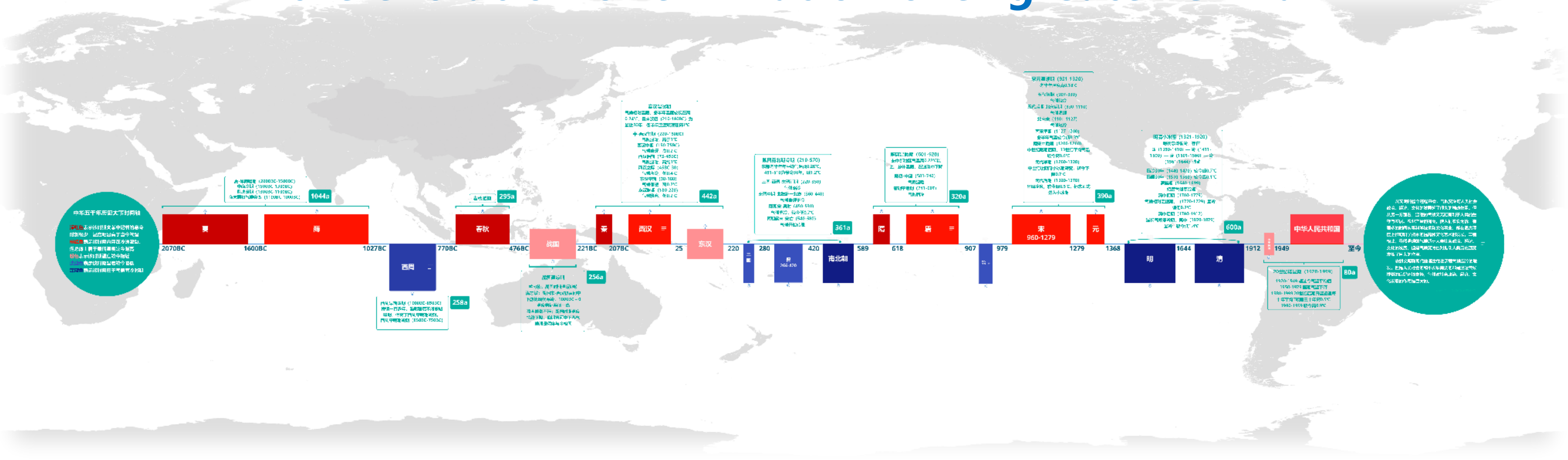
Self-Sustained Multi-Centennial Oscillation of Atlantic Thermohaline Circulation

YANG Haijun (杨海军)[1,2], LI Yang (李洋)[2] and SHI Jiaqi (石佳琪)[2]
[1]Department of Atmospheric and Oceanic Sciences, Fudan University
[2]LaCOAS and Department of Atmospheric and Oceanic Sciences
School of Physics, Peking University
Email: yanghj@fudan.edu.cn

Multi-Centennial Variability: *200-300 (?)* Years

Warm and Cold period during the past 5000 years in the evolution of civilization over greater China



FUDAN UNIVERSITY

Our Questions

500±300 Years

1. ***Natural Centennial-Millennial oscillation*** **in climate system?**

   地球气候系统是否存在百年−千年尺度自然振荡?

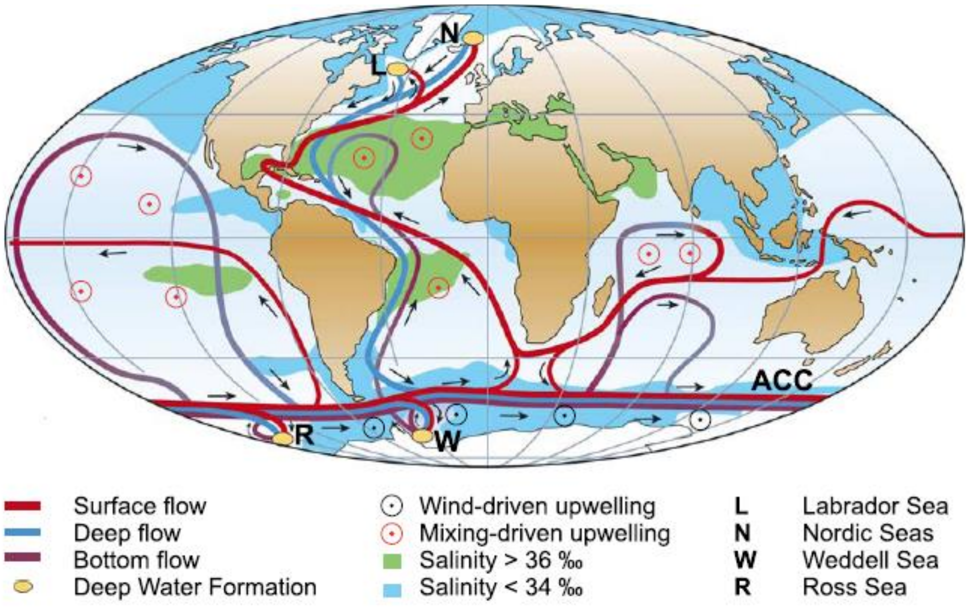
2. **Connection to the *evolution of human civilization*?**

   这种振荡与人类文明演化是否有关系?

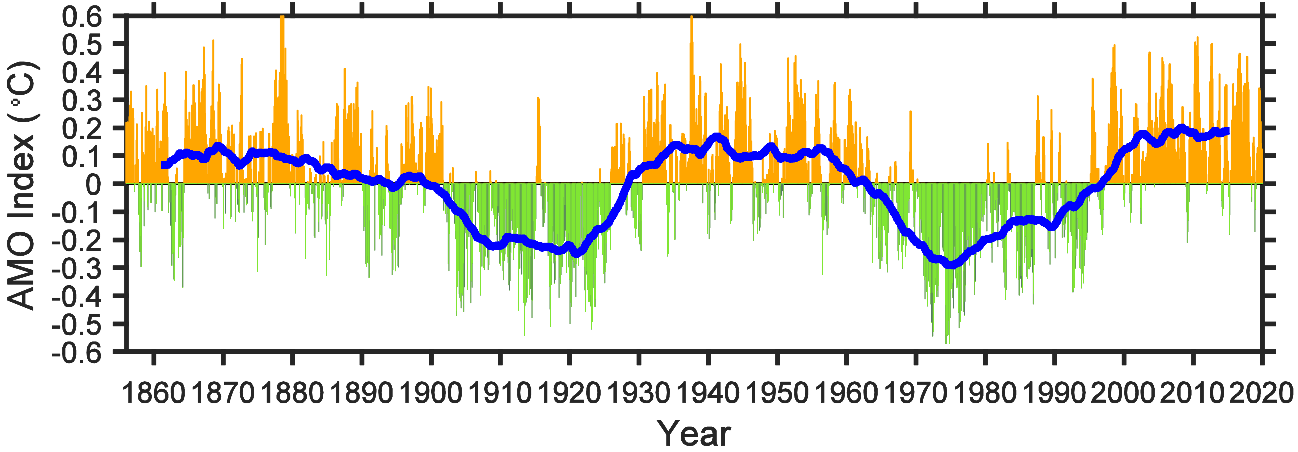
Contents

1. **Common Knowledge**
2. Motivation
3. Observation
4. Theory
5. Modeling

Great Conveyor Belt: *Thousands'* Years



AMO: *60-80* Years



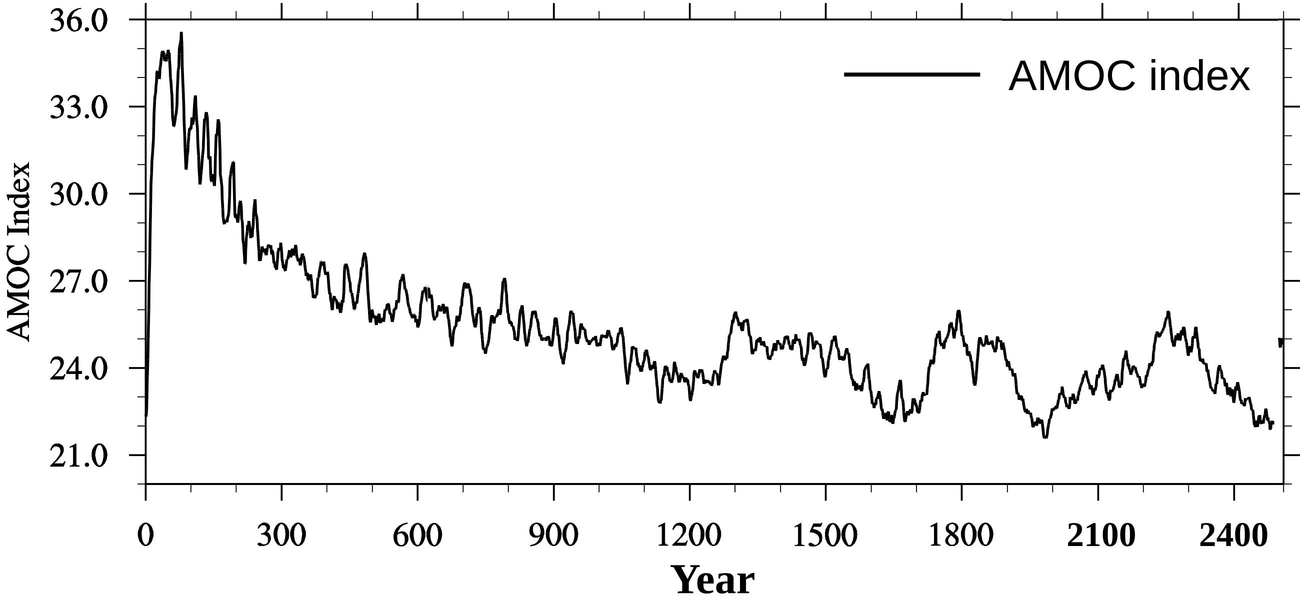
Kaplan SST (Kaplan et al., 1998; Drinkwater et al., 2014)

