Internal modes of the ocean circulation on decadal to centennial time scales and their mechanism

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Outline: *process studies with idealized ocean and atmosphere models*

- two different mechanisms for interdecadal variability of the ocean thermohaline circulation under constant flux and mixed surface boundary conditions
- which one is relevant with more realistic atmospheric coupling?

Introduction

Variability in the climate system

- "external" forcing (solar volcanic anthropogenic)
- coupled ocean-atmosphere modes (ENSO)
- atmospheric modes (NAO)
- internal ocean modes, unstable or damped (and sustained by atmospheric synoptic noise)

+ modes involving feedbacks with snow, ice, biosphere...

Aim : exhibit internal modes of the ocean circulation, and understand their mechanism and robustness.

Methods

- nonlinear integrations under prescribed forcing (unstable)
- nonlinear integrations with stochastic forcing (weakly damped)
- linear stability analysis exhibit all modes

Interdecadal ocean variability

Several **ocean models** have shown variability on **interdecadal time scales** under different types of forcing:

- **mixed boundary conditions** (Weaver and Sarachik 1991, Weaver et al. 1991, 1993)
- **constant fluxes** of heat (Greatbatch and Zhang 1995, Huck et al. 1999, te Raa and Dijkstra 2002) or freshwater (Huang and Chou 1994)

Several mechanism have been proposed: advective, boundary waves, large scale ‘generalized’ baroclinic instability

- *Are all these interdecadal oscillations similar, based on a single mechanism? what is it?*
- *How do they survive with more realistic configurations and atmospheric coupling?*

The ocean model

3D 'large-scale' ocean model
- planetary geostrophic dynamics
- flat bottom
- one-hemisphere configuration
- linear equation of state

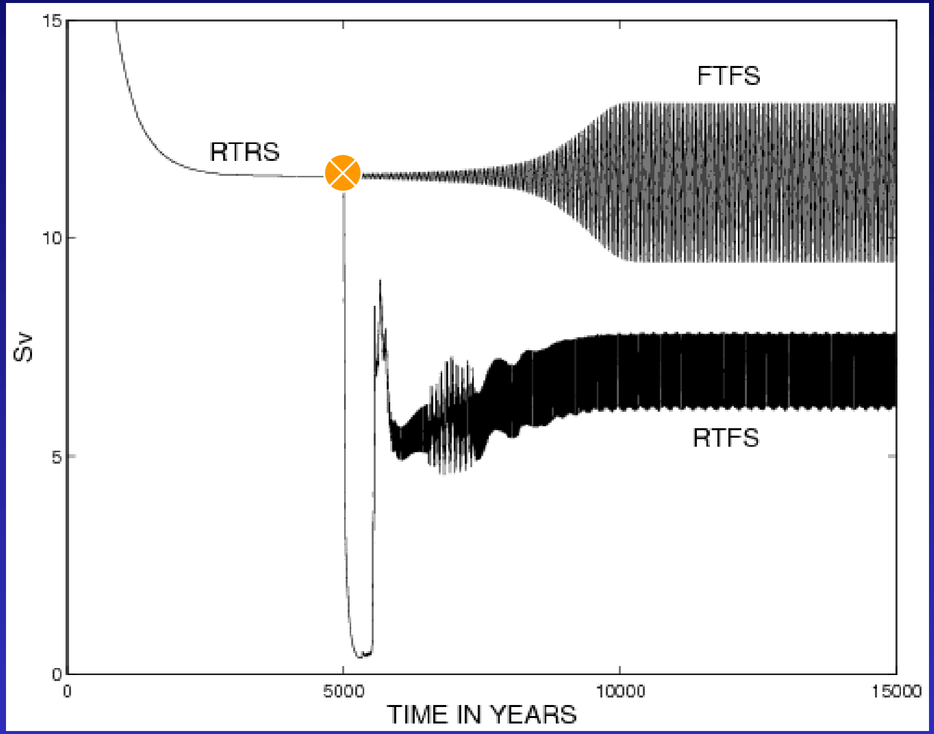
RTRS: relaxation of both surface temperature and salinity
➢steady state

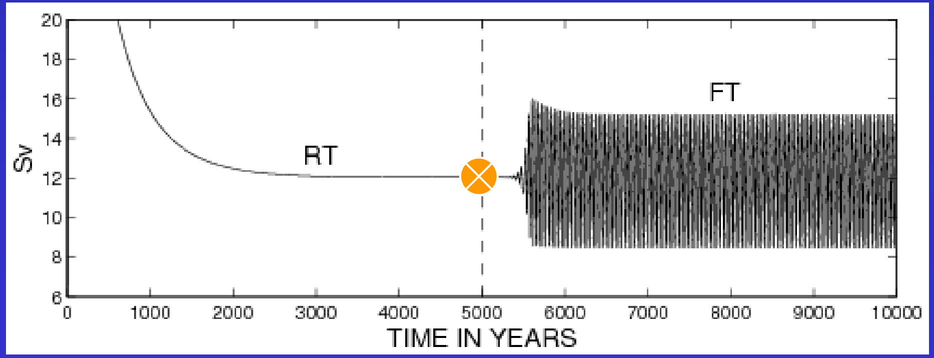
FTFS: diagnosed surface fluxes of heat and salt, prescribed
➢57 yr oscillation

RTFS: mixed boundary conditions
➢19 yr oscillation after large shift

RT FT: same for temperature only

Linear stability analysis
-unstable oscillation under FTFS&FT
-unstable real mode under RTFS

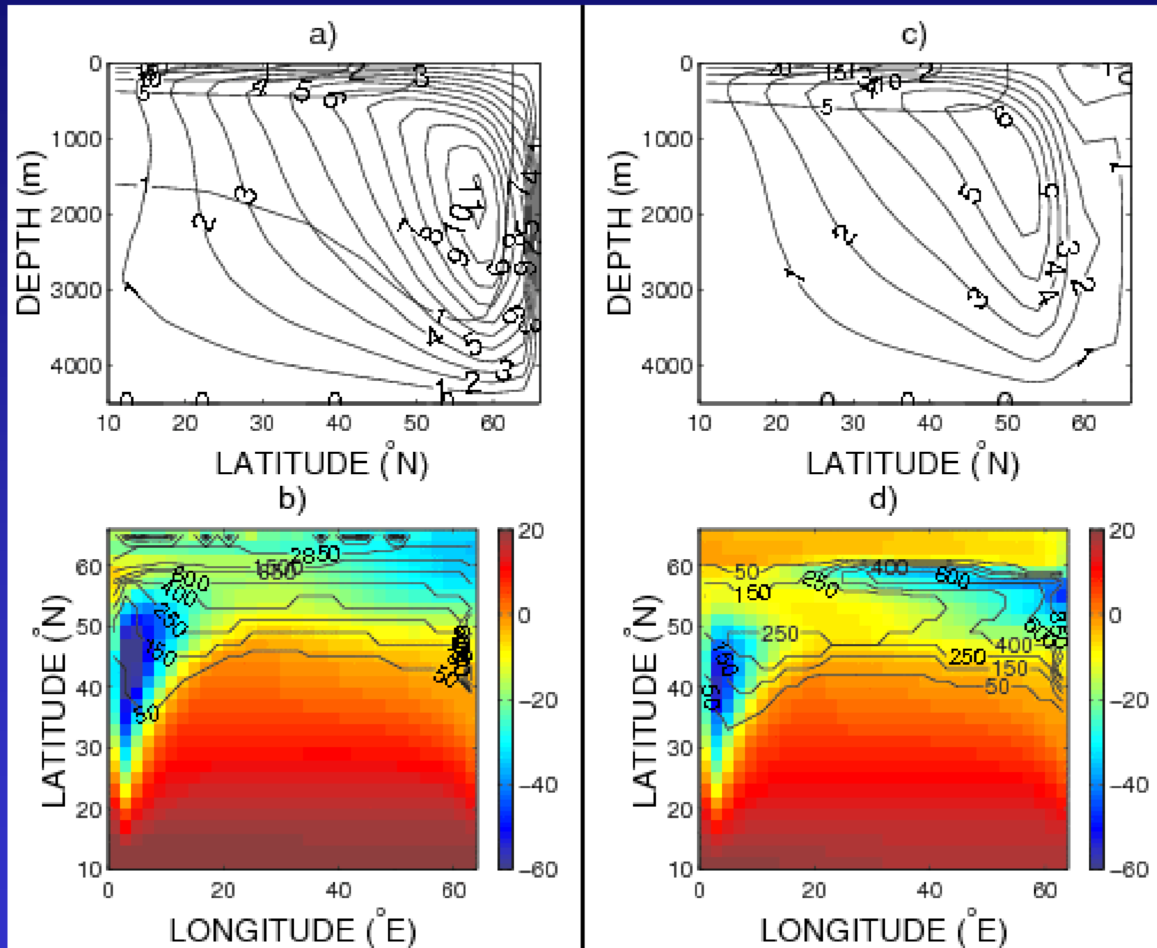




The ocean mean state

Meridional overturning (Sv) and zonally averaged temperature (ºC)

Surface heat flux (W/m^2) and convection depth (m)

