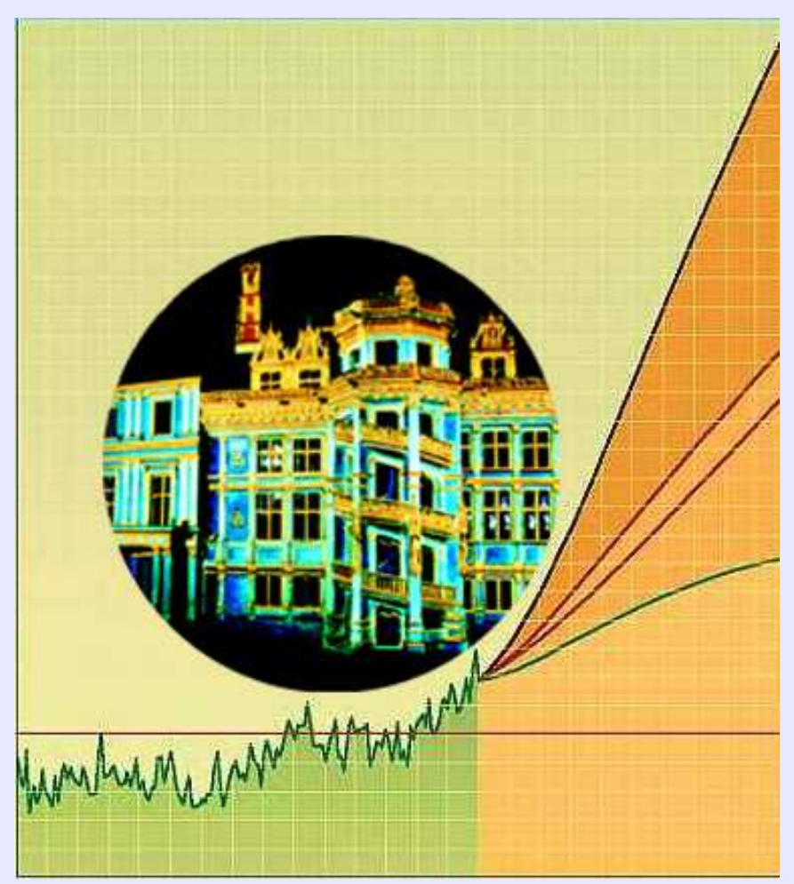

Natural modes of climate variability associated with the oceanic thermohaline circulation

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ABSTRACT

Instabilities and modes of the large-scale ocean circulation contribute to climate variability on interannual to millenial timescales. Ocean basin modes, standing or propagating waves resonating through boundary adjustment (just like the resonance of music notes, fundamental and harmonic waves played by a string) , can feed on the mean flow available potential energy and grow spontaneously, as long as the mean circulation is sustained by differential surface heating or wind stress. Even weakly damped modes (most likely through interaction with bottom topography) may still be sustained by atmospheric stochastic forcing. We review here several modes of variability of the large-scale ocean circulation, on decadal to millenial time scales, often depending on surface boundary conditions for temperature and salinity. In order to understand their physical mechanism, we use basic tools from dynamical system theory, like linear stability analysis and weakly nonlinear multiple timescale expansion. We perform density variance budgets that enable to identify the source of the variability (internal hydrodynamic instability or surface forcing), and provide an objective criteria that allow to distinguish different oscillations types in the same frequency range. We finally discuss the mechanism of these oscillations before concluding on their relevance for the Earth climate system.

1. INTRODUCTION

Numerous analysis of historical and proxy climatological time series show significant climate variability on interannual to millenial timescales. Several paradigms apply to this low frequency variability, from external forcing variability (solar cycles, volcanic eruption, atmospheric composition), to integration of atmospheric white noise by the ocean into a red spectrum to intrinsic modes of variability of the atmospheric, oceanic, or coupled systems. For timescales longer than interannual, the ocean circulation is likely a major player, given its large heat capacity and long adjustment.

Typical time scales for the thermohaline circulation

$$\begin{aligned}
&\text{spin up time scale:} && \frac{L}{C_{\text{Rossby}}} = \frac{5000\ \text{km}}{2.5\ \text{km/day}} \approx 5\ \text{yr}\\
&\text{advective time scale:} && \frac{\text{basin scale}}{U} = \frac{10000\ \text{km}}{0.1\ \text{km/day}} \approx 250\ \text{yr}\\
&\text{diffusive time scale:} && \frac{(\text{depth})^2}{\text{vertical mixing}} = \frac{(4000\ \text{m})^2}{10^{-4}\ \text{m}^2\ \text{s}^{-1}} \approx 3000\ \text{yr}
\end{aligned}$$

Surface boundary conditions for ocean models

• *restoring boundary conditions*, appropriate for temperature?
(+) sensible heat flux dependance on sea surface temperature: 5–65 W m^{-2}?
(-) restoring SST implies infinite atmospheric heat capacity, but heat capacity resides in the ocean (1000×atmospheric heat capacity): large-scale ocean heat anomalies largely influence the atmosphere!

• *constant flux boundary conditions*, appropriate for salinity?
(+) evaporation and precipitation independant of sea surface salinity (SSS)
(-) climatological precipitation, very poorly known, leads to large model drifts

⇒ *realistic ocean models are forced by both terms*: mean state may be plausible, but forcing implies *large and unrealistic damping of ocean internal variability!*

• *mixed boundary conditions*: restoring SST, prescribed freshwater flux
⇒ idiosyncratic behavior, like polar halocline catastrophe ...

Summary

To the extent that the ocean intrinsic modes play an important role, identifying their dynamical nature is crucial for climate prediction. As a first step, we study the time-dependent wind-driven quasi-geostrophic circulation as a prototype of decadal-scale variability. Then we investigate three-dimensional thermally-driven and thermohaline circulation ocean models and analyze their interdecadal variability. Finally, we focus on centennial to millenial timescales with a simple two-dimensional (latitude-depth) ocean model.

2. OCEAN BASIN MODES: DECADAL TIMESCALE

Physical processes: [Cessi&Primeau2001,BenJelloul&Huck2003,2004]...
- baroclinic Rossby waves (interannual to interdecadal basin crossing period)
- resonance through equatorial and boundary waves (mass conservation)
- these modes may become unstable through large-scale baroclinic instability, when the mean flow is energetic enough and/or the dissipation small enough

One-layer quasi-geostrophic dynamics

$$\partial_t\left(\nabla^2\psi - \mathsf{Bu}^{-1}\psi\right) + \beta\partial_x\psi + \epsilon J\left(\psi, \nabla^2\psi\right) = \text{Dissipation},$$

+ no normal flow at the boundaries and *mass conservation constraint*:

$$\forall\, \mathbf{x} \in \delta\mathcal{D},\ \psi(\mathbf{x}) = \psi_b(t), \quad \iint_{\mathcal{D}} dx\, dy\, \psi = 0.$$

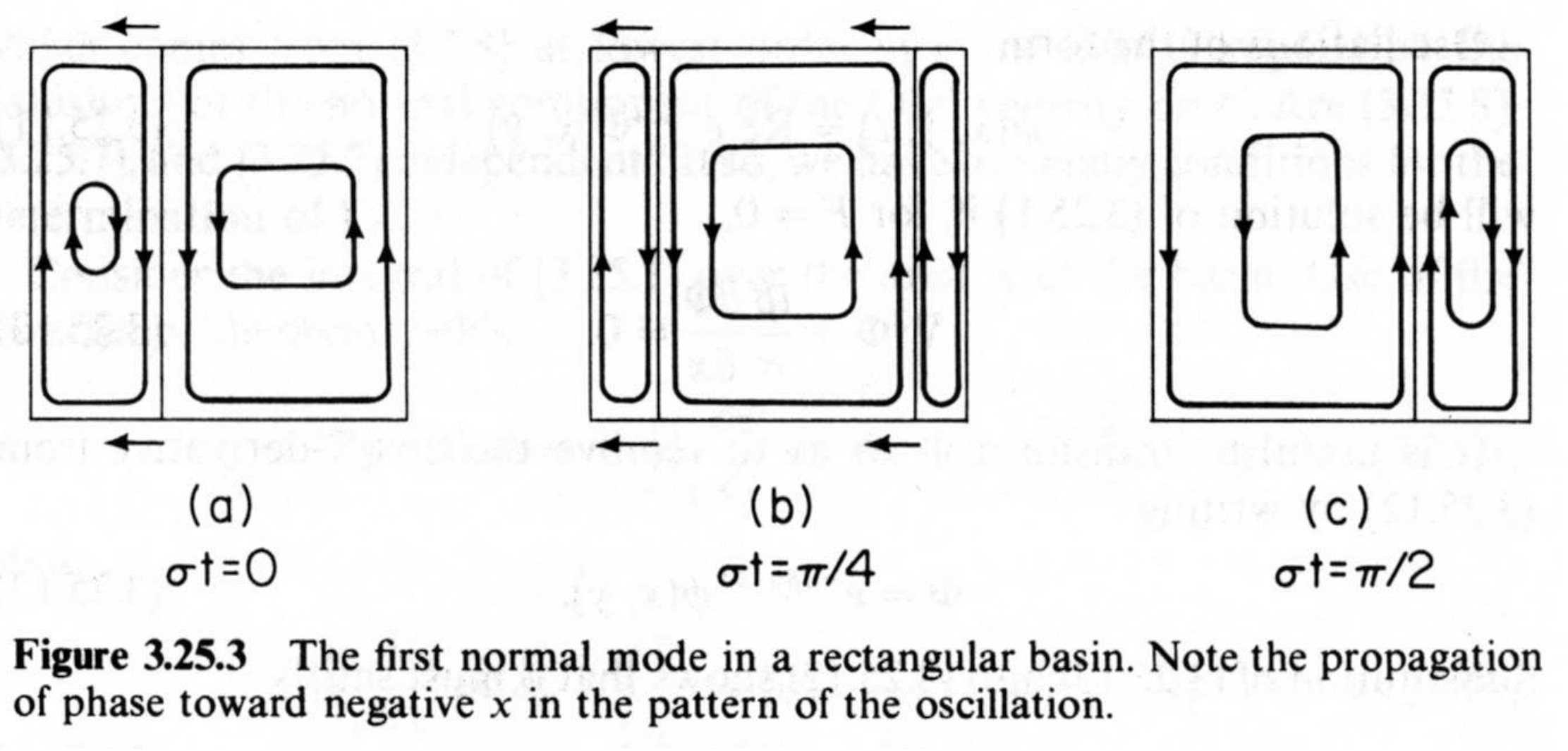

Figure 3.25.3 The first normal mode in a rectangular basin. Note the propagation of phase toward negative *x* in the pattern of the oscillation.

Figure 1: *Rossby basin modes [Pedlosky 1987].*

Two-layer quasi-geostrophic dynamics

interaction between wind-driven barotropic flow and baroclinic basin modes
⇒ basin modes westward propagation may be arrested by the mean flow
→ slow modes are trapped in the recirculation gyre (closed PV contours)

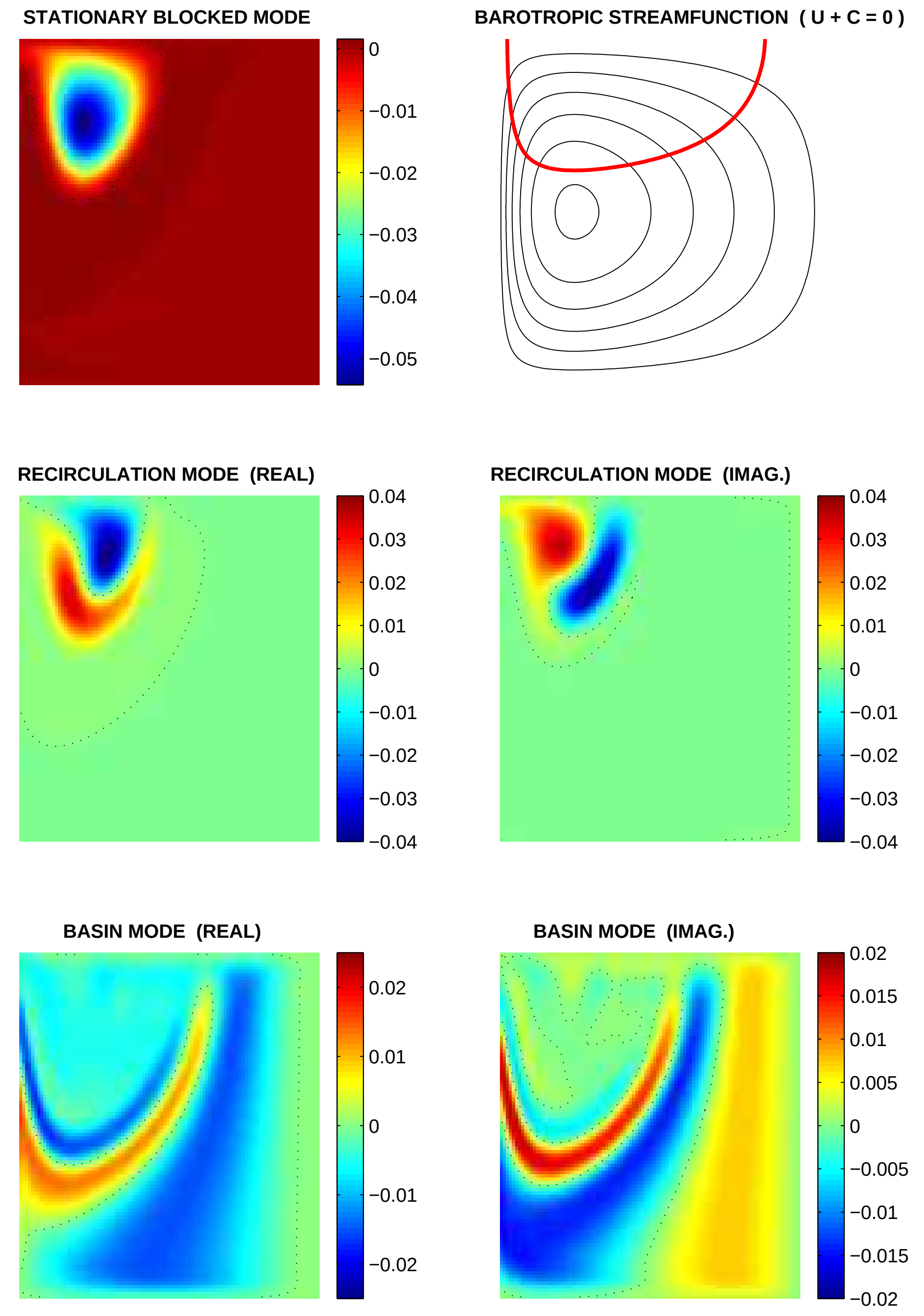

Figure 2: *Stationary modes (upper left), recirculating modes (middle), and basin modes (lower) in a subtropical gyre (upper right). Real and imaginary parts of oscillatory modes are displayed.*

3. TWO TYPES OF INTERDECADAL VARIABILITY

At least two types of interdecadal thermohaline variability may be distinguished depending on surface boundary conditions (Arzel et al. 2004):
- flux-type under constant heat or freshwater flux (FTFS),
- mixed-type under mixed boundary conditions (RTFS).

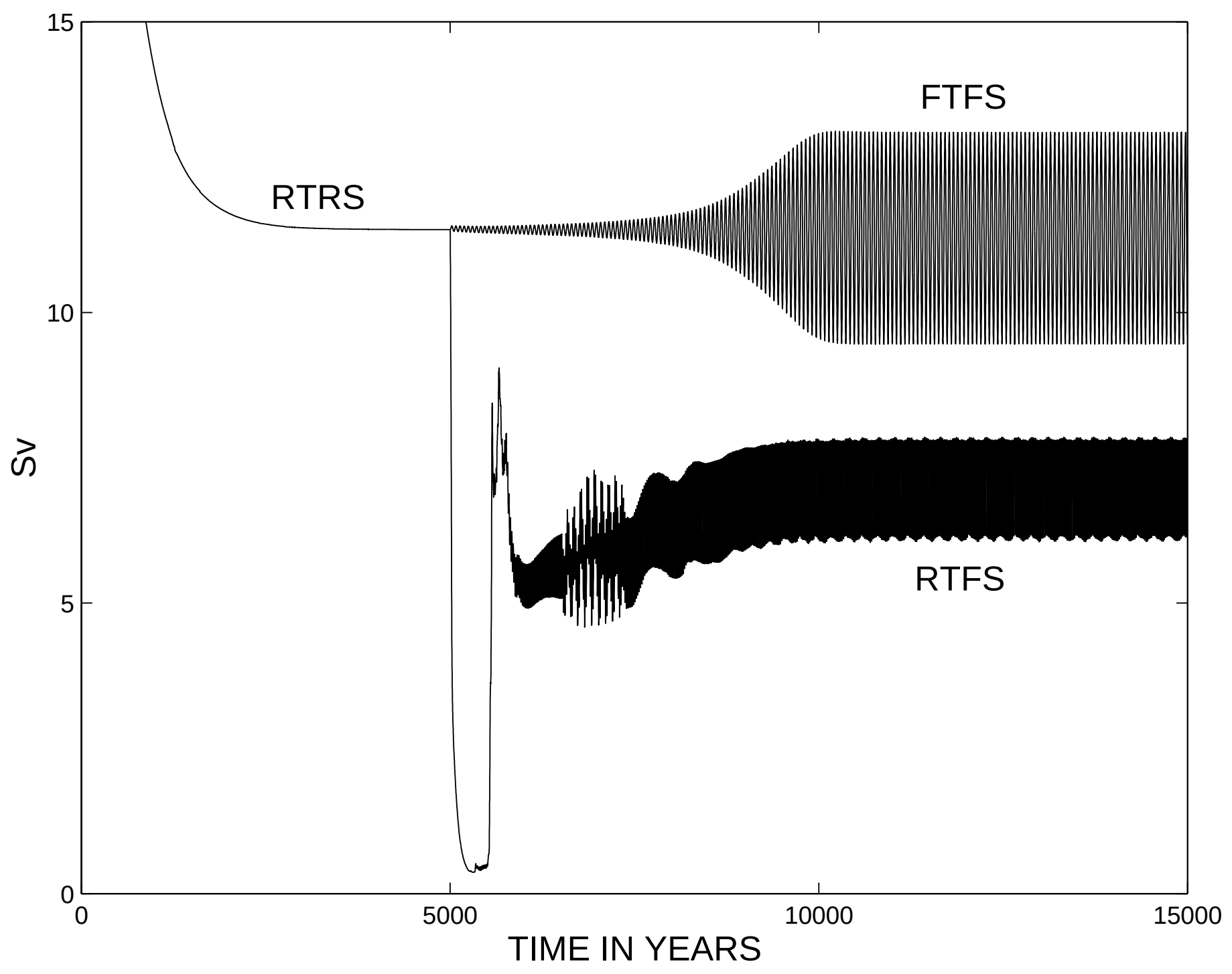

Figure 3: *Meridional overturning as a function of time after a switch in surface boundary conditions: first restoring both temperature and salinity (RTRS), then flux type (FTFS) or mixed (RTFS).*

Density variance budget: A yardstick measure of thermohaline variability

A simple and straightforward measure of the thermohaline variability is the temperature and salinity variance in terms of density, related to available potential energy in the quasi-geostrophic approximation (Lorenz 1955).

$$\rho' = \alpha T' + \beta S' : \ \tfrac{1}{2}\partial_t < \rho'^2 >= - < \mathbf{u}'\rho'.\nabla\bar{\rho} > + < \rho' B' > + < \rho' D' >$$

	$- < \mathbf{u}'\rho'.\nabla\bar{\rho} >$	$< \rho' B' >$	$< \rho' D' >$
exp. FTFS:	**4.9**	0	−4.9
exp. RTFS:	5.8	**68.7**	−74.5

sinks: horizontal and vertical mixing and convection *D*
sources: internal hydrodynamical instabilities (FTFS), air-sea fluxes through a positive feedback between convection and restoring temperature (RTFS)

4. CENTENNIAL TO MILLENIAL TIMESCALE

On such long timescales, the ocean circulation is adjusted to the forcing, even in zonal-average, such that a two-dimensional model is appropriate (latitude-depth). Under mixed boundary conditions, the *freshwater flux amplitude* controls the occurence and period of the oscillations.

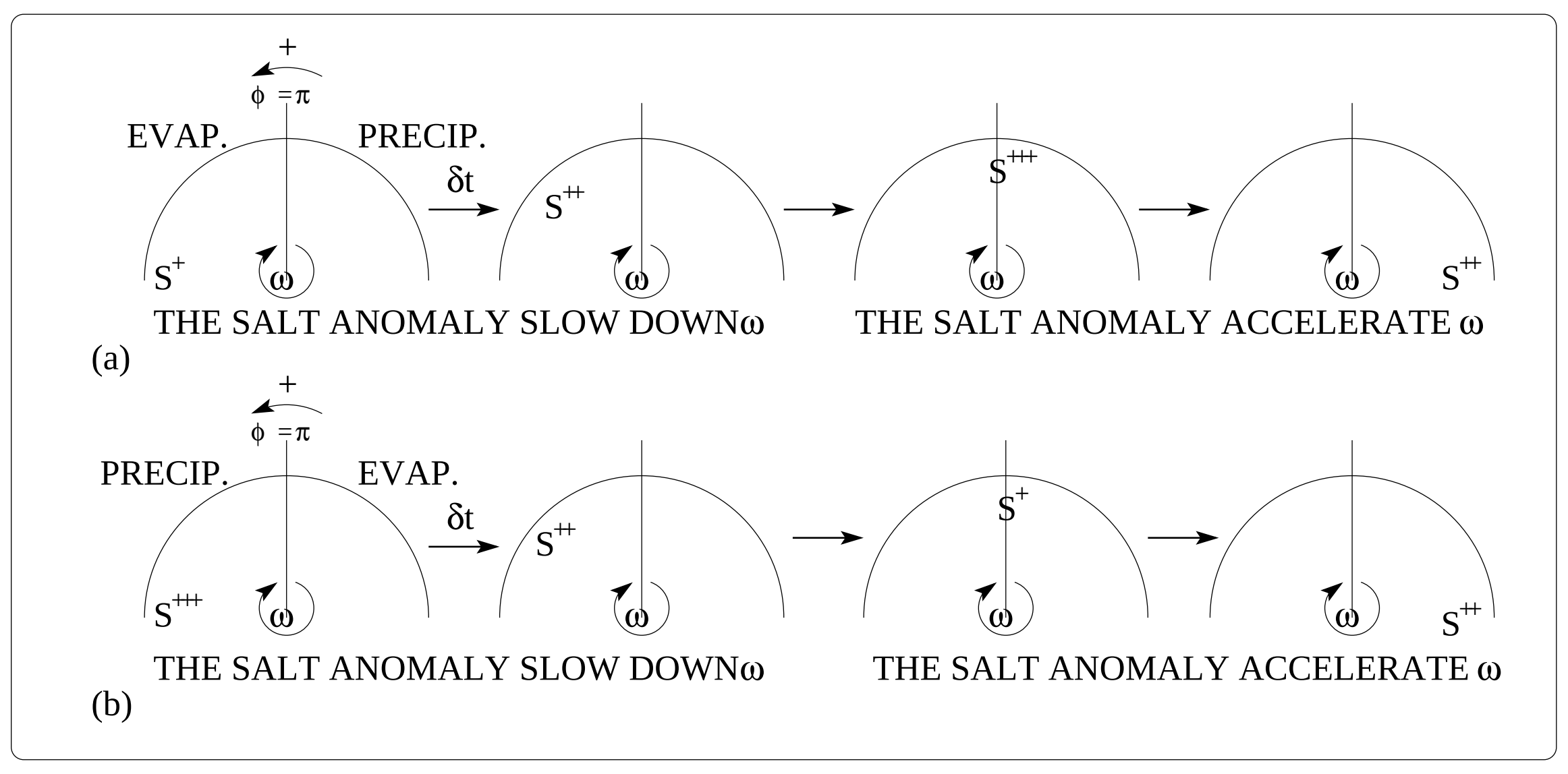

Figure 4: *Howard-Malkus loop oscillator mechanism.*

Source of energy sustaining the oscillations: restoring surface temperature, through positively correlated T–S anomalies!

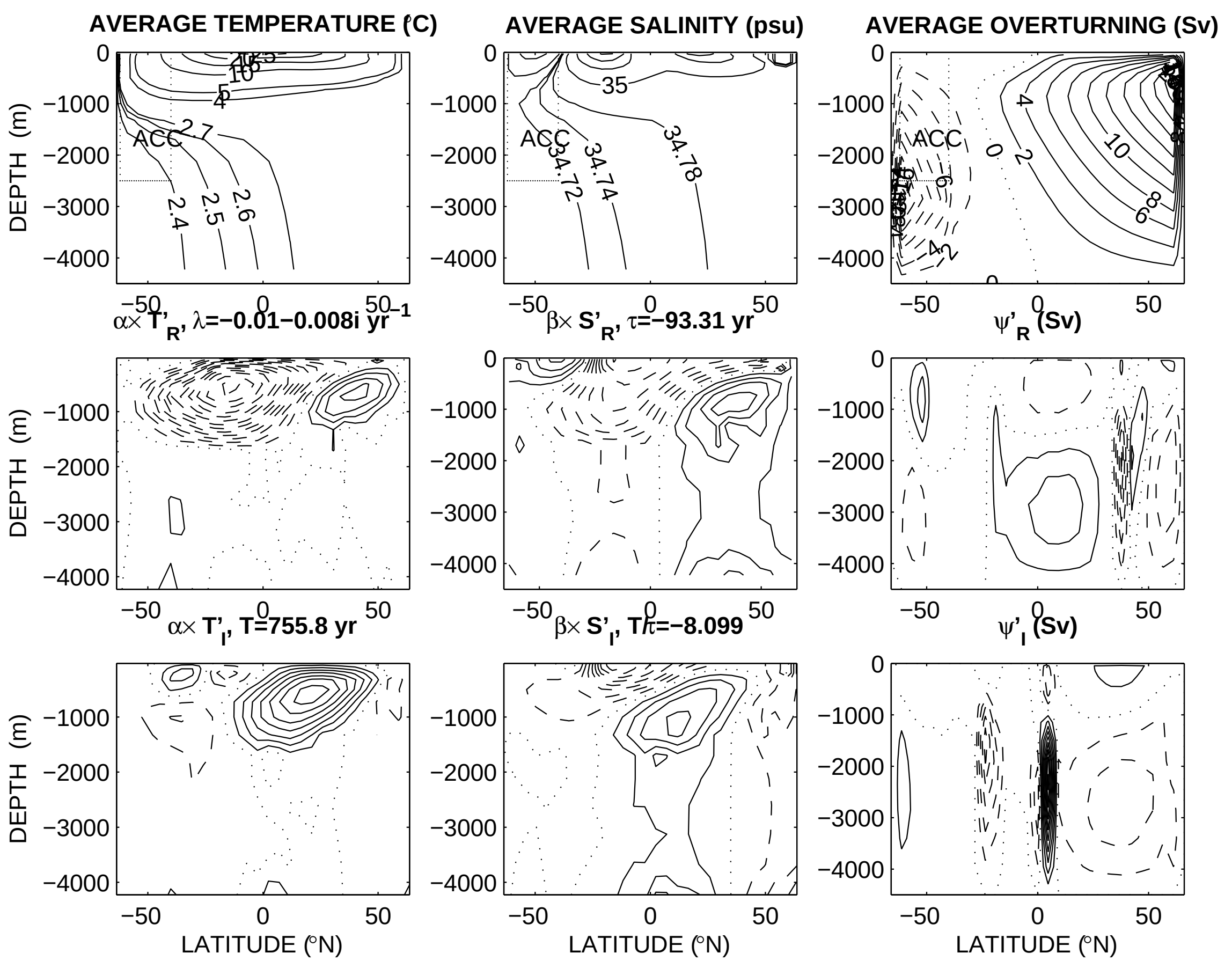

Figure 5: *Linear mode for an asymmetric bihemispheric configuration with ACC.*

5. CONCLUSION

In ocean-only models, decadal to millenial variability strongly depends on the surface boundary conditions used for temperature and/or salinity: Most oscillating modes are sustained through surface temperature restoring boundary conditions (implicitly implying infinite atmospheric heat capacity, although it really resides in the ocean!). A single interdecadal mode is linked with a large-scale baroclinic instability of the three-dimensional thermohaline circulation, but may be weakly damped in realistic configurations. This is to be checked through the stability analysis of the ocean general circulation in a global model with realistic coastline, bathymetry and forcing.

Hence, climate variability **must** be studied in coupled models, a single component (ocean or atmosphere) requiring parameterization of the forcing that may not be energetically consistent! The ice component of the climate system should also be included as strongly impacting the air-sea fluxes.

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