Contents

1. Common Knowledge
2. **Motivation**
3. Observation
4. Theory
5. Modeling

Motivation

Earlier in **2013**, we confused …

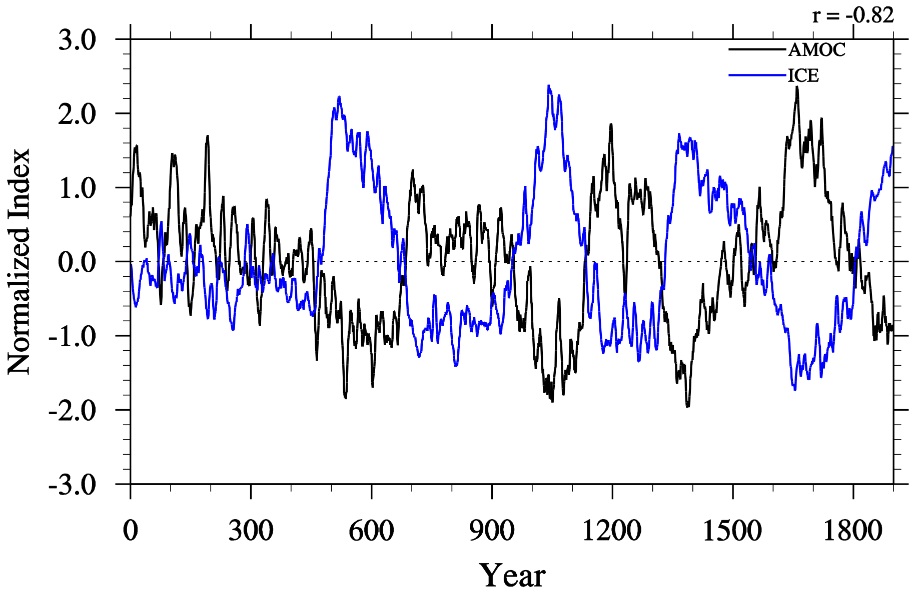


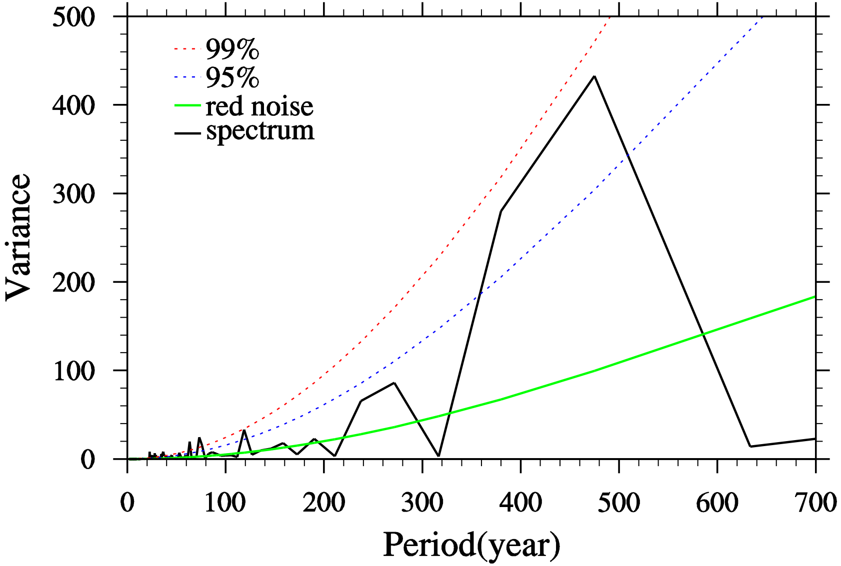
2500 years control run using NCAR-CESM1.0

FUDAN UNIVERSITY

Sea Ice ➔ AMOC ?