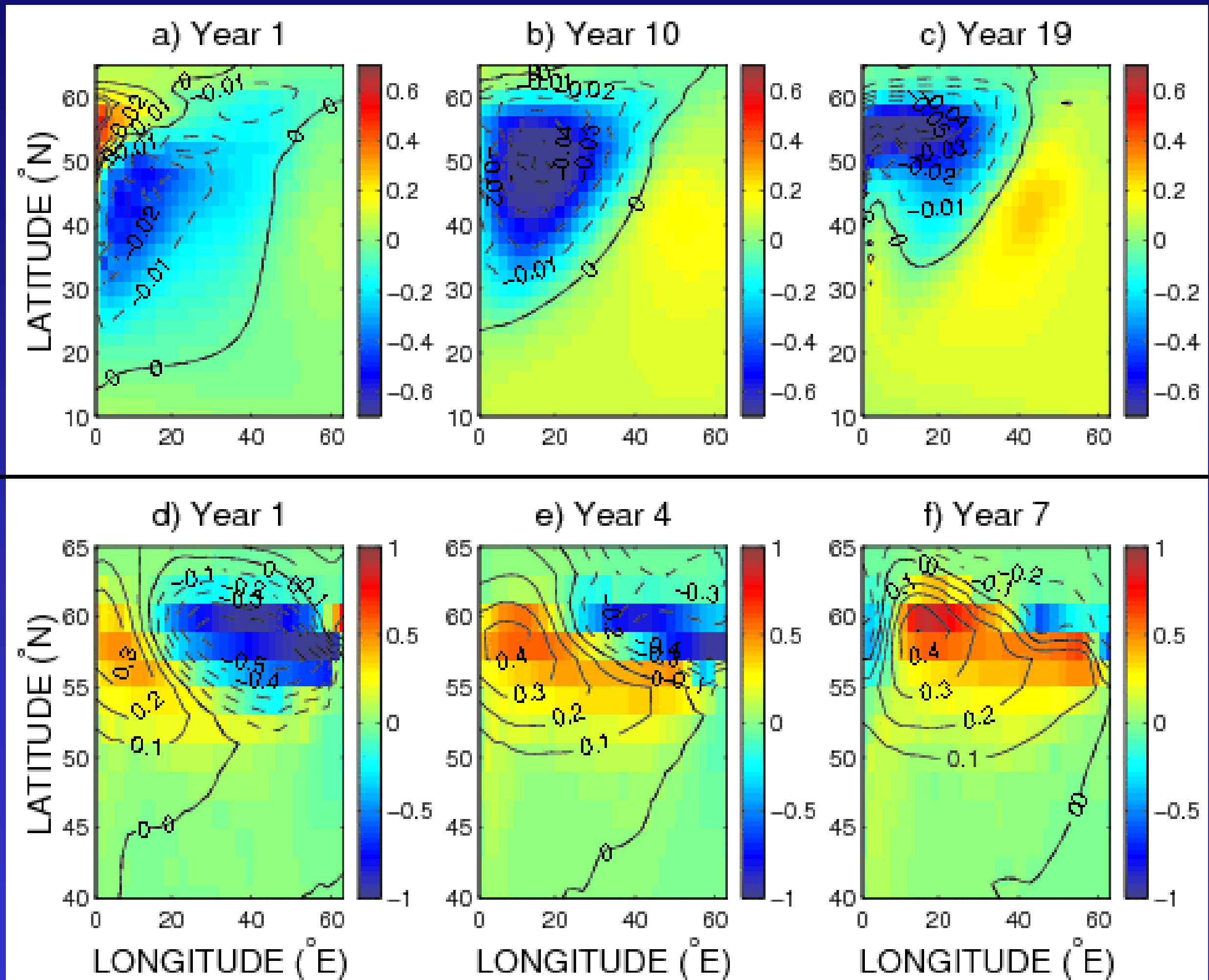


FTFS (constant flux) | RTFS (mixed)

Anomalies time evolution

FTFS (flux): cyclonic recirculation in north-west corner

RTFS (mixed): eastward propagation

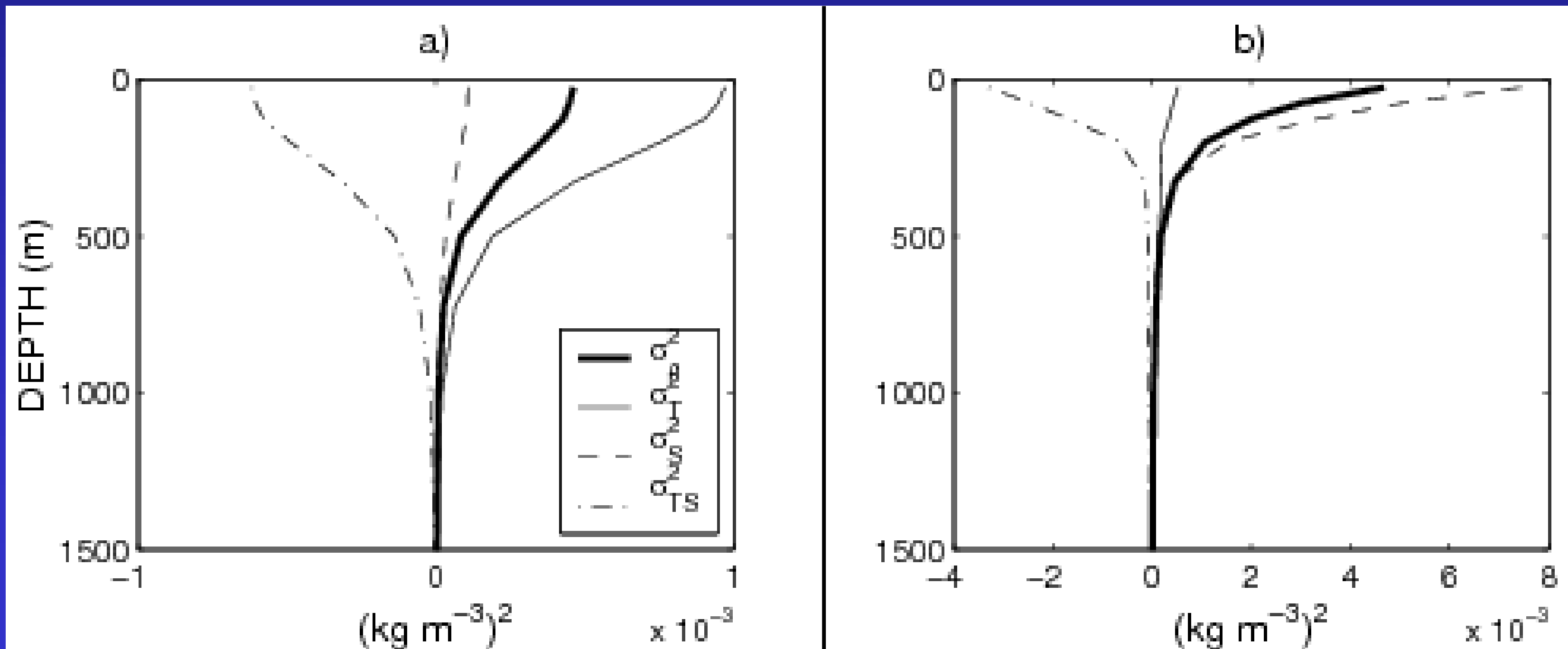


SST (color, K) and SSS (contour, psu) anomalies during half a period

Temperature or salinity?

Horizontal basin-averaged perturbation density variance as a function of depth in terms of temperature and salinity

$$\sigma_T^2=\overline{\langle\alpha^2T'^2\rangle}\ ;\ \sigma_S^2=\overline{\langle\beta^2S'^2\rangle}\ ;\ \sigma_{TS}^2=-2\overline{\langle\alpha\beta T'^2S'^2\rangle}$$



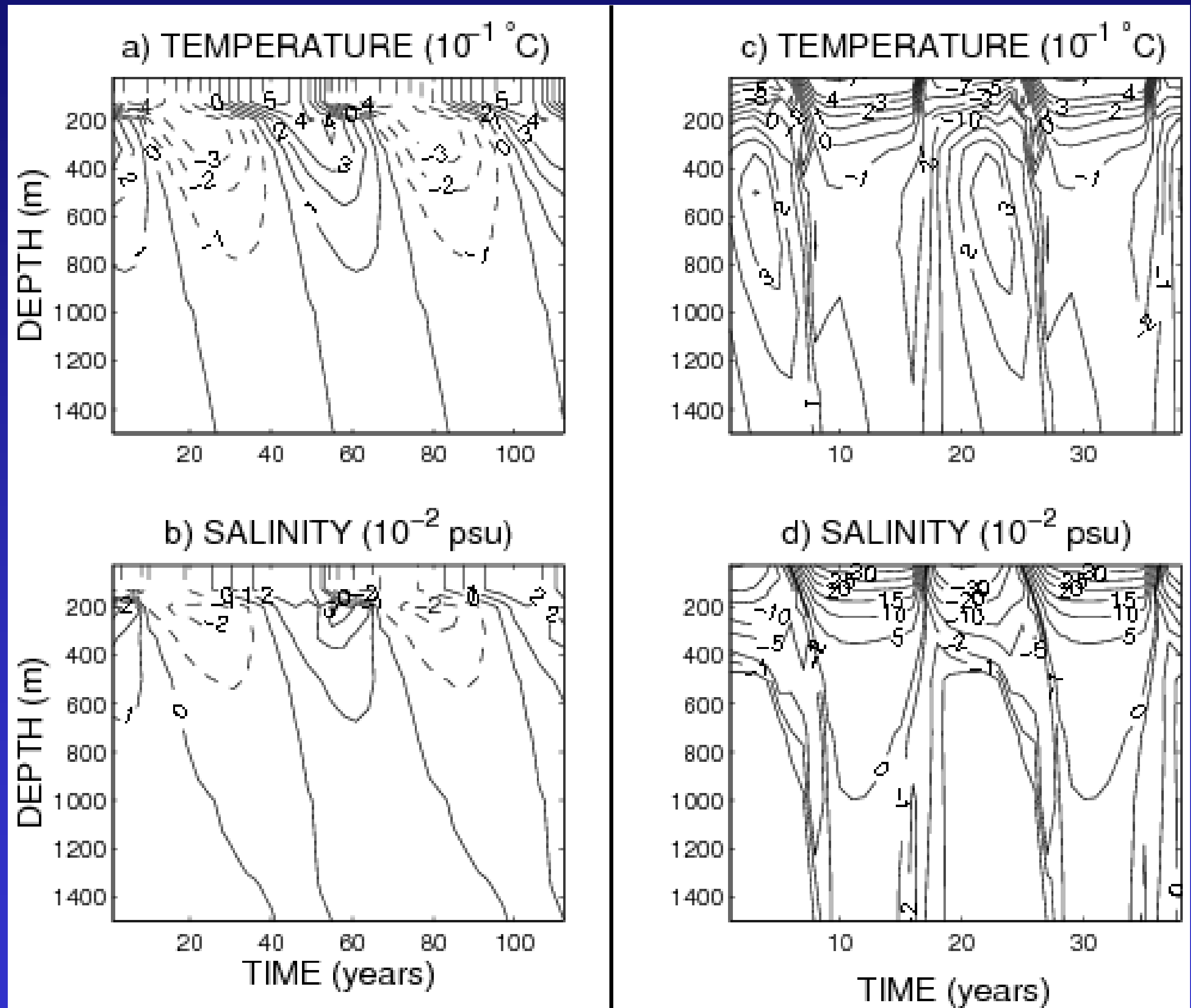
FTFS (flux): *temperature*

RTFS (mixed): *salinity*

Vertical structure of the perturbations

Phase diagram of temperature and salinity anomalies in the most unstable region for each experiment:

- ➢vertical phase lag under flux bc
- ➢dipolar structure in temperature under mixed bc



FTFS (flux): 49ºN-10ºE

RTFS (mixed): 59ºN-39ºE

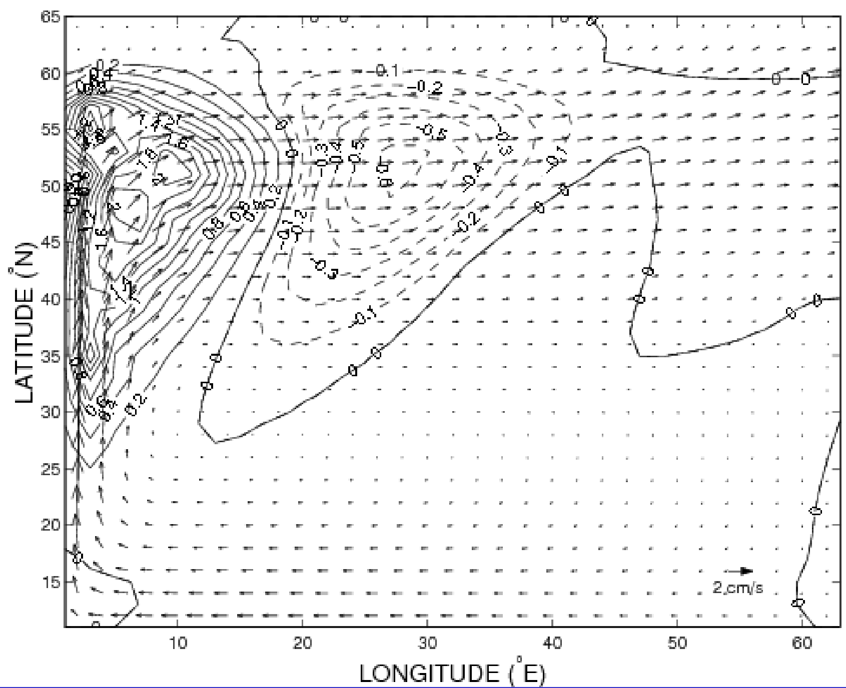
Density variance budget

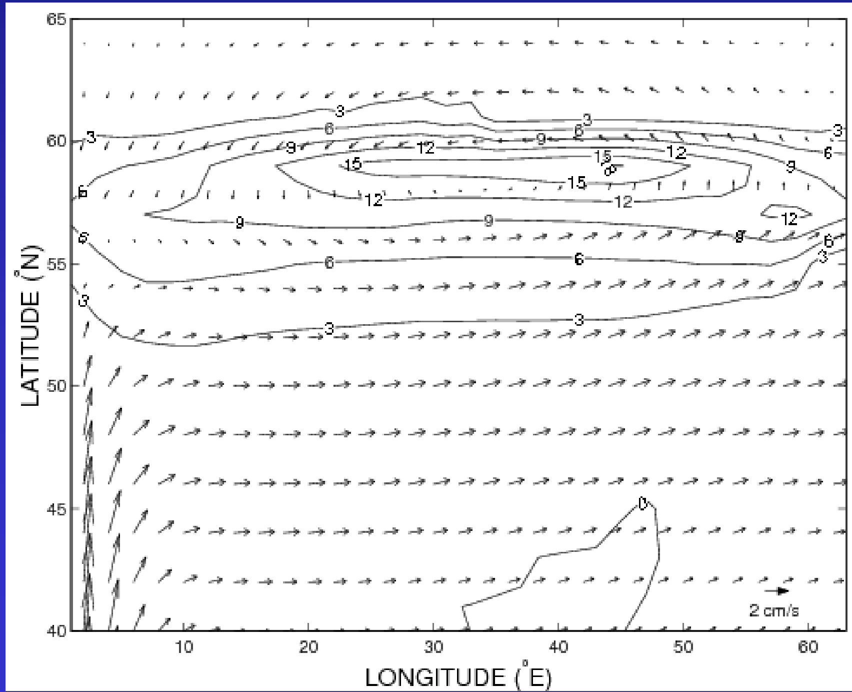
$$\rho' = -\alpha T' + \beta S'$$

$$\partial_t \rho' + \overline{\mathbf{u}} \cdot \nabla \rho' + \mathbf{u}' \cdot \nabla \overline{\rho} = D' + H(z - z_m) B'$$

$$\frac{1}{2} \partial_t \left\langle \overline{\rho'^2} \right\rangle = -\left\langle \overline{\mathbf{u}' \rho'} \cdot \nabla \overline{\rho} \right\rangle + \left\langle H(z - z_m) \overline{\rho' B'} \right\rangle + \left\langle \overline{\rho' D'} \right\rangle$$

Driving term for density variance (source):





FTFS (flux): $\rho_0^2 \alpha^2 \overline{v'T'} \partial_y \overline{T} \times 10^{-3} kg^2 m^{-6} yr^{-1}$ RTFS (mixed): $\rho_0^2 \alpha \beta \lambda \overline{T'S'} \times 10^{-2} kg^2 m^{-6} yr^{-1}$

Summary

Forcing	**FTFS (flux)**	**RTFS (mixed)**
Density controlled by	temperature	salinity
Energy source	downgradient eddy temperature flux	positive correlation between SST' and SSS'
Mechanism	baroclinic instability	positive convective surface heat flux feedback
Mode	linear, Hopf bifurcation	nonlinear
Role of salinity	damping, increasing T	crucial
Is convection critical?	no	yes
Perturbations vertical structure	vertical phase lag of quarter period	dipolar structure of T', no vertical phase lag

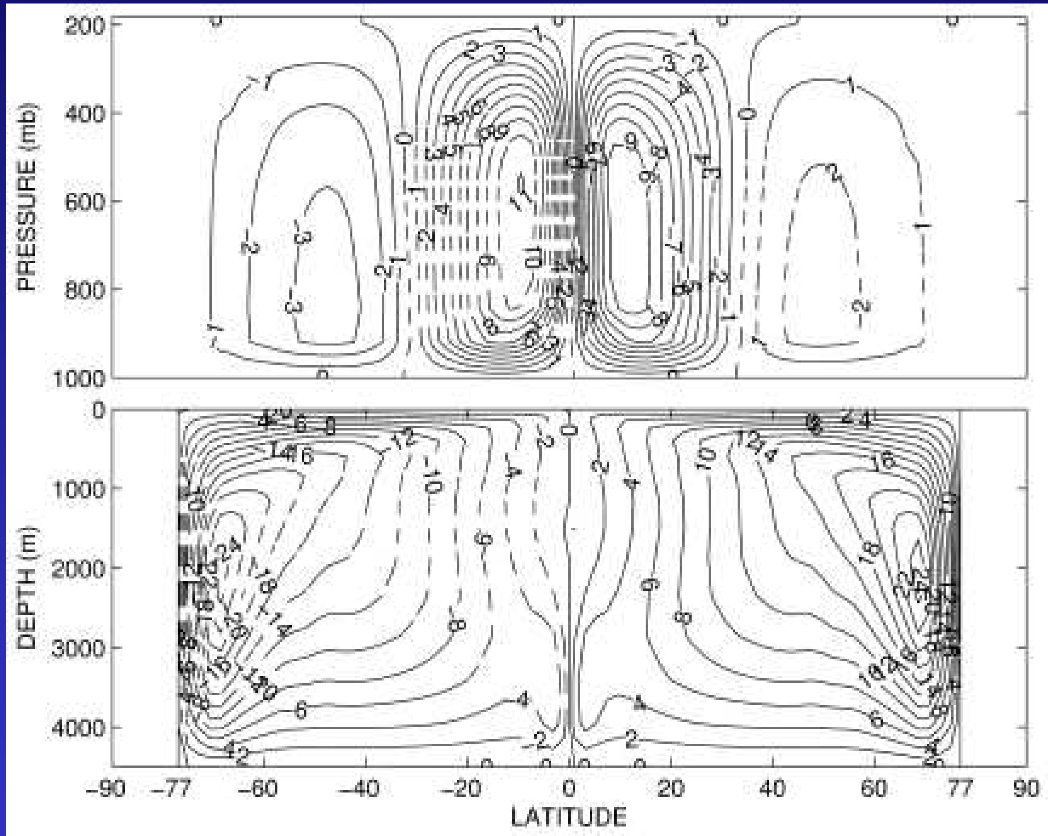
Interdecadal oscillations under constant flux and mixed boundary conditions have two different mechanisms

- *which one (if any) is relevant to more realistic atmospheric coupling?*

Coupling with an axisymmetric atmospheric model

2D atmospheric model:

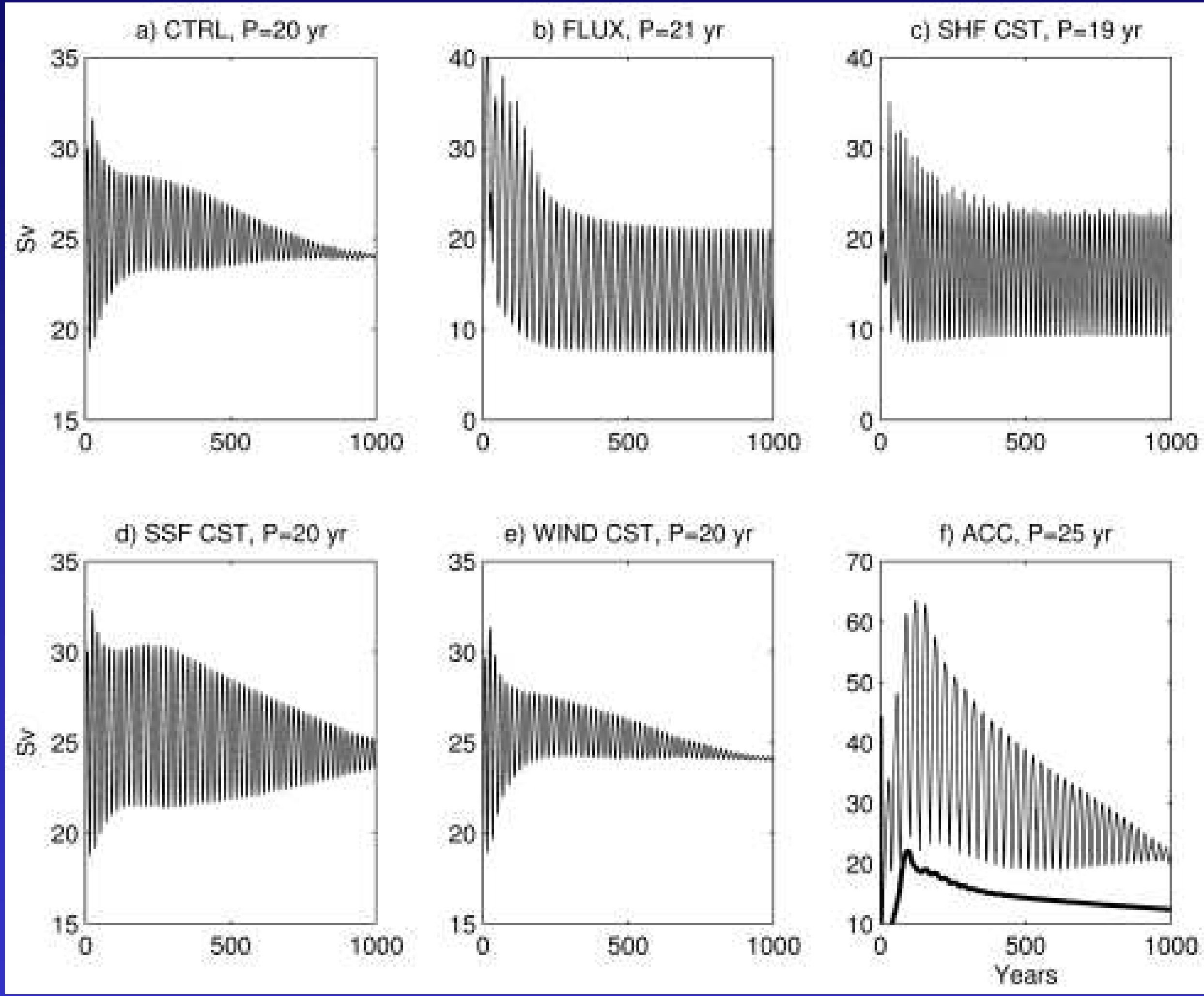
- primitive equations with full hydrological cycle
- parameterizations for meridional eddy transport of momentum, heat and moisture (Yao and Stone 1987, Stone and Yao 1990)
- cumulus convection (Manabe et al. 1965)



Coupled model climatology with symmetric ocean: zonally-averaged circulation in the atmosphere (megaton/s) and ocean (Sv)

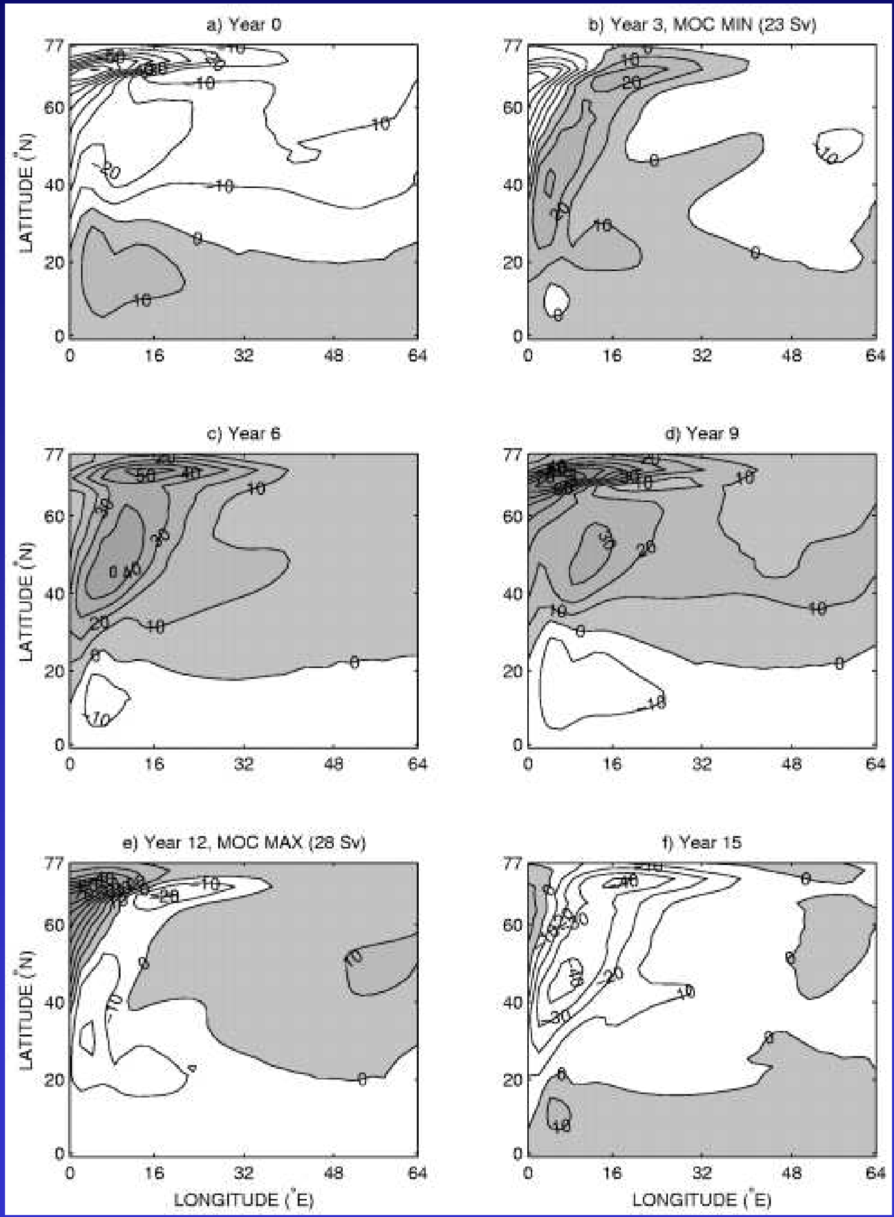
Weakly damped interdecadal variability

Maximum meridional overturning streamfunction (Sv) in the Northern hemisphere for the coupled model, and for the stand-alone ocean model forced by combinations of constant surface fluxes of heat, freshwater and momentum



➢*The oscillation mechanism lies in the ocean, the atmosphere surface heat flux feedback damps the variability*

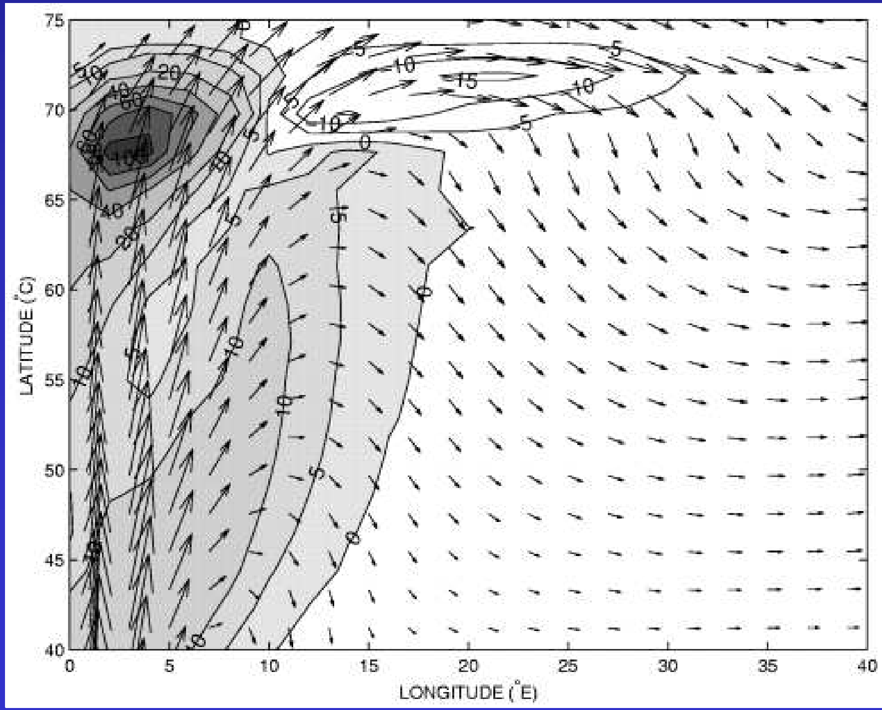
Same mechanism as the "thermal" mode



Ocean surface density anomalies (10^{-3} kg m^{-3}) over an oscillation

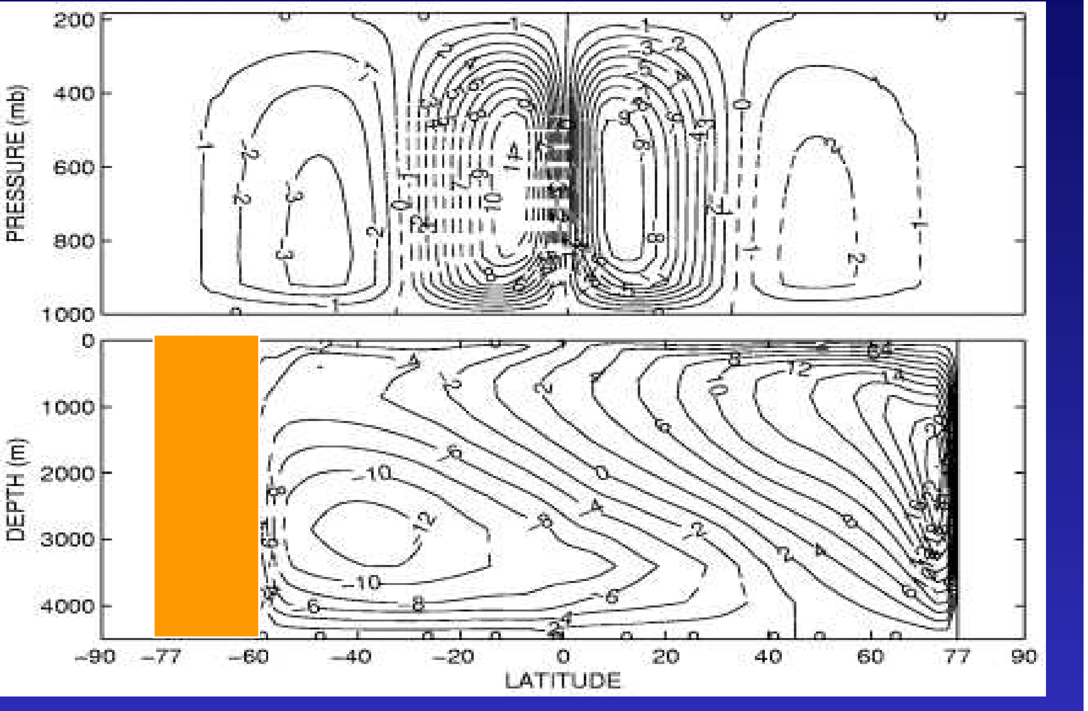
Driving term for the ocean density variance:

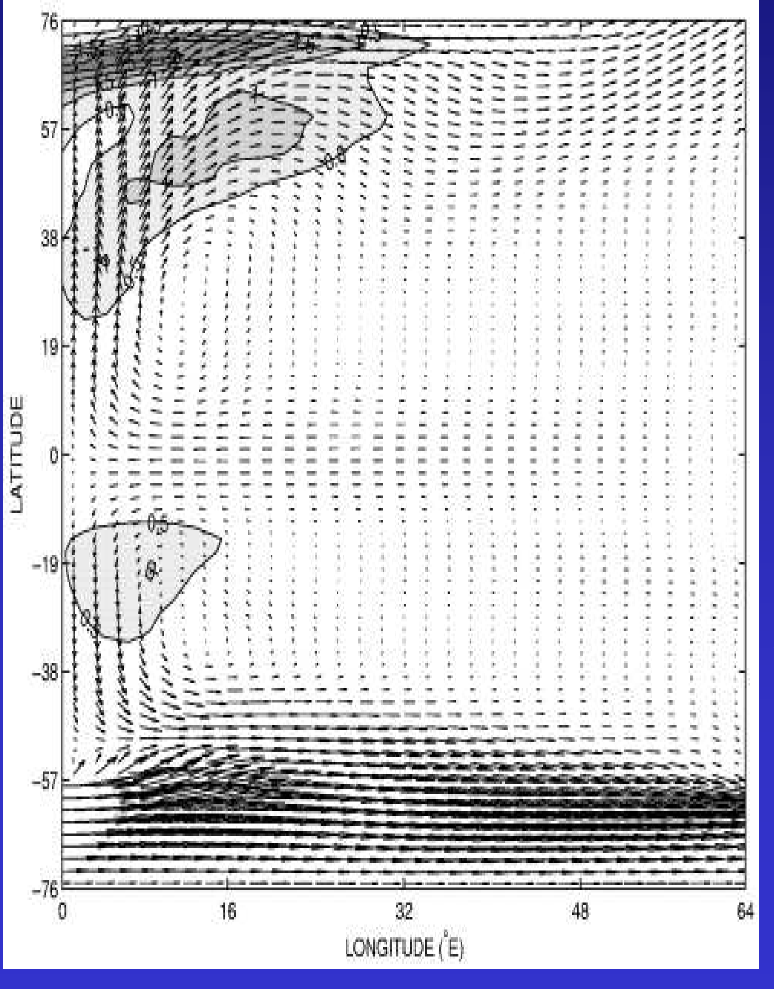
$$-\overline{\mathbf{u}'\rho'} \cdot \nabla\overline{\rho} \times 10^{-4} kg^2 m^{-6} yr^{-1}$$



Asymmetric configuration with ACC

ocean with periodic channel 77ºS-60ºS
➢22 yr oscillation





Ocean surface density variance (10^3 kg^2/m^6), superposed on mean surface current 0-250m

➢ variability restricted to northern hemisphere

Conclusions

- Theses 'simple' oscillations provide prototypes to understand physical mechanisms of oscillations in more complex (coupled) models
- The density variance budget provides a method to identify different sources of variability, that can be applied to realistic and coupled models
- These mechanisms found in idealized geometry need to be tested in more realistic configurations (see poster by Sévellec et al. about optimal surface salinity perturbations)
- Unfortunately, interdecadal variability in state-of-the-art coupled models seems most often due to coupled mechanisms:
  what happens to these internal ocean modes?

Internal modes of the thermohaline circulation and their mechanism

Period	Models	Mechanism	Observation?
decadal	3D mixed	nonlinear mixed mode	
interdecadal	3D flux 3D coupled	Hopf bifurcation thermal mode baroclinic instability	Atlantic Multidecadal Oscillation
centennial	box, 1D, 2D, 3D, mixed coupled EBM	Hopf bifurcation Howard Malkus loop	
millenial	box, 2D, 3D	global bifurcation (no stable equilibrium)	Dansgaard-Oeschger Oscillation

Tools: density variance budget, linear stability analysis, bifurcation diagrams, dynamical system theory