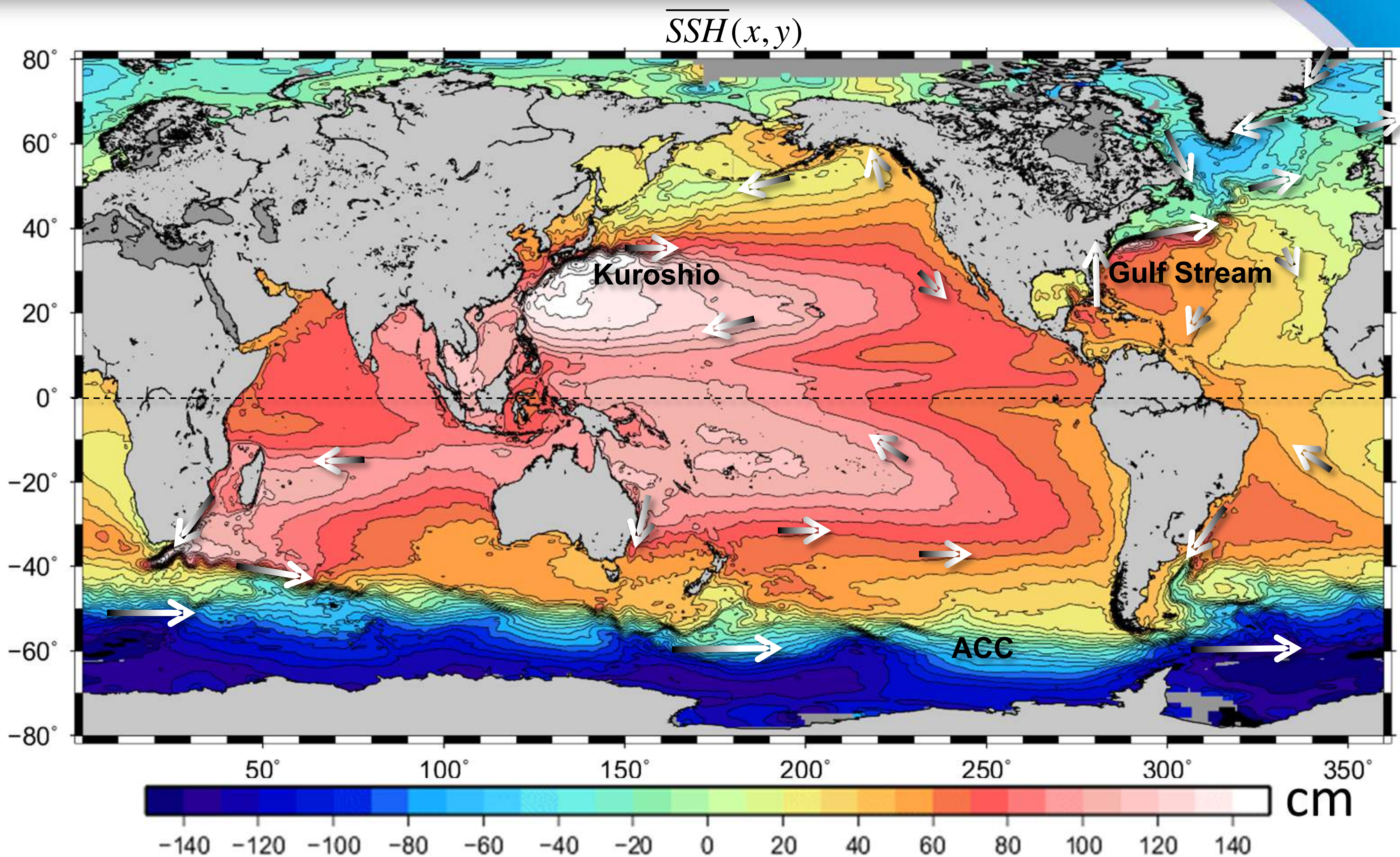


Because of the Earth's rotation Ω, ocean currents away from the equator are in *geostrophic balance* at scales larger than a few days and a few tens of km: **surface geostrophic velocity vectors $\boldsymbol{V_g}$ are parallel to SSH contours (iso-pressure).**



$$f = 2.\Omega.\sin(latitude)$$
$$u_g = -g/f.\partial\eta/\partial y$$
$$v_g = +g/f.\partial\eta/\partial x$$

① Sea-level: mean SSH, mean geos. currents



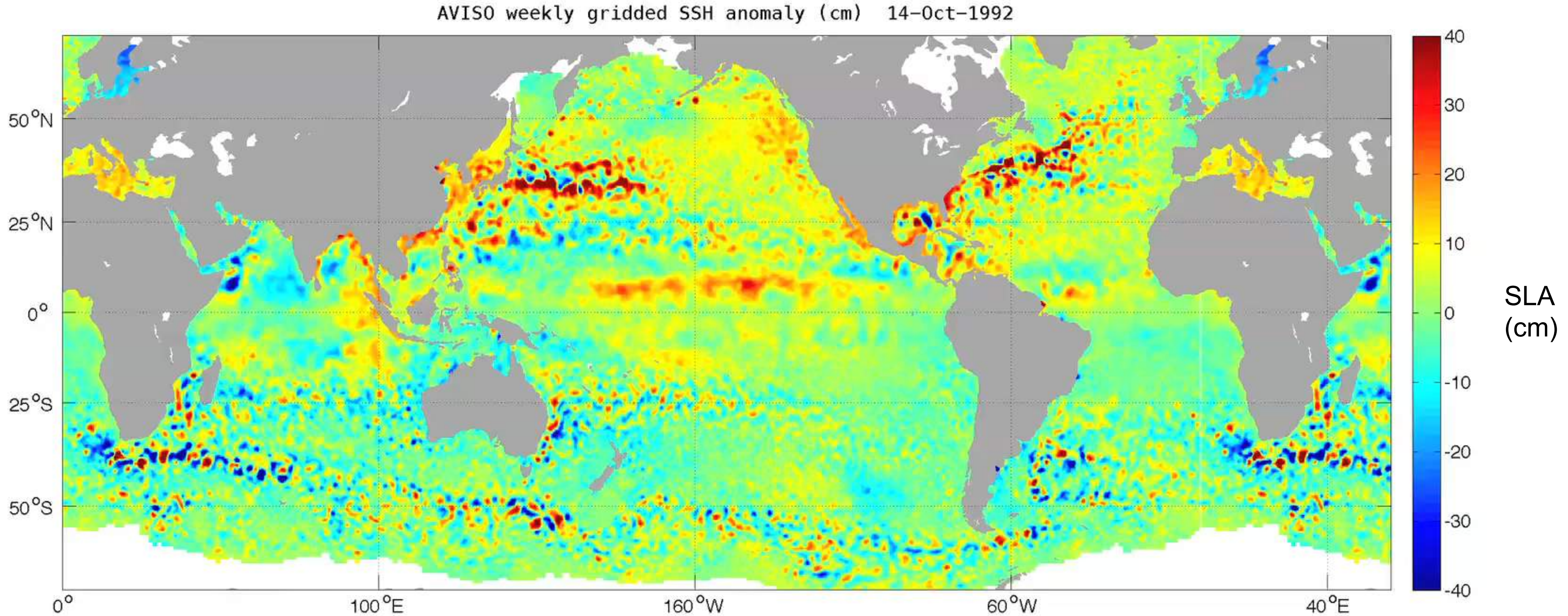
Rio et al, JGR 2011. Based on altimetry, GRACE geoid, ERA-interim wind stress, drifting buoy velocities, T/S(z) profiles

① Sea-level: AVISO SLA(x,y,t)

AVISO SLA(x,y,t) dataset
- every week since 1992
- ~100 km scales
- quasi-global

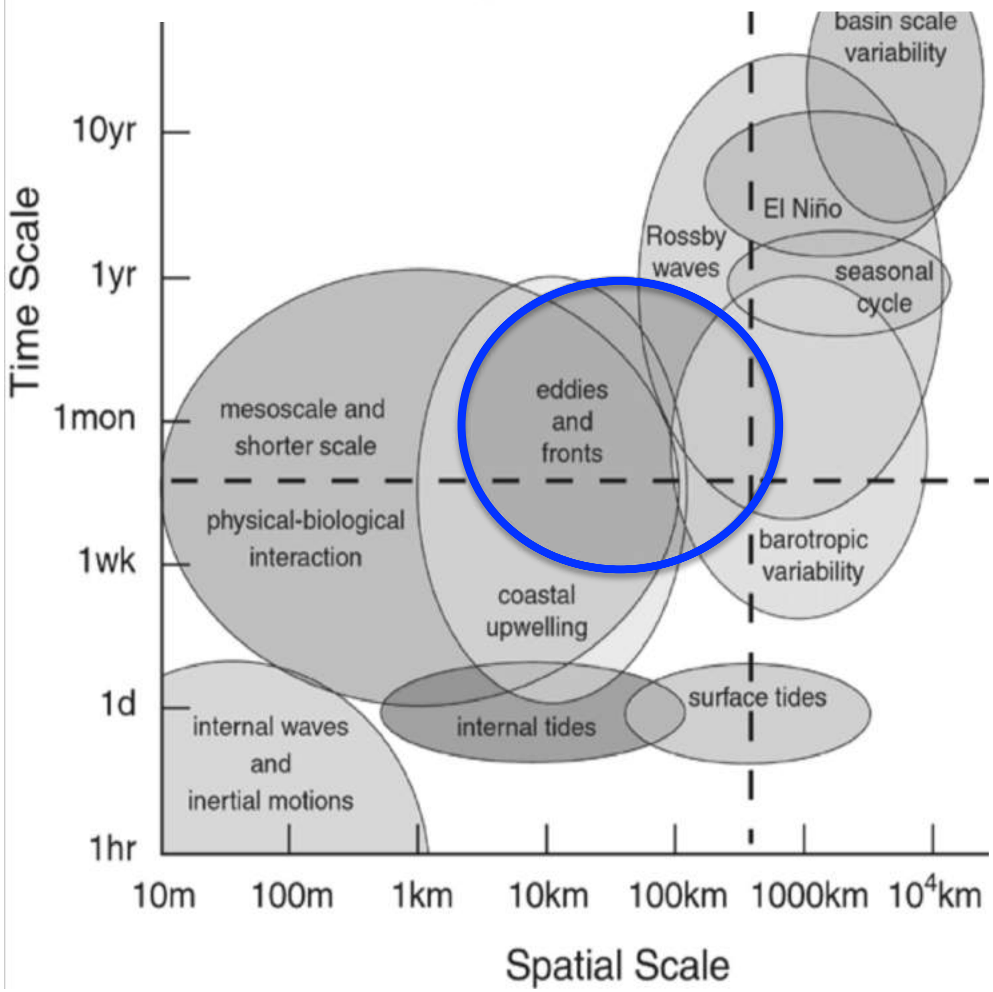
Limitations
- No small scales
- Vertical integral
- No data under sea-ice

- Allows a **global** monitoring of the ocean variability **over a wide range of scales (from mesoscale to climate-relevant scales)**
- revolutionized oceanographic research, and gave birth to operational oceanography

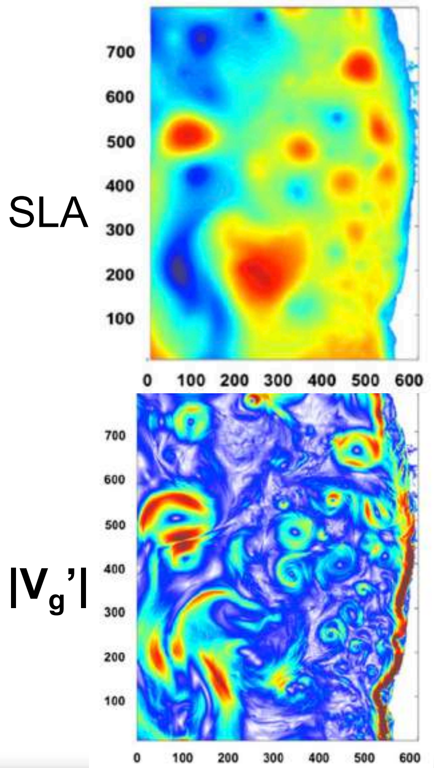


① Sea-level: observable processes

mesoscale eddies *« climatic » scales*

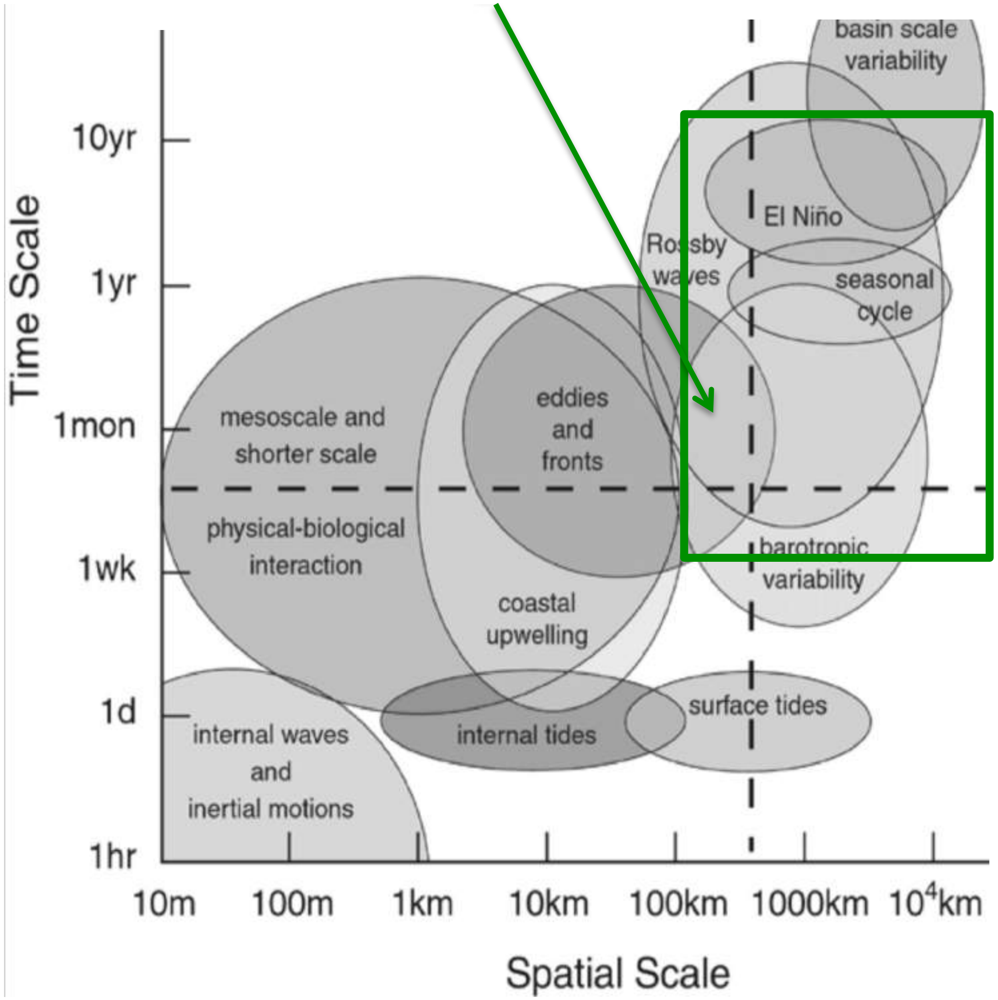


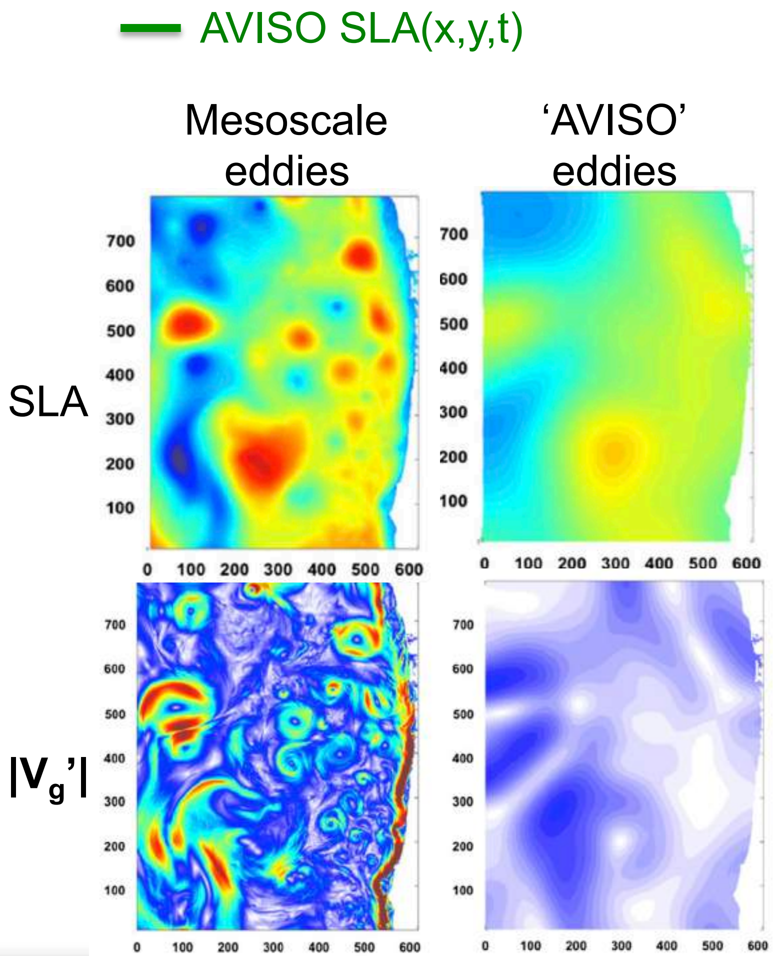
Mesoscale eddies



① Sea-level: observable processes

'AVISO' eddies *« climatic » scales*

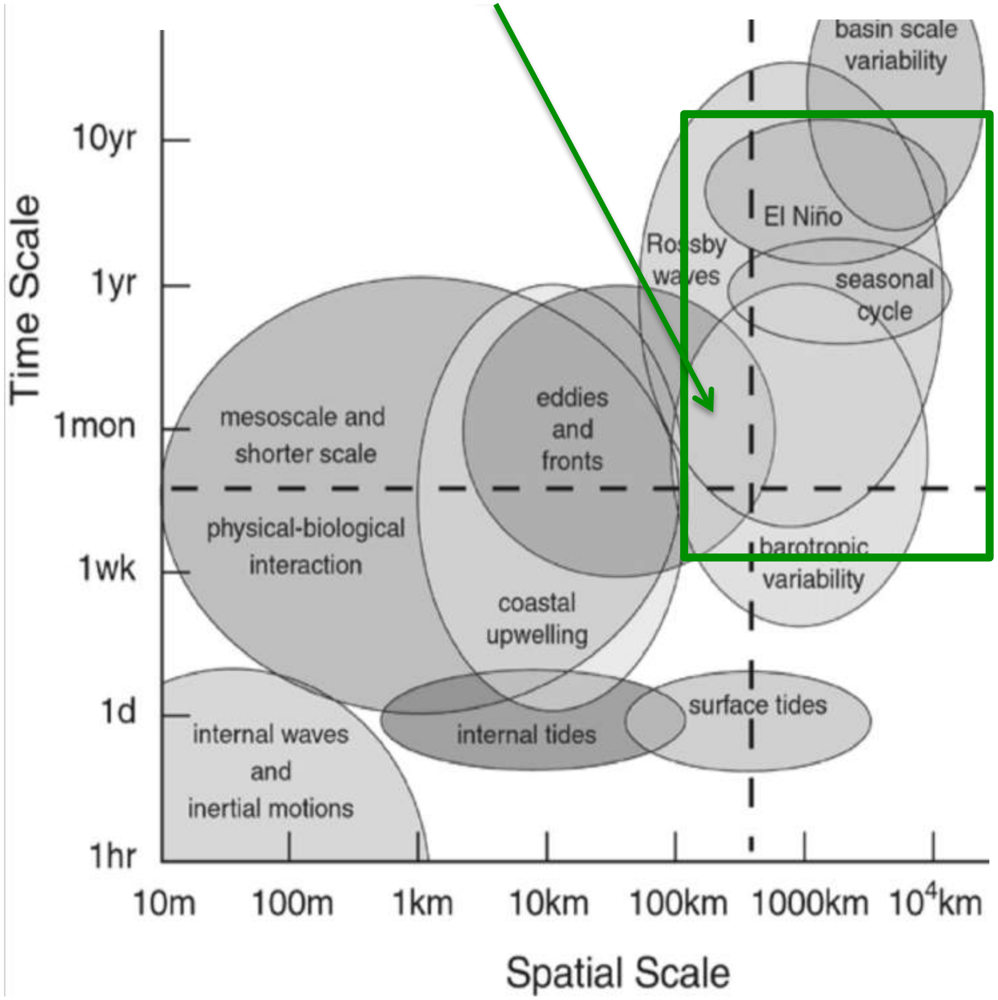




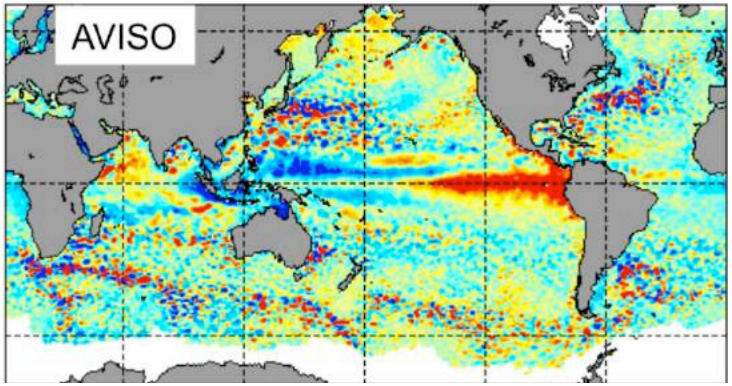
Fu & Ubelmann JAOT 2014

① Sea-level: observable processes

'AVISO' eddies   *« climatic » scales*

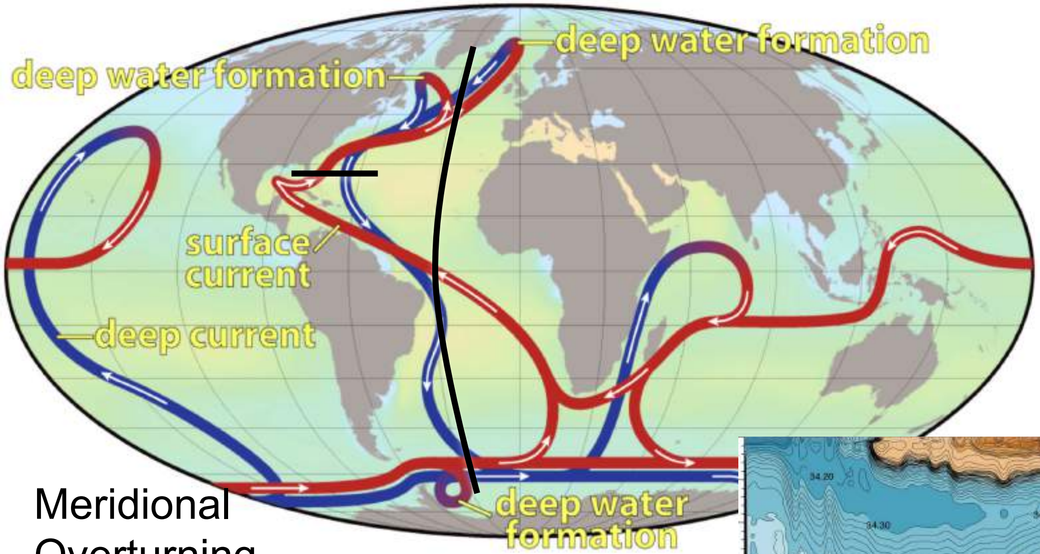


— AVISO SLA(x,y,t)

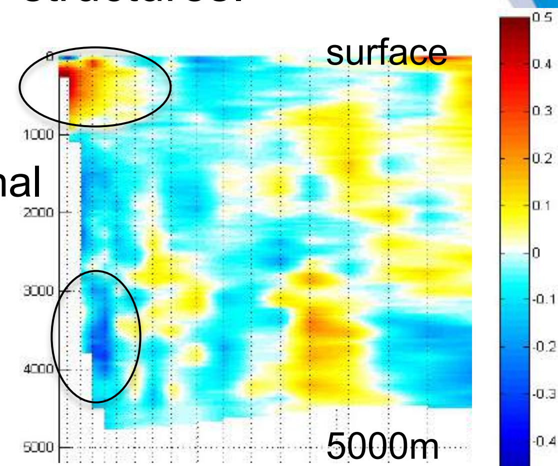


① Sea-level observations… and below?

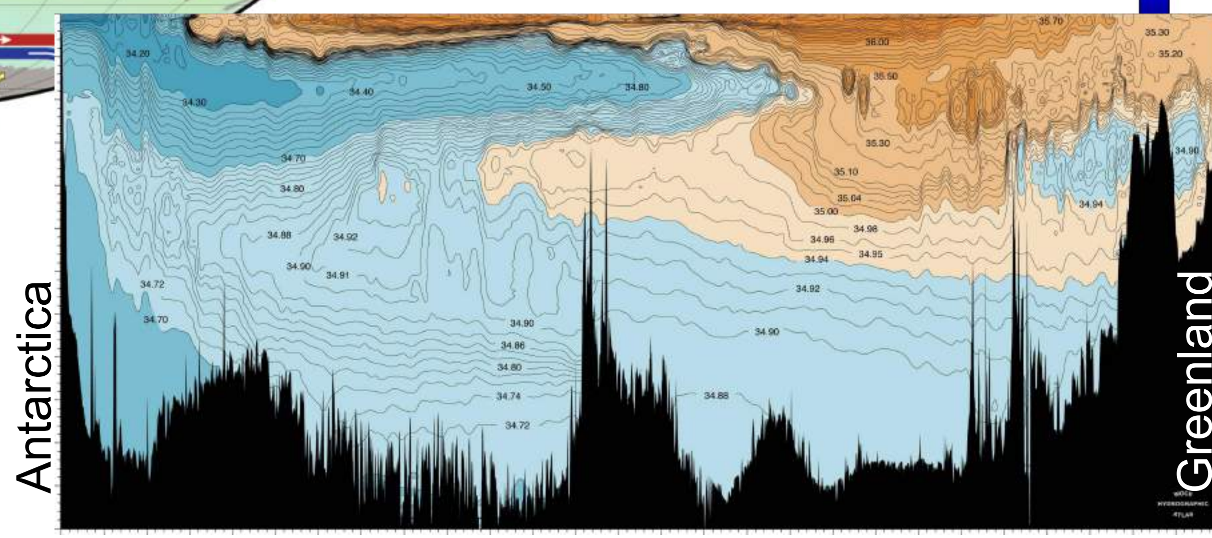
The ocean circulation is generally strongest at the surface, but has a complex vertical structure, strongly coupled to the 3D temperature and salinity structures.



Meridional Overturning Circulation (MOC)



Meridional Velocity At 30°N



Salinity At 20°W

Outline

① Altimetry — Sea-level — Surface circulation

② Models — Resolution and processes

③ Variability — [2° vs 1/4°] models vs AVISO

④ North Atlantic scale interactions — Intrinsic variability

⑤ Conclusion — Perspectives

② Ocean models

A model is a mathematical system that represents a physical process, or an ensemble of interacting processes.

↓ ↓

Conceptual models

- Simplified dynamics
- Idealized geometry, forcing, etc

To study a given ocean process in an idealized setting for an in-depth understanding of its dynamics

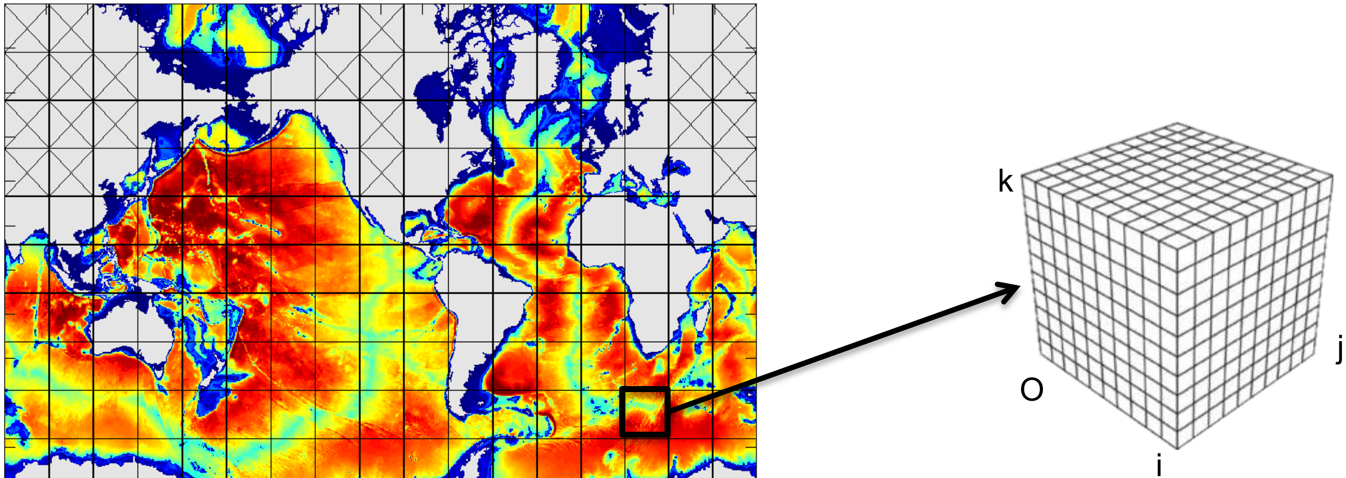
Realistic Models (“virtual ocean”)

- Most complete dynamics
- Most realistic geometry, forcing, etc

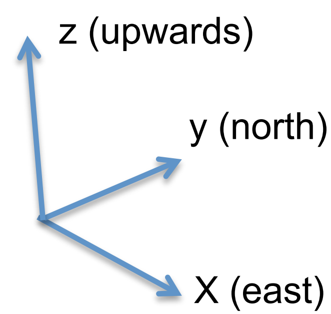
To represent many dynamical processes simultaneously, and the actual ocean circulation with maximum accuracy

Conceptual and realistic models fruitfully complement observations : quasi-continuous 4D multivariate description of the ocean state, dynamical scenarios, dominant processes, sensitivity experiments, multiple realizations…

② Ocean models



160 processors
up to 4000
For 1/12°



A « realistic » model (or Ocean General Circulation Model, OGCM) is a software that solves the primitive equations on a discrete mesh.

② Ocean models: primitive equations

7 unknowns u, v, w, p, T, S, ρ depending on (x,y,z,t)

		Advection	Geostrophy	Forcing, Dissip.	

7 equations :

Momentum equations

zonal $\partial u/\partial t = -\underline{u}.\nabla u + fv - p_x/\rho_0 + F_u + D_u$ (1)

meridional $\partial v/\partial t = -\underline{u}.\nabla v - fu - p_y/\rho_0 + F_v + D_v$ (2)

vertical $p_z = -\rho g$ (3) *(hydrostatic)*

Mass conservation equation $u_x + v_y + w_z = 0$ (4) *(continuity)*

Temperature and salinity equations

$\partial T/\partial t = -\underline{u}.\nabla T + F_T + D_T$ (5)

$\partial S/\partial t = -\underline{u}.\nabla S + F_S + D_S$ (6)

Equation of state $\rho = \rho(T, S, P)$ (7)

Boundary conditions

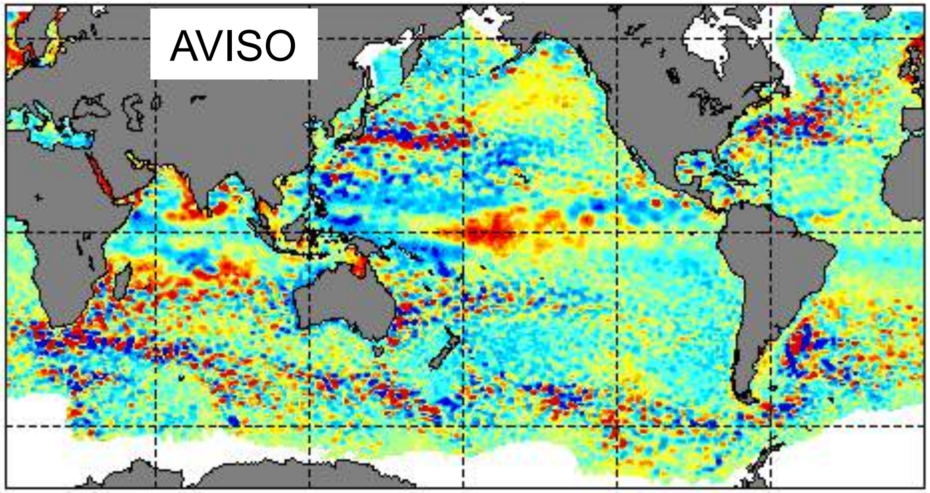
Bottom $w_{bot} = -\underline{u_h}.\nabla_h H$ *No flow through ocean topography*

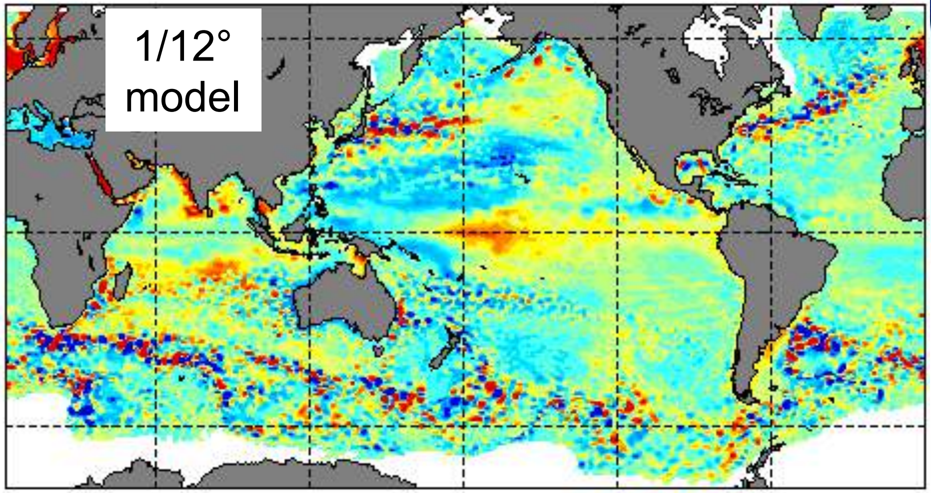
Surface $\frac{\partial \eta}{\partial t} = -\nabla.[(H+\eta).\overline{\underline{u_h}}] + P + R - E$ *(sea level, freshwater)*

Surface heat flux, momentum flux (wind stress)

+ Initial Conditions

② NEMO model: SLA *(no data assimilation)*





AVISO

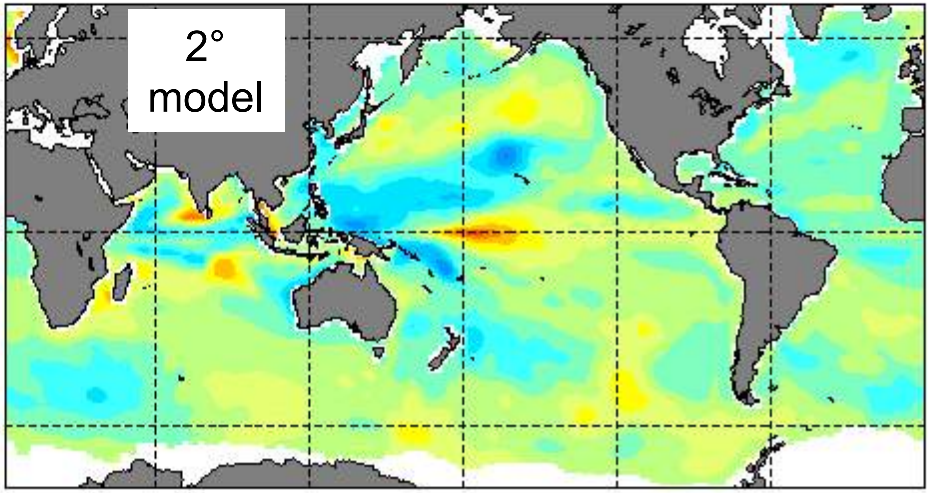
ORCA12

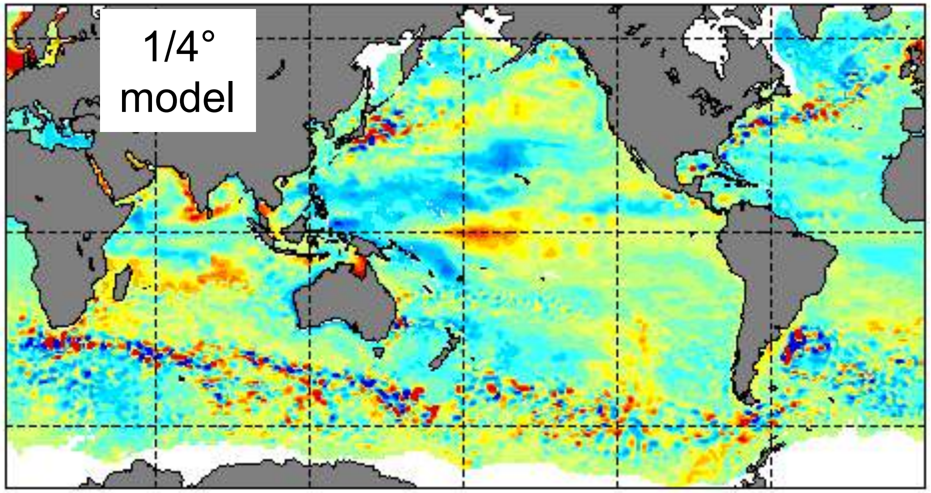
-20 to +20 centimeters

06 / 01 / 1993

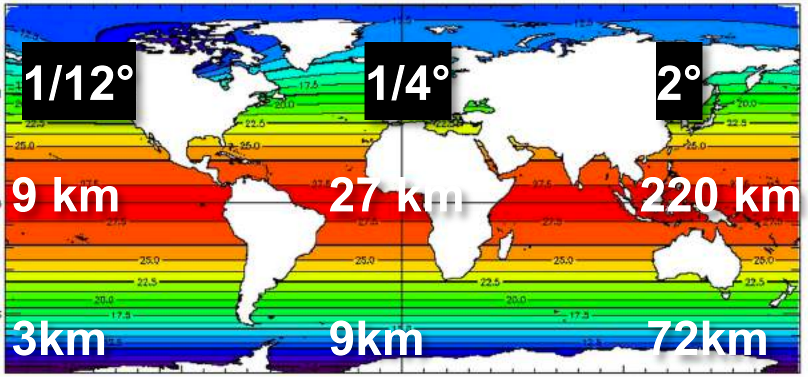
ORCA2

ORCA025



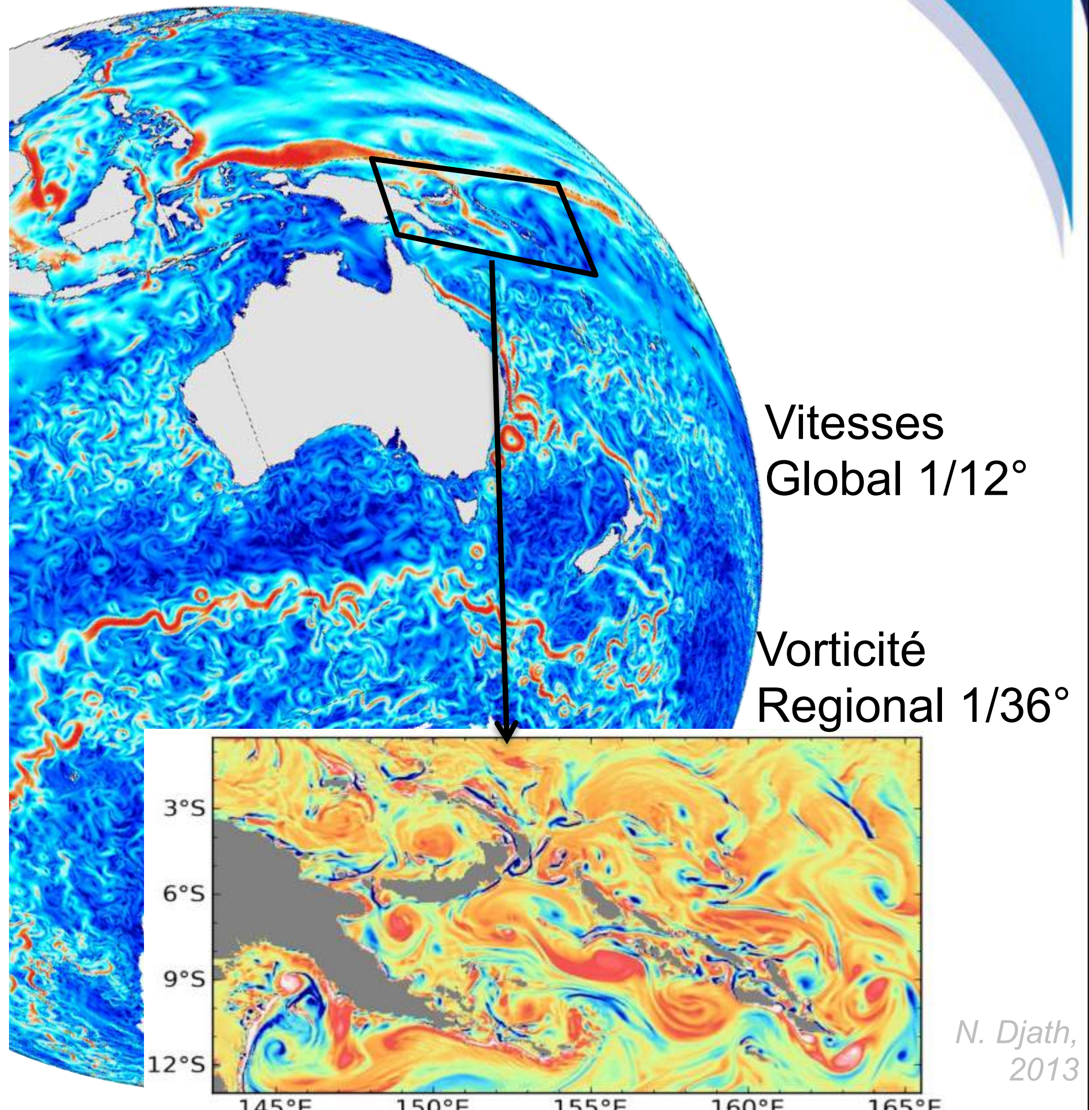


② Ocean models: resolution



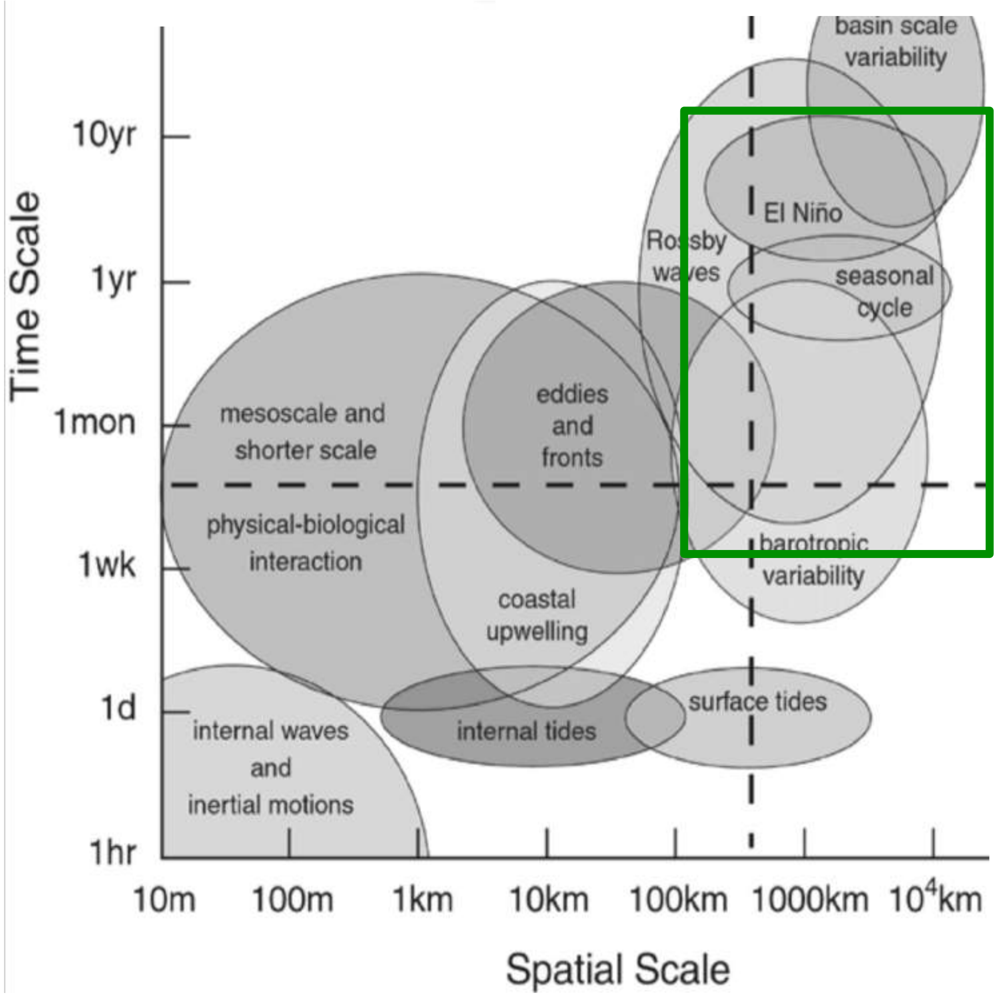
Fine resolution → more fine scales
→ Weaker dissipation (less viscosity)
→ Stronger nonlinear (advection) terms
→ Larger Reynolds Number (adv/visc)
→ Turbulence & scale interactions

$$\partial u/\partial t = -\underline{u}.\nabla u + fv - p_x/\rho_0 + F_u + D_u$$
$$\partial v/\partial t = -\underline{u}.\nabla v - fu - p_y/\rho_0 + F_v + D_v$$
$$p_z = -\rho g$$

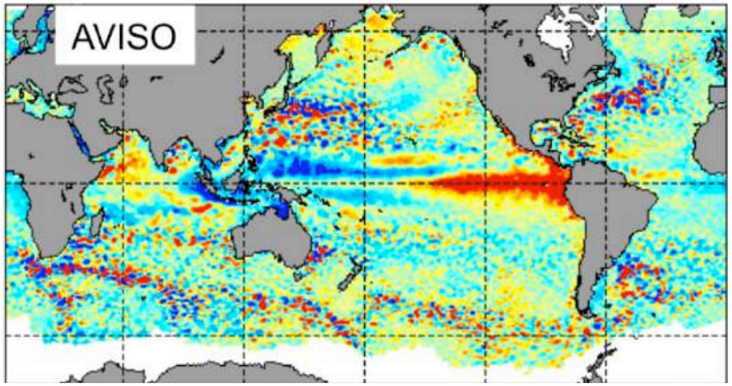


② Ocean models: resolution & processes

'AVISO' eddies *« climatic » scales*

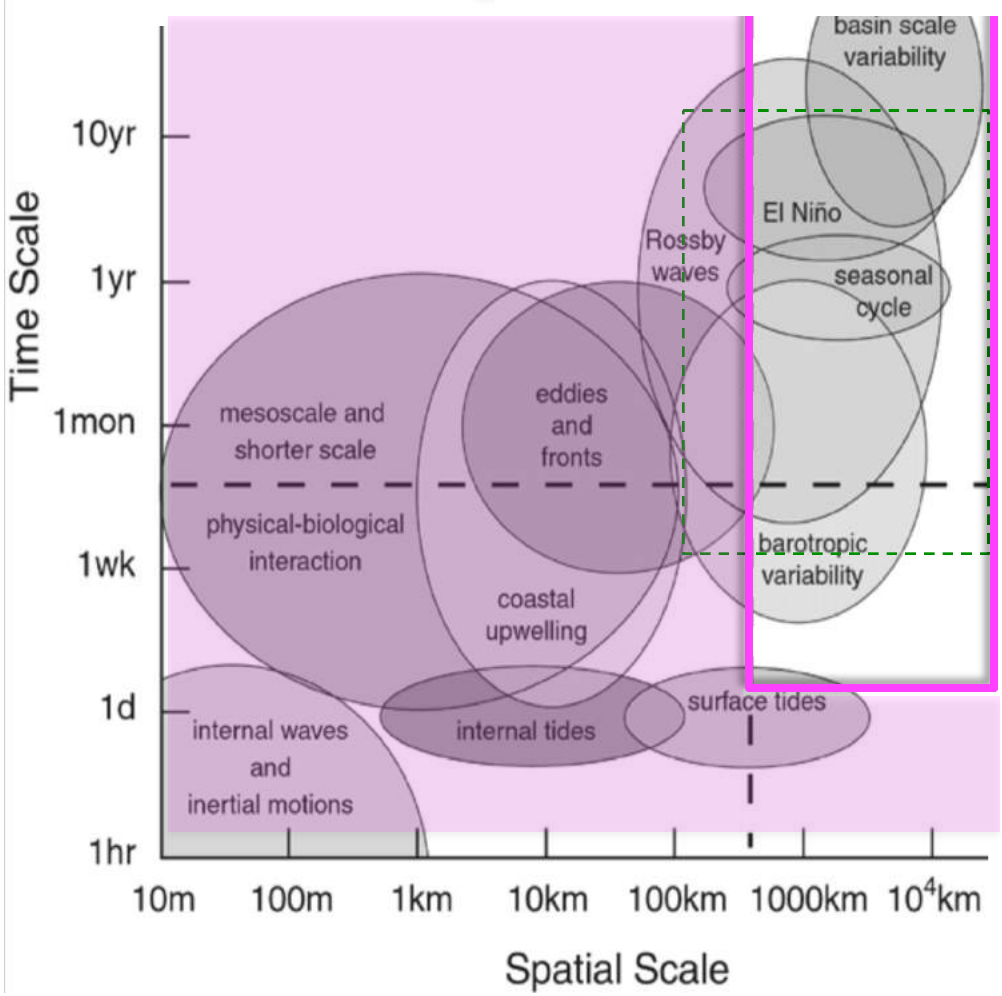


— AVISO SLA(x,y,t)



② Ocean models: resolution & processes

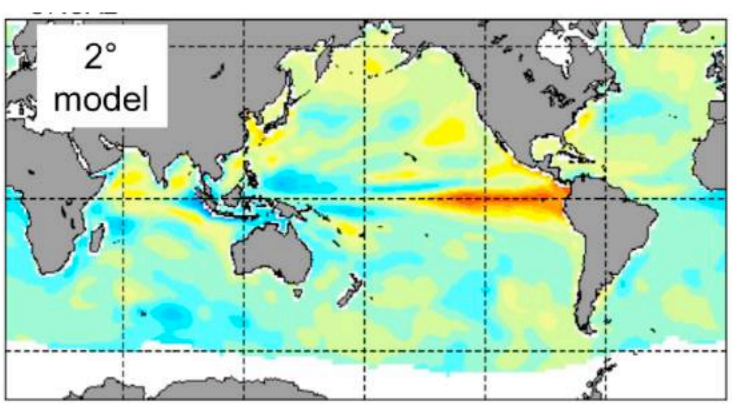
~~Mesoscale eddies~~ « climatic » scales



Inside boxes : resolved processes
Outside ___ : parameterized ___

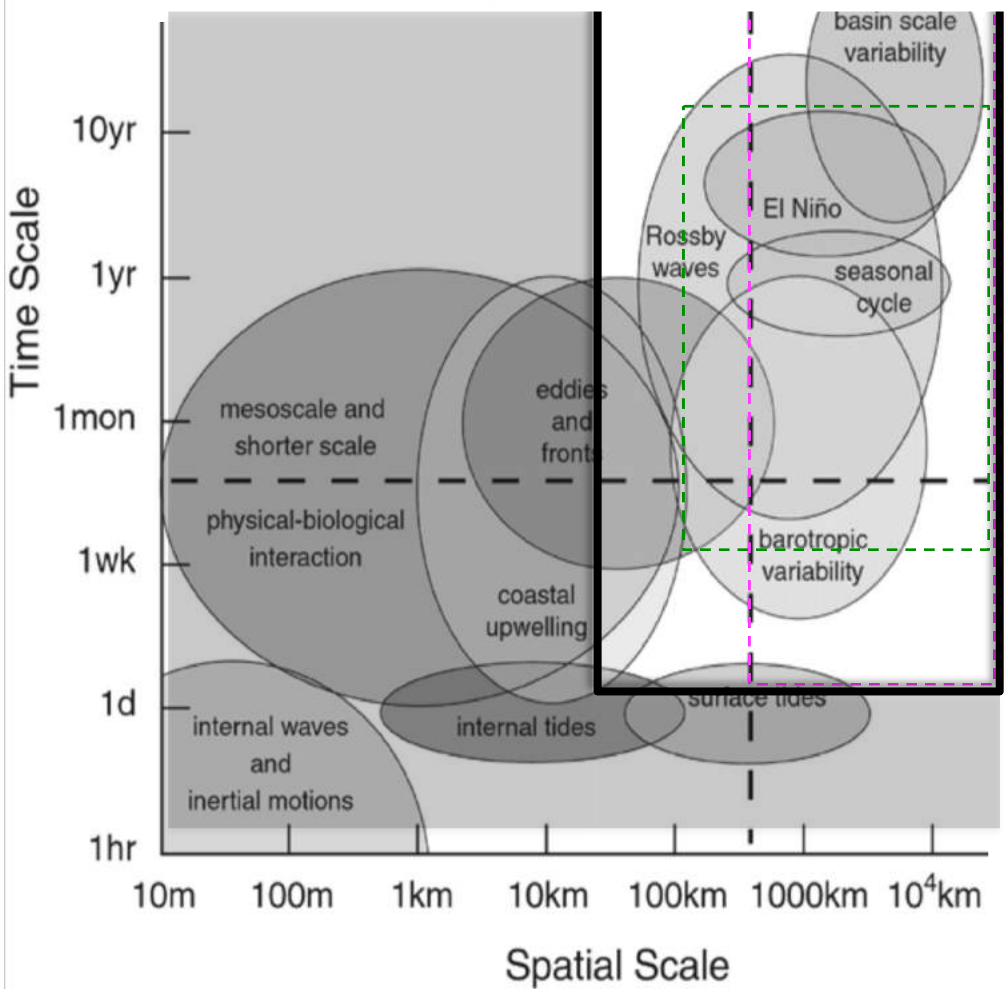
— AVISO SLA(x,y,t)

— 2° global ocean model



② Ocean models: resolution & processes

*(some) Mesoscale eddies **AND** « climatic » scales*

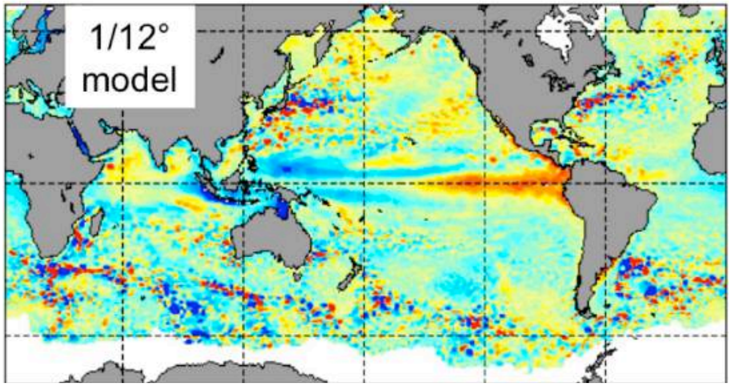


Inside boxes : resolved processes
Outside ___ : parameterized ___

AVISO SLA(x,y,t)

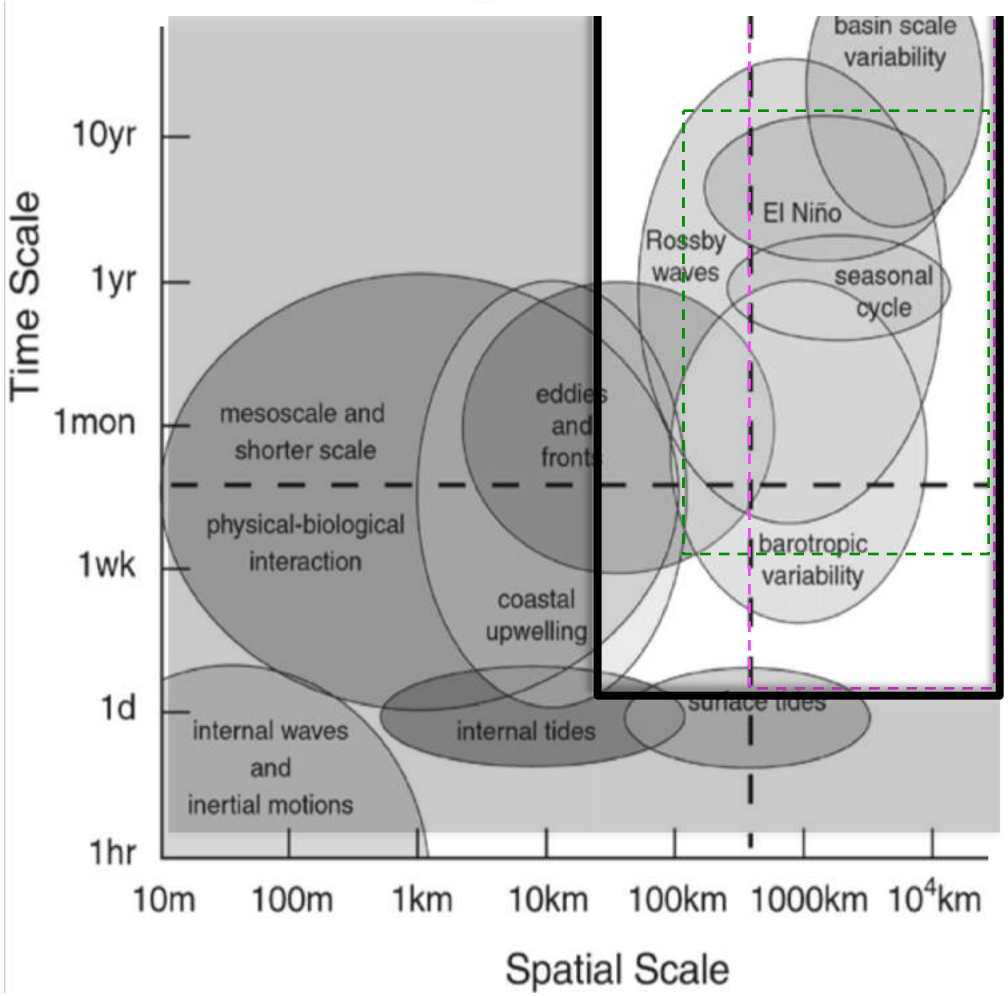
2° global ocean model

1/12° global ocean model



② Ocean models: resolution & processes

*(some) Mesoscale eddies **AND** « climatic » scales*



Inside boxes : resolved processes
Outside ___ : parameterized ___

AVISO SLA(x,y,t)

2° global ocean model

1/12° global ocean model

- **Is the simulated « climatic » SLA variability more realistic, or different, when eddies are explicitly simulated ?**
  ➔ [2° vs 1/4°] models vs AVISO
- **What does this comparison tell us about the role of eddies in the real ocean climate ?**

Outline

① Altimetry — Sea-level — Surface circulation

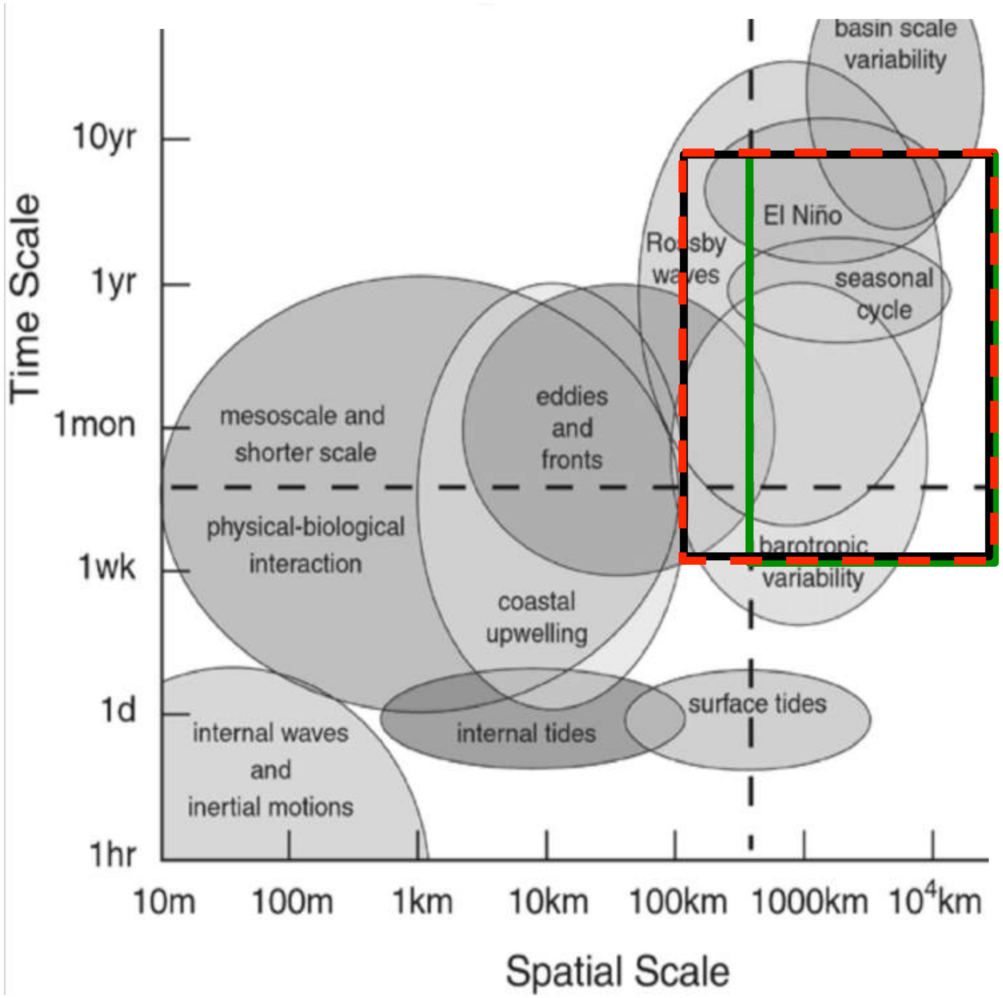
② Models — Resolution and processes

③ Variability — [2° vs 1/4°] models vs AVISO

④ North Atlantic scale interactions — Intrinsic variability

⑤ Conclusion — Perspectives

③ Variability: [2° vs 1/4°] models vs AVISO



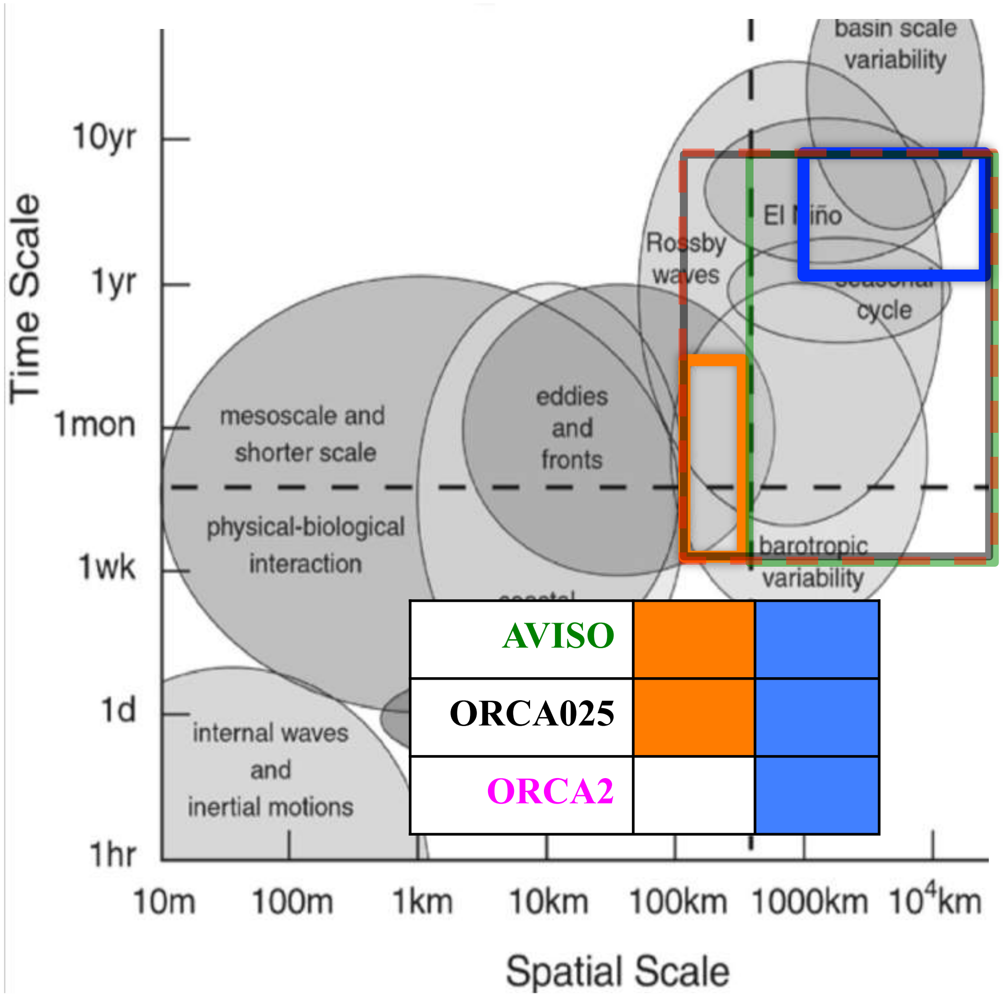
Comparing 3 SLA(x,y,t) datasets over 1993-2007

AVISO	1/3°	1993-2007
ORCA2	2°	1958-2007
ORCA025	1/4°	1958-2007

Atmospheric forcing:
- Based on ERA-40 (all air-sea fluxes)
- Identical in both simulations

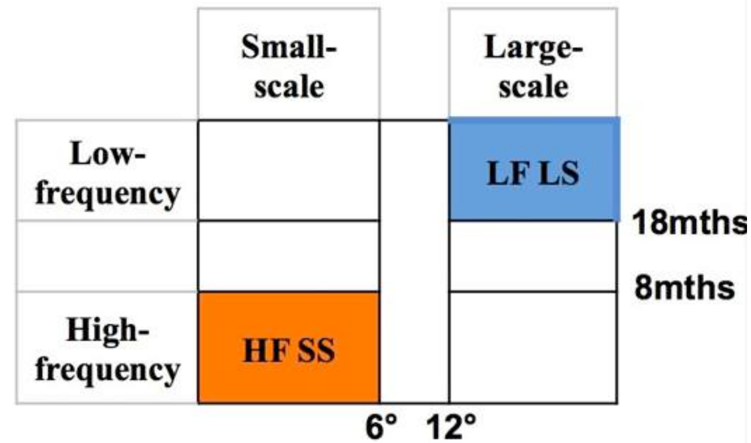
(Penduff et al, Ocean Science 2010)

③ Variability: [2° vs 1/4°] models vs AVISO



Filtering the 3 SLA(x,y,t) datasets into « climatic » and « eddy » signals.

Using 1D and 2D Lanczos low-pass filters

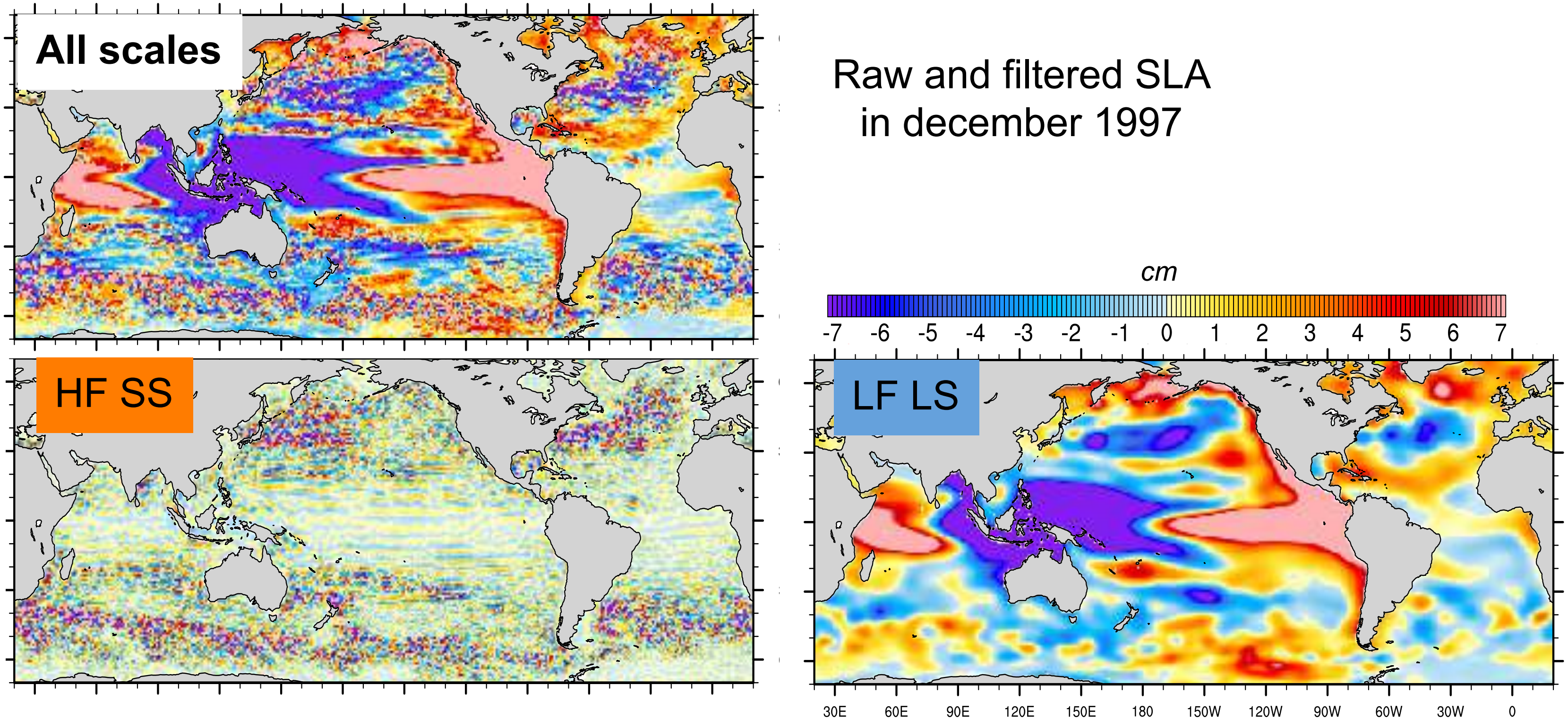


How do ORCA2 and ORCA025 represent the observed « climatic » variability ?

- Distribution
- Strength
- Phase agreement

(Penduff et al, Ocean Science 2010)

③ Typical SLA scales in a turbulent model



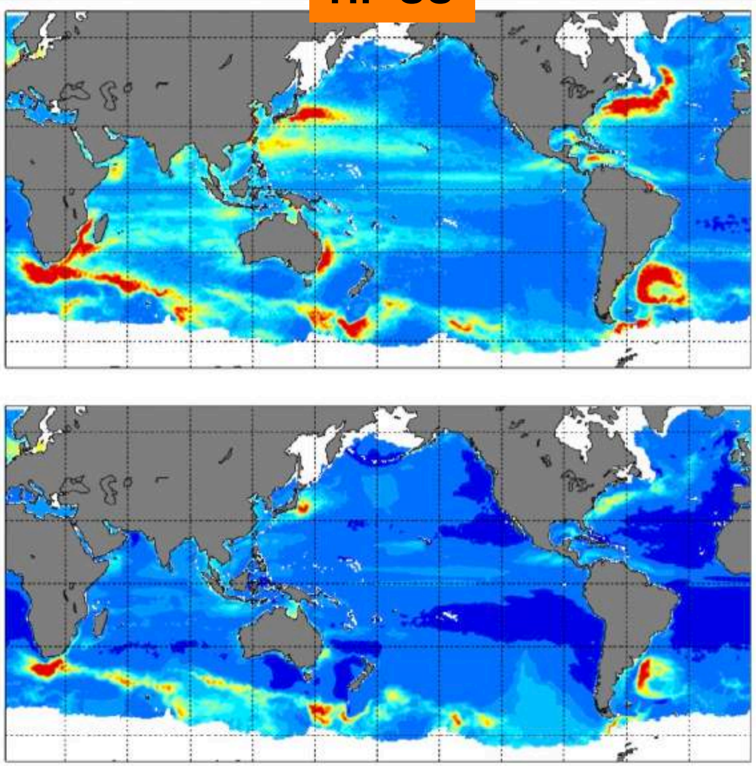
Raw and filtered SLA
in december 1997

	Small-scale		Large-scale
Low-frequency			LF LS
High-frequency	HF SS		

.. Now computing the Standard deviation of SLA(t) from each dataset at each location.

③ Mesoscale variability: models vs AVISO

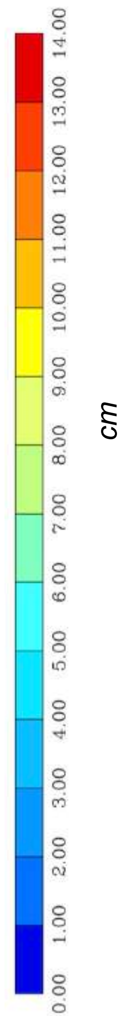
HF SS



AVISO

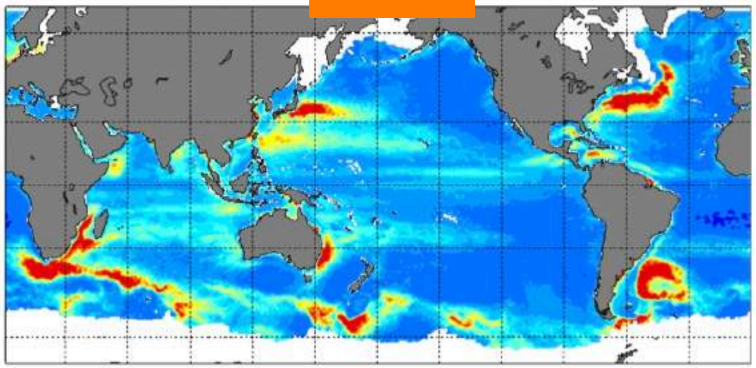
ORCA025

None
In ORCA2

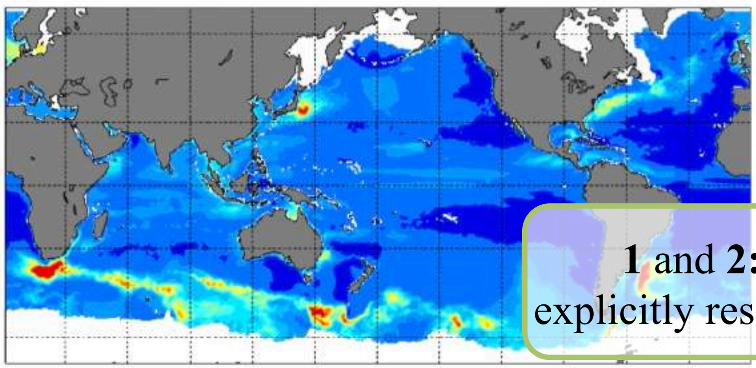


③ Mesoscale variability: scale interactions

HF SS



AVISO

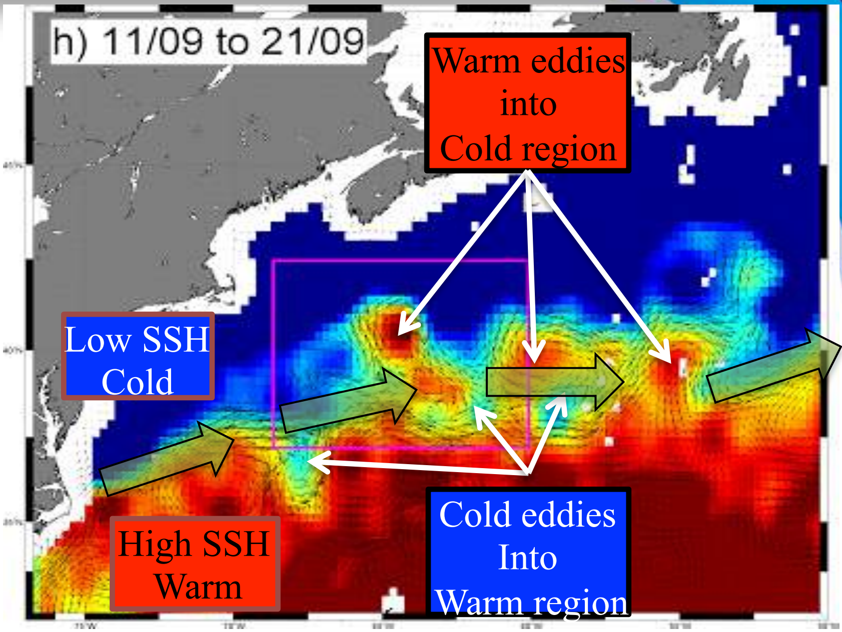


ORCA025

1 and **2:**
explicitly resolved

None
In ORCA2

1: absent
2: parameterized



Scale interactions:

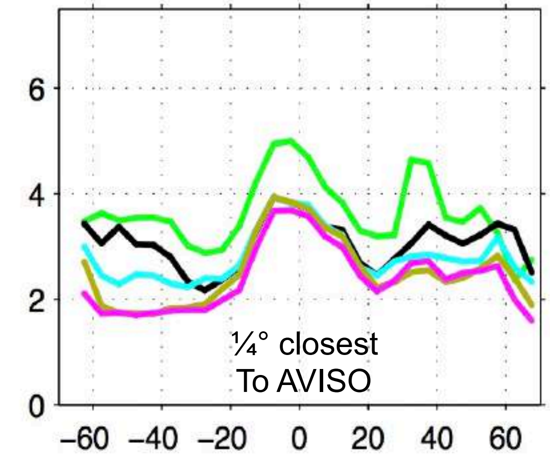
1) LS ➔ SS: Baroclinic instability
Large-scale $\nabla T, \nabla SSH$
→ Geostrophic current → gets unstable
→ Meanders → Mesoscale eddies

2) LS 🡐 SS: Turbulent heat flux
Warm eddies into cold waters
Cold eddies into warm waters
Large-scale $\nabla T, \nabla SSH$ and current: reduced

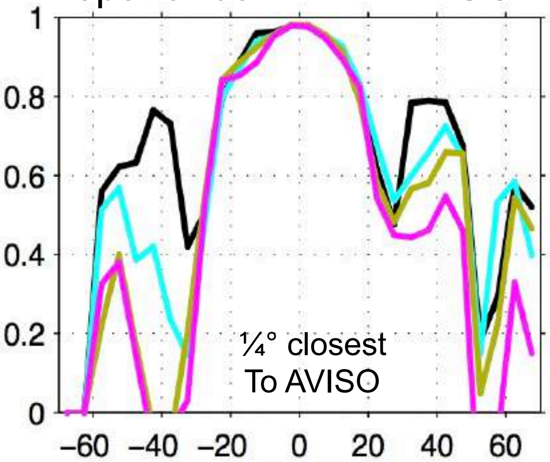
 (Penduff et al, Ocean Science 2010)

③ « Climatic » variability: models vs AVISO

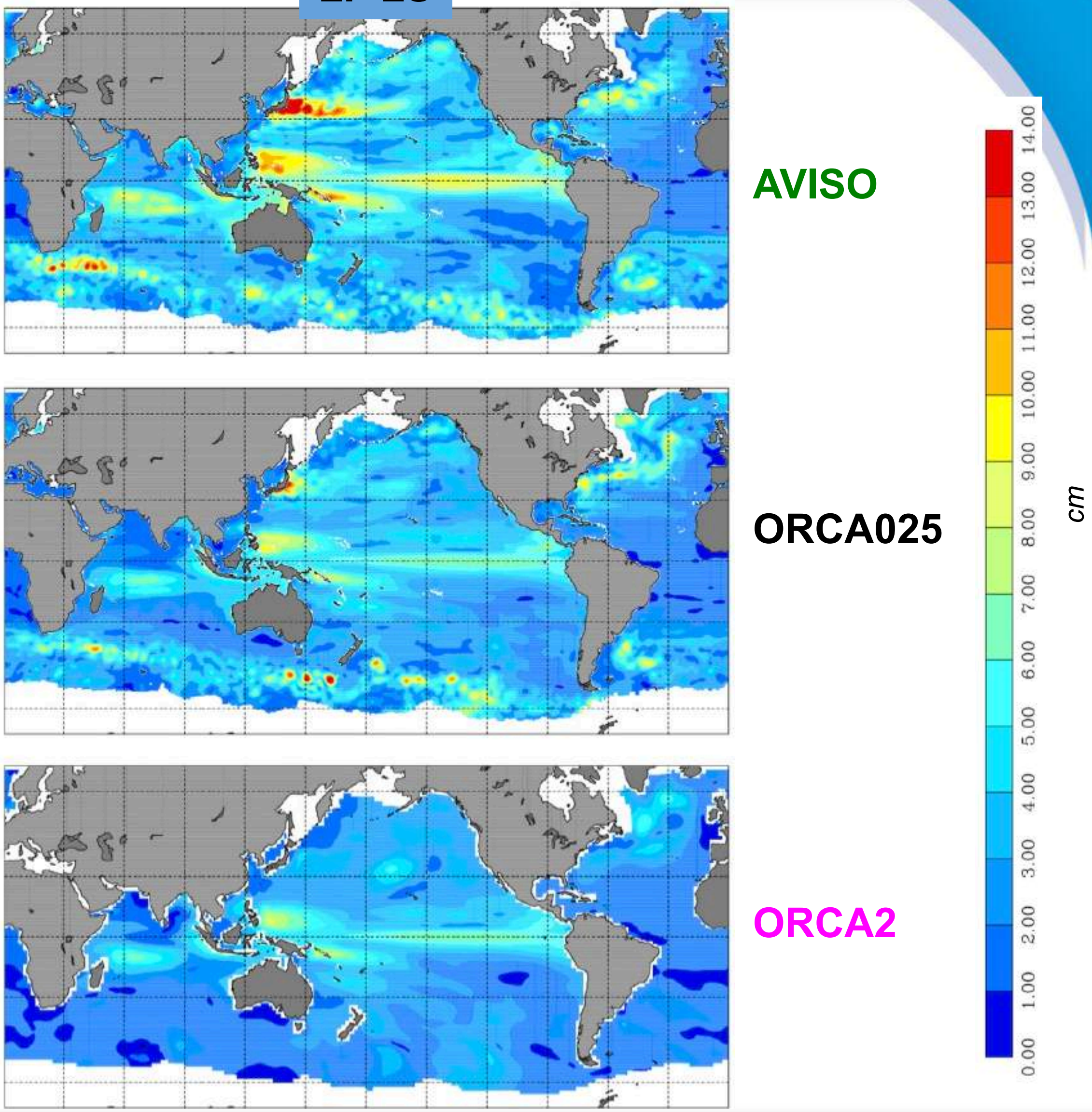
Strength: std(SLA)



Distribution:
spatial corr. with AVISO



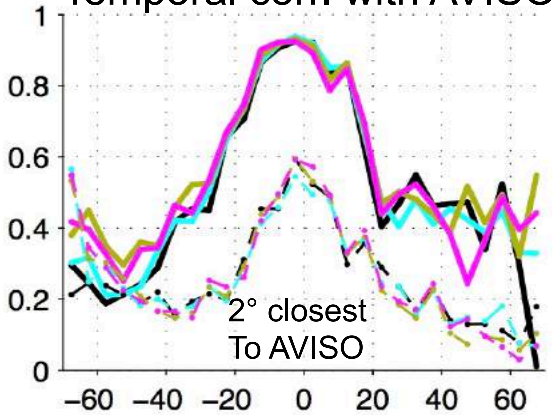
LF LS

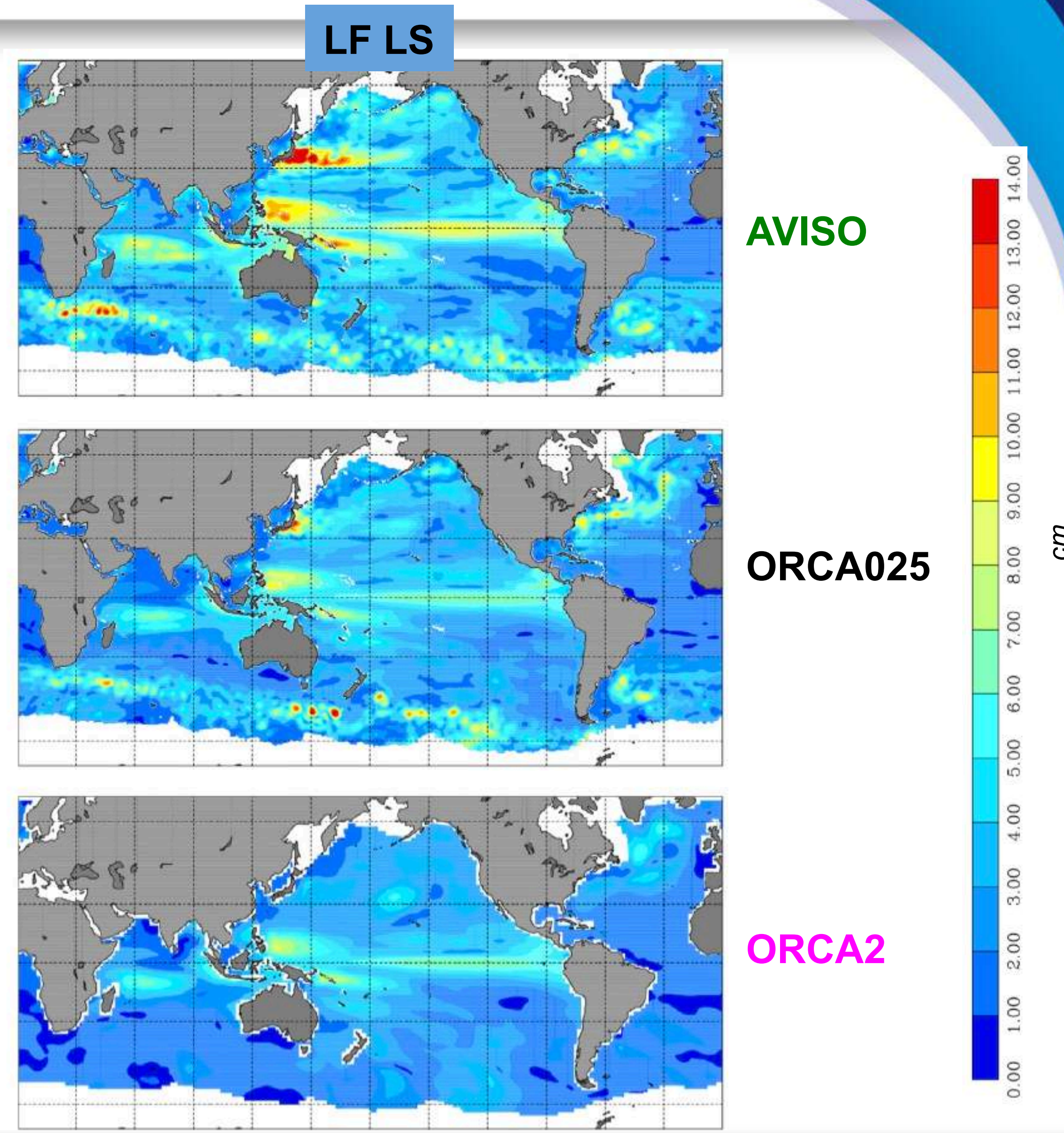


(Penduff et al, Ocean Science 2010)

③ « Climatic » variability: models vs AVISO

Phase agreement
Temporal corr. with AVISO





Despite largely improved dynamics and solution when mesoscale eddies are present, the « climatic » SLA variability is better correlated with AVISO at 2° resolution.

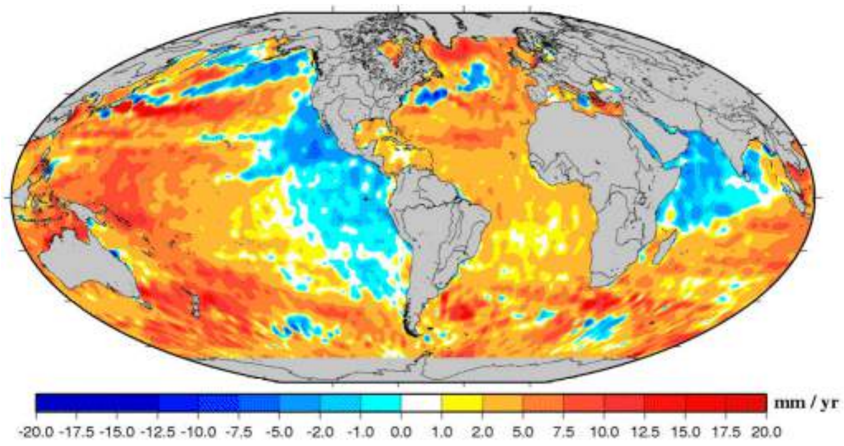
Is LFLS variability more « noisy » in ORCA025

(Penduff et al, Ocean Science 2010)

③ (Regional) SLA trends: models vs AVISO

Trend $T_{SLA}(x,y)$ is observed by altimetry.

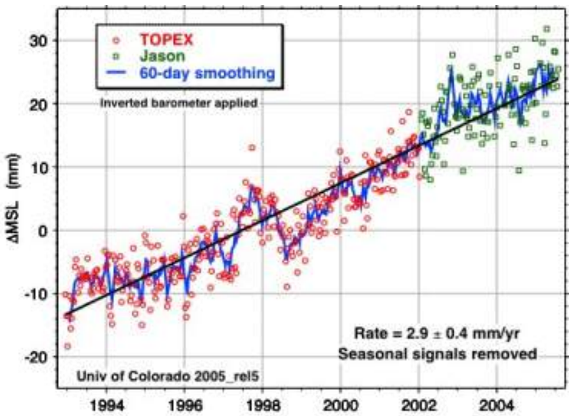
$$T_{SLA}(x,y) = \frac{\overline{SLA(x,y)}^{2001} - \overline{SLA(x,y)}^{1993}}{2001 - 1993}$$



Globally-averaged SLA trend (AVISO)

$$\overline{\overline{T}}^{x,y}$$

(~3mm/yr)



How well do numerical models ?

Greatbatch, 1994: ocean models conserve mass instead of volume (Boussinesq approximation)

➔ Globally-averaged SLA trends $\overline{\overline{T}}^{x,y}$ are inexact in models

➔ $\overline{\overline{T}}^{x,y}$ must be computed and removed from AVISO and simulations

➔ AVISO and models are compared in terms of **Regional SLA trends :**

$$T'_{SLA}(x,y) = T_{SLA}(x,y) - \overline{\overline{T}}^{x,y}$$

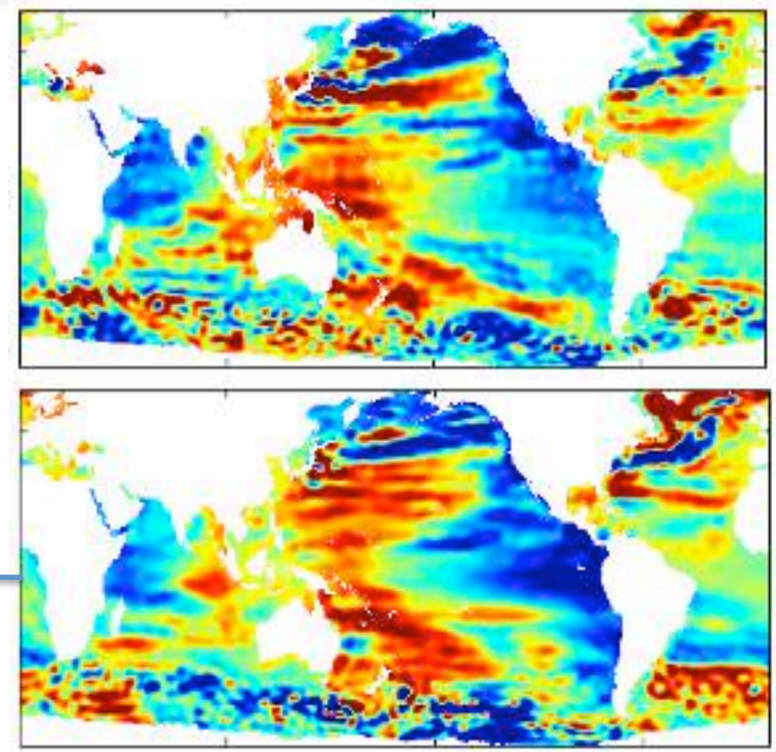
See Lombard et al, Ocean Dynamics (2009)

③ (Regional) SLA trends: models vs AVISO

$$T'_{SLA}(x,y) = T_{SLA}(x,y) - \overline{\overline{T}}^{x,y}$$

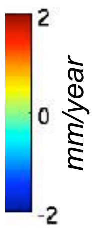
Large-scale patterns:

AVISO ~ ORCA025



AVISO

ORCA025



3D Model Fields : most of the regional SLA trend comes from

① Temperature changes 0-750m (most regions)

② Deep salinity changes (some regions)

See Lombard et al, Ocean Dynamics (2009)

③ (Regional) SLA trends: models vs AVISO

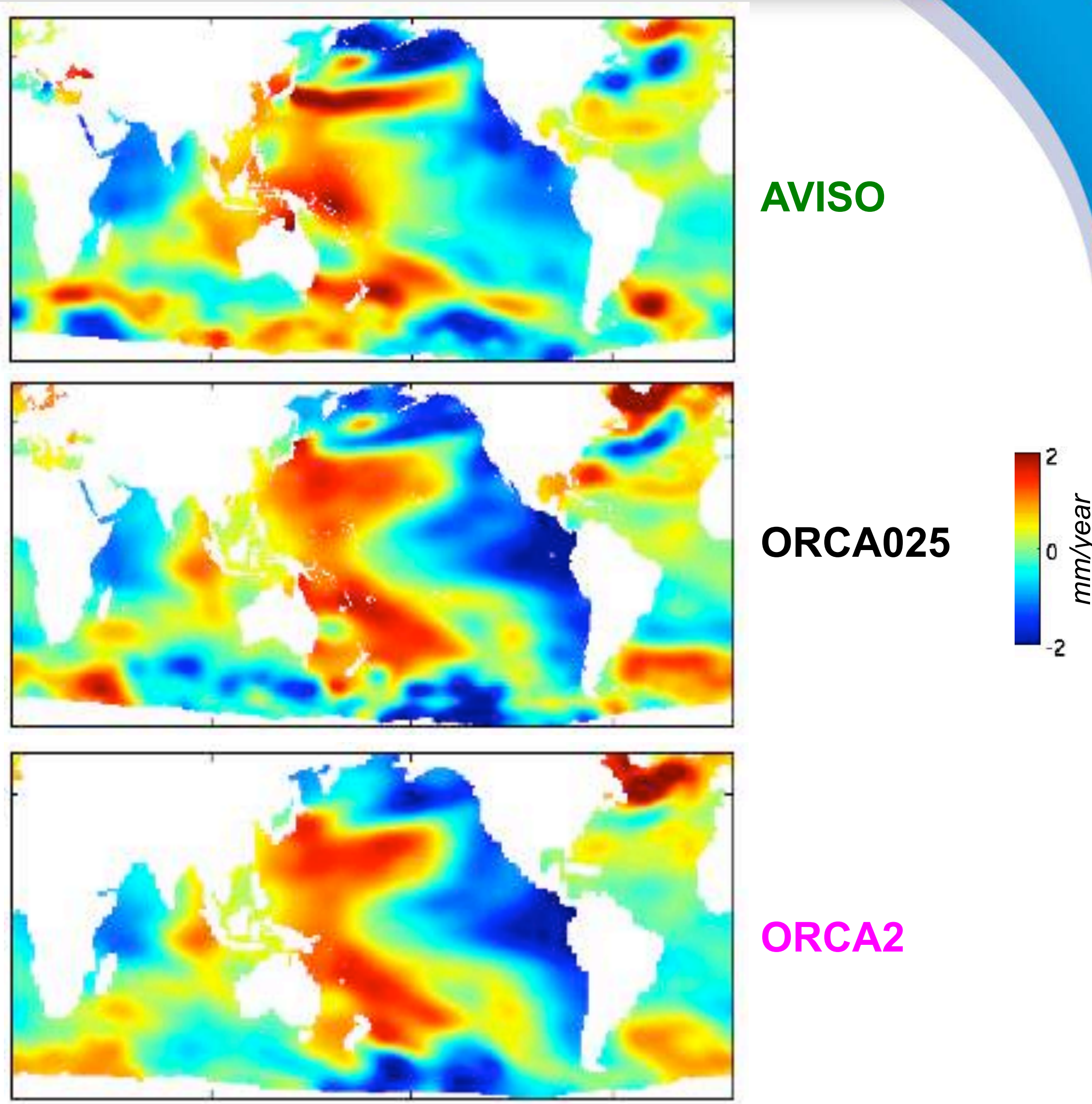
$$T'_{SLA}(x,y) = T_{SLA}(x,y) - \overline{\overline{T}}^{x,y}$$

Large scales only

AVISO ~ ORCA025 ~ ORCA2

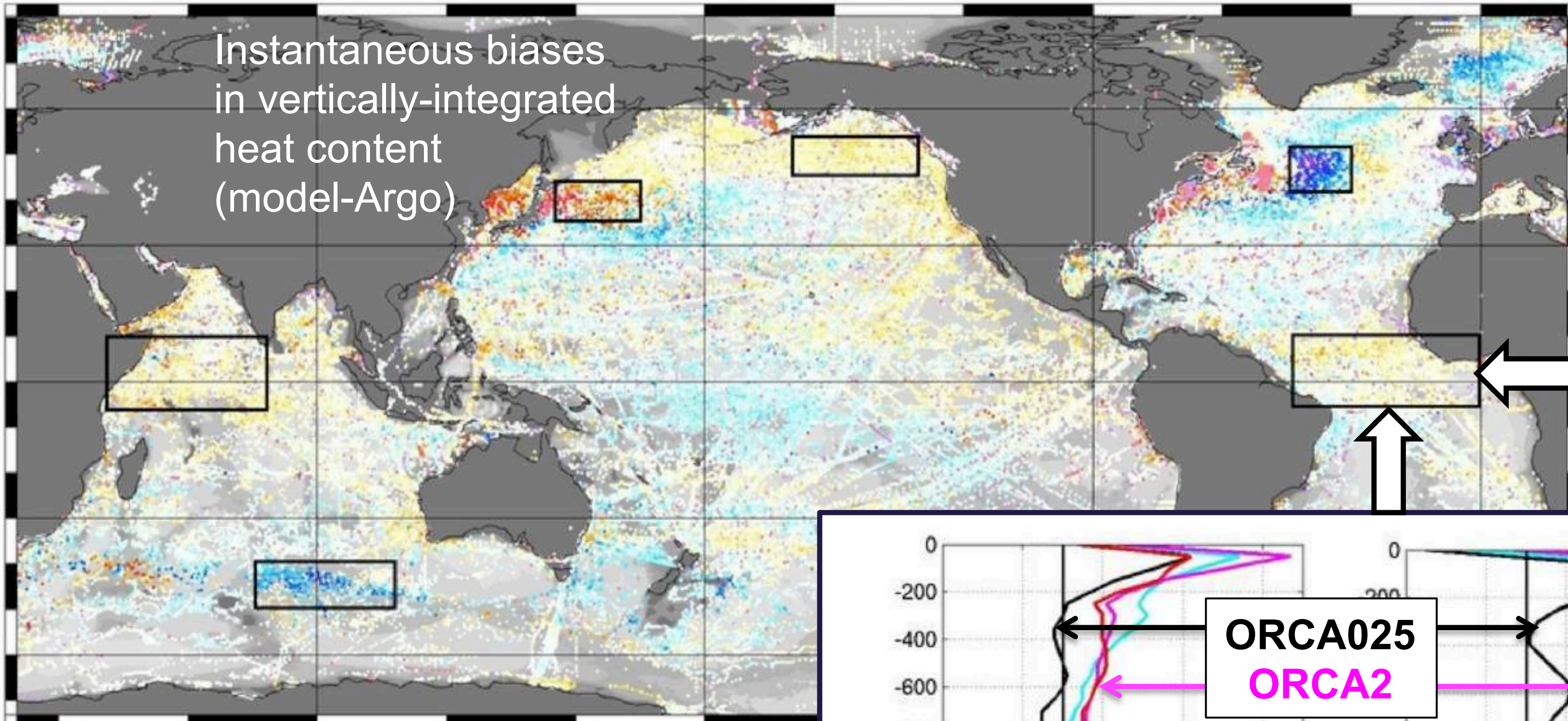
Increased resolution does not improve the large-scale patterns of SLA trends

- ➔ Consistent with their mainly steric (thermodynamic) origin
- ➔ Mostly controlled by surface heat / freshwater fluxes
- ➔ Eddies do not impact large scale trend

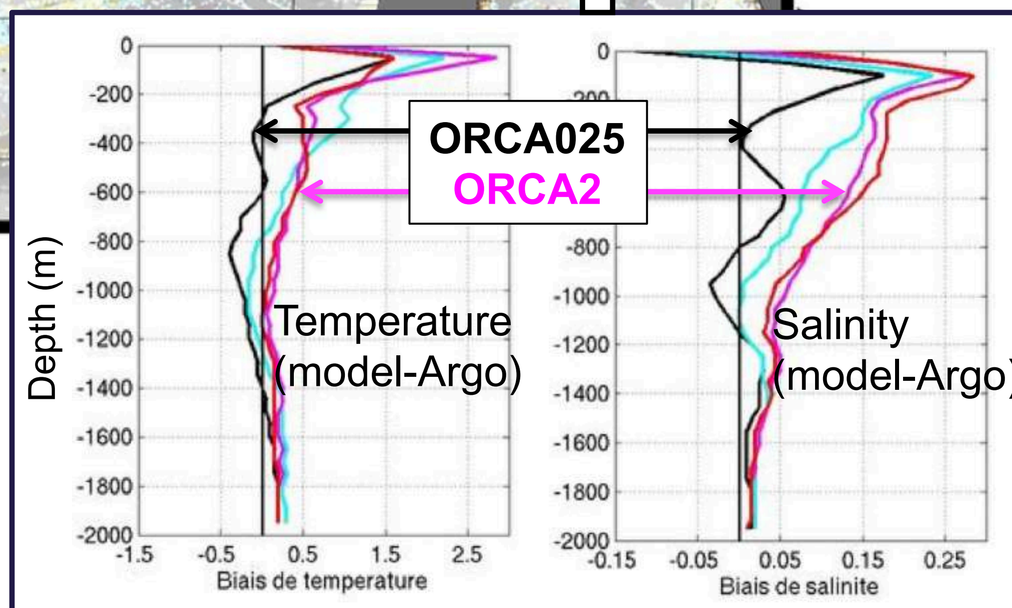


See Juza, (2011)

③ Below the surface: models vs Argo T/S(z)



Warm fresh
Bias ➔
SLAs too high



¼° and 2° simulations were collocated on Argo T/S(x,y,z,t) profiles. Equatorial T/S biases below 400m are largely reduced at ¼°, but surface biases remain. **Interpreting SLA dynamics (& biases) requires subsurface information**

(Juza, 2011)

Outline

① Altimetry — Sea-level — Surface circulation

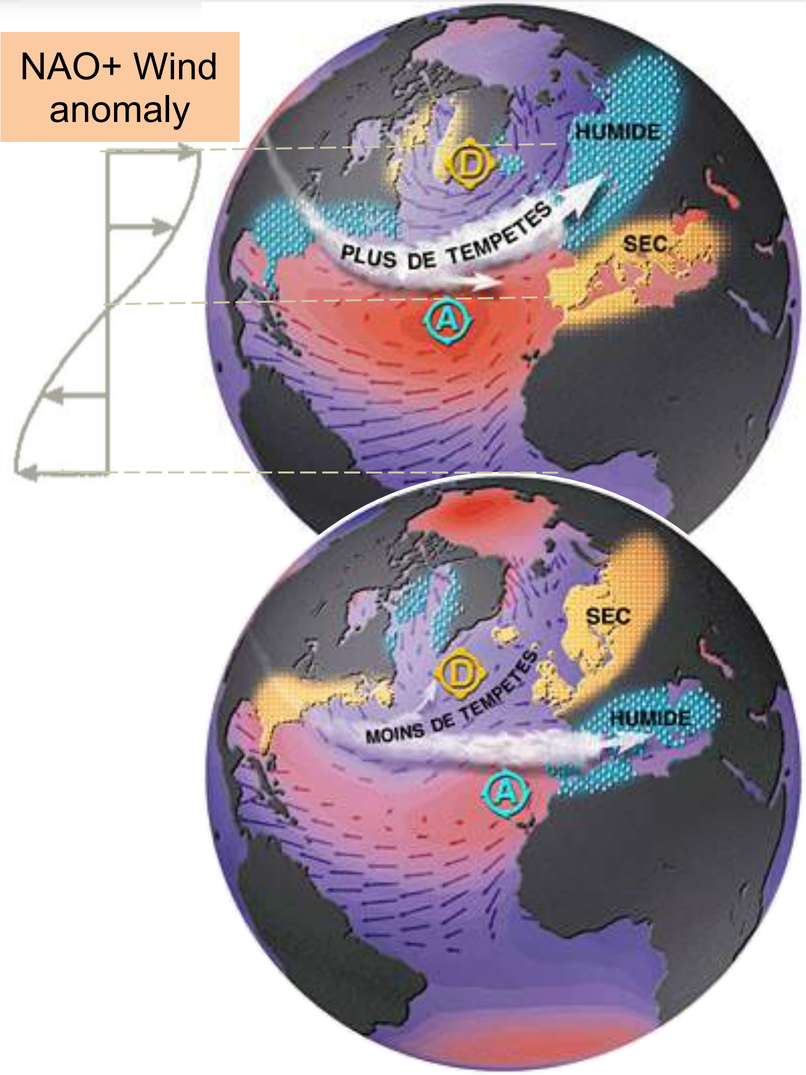
② Models — Resolution and processes

③ Variability — [2° vs 1/4°] models vs AVISO

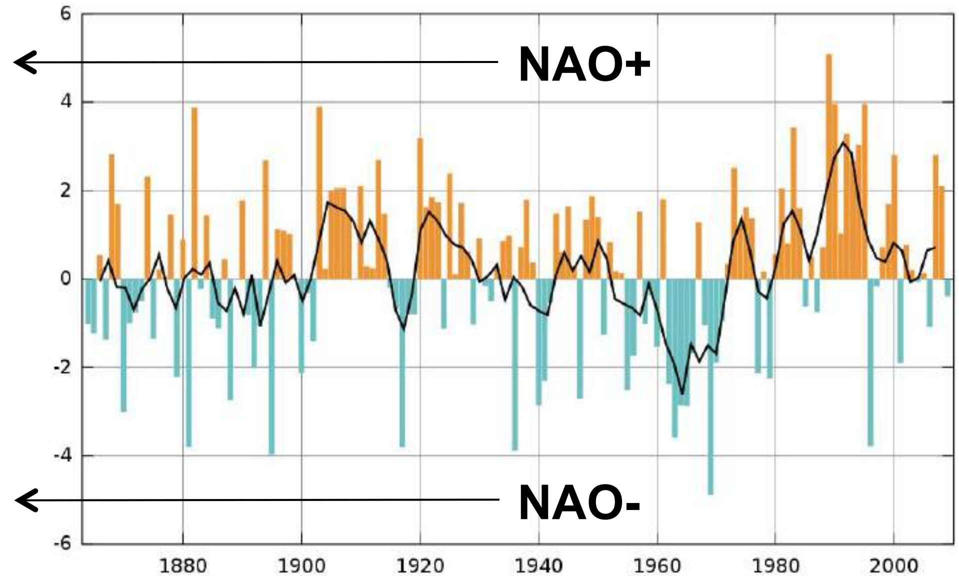
④ North Atlantic scale interactions — Intrinsic variability

⑤ Conclusion — Perspectives

④ North Atlantic Oscillation: atmosphere



NAO index: normalized atm pressure difference (Portugal – Iceland)

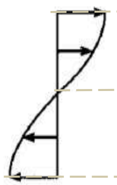


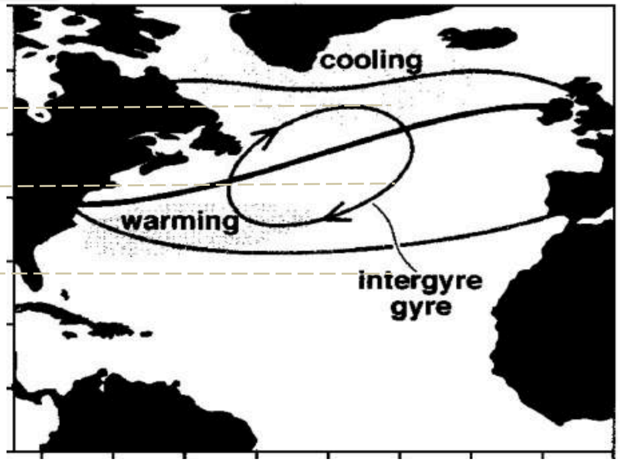
NAO captures a large part of the
Interannual atmospheric variability
over the North Atlantic.
Impact on SLA at LFLS & HFSS scales?

④ North Atlantic Oscillation: LFLS SLA

NAO⁺ : typical ocean circulation anomaly

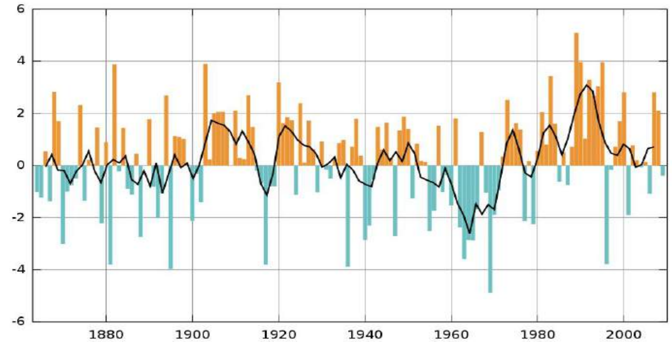
NAO⁺ Wind anomaly





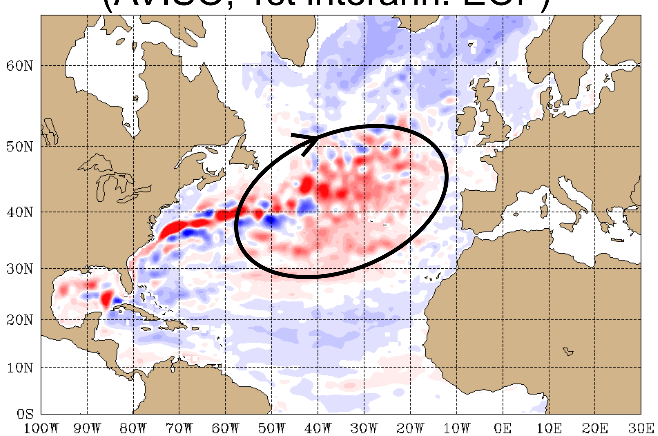
IDEALIZED (Marshall et al, J. Clim 2001)

NAO index

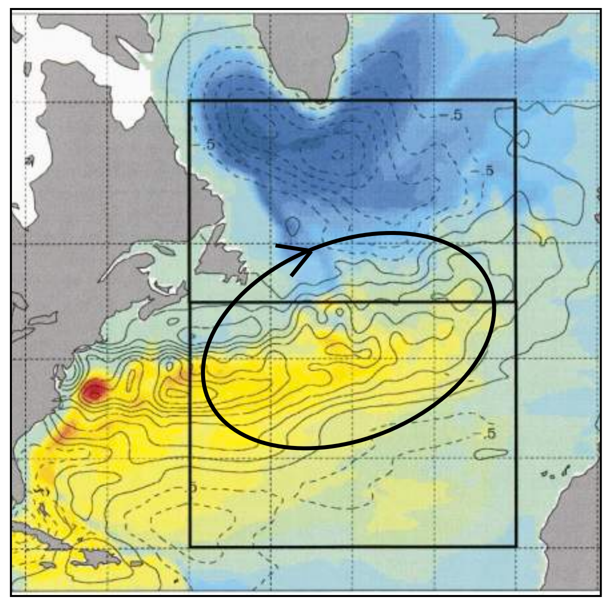


NAO⁺ SLA tripolar anomaly (AVISO, 1st interann. EOF)

AVISO



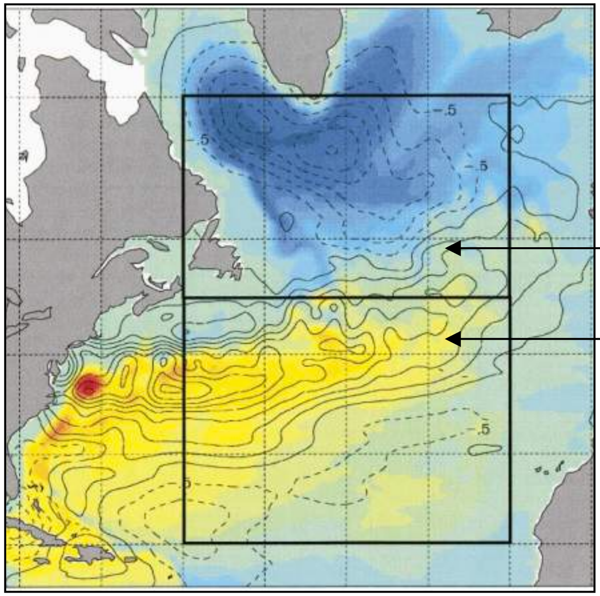
Colors : mean barotropic streamfunction
Contours : NAO⁺-NAO⁻ tripolar anomaly



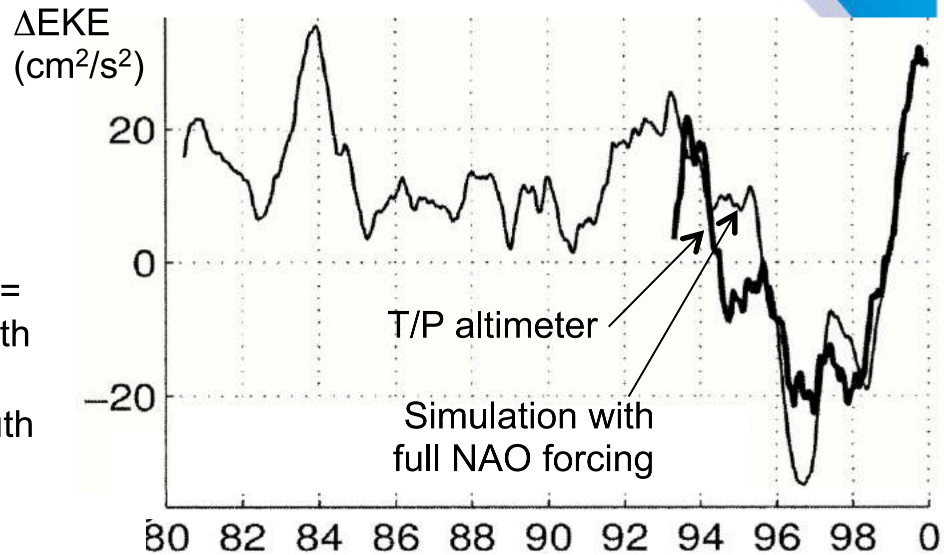
REALISTIC 1/6° CLIPPER MODEL (Penduff et al, JPO 2004)

④ North Atlantic Oscillation: HFSS SLA

1/6° CLIPPER model
Colors : mean barotropic streamfunction
Contours : NAO⁺-NAO⁻ tripolar anomaly



Surface ΔEKE(t)=
Eddy activity North
Minus
Eddy activity South



Suggested processes:

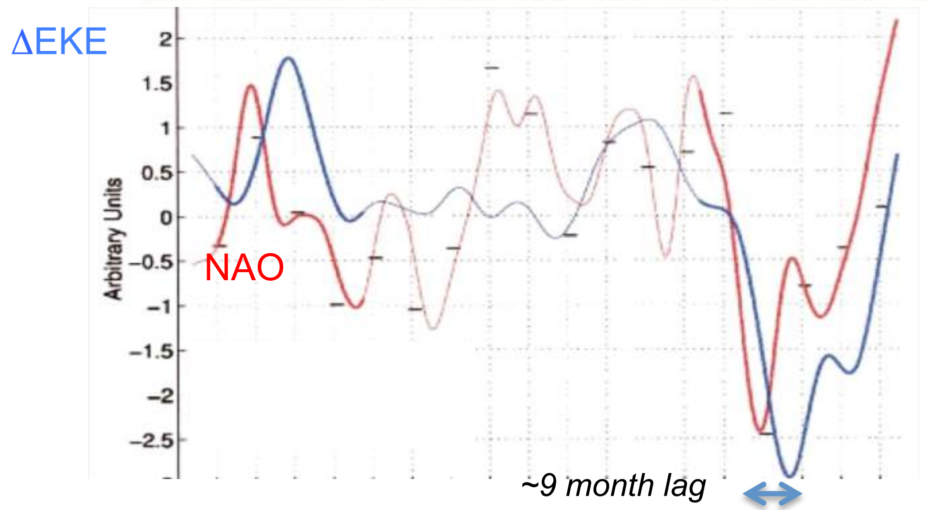
Interannual NAO changes

⇩

Location/Strength of main currents (LFLS)

⇩

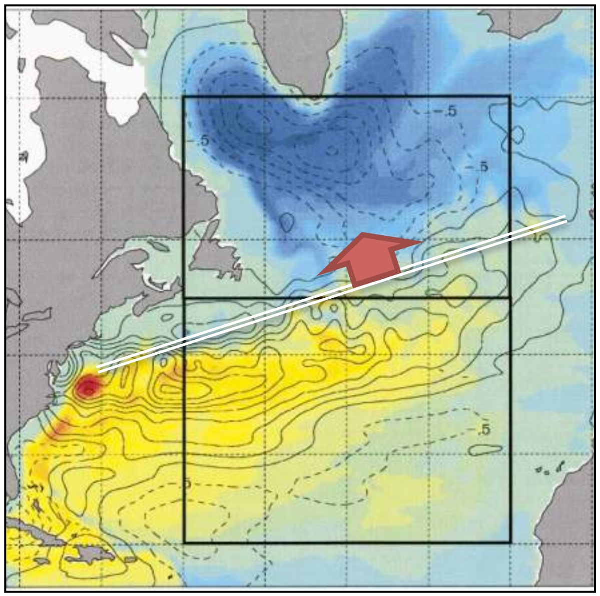
EKE contrast (HFSS)

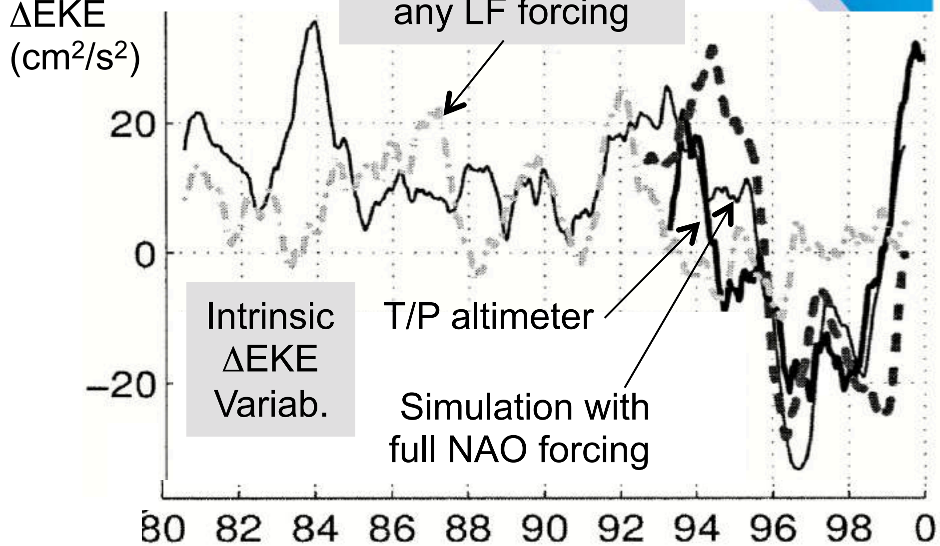


(Penduff et al, JPO 2004)

④ North Atlantic Oscillation: not only cause

1/6° CLIPPER model
Colors : mean barotropic streamfunction
Contours : NAO^+-NAO^- tripolar anomaly





Suggested processes:

Interannual NAO changes

⇩

Location/Strength of main currents (LFLS)

⇩

EKE contrast (HFSS)

High resolution → **LF intrinsic variability**

- ΔEKE (this slide) *Penduff et al 2004*
- Intergyre heat flux *Hall et al 2004*
- SLA at all scales *Sérazin et al (submitted)*
- SST at all scales
- Atlantic overturning (MOC) *Grégorio et al (submitted)*

④ Intrinsic LF variability (eddying models)

atmosphere

low-freq ocean

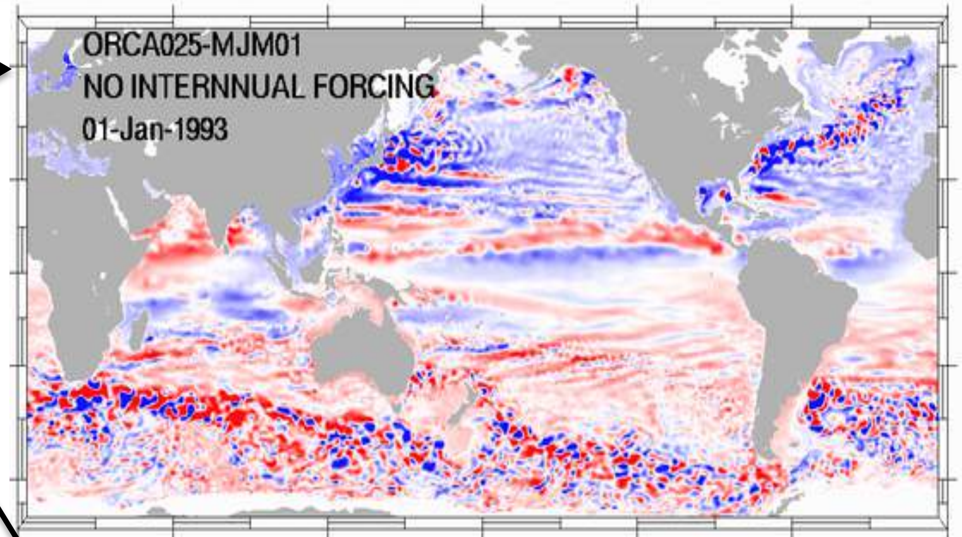
Seasonal cycle

Full forcing (50y)

DRAKKAR ocean sea-ice model 1/4° or 1/12°

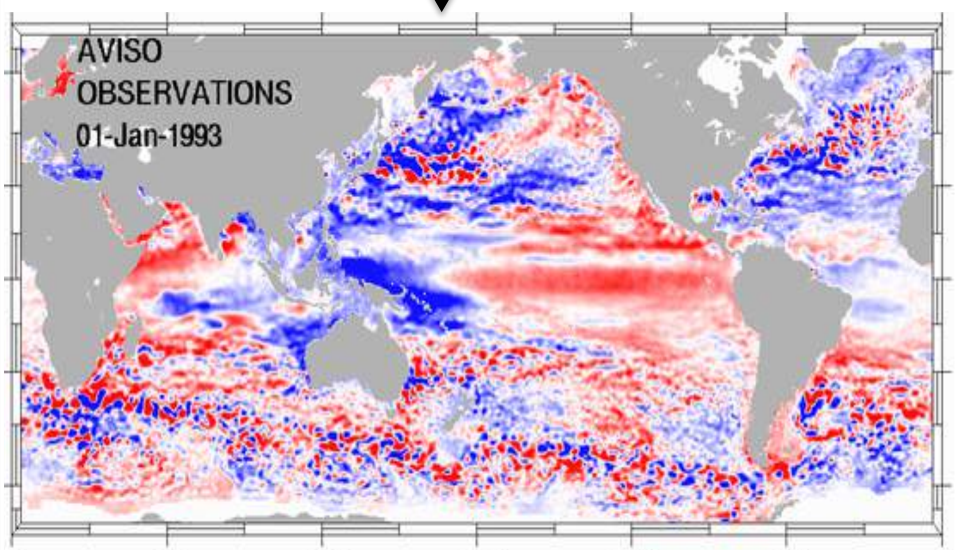
Pure Intrinsic

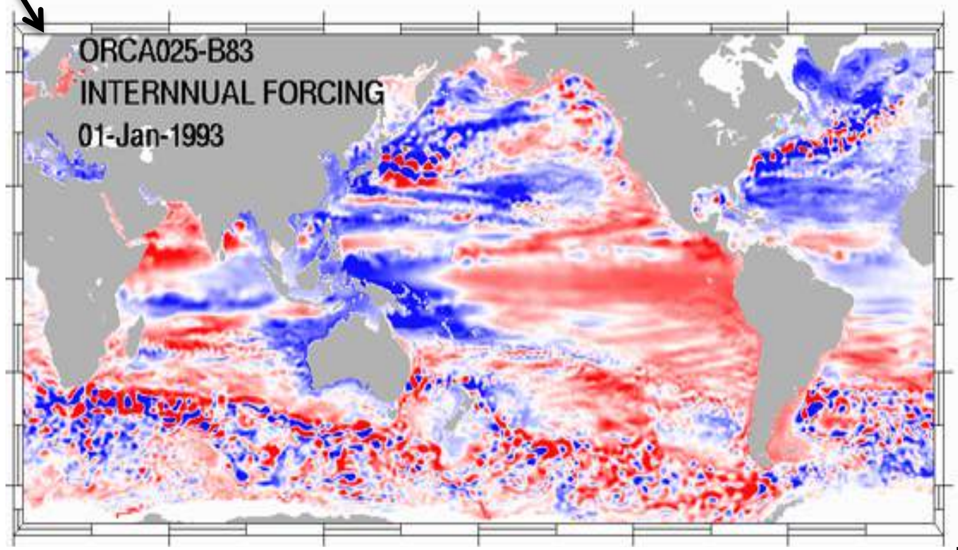
Forced Intrinsic



SLA

AVISO





④ *Intrinsic LF variability (eddying models)*

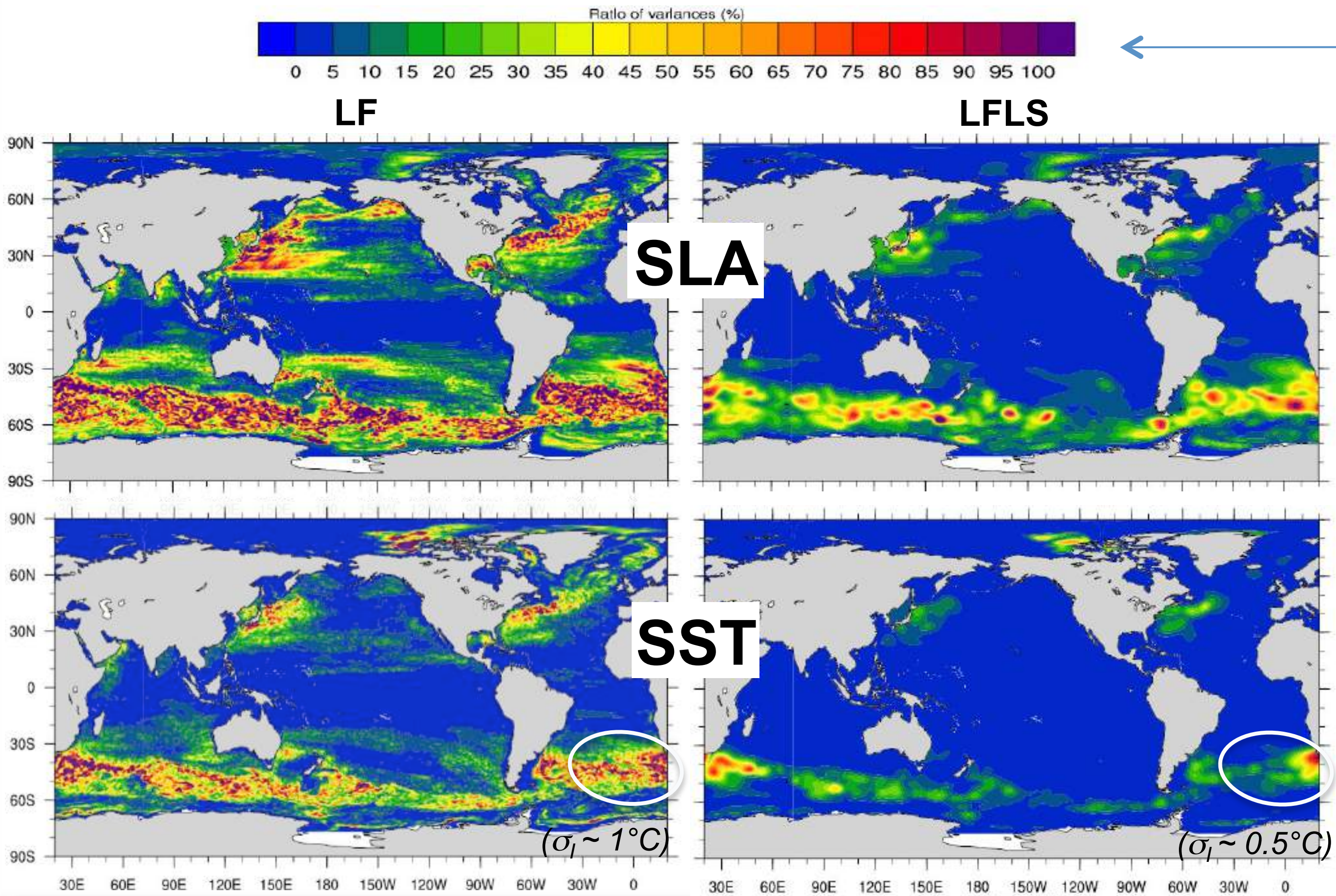
atmosphere | low-freq ocean

Seasonal cycle → DRAKKAR ocean sea-ice model 1/4° or 1/12° → Pure Intrinsic → σ_I^2

Full forcing (50y) → DRAKKAR ocean sea-ice model 1/4° or 1/12° → Forced Intrinsic → σ_T^2

$R = \sigma_I^2 / \sigma_T^2$ — Intrinsic fraction of low-freq variance

R (%)



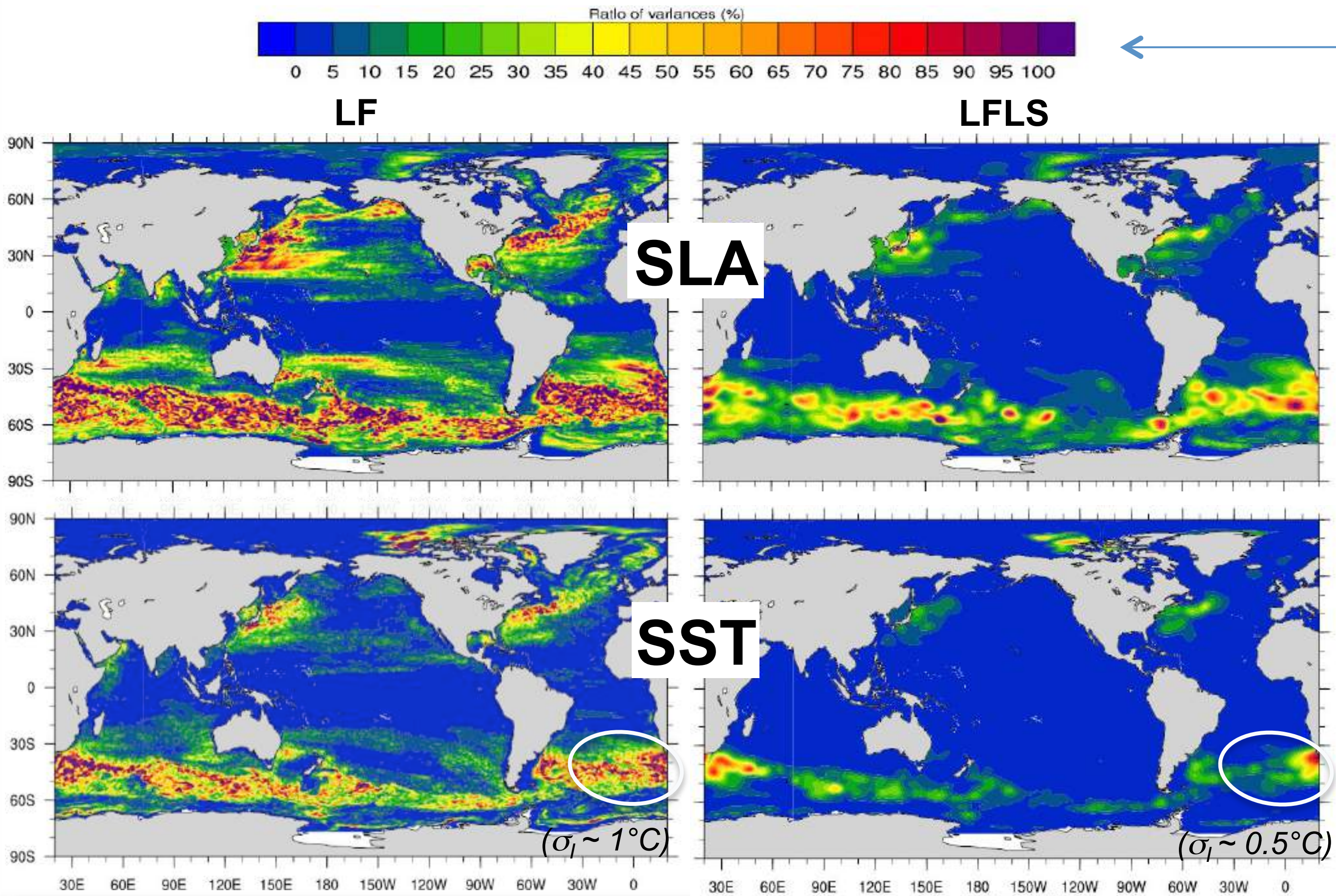
④ Intrinsic LF variability *(eddying models)*

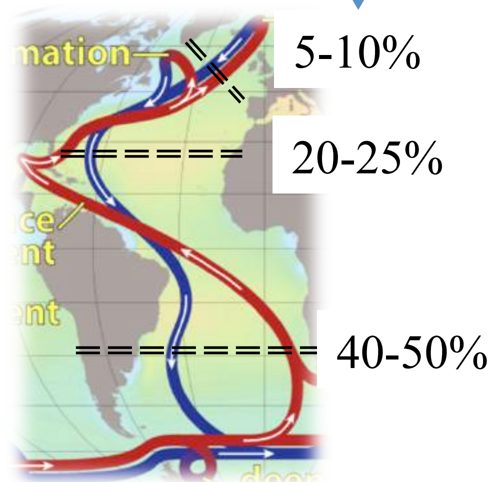
atmosphere — low-freq ocean

- Seasonal cycle → DRAKKAR ocean sea-ice model 1/4° or 1/12° → Pure Intrinsic → σ_I^2
- Full forcing (50y) → DRAKKAR ocean sea-ice model 1/4° or 1/12° → Forced Intrinsic → σ_T^2

$R = \sigma_I^2 / \sigma_T^2$ — Intrinsic fraction of low-freq variance

R (%)





MOC

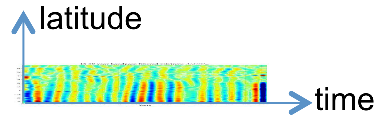
Grégorio et al (submitted, JPO)

④ Intrinsic LF variability (eddying models)

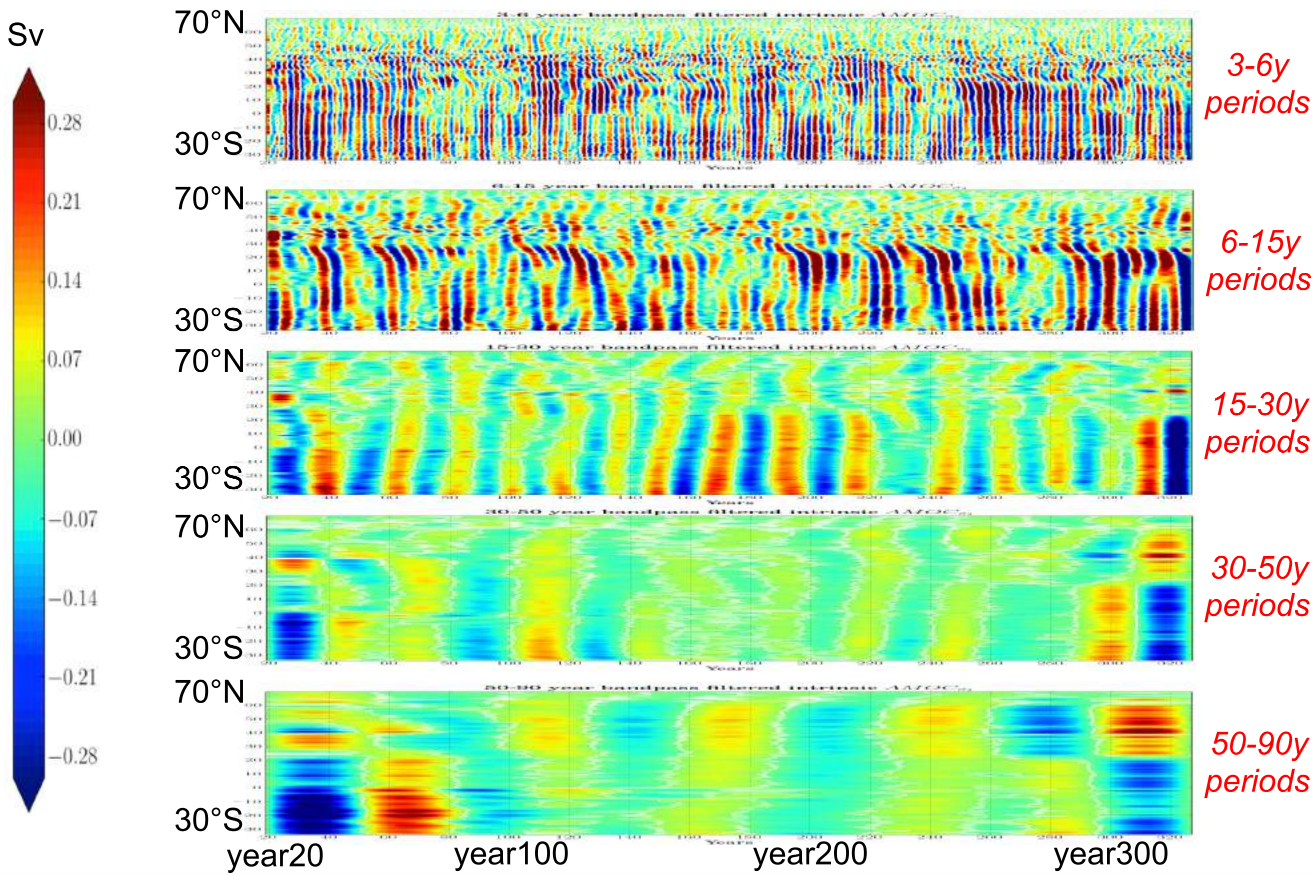
atmosphere — low-freq ocean

Seasonal cycle — DRAKKAR ocean sea-ice model 1/4° or 1/12° — Pure Intrinsic

↓



Intrinsic MOC fluctuations



Intrinsic MOC during 327-year seasonal simulation

Variability timescales: 1→ 80-90 years

Intermittent, chaotic character

Basin-wide patterns

Complex propagation features

…Correlated with certain SLA patterns

Grégorio et al (submitted, JPO)

④ Intrinsic LF variability : chaotic character

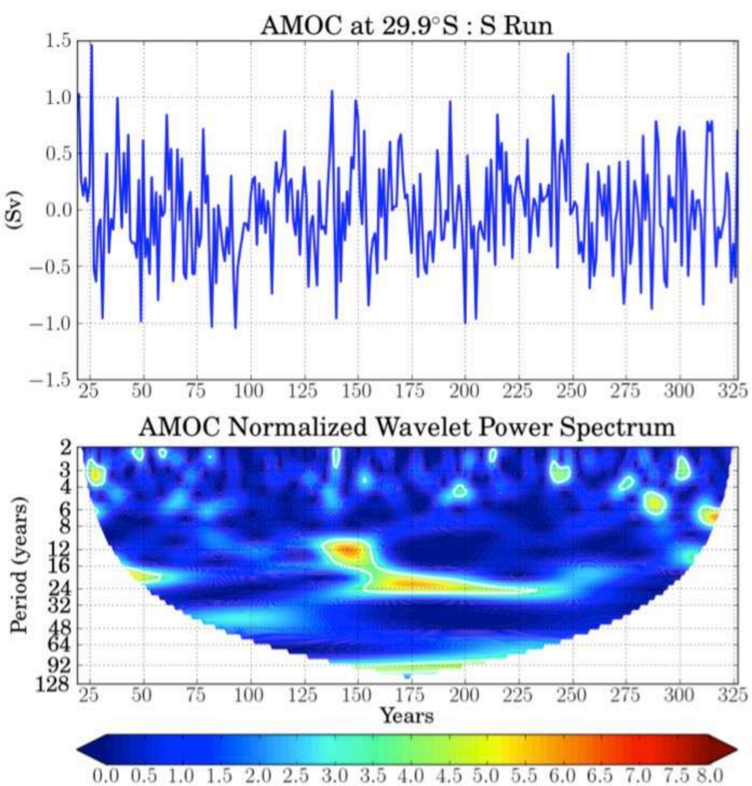
atmosphere | low-freq ocean

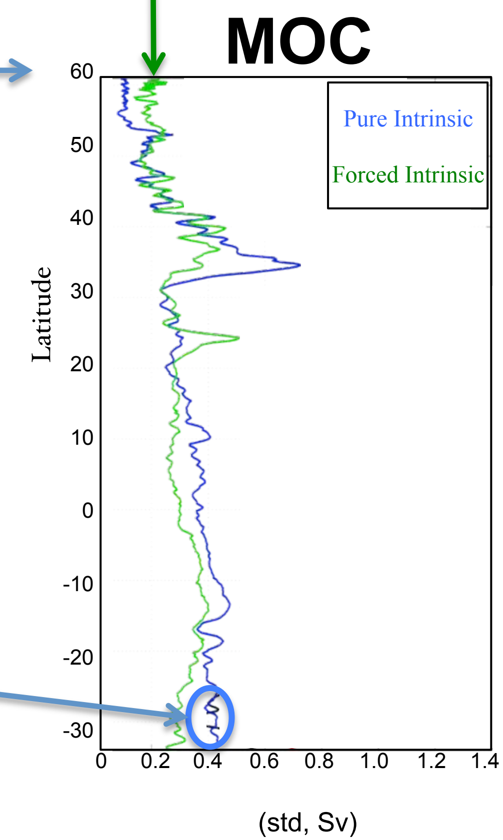
- Seasonal cycle → DRAKKAR ocean sea-ice model 1/4° or 1/12° → Pure Intrinsic
- Full forcing (50y) → DRAKKAR ocean sea-ice model 1/4° or 1/12° → Forced Intrinsic

$\sigma_I^* = \sigma(diff)/\sqrt{2}$ *(Hirschi et al 2013)*

Pure intrinsic MOC variability:

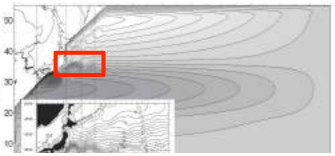
is chaotic, intermittent, broadband

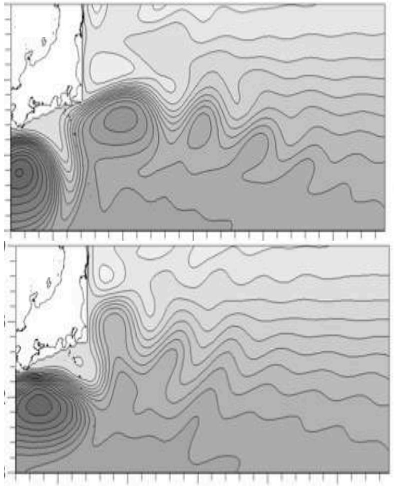




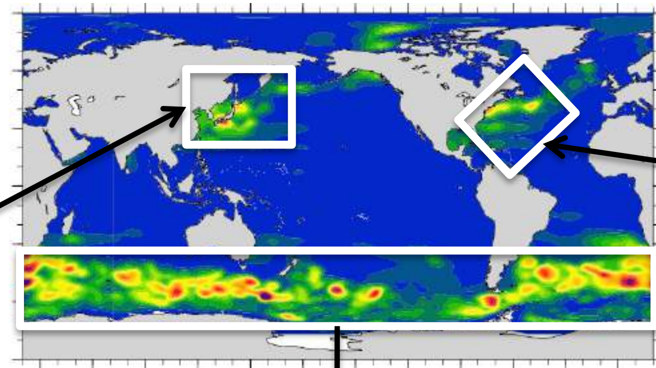
④ Intrinsic LF variability *(idealized models)*

North Pacific
Pierini JPO 2006

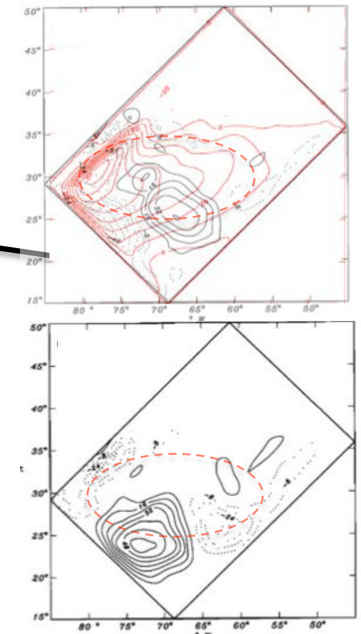




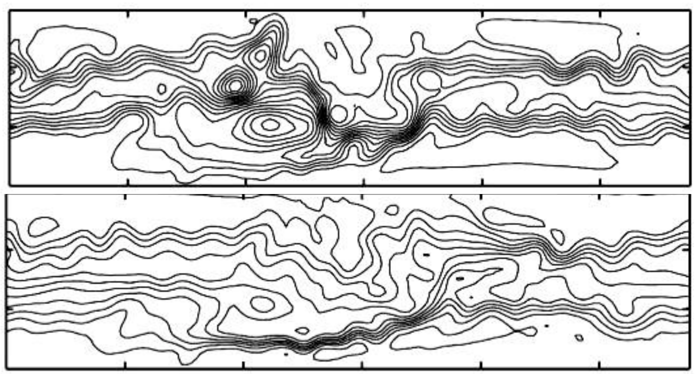
Global realistic model



North Atlantic
Hazeleger & Drijfhout JGR 2000



ACC: *Hogg & Blundell JPO 2006*



« Relaxation oscillation »

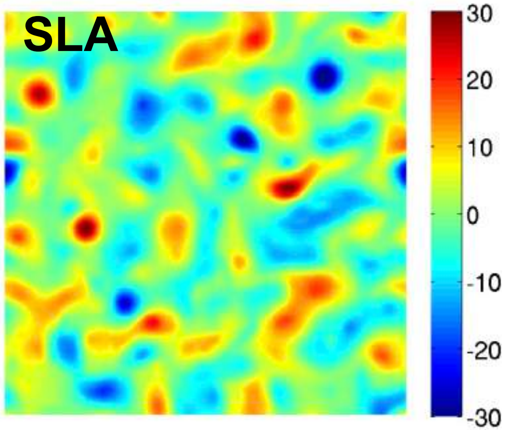
Crucial role of Reynolds number through nonlinear Scale interactions

$$-\underline{u}.\nabla u$$
$$-\underline{u}.\nabla v$$

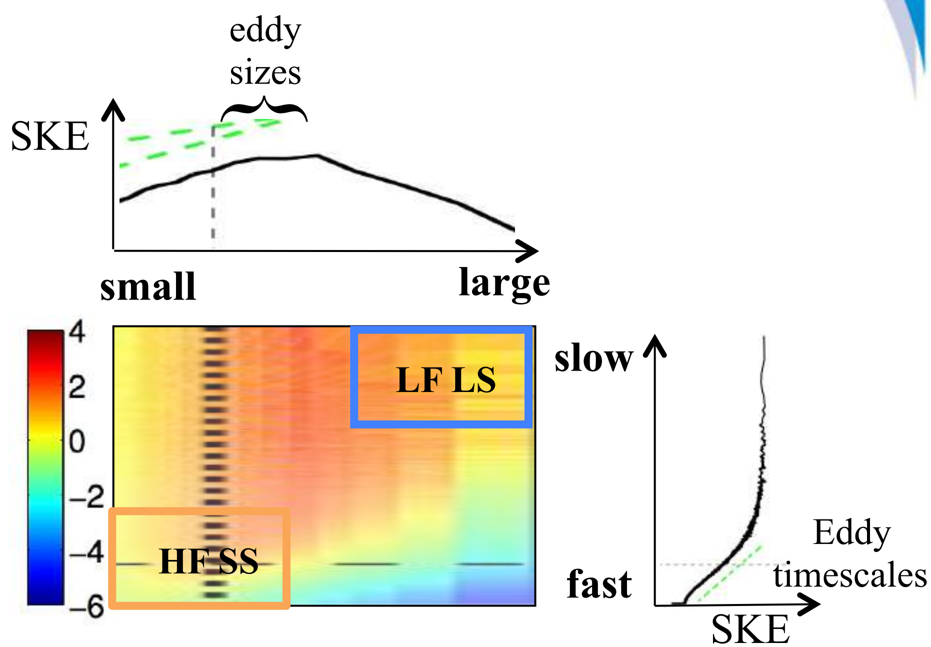
④ *Inverse cascades of KE (space and time)*

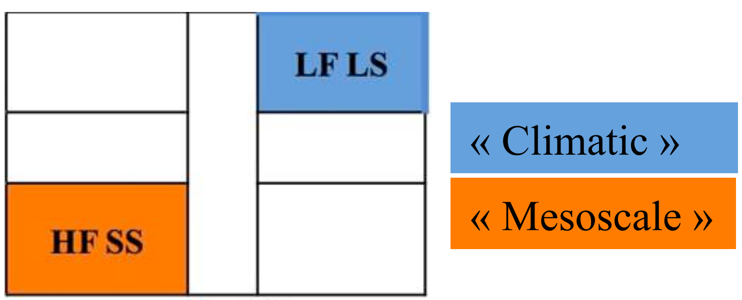
Idealized 2-layer QG simulation with **constant forcing** spontaneously generates **chaotic variability** at both **Mesoscale and « climatic » scales**

(Arbic et al, JPO 2014)



Surface Kinetic Energy Spectrum (size,freq.)



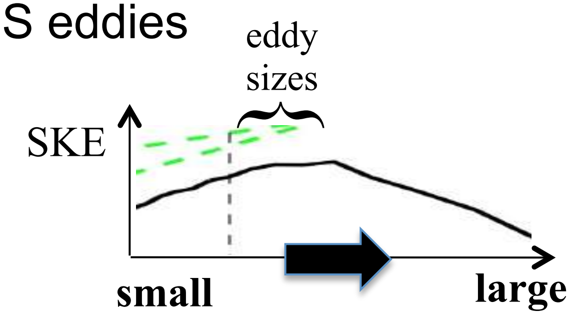


④ Inverse cascades of KE *(space and time)*

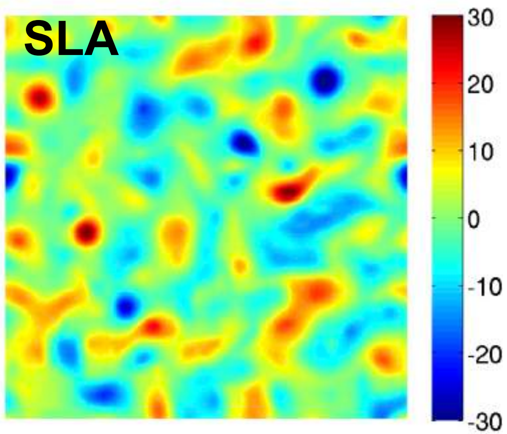
Non-linear SKE exchanges across time and space scales reveal that:
(1) Baroclinic instability: large-scale ➔ HFSS eddies
(2) Eddy SKE ➡ larger & slower scales

$$T_{KE,1}(k,l,\omega) = Re\Big[\frac{\delta}{1+\delta}\widehat{\psi_1}^*(k,l,\omega)\widehat{J(\psi_1,\nabla^2\psi_1)}(k,l,\omega)\Big]$$

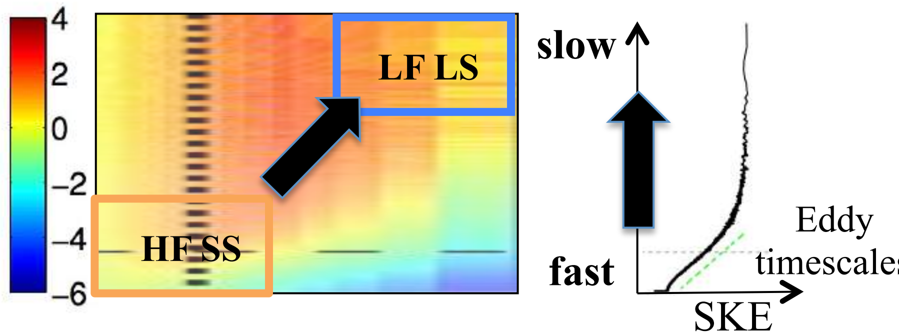
(Arbic et al, JPO 2014)



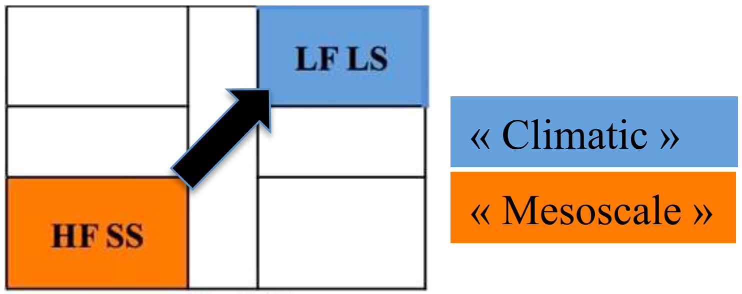
Intrinsic production of chaotic « climatic » ocean variability by mesoscale eddies?



Surface Kinetic Energy Spectral fluxes (size,freq.)



Confirmed by theory, QG, 1/12° HYCOM,NEMO
AVISO is too smooth for clear signal → SWOT
Presently evaluating the longest timescales concerned by this effect



Outline

① Altimetry — Sea-level — Surface circulation

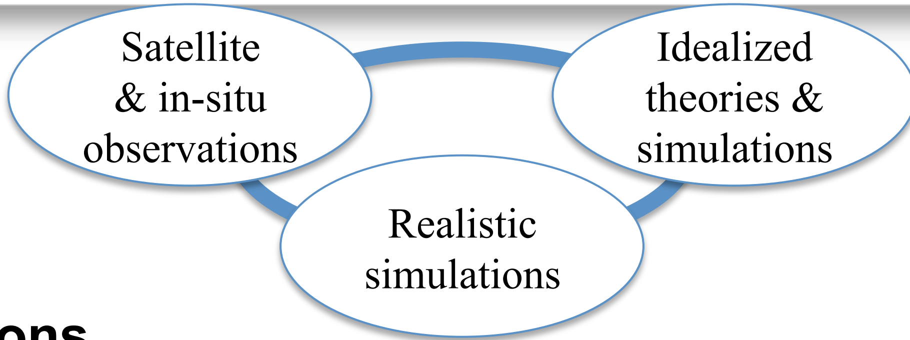
② Models — Resolution and processes

③ Variability — [2° vs 1/4°] models vs AVISO

④ North Atlantic scale interactions — Intrinsic variability

⑤ Conclusion — Perspectives

Conclusion



Realistic simulations

- Are evaluated & improved using altimetry
- Tend toward altimetry as resolution increases (…but temporal decorrelation)
- Are virtual oceans → sensitivity experiments → understanding observations
  → testing theories

Physics

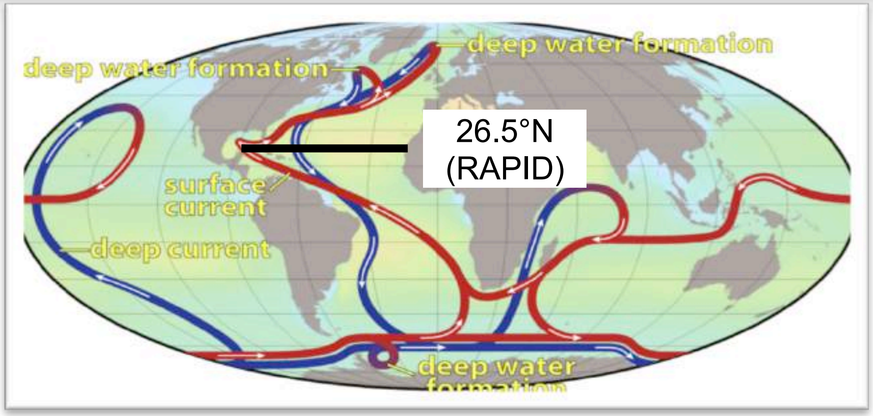
- Scale interactions: instabilities, turbulent fluxes, LF intrinsic variability

  Locally up to 100% 100% 50%

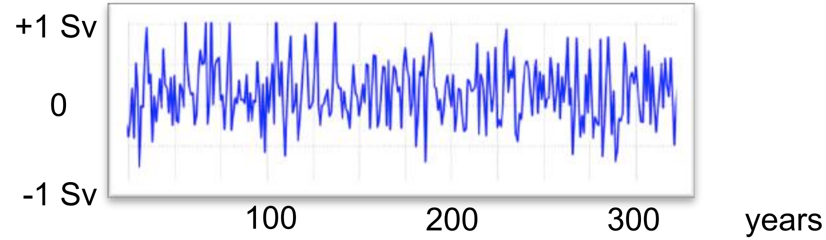
- **Mesoscale**: LF oceanic variability is Forced * **Intrinsic** (SLA, SST, MOC, …)

  No mesoscale: Forced **~ ø**
- Strong LFLS intrinsic variability in eddying regions

Perspectives



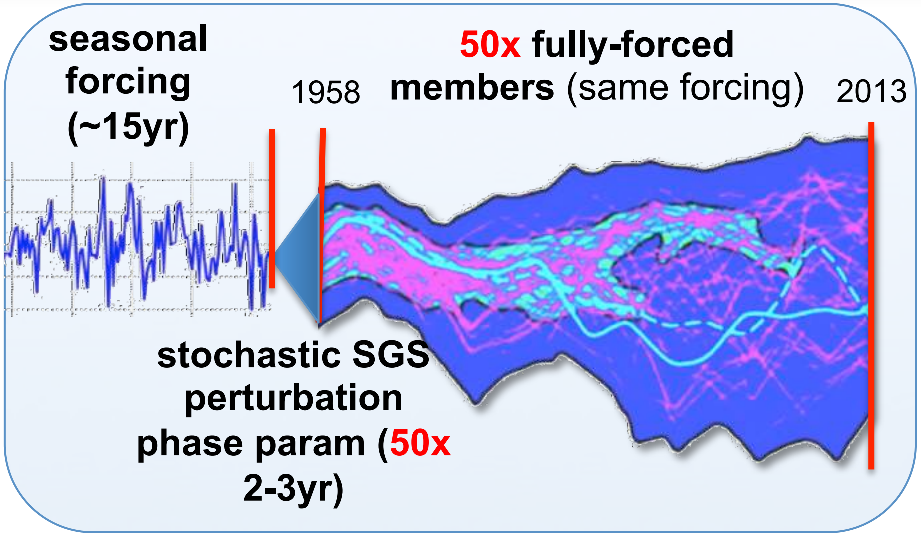
low-freq intrinsic MOC variability at 26.5°N
is intermittent and chaotic (R ~25%)

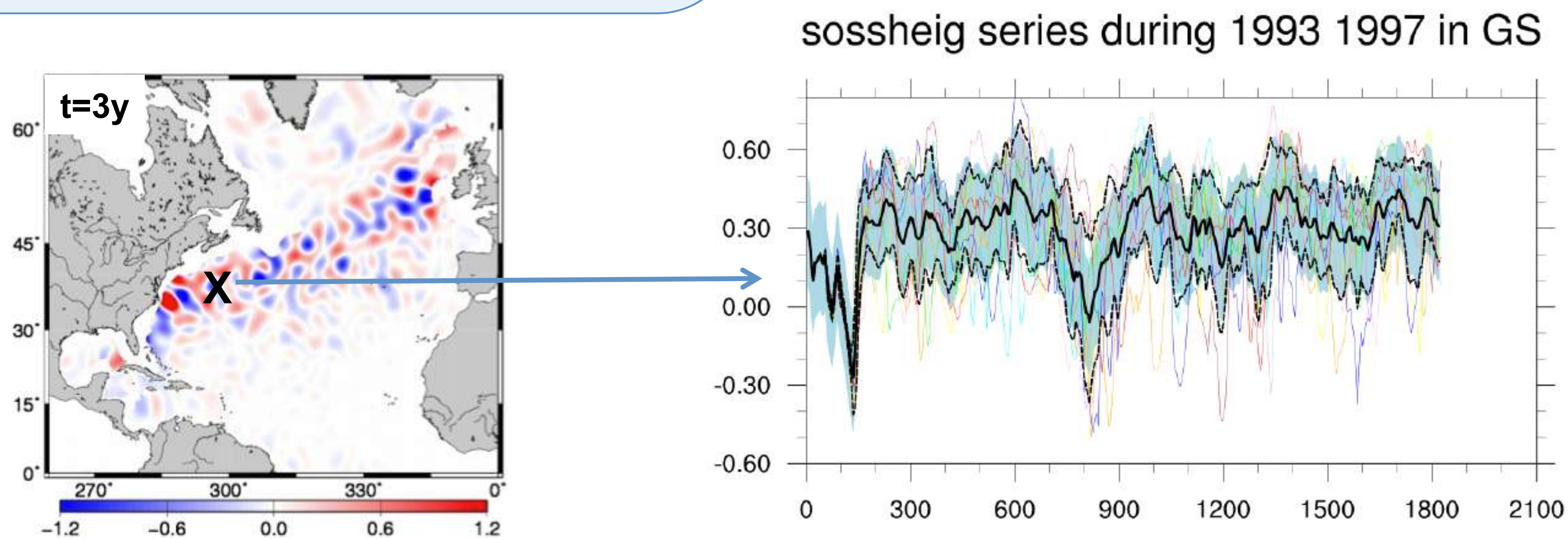


1. **Chaotic character of the « climatic » ocean variability**
   - Processes ? 3D observational imprints ?
   - Coupled models: Impact on atmosphere, climate ? biogeochemistry ?
2. **Anticipating future satellite observations (SWOT2020, ocean color, etc)**
   - Kilometric processes at work in 3D ? observable from space ?
   - Interactions with « Climatic » time/space scales ?

Study OGCM runs **with dynamicists & observationalists** ➔ *CHAOCEAN project*
Probabilistic studies with **ensemble simulations** ➔ *OCCIPUT project*
Towards **kilometric realistic** simulations ➔ *DRAKKAR consortium*

OCCIPUT: probabilistic ocean modelling





References

- Rio, M. H., S. Guinehut, and G. Larnicol (2011), New CNES-CLS09 global mean dynamic topography computed from the combination of GRACE data, altimetry, and in situ measurements, J. Geophys. Res., 116, C07018, doi:10.1029/2010JC006505
- Fu, L.L and C. Ubelmann: On the transition from profile altimeter to swath altimeter for observing global ocean surface topography, Journal of Atmospheric and Oceanic Technology, 2013
- Djath B., Melet A., Verron J., Molines J.-M., Barnier B., Gourdeau L., and Debreu L. : A 1/36 degrees model of the Solomon Sea embedded into a global ocean model: on the setting up of an interactive open boundary nested model system. Journal of Operational Oceanography, 7(1), 34-46, 2014
- Marshall, J., H. Johnson, J Goodman, 2001: A Study of the Interaction of the North Atlantic Oscillation with Ocean Circulation. J. Climate, 14, 1399–1421.
- Hall N., Barnier B., Penduff T., Molines. J.M.: Interannual variation of Gulf Stream heat transport in a high resolution model forced by reanalysis data, Climate Dynamics, Climate Dynamics, 23, 341-351, 2004.
- Sérazin, G., T. Penduff, L. Terray, S. Grégorio, B. Barnier, and Jean-Marc Molines : Spatial scales of the low-frequency intrinsic sea-level variability: a global model study. J. Climate, submitted.
- Grégorio, S., T. Penduff, G. Sérazin, J. Le Sommer, J.-M. Molines, and B. Barnier : Intrinsic variability of the Atlantic Meridional Overturning Circulationat interannual-to-multidecadal timescales. J. Phys. Oceanogr., submitted.
- Pierini, S. (2014). Kuroshio extension bimodality and the north pacific oscillation : a case of intrinsic variability paced by external forcing. Journal of Climate, 27 :448–454.
- Hazeleger, W. and Drijfhout, S. (2000). A model study on internally generated variability in subtropical mode water formation. J. Geophys. Res., 105(C6) :13,965–13,979.
- Hogg, A. M. and Blundell, J. (2006). Interdecadal variability of the southern ocean. J. Phys. Oceanogr., 36(8) :1626–1645.
- Arbic, B.K., M. Müller, J.G. Richman, J.F. Shriver, A.J. Morten, R.B. Scott, G. Sérazin, and T. Penduff, 2014: Geostrophic turbulence in the frequency-wavenumber domain: Eddy-driven low-frequency variability. J. Phys. Oceanogr., 44, 2050–2069. doi:10.1175/JPO-D-13-054.1
- Penduff, T., Barnier B., Dewar W.K., O'Brien. J.J., Dynamical response of the oceanic eddy field to the north Atlantic oscillation: a model-data comparison. J. Phy. Oceanogr., 34(12), 2615-2629, 2004.
- Penduff, T. M. Juza, and B. Barnier, 2007: Assessing the realism of ocean simulations against hydrography and altimetry. Clivar Exchanges, No 42 (vol 12 No 3), 11-12.
- Penduff, T., M. Juza, L. Brodeau, G.C. Smith, B. Barnier, J.-M. Molines, A.-M. Treguier and G. Madec, 2010 : Impact of global ocean model resolution on sea-level variability with emphasis on interannual time scales. Ocean Sci., 6, 269–284.
- Penduff, T., M. Juza, B. Barnier, J. Zika, W.K.Dewar, A.-M. Treguier, J.-M. Molines, and N. Audiffren, 2011: Sea-level expression of intrinsic and forced ocean variabilities at interannual time scales. J. Climate, 24, 5652–5670. doi: 10.1175/JCLI-D-11-00077.1.
- Lombard, A., G. Garric, and T. Penduff, 2009 : Regional patterns of observed sea level change: Insights from a 1/4° global ocean/sea-ice hindcast. Ocean Dynamics, 59, 3, 433-449.
- Juza M, 2011: Modélisation numérique et observations de l'océan global: développement des interfaces, évaluation de simulations et de réseaux d'observations, investigations dynamiques. Doctorat de l'Université J.Fourier, 15 septembre 2011.