Excellent correlation, but ***causality?***





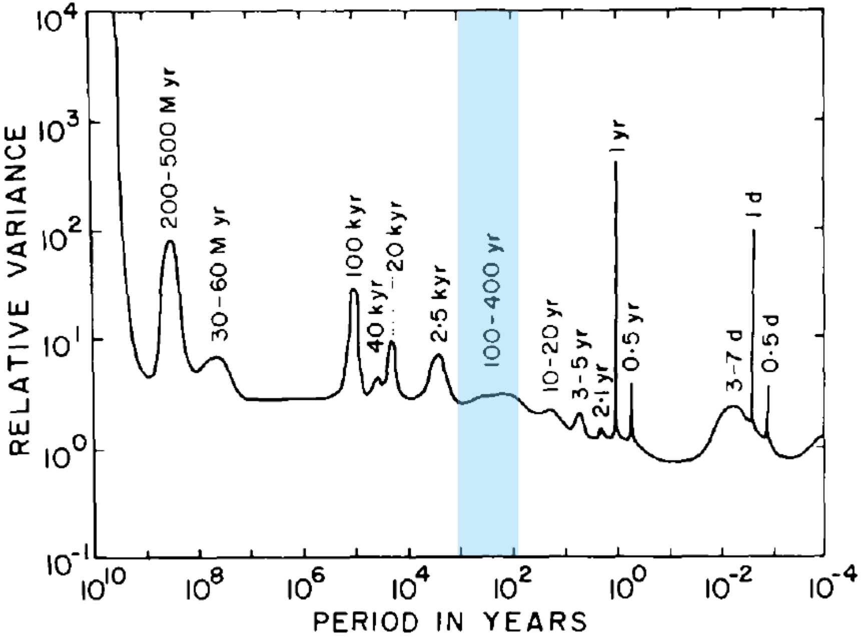
Confused …

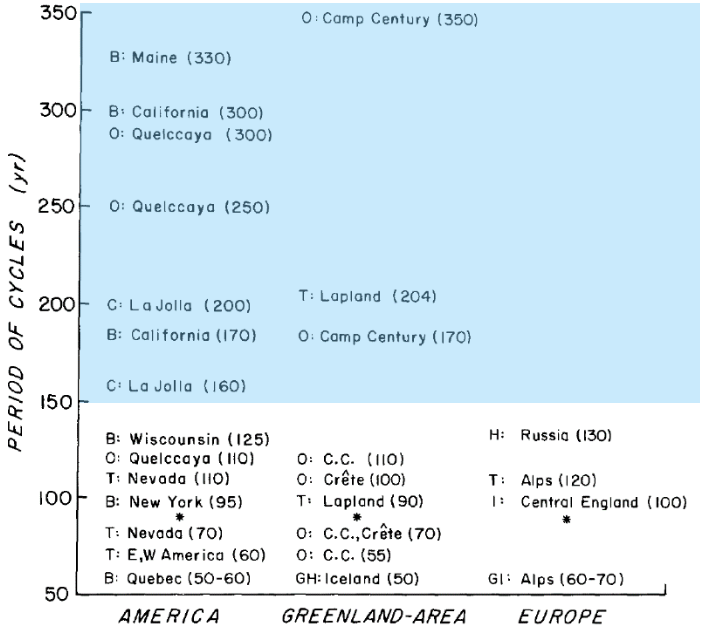
FUDAN UNIVERSITY

Contents

1. Common Knowledge
2. Motivation
3. **Observation**
4. Theory
5. Modeling

Centennial Variability in *Proxy* Data

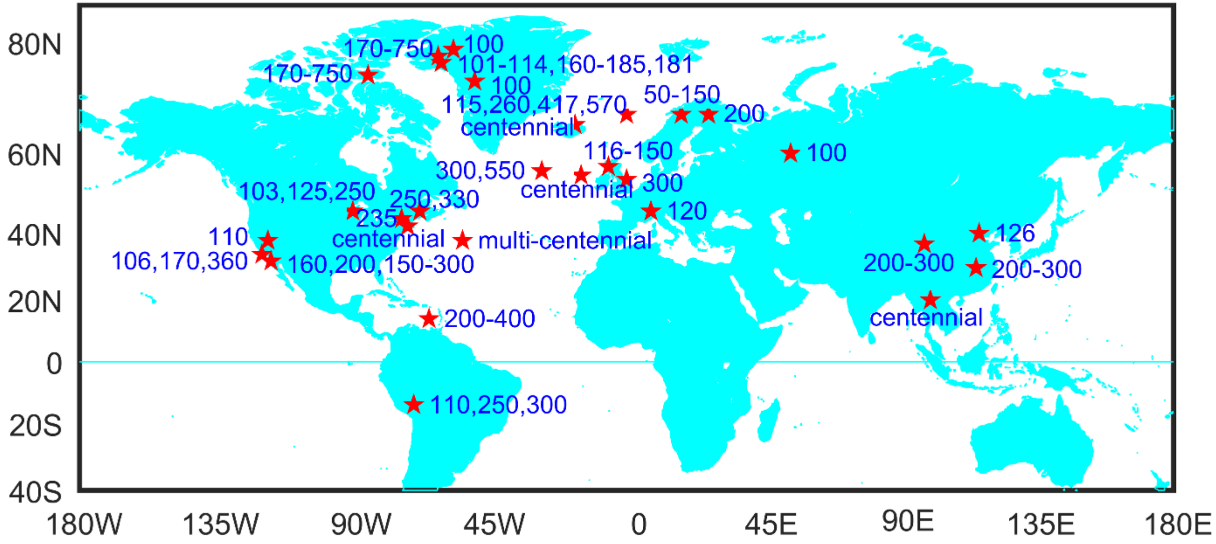




Stocker and Mysak (1992): Climatic fluctuations on the century time scale: A review of high-resolution proxy data and possible mechanisms. Climate Change.

FUDAN UNIVERSITY

Centennial Variability: ***200-300*** **(?)** Years



石佳琪，杨海军，2021：关于观测的百年到千年时间尺度气候振荡。科学通报，待投稿。

FUDAN UNIVERSITY

Centennial Variability: ***200-300 (?)*** Years

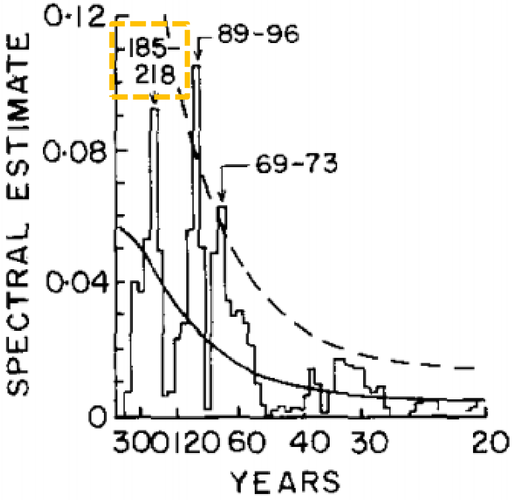
文献出处	位置	代用指标	周期(年)
Siren et al., 1961 Lamb et al., 1977	拉普兰德	树轮	70,90,200
Soutar and Isaacs., 1969	加利福尼亚	海底沉积物	106,170,360
Johnsen and Dansgaard, 1970	格陵兰	冰芯	53-56,69-73,104-144,160-185
LaMarche et al., 1974	美国内华达州	树轮宽度	70,110
Schweingruber et al., 1976	瑞士	树轮宽度	30,120
Lamb et al., 1977	英国，俄罗斯	冬天严寒程度	300, 100
Neftel et al., 1981 Sonett et al., 1984	加利福尼亚	树轮中的 C 放射	150-300, 160,200
Fisher et al., 1982	格陵兰 加拿大	冰芯	170-185,300-330,147-435,625-714
Hameed et al., 1983	中国北京	降水记录	56,84,126
Thompson et al., 1989	秘鲁安第斯山脉	冰芯	110,250
Gajewski, 1988	Hells Kitchen 湖（美国威斯康辛州）	湖底沉积物中的花粉	90-120, 230-250
Stuiver and Braziunas., 1989	/	树轮中的 14C	45,52,67, 143,218,420
Rothlisberger et al., 1989	/	树轮和冰川振荡	88,102-104,123-143

文献出处	位置	代用指标	周期(年)
Briffa et al., 1990	Fennoschandia	树轮	50-150
Anklin et al., 1998	格陵兰岛	冰川雪和冰芯	100,200
Chapman and Shackleton., 2000	北大西洋	深海沉积物	550
McDernott et al., 2001	爱尔兰西南部	/	78,169,625
Proctor et al., 2002	苏格兰西北部	石笋	72-96,116-150
Nyberg et al., 2002	加勒比东北部	有孔虫	200-400
Risebrobakken et al., 2003	挪威海	岩芯	80-115,260, 417,550-570
Oppo et al., 2003	大西洋东北部	有孔虫	百年
Sicre et al., 2008	冰岛北部	冰芯	50-150
J. Zheng et al., 2010	中国东部、西部、青藏高原	历史文献、树轮、降水	200-300 百年
Perner et al., 2013	格陵兰西部	有孔虫	百年
Newby et al., 2014	北美洲	湖底沉积物	几百年
Thirumalai et al., 2018	Garrison 海盆	有孔虫	百年

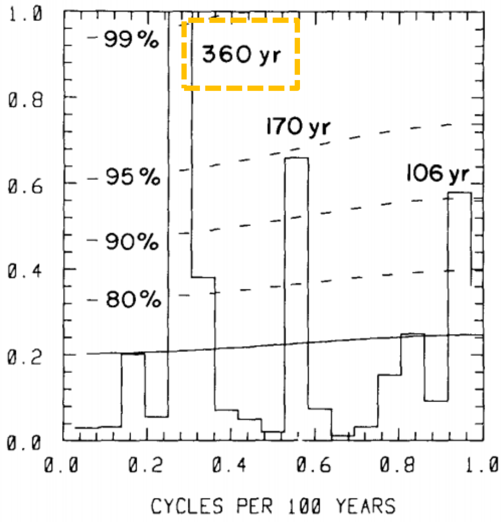
石佳琪，杨海军，2021：百年-千年气候变率：观测、理论与模拟。科学通报，待投稿。

Centennial Variability in *Proxy* Data

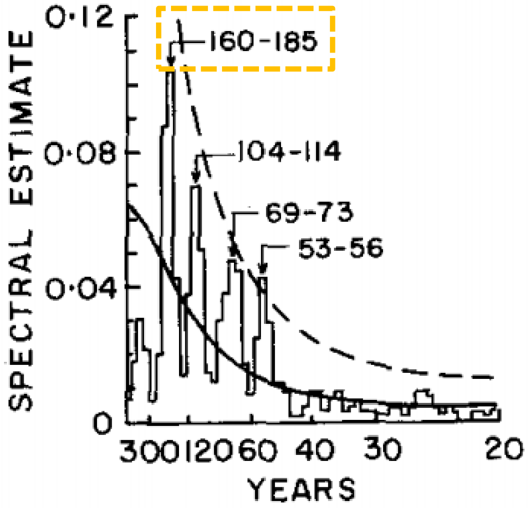
Lapland
Tree rings width



Santa Barbara Basin sediment minimum population of hake



Camp Century
Cores (氧同位素)

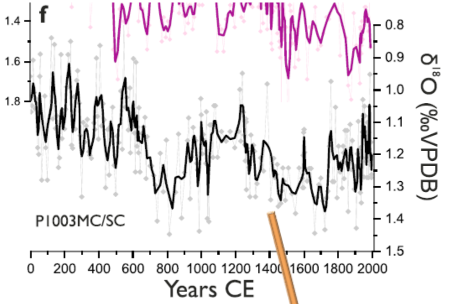


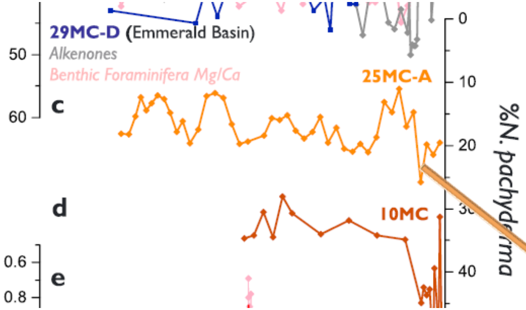
Siren et al. (1961), Lamb et al. (1977); Soutar and Issacs (1969); Johnsen and Dansgaard (1970)

FUDAN UNIVERSITY

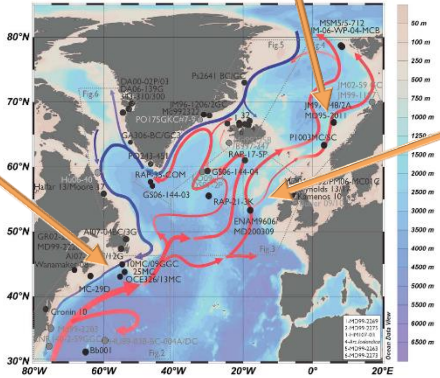
Centennial Variability in *Proxy* Data

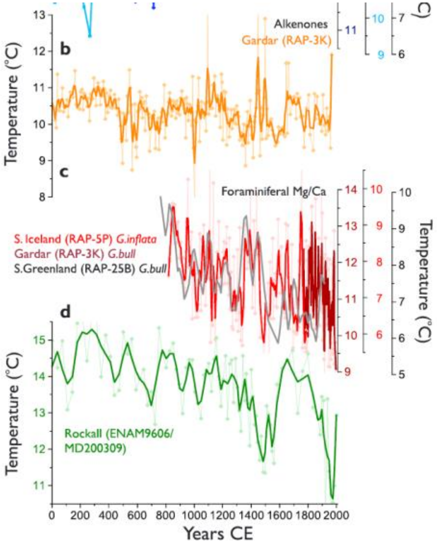
(f) $\delta^{18}O_{foram}$ from P1003MC/SC





