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

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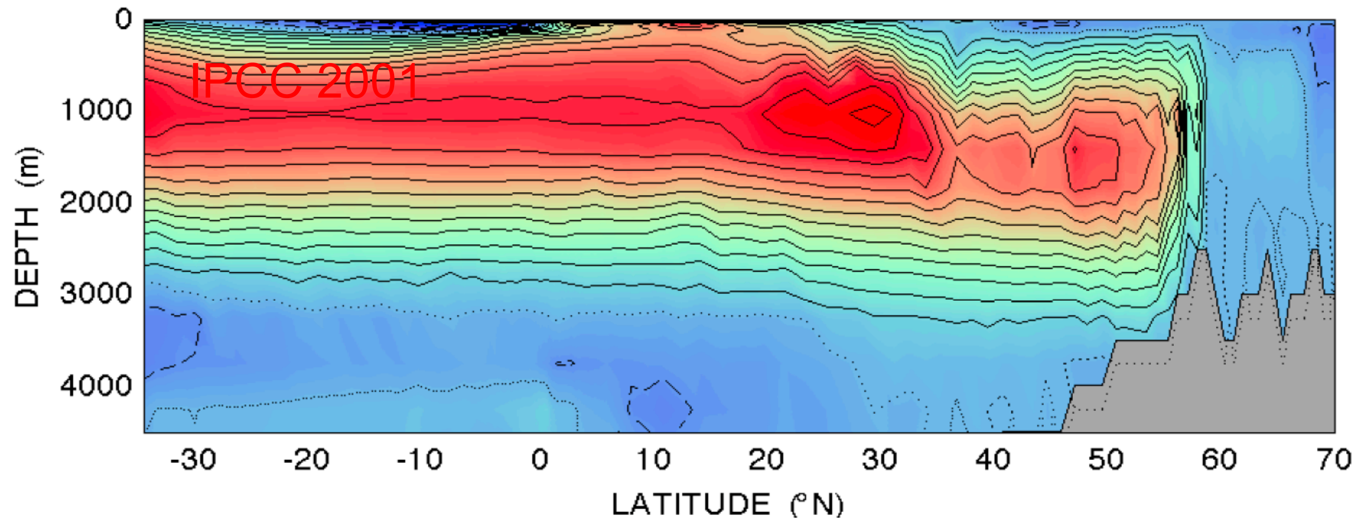
July 2011

Atlantic Meridional Overturning Circulation (AMOC)



AMOC and its variability

Change in Atlantic THC [10^6 m^3/s]

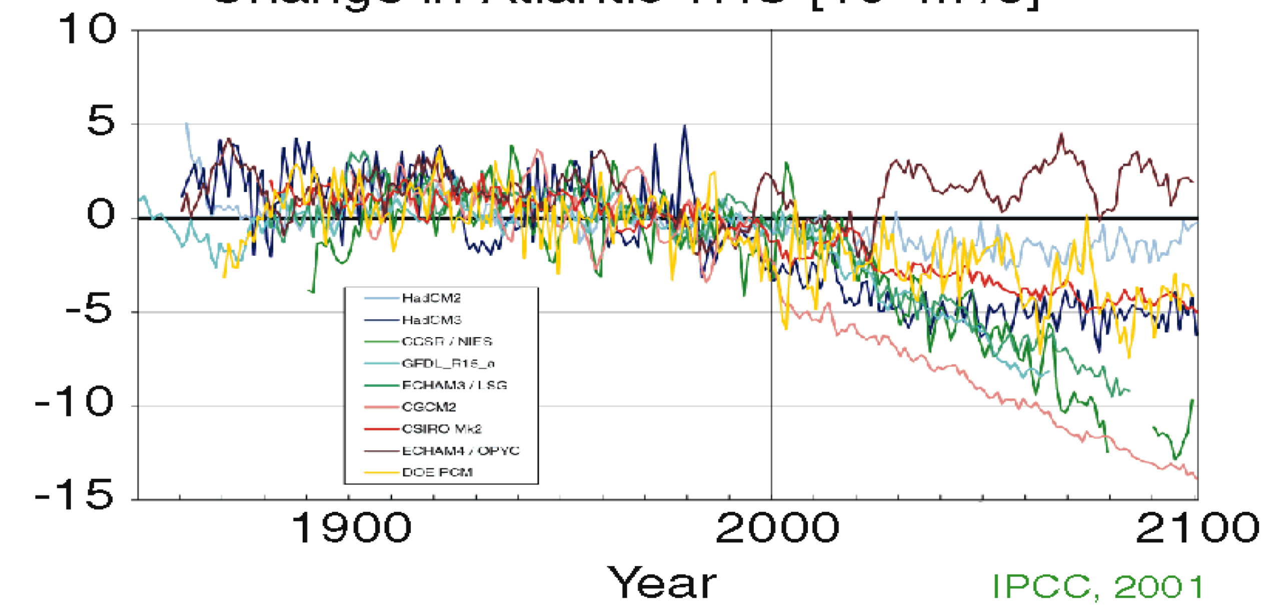
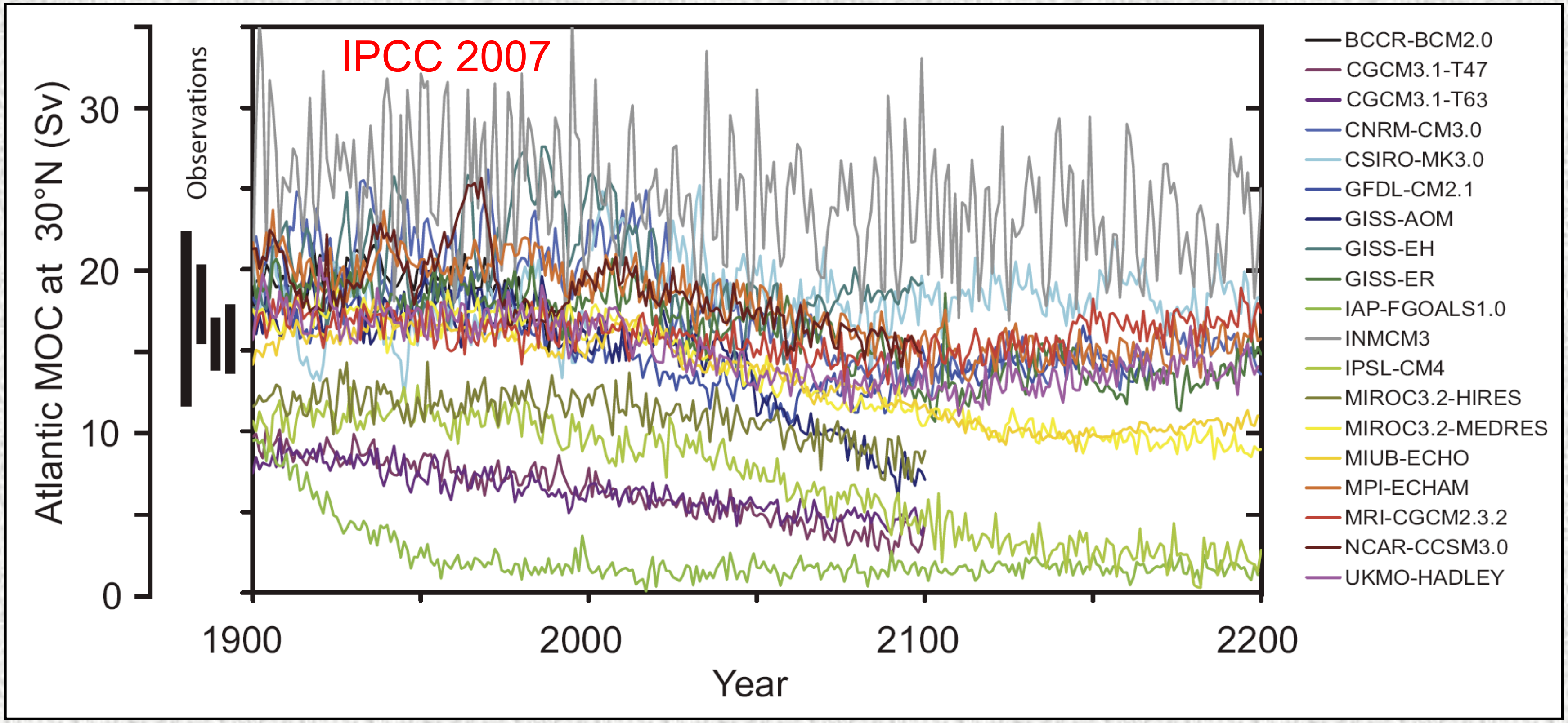
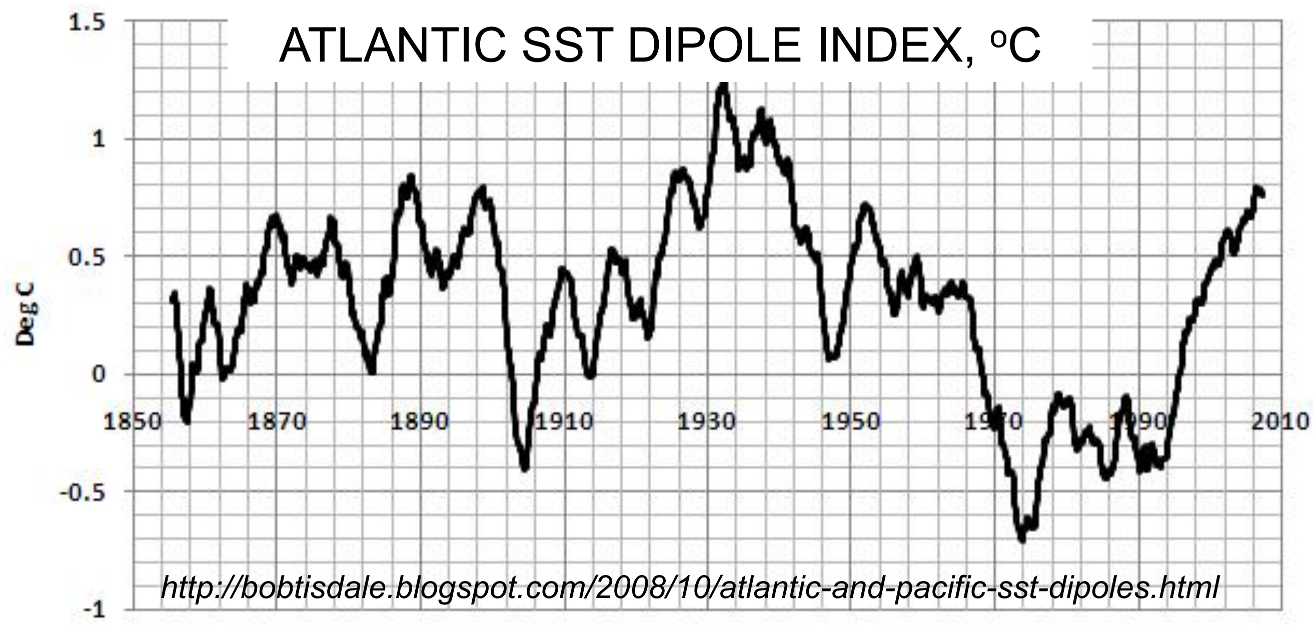
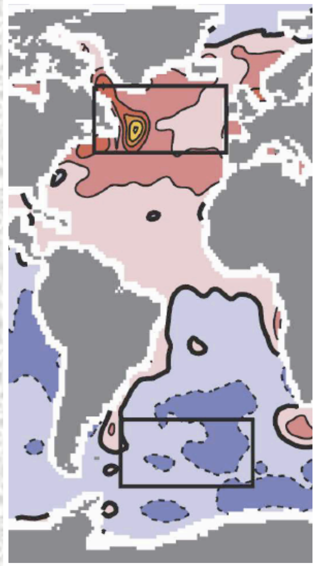


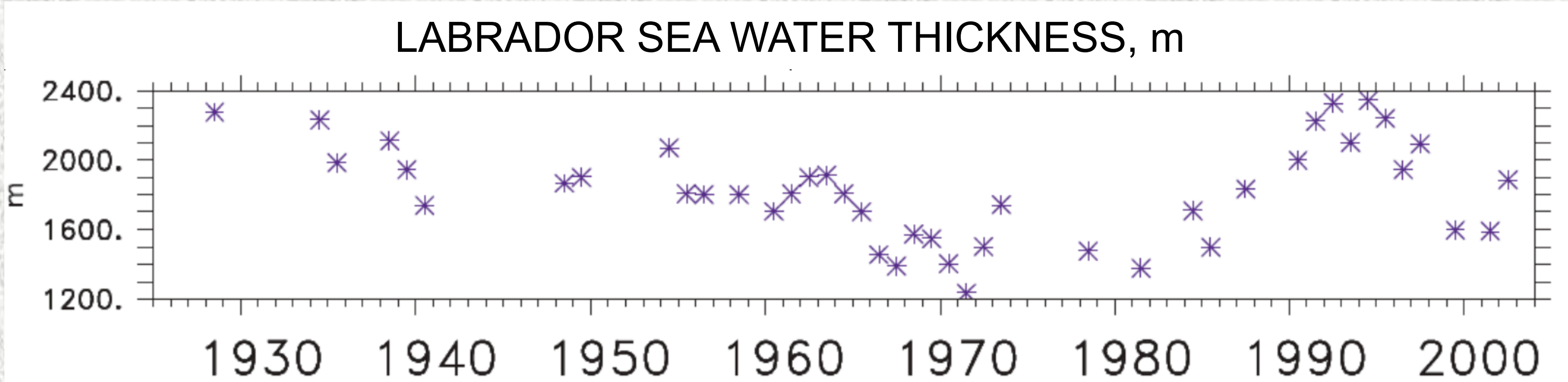
Fig. 1.22 (after Cubasch et al. 2001): Simulations of the Atlantic THC strength under CO_2 increase, relative to the means of the years 1961-1990.


IPCC 2007
Observations
Atlantic MOC at 30°N (Sv)
0
10
20
30
1900
2000
2100
2200
Year
BCCR-BCM2.0
CGCM3.1-T47
CGCM3.1-T63
CNRM-CM3.0
CSIRO-MK3.0
GFDL-CM2.1
GISS-AOM
GISS-EH
GISS-ER
IAP-FGOALS1.0
INMCM3
IPSL-CM4
MIROC3.2-HIRES
MIROC3.2-MEDRES
MIUB-ECHO
MPI-ECHAM
MRI-CGCM2.3.2
NCAR-CCSM3.0
UKMO-HADLEY





Latif et al 2006



Curry et al 1998

Potential mechanisms of AMOC variability:

- ***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 northern Atlantic (shorter periods):***

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

Goal:

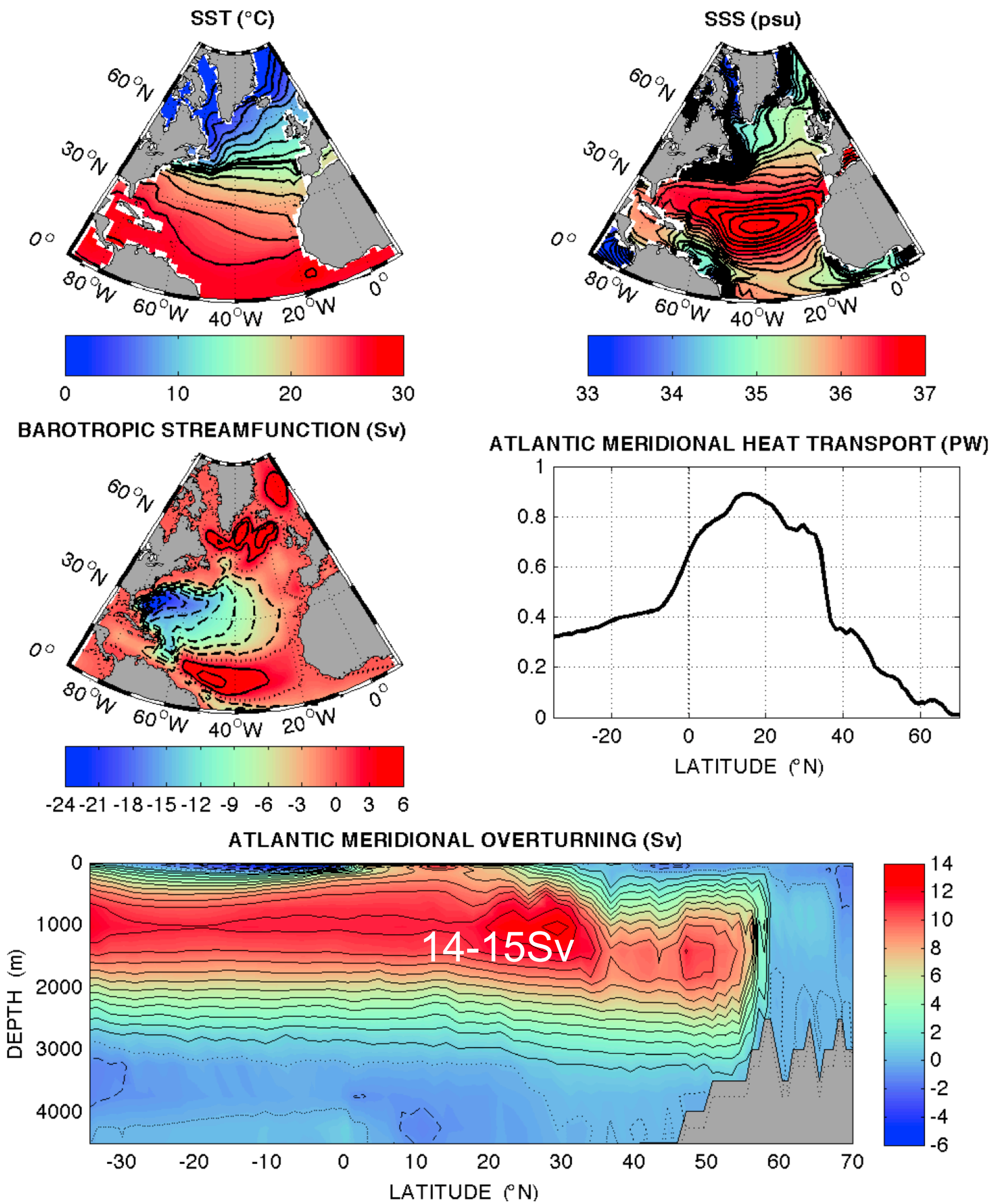
To show rigorously the existence of a damped "AMOC" eigenmode based solely on ocean dynamics and explore its mechanism and excitation

