Non-normal Amplification of the Thermohaline Circulation

Laure Zanna*, Eli Tziperman and Patrick Heimbach

*Dept of Earth and Planetary Sciences, Harvard University, zanna@fas.harvard.edu

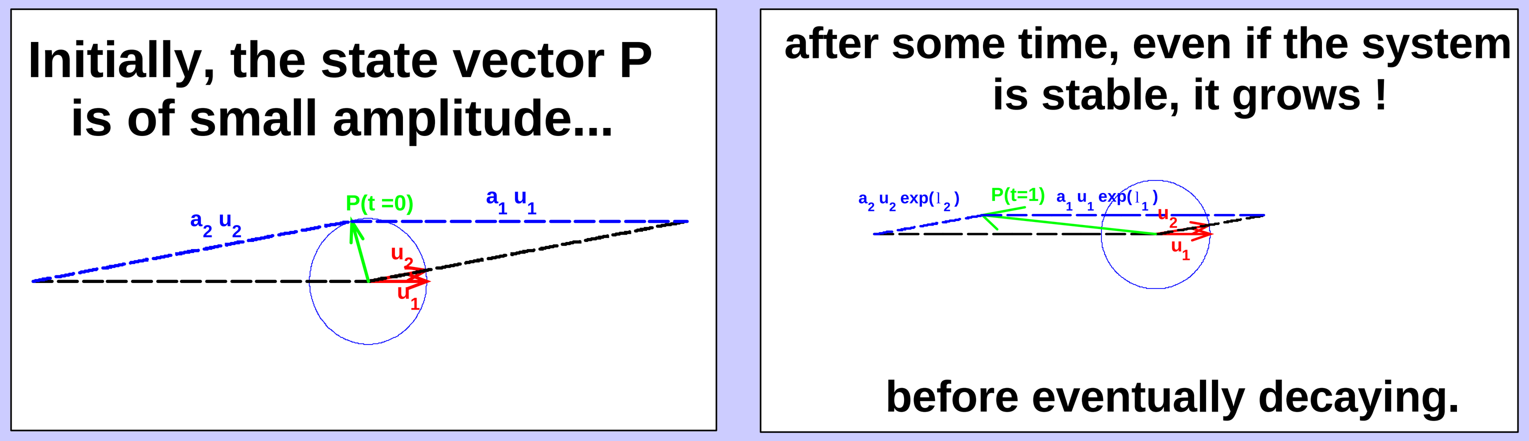
Abstract

- An idealized coupled ocean-atmosphere model is used to analyze possible **transient amplification** of the thermohaline circulation (THC).
- We find that in a stable regime, in which all small perturbations eventually decay, optimal initial conditions lead to **a dramatic amplification of the THC anomalies**, as well as of the temperature and salinity anomalies (amplified by factors of 400 and 20 respectively) after ~ 40 years. The anomalies eventually decay on a centennial time scale.
- Such large amplification of small initial anomalies of the THC, temperature and salinity may play an important role in the THC and climate variability if excited by atmospheric forcing.

1 Introduction

- The **THC** appears to have been fairly stable with a small amplitude variability for the past 10,000 years. Its variability might be described by linear dynamics excited by stochastic forcing ***(e.g. Griffies and Tziperman, 1995).***
- **Non normal growth and transient amplification**
  Non-normal stable linear system = set of non-orthogonal decaying eigenvectors ⇒ may lead to transient amplification due to an interaction between several decaying eigenmodes of the system.