(c) % N.pachyderma from Laurentian Fan (25MC-A)

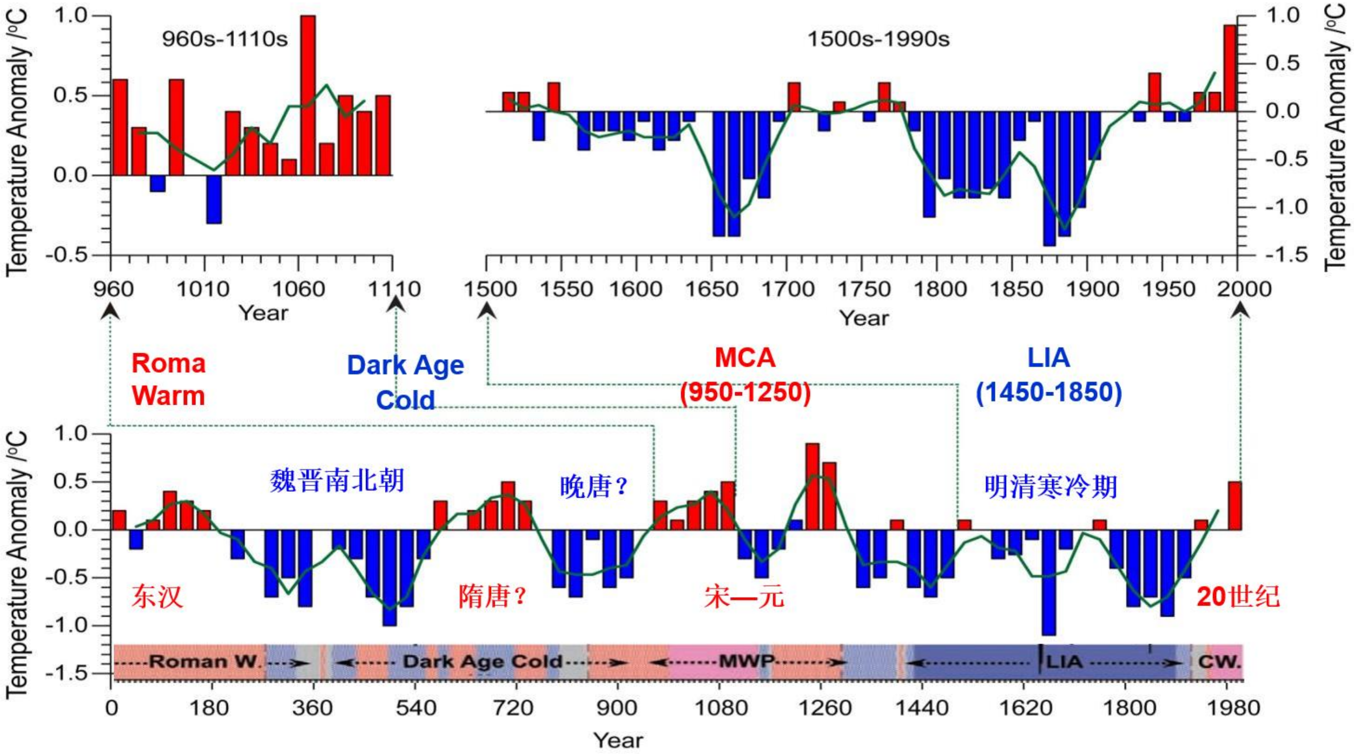




(b) alkenone records from RAPiD-21-3K;
(d) foraminiferal Mg/Ca-based temperature reconstructions from Rockal Trough ENAM9606/M2003209

Moffa-Sánchez et al. (2019), Paleoceanography and Paleoclimatology

Centennial Variability: 200-300 (?) Years



葛全胜，郑景云，满志敏，方修琦，张丕远，2002：过去2000a中国东部冬半年温度变化序列重建及初步分析。地学前沿，9(1)，169-181.

Contents

1. Common Knowledge
2. Motivation
3. Observation
4. **Theory, Simple Model: Previously**
5. Modeling

2-Box Model and Multi-Equilibrium

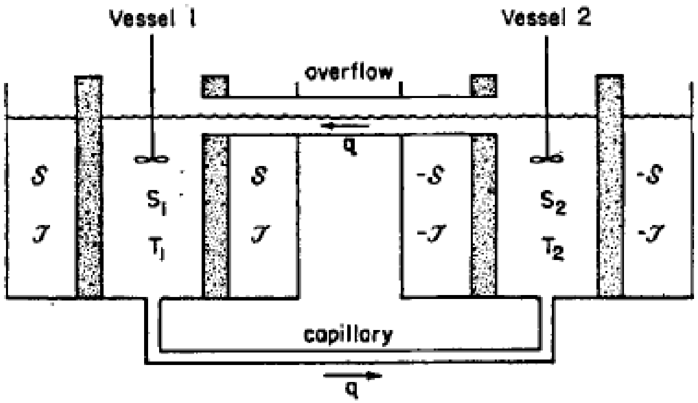
Thermohaline Convection with Two Stable Regimes of Flow

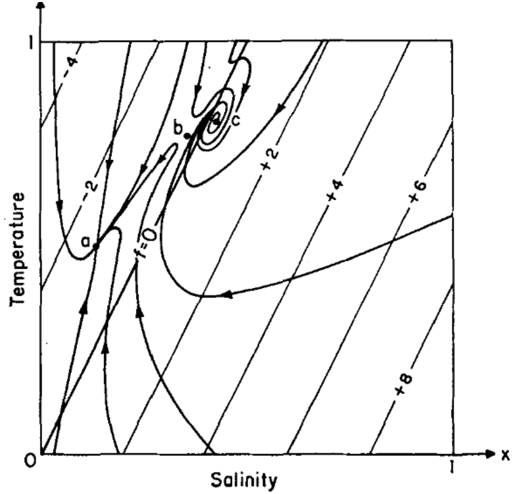
By HENRY STOMMEL, Pierce Hall, Harvard University, Massachusetts

(Manuscript received January 21, 1961)

Abstract

Free convection between two interconnected reservoirs, due to density differences maintained by heat and salt transfer to the reservoirs, is shown to occur sometimes in two different stable regimes, and may possibly be analogous to certain features of the oseanic circulation.

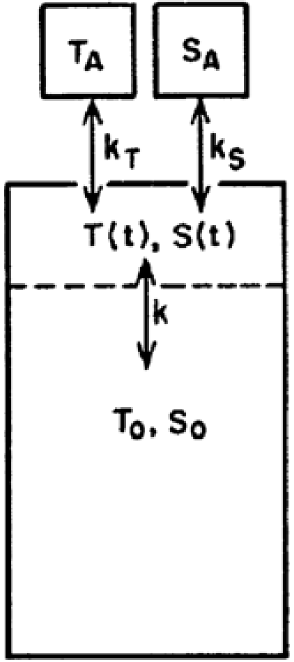


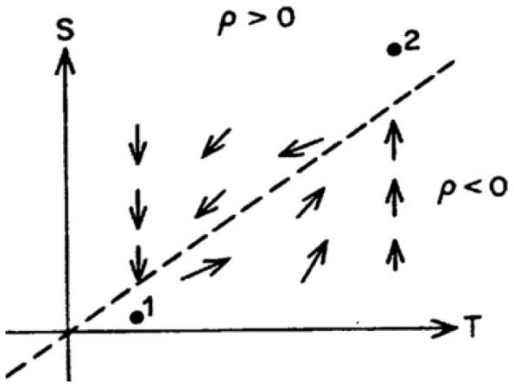


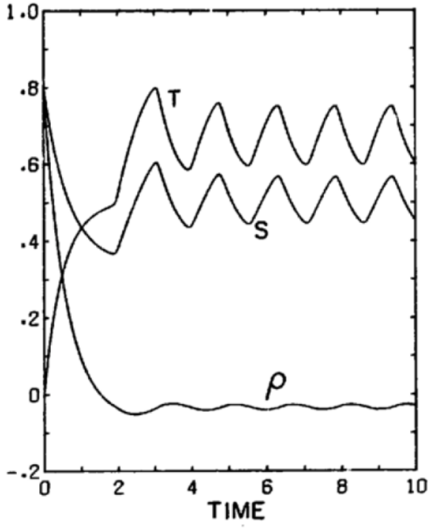
Henry Stommel (Tellus, 1961)

FUDAN UNIVERSITY

Energy Source: *Ocean Convection*



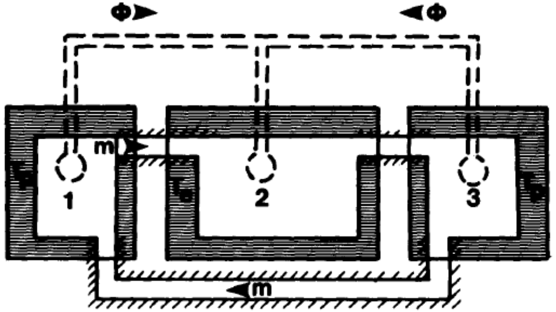




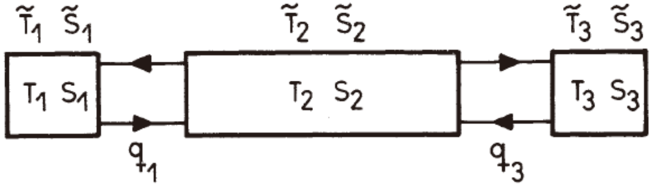
- ***Flip-Flop model***
- **Self-sustained oscillation with increasing vertical turbulent mixing**

Pierre Welander (1982), A simple heat-salt oscillator. Dyn. Atmos. Oceans.