Approach:

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

Simple two-level model

Coupled GCM: IPSL (OPA+ full atmosphere)



Ocean GCM:

OPA 8.2
2° global configuration
31 levels
(ORCA2)

We used tangent linear and adjoint versions of the model

1. Ocean GCM :

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

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 varying mean state of the ocean

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

Non-autonomous

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

$$\tilde{\mathbf{M}} = \mathbf{M}(t, t + n \cdot year) \quad i.e.\ Poincare\ \ section$$

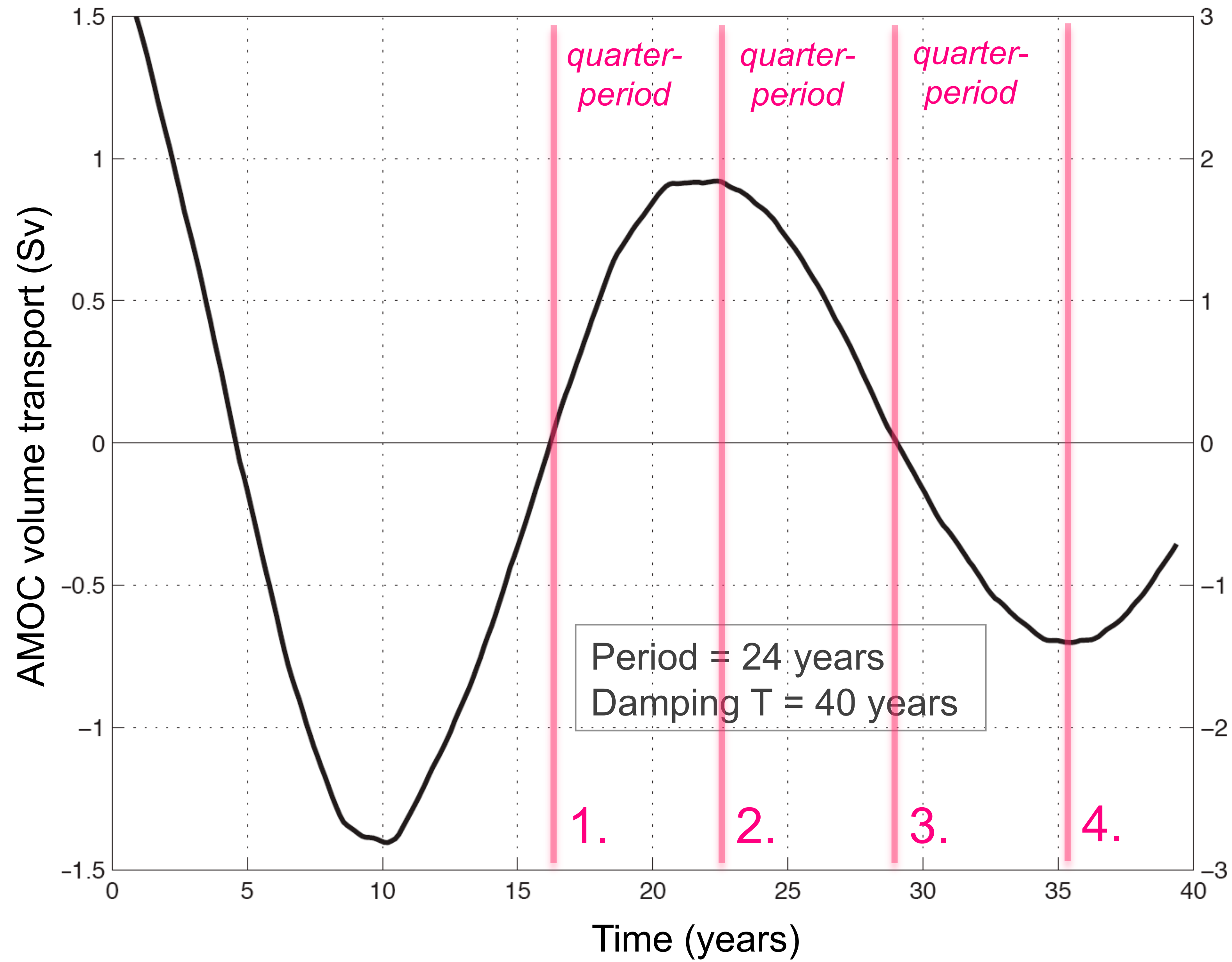
$5.$ *Calculate eigenvectors and eigenvalues of* $\tilde{\mathbf{M}}$

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

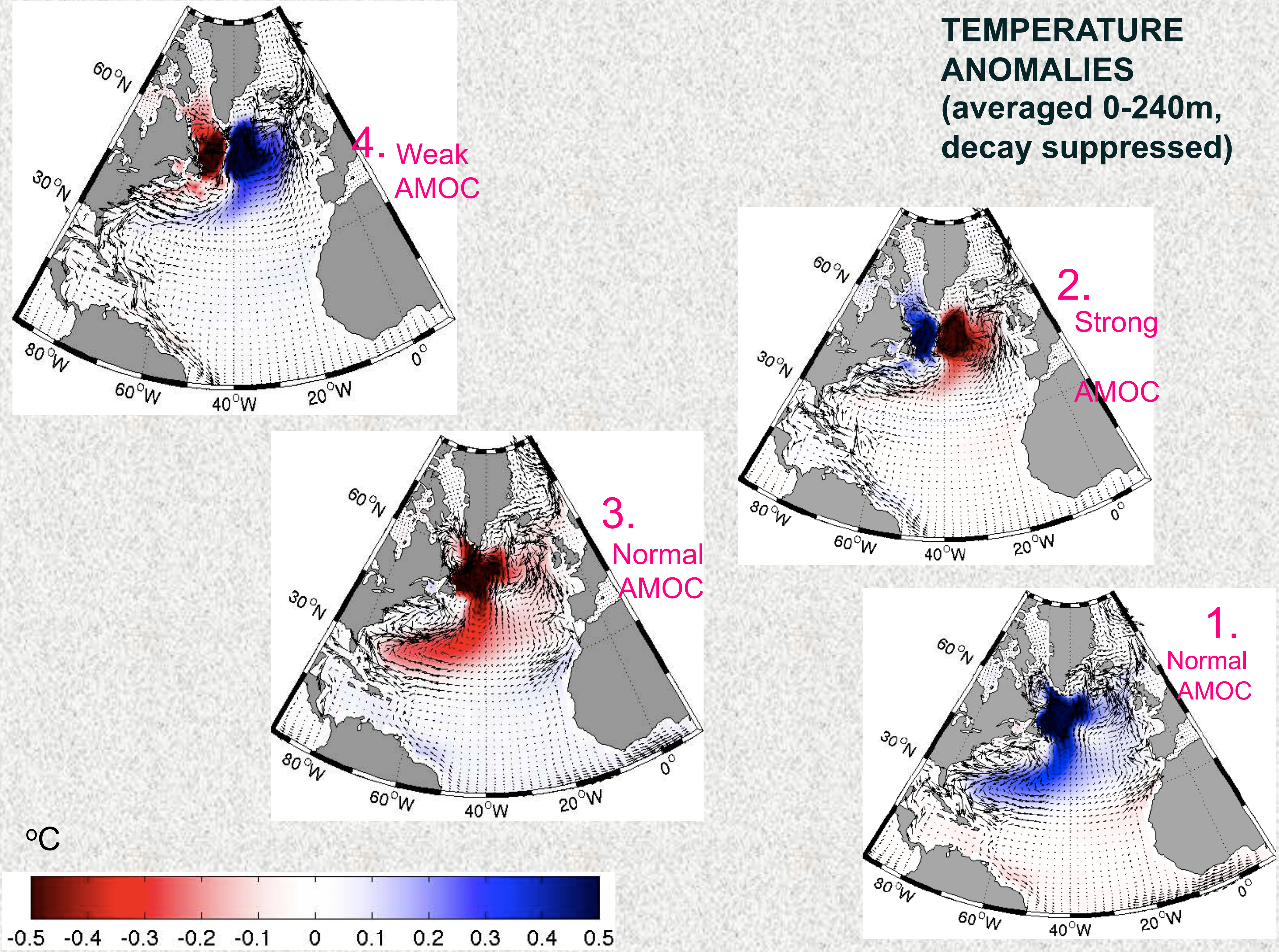
(to compute optimal initial perturbations)

$7.$ *Identify the least damped eigen - mode and examine its properties*

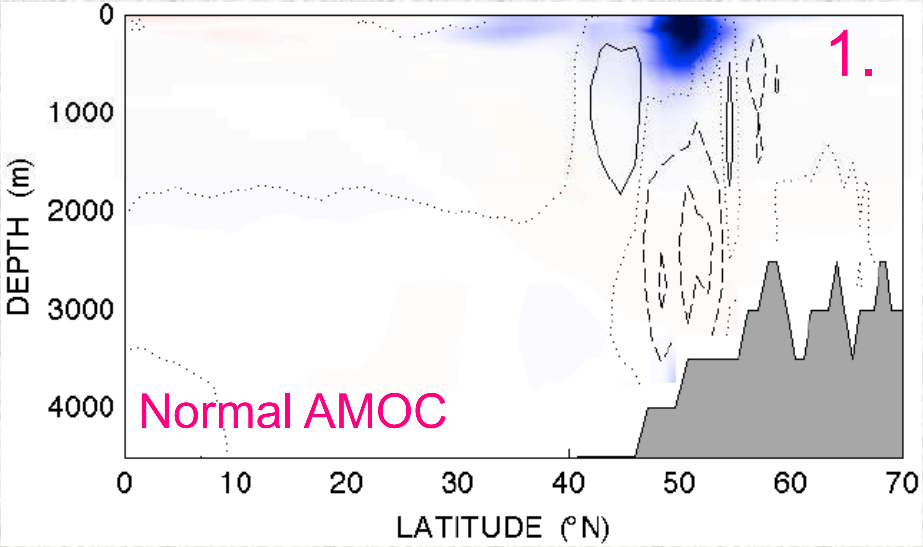
The least-damped mode: AMOC variations

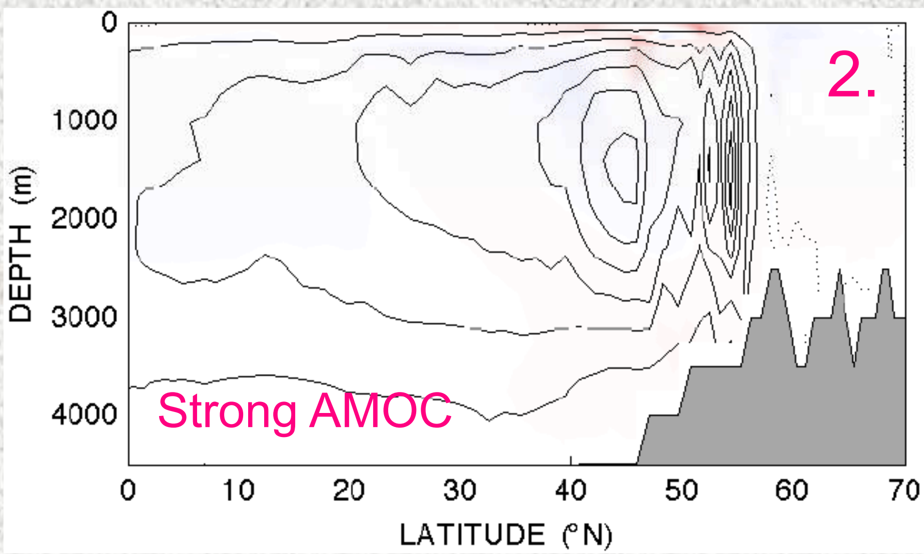


TEMPERATURE ANOMALIES (averaged 0-240m, decay suppressed)

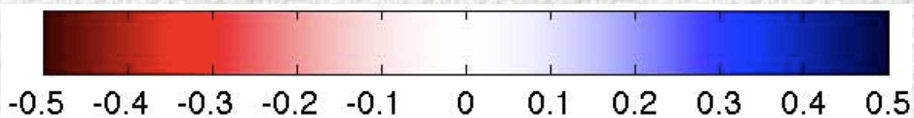


STREAMFUNCTION and TEMPERATURE ANOMALIES (zonally-averaged, decay suppressed)