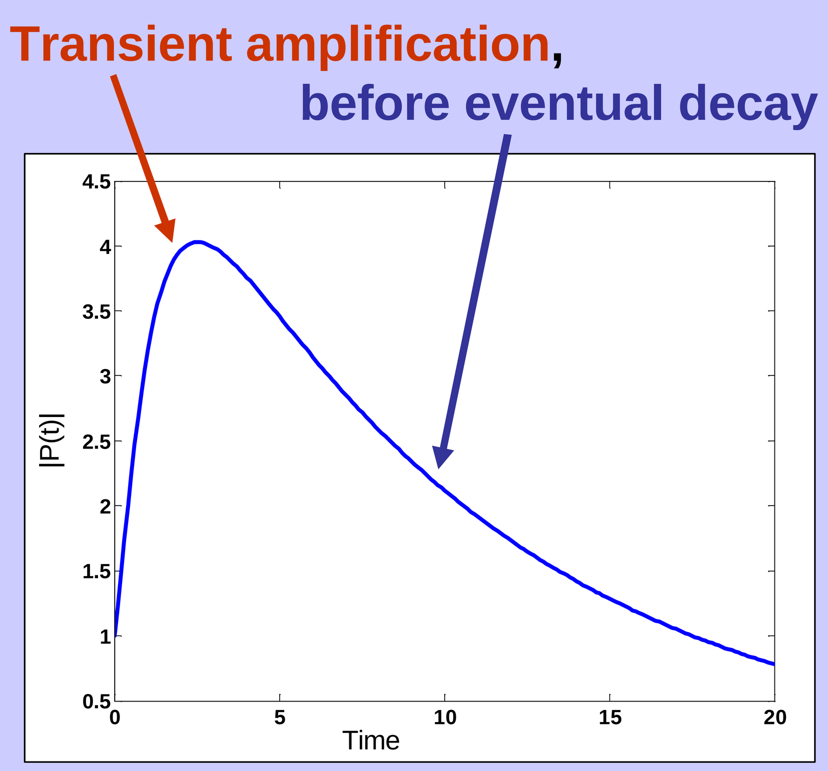
2D example:



Conditions for transient amplification in a stable linear system

1. Non-orthogonal eigenvectors
2. Partial initial cancellation
3. Different decay rates of the eigenvectors

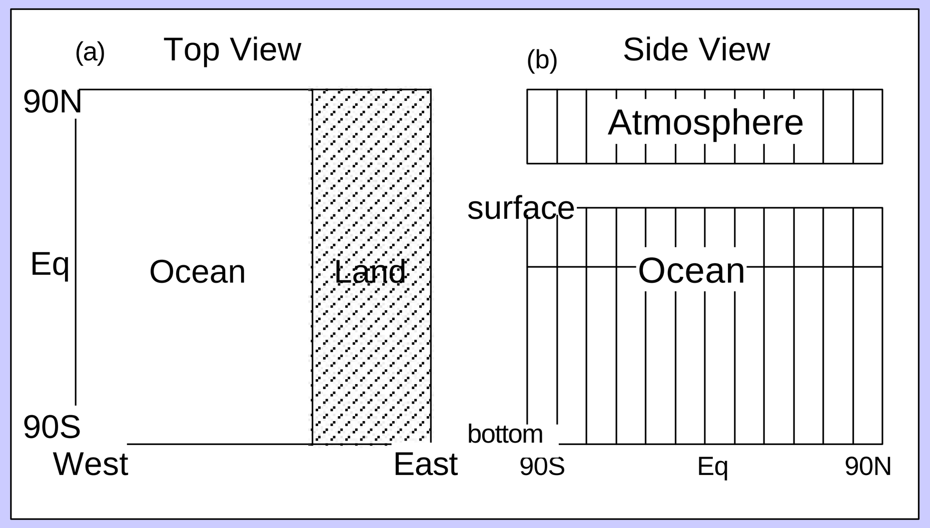
(e.g. Farrell & Ioannou, 1996, previous application to the THC in a simple box model by Tziperman & Ioannou, 2002 ; Lohmann & Schneider, 1999 or to ENSO by Moore & Kleeman, 1997 and Penland & Sardeshmukh, 1995)



2 Model Description

(based on Sayag et al, 2004)

Fig.1: 2D zonally averaged coupled ocn-atm model (a) Top View: the ocean represents 70% of the total surface, (b) Side View: 2 vertical layers for the ocean; 1 vertically integrated layer for the atmosphere.