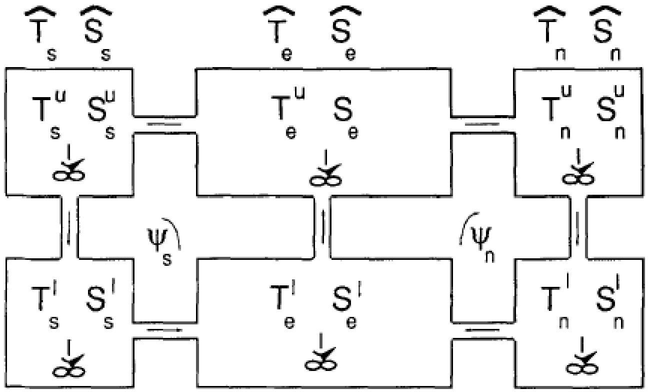
3-Box Model and Multi-Equilibrium



Claes Rooth (1982)



Pierre Welander (1986)



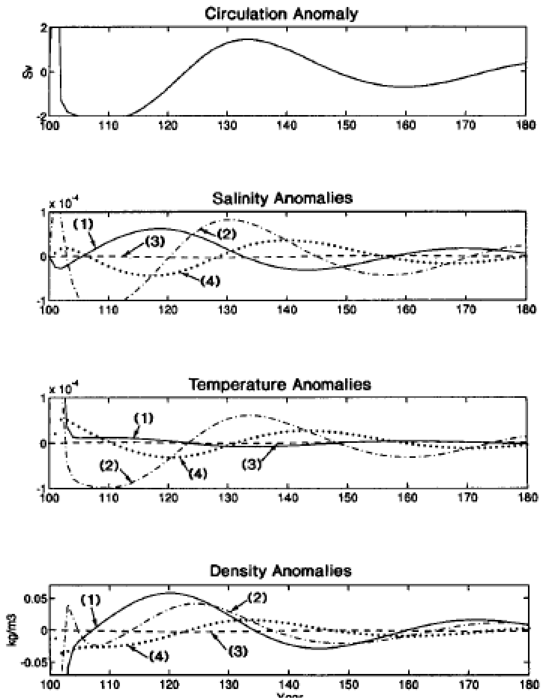
2D Model and 2-, 3-Box Model

Olivier Thual & James C. Mcwilliams (1992)

Climate transition between different stable regimes, with global and centennial-millennium timescale

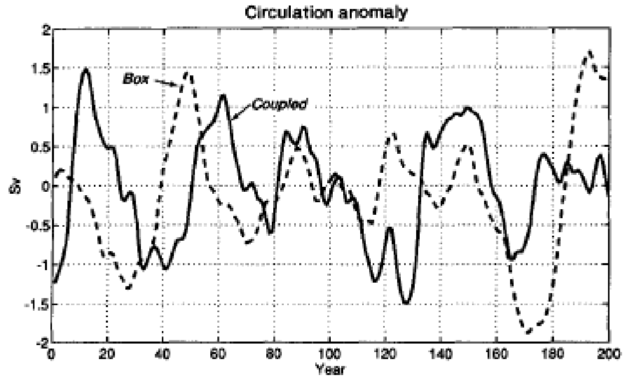
FUDAN UNIVERSITY

Energy Source: *Atmosphere* Perturbation



🡐: Damped Oscillation Mode

Circulation under random thermal forcing 🡒



- **2-Box: Interdecadal variability of THC**
- **Linear interpretation**
- **Excited by atmospheric random forcing**

Stephen Griffies and Eli Tziperman (1995): A linear thermohaline oscillator driven by stochastic atmospheric forcing. J. Climate

Energy Source: *Ocean Advection* Feedback

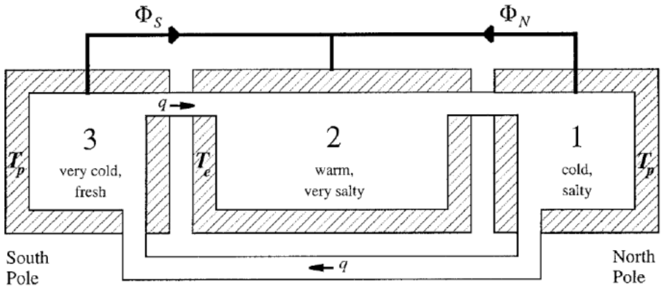
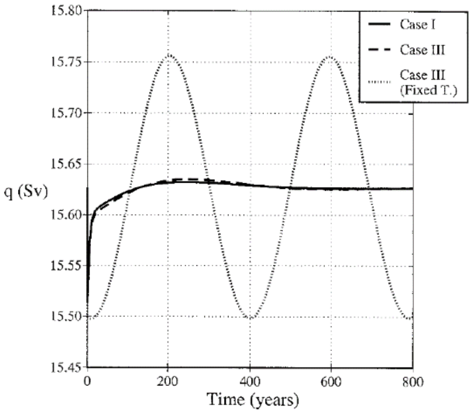
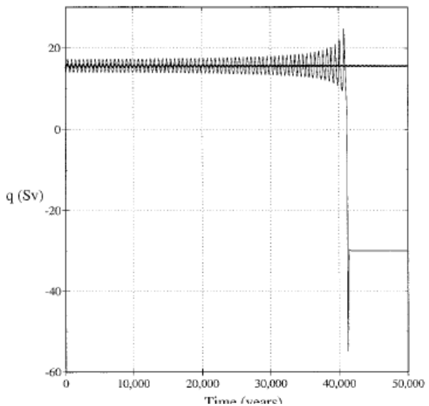


FIG. 1. Rooth's conceptual three-box model of thermohaline circulation, showing equilibrium conditions for Northern Hemisphere sinking. The separation between high- and low-latitude boxes is assumed to occur near the peak in atmospheric transports due to baroclinic eddy fluxes, i.e., about 35° latitude.





3-Box model with asymmetrical freshwater forcing / Stability of the equilibrium

Periodic oscillation with constant Temperature / Collapse under some parameters

Jeffery Scott, Jochem Marotzke and Peter Stone (1999): Interhemispheric thermohaline circulation in a coupled box model. JPO.

FUDAN UNIVERSITY

Single Equilibrium: *Self-Sustained Oscillation*

Self-sustained oscillation with nonlinear close condition

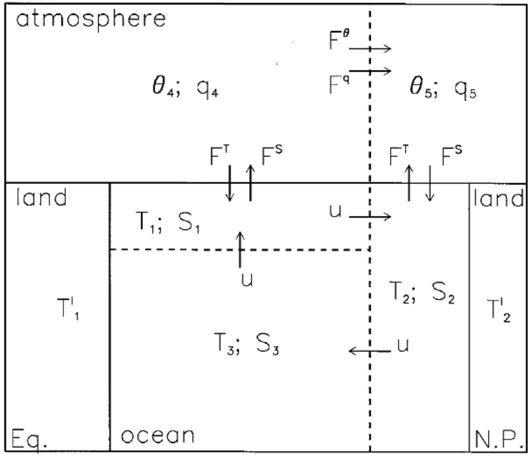
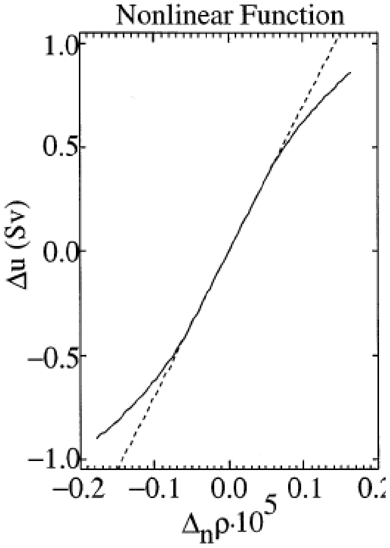


FIG. 1. The box model geometry.