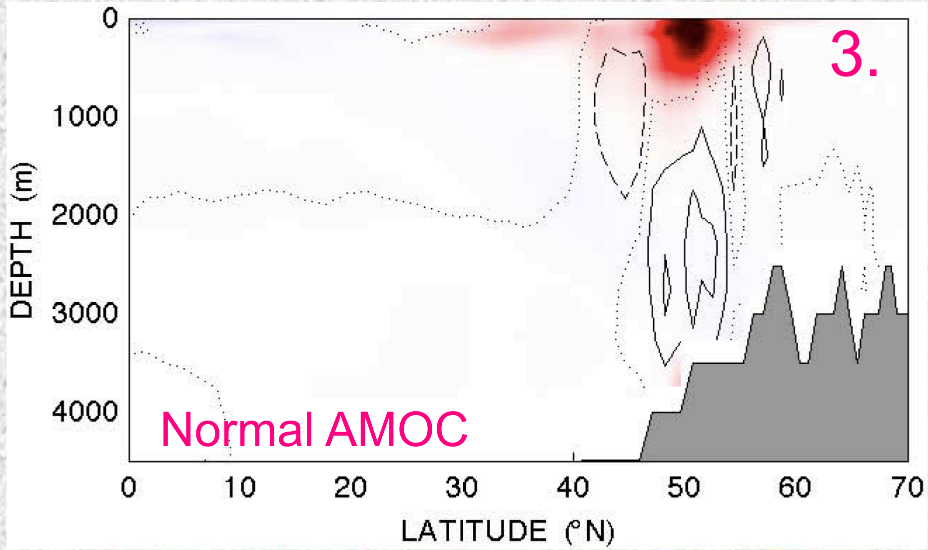


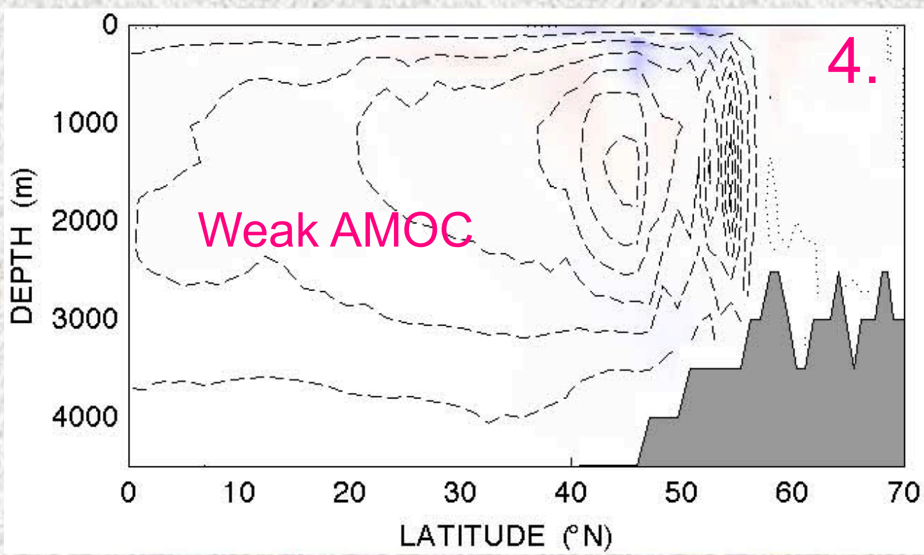


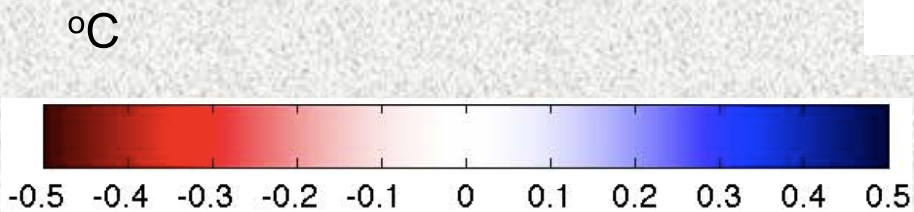
°C

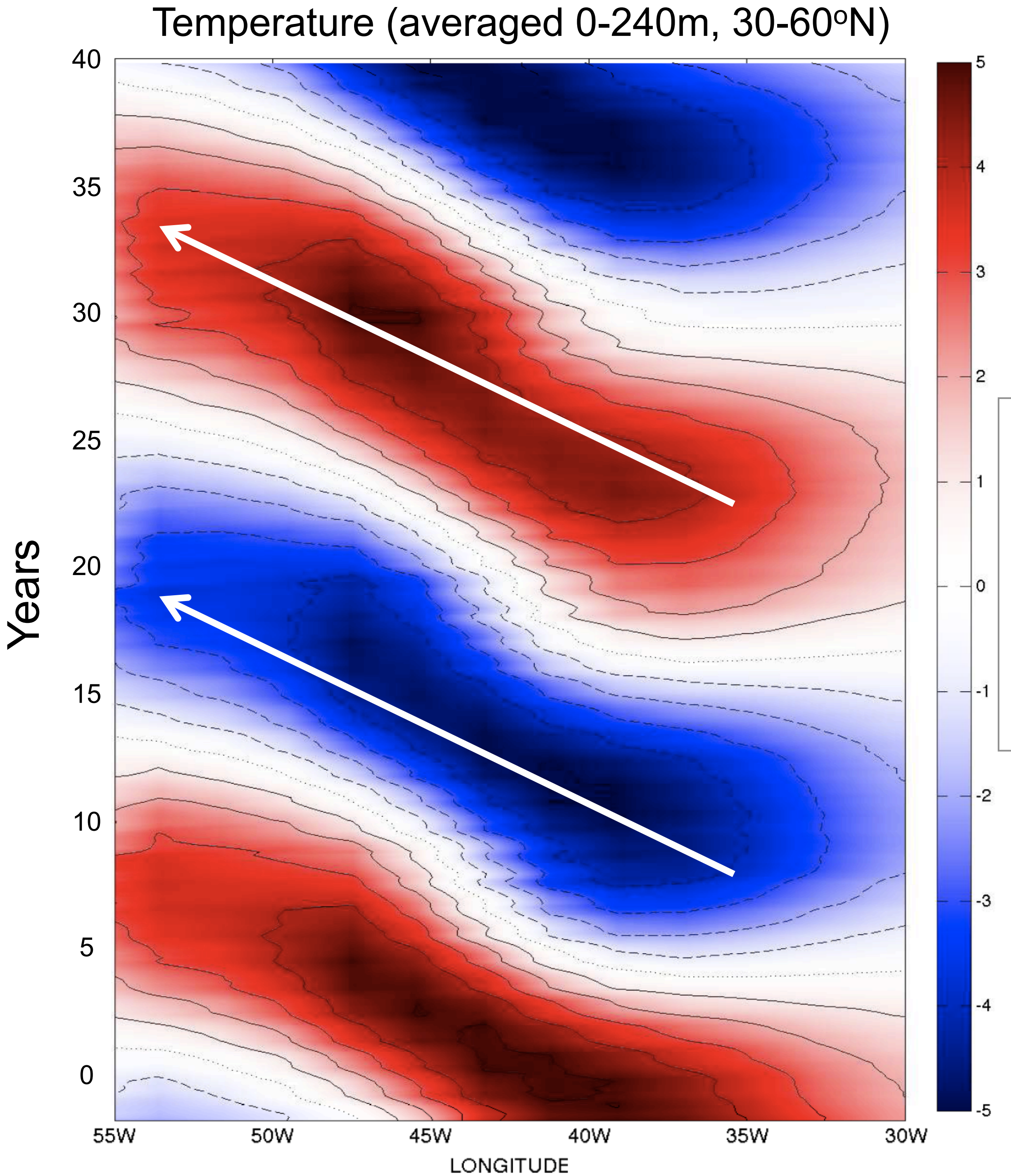


STREAMFUNCTION and TEMPERATURE ANOMALIES (zonally-averaged, decay suppressed)







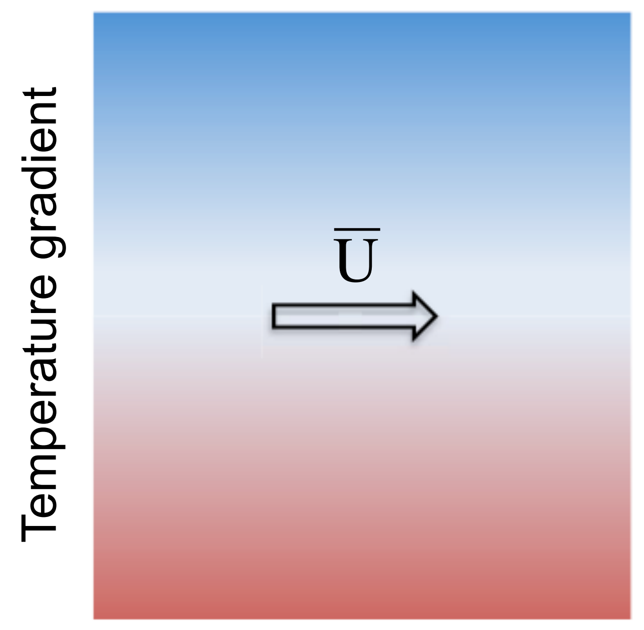


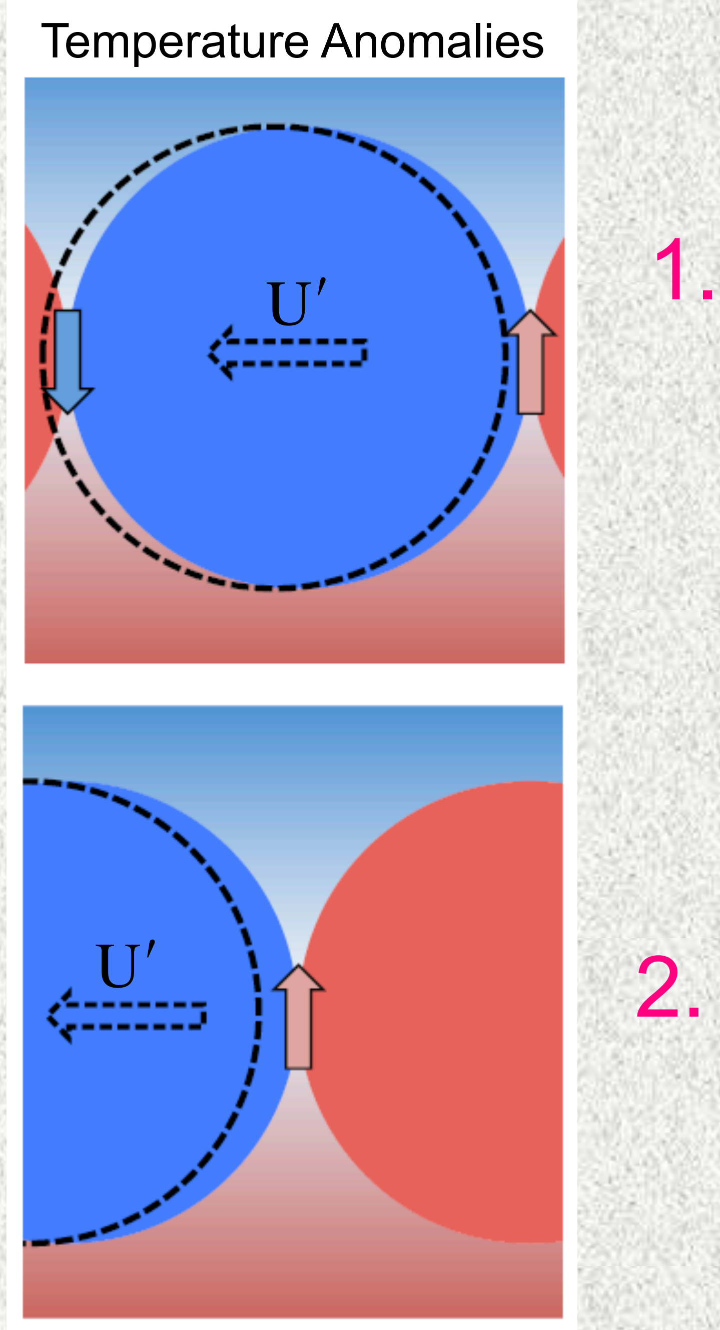
Hovmoller diagram for temperature anomalies;

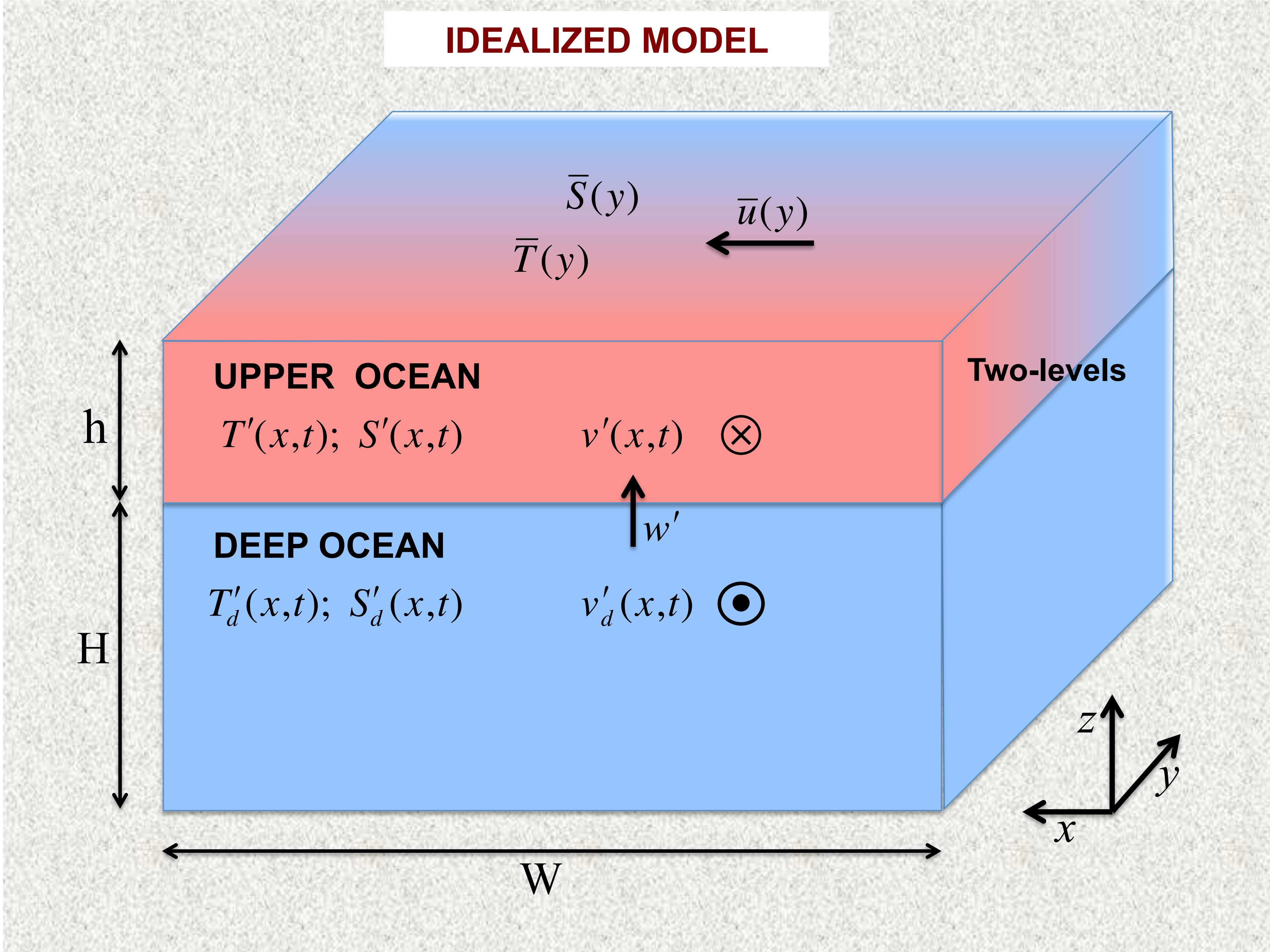
Decay suppressed

MODE MECHANISM:

Westward propagation of large-scale temperature anomalies






IDEALIZED MODEL
$\overline{S}(y)$
$\overline{T}(y)$
$\overline{u}(y)$
UPPER OCEAN
$T'(x,t);\ S'(x,t)$
$v'(x,t)$
Two-levels
w'
DEEP OCEAN
$T'_d(x,t);\ S'_d(x,t)$
$v'_d(x,t)$
h
H
W
z
y
x

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*

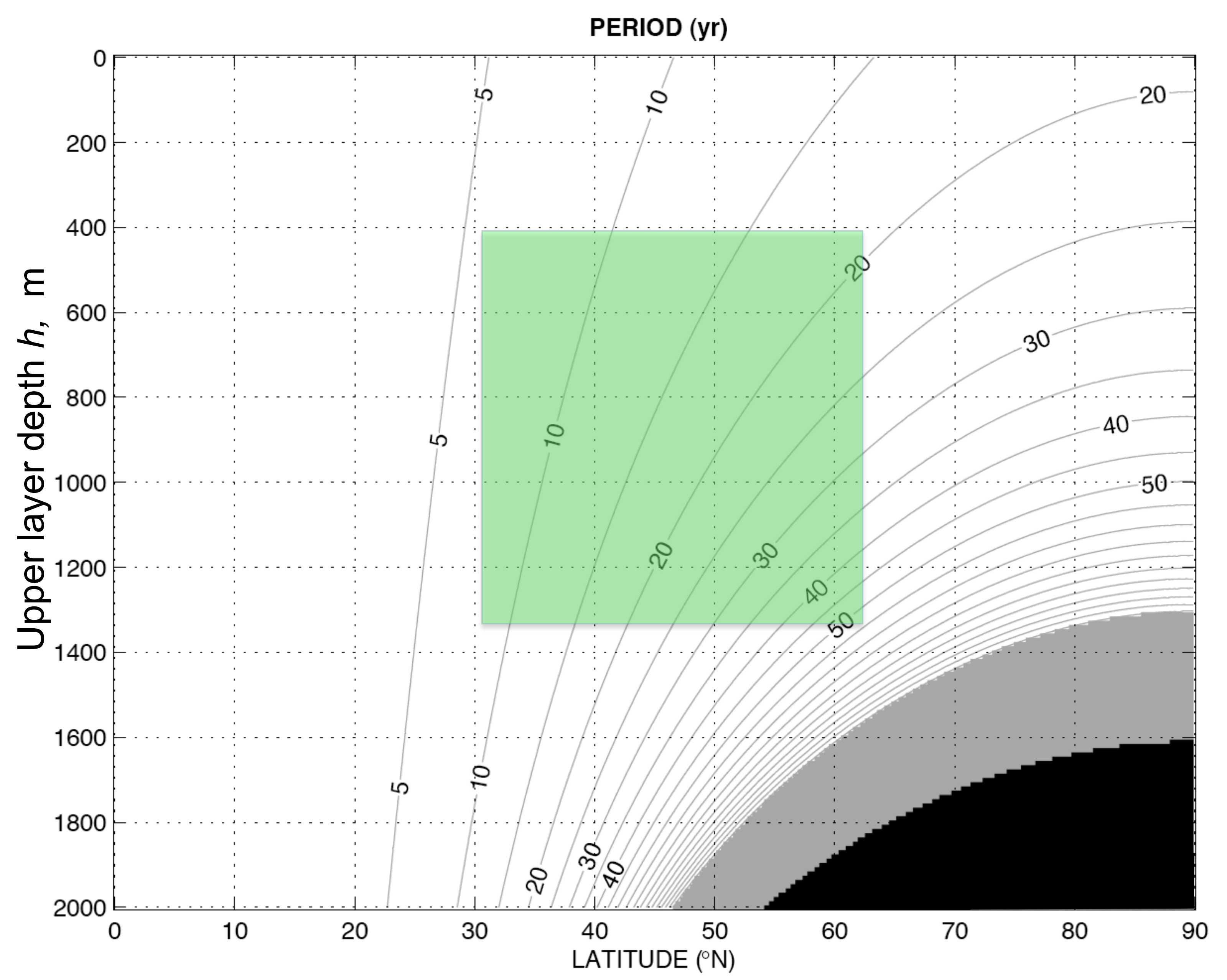
k - *horizontal diffusivity*

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

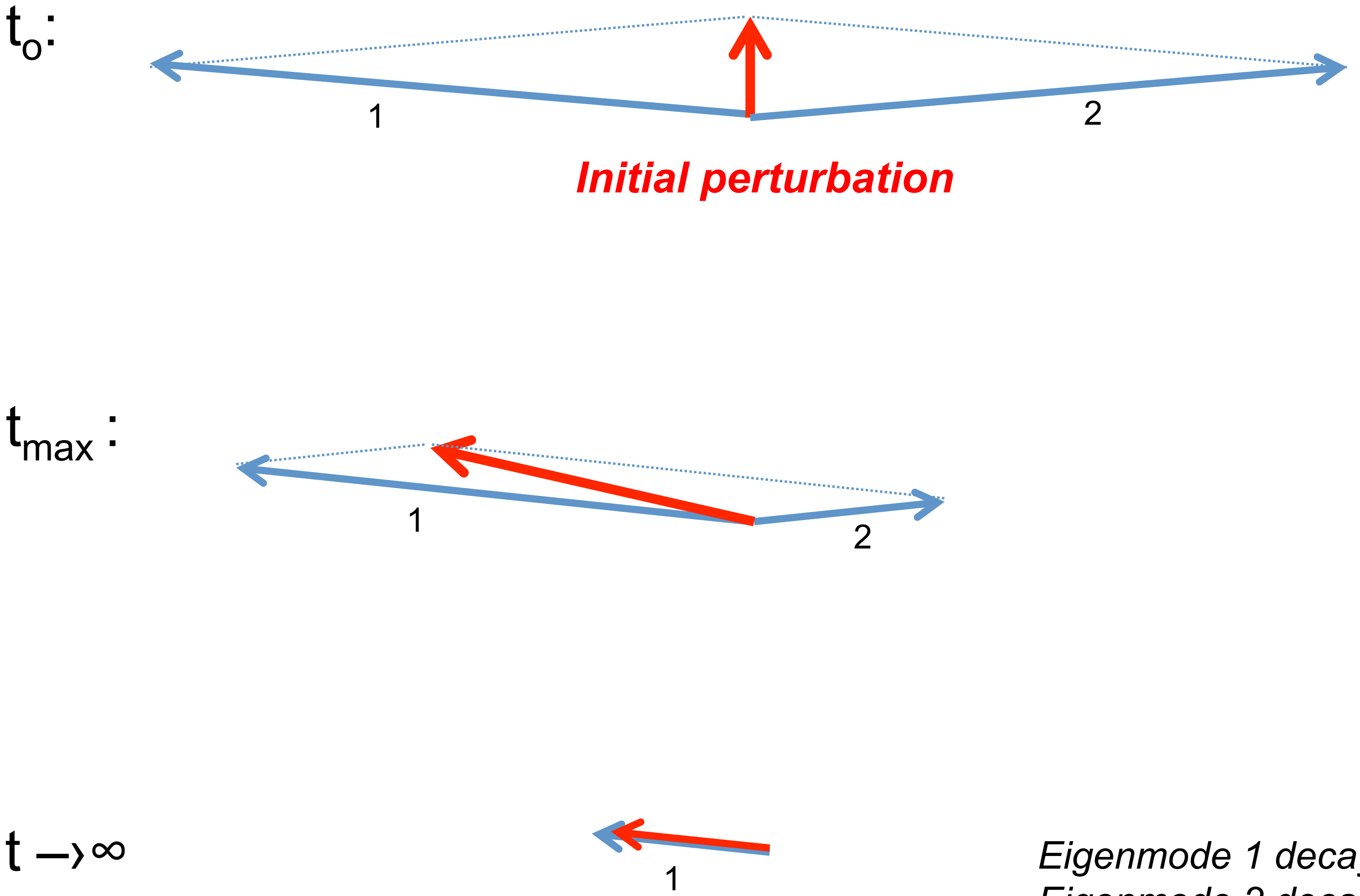
$U' = \frac{\alpha g h}{f}\partial_y \overline{T}$ - *effective amomalous westward advection*

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

OSCILLATION PERIOD



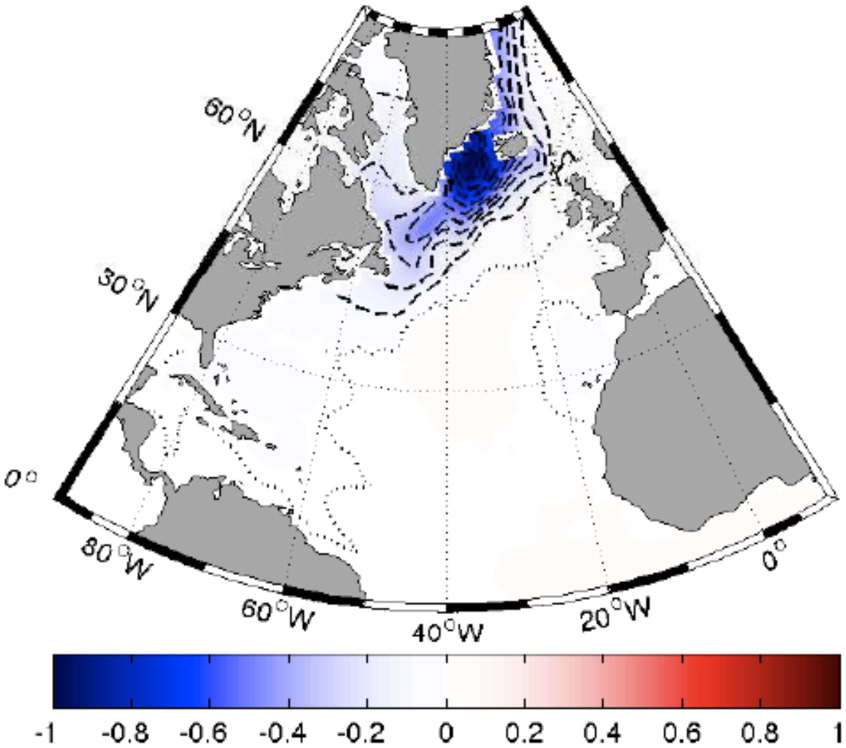
Nonnormality: an example of two decaying non-orthogonal eigenmodes creating transient growth



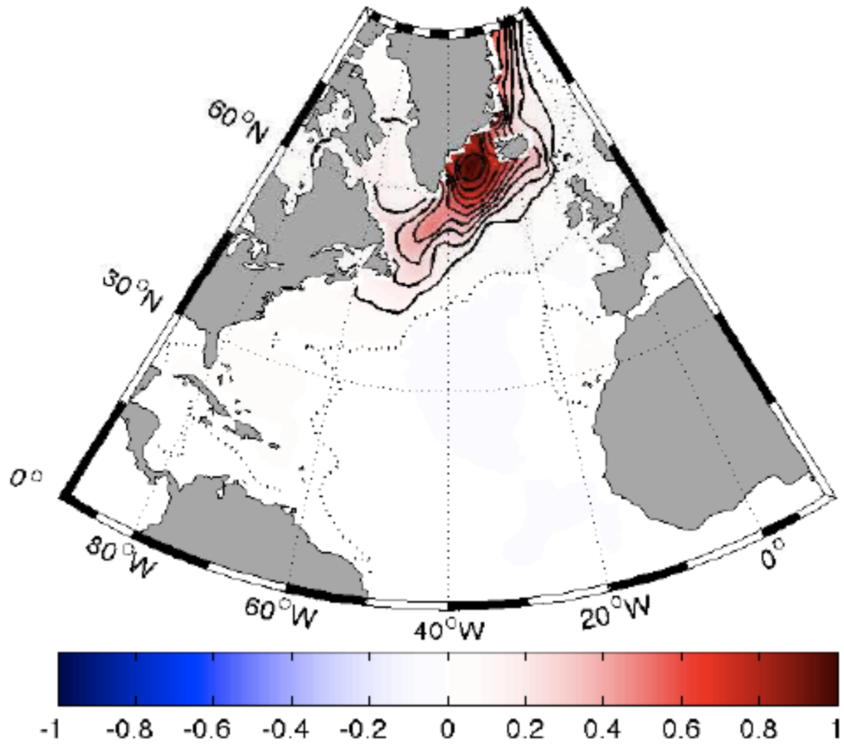
Eigenmode 1 decays slowly
Eigenmode 2 decays fast

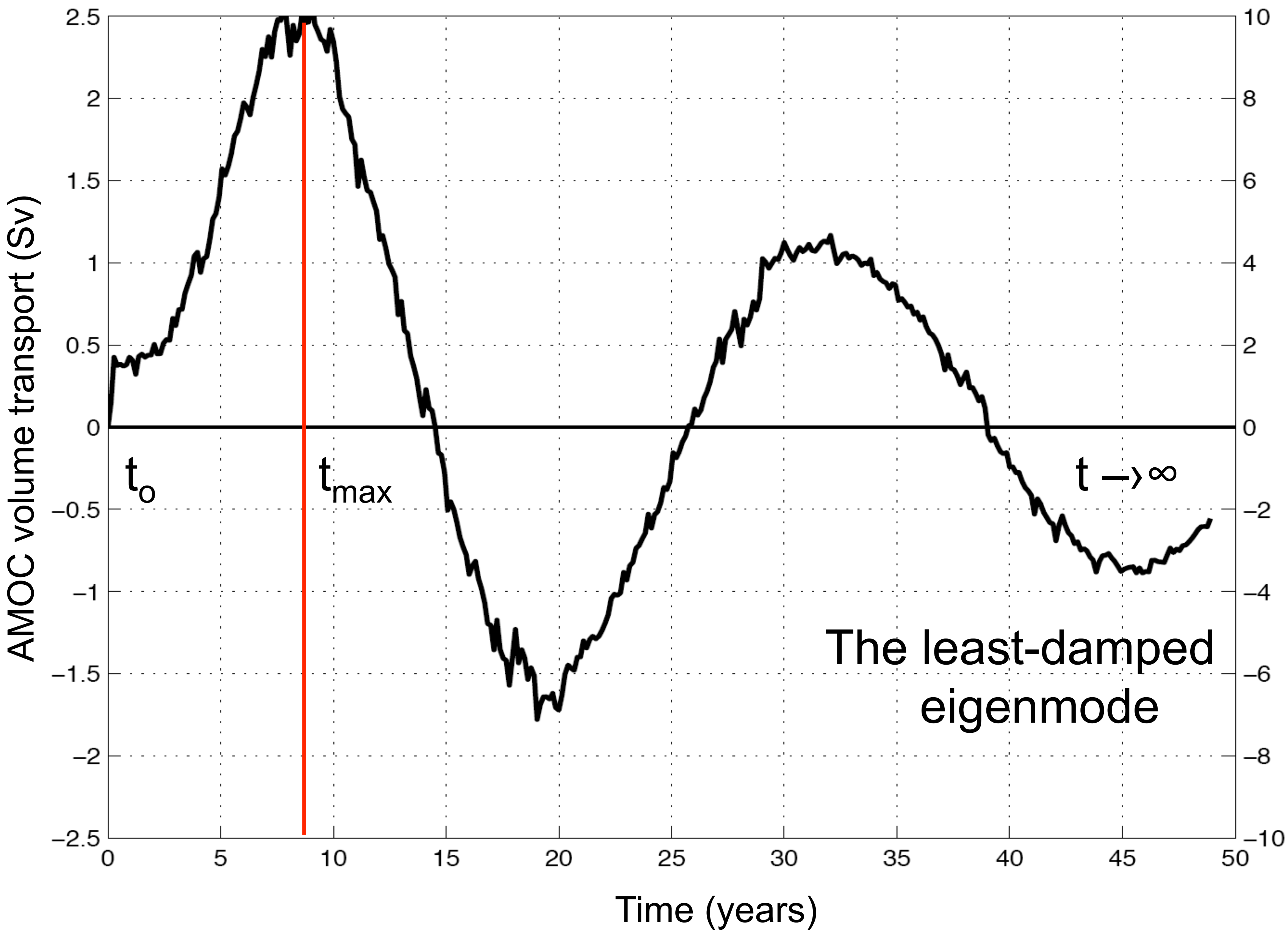
OPTIMAL INITIAL PERTURBATIONS

Optimal SST anomalies



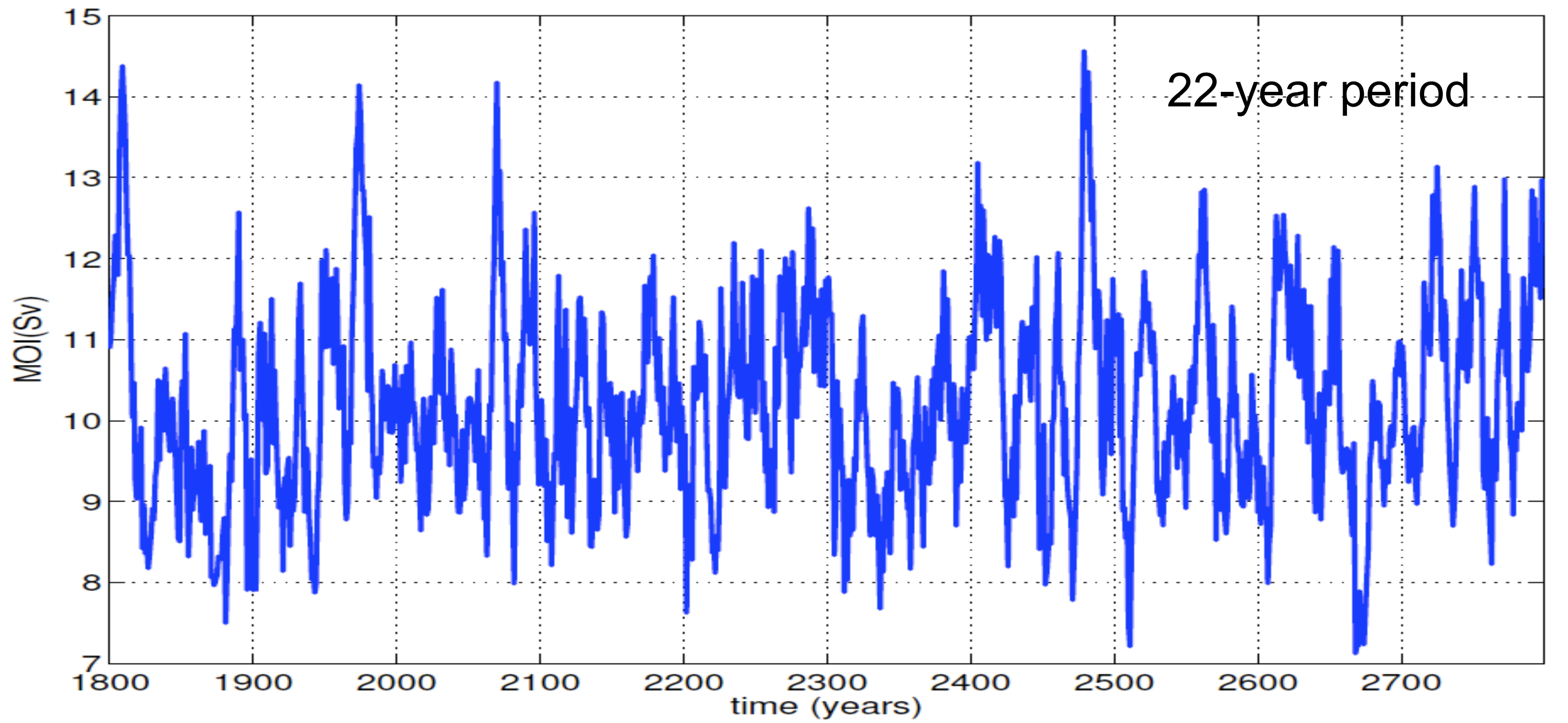
Optimal SSS anomalies

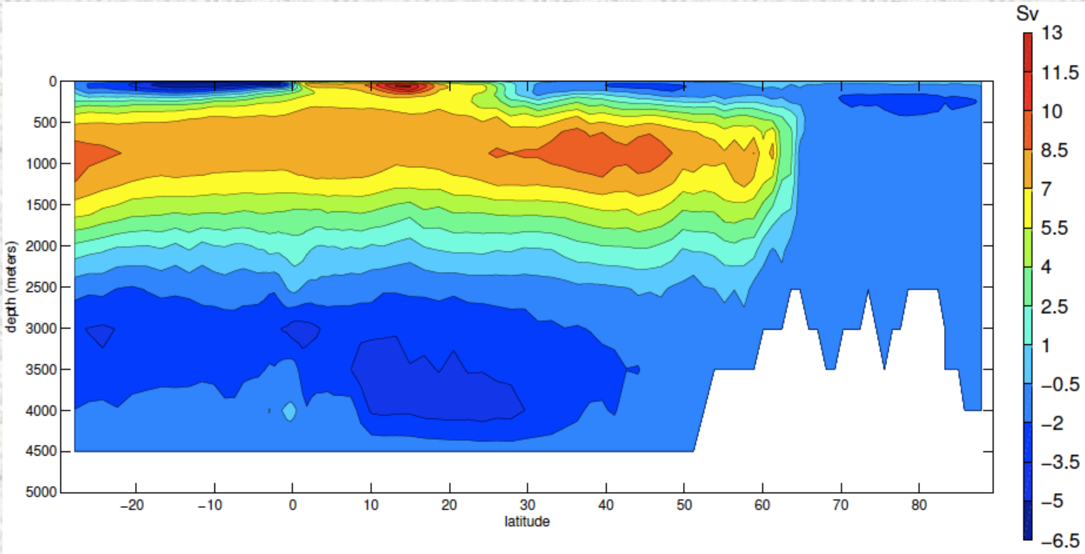




AMOC volume transport (Sv)
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
10
8
6
4
2
0
−2
−4
−6
−8
−10
0
5
10
15
20
25
30
35
40
45
50
Time (years)
t_o
t_{max}
t –› ∞
The least-damped eigenmode

COUPLED GCM

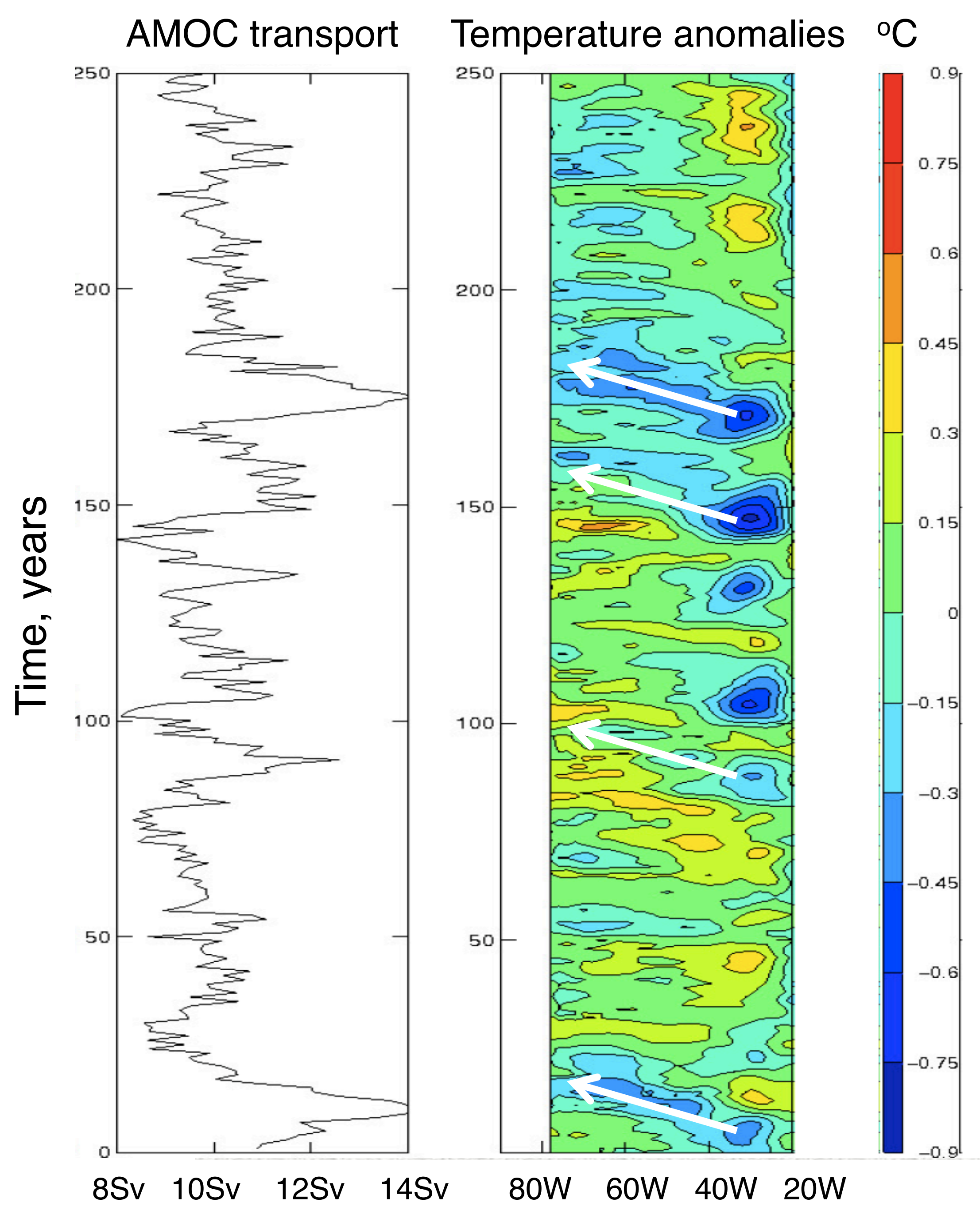




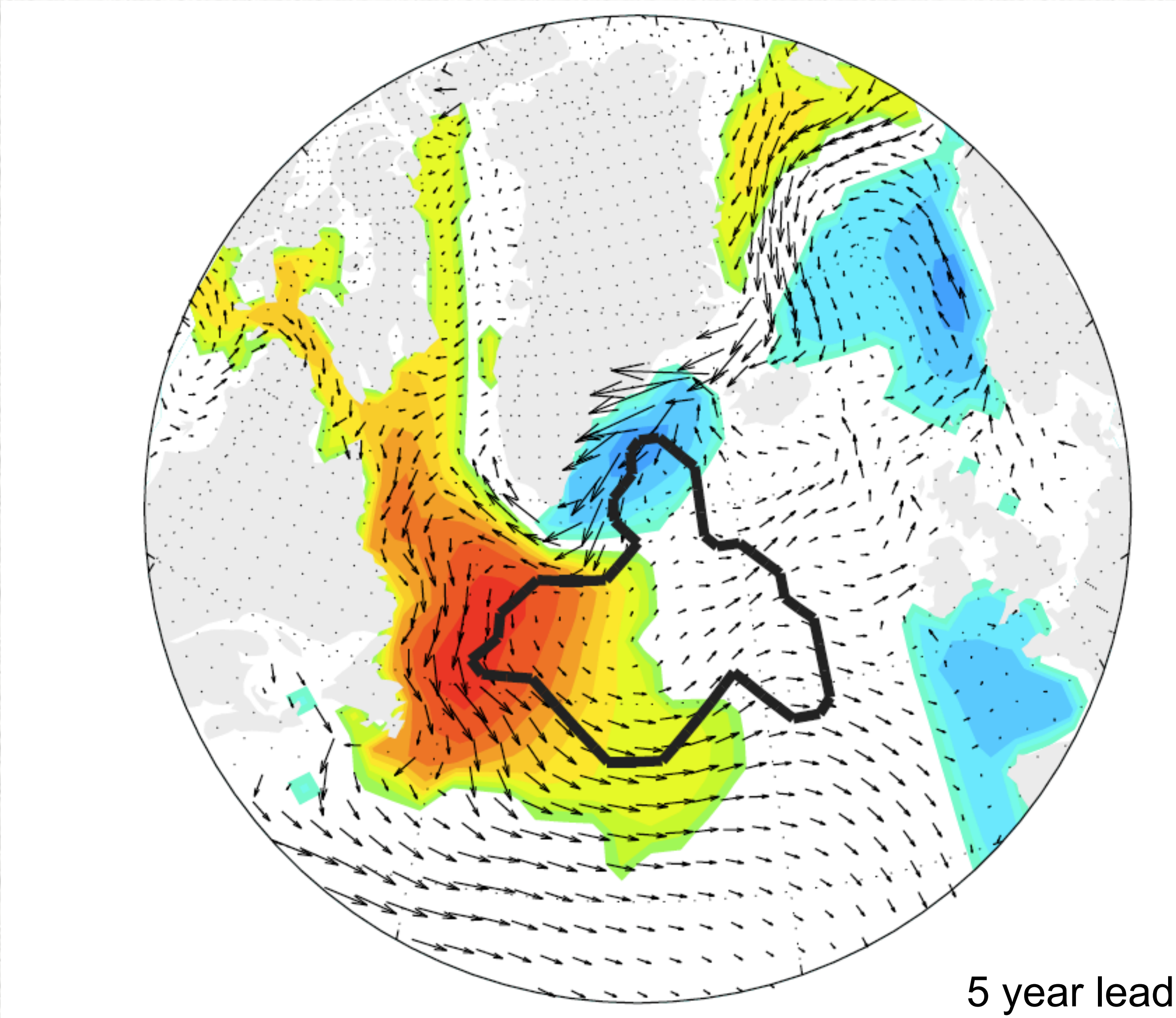
OPA 9
coupled to
LDMG = IPSL
coupled model

In collaboration with Juliette Mignot

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



Mode excitation



Summary

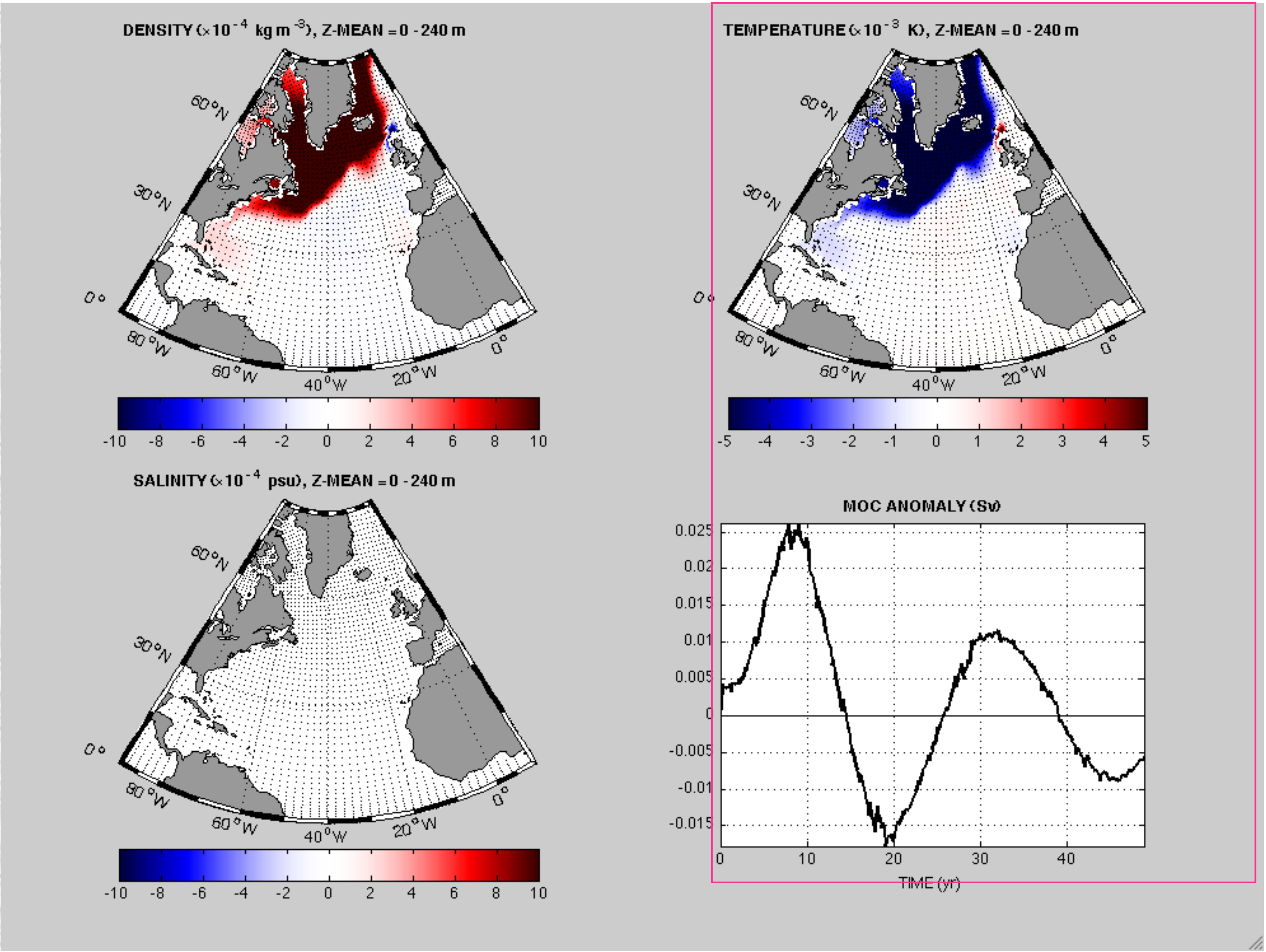
- *We have identified the leading interdecadal, weakly-damped oscillatory eigenmode of the AMOC in a realistic ocean GCM (T≈ 24 years) based on ocean dynamics*

- *The mechanism of the mode is related to westward propagating temperature anomalies in the upper 500-1000m in the northern Atlantic (partially compensated by salinity)*

- *The mode can be efficiently excited by optimum salinity and/or temperature perturbations centered east of Greenland*

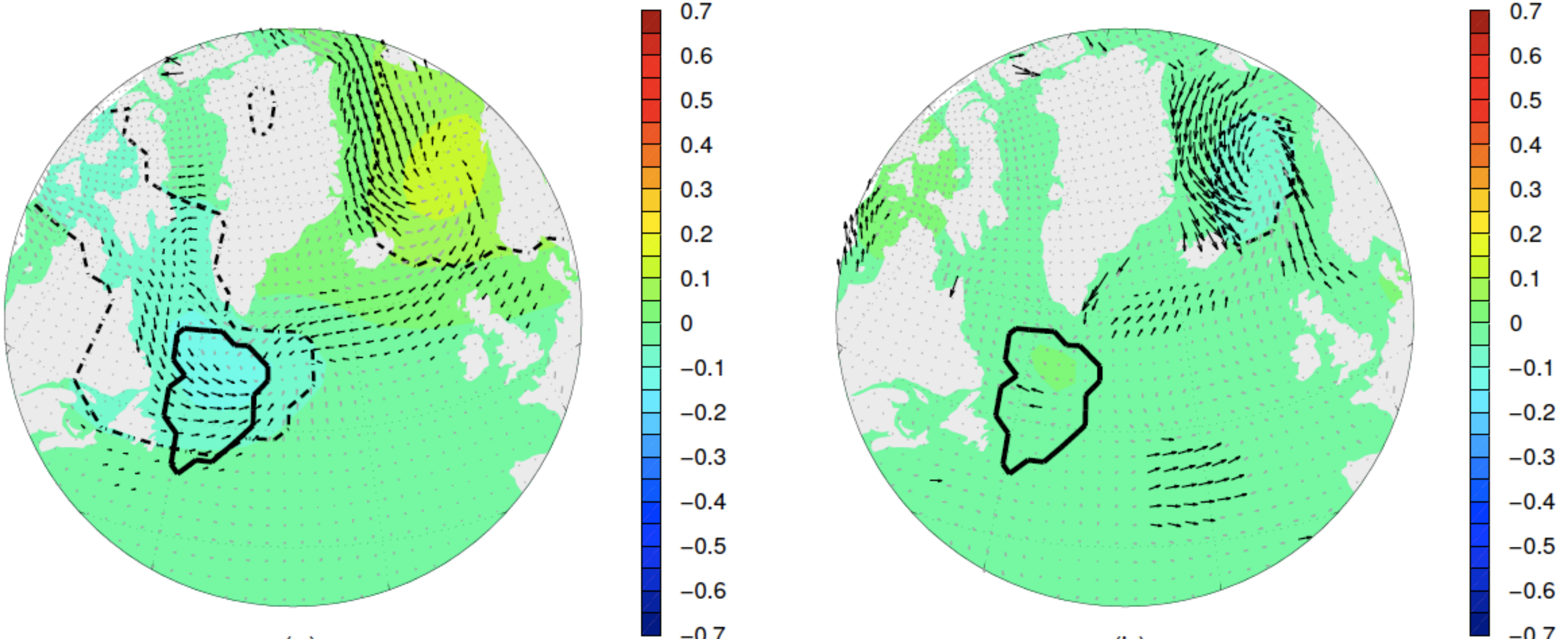
- *The mode is present in the coupled model and possibly excited by optimal perturbations*

Claim: This eigenmode should be relevant to other GCMs with AMOC variability in the range 10-50 years



DENSITY (×10⁻⁴ kg m⁻³), Z-MEAN = 0 - 240 m
TEMPERATURE (×10⁻³ K), Z-MEAN = 0 - 240 m
SALINITY (×10⁻⁴ psu), Z-MEAN = 0 - 240 m
MOC ANOMALY (Sv)
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
-5 -4 -3 -2 -1 0 1 2 3 4 5
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



(a)

(b)

IDEALIZED MODEL

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

v' - *meridional velocity anomaly*

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

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

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

h - *upper layer thickness*

α - *thermal expansion*

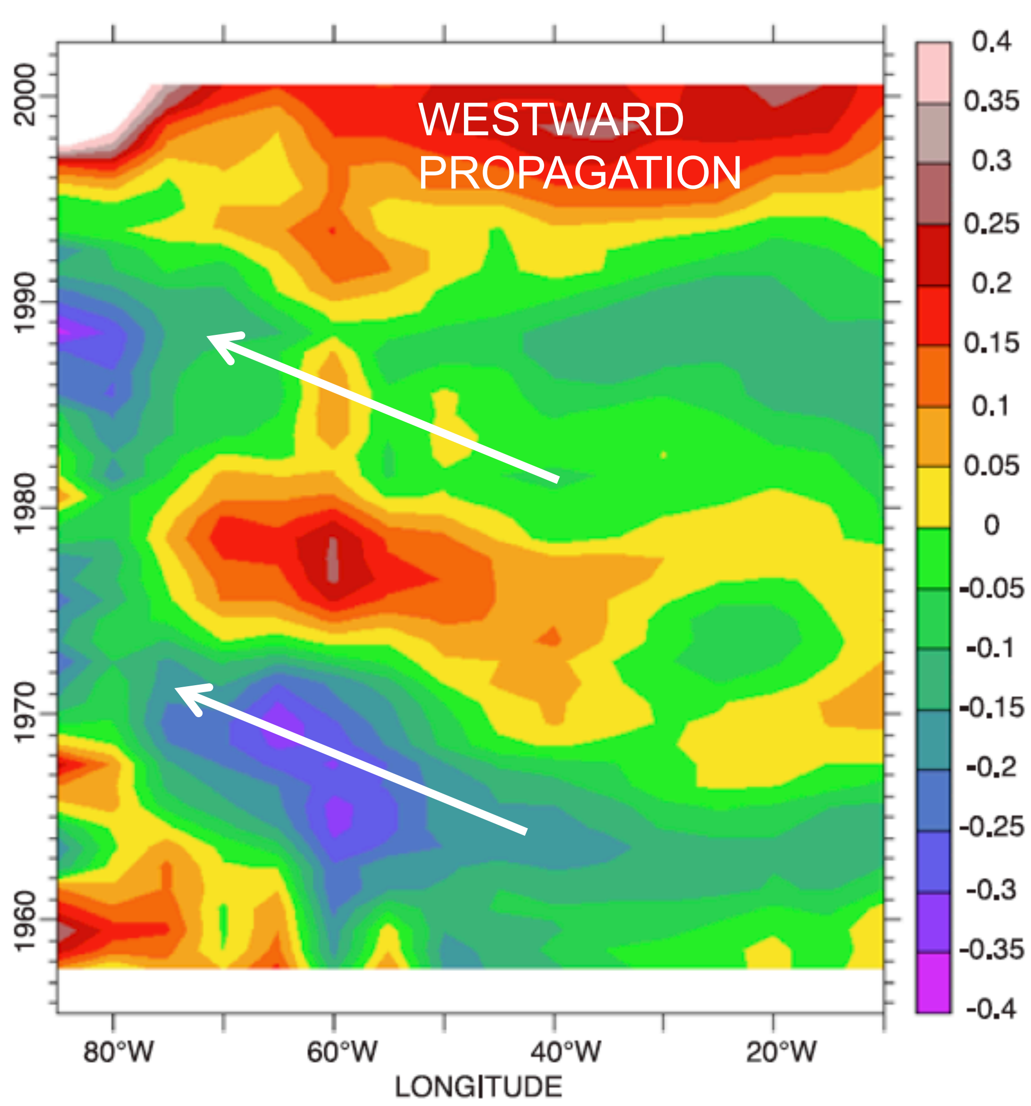
g - *acceleration of gravity*

f - *Coriolis parameter*

k - *horizontal diffusivity*

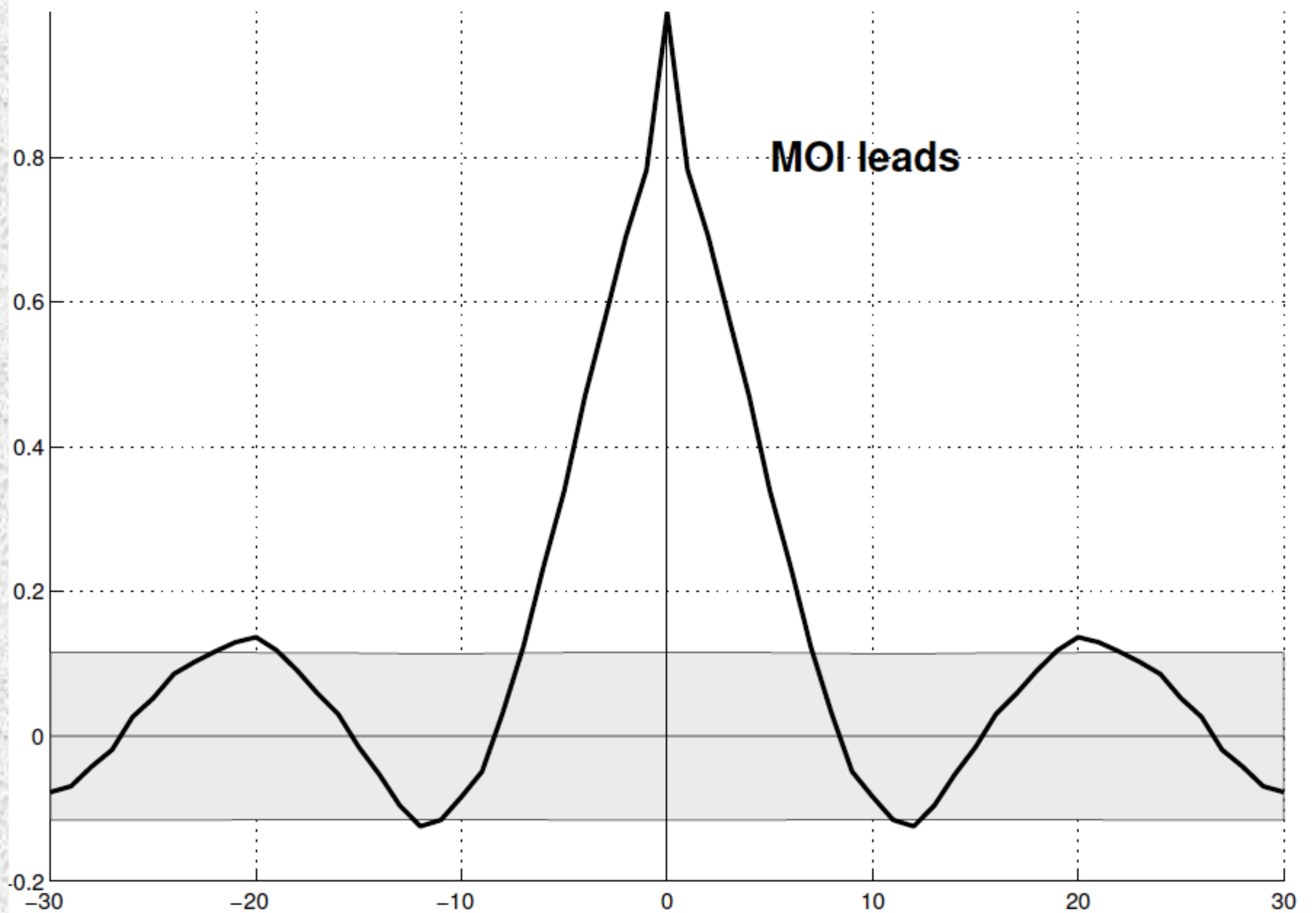
c_{Rossby} - *baroclinic Rossby wave speed (β - effect)*

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

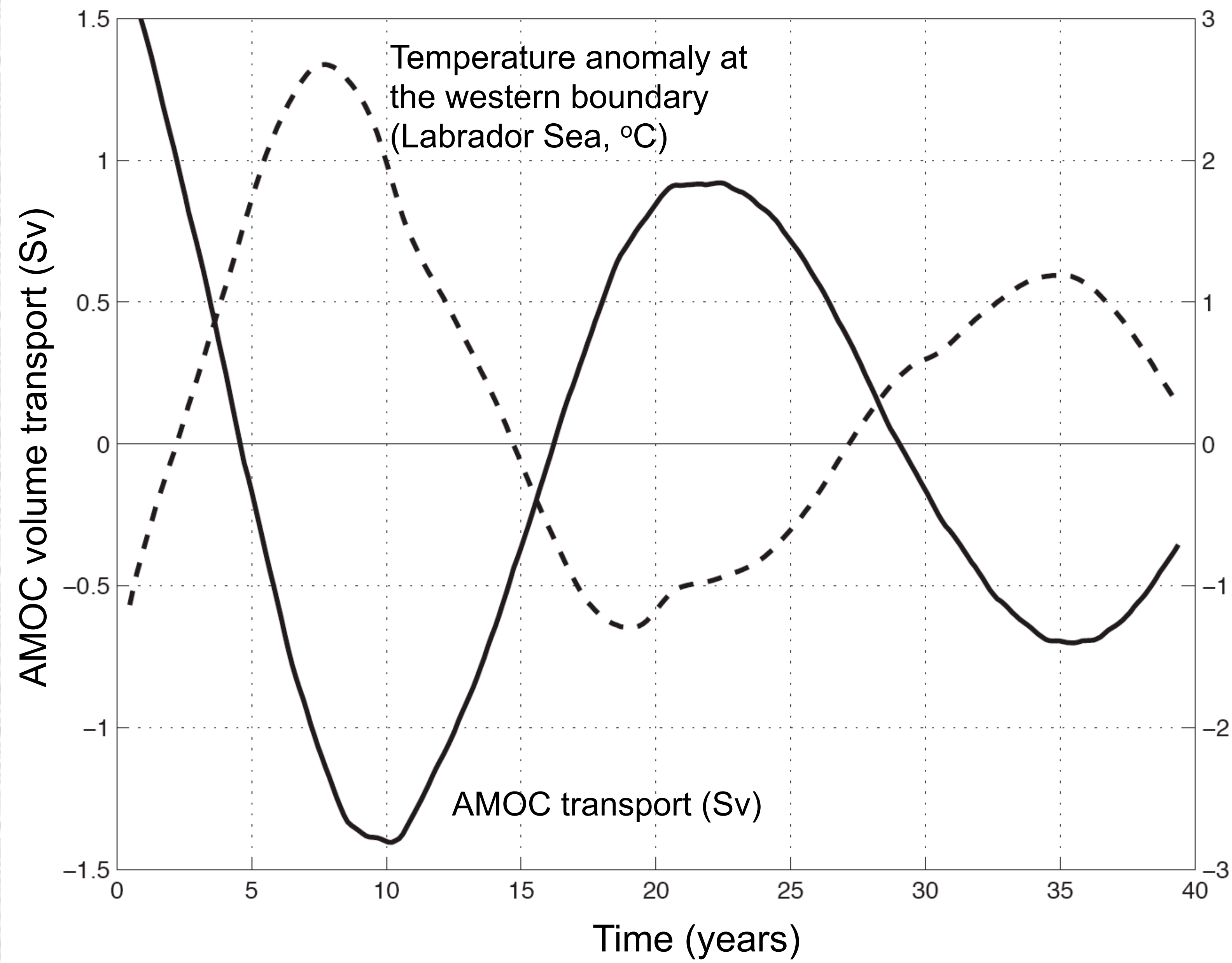


Frankcombe et al 2008

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


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

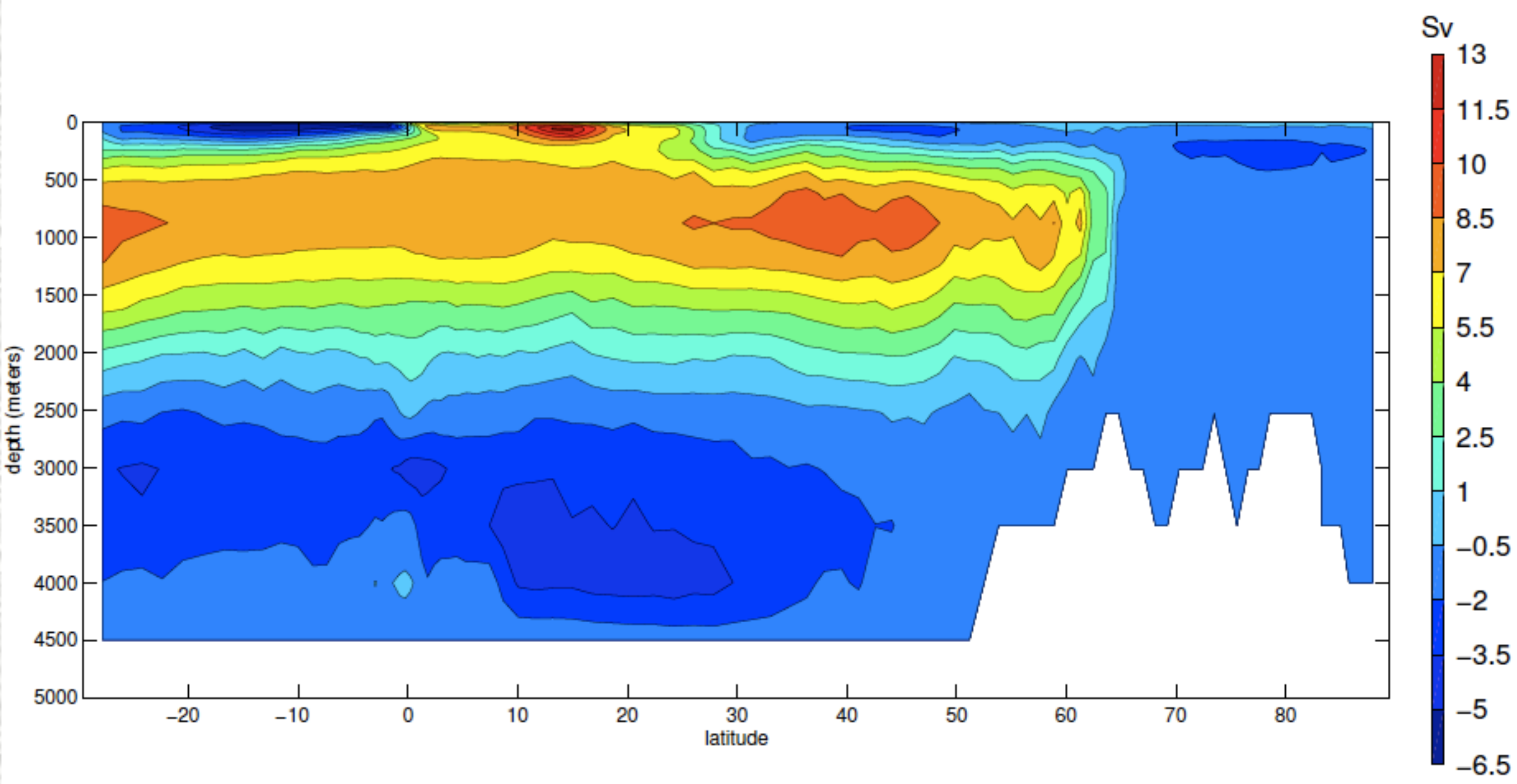


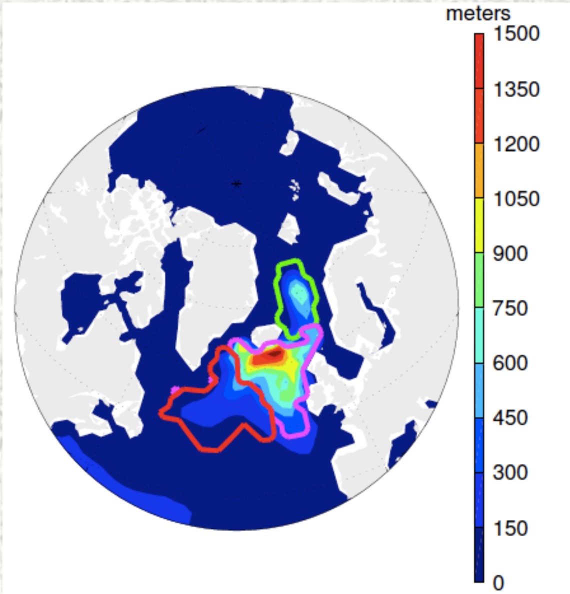
MODE MECHANISM AND EXCITATION:

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
−2
−3.5
−5
−6.5
depth (meters)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
−20
−10
0
10
20
30
40
50
60
70
80
latitude


meters
1500
1350
1200
1050
900
750
600
450
300
150
0

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*

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

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

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

h - *upper layer thickness*

α - *thermal expansion*

g - *acceleration of gravity*

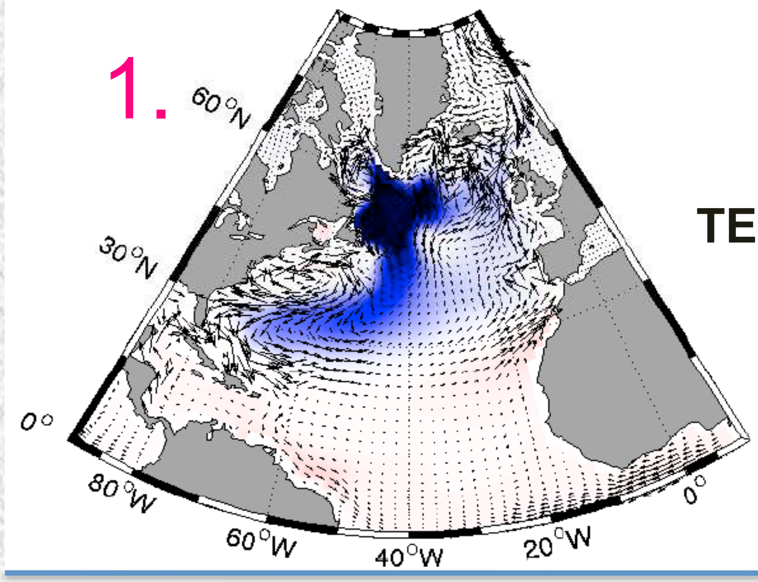
f - *Coriolis parameter*

k - *horizontal diffusivity*

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

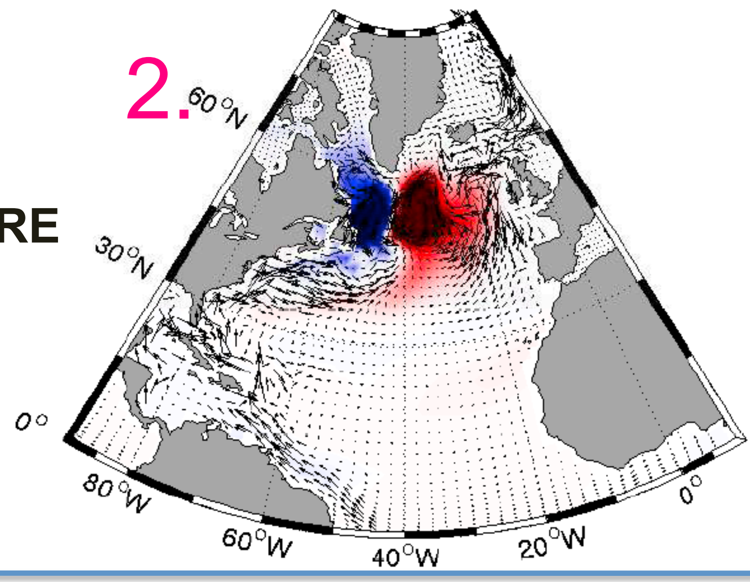
$$U' = \frac{\alpha g h}{f}\partial_y \overline{T} \quad \text{- effective anomalous westward advection}$$

$-\alpha\varrho_0\times$TEMPERATURE (kg m^{-3}), Z-MEAN = 0 - 240 m

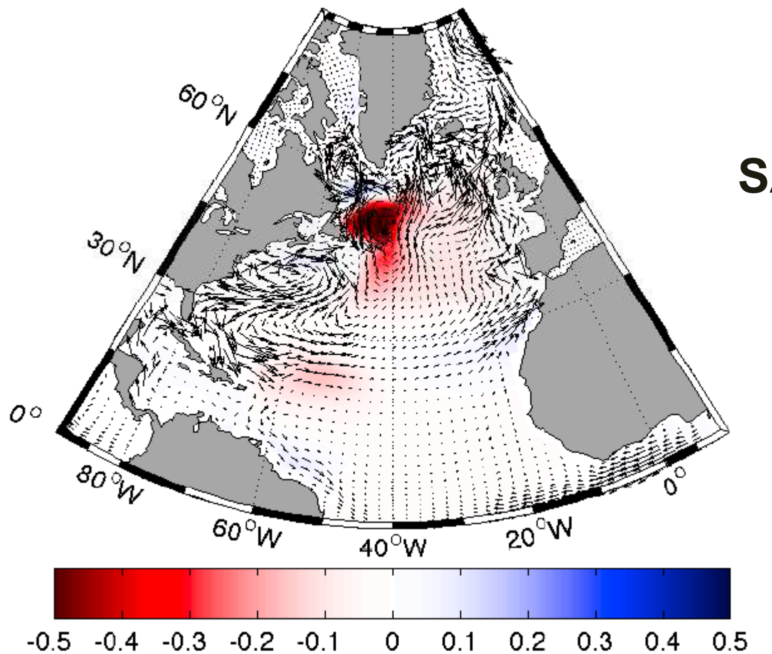


TEMPERATURE

$-\alpha\varrho_0\times$TEMPERATURE (kg m^{-3}), Z-MEAN = 0 - 240 m

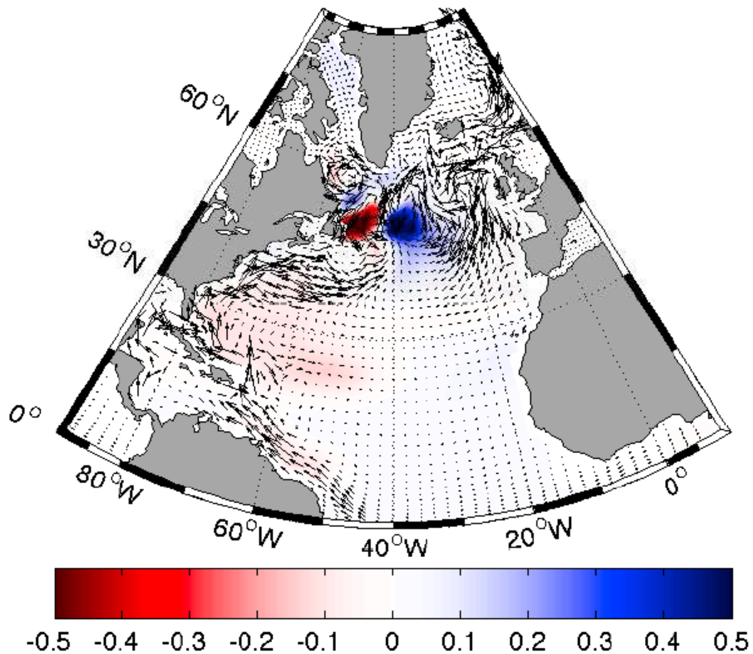


$\beta\varrho_0\times$SALINITY (kg m^{-3})



SALINITY

$\beta\varrho_0\times$SALINITY (kg m^{-3})



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

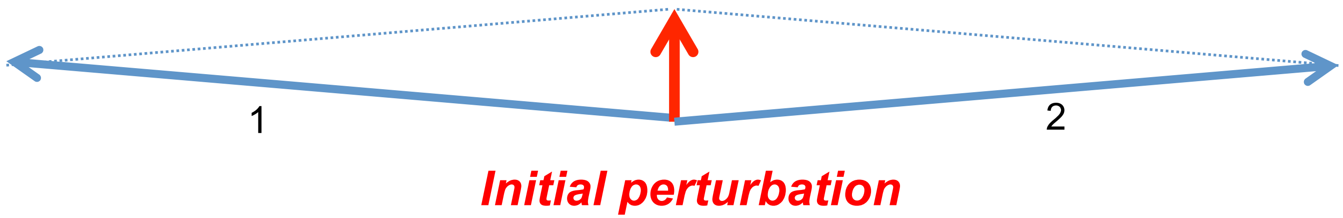
The eigenvectors of the tangent linear model are not orthogonal

=>

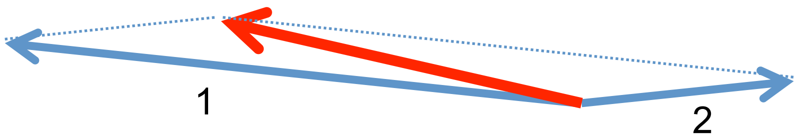
fast transient growth is possible

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

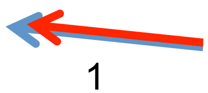
t_o:



t_{max} :

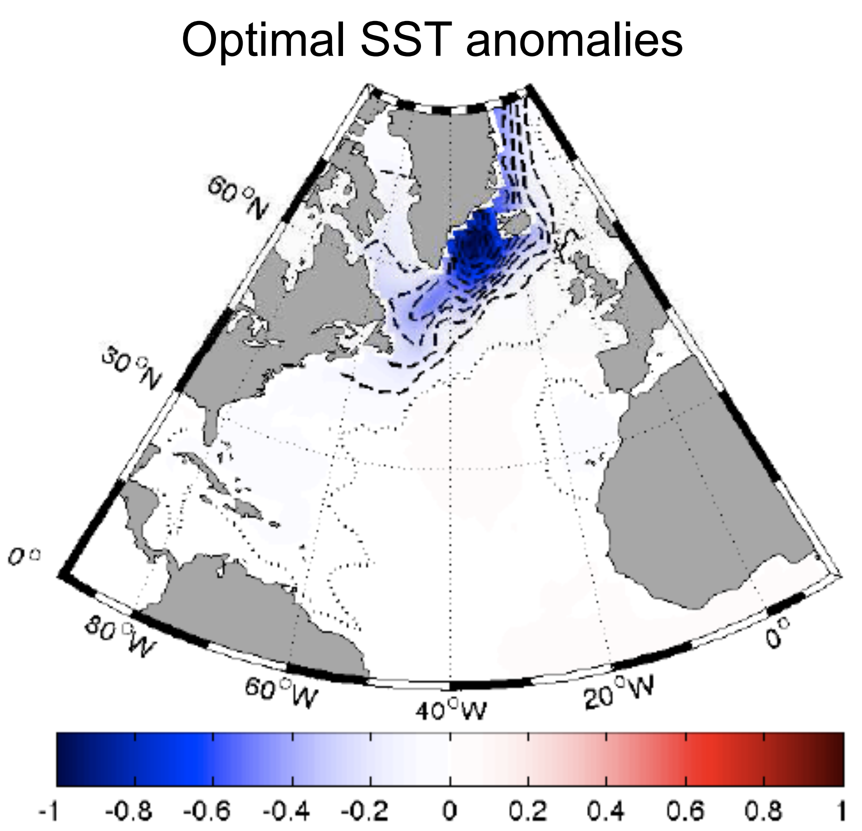


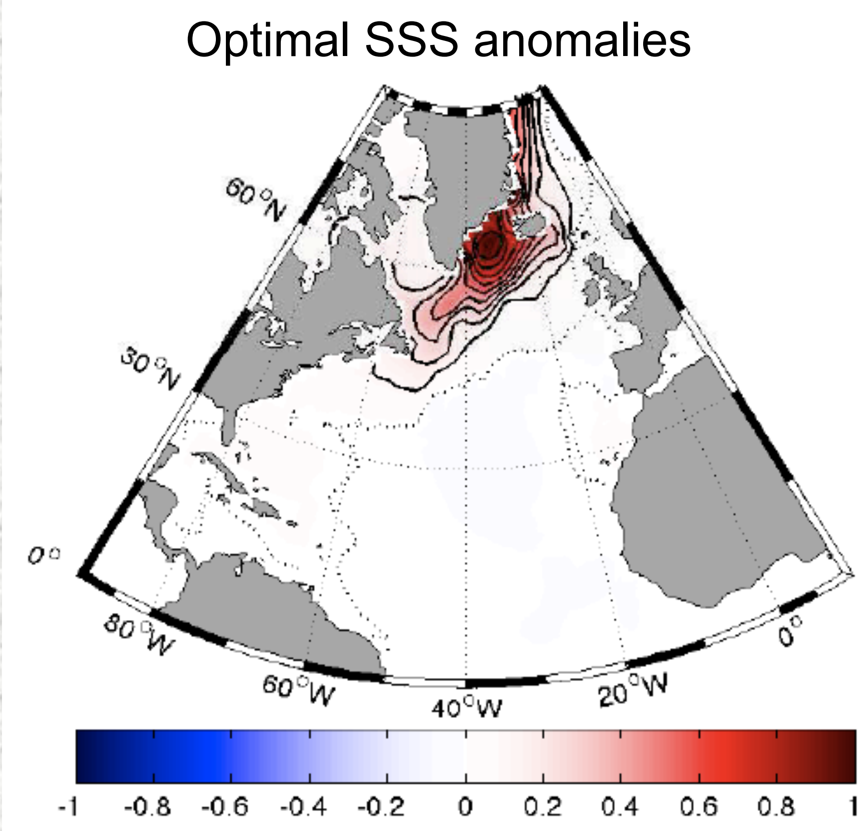
$t \to \infty$

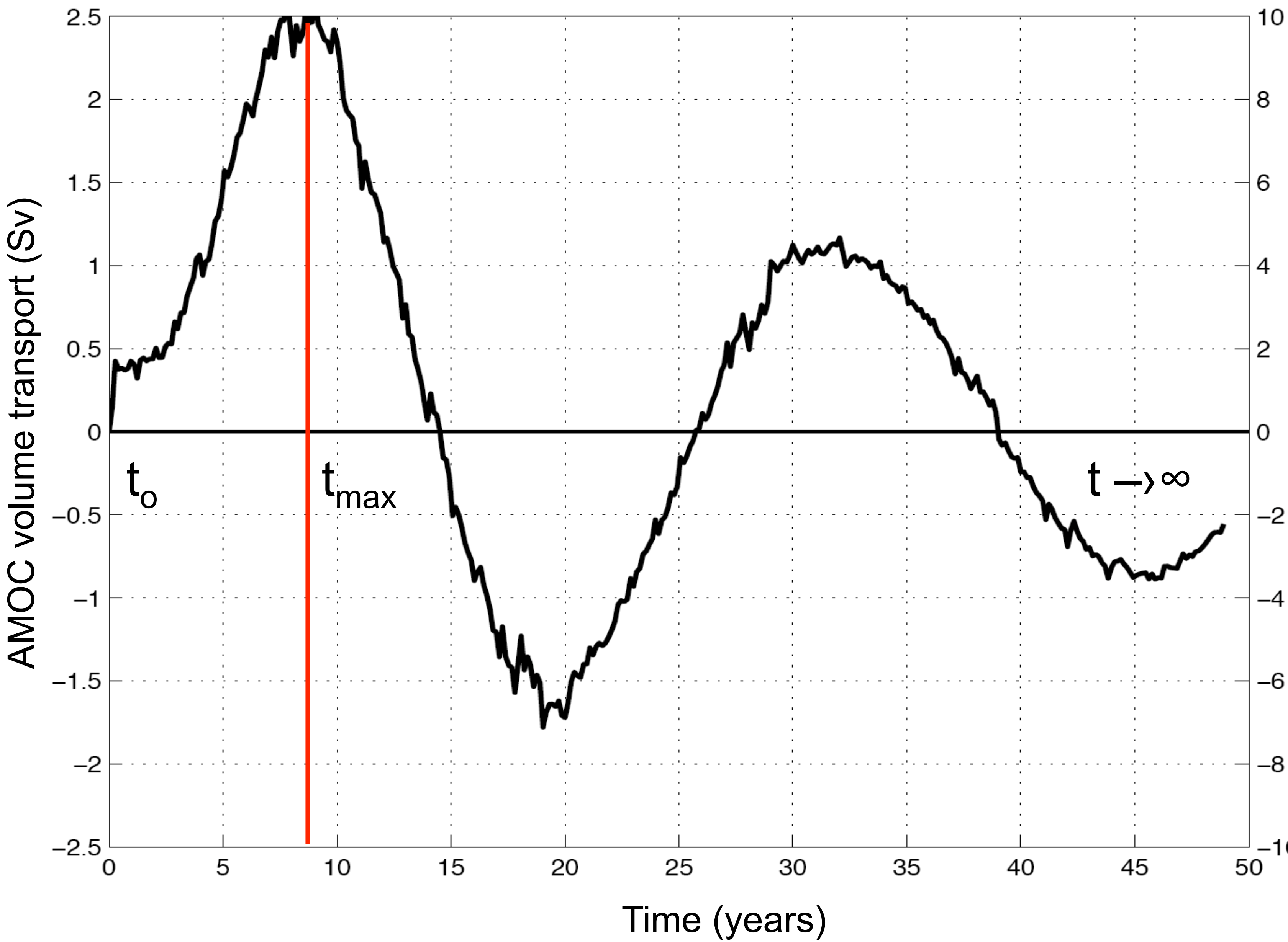


Eigen-mode 1 decays slowly
Eigen-mode 2 decays fast

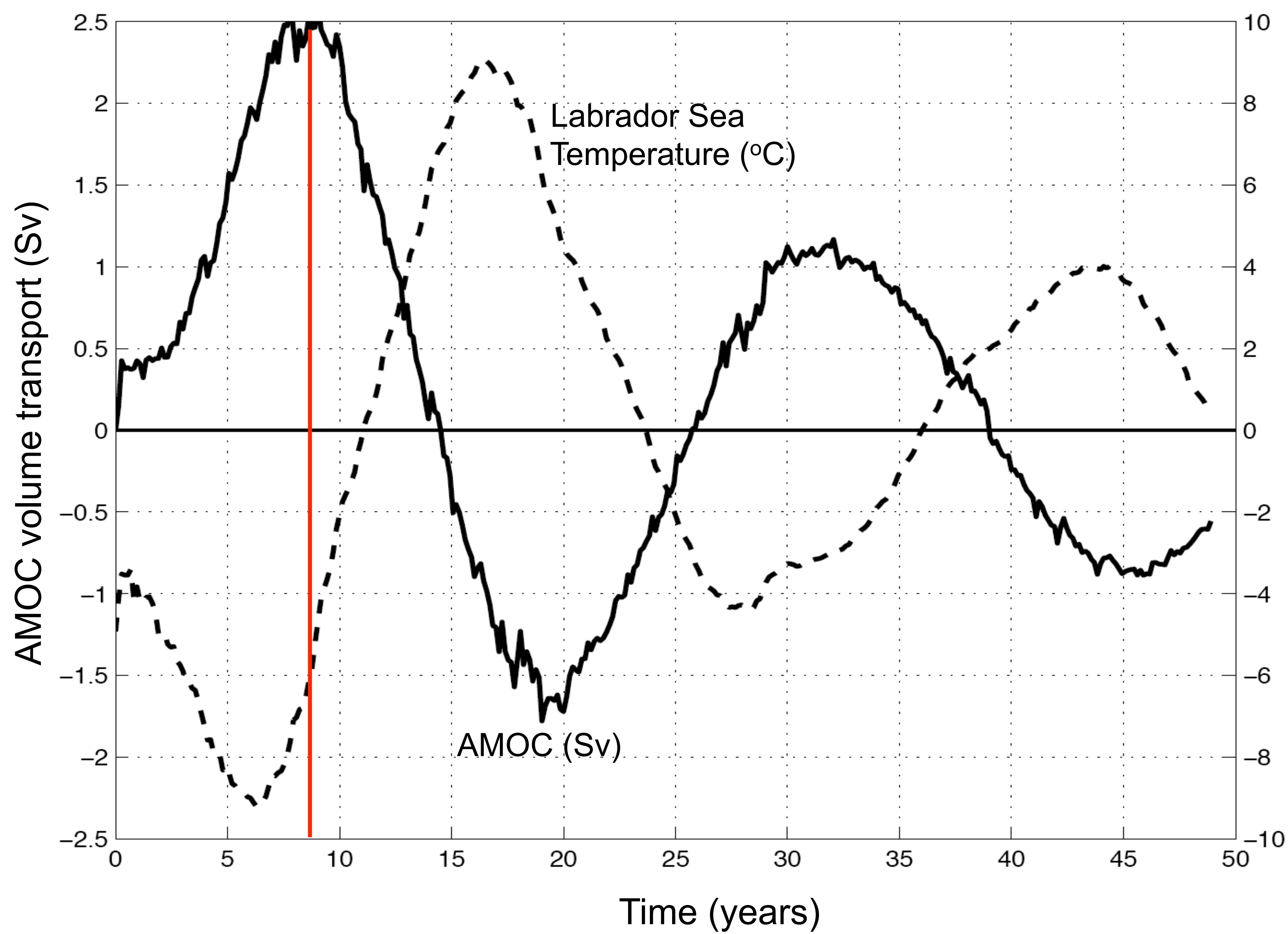
OPTIMAL INITIAL PERTURBATIONS

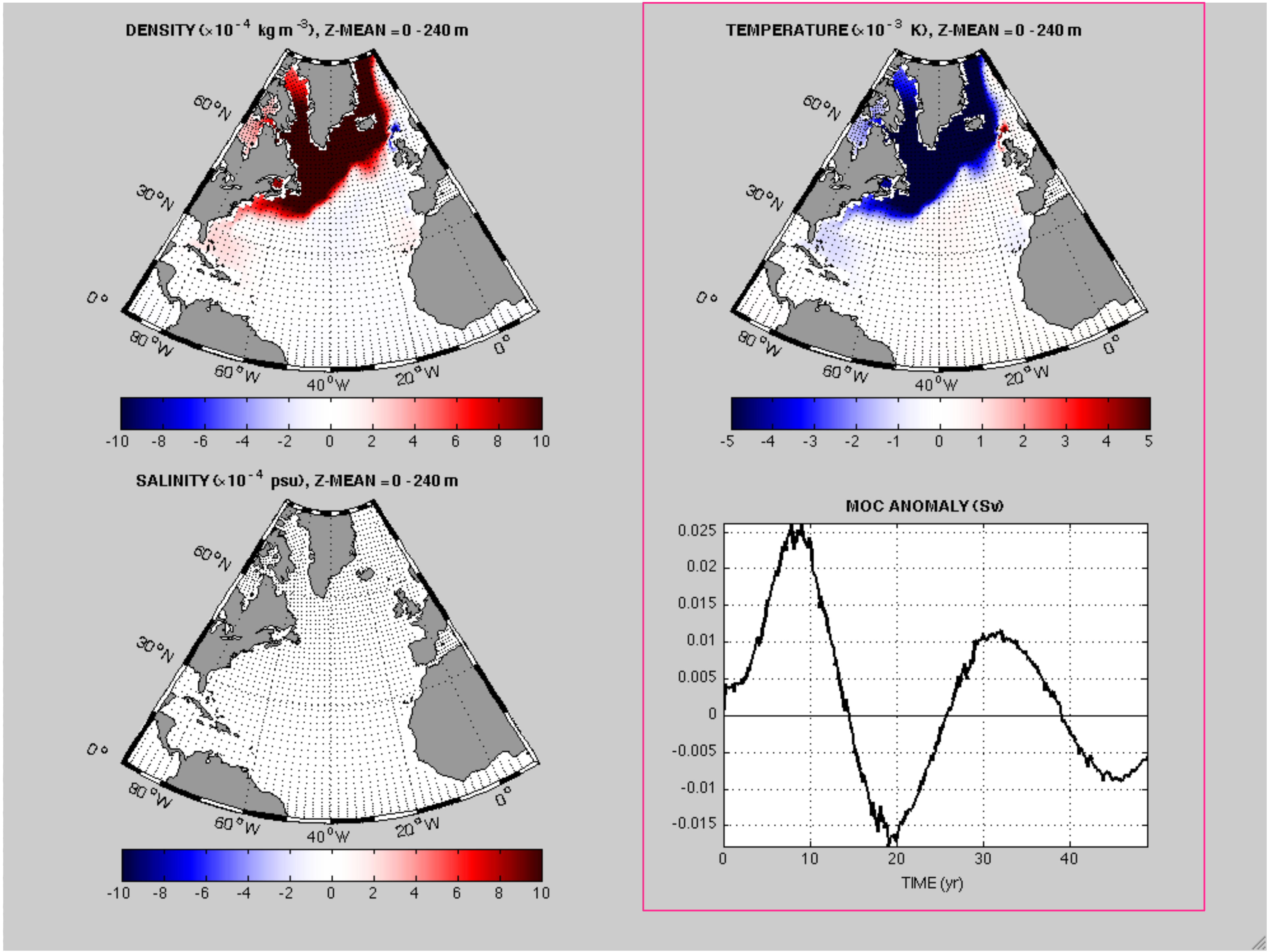






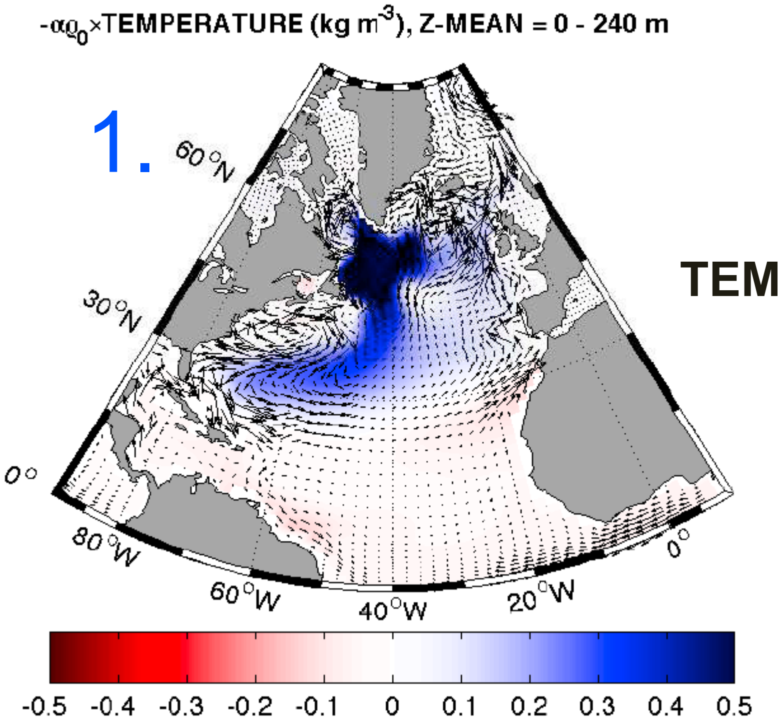
AMOC volume transport (Sv)
Time (years)
t_o
t_{max}
$t \to \infty$
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
0
5
10
15
20
25
30
35
40
45
50
10
8
6
4
2
0
−2
−4
−6
−8
−10


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
0 5 10 15 20 25 30 35 40 45 50
10
8
6
4
2
0
−2
−4
−6
−8
−10

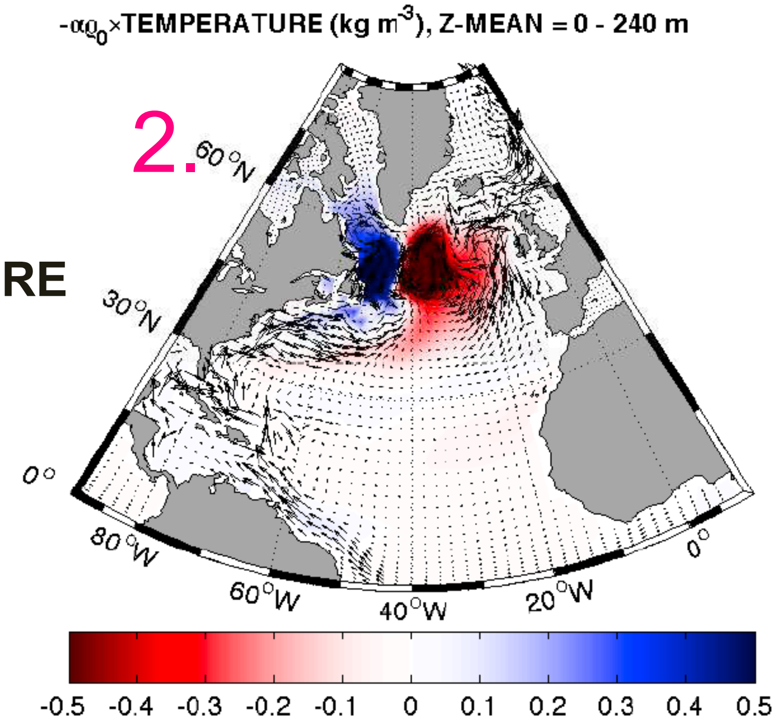

DENSITY (×10^-4 kg m^-3), Z-MEAN = 0 - 240 m
60°N
30°N
0°
80°W
60°W
40°W
20°W
0°
-10 -8 -6 -4 -2 0 2 4 6 8 10
TEMPERATURE (×10^-3 K), Z-MEAN = 0 - 240 m
60°N
30°N
0°
80°W
60°W
40°W
20°W
0°
-5 -4 -3 -2 -1 0 1 2 3 4 5
SALINITY (×10^-4 psu), Z-MEAN = 0 - 240 m
60°N
30°N
0°
80°W
60°W
40°W
20°W
0°
-10 -8 -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:

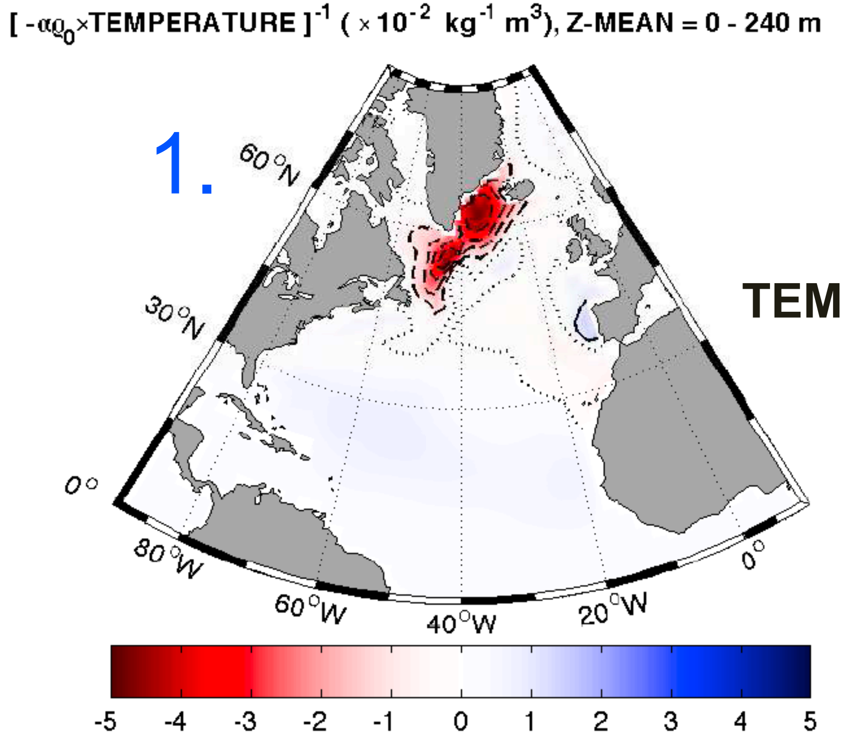
- *The system is nonnormal, so that*
  - *optimal initial perturbations for the interdecadal mode have a different structure - they are centered off the east coast of Greenland*
  - *atmospheric noise can efficiently excite this mode through this optimal initial perturbations*



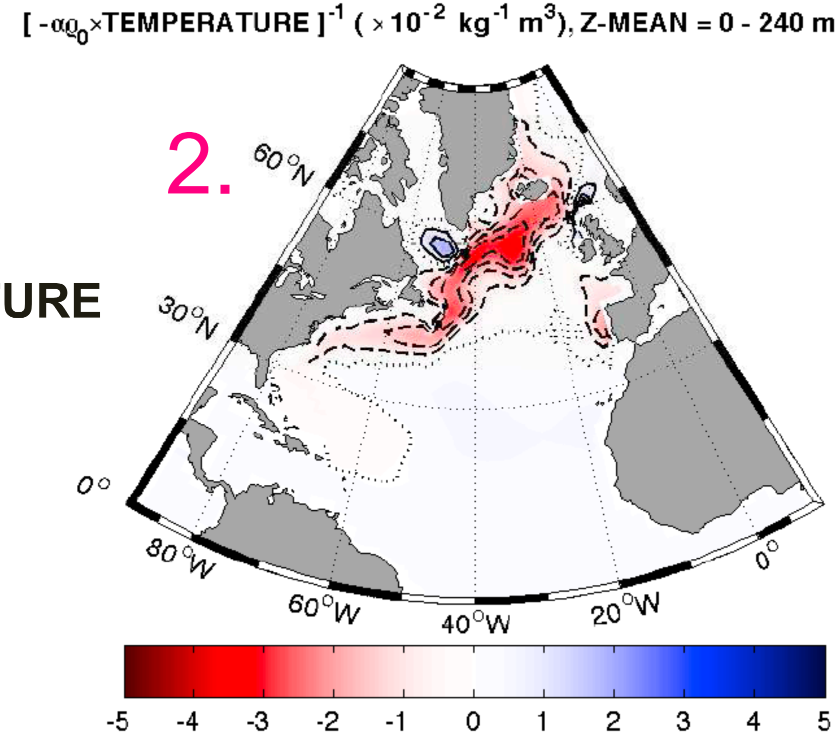
TEMPERATURE



The least-damped mode of the tangent linear model



TEMPERATURE



The least-damped mode of the adjoint