Atmosphere: Energy Balance Model (temperature & moisture)
Ocean: Advection- Diffusion Equation for salinity and temperature.
Coupling: Air-sea heat flux + freshwater flux
The horizontal transport in the ocean (**THC**) is proportional to **density gradients**. ***(Stommel,1961)***

3 Solving for optimal initial conditions *(e.g. Farrell, 1988)*

- Linearization of the full nonlinear model about steady state

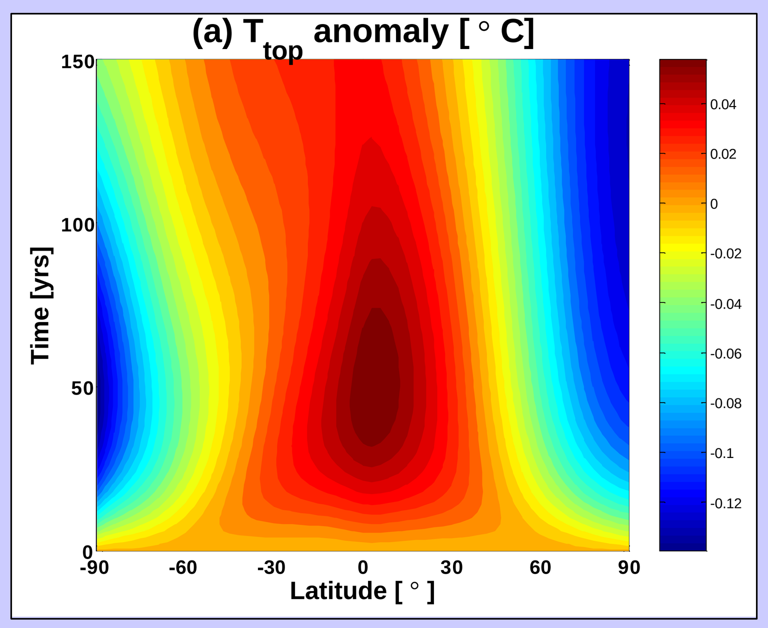
Linearized model: $\frac{d\vec{P}'}{dt} = A\vec{P}'$, $\vec{P}'(t) = e^{At}\vec{P}'_0$ *where* $\vec{P}' = [q', q', T', S']^T_{1\times366}$

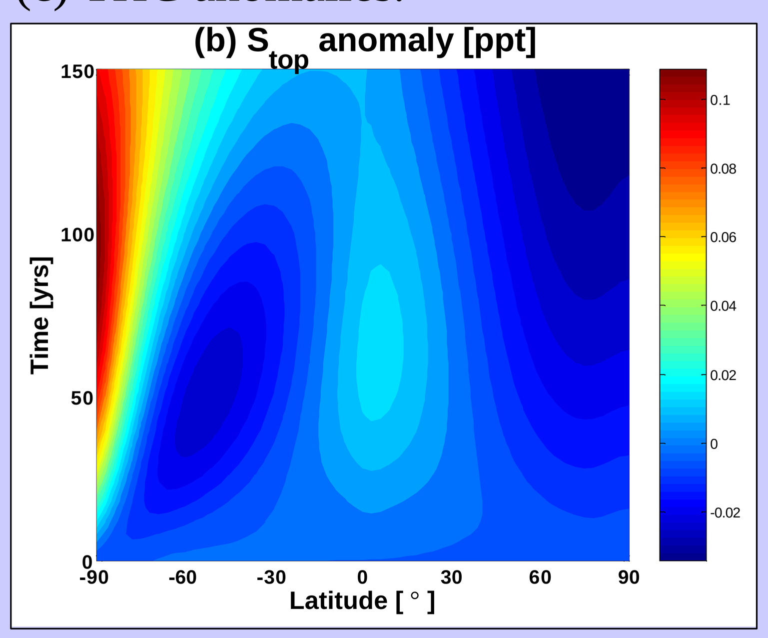
- Maximize THC anomaly $\int |THC'(t,y)|^2 dy$ over both hemispheres at t=t, to find optimal initial conditions $\vec{P}'_0$ under a given norm.

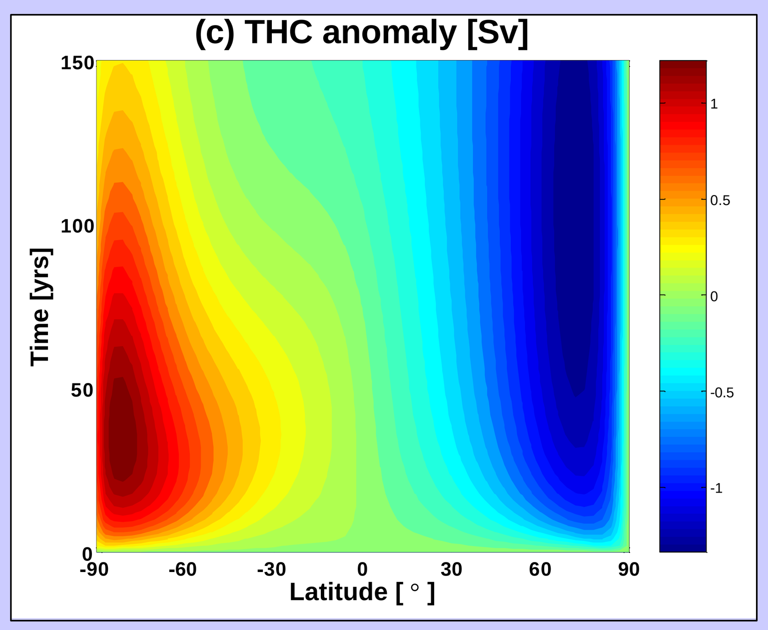
- Solving the generalized eigenproblem for the optimal i.c $\vec{P}'_0$.

4 Results: DRAMATIC AMPLIFICATION of the THC, TEMPERATURE and SALINITY anomalies after 42 years.

Fig. 2: Linearized model evolution starting from the optimal initial conditions resulting in a maximum amplification of the THC after 42 years. The variables are shown as a fct of time and latitude.
(a) surface temperature (grows by a factor of ~400),
(b) surface salinity (grows by a factor of ~20),
(c) THC anomalies.







5.1 Mechanism: Interaction of 5 eigenmodes with decaying time-scale from 20 to 800 years

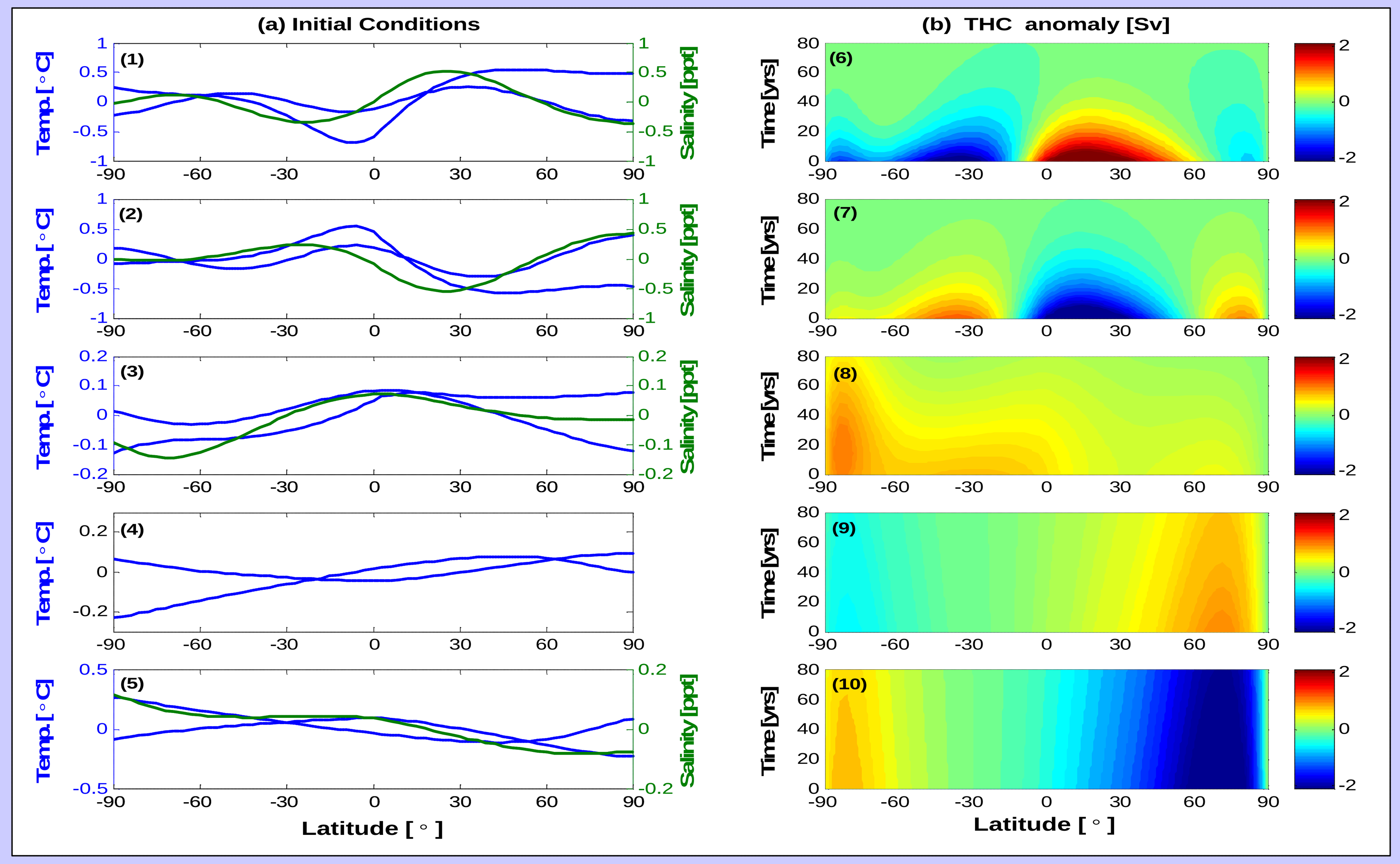


Fig. 3: Principal eigenmodes participating in the transient amplification (a) Initial conditions for the 5 dominant eigenmodes contributing to the transient growth of the THC anomalies. Eigenmodes with decay time scale of (1) 23 years, (2) 25 years, (3) 87 years, (4) 281 years, (5) 784 years; (b) (6)-(10) Time evolution of the THC anomalies resulting from the initial anomalies (1)-(5) .

5.2 Mechanism : amplification is due to the advection of the mean flow by the THC anomalies

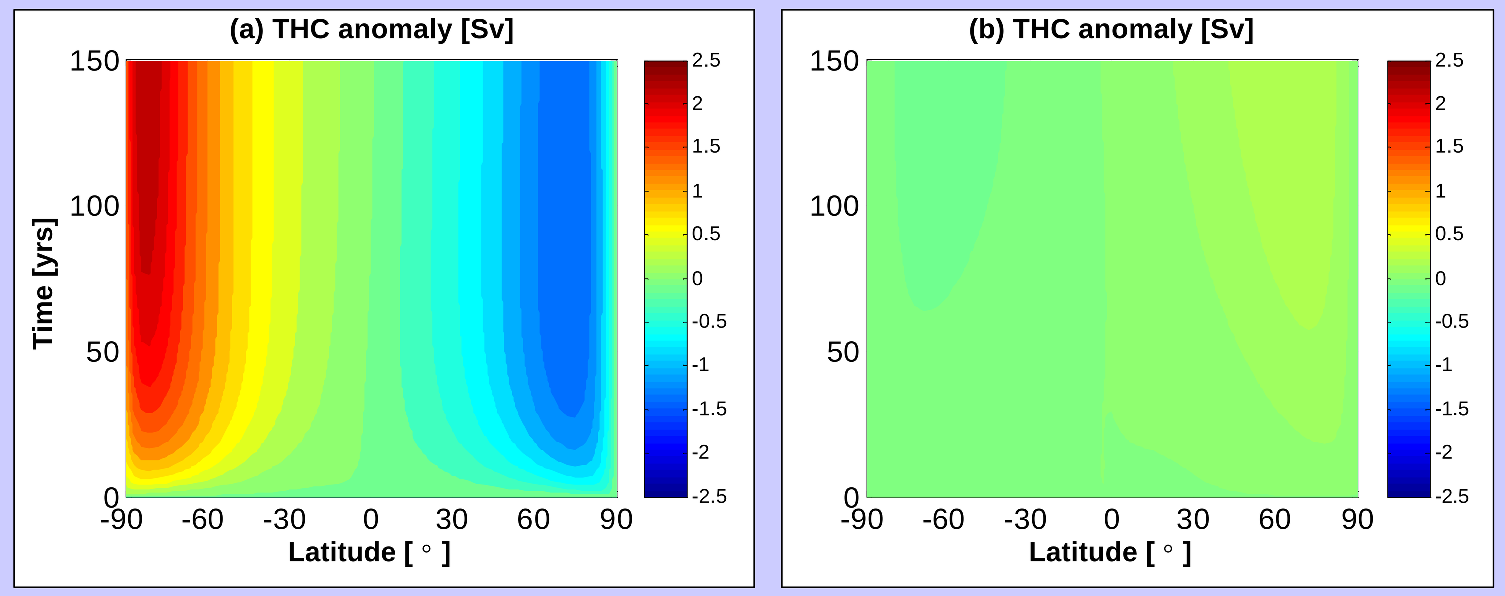


Fig. 4: Evolution of the THC anomalies in different experiments as a function of latitude and time, (a) a model experiment where $\bar{v}\nabla T'$ and $\bar{v}\nabla S'$ are eliminated, (b) a model experiment where $v'\nabla\bar{T}$ and $v'\nabla\bar{S}$ are eliminated. **Both T and S are critical to this mechanism, unlike in typical THC instability.**

5 Conclusions

We found a mechanism for transient growth of the THC anomaly with a time scale of ~40yrs

- THC (t=0)= 0 (T' / S' mutually cancelled)
- Dramatic growth of THC & model variables
- Interaction of fast & slow decaying eigenmodes
- Growth due to advection of the mean flow by the THC perturbations

•*Small* initial perturbations ? *Large* amplification !
•Transient amplification may play an important role in THC/climate variability if excited by atmospheric forcing.

References

Farrell, B.F. and P.J. Ioannou, 1996: Generalized stability theory part I: Autonomous operators. J. Atmos. Sci., 53, 2025-2040; **Farrell, B. F., 1988:** Optimal excitation of neutral Rossby waves. J. Atmos. Sci., 45, 163-172; **Griffies, S. M. and E. Tziperman, 1995:** A linear thermohaline oscillator driven by stochasting atmospheric forcing. J. Climate, 8, 2440-2453; **Moore, A. M. and R. Kleeman, 1997:** The singular vectors of a coupled ocean-atmosphere model of ENSO. Q. J. R. Meteor. Soc., 123, 953-1006; **Penland, C. and P.D. Sardeshmukh, 1995:** The optimal-growth of tropical sea-surface temperature anomalies. J Climate, 8, 1999-2024; **Stommel, 1961:** Thermohaline convection with two stable regimes of flow. Tellus, 13, 224-230; **Tziperman, E. and P. J. Ioannou, 2002:** Transient growth and optimal excitation of thermohaline variability. J. Phys. Oceanog., 32, 3427-3435; **Zanna and Tziperman, 2005:** Non-normal amplification of the thermohaline circulation. J. Phys. Oceanog., 35, 1593-1605