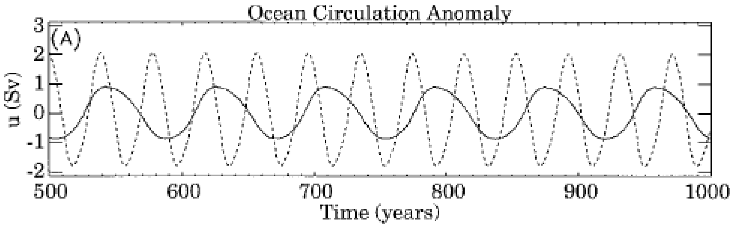
3-Box coupled model



$$u = \bar{u} + u' = \bar{u} + \xi(u_0, \Delta_n\rho')\Delta_n\rho', \qquad (2)$$

where

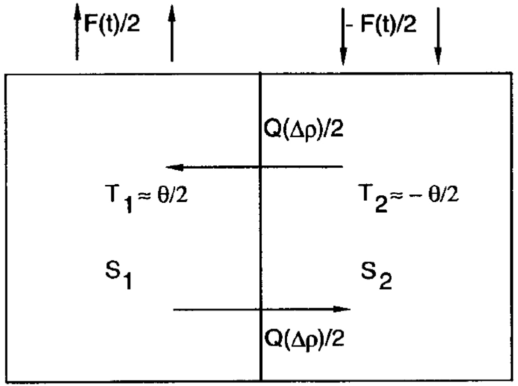
$$\xi(C,x) = \begin{cases} C\frac{x_+}{x}\left[k\left(\left[\frac{x}{x_+}\right]^{1/k} - 1\right) + 1\right] & \text{if } x > x_+ \\ C & \text{if } x_+ \ge x \ge x_- \\ C\frac{x_-}{x}\left[k\left(\left[\frac{x}{x_-}\right]^{1/k} - 1\right) + 1\right] & \text{if } x < x_-. \end{cases} \qquad (3)$$

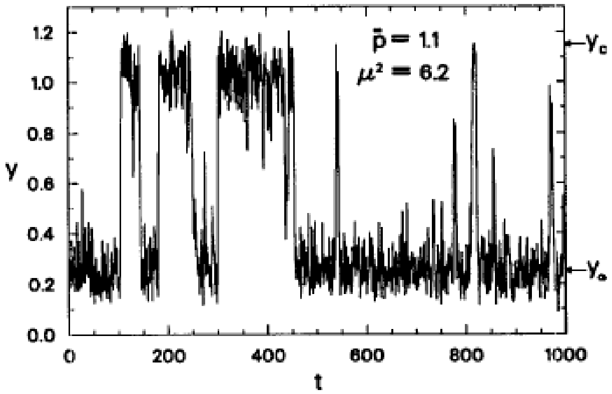


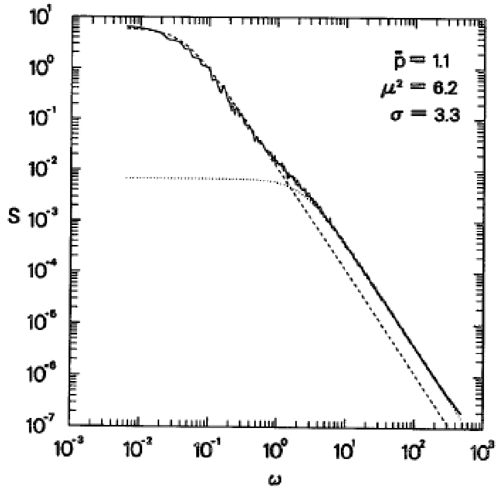
Rivin & Tziperman (1997): Linear versus self-sustained interdecadal thermohaline variability in a coupled box model. JPO

Multi-Equilibrium: *Forced Regime Shift*

Stommel 2-Box model, no *intrinsic* variability, stochastic forced variability







Middle: Multi-equilibrium and forced oscillation; Right: Power spectrum

Paola Cessi (1994), A simple box model of stochastically forced thermohaline flow. JPO

FUDAN UNIVERSITY

Single Equilibrium: *Forced Oscillation*

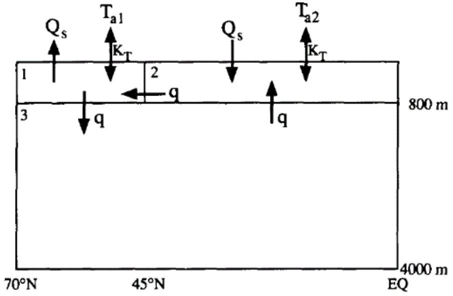
Atmosphere Lorenz model and Ocean 3-Box model

Lorenz (1984, 1990) introduced a low-order atmospheric "general circulation" model, defined by three ordinary differential equations:

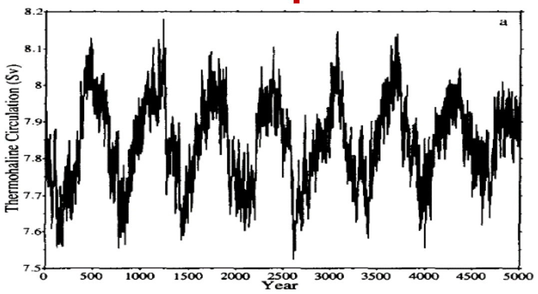
$$\frac{dX}{dt} = -Y^2 - Z^2 - aX + aF, \quad (1)$$

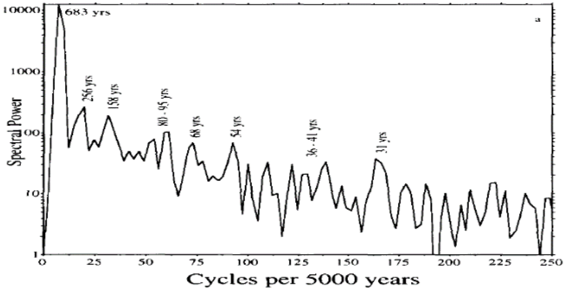
$$\frac{dY}{dt} = XY - bXZ - Y + G, \quad (2)$$

$$\frac{dZ}{dt} = bXY + XZ - Z. \quad (3)$$

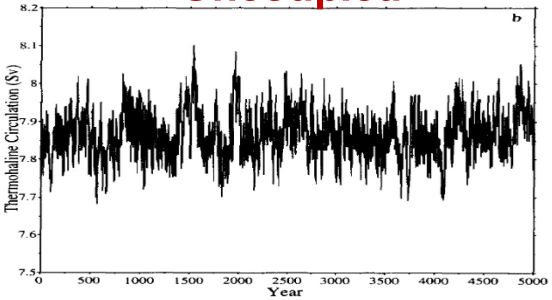


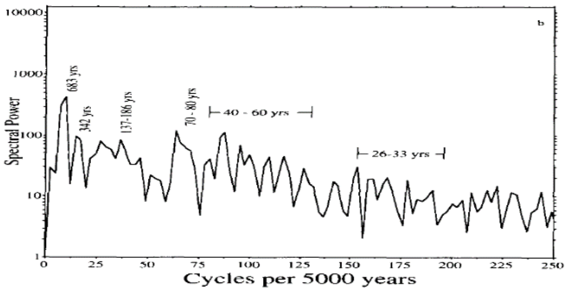
Coupled





Uncoupled

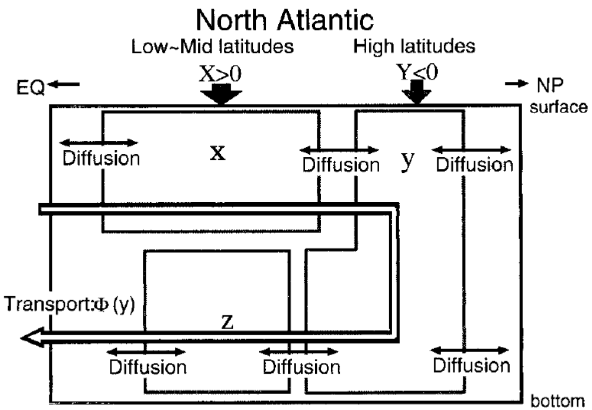


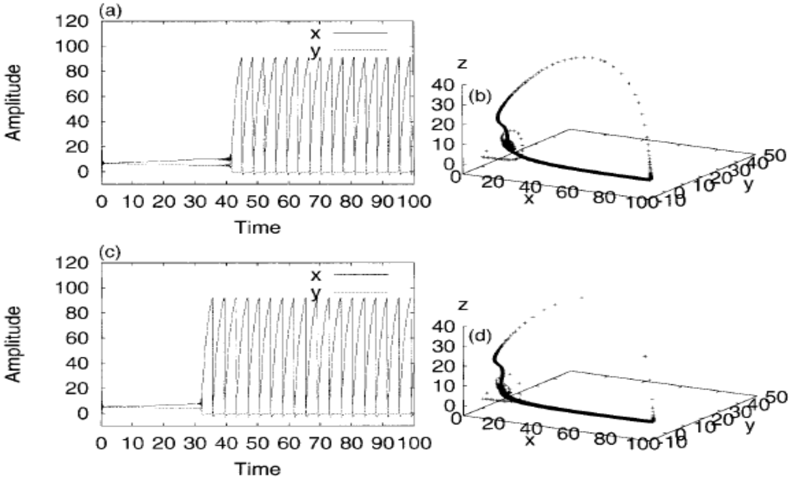


Paul Roebber (1995), Climate variability in a low-order coupled atmosphere-ocean model. Tellus-A

3-Box Model for Bond Cycle

A 3-Box with only Salinity considered, internal *Millennial* oscillation





Bifurcation: from a stable solution to an unsteady bounded oscillation

Sakai & Peltier (1999), A dynamical systems model of the Dansgaard-Oeschger oscillation and the origin of the bond cycle. JC

3-Box model, hysteresis behavior under freshwater forcing

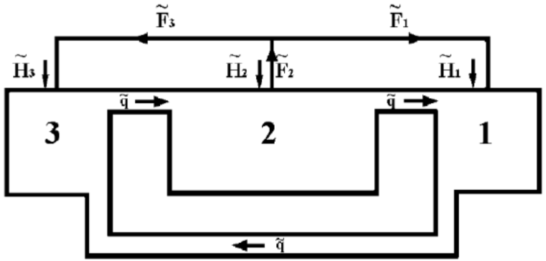
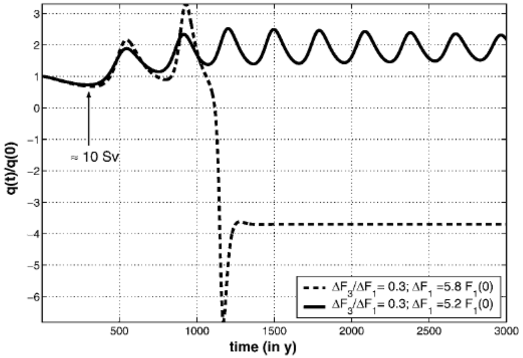
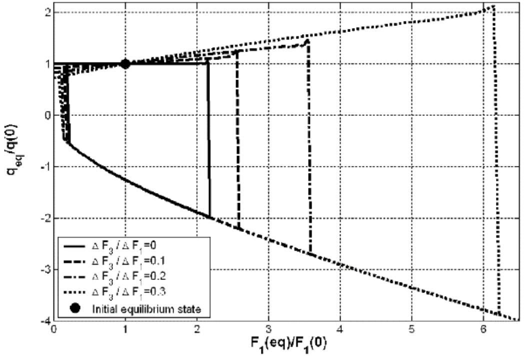


FIG. 1. Schematic picture of the interhemispheric box model.





Lucarini & Stone (2005), Thermohaline circulation stability: a box model study. Part I: uncoupled model. JC

Thermohaline Circulation Centennial Oscillation

2-D with random forcing, *200-300* years oscillation

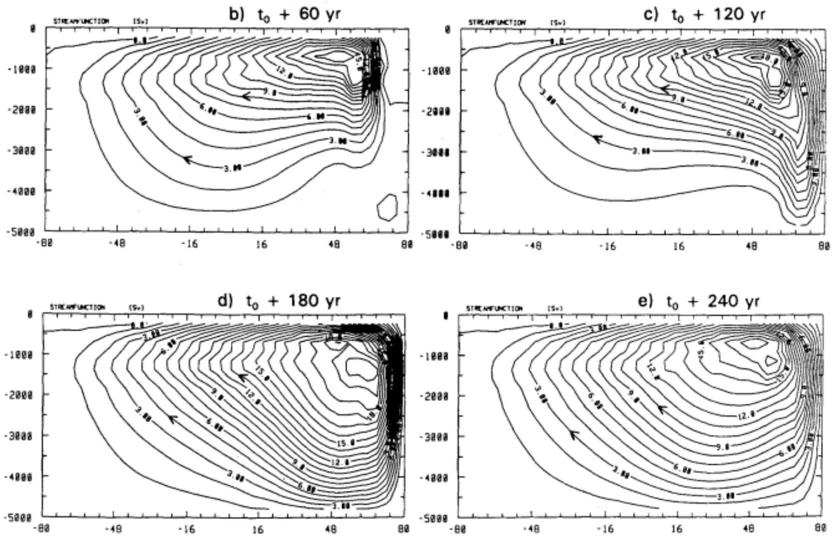
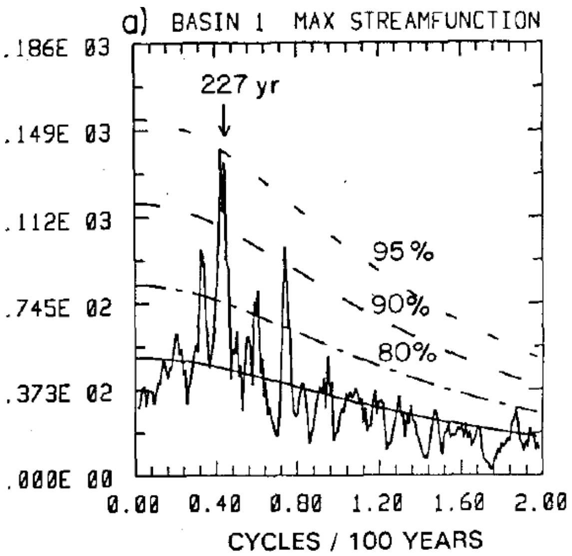


Fig. 3a–e. Streamfunction contours at 60-yr intervals which span the 240-yr oscillation EE′ in Fig. 2. **a** $t=6830$ yr $\equiv t_0$; **b** t_0+60 yr; **c** t_0+120 yr; **d** t_0+180 yr, and **e** t_0+240 yr (end of oscillation)



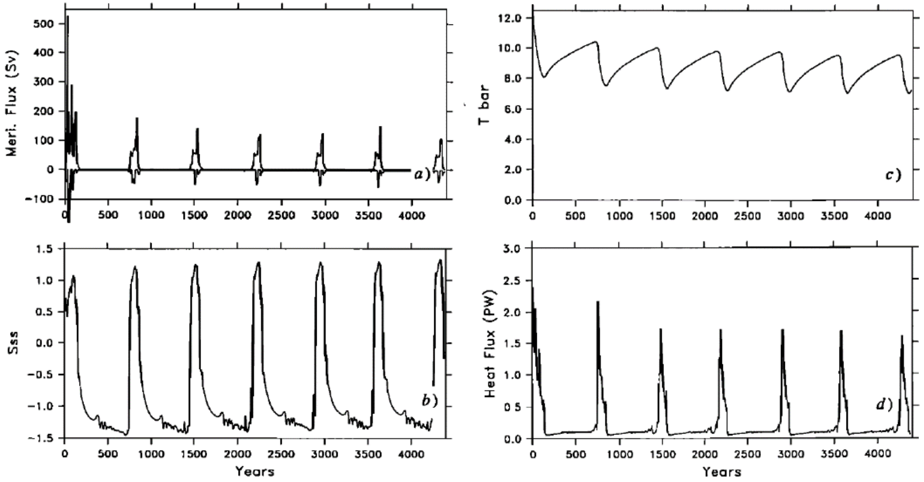
Period: 200-300 years of AMOC, Salinity advection feedback

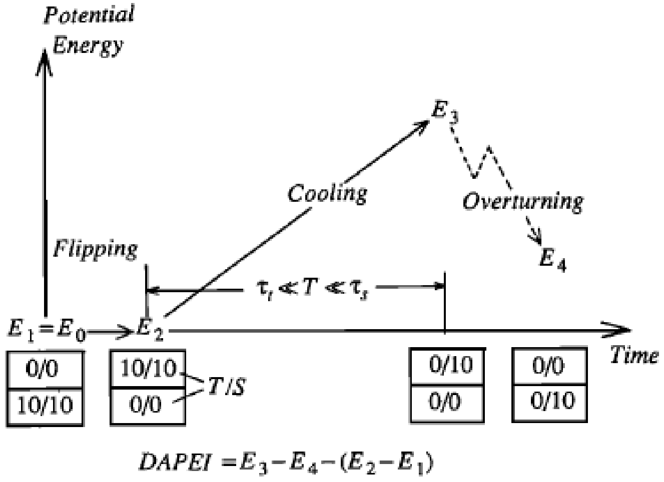
Mysak et al., Climate Dynamics, 1993: Century-scale variability in a randomly forced, 2-D thermohaline ocean circulation model.

FUDAN UNIVERSITY

Energy Source: *Ocean Convection*

3-D OGCM with freshwater forcing, *centennial-millennial* oscillation





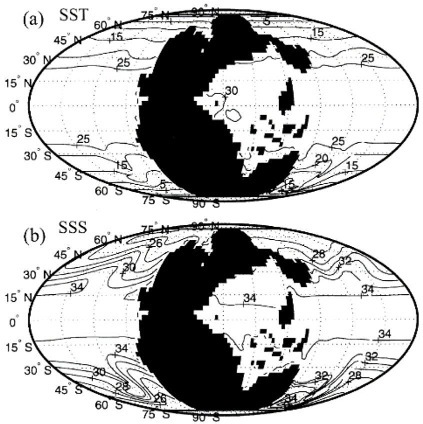
- **Periodic oscillation of saline mode**
- **DAPE provides energy to saline mode's oscillation**

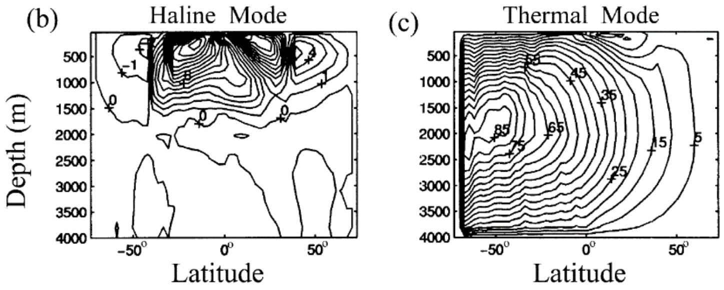
Huang (1994): Thermohaline circulation: Energetics and variability in a single-hemisphere basin model. JGR-ocean

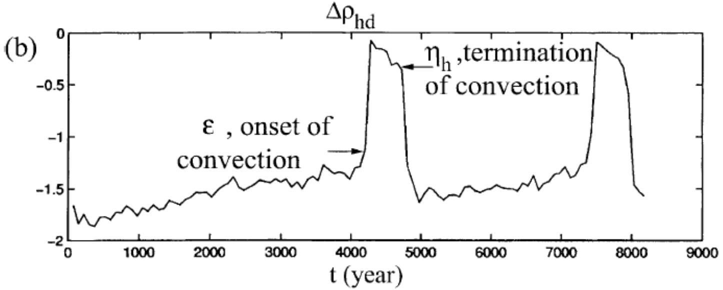
FUDAN UNIVERSITY

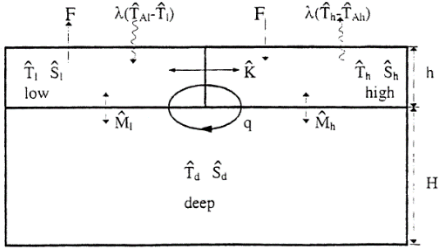
Multi-Equilibrium: *Self-Sustained Oscillation*

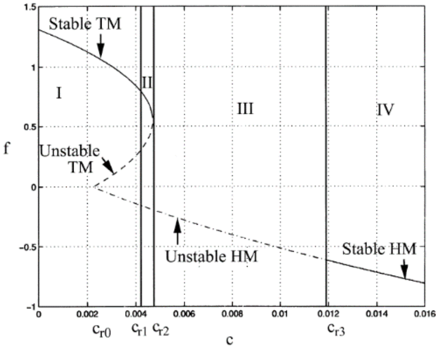
Late Permian, Equable climate and regime shift, *Millennial* oscillation









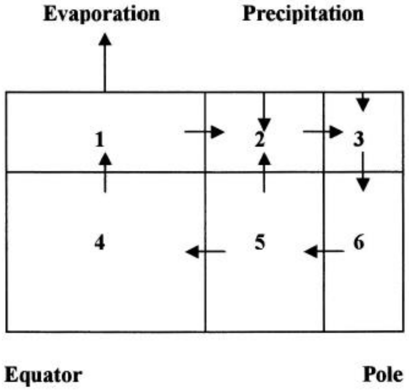


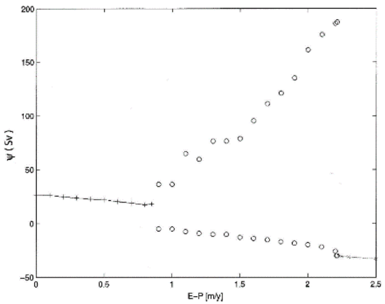
Such oscillations do not appear to occur in the modern ocean, because, apparently, the surface freshwater forcing is not strong enough. Mode switching is more likely to occur, perhaps, during glacial periods in which the freshwater forcing due to ice melting at polar regions is much stronger, or during warm equable paleoclimates such as the late Permian, or mid-Cretaceous in which the buoyancy forcing due to freshwater flux may have been stronger than the air–sea heat flux

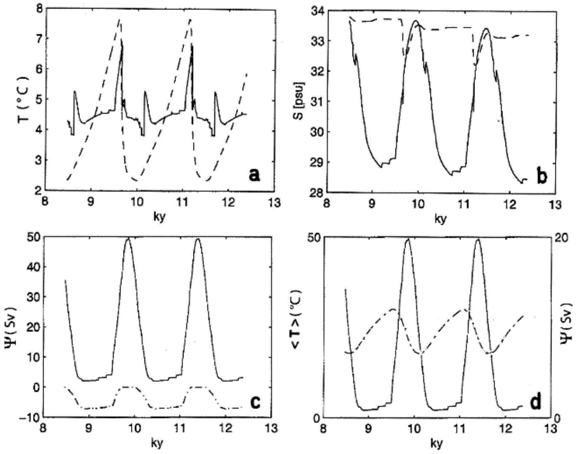
Zhang et al. (2002), Mechanism of thermohaline mode switching with application to warm equable climates. JC

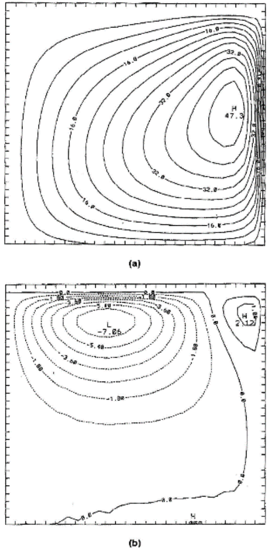
Multi-Equilibrium: *Self-Sustained Oscillation*

Lowest-order 3x2-Box and 2D model, internal *Millennial* oscillation









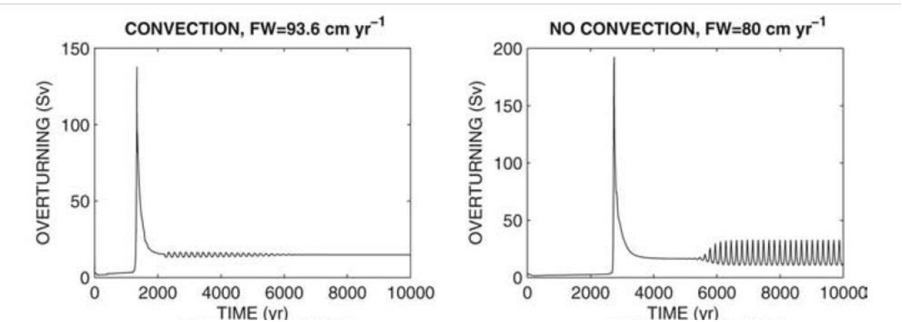
E-P increasing: stable thermal mode ➔ oscillation mode ➔ steady haline mode.

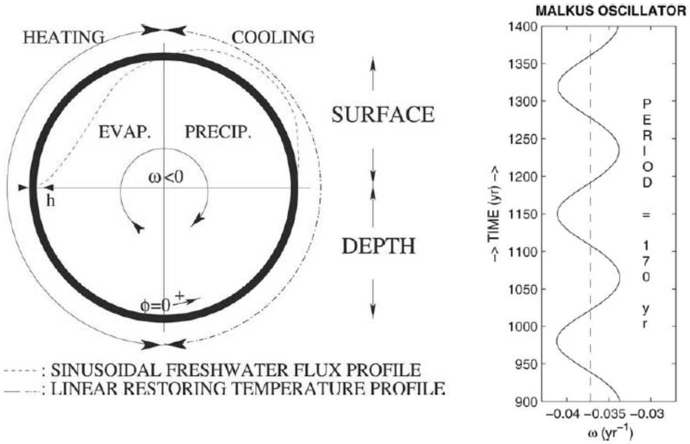
Colin De Verdière, Jelloul and Sevellec (2006), Bifurcation structure of thermohaline millennial oscillations. JC

FUDAN UNIVERSITY

Beyond Box Model

2-D model and 1-D Howard-Malkus loop model, internal *Centennial* oscillation





Left: 2-D model; Right: 1-D model of Howard-Malkus loop

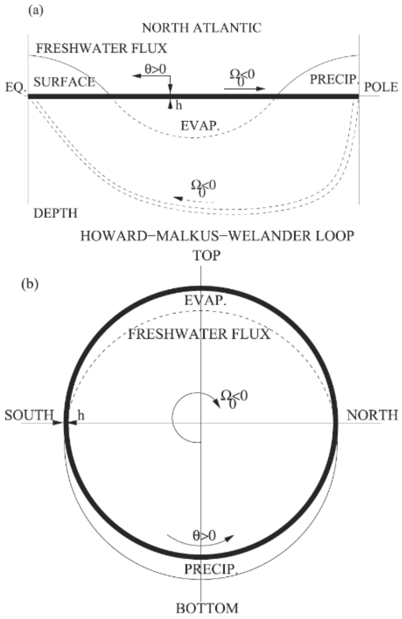
Not self-sustained: either strong damