Multidecadal variability of the overturning circulation in presence of eddy turbulence

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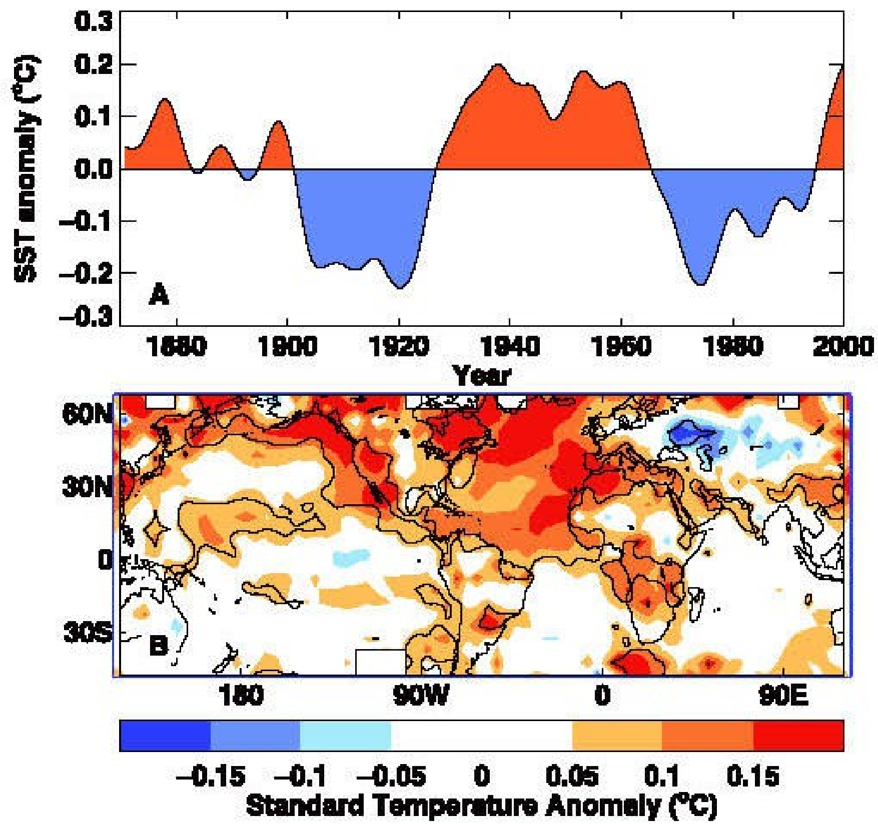
Observations in the North Atlantic reveal prominent multidecadal scale variability, the Atlantic Multidecadal Oscillation / Variability, often related to variations of the Meridional Overturning Circulation
(Kushnir'94,Delworth&Mann'00)

Dominant timescale 50-80 yr, but also 20-30 yr (Frankcombe&Dijkstra'09,Chylek&al'11)

Its mechanism is still unresolved

➤ here we build on an oceanic paradigm for the AMO in idealized ocean models

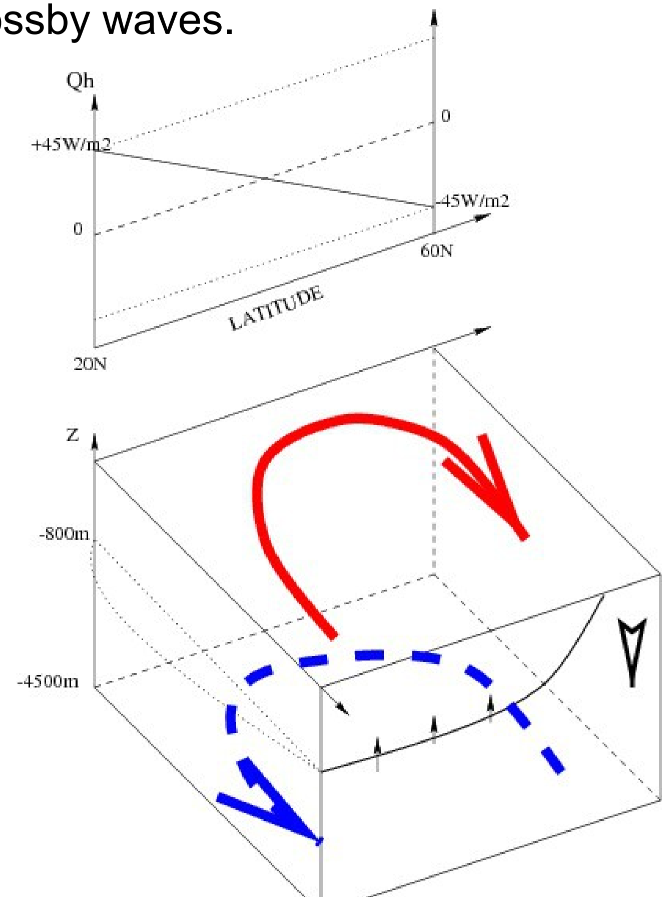


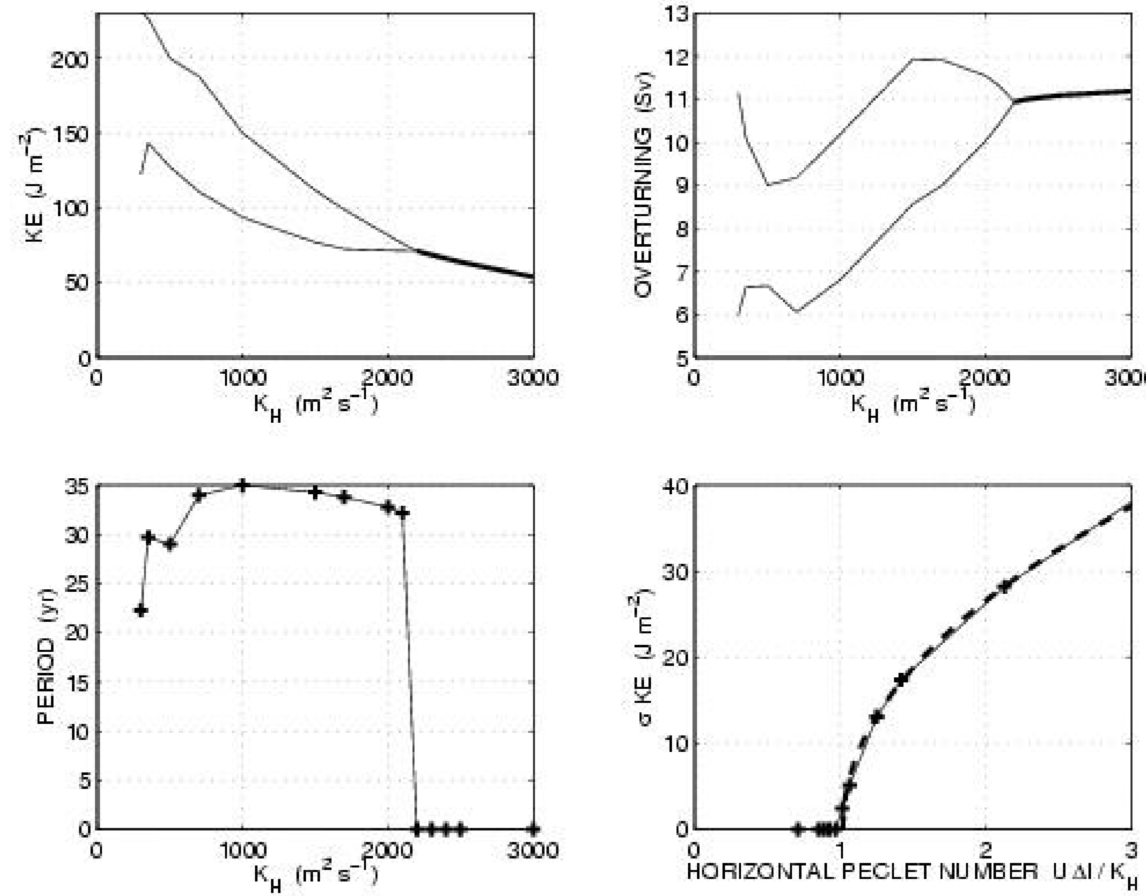
(figure from Knight&al'05)

An overlooked paradigm for the low-frequency variability of the Overturning Circulation

Toy model:
- flat-bottom mid-latitude ocean basin,
- buoyancy forcing through **prescribed surface flux**, varying linearly with latitude.

➤ low resolution O(1°) PE model integrations lead to multidecadal oscillations **depending on horizontal eddy diffusivity coefficient.**
Mechanism: large-scale baroclinic instability, period O(25yr) associated with planetary Rossby waves.





Bifurcation diagram as a function of horizontal eddy diffusivity coefficient, typical of a **Hopf bifurcation**.
Linear stability analysis show unstable mode with growth time scale of 50 yr, ie **extremely sensitive to surface restoring**.
➤ Critical diffusivity at bifurcation 2200 m^2/s in the range of observational estimates !

(Huang&Chou'94,Greatbatch&Zhang'95,Huck&al'99,ColindeVerdière&Huck'99,Huck&Vallis'01,teRaa&Dijkstra'02

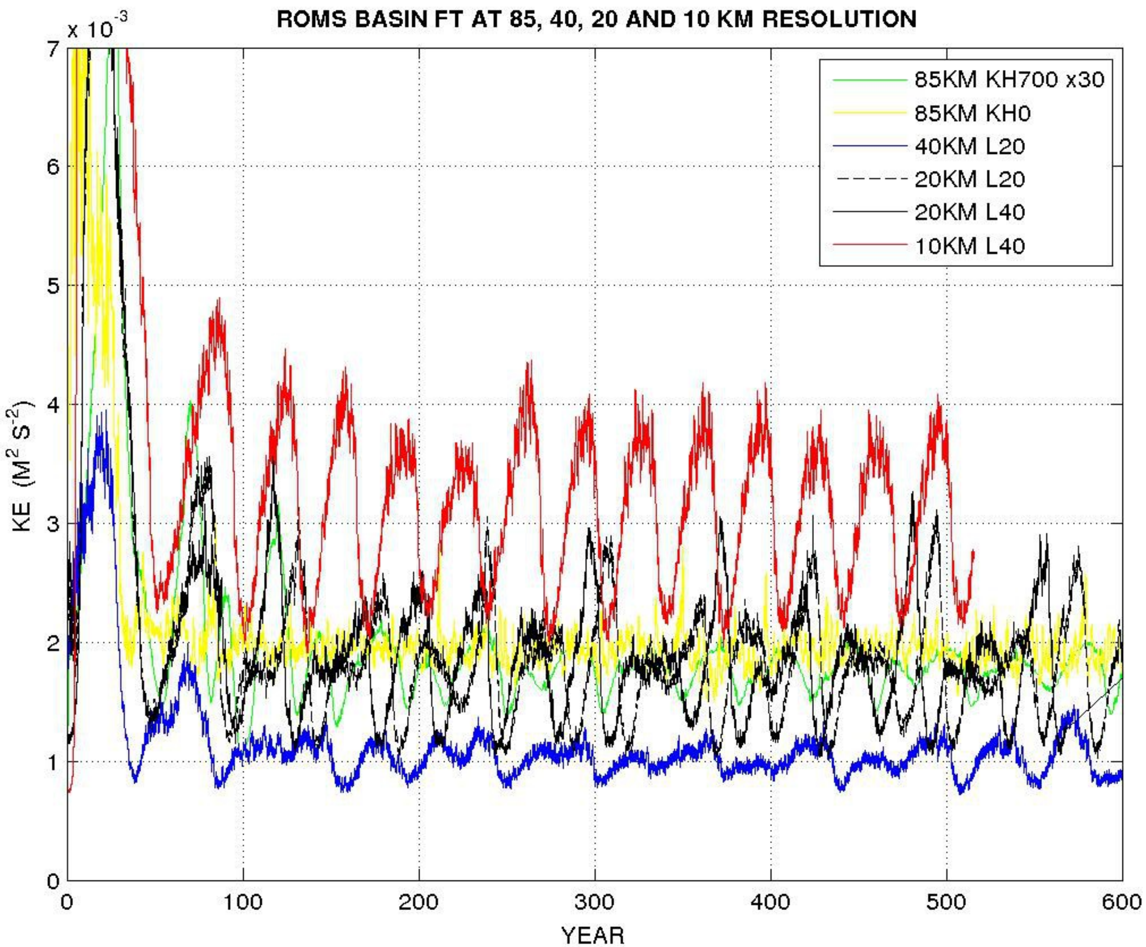
In what regime is a more realistic eddying ocean?

- stability/coherence of Rossby wave fronts regarding baroclinic instability? (LaCasce&Pedlosky'04,Isachsen&al'07)

- explicitly resolve horizontal eddy diffusivity critical to multidecadal oscillations

➤ Same idealized experiment (constant heat flux) conducted with PE ocean model ROMS at increasing horizontal and vertical resolution:
- **85, 40, 20, and 10 km**, 20 to 40 vertical levels,
- for 3 values of vertical mixing
  Kv = 10^{-4}, 3.10^{-5} and 10^{-5} m^2/s,
- for at least 500 yr.

Flat-bottom Cartesian beta-plane
20°N-60°N, 60° wide, 3800m deep
- prescribed heat flux +/-50 W/m^2 f(lat.)
- no wind forcing
- no explicit eddy viscosity/diffusivity (except at 85 km) → implicit/advection

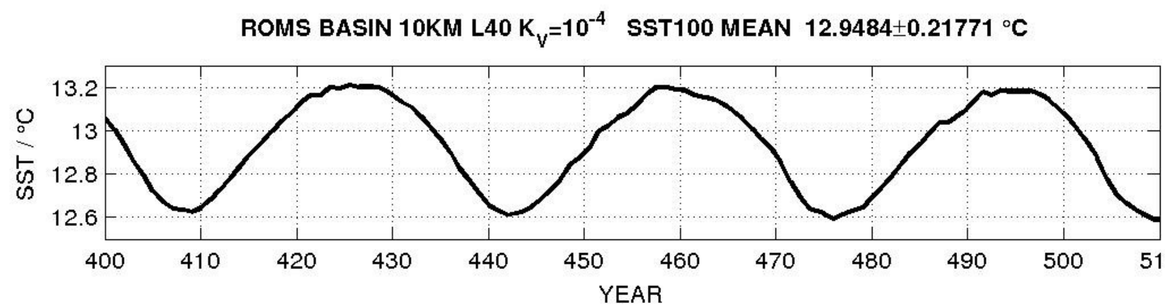


➤ ***The existence of multidecadal oscillations is not affected by resolved mesoscale turbulence.***

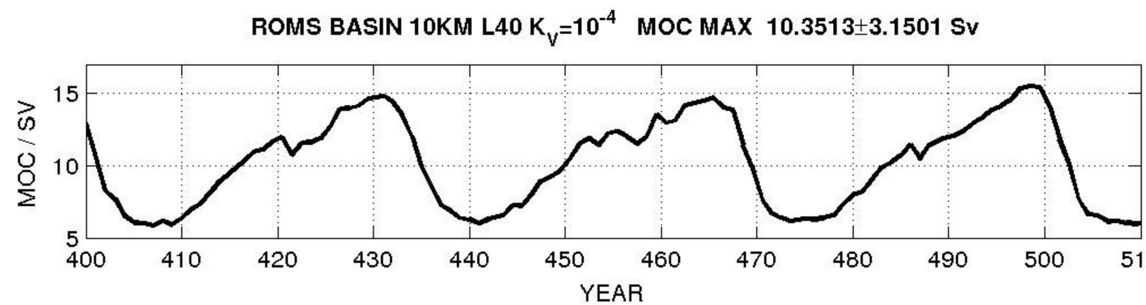
Reference case Kv=10^{-4} m^2/s at 10 km resolution

- reasonable mean overturning circulation around 10 Sv, with large amplitude variations
- amplitude of basin-averaged SST ~ 0.6°C (AMO), with SST anomalies O(2-3°C)

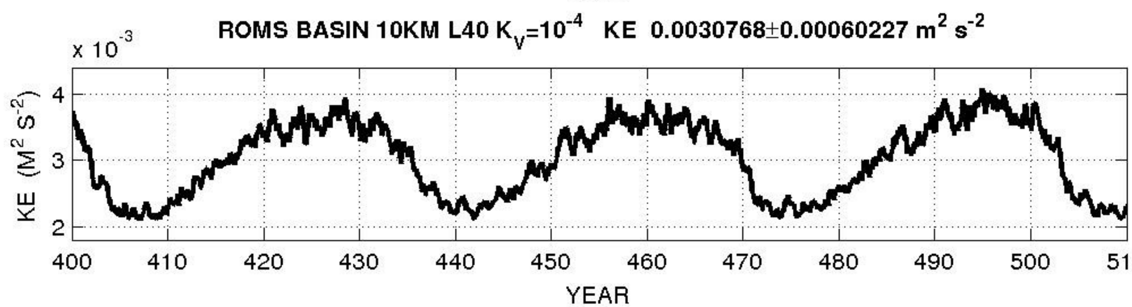
- Basin-averaged annual-mean SST



- MOC maximum
  based on annual-mean velocity



- and Total KE (daily frequency)



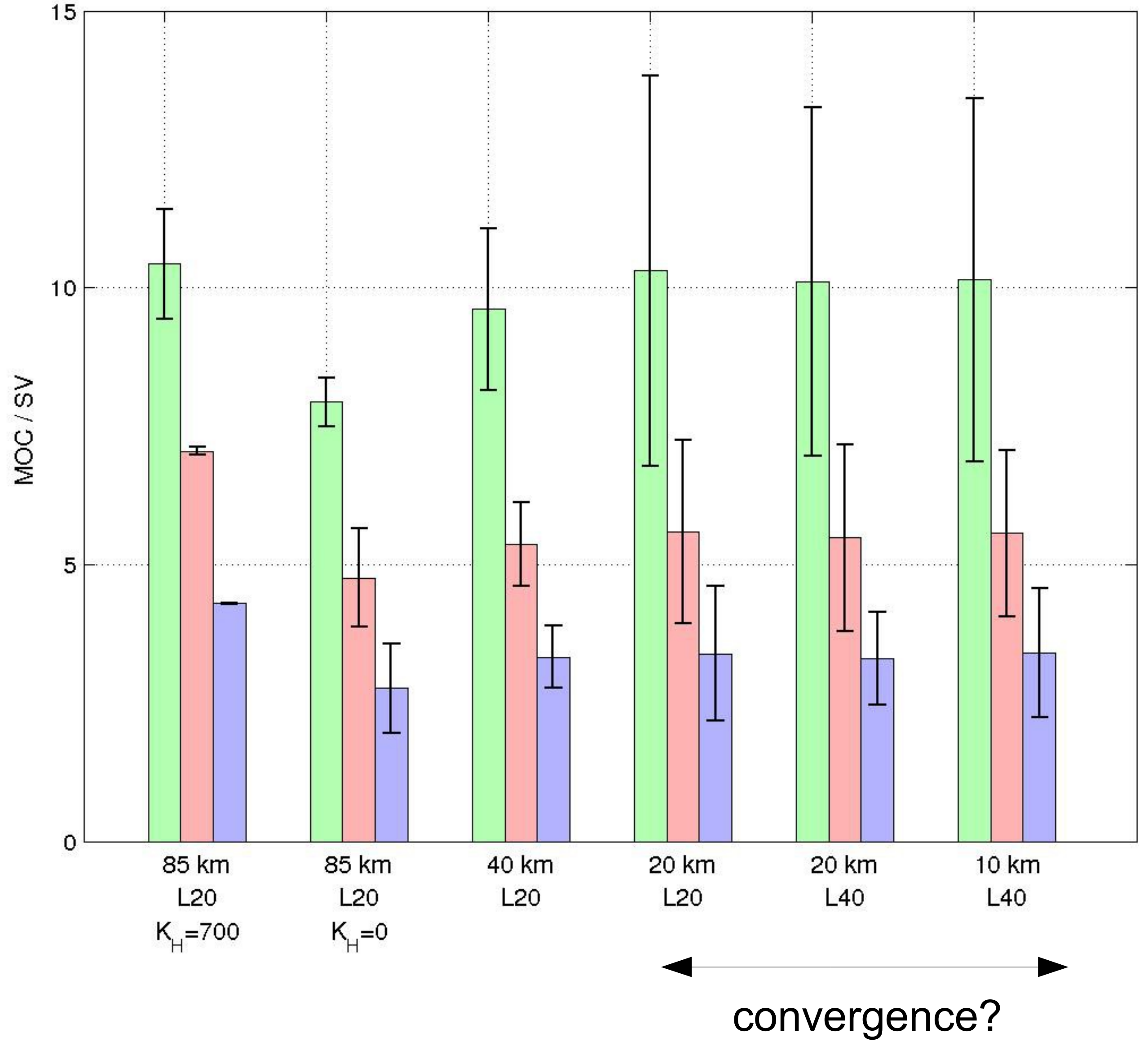
➤ **vary almost in phase.**

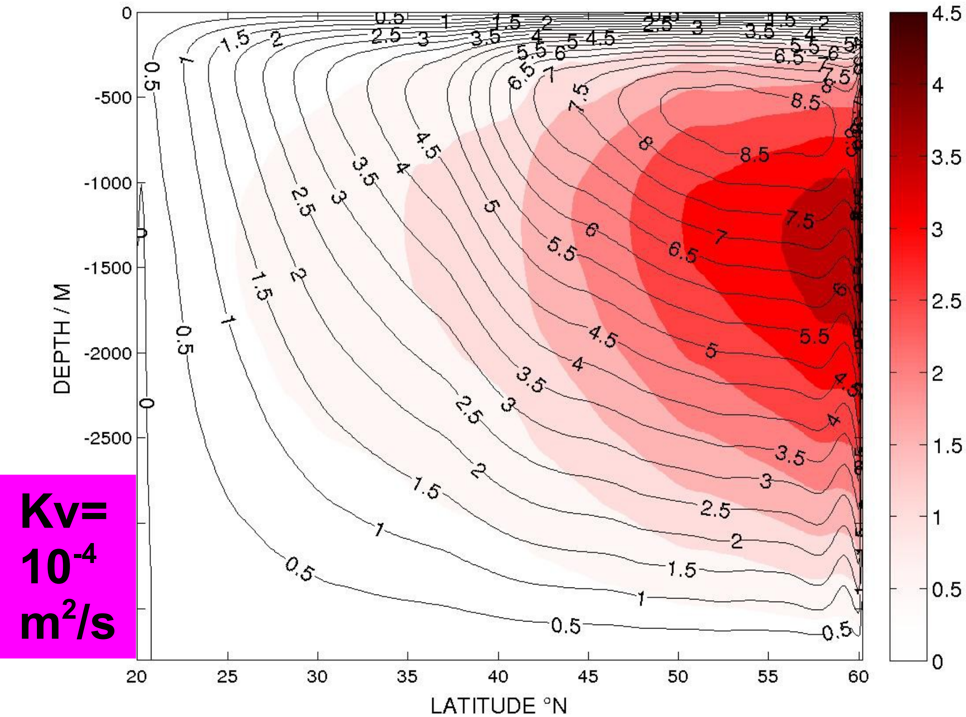
Considering all 10 km experiments with varying Kv : KE ∝ MOC
➤ efficiency of baroclinic instability to convert large scale APE reservoir into EKE

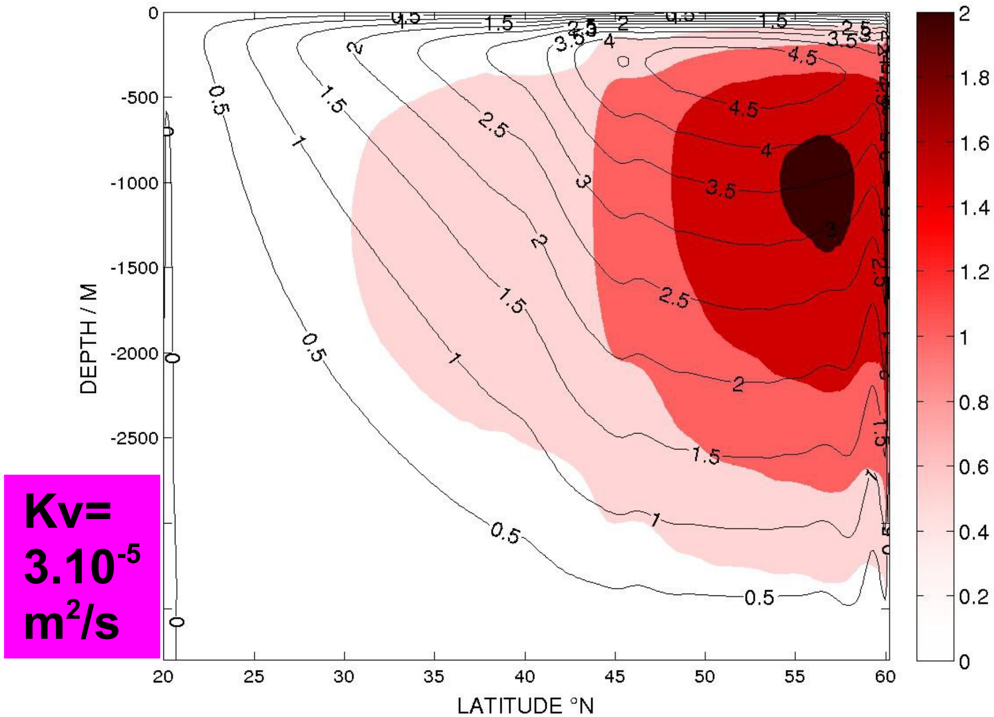
Meridional Overturning Circulation: mean and decadal variability, as a function of resolution and vertical mixing (Kv = 10^{-4}, 3.10^{-5}, 10^{-4} m^2/s)

► one hemisphere geometry: mean overturning scales as $Kv^{1/2}$ (Huang&Chou'94), unaffected by mesoscale eddies

► decadal oscillations amplitude increases with increasing resolution, due to reduced eddy diffusivity with weaker shear? and/or stochastic excitation of damped mode?

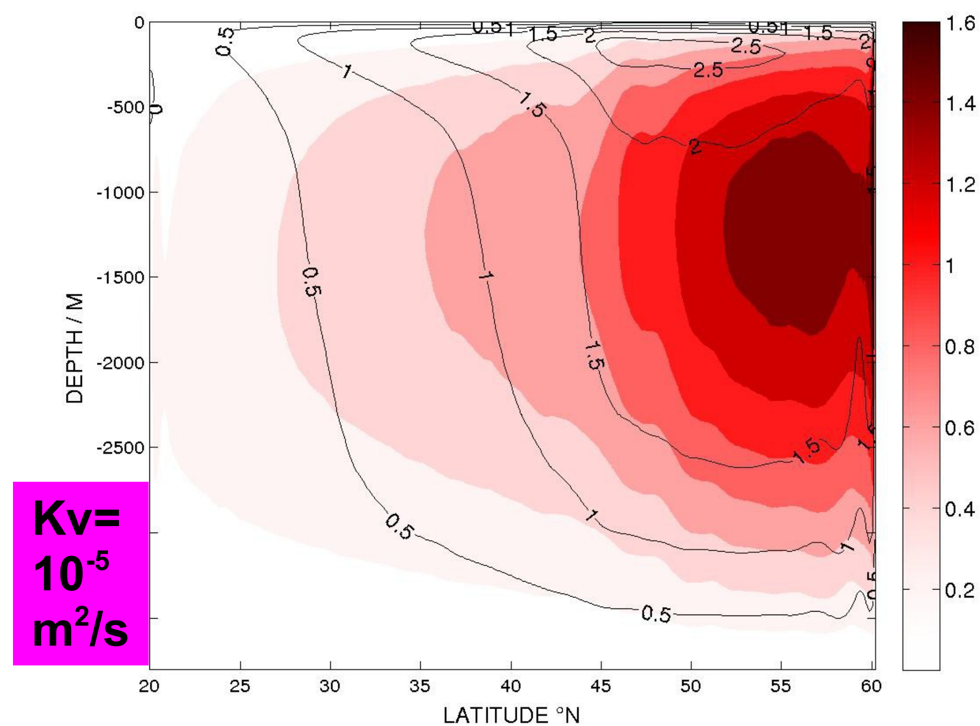






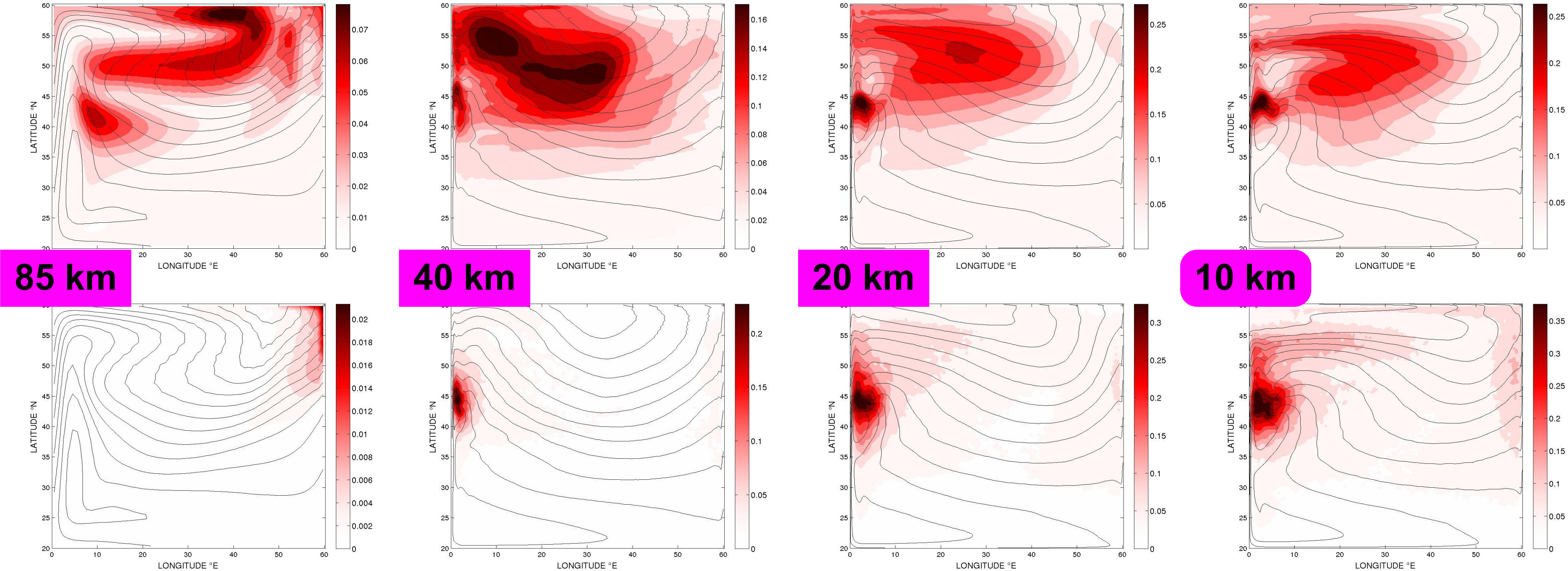
MOC mean (contours) and standard deviation (color) for the 10 km resolution experiments

►decadal oscillations more robust to low vertical mixing and overturning with resolved eddies



The Mesoscale Turbulence

Top: standard deviation of SSH low-frequency variations (annual average, m) > decadal.

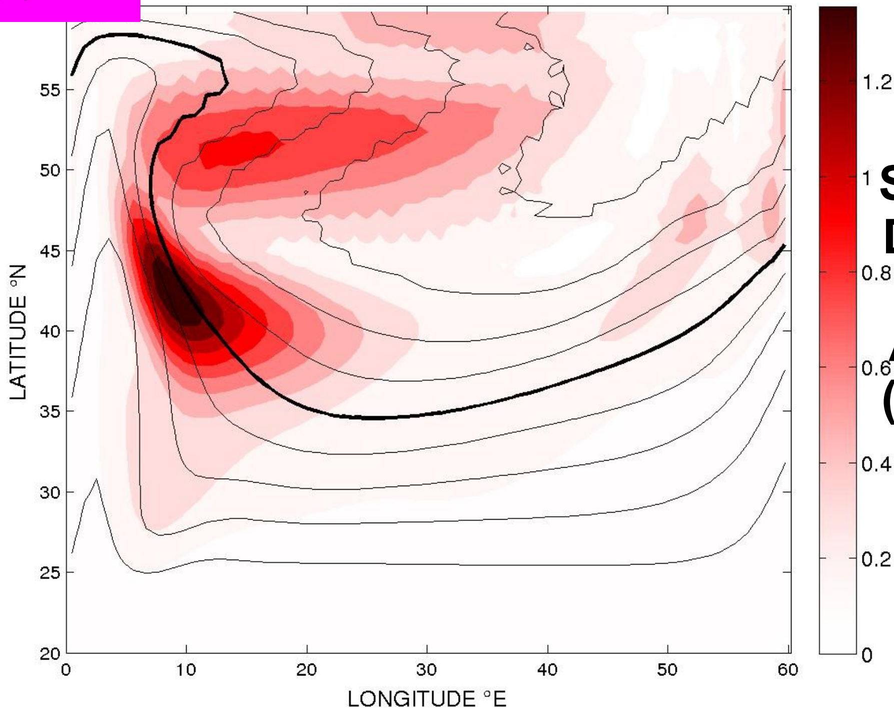


Bottom: standard deviation of SSH residual high-frequency variations (m) > mesoscale, for Kv=10^{-4} m^2/s.

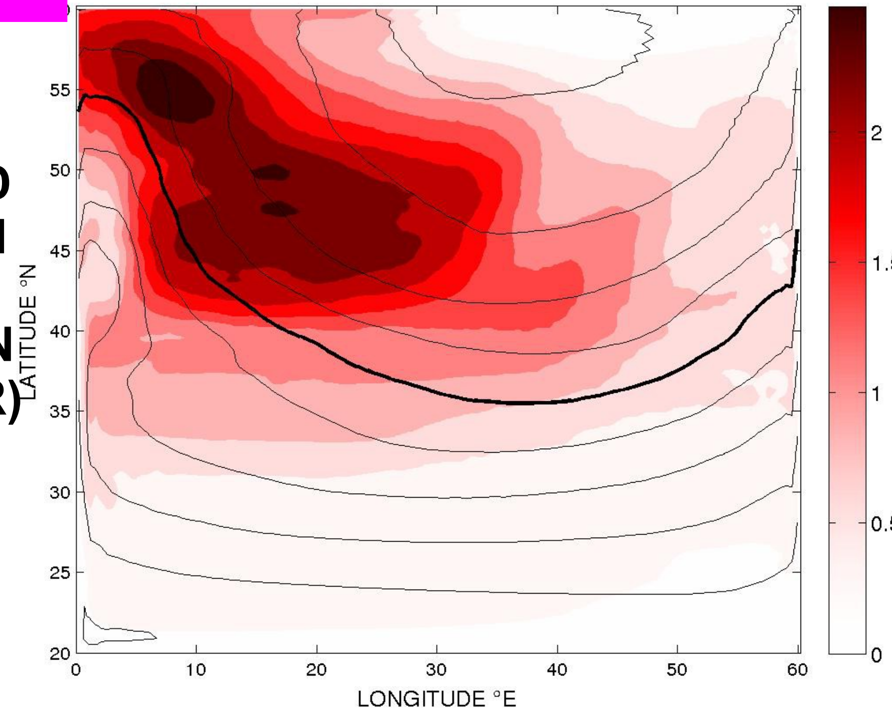
➤ At 10 and 20 km resolution, SSH HF variability (35 cm) and surface EKE (0.3 m^2/s^2) reach levels comparable to observations, even with no wind forcing.

➤ Distinct location of multidecadal (NW,downstream) and mesoscale (WBC detachment) SSH variability.

85 km

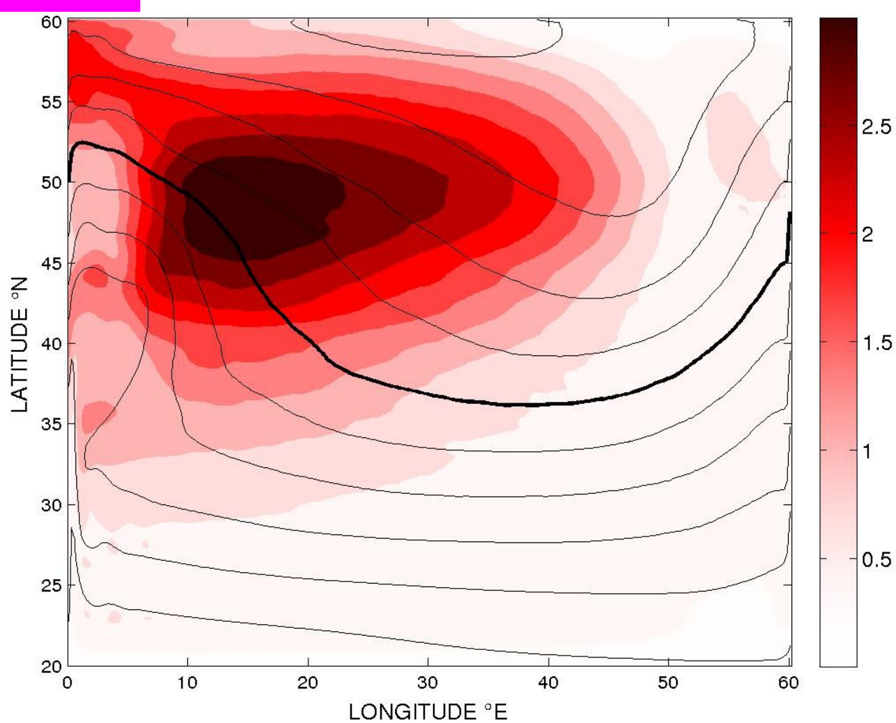


40 km



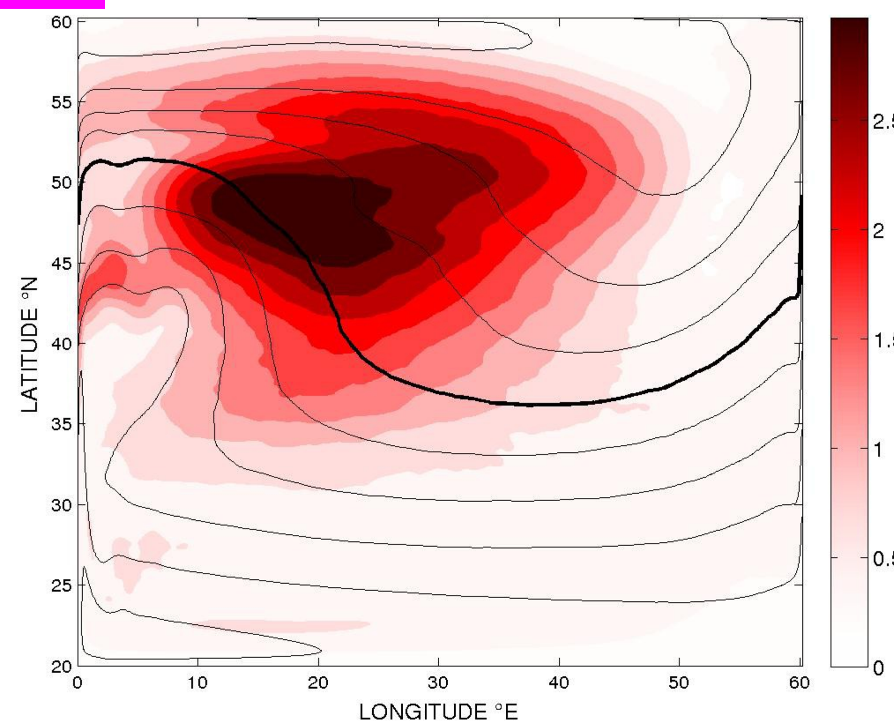
SST 0-100m STANDARD DEVIATION (COLOR) AND MEAN (CONTOUR) BASED ON ANNUAL MEAN FIELDS

20 km

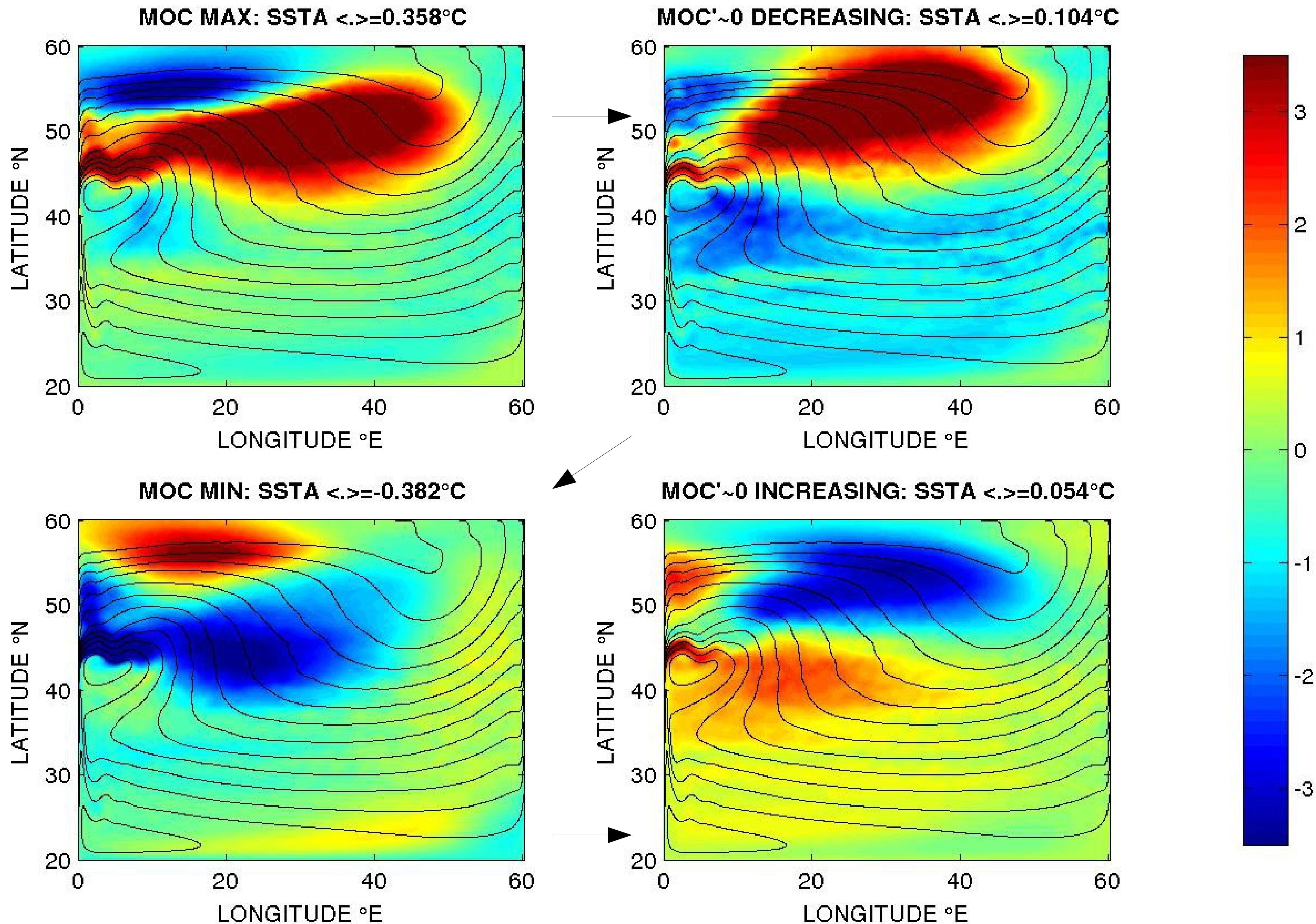


$Kv = 10^{-4}$ m^2/s

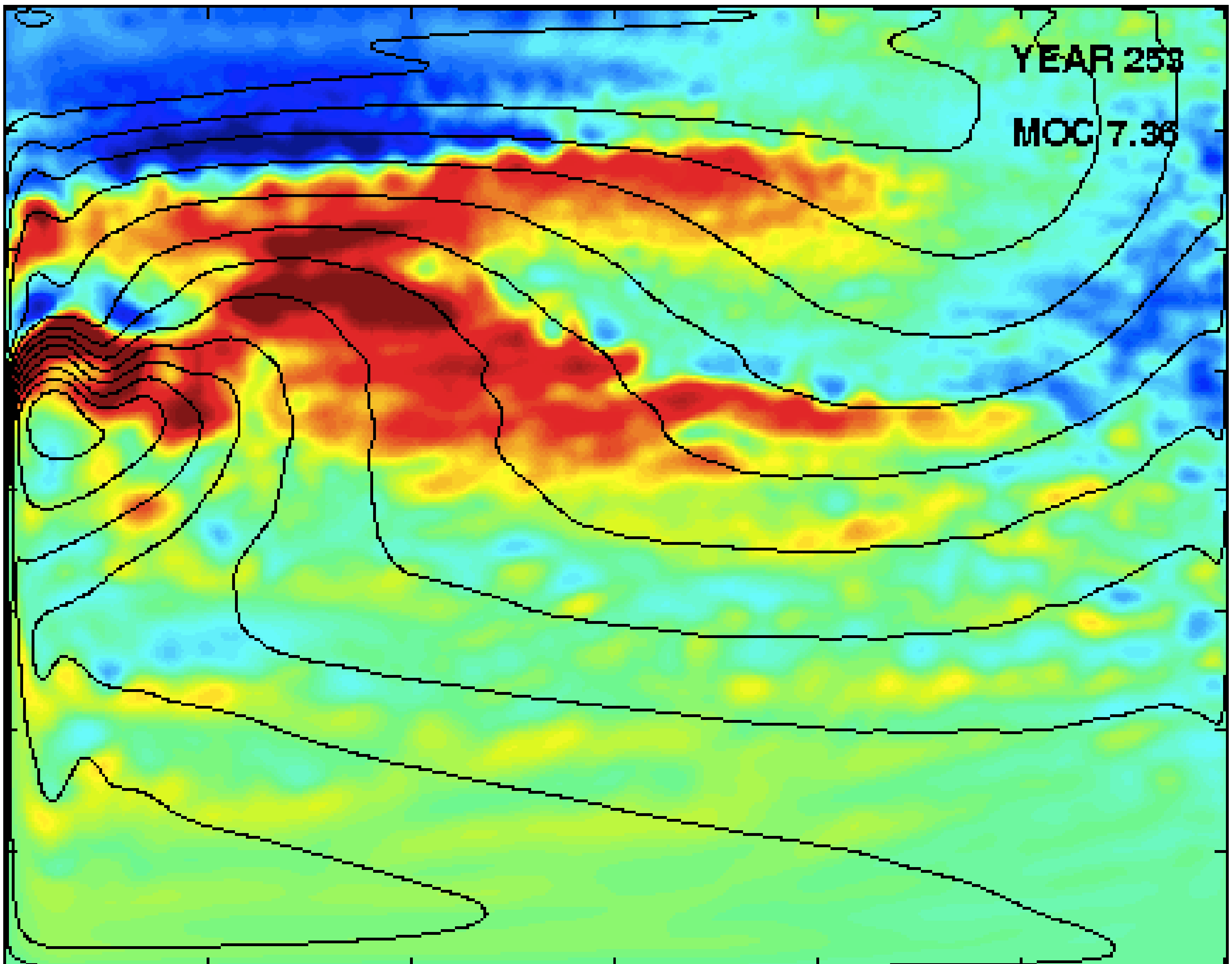
10 km



COMPOSITE SST ANOMALY FOR 4 CONSECUTIVE PHASES OF THE OSCILLATION
10 km resolution experiment for Kv=3.10^{-5} m^2/s



10 km resolution experiment for Kv=3.10^{-5} m^2/s annual-mean SLA (colorbar±25cm) on mean contours



The Oscillation Period

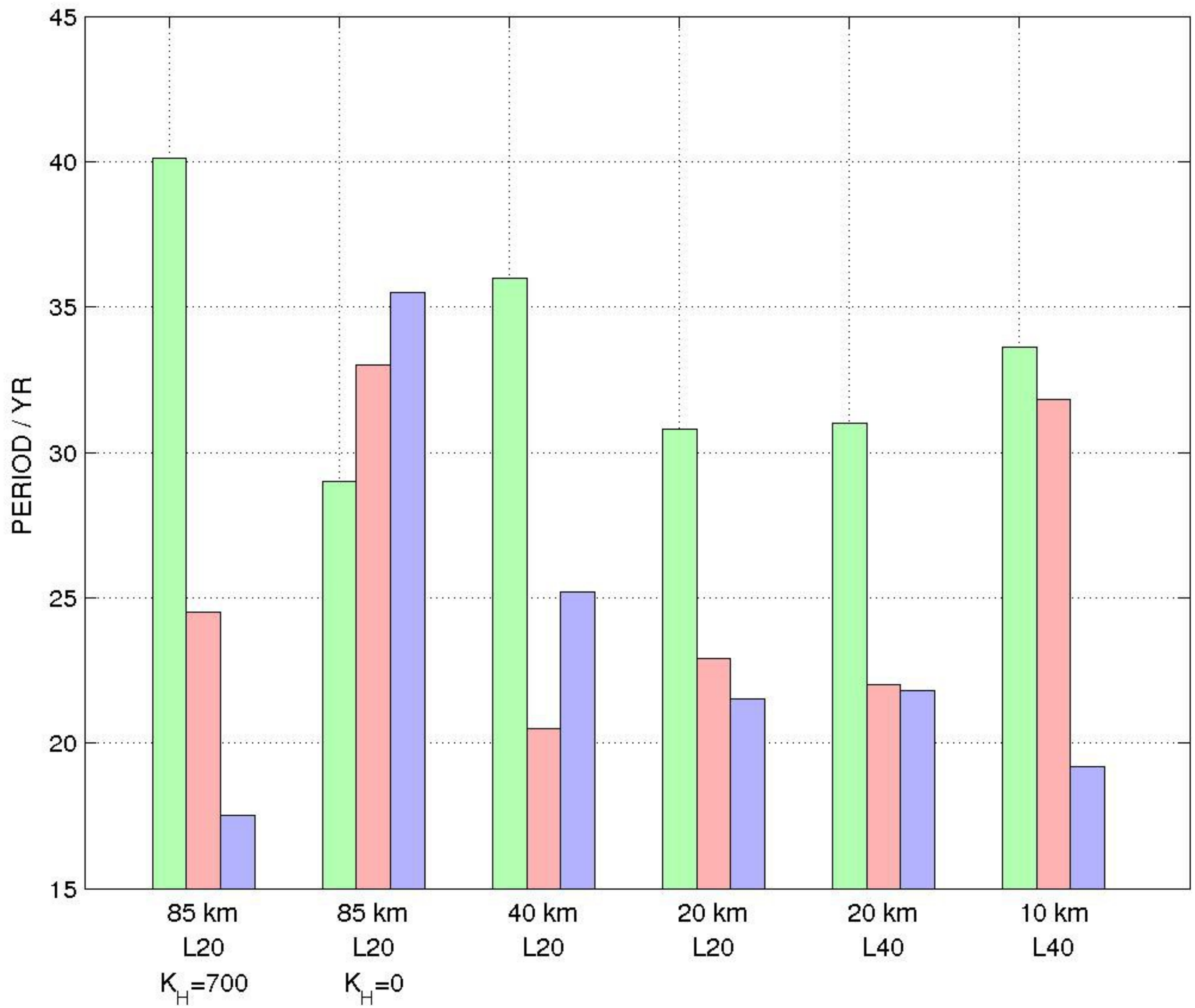
- O(20-30 yr)

- generally increases with vertical mixing, as baroclinic Rossby wave velocity c and first Rossby radius of deformation L_D decrease, following previously suggested scaling:

$$T = L_B / c \quad \text{with } c = \beta L_D^2$$

$$L_D = NH / f$$

►Timescale of AMO/AMV? growing evidence that North Atlantic interdecadal variability dominated by oscillations with period in the 20-30 yr range (Frankcombe&Dijsktra'09, Chylek&al'11, Vianna&Menezes'13)



Kv = 10^{-4}, 3.10^{-5}, 10^{-4} m^2/s

Maintenance of Rossby wave fronts?

Large-scale Rossby wave fronts prone to baroclinic instability and break up into eddies along westward propagation?

if BCI growth time $Tg=L_D/U$ < basin crossing time $T_R = L_B/(\beta L_D^2)$

(LaCasce&Pedlosky'04,Isachsen&al'07)

Here $Z = T_R / Tg \sim 1000$!

⇒ Rossby waves should never make it to the western boundary?

Hints?

►Equilibrated eddies feed large-scale through inverse cascade

►Rossby waves growth through mean flow APE extraction

►Rossby waves - mean flow feedback?

Conclusions

► multidecadal oscillations appear more robust to low vertical mixing/overturning with resolved eddies

► mean state largely changes with increasing resolution, but not MOC amplitude

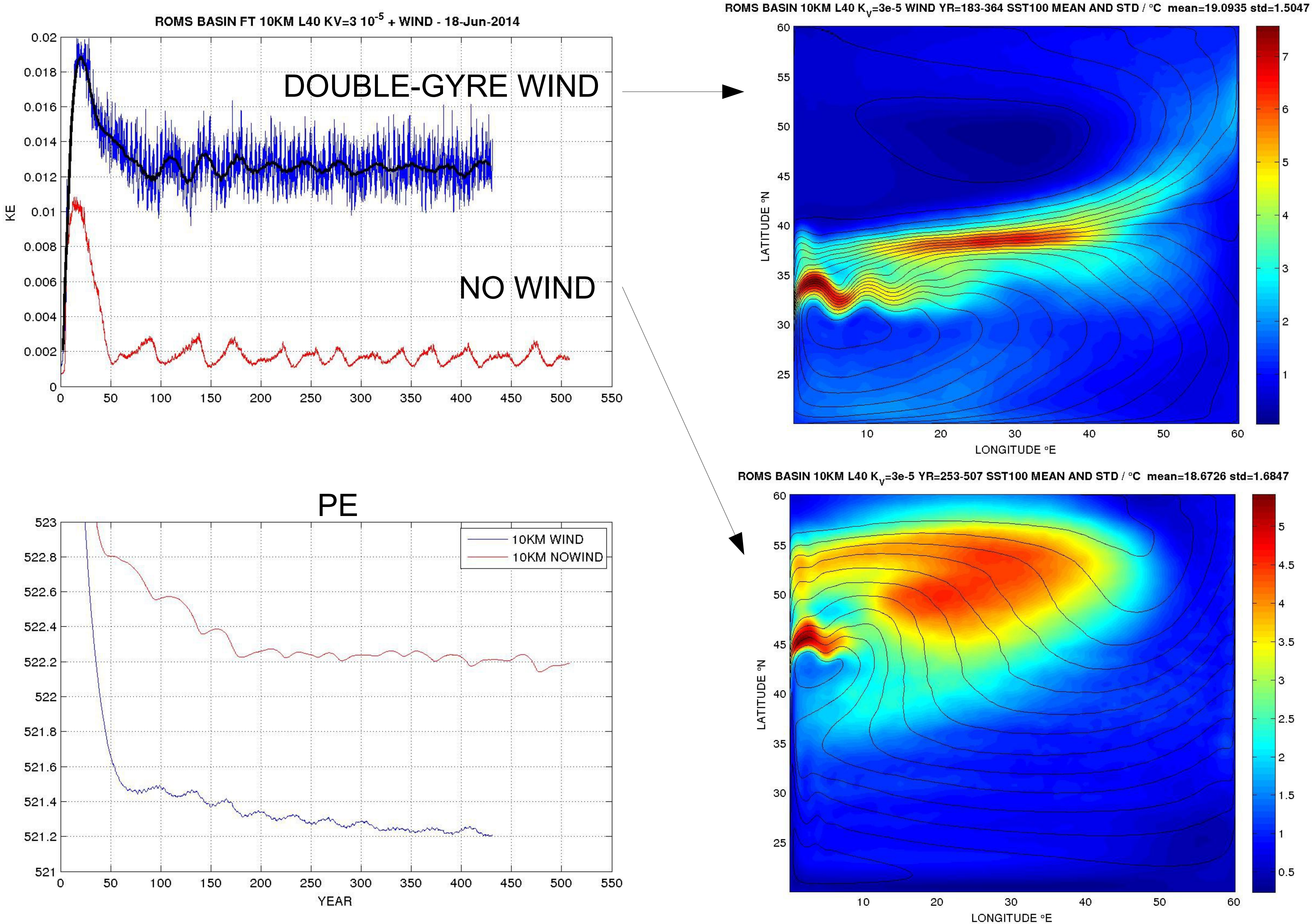
► patterns of variability affected by resolution of mesoscale eddies

► oscillation period O(20-30 yr) mostly unchanged with varying resolution

► fundamental processes for spontaneous multidecadal variability of the buoyancy-driven circulation appear unaffected by resolved mesoscale turbulence: large-scale baroclinic Rossby waves extracting energy from mean density field against dissipation

This mechanism may apply in realistic configurations and forcing/coupling, with comparable period and pattern shifted to the North Atlantic subpolar gyre (Arzel&al'12,Buckley&al'12,Sévellec&Fedorov'13)

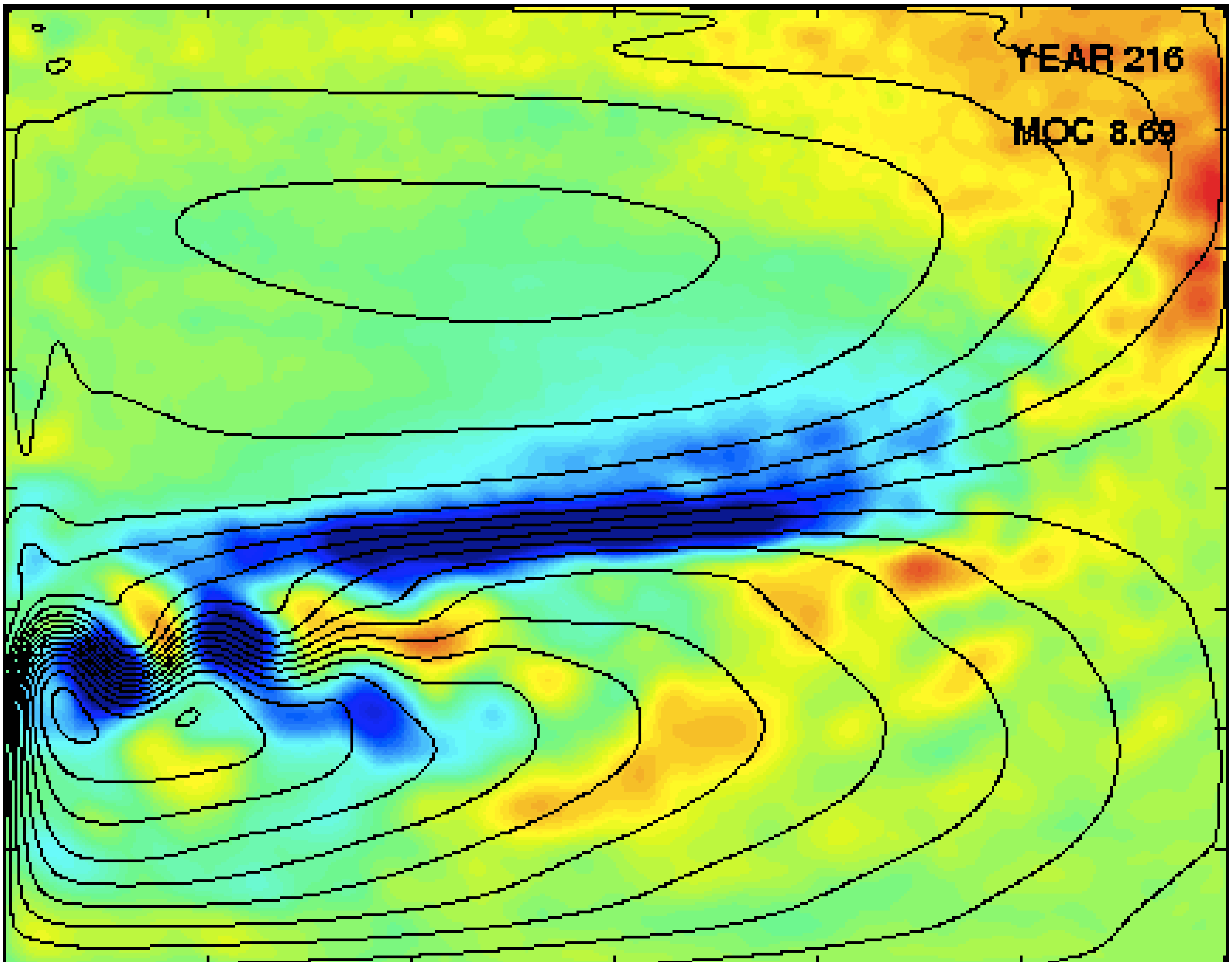
Preliminary results with addition of double-gyre wind forcing show:
- period in same 20-30 yr range
- shift in location of SST/SLA variability to intergyre
- propagation of multidecadal SST/SLA anomalies from western boundary around the subpolar gyre (Sutton&Allen'97,Vianna&Menezes'13)



► eddy-driven wind-induced variability at higher interannual frequency

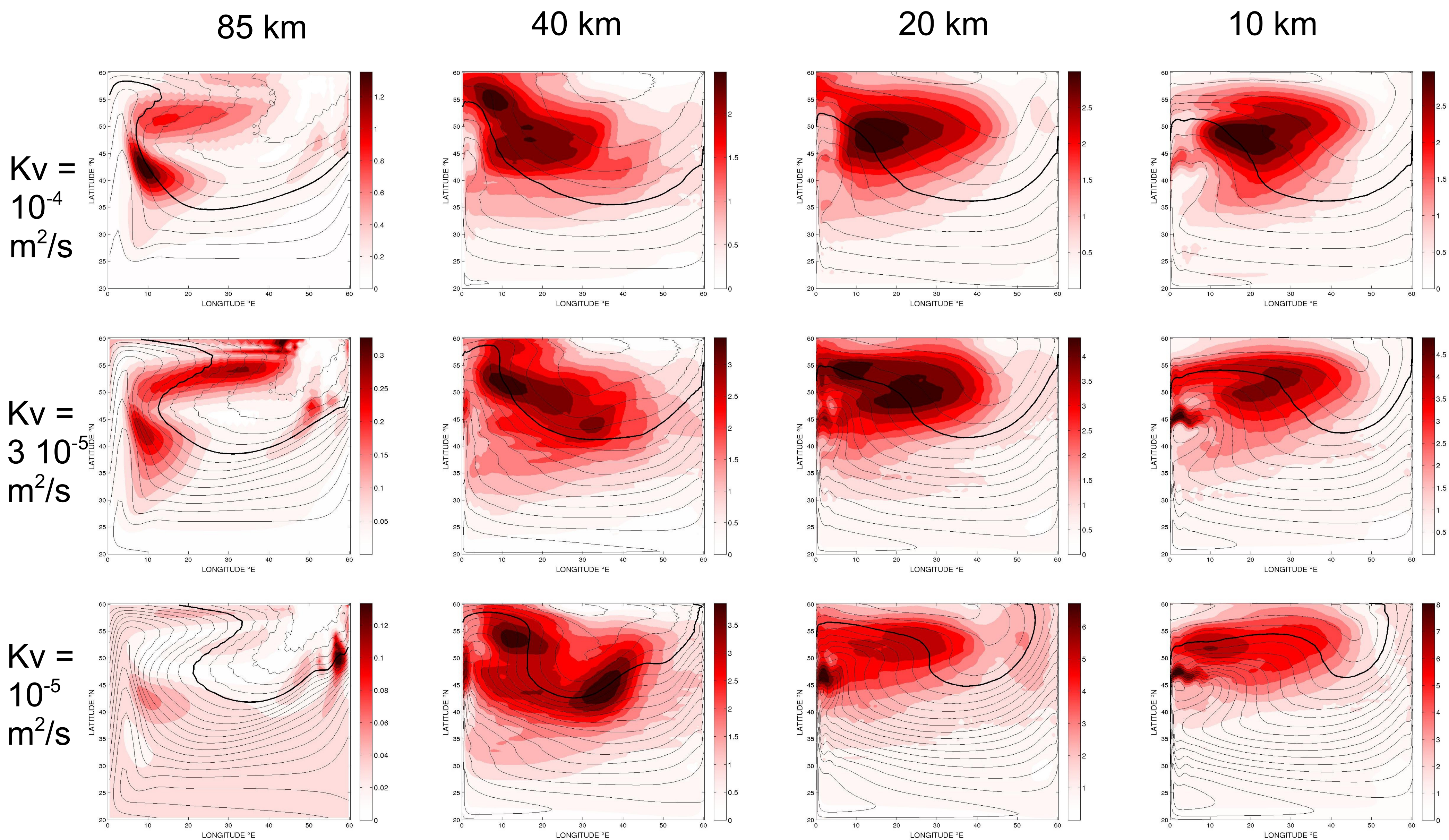
► decadal scale SST/SLA anomalies propagate around subpolar gyre

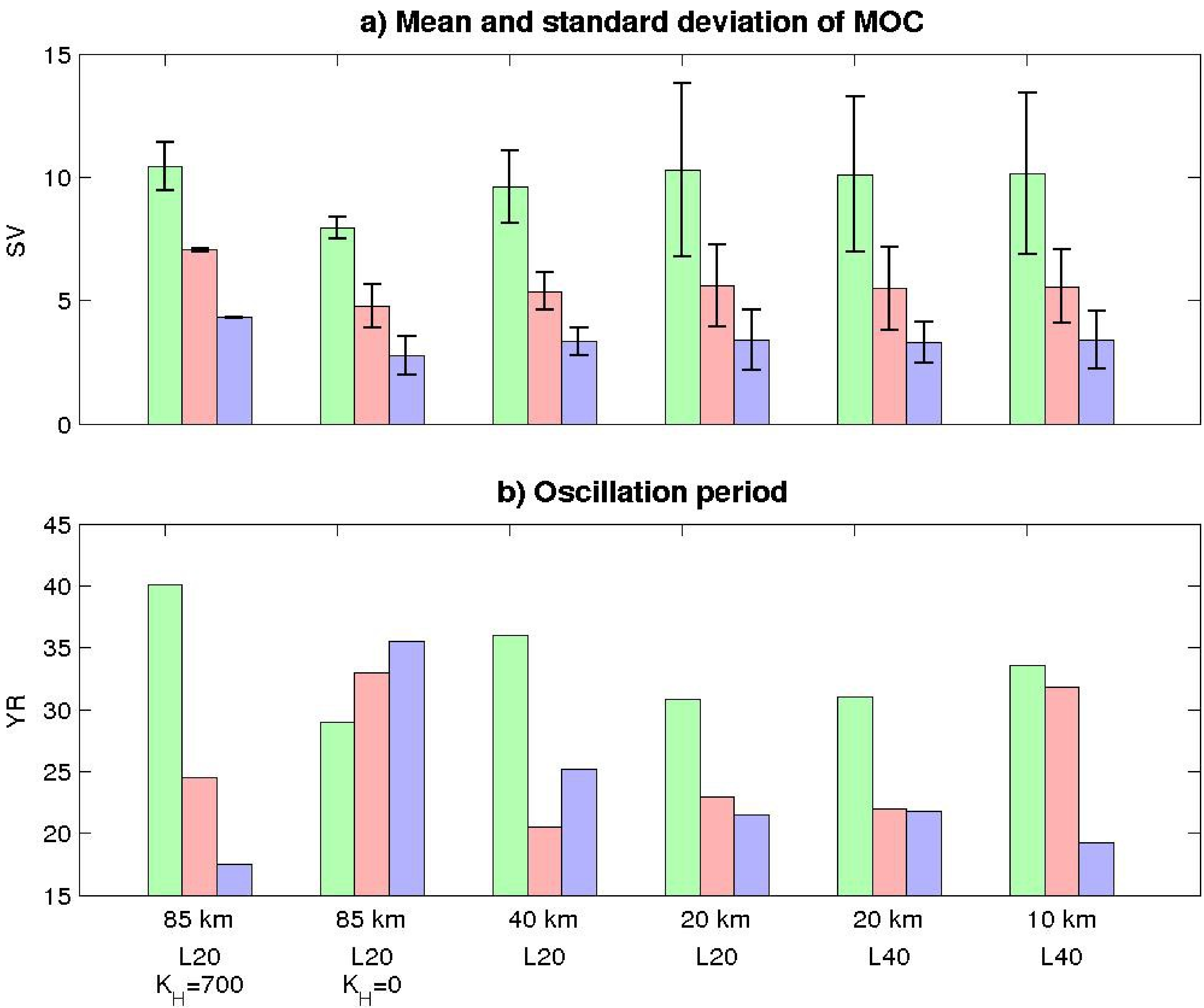
10 km resolution experiment for Kv=3.10^{-5} m^2/s, with double-gyre wind forcing 10-yr running mean SLA (colorbar±25cm)



Thank you for your attention

SST 0-100m mean (contours) and standard deviation based on annual-mean fields





a) Mean and standard deviation of MOC
SV
15
10
5
0
b) Oscillation period
YR
45
40
35
30
25
20
15
85 km
L20
K_H=700
85 km
L20
K_H=0
40 km
L20
20 km
L20
20 km
L40
10 km
L40

Similar multidecadal oscillations in more realistic model configurations

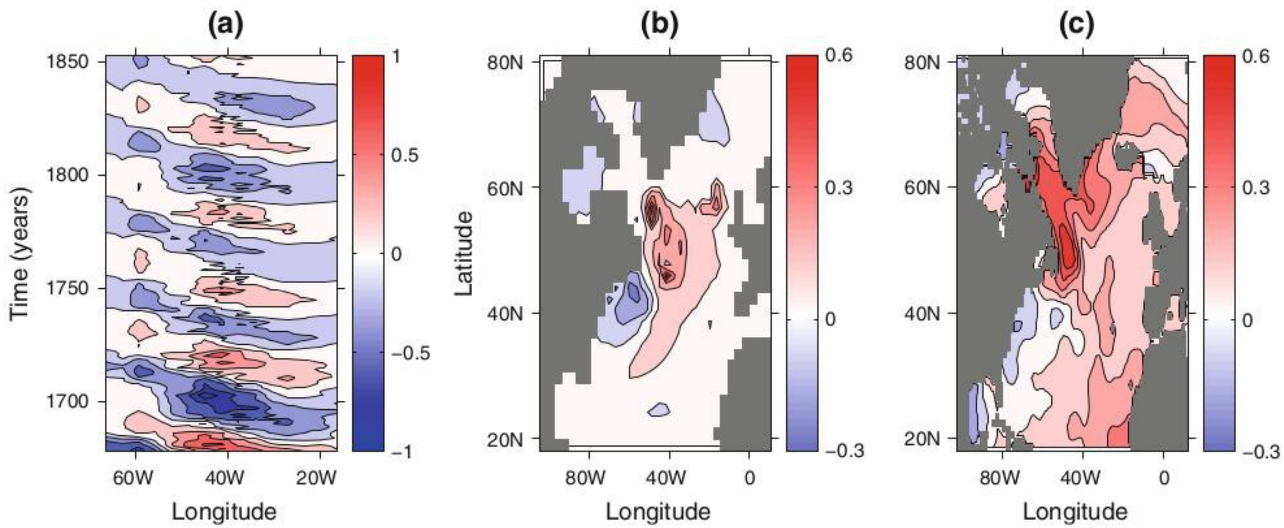


Fig. 14 Surface temperature pattern associated with the first interstadial phase (years 1650–1850) of the glacial experiment using an atmospheric CO_2 concentration of 190 ppm and a freshwater forcing of −0.21 Sv. **a** Characteristic *x*–*t* diagram of meridionally averaged (43°N–54°N) SST anomalies in the Atlantic basin. **b**, **c** SST anomalies associated with one positive standard deviation of the AMO index, calculated by regression of surface temperatures with the index and multiplied by its standard deviation, similar to Knight et al. (2005), in the model (**b**) and in observations (**c**). See text for further details

UVIC intermediate complexity coupled model (Energy Moisture Balanced Atmosphere), around 3° resolution
► interdecadal oscillations during interstadials of millennial variability in a global coupled model (Arzel et al. 2012 CD)

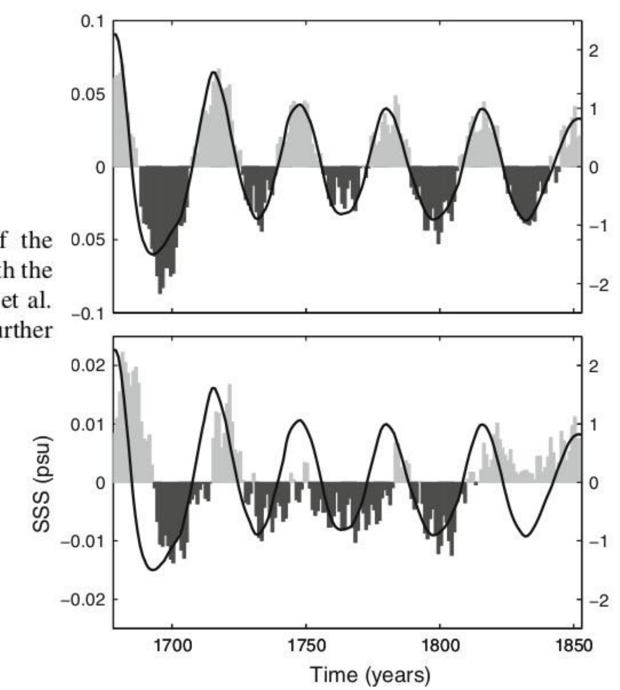


Fig. 11 Linearly detrended time series of maximum strength of the AMOC (*black solid line*), overlaid by detrended area weighted mean North Atlantic (0–70°N), **a** SST and **b** SSS annual mean anomalies during the first interstadial phase (years 1650–1850) of the glacial experiment using an atmospheric CO_2 concentration of 190 ppm and a freshwater forcing of −0.21 Sv (see Fig. 5). The AMO index corresponds to the SST timeseries in the *upper panel*

MIT coupled model in idealized 2 basins configuration at low resolution ~4° : multidecadal oscillation sensitive to topography (Buckley et al. 2012 JClim)

►PhD research of Quentin Jamet in Brest : sensitivity of these oscillations to horizontal resolution. At 2° and 1°, oscillations are robust, with more complex MOC variability pattern at 1°

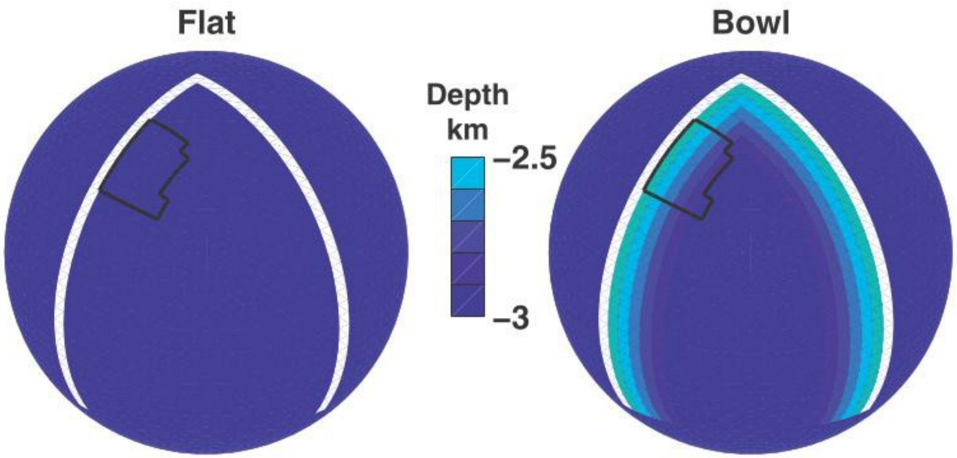


FIG. 1. Ocean geometry and depth (km) for (left) Flat and (right) Bowl. Two strips of land (white) extend from the north pole to 34°S, dividing the World Ocean into a small basin, a large basin, and a zonally unblocked southern ocean. In Flat
In Bowl bathymetry is added to the small basin and t
center of the basin to 2.5 km next to the meridional
region along the western boundary of the subpolar
boundary buoyancy (WBB) time series in section 3d.

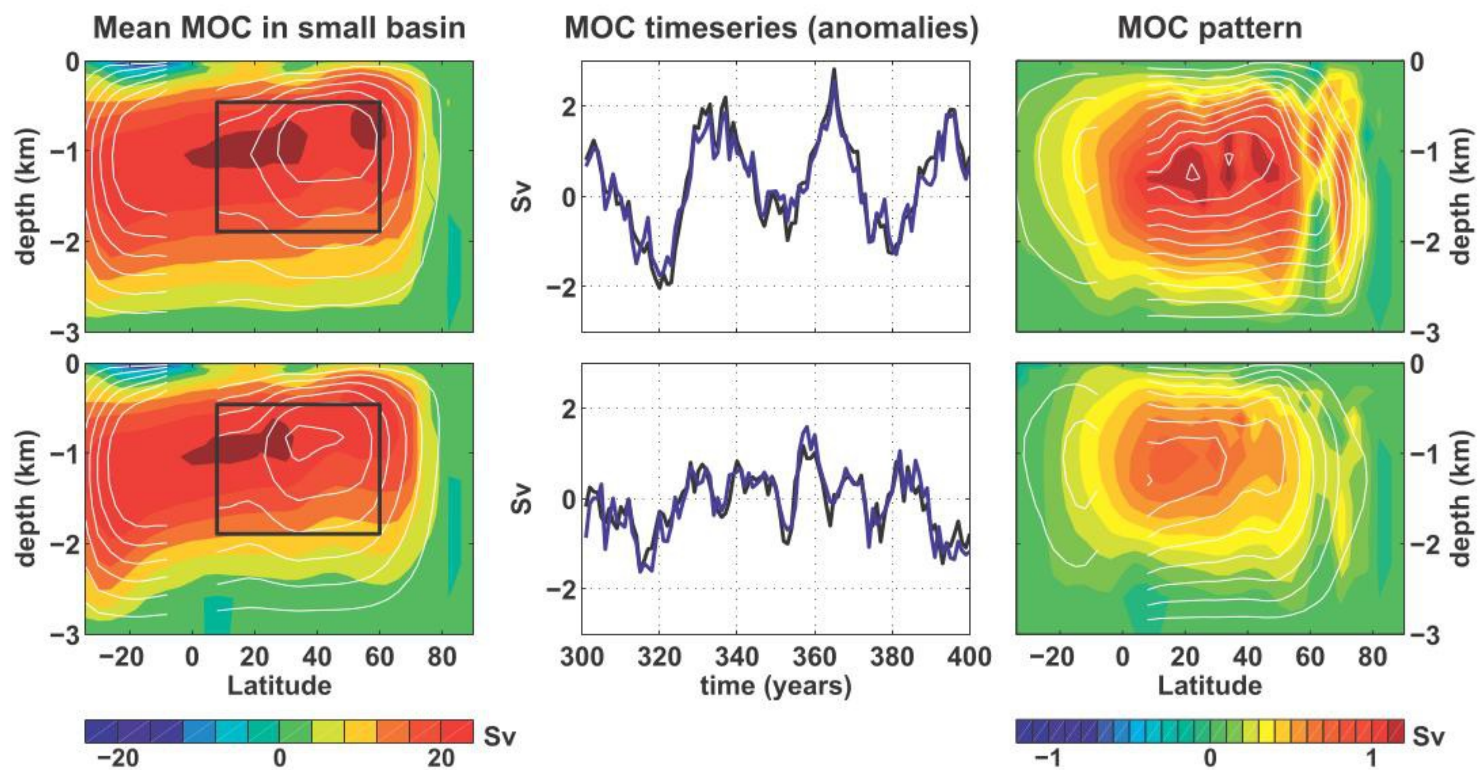


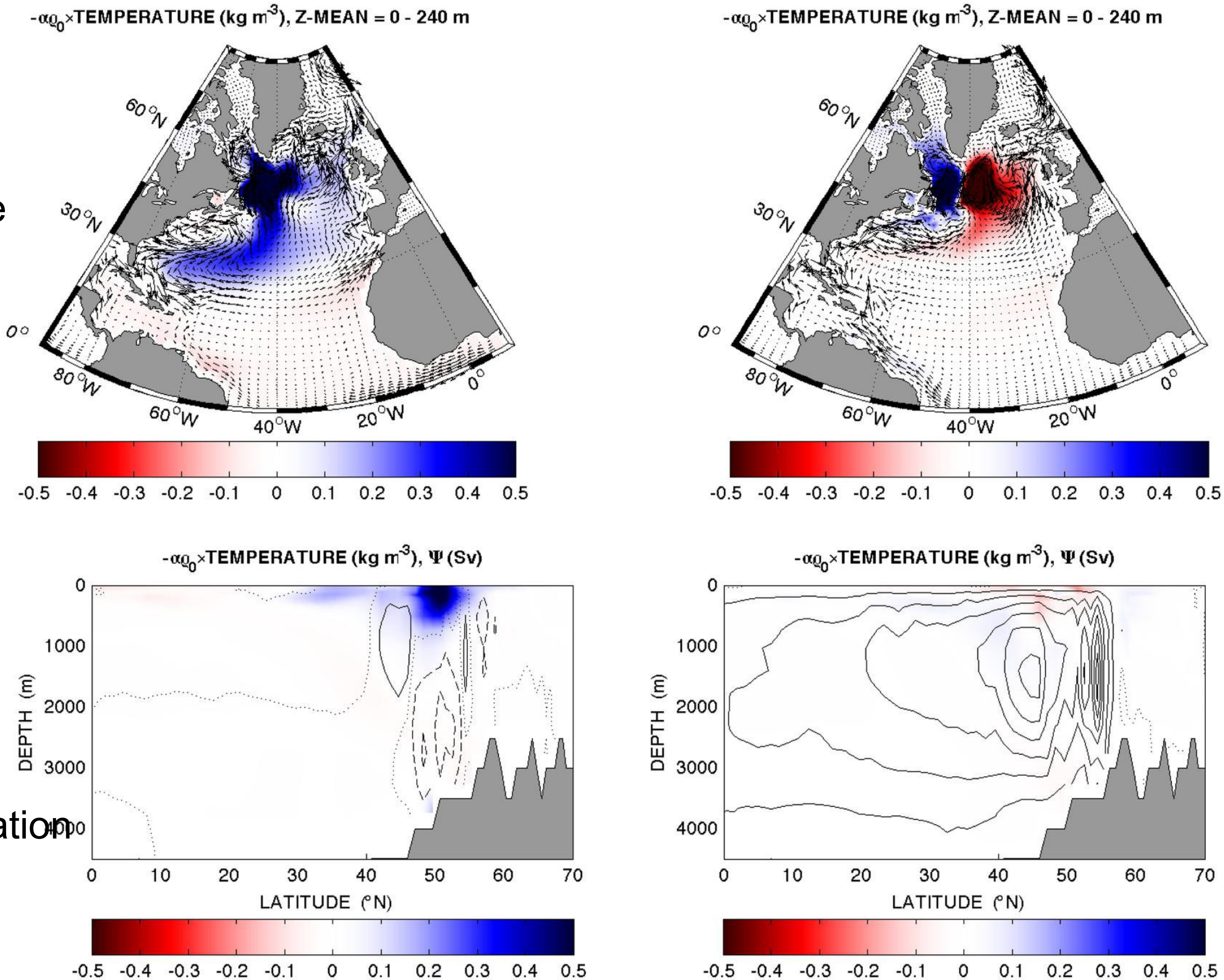
FIG. 3. (left) The residual mean MOC in the small basin (colors) and the MOC diagnosed from Eq. (5) (black/white contours) for (top) Flat and (bottom) Bowl. White (black) contours correspond to a positive (negative) MOC and the contour interval for both colors and black/white contours is 4 Sv. The black box shows the latitude and depth range (8°–60°N, 460–1890-m depth) used to define the MOC time series. (middle) A 100-yr segment of anomalies of the yearly MOC time series (black) and reconstructed MOC time series [diagnosed from Eq. (5), blue] for (top) Flat and (bottom) Bowl. (right) The spatial patterns of MOC variability obtained by projecting MOC anomalies onto the MOC index (colors) and projecting MOC anomalies diagnosed from Eq. (5) onto the reconstructed MOC index (black/white contours) for (top) Flat and (bottom) Bowl. White (black) contours correspond to positive (negative) MOC anomalies and the contour interval for both the colors and black/white contours is 0.1 Sv.

OPA ORCA2° model configuration + OPATAM (Sévellec&Fedorov 2013)

Anomalies of
upper-ocean temperature
(0-240m)
and surface currents.
Temperature is given
in terms of density.

Anomalies of
meridional
streamfunction
and zonally averaged
temperature.

for 2 phases of the oscillation
Amplitude is arbitrary
(linear mode).



Spatial structure of the least-damped eigenmode of the tangent linear model: (left) a large temperature anomaly spreads over the northern Atlantic, but the AMOC anomaly is close to zero; (right) it evolves 6 yr later into a dipole-like anomaly, associated with a strong AMOC.

Contribution to Chaocean: from ORCA2 to ORCA12...

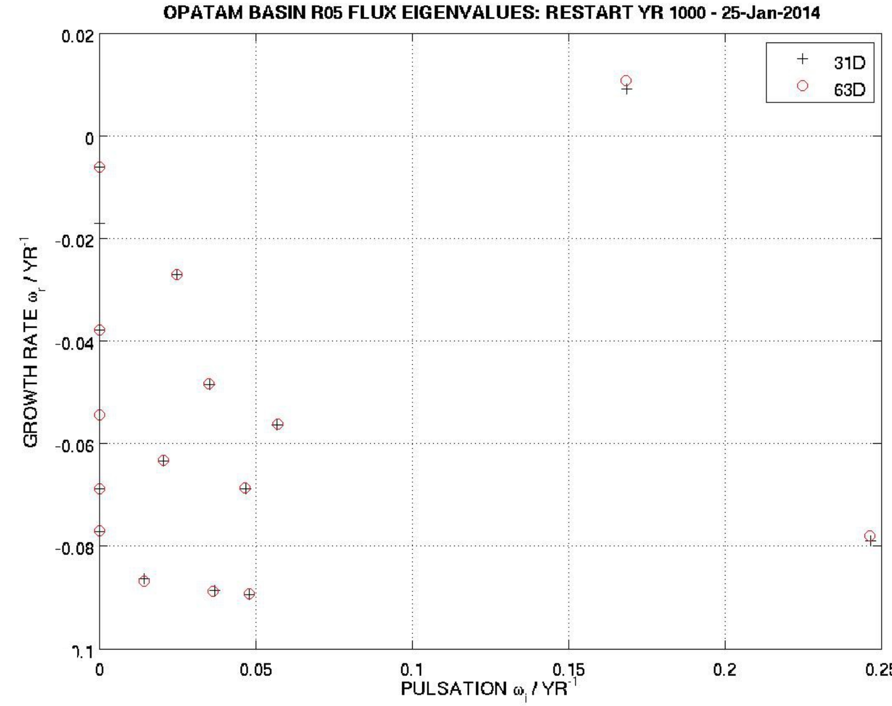
Development/use of several tools from dynamical system theory:

- linear stability analysis, allowing to forecast growing modes of variability, but also more interestingly damped modes that can develop under some excitation (atmospheric or eddies)
- "empiral" LSA (Sévellec&Fedorov 2013), far more efficient if you know what you are looking for
- optimal perturbations (Sévellec et al. 2008 JPO), for what measure?

All are based on tangent **linear** and/or adjoint model integration (OPATAM... NEMOTAM), for now in ORCA2° or simpler configs.

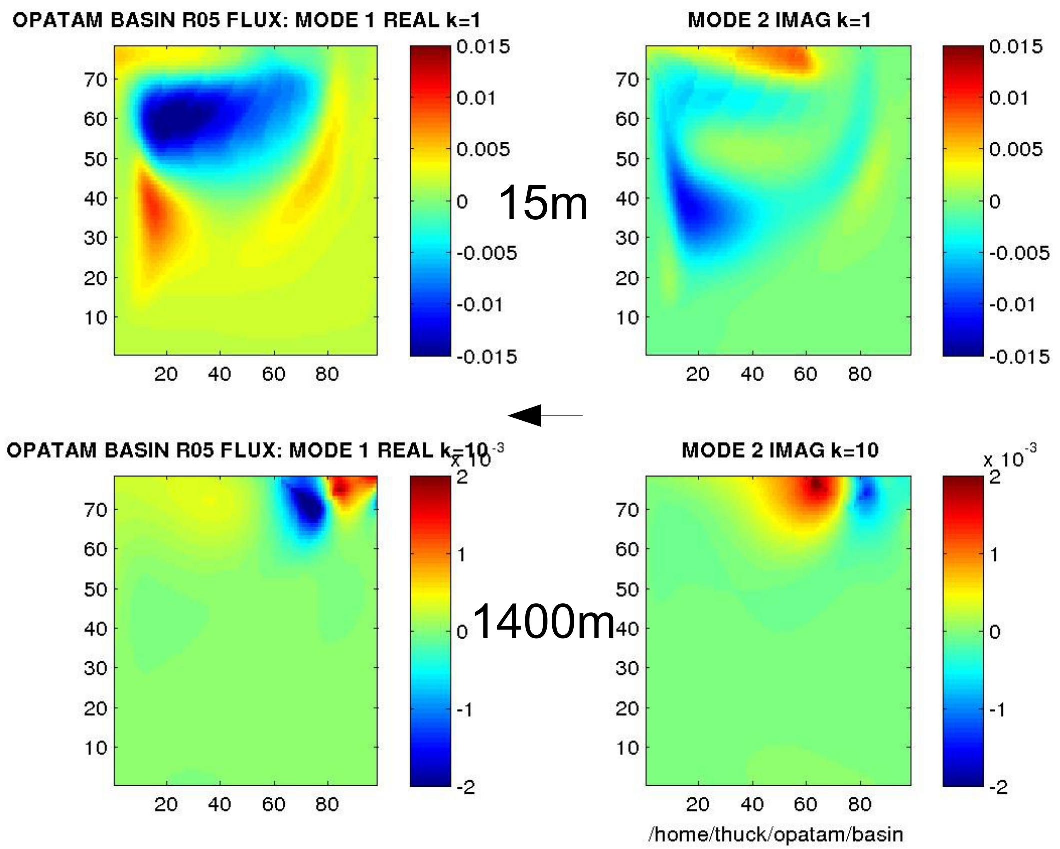
►Plan to use some of these methods to find leading modes on mean state/seasonal cycle from various models: ORCA025...
- link between model variability and leading eigenmodes?

Linear Stability Analysis with OPATAM+ARPACK



leading eigenvalues spectrum →
one unstable mode, period 37yr
growth time scale 109yr

t+9yr t



►full LSA of an idealized basin configuration of OPA, in good agreement with results obtained in planetary geostrophic dynamics (Huck&Vallis 2001)

►now at 1/2° resolution to test timing & methods before moving to ORCA2 realistic configuration

Issues

With increasing model resolution,
- large-scale instabilities usually grow/decay slowly O(1-100 yr)
- mesoscale instabilities grow fast O(20d) on scales nxRd

►a linearized model with eddy-resolving parameters may only see the latter.

Two approaches:
A. remain at low-resolution and parameterize the eddies (now)
B. use eddy-resolving models but filter the scale of the perturbations for LSA (next?)

Practical issues right now

A1. project/interpolate HR model outputs on LR model grid... (not tested yet because annual-cycle trajectory necessary for the tangent model)
A2. use robust-diagnostic LR simulation to hopefully match HR state? (usually difficult to be satisfied with both tracer and velocity fields/MOC...)
presently using seasonal cycle with strong O(30-60d) 3D restoring decaying/depth.

B2. perform analysis on high-resolution model with some filter on the scale (NEMOTAM parallelized),
B1. filtering to be tested in a shallow-water model first

Conclusions

►at least 2 processes generating **intrinsic** Low-Frequency Oceanic Variability:
- wind-forced eddy-driven variability (interannual, intergyre)
- multidecadal oscillations of the "thermohaline" circulation when forced by prescribed fluxes of buoyancy instead of restoring surface properties (more appropriate for the largest scales)

We believe these are generic property of the ocean circulation as soon as the amplitude of the forcing is large enough and/or the damping through diffusivity/viscosity low enough.

►can we distinguish eddy-driven vs large-scale processes?
the latter results from a linear instability of the large-scale circulation...

►how sensitive are least damped modes to mean circulation, model resolution, sub-grid-scale parameterizations, seasonal cycle?

References cited

Arzel, O., M. H. England, A. Colin de Verdière, and T. Huck, 2012: Abrupt millennial variability and interdecadal-interstadial oscillations in a global coupled model: sensitivity to the background climate state. Clim. Dyn., 39, 259-275.*

Buckley, M. W., D. Ferreira, J.-M. Campin, J. Marshall, and R. Tulloch, 2012: On the relationship between decadal buoyancy anomalies and variability of the Atlantic meridional overturning circulation. J. Clim., 25, 8009-8030.

Huck, T., G. K. Vallis, and A. Colin de Verdière, 2001: On the robustness of the interdecadal modes of the thermohaline circulation. J. Clim., 14, 940-963.*

Huck, T., and G. K. Vallis, 2001: Linear stability analysis of the three-dimensional thermally-driven ocean circulation: application to interdecadal oscillations. Tellus, 53A, 526-545.*

Greatbatch, R. J., and S. Zhang, 1995: An interdecadal oscillation in an idealized ocean basin forced by constant heat flux. J. Clim., 8, 81-91.

Sévellec, F., T. Huck, M. Ben Jelloul, N. Grima, J. Vialard, and A. Weaver, 2008: Optimal surface salinity perturbations of the meridional overturning and heat transport in a global ocean general circulation model. J. Phys. Oceanogr., 38, (12) 2739-2754,*

Sévellec, F., A. V. Fedorov, 2013: The leading, interdecadal eigenmode of the Atlantic meridional overturning circulation in a realistic ocean model. J. Clim.,26, 2160-2183.

te Raa, L. A., and H. A. Dijkstra, 2002: Instability of the thermohaline ocean circulation on interdecadal time scales. JPO, 32, 138-160.

*available on my website http://www.ifremer.fr/lpo/thuck/publis/publications.html