The leading, interdecadal eigenmode of the Atlantic overturning meridional circulation (AMOC) in a hierarchy of ocean and climate models

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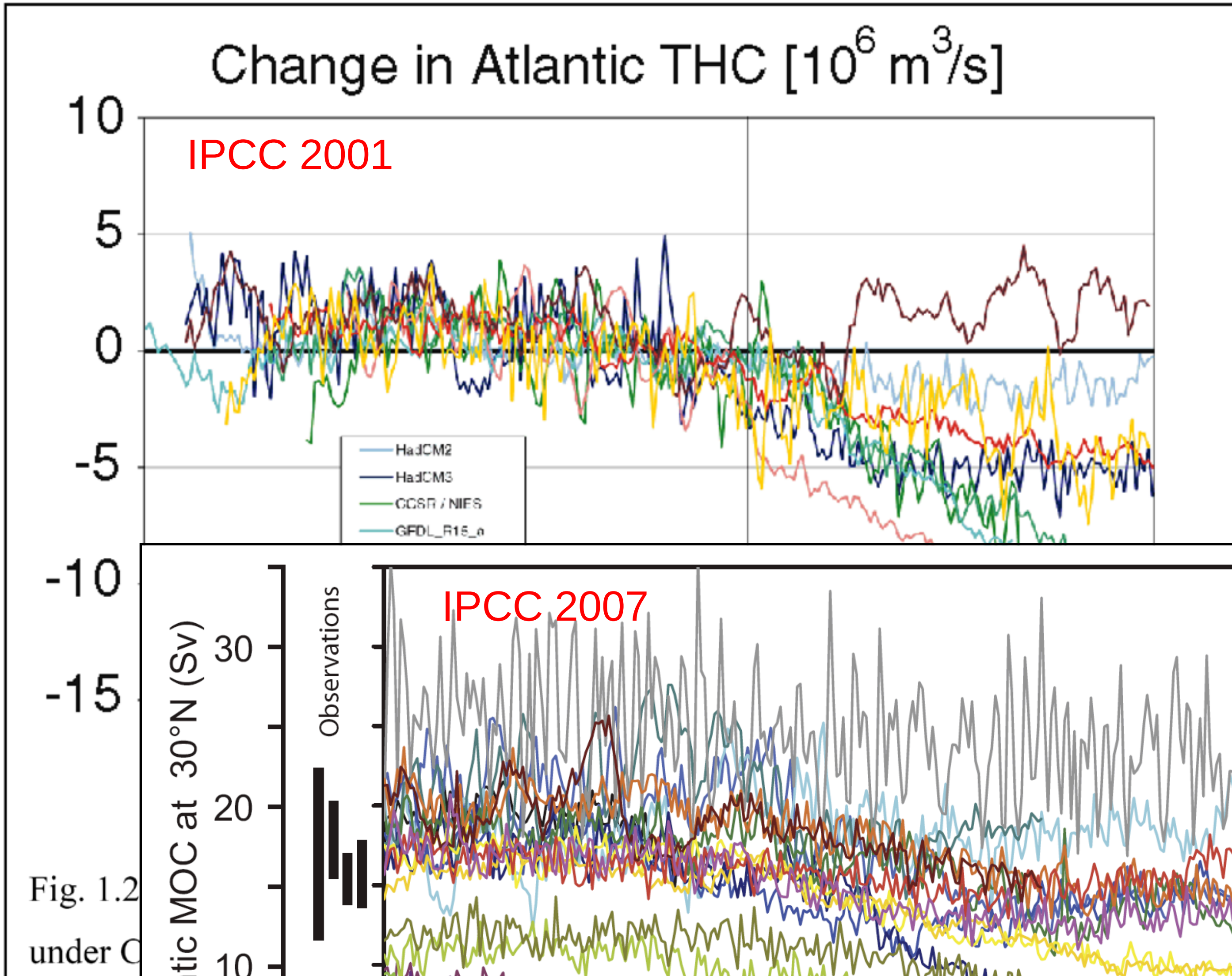
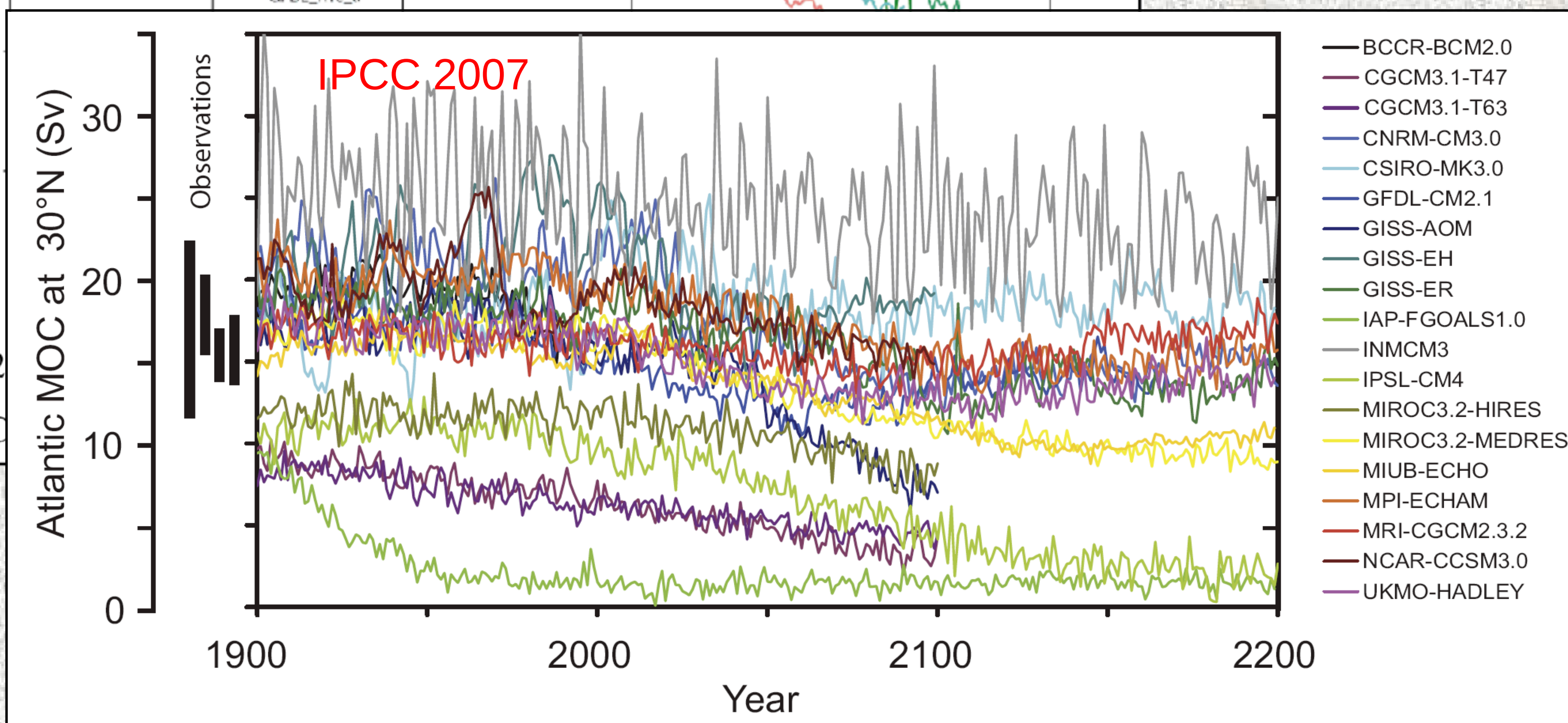
in collaboration with Florian Sevellec

Yale University

September 2011



AMOC decadal and multi-decadal variability



Potential mechanisms of AMOC variability related to ocean dynamics:

- ***Emphasis on meridional advection of salinity anomalies (possibly longer periods):***

Yoshimori et al. 2010, Latif et al. 1997, Dong and Sutton 2005, D'Orgeville and Peltier 2009, Msadek and Frankignoul 2009, Frankignoul et al. 2009, Cheng et al. 2004, Danabasoglu 2008, Sirkes and Tziperman 2001 …

- ***Emphasis on (westward) propagation of temperature anomalies in the North Atlantic:***

Huck et al. 1999, Colin de Verdière and Huck 1999, Marshall et al 2000, te Raa and Dijkstra 2002, Dijkstra et al. 2006, Frankcombe et al. 2009, Sévellec et al. 2009 …

Goal:

*To extract the leading AMOC interdecadal (**eigen)**mode related to ocean dynamics and explore how it is excited in realistic ocean and climate models*

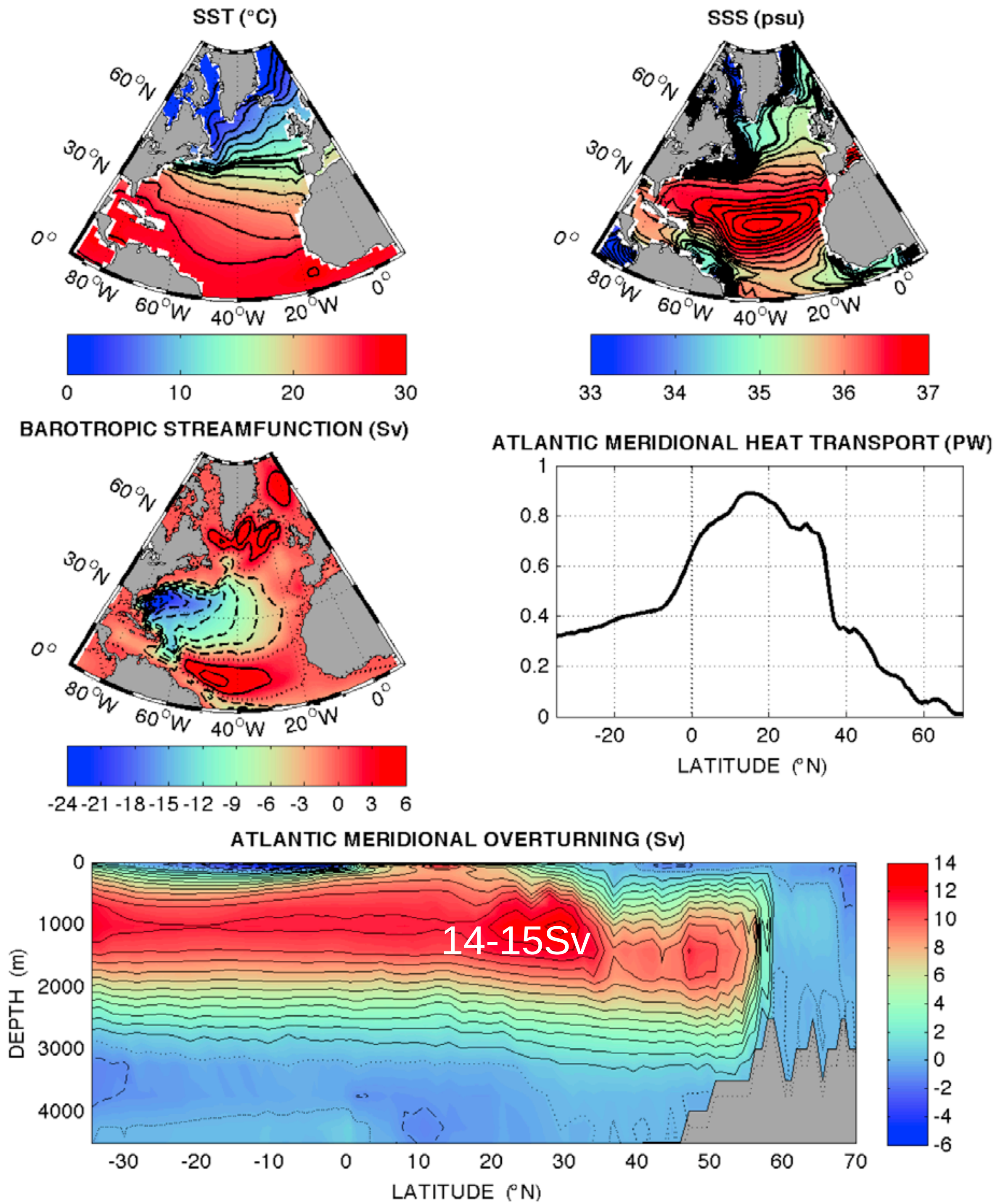
Approach:

Ocean GCM and its tangent linear and adjoint versions (OPA)

Simple two-layer models

Coupled GCM: IPSL-CM5 (OPA + LMD5)

CCSM3 and CESM and other models in CMIP3 and 5



Ocean GCM:

OPA 8.2
2º global configuration
31 levels
(ORCA2)

We used tangent linear and adjoint versions of the model

1. Ocean GCM :

$$\frac{d\mathbf{X}}{dt} = F(\mathbf{X}, t)$$

Non-autonomous

X - the state vector of the ocean

2. Linearize

$$\frac{d\mathbf{x}'}{dt} = \left.\frac{\partial F}{\partial \mathbf{X}}\right|_{\mathbf{X}_o} \mathbf{x}'$$

$\mathbf{X} = \mathbf{X}_o + \mathbf{x}'$

$\mathbf{X}_o$ - seasonally varyi

x' - anomalies

3. Integrate between t_1 and t_2

$$\mathbf{x}(t_2) = \mathbf{M}(t_1, t_2)\mathbf{x}(t_1)$$

M - the linear propagator of the system

4. Eliminate the seasonal cycle from $\mathbf{M}$

$\tilde{\mathbf{M}} = \mathbf{M}(t, t + n \cdot year)$ $\;->$ *a Poincare section,*

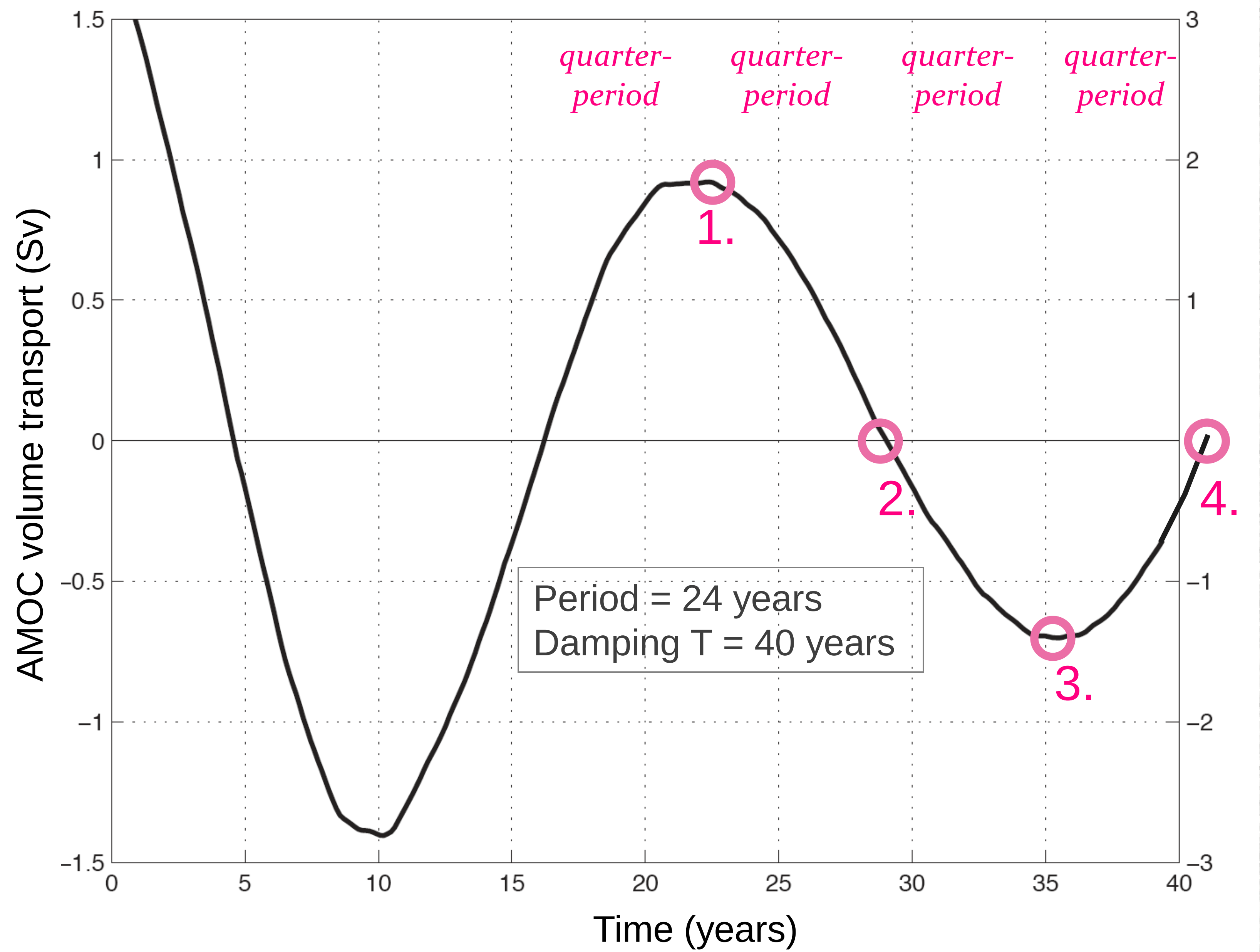
e.g. consider $\mathbf{M}$ *on every Jan* 1

5. Calculate eigenvectors and eigenvalues of $\tilde{\mathbf{M}}$

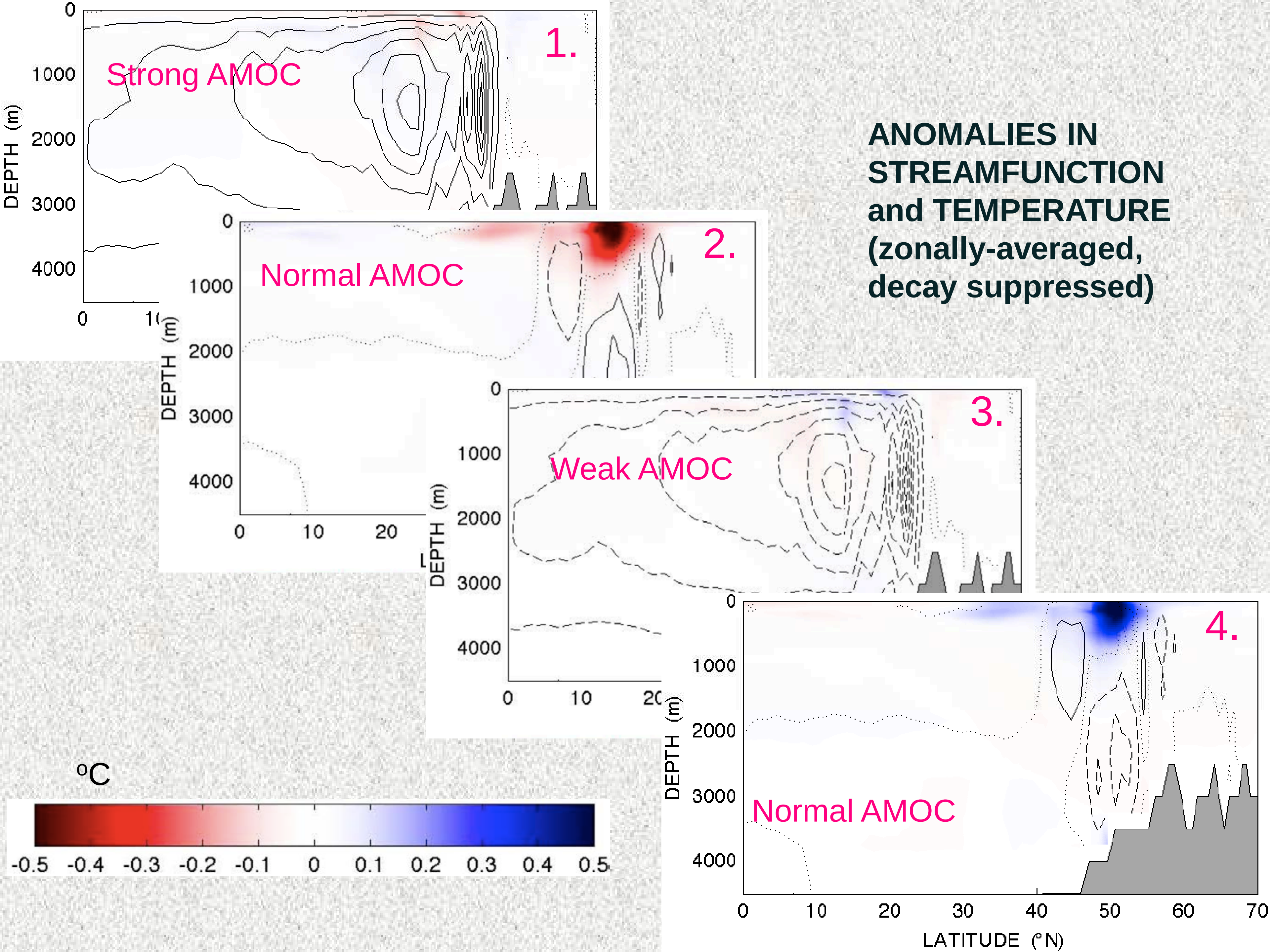
6. Calculate an adjoint to $\tilde{\mathbf{M}}$

7. Identify the least damped eigen-mode and obtain its optimal initial perturbations in temperature or salinity

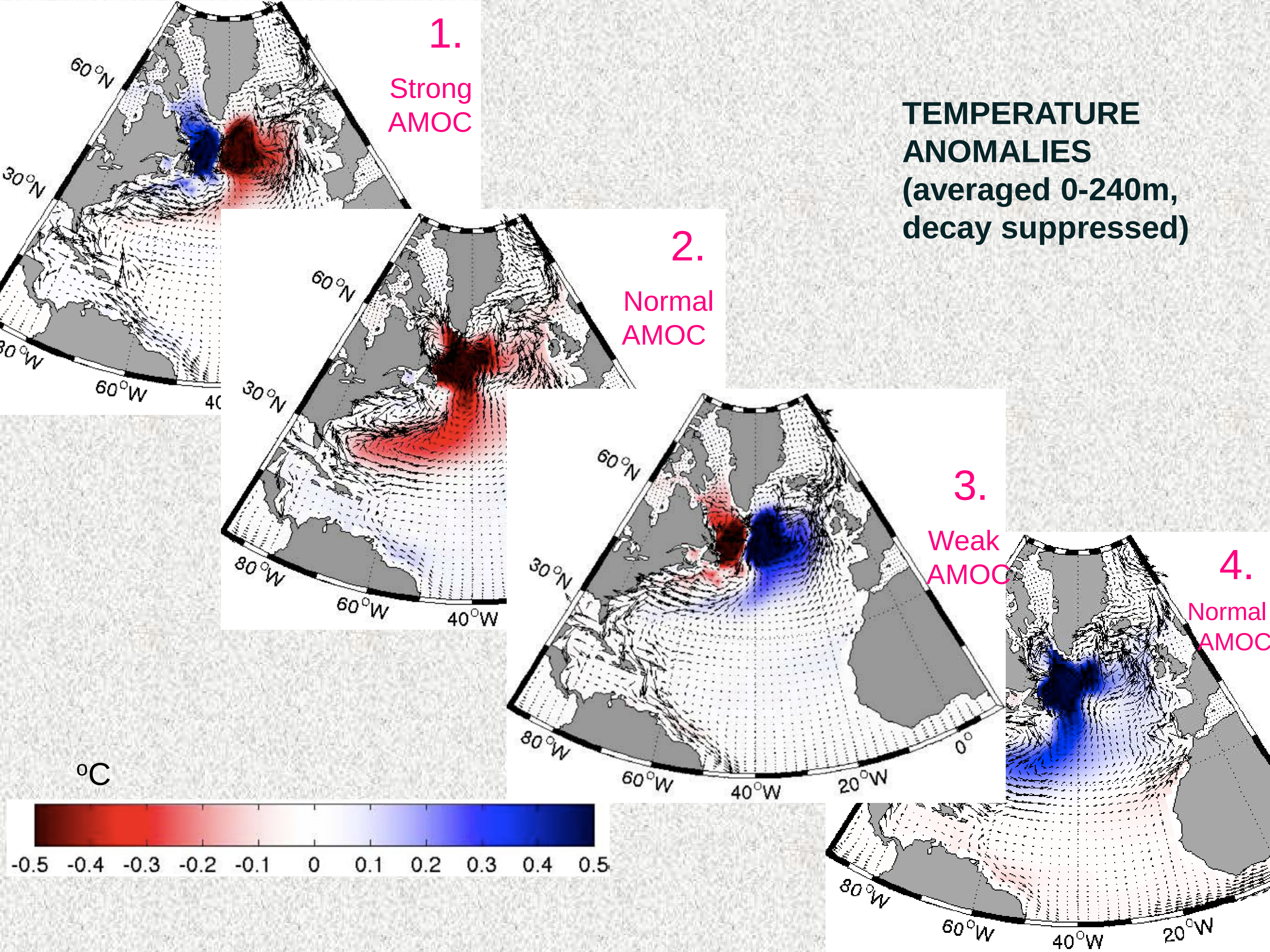
The least-damped mode: AMOC variations

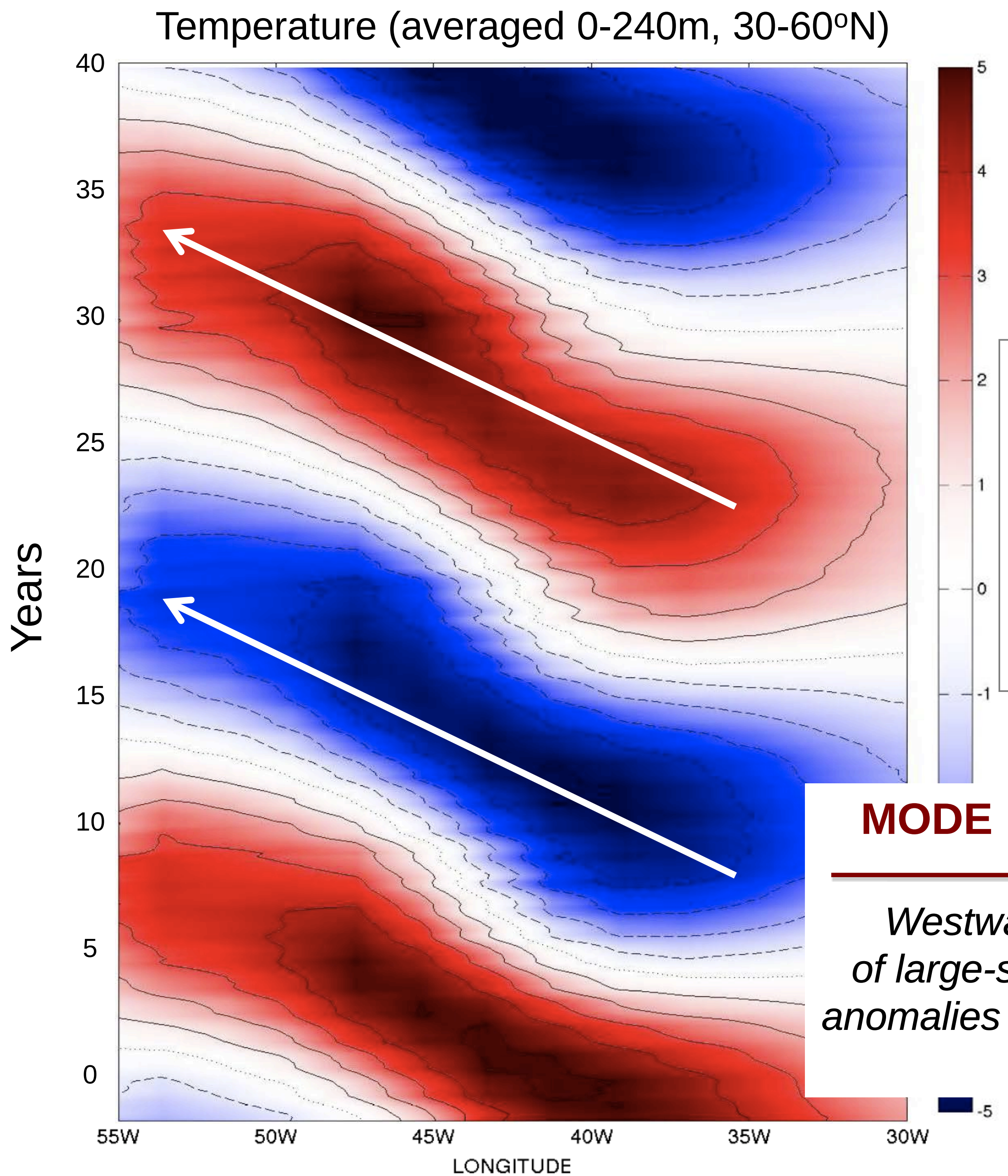


ANOMALIES IN STREAMFUNCTION and TEMPERATURE (zonally-averaged, decay suppressed)



TEMPERATURE ANOMALIES (averaged 0-240m, decay suppressed)





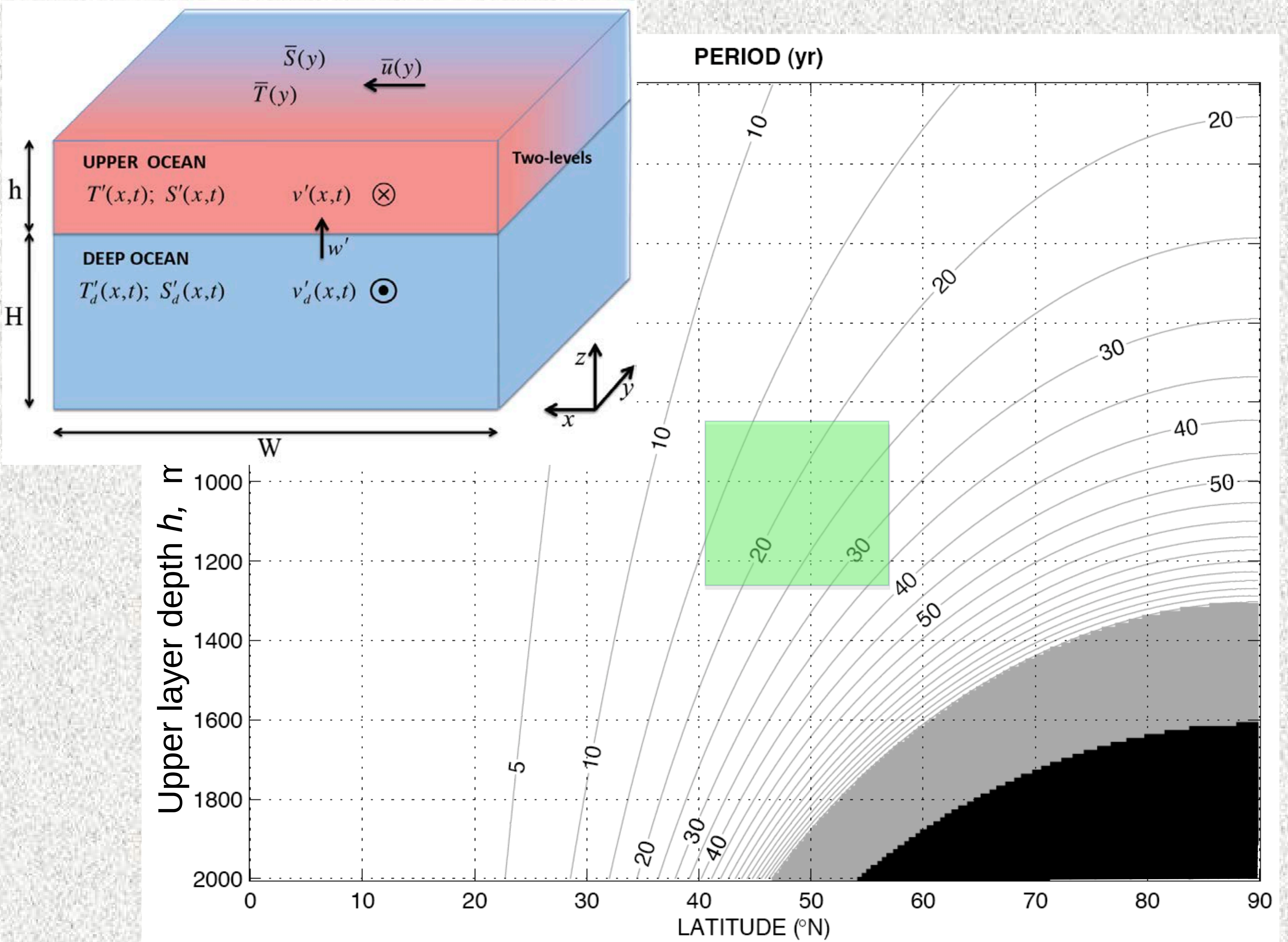
Hovmoller diagram for temperature anomalies;

Decay suppressed

MODE MECHANISM:

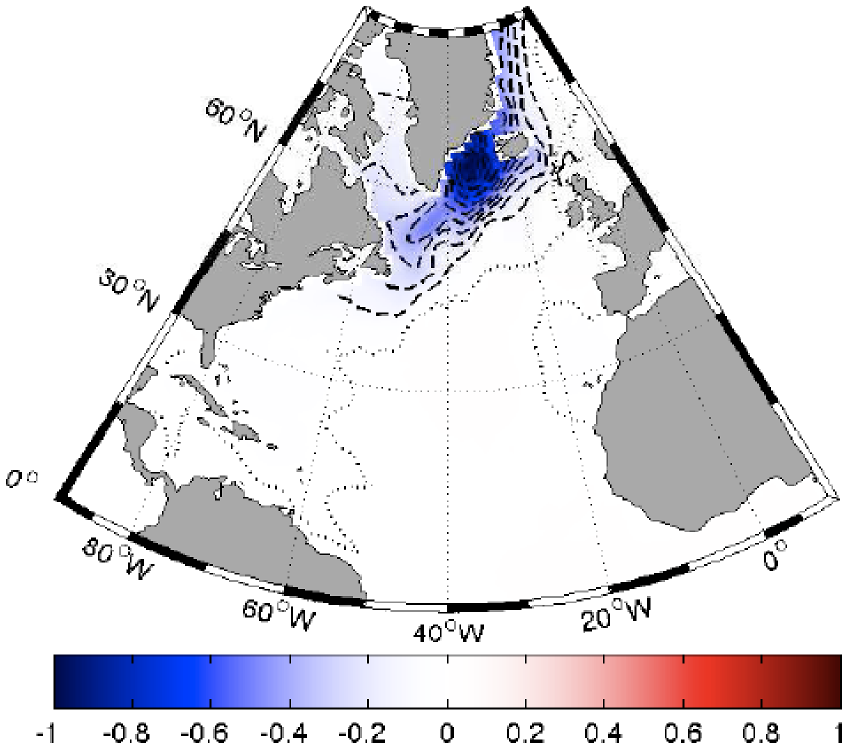
Westward propagation of large-scale temperature anomalies interacting with the AMOC

OSCILLATION PERIOD: idealized 2-layer model

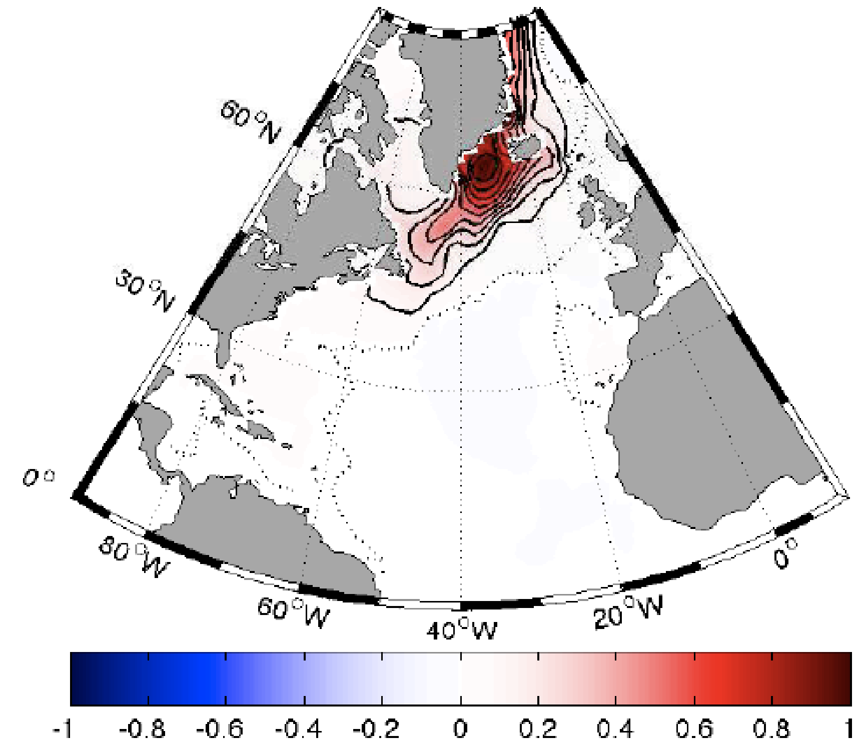


OPTIMAL INITIAL PERTURBATIONS

Optimal SST anomalies

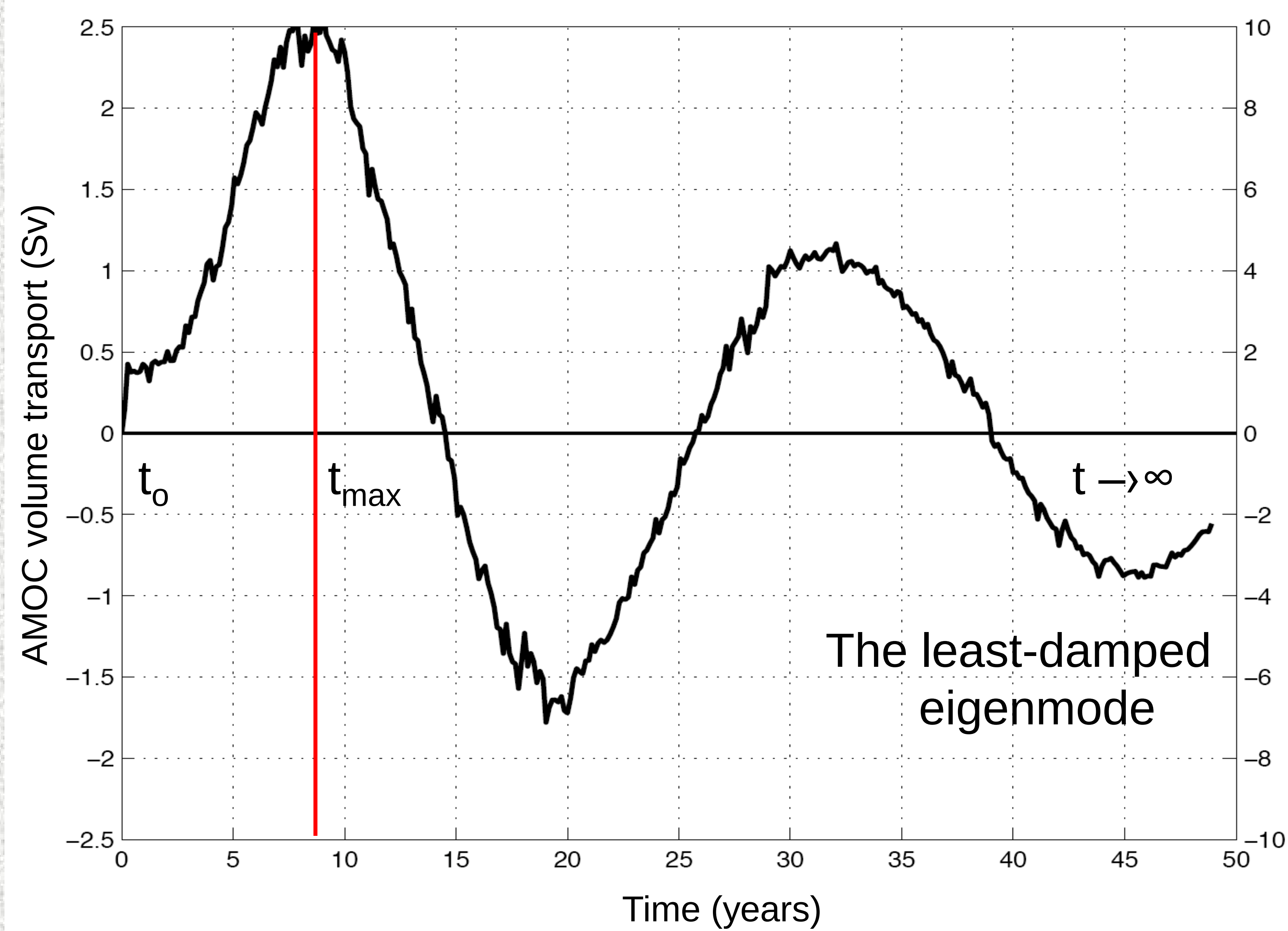


Optimal SSS anomalies

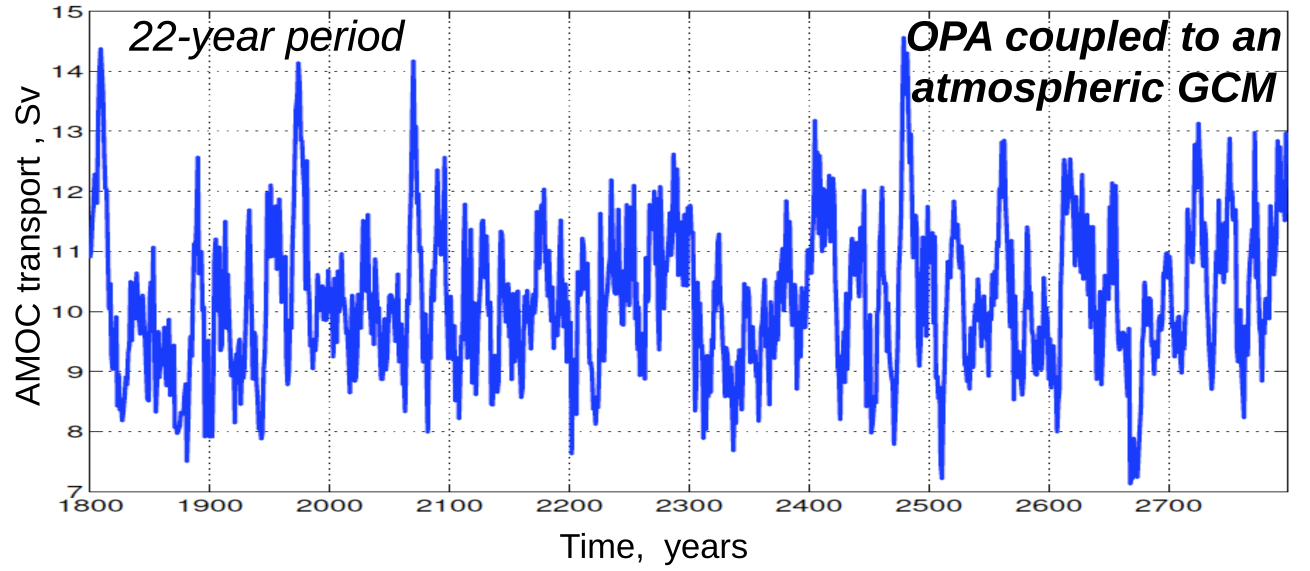


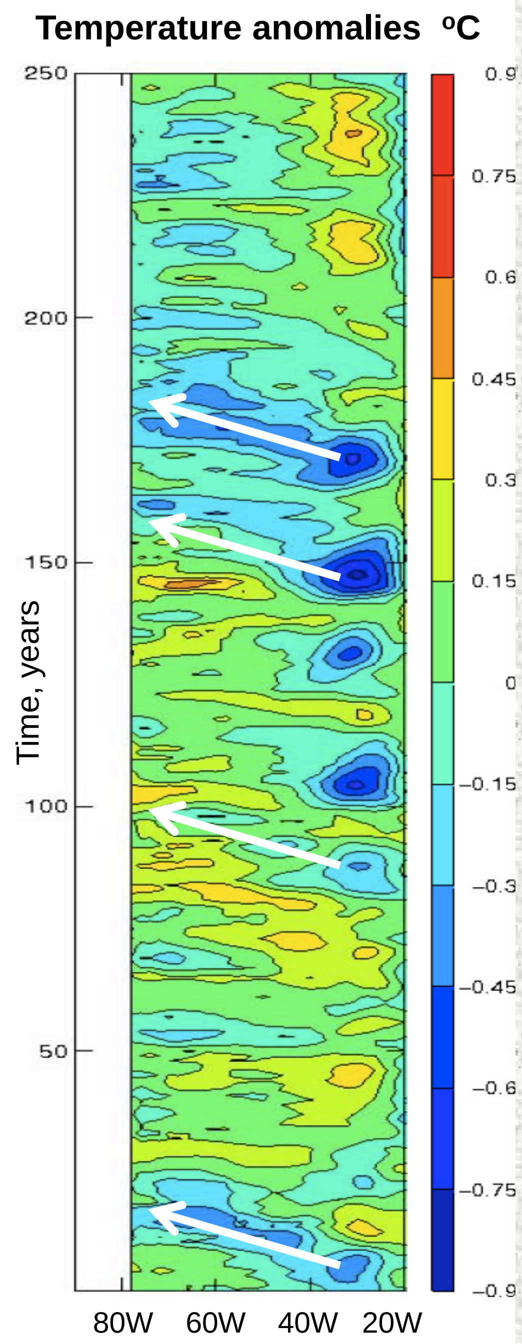
MODE EXCITATION:

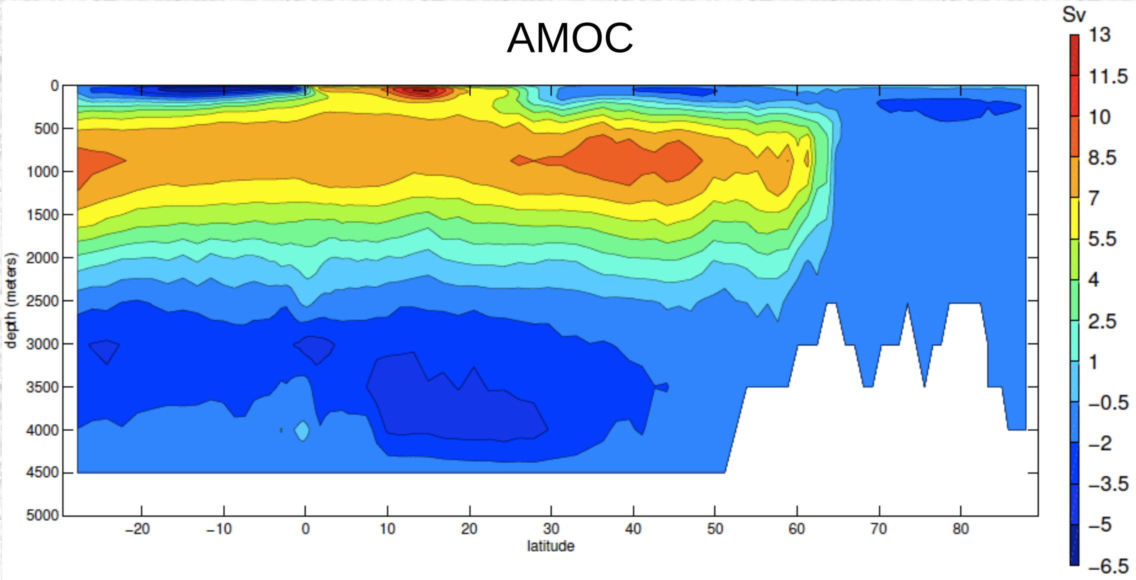
Initial salinity perturbations are the most efficient


AMOC volume transport (Sv)
Time (years)
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
10
8
6
4
2
0
−2
−4
−6
−8
−10
0
5
10
15
20
25
30
35
40
45
50
t_o
t_{max}
t –› ∞
The least-damped
eigenmode

COUPLED GCM: IPLS-CM5

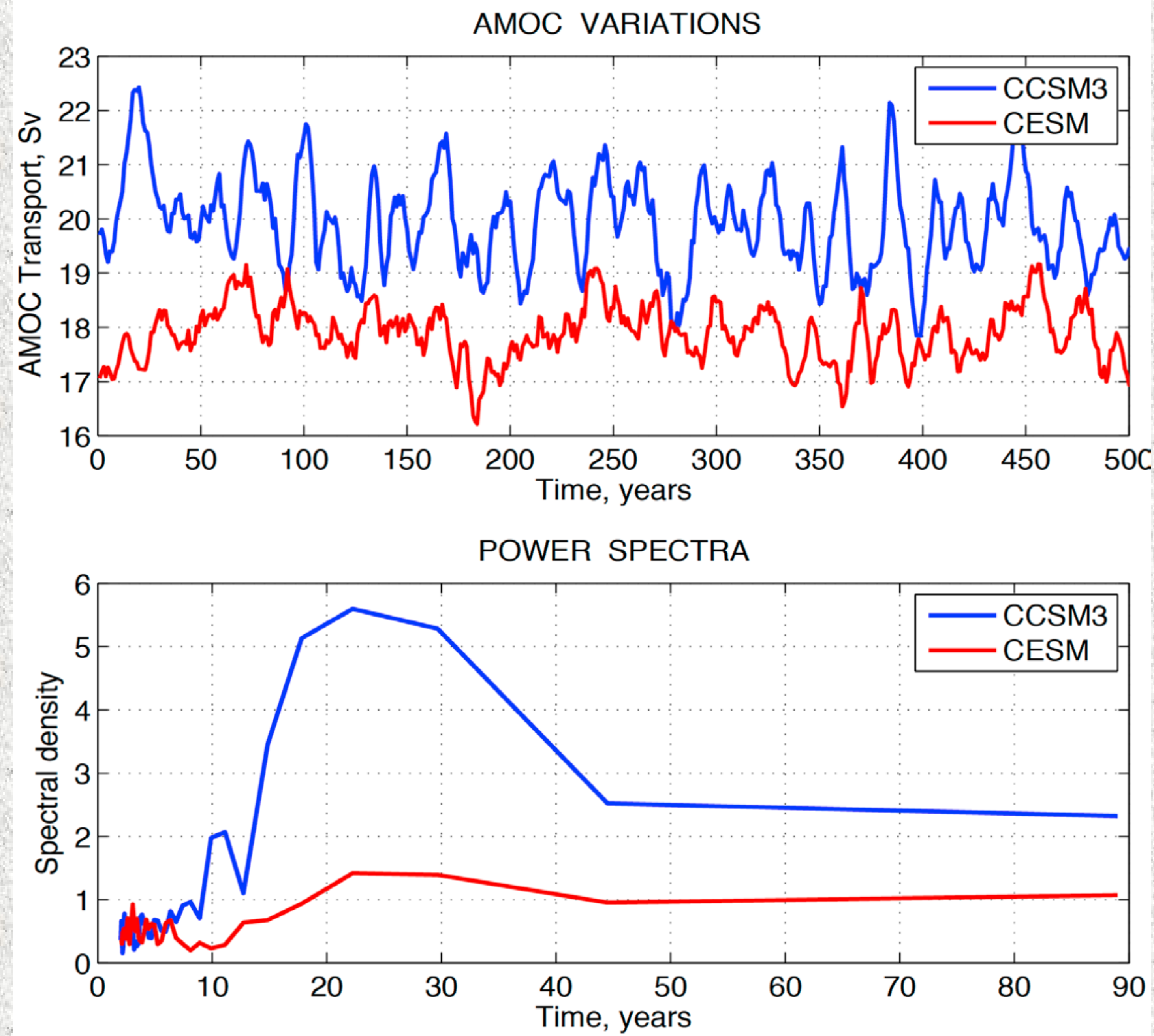






In collaboration with Juliette Mignot, IPSL, France

COUPLED GCM: CCSM3 and CESM



Summary

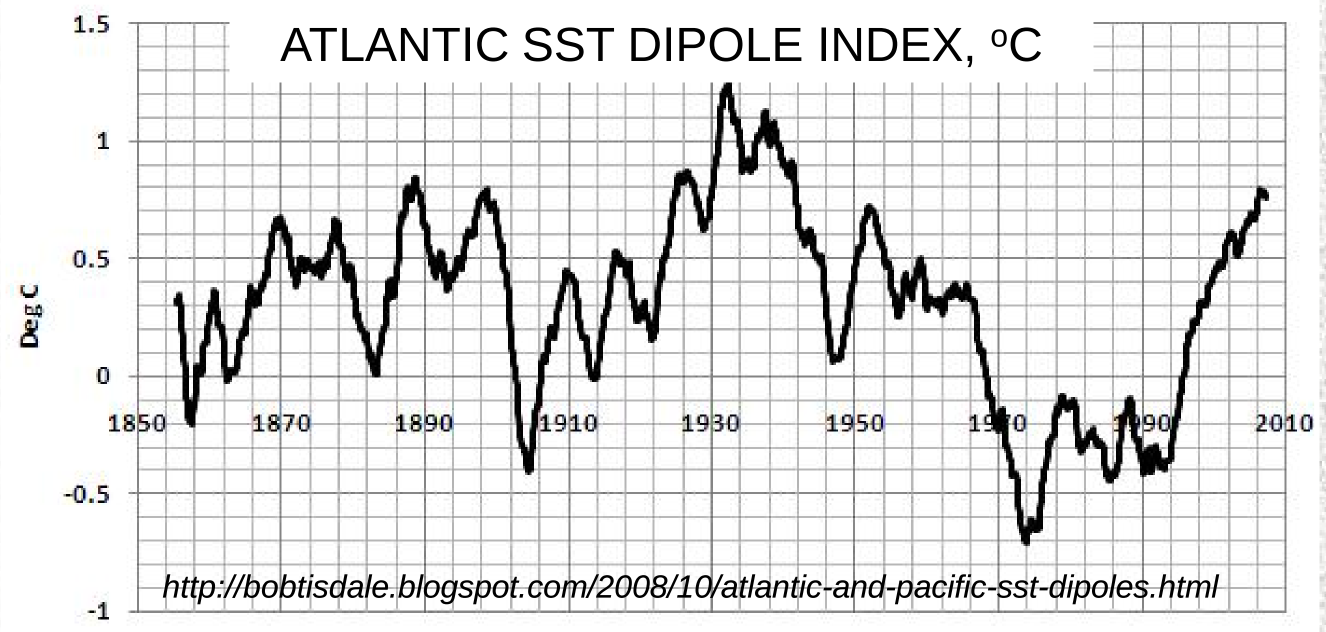
- *We have rigorously identified the leading, interdecadal weakly-damped oscillatory eigenmode of the AMOC in a realistic ocean model (T≈ 24 years)*

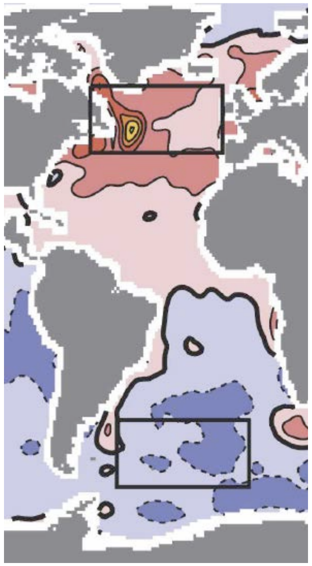
- *The mode mechanism is related to westward-propagating temperature anomalies in the upper ocean in the northern Atlantic that interact with the AMOC*

- *The mode can be efficiently excited by optimum salinity (or temperature) perturbations centered east of Greenland and south of the Denmark strait*

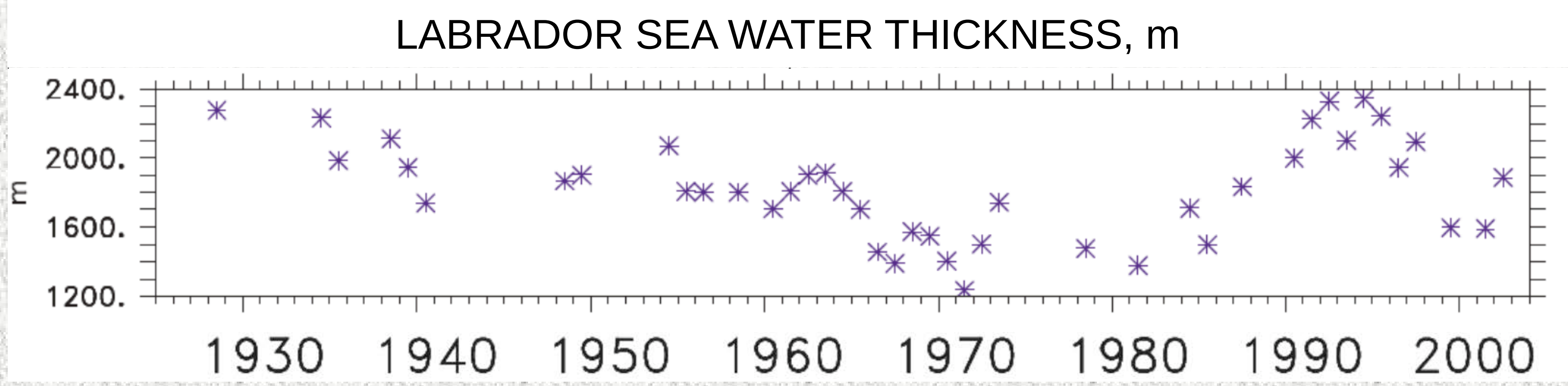
- *This eigenmode appears to be present and robust in coupled models (IPSL-CM5, CCSM3, CESM,…)*

- ***Claim**: Interdecadal AMOC variability in coupled GCMs depends on the strength of (1) the damping of this eigenmode and (2) the projection of atmospheric forcing onto the optimal perturbations*





Latif et al 2006



Curry et al 1998

IDEALIZED MODEL

$$\frac{\partial T'}{\partial t} = -\left(\overline{U} + c_{rossby} + U'\right)\partial_x T' + k\partial_{xx} T'$$

where T' - *temperature anomaly at the upper level*

Zonal propagation speed of temperature anomalies

$$c = \overline{U} + U' + c_{rossby}$$

h - *upper layer thickness*

α - *thermal expansion*

g - *acceleration of gravity*

f - *Coriolis parameter*

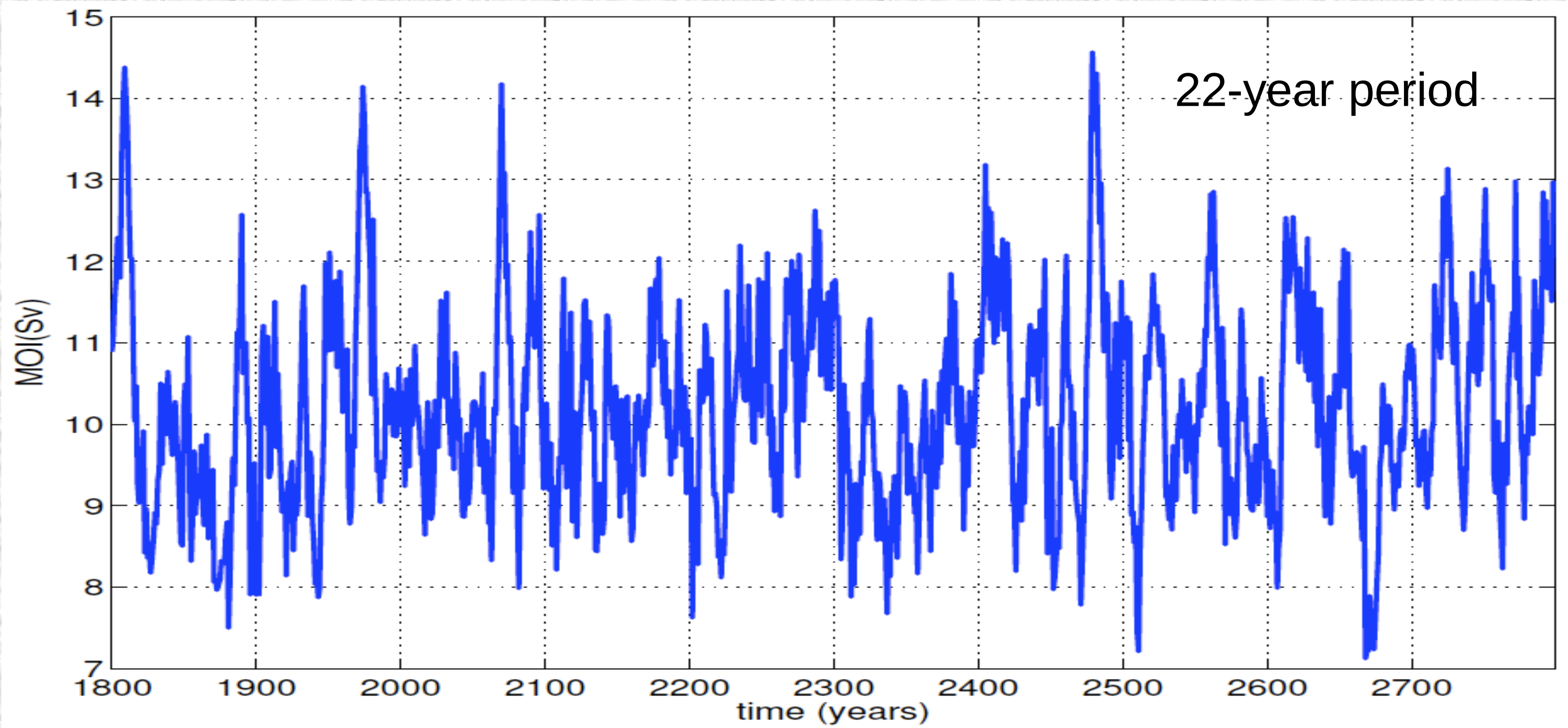
k - *horizontal diffusivity*

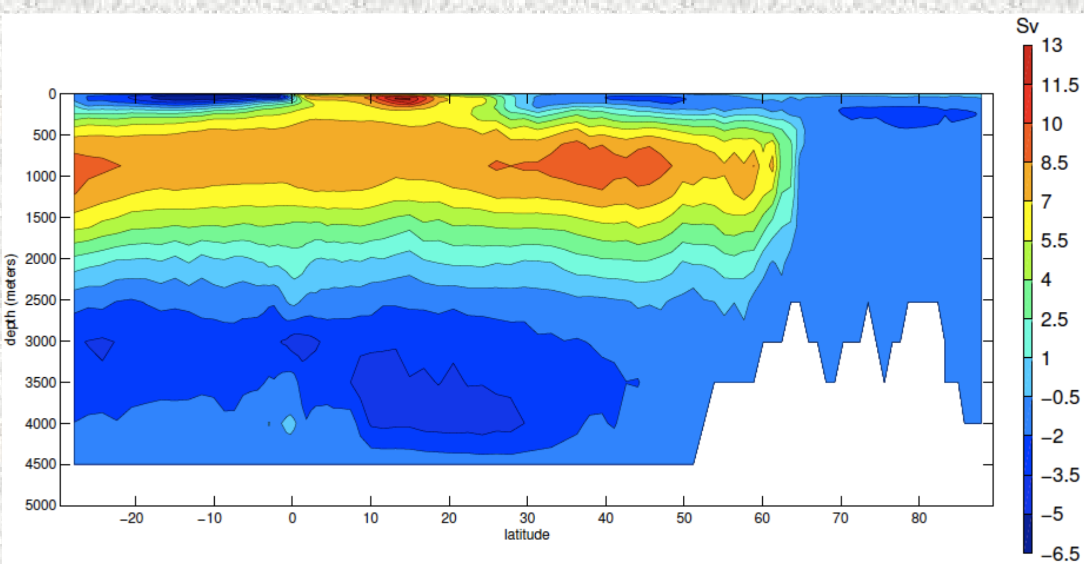
$\overline{U}$ - *mean eastward zonal advection*

$$U' = \frac{\alpha g h}{f}\partial_y \overline{T}$$ - *effective amomalous westward advection*

c_{rossby} - *long baroclinic Rossby wave speed (the* β*-effect)*

COUPLED GCM

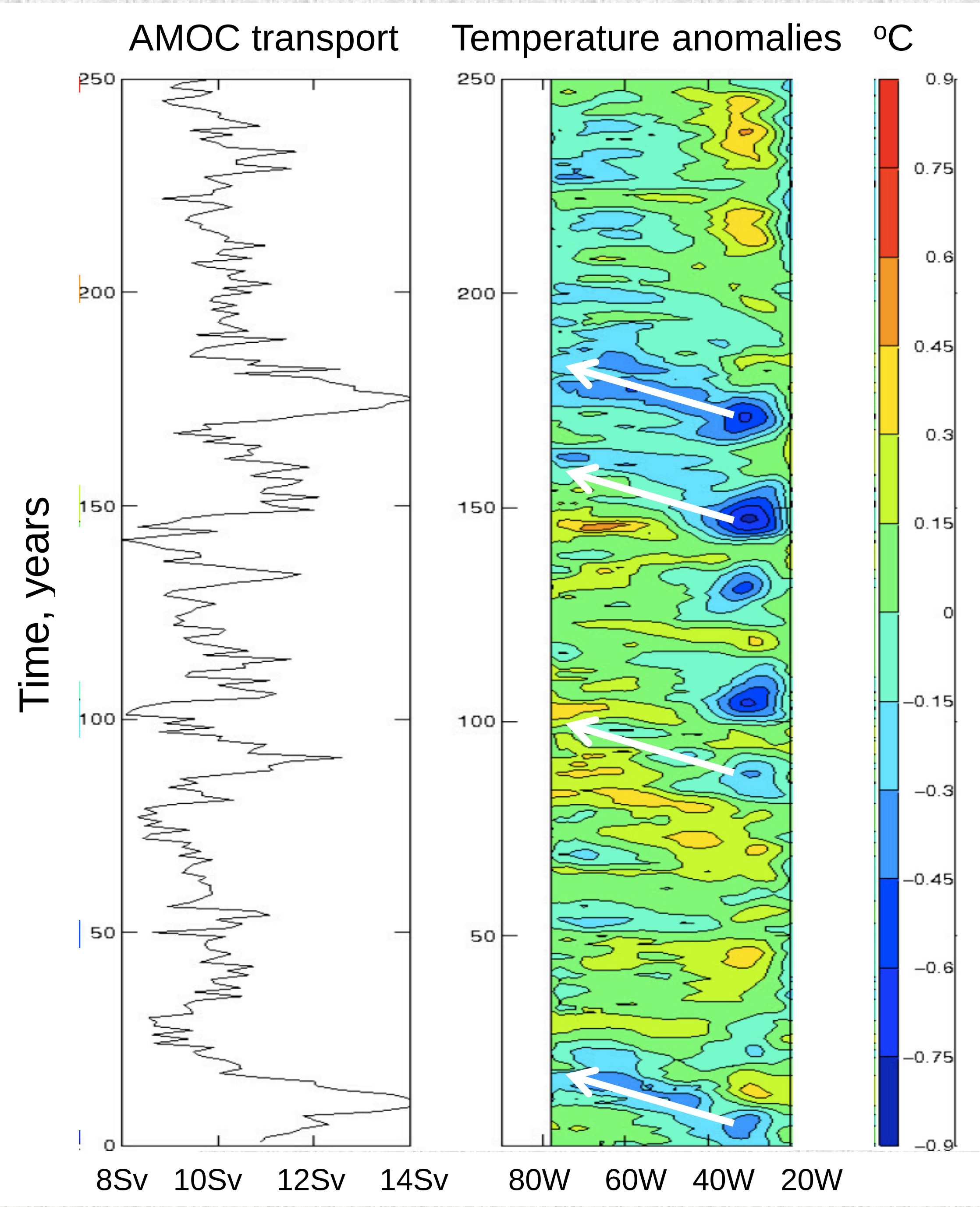




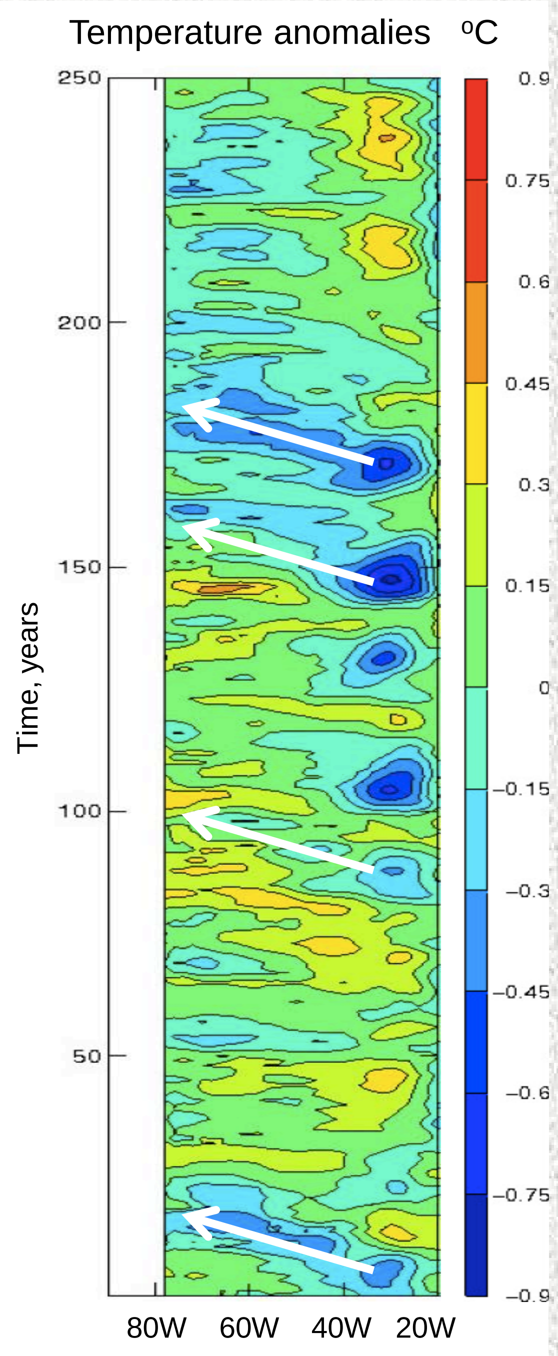
OPA
coupled to a full
atmospheric GCM =
IPSL coupled model

In collaboration with Juliette Mignot

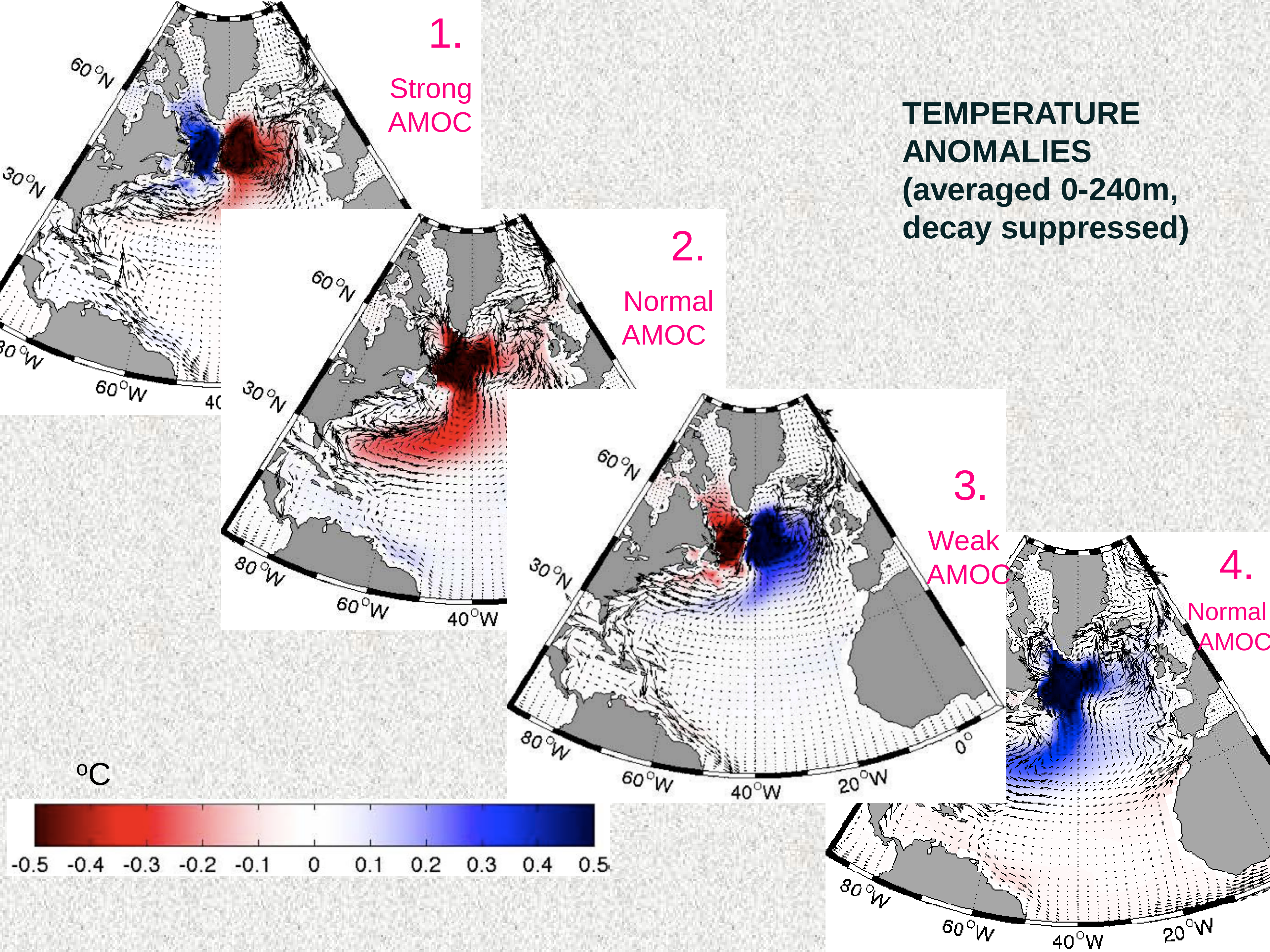
AMOC volume transport and 500m-averaged temperature anomalies averaged between 30N and 60N in the IPSLCM5A coupled model



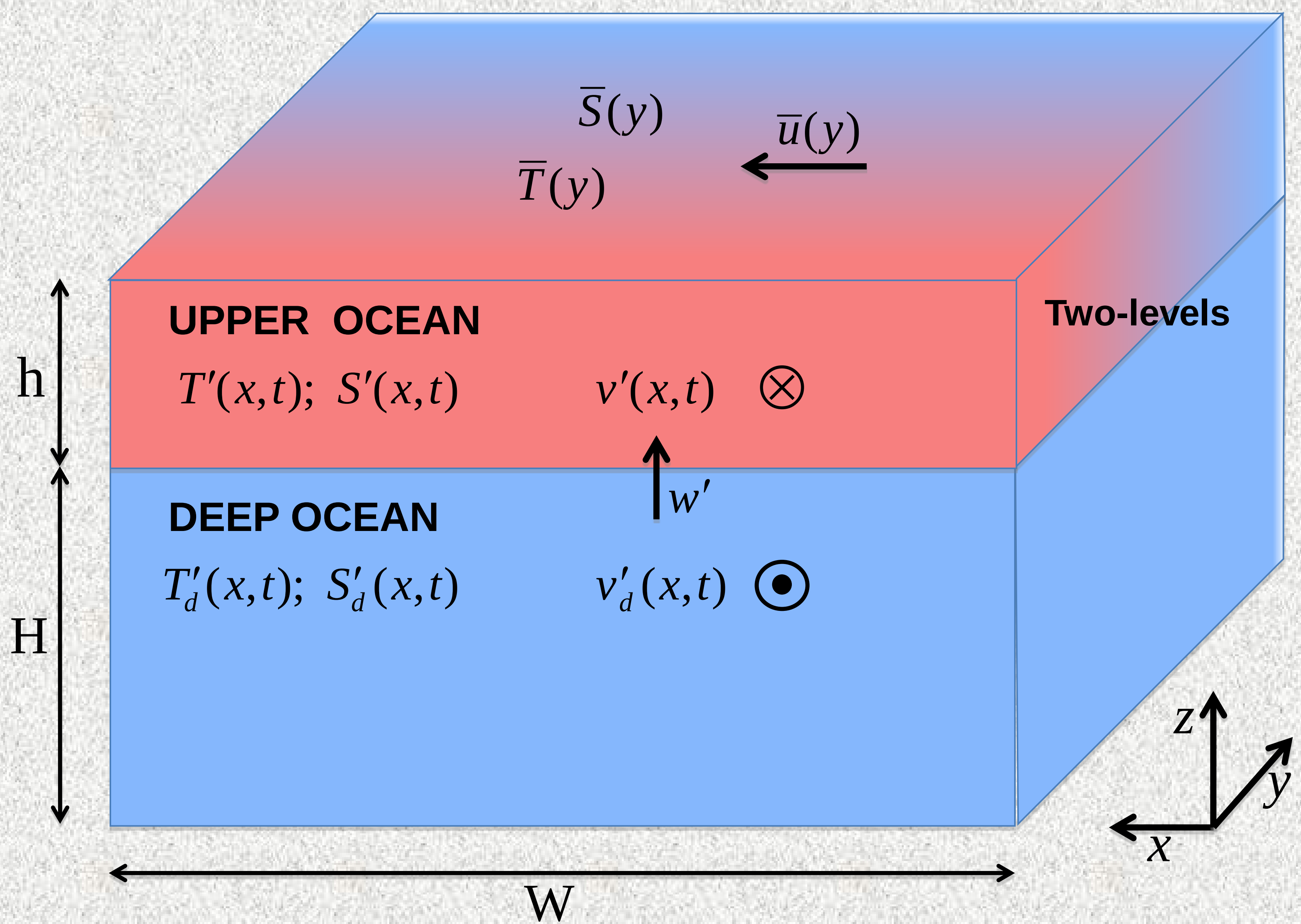
AMOC volume transport and 500m-averaged temperature anomalies averaged between 30N and 60N in the IPSLCM5A coupled model



TEMPERATURE ANOMALIES (averaged 0-240m, decay suppressed)

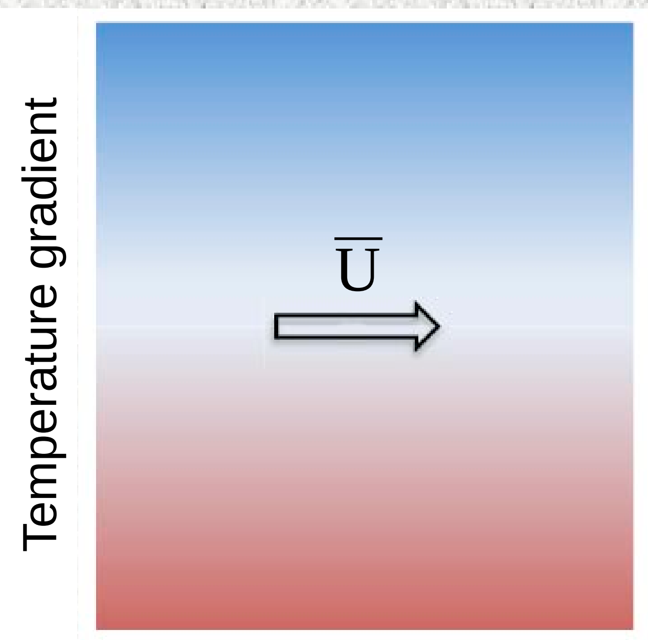


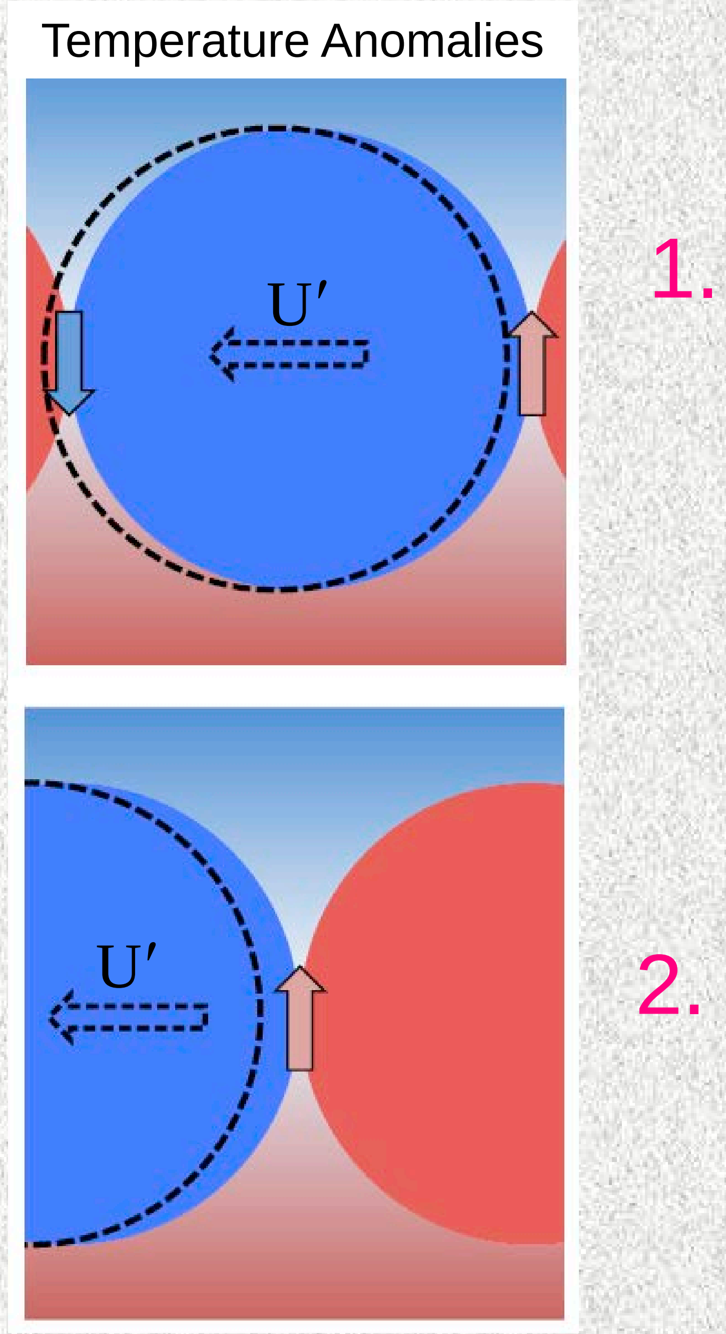
IDEALIZED MODEL

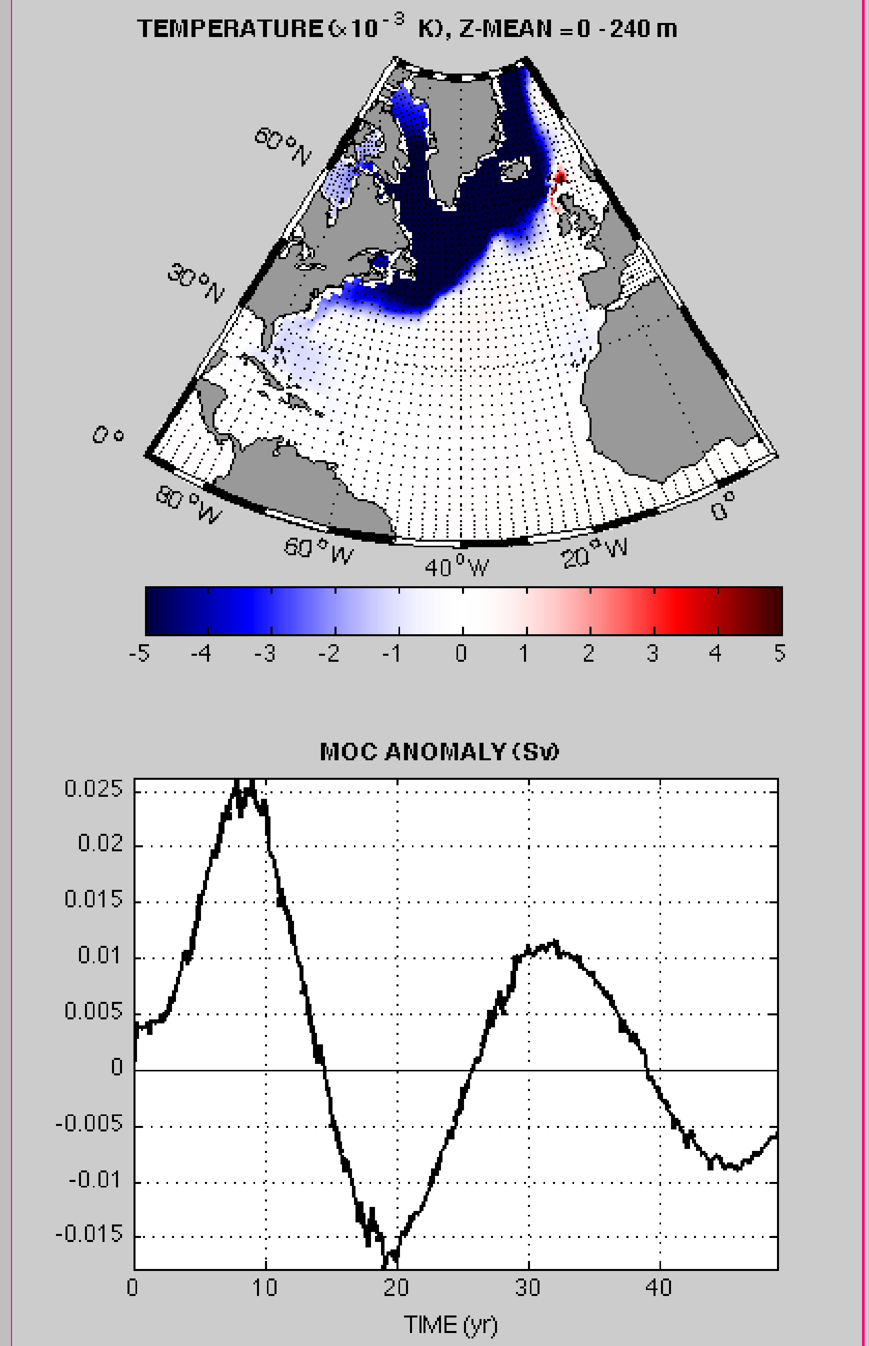


MODE MECHANISM:

Westward propagation of large-scale temperature anomalies

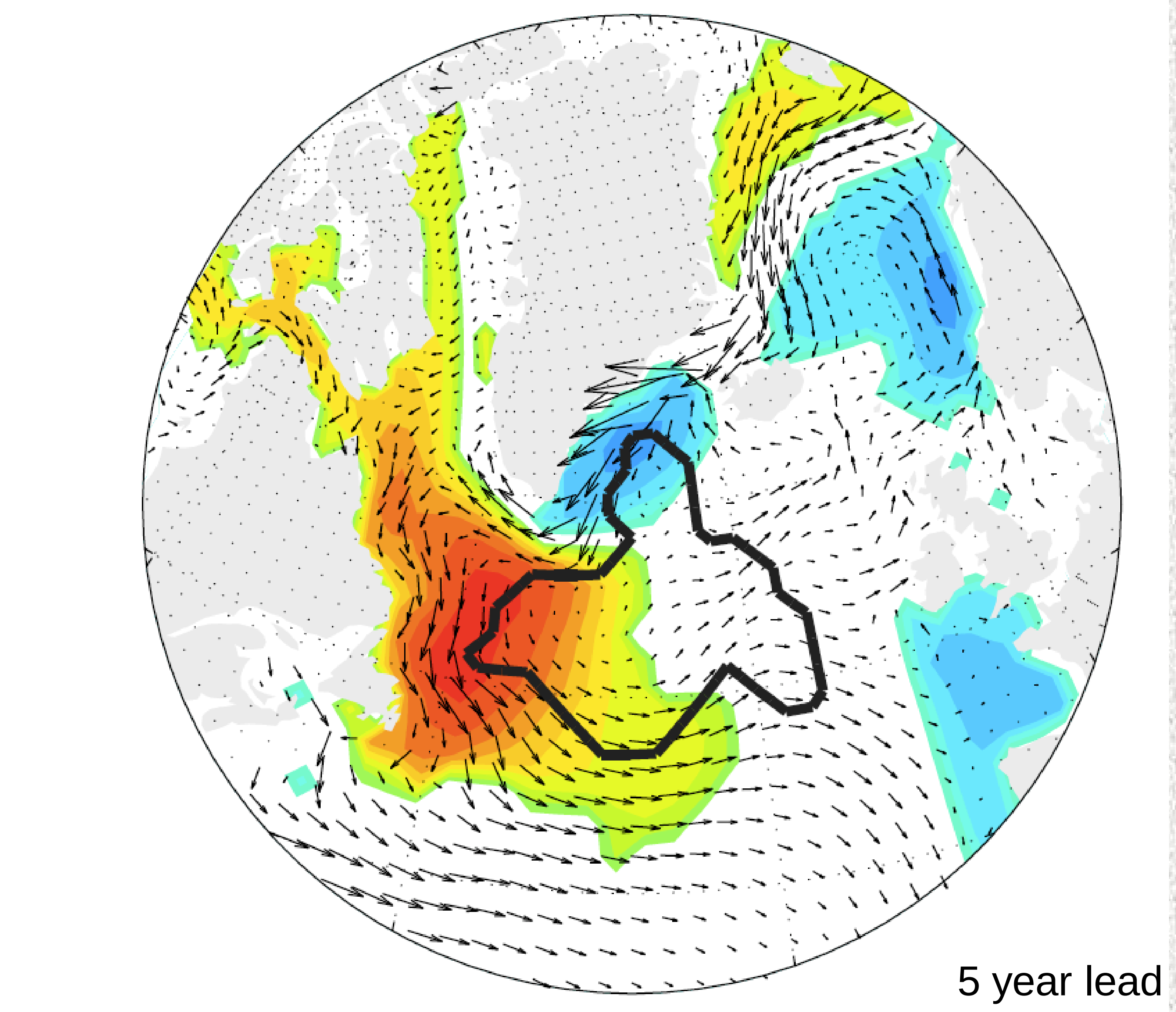




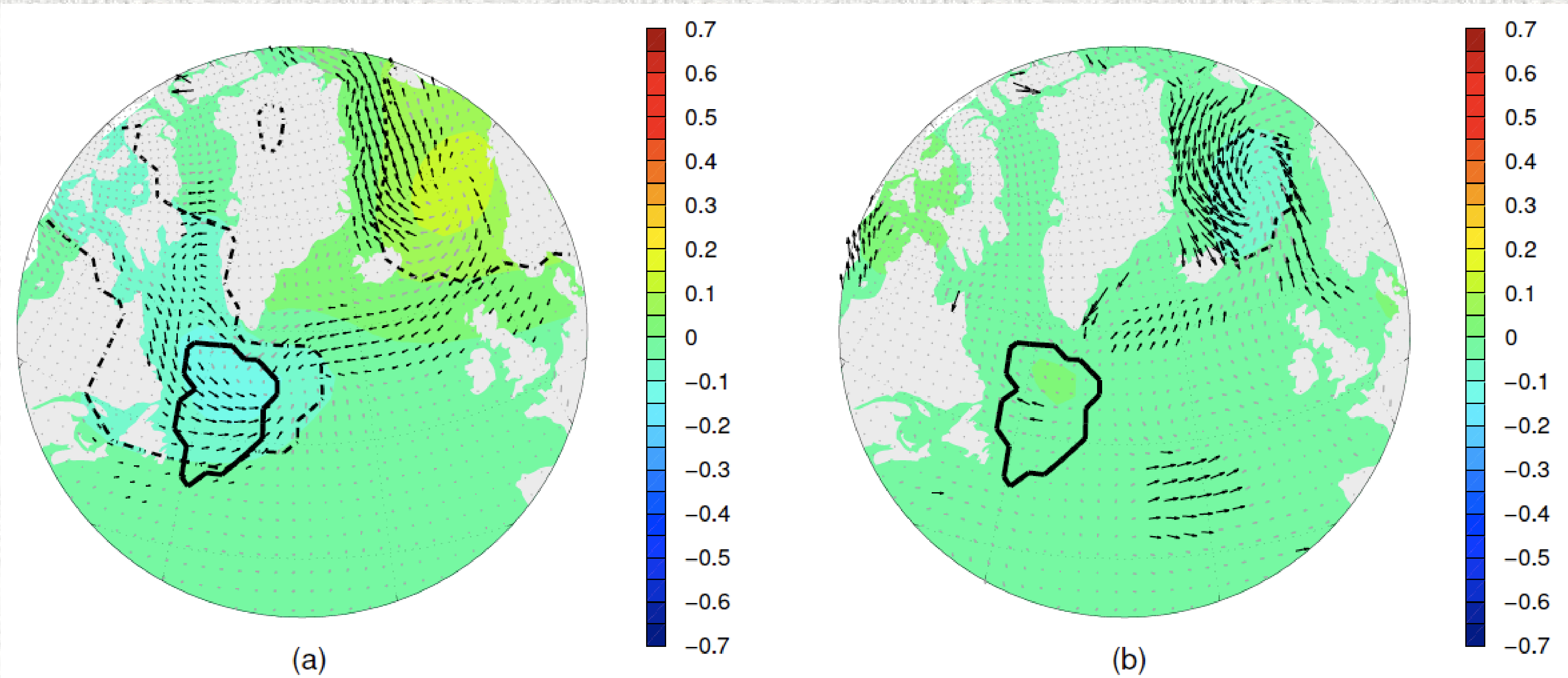


TEMPERATURE (x10⁻³ K), Z-MEAN = 0 - 240 m
60°N
30°N
0°
80°W
60°W
40°W
20°W
0°
-5 -4 -3 -2 -1 0 1 2 3 4 5
MOC ANOMALY (Sv)
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
0 10 20 30 40
TIME (yr)

Mode excitation



Mode excitation



IDEALIZED MODEL

T' - *temperature anomaly in the upper layer;*

v' - *meridional velocity anomaly*

$$\frac{\partial T'}{\partial t} = -\left(\overline{U} + c_{rossby}\right)\partial_x T' - v'\partial_y \overline{T} + k\partial_{xx} T'$$

$$v' = \frac{\alpha g h}{f}\partial_x T' \text{ - thermal wind balance}$$

$$\frac{\partial T'}{\partial t} = -\left(\overline{U} + c_{rossby} + U'\right)\partial_x T' + k\partial_{xx} T'$$

h - *upper layer thickness*

α - *thermal expansion*

g - *acceleration of gravity*

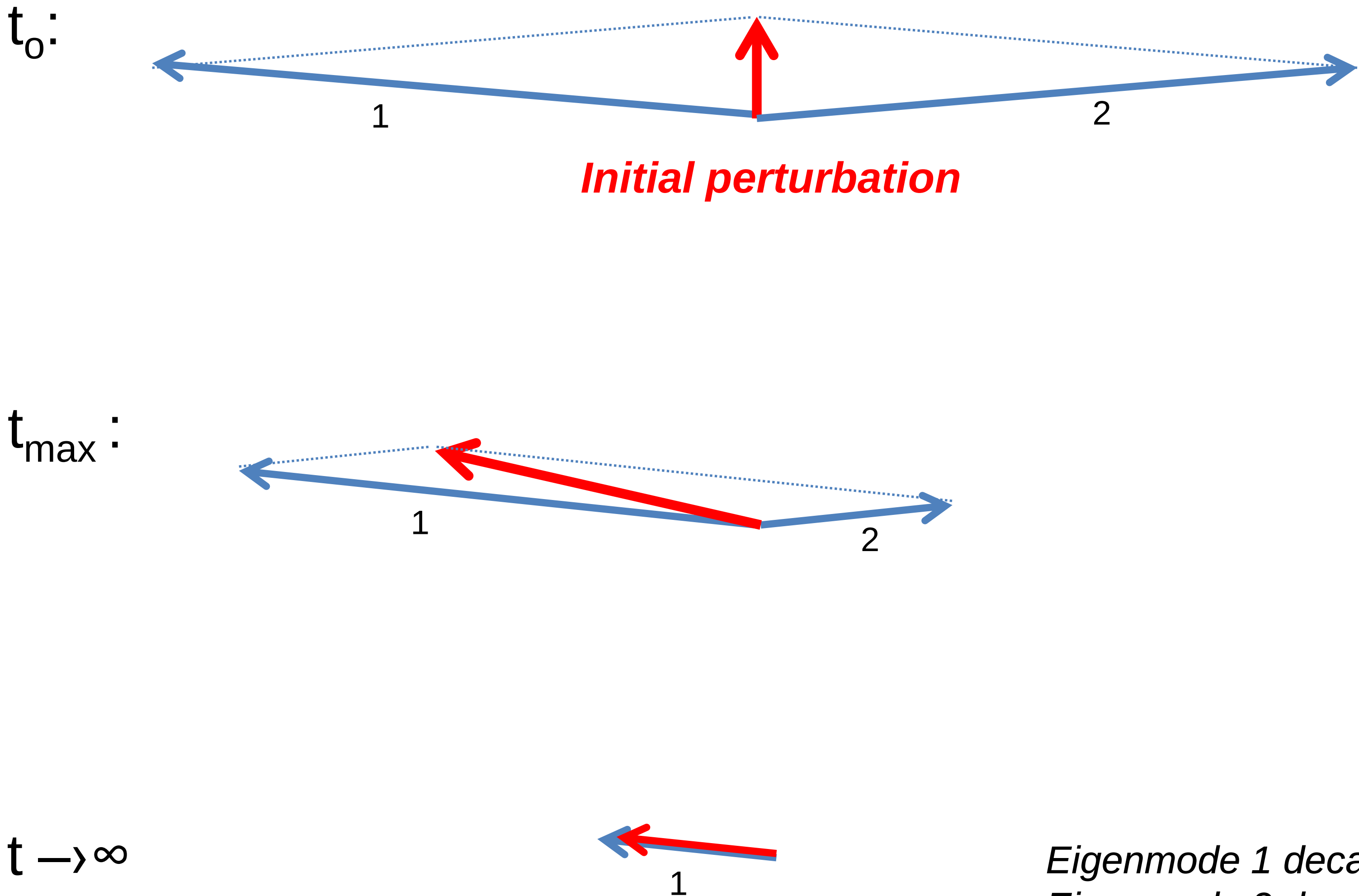
f - *Coriolis parameter*

k - *horizontal diffusivity*

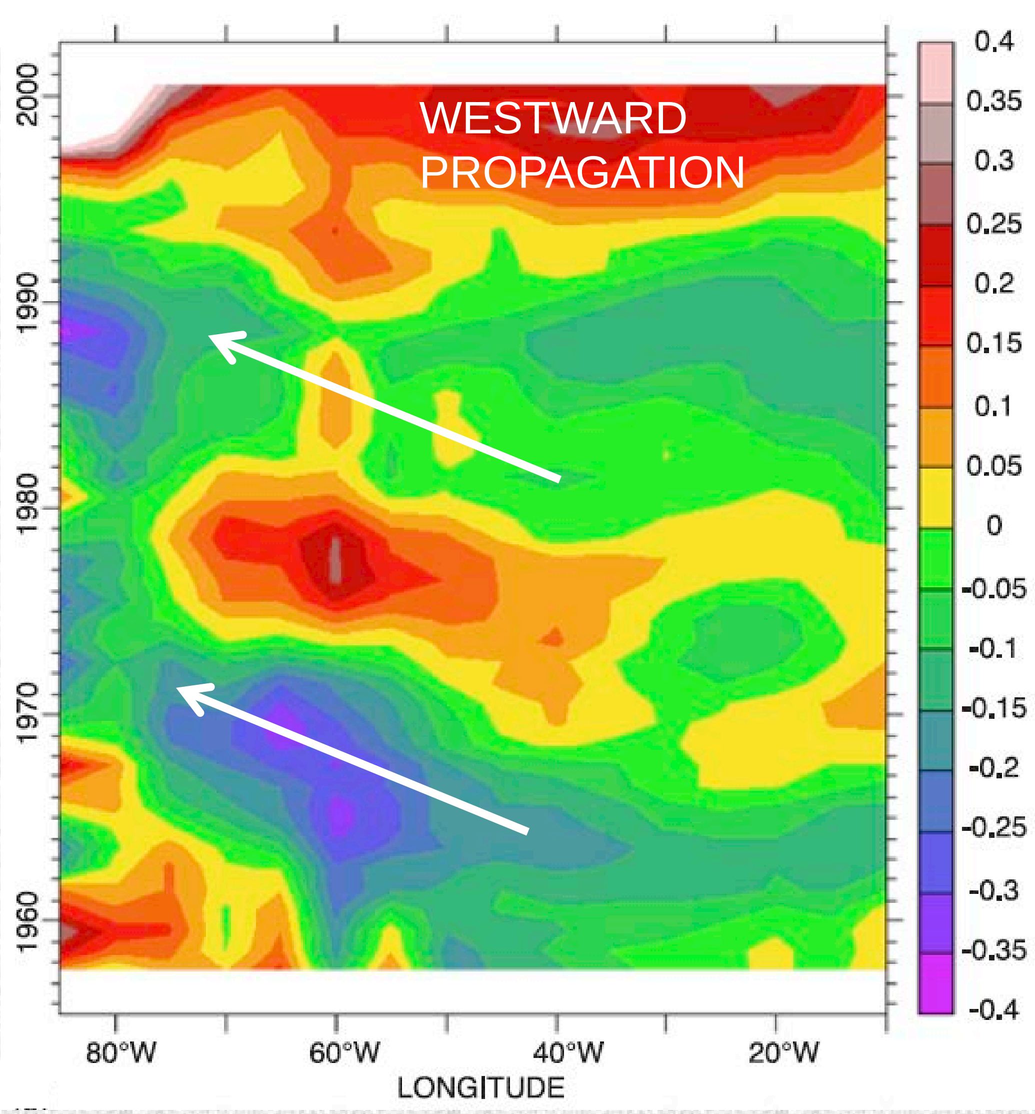
c_{Rossby} - *baroclinic Rossby wave speed* (β - *effect*)

$$U' = \frac{\alpha g h}{f}\partial_y \overline{T} \text{ - effective anomalous westward advection}$$

Nonnormality: an example of two decaying non-orthogonal eigenmodes creating transient growth



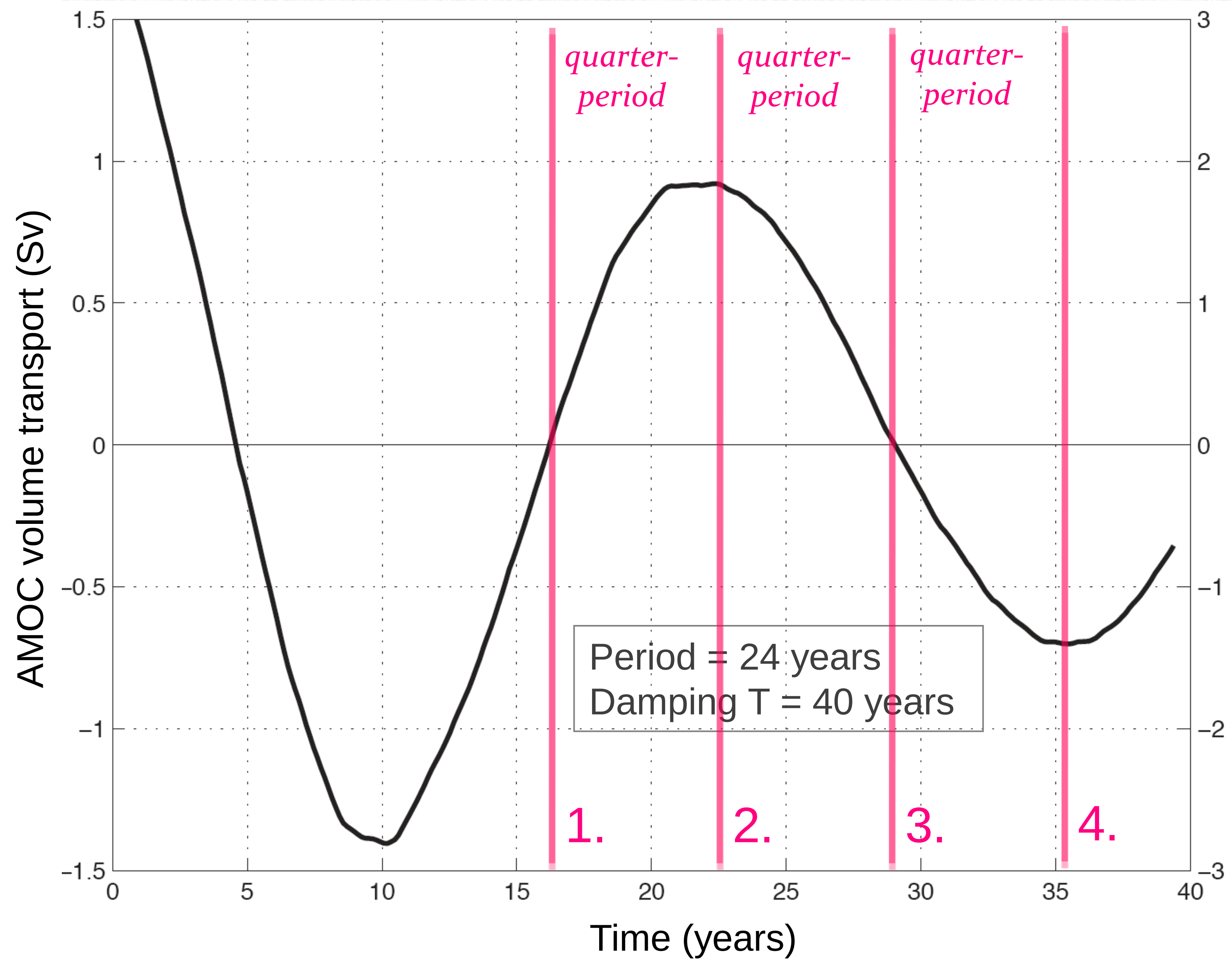
Eigenmode 1 decays slowly
Eigenmode 2 decays fast

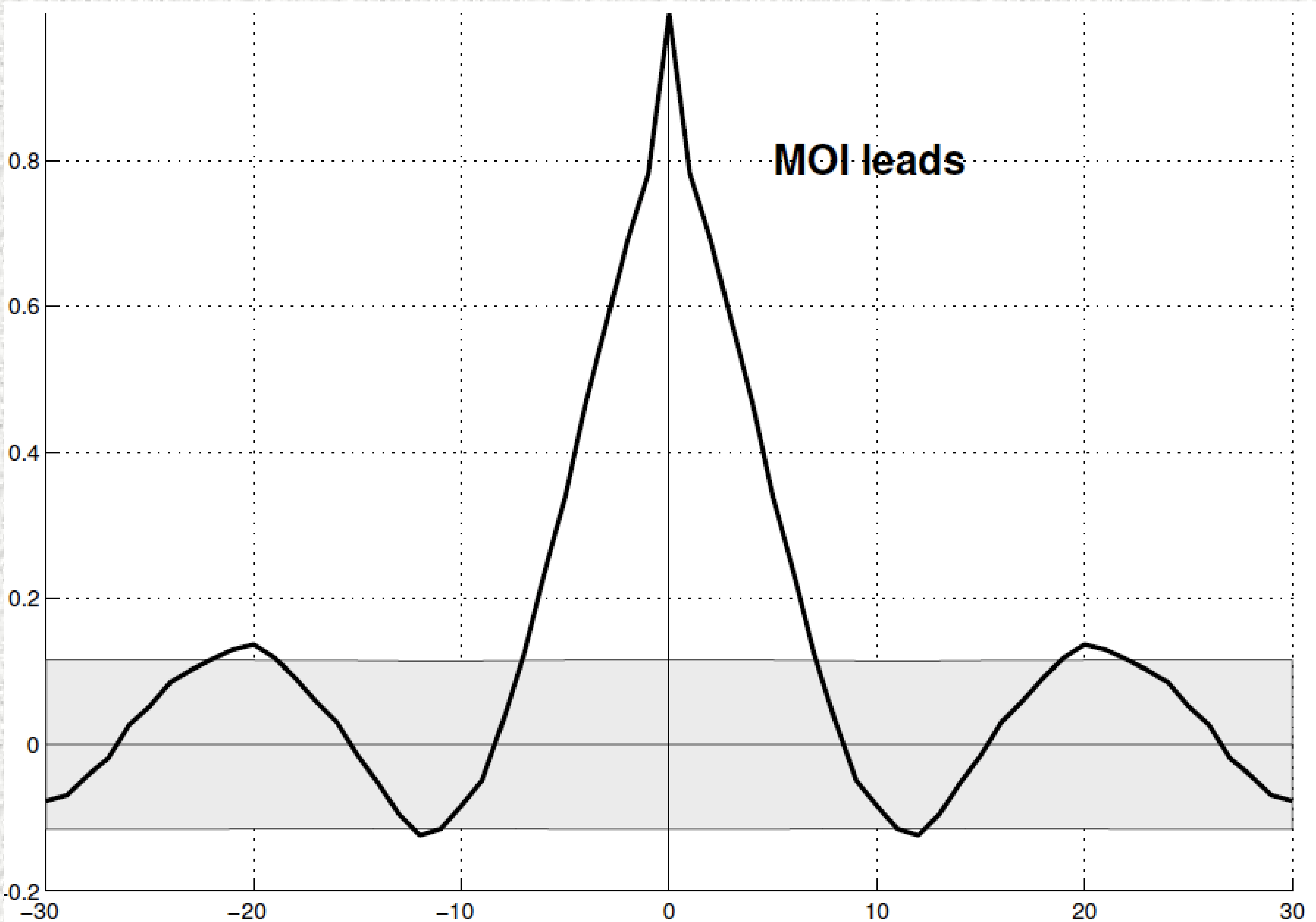


Frankcombe et al 2008

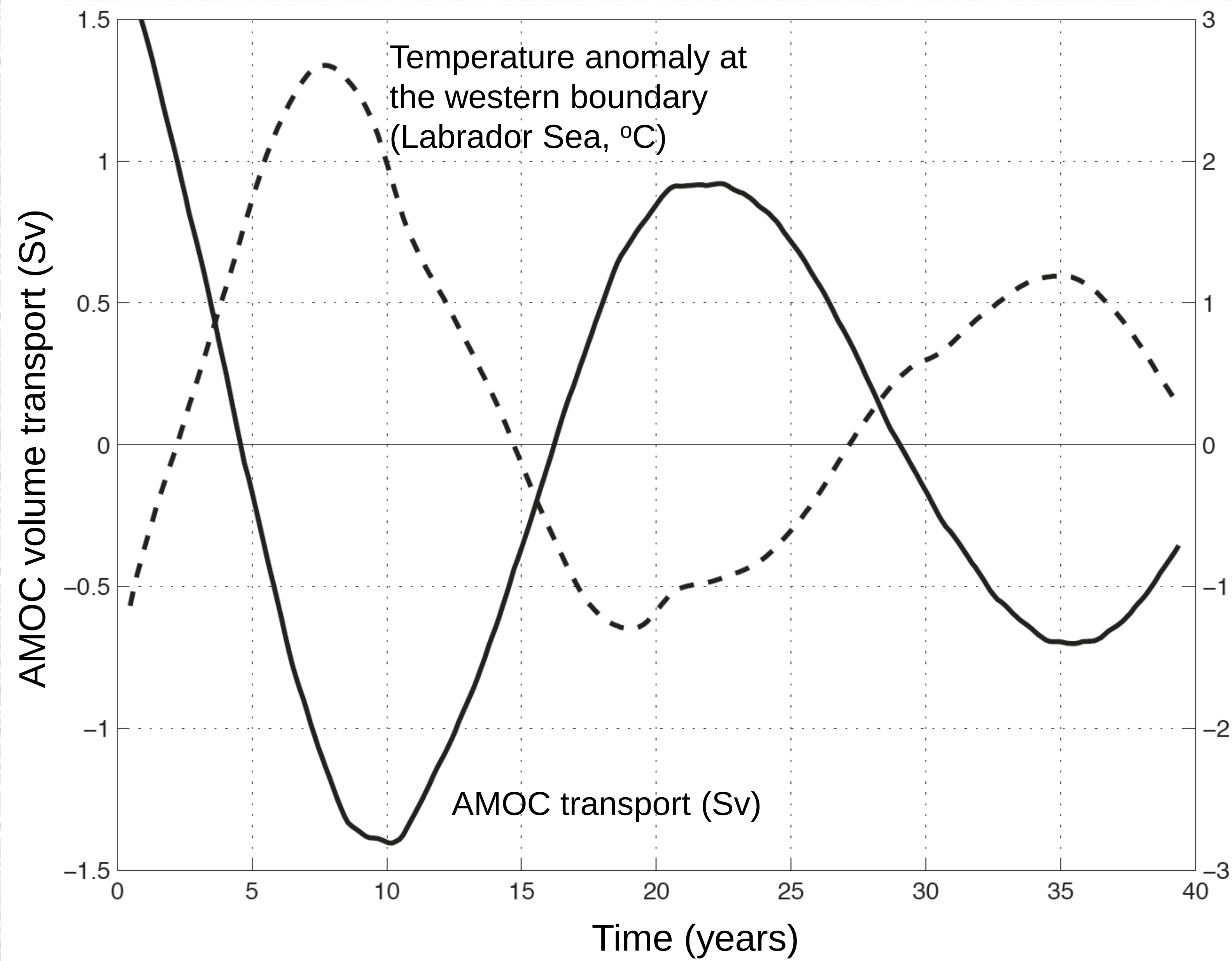
A Hovmoller diagram of observed temperature anomalies averaged between 300-400m and over 10–60ºN across the North Atlantic (XBT data)

The least-damped mode: AMOC variations




MOI leads
0.8
0.6
0.4
0.2
0
-0.2
−30
−20
−10
0
10
20
30

The least-damped mode: AMOC variations

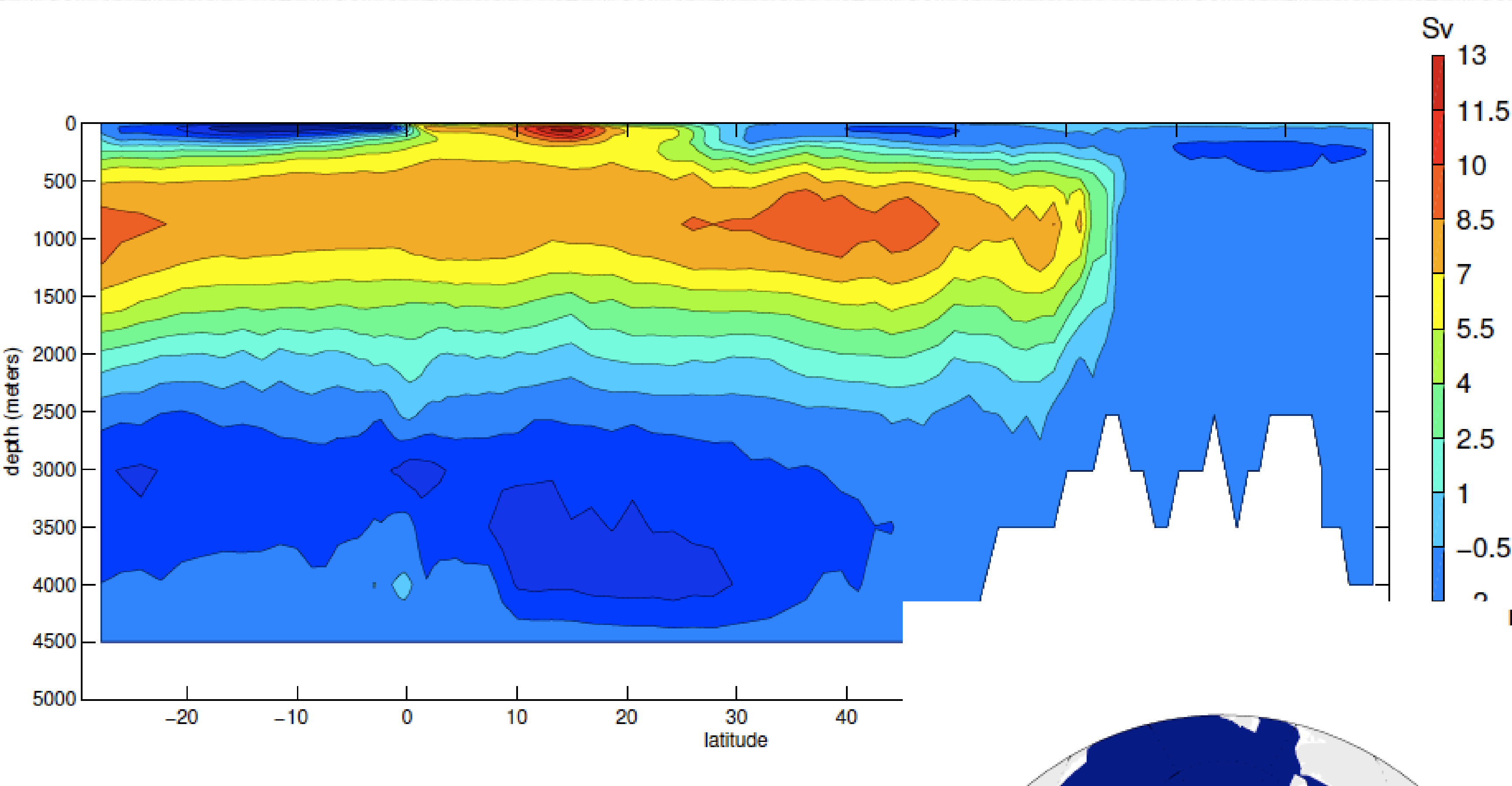


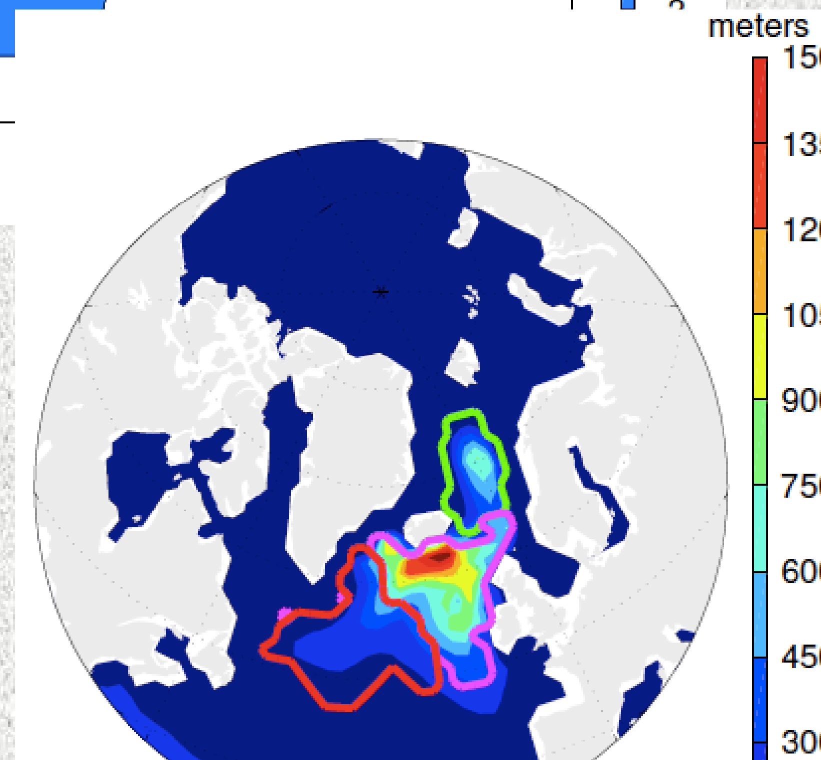
MODE MECHANISM AND EXCITATION:

1) *westward propagation of temperature anomalies?*

2) *how temperature anomalies affect the AMOC transport?*

3) *how the mode can be excited?*


Sv
13
11.5
10
8.5
7
5.5
4
2.5
1
−0.5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
depth (meters)
−20
−10
0
10
20
30
40
latitude


meters

How do westward-propagating temperature anomalies T' affect the AMOC?

$$v' = \frac{\alpha g h}{f} \partial_x T'$$ - Meridional velocity anomaly

integrate zonally

$$V' = -\frac{\alpha g h}{f} T' \Big|_{X = X_{WEST}}$$ - AMOC volume transport anomaly

IDEALIZED MODEL

T' - *temperature anomaly in the upper layer;*

v' - *meridional velocity anomaly*

$$\frac{\partial T'}{\partial t} = -\left(\overline{U} + c_{rossby}\right)\partial_x T' - v'\partial_y \overline{T} + k\partial_{xx} T'$$

$$v' = \frac{\alpha g h}{f}\partial_x T' \text{ - thermal wind balance}$$

$$\frac{\partial T'}{\partial t} = -\left(\overline{U} + c_{rossby} + U'\right)\partial_x T' + k\partial_{xx} T'$$

h - *upper layer thickness*

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g - *acceleration of gravity*

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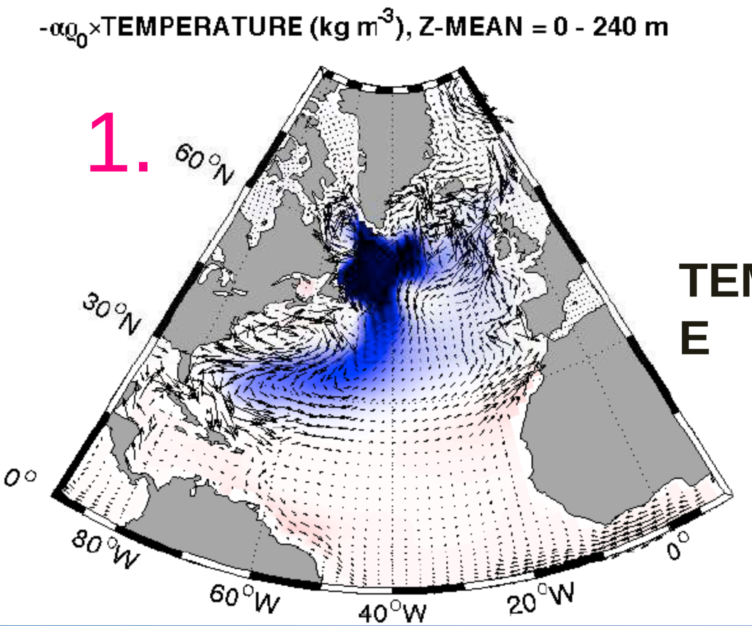
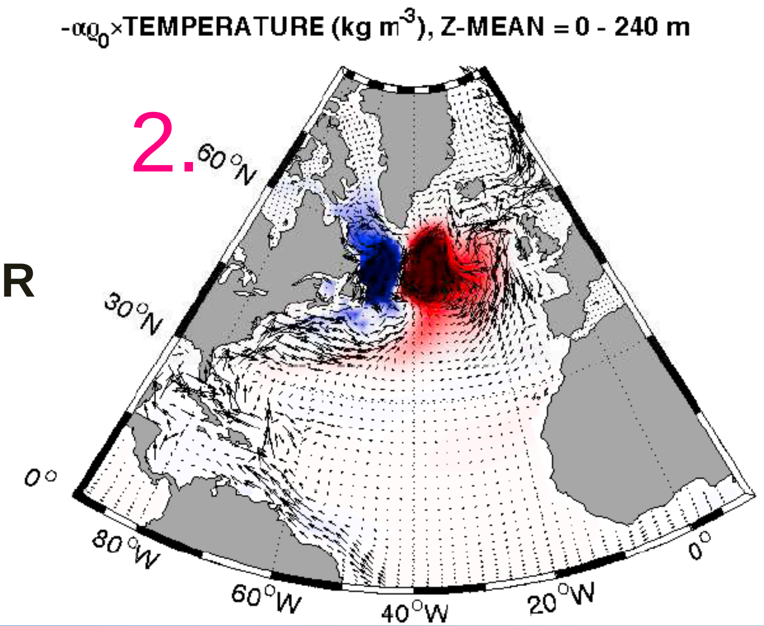
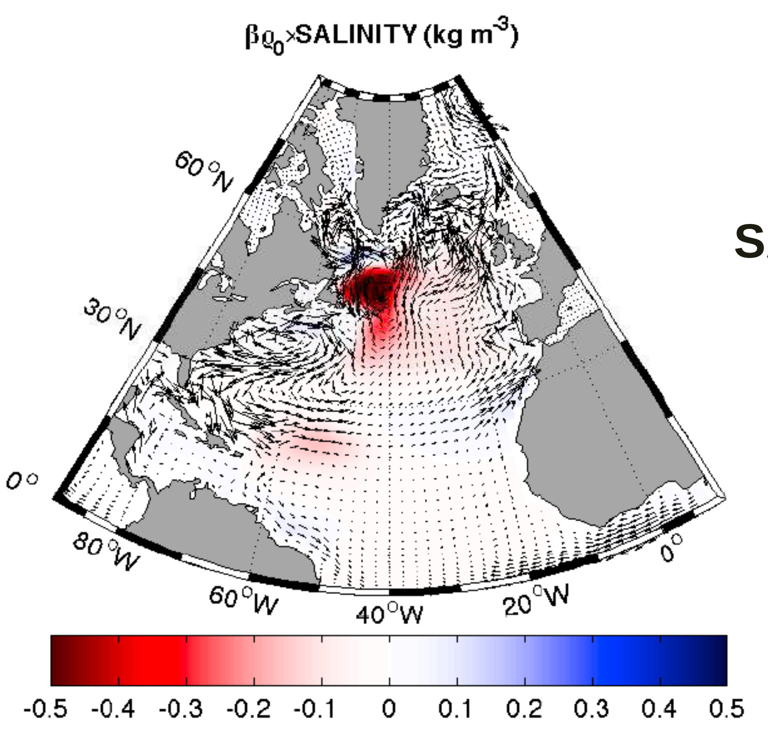
$$U' = \frac{\alpha g h}{f}\partial_y \overline{T} \text{ - effective anomalous westward advection}$$

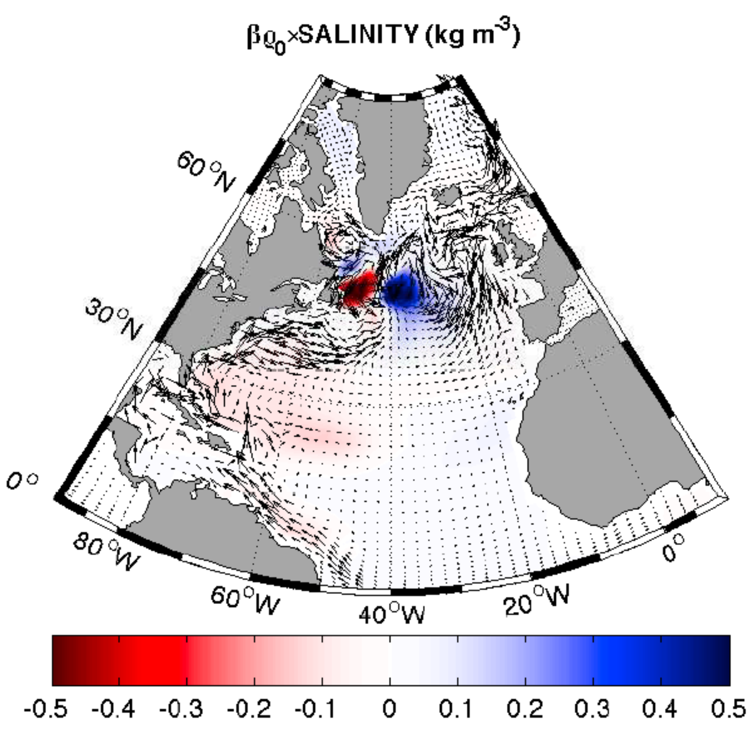




TEMPERATUR
E



SALINITY



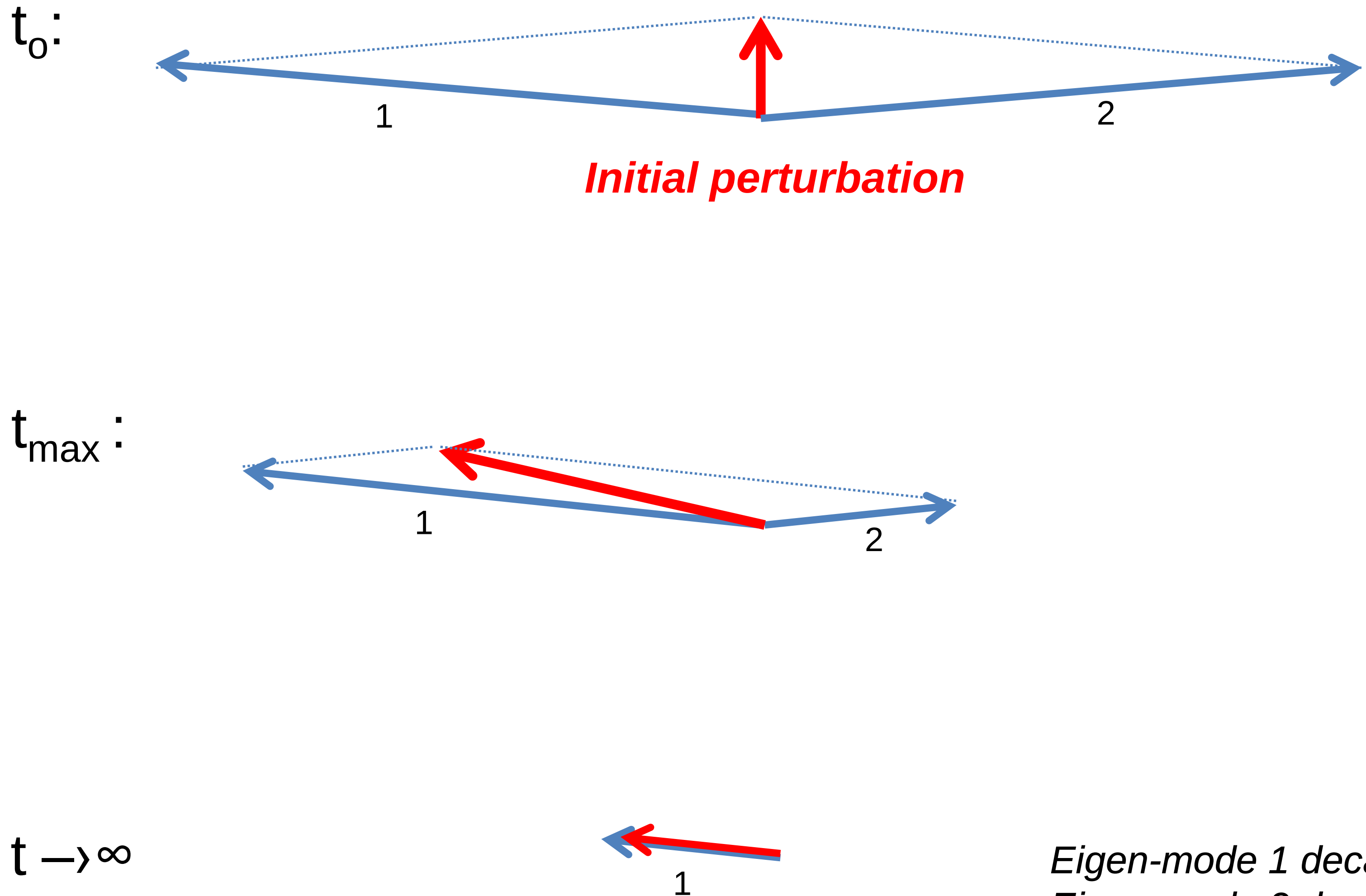
The system is nonnormal (nonnormality is related to the preferential westward propagation), i.e.

The eigenvectors of the tangent linear model are not orthogonal

=>

fast transient growth is possible

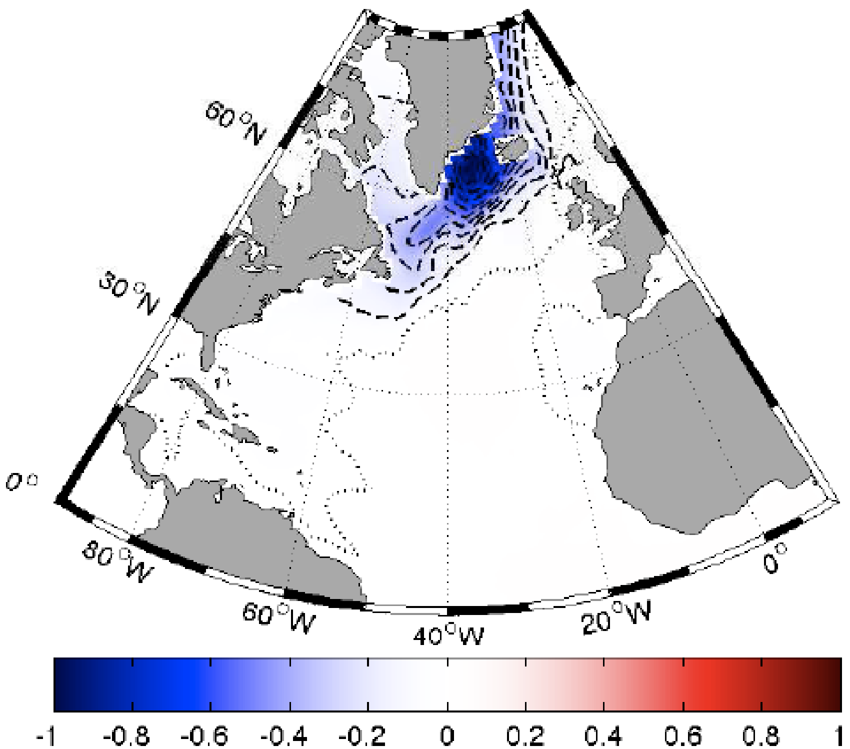
Nonnormality: an example of two decaying non-orthogonal eigen-modes creating transient growth



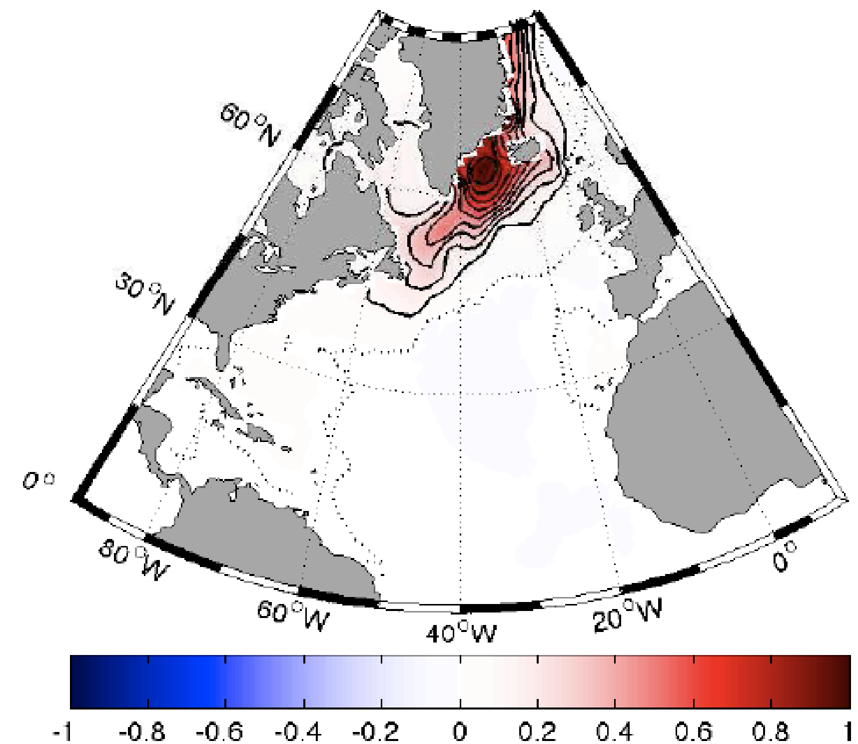
Eigen-mode 1 decays slowly
Eigen-mode 2 decays fast

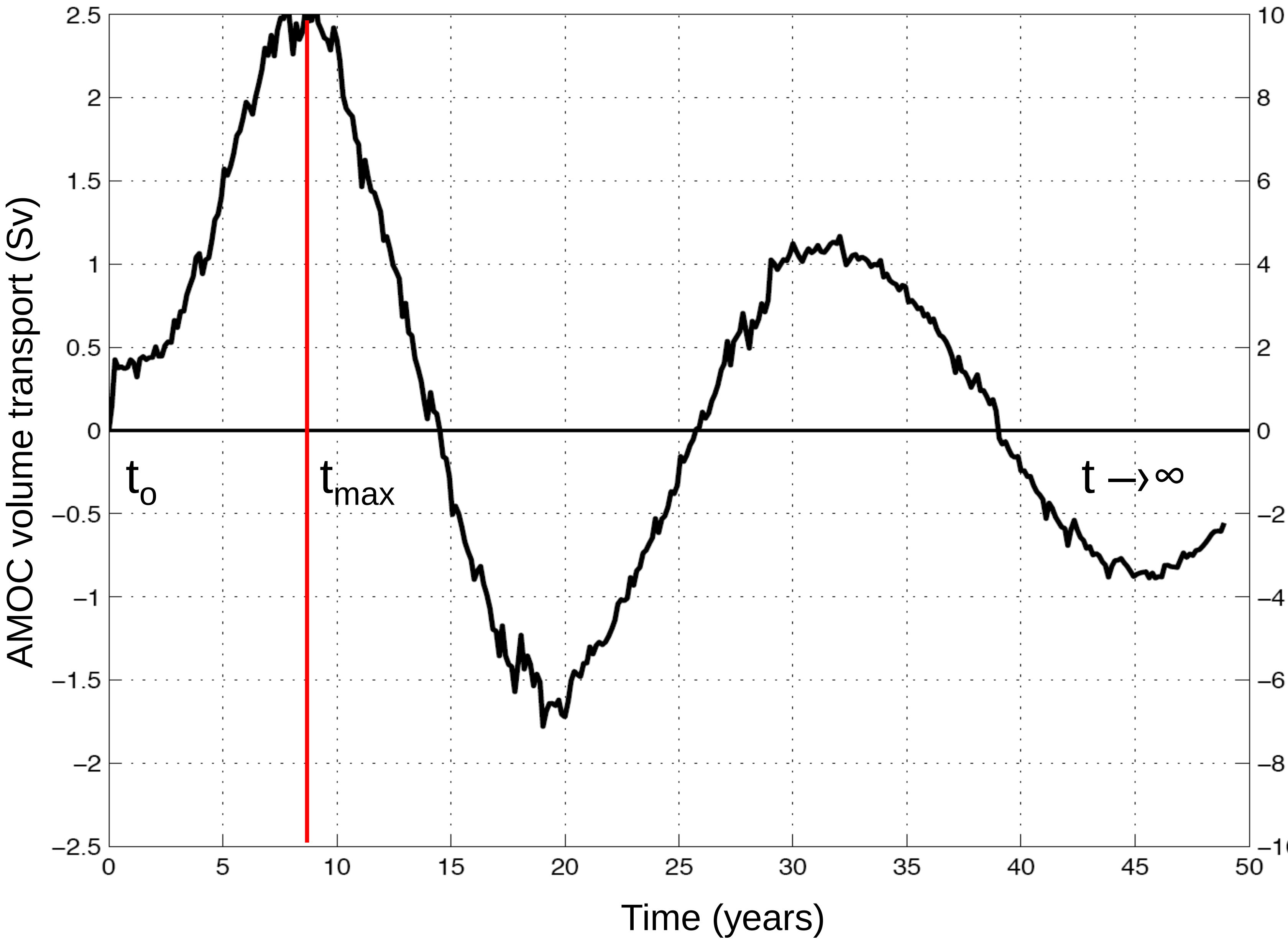
OPTIMAL INITIAL PERTURBATIONS

Optimal SST anomalies

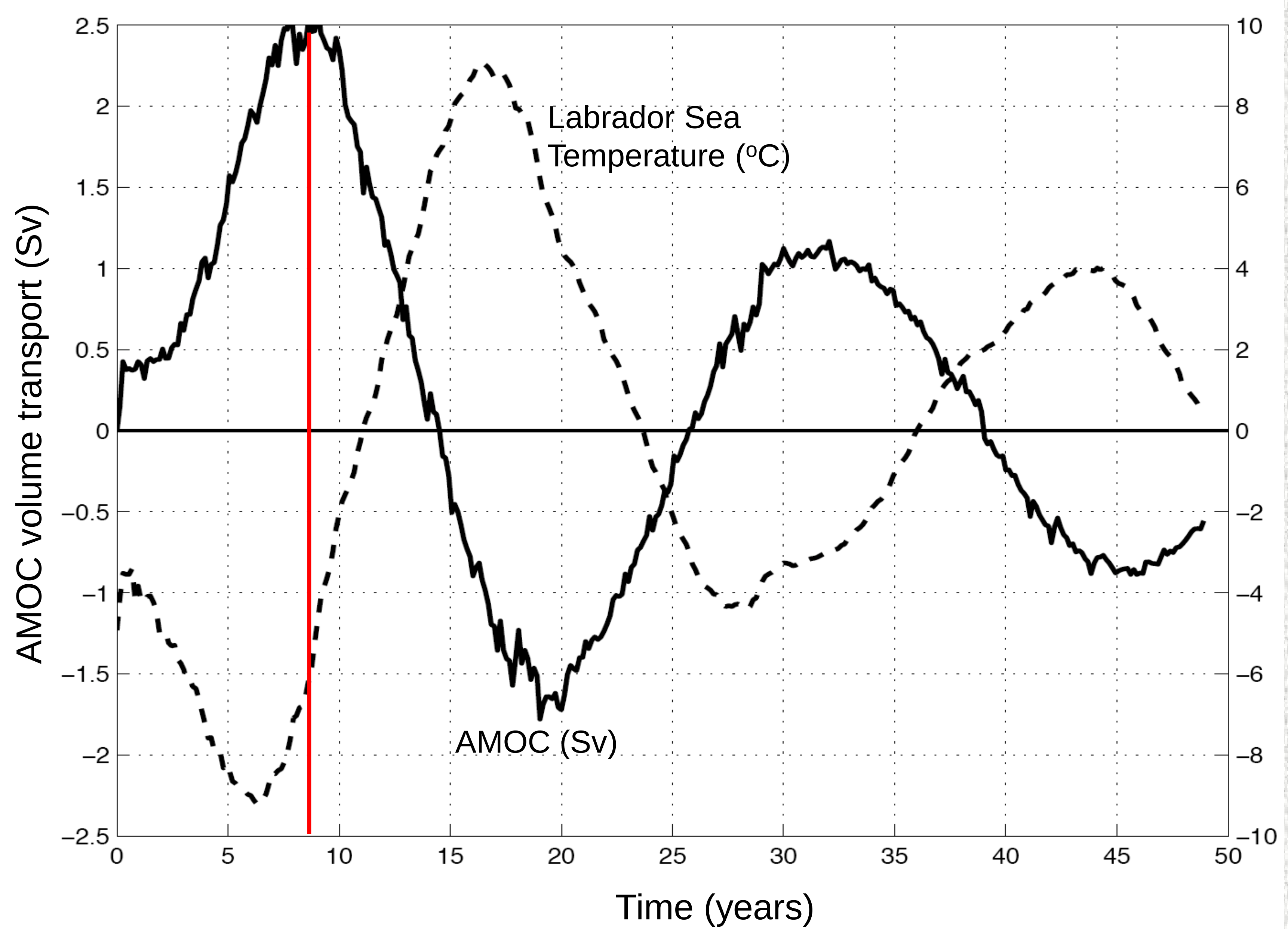


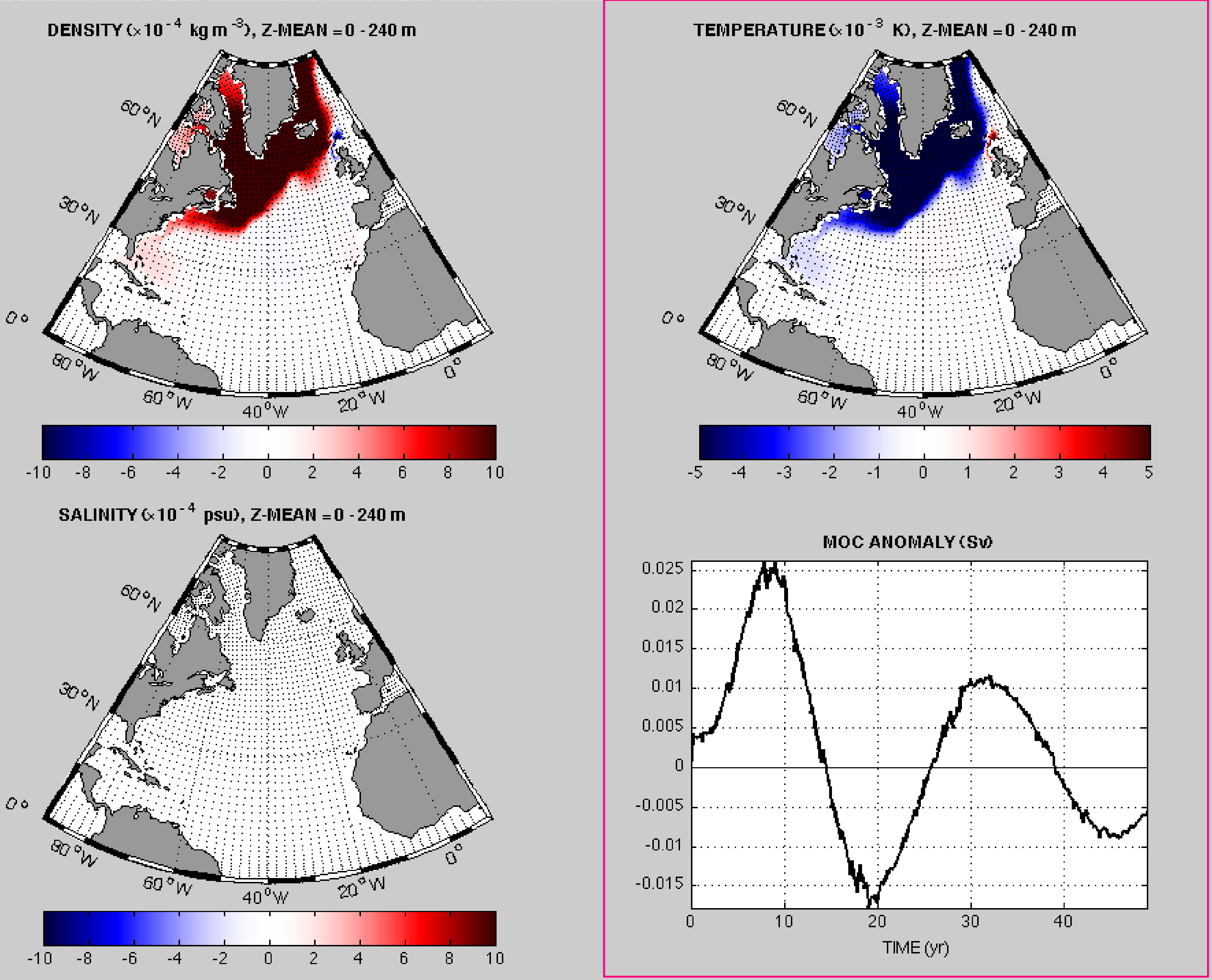
Optimal SSS anomalies





AMOC volume transport (Sv)
Time (years)
t_o
t_{max}
t –› ∞
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
10
8
6
4
2
0
−2
−4
−6
−8
−10
0
5
10
15
20
25
30
35
40
45
50

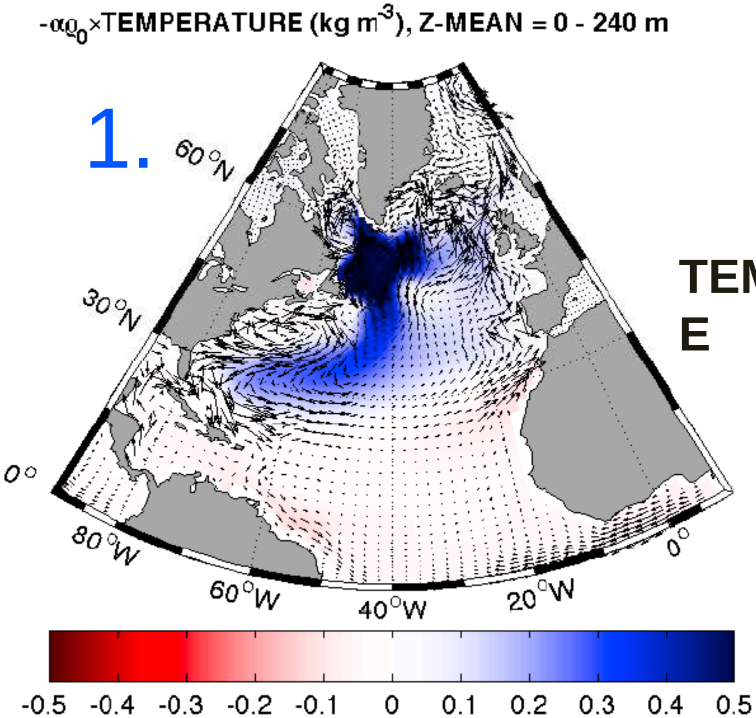

Labrador Sea
Temperature (oC)
AMOC (Sv)
AMOC volume transport (Sv)
Time (years)
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
10
8
6
4
2
0
−2
−4
−6
−8
−10
0
5
10
15
20
25
30
35
40
45
50



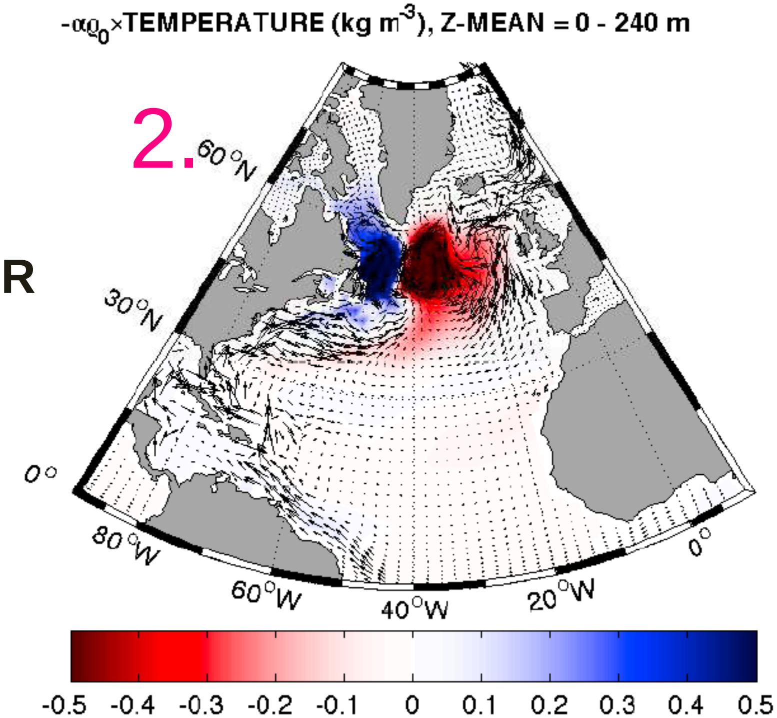
DENSITY (×10⁻⁴ kg m⁻³), Z-MEAN = 0 - 240 m
60°N
30°N
0°
80°W
60°W
40°W
20°W
0°
-10 -8 -6 -4 -2 0 2 4 6 8 10
TEMPERATURE (×10⁻³ K), Z-MEAN = 0 - 240 m
60°N
30°N
0°
80°W
60°W
40°W
20°W
0°
-5 -4 -3 -2 -1 0 1 2 3 4 5
SALINITY (×10⁻⁴ psu), Z-MEAN = 0 - 240 m
60°N
30°N
0°
80°W
60°W
40°W
20°W
0°
-10 -8 -6 -4 -2 0 2 4 6 8 10
MOC ANOMALY (Sv)
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
0 10 20 30 40
TIME (yr)

Summary 2:

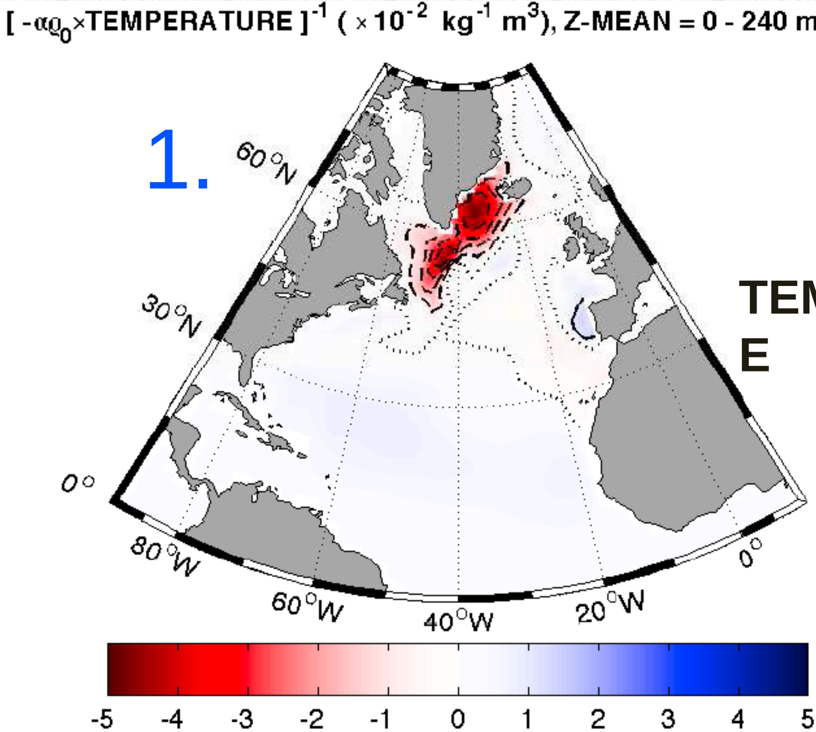
- *The system is nonnormal, so that*
  - *optimal initial perturbations for the interdecadal mode have a different structure - they are centered off the east coast of Greenland*
  - *atmospheric noise can efficiently excite this mode through this optimal initial perturbations*



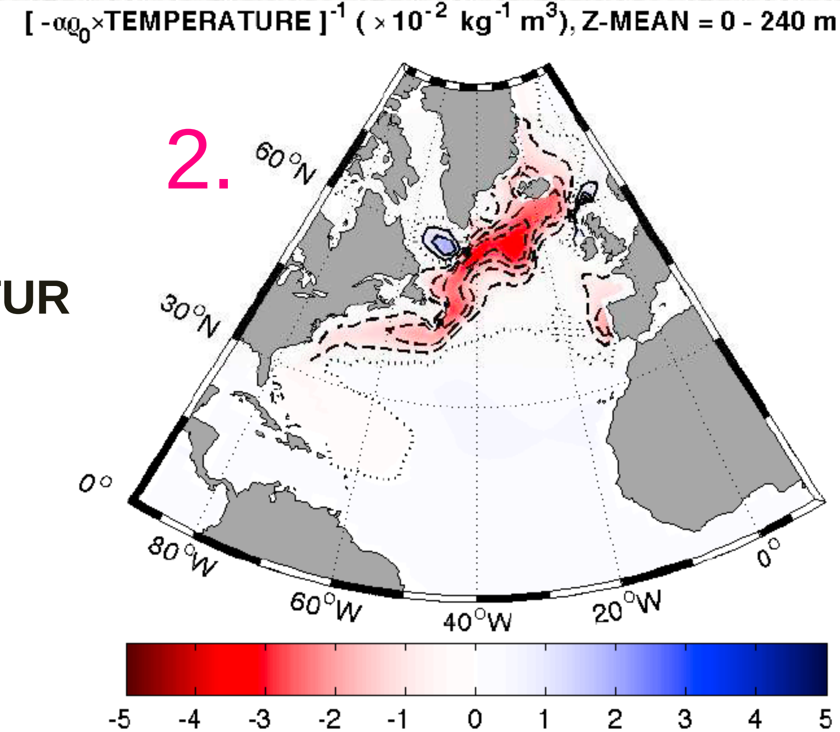
TEMPERATURE



The least-damped mode of the tangent linear model



**TEMPERATUR
E**



The least-damped mode of the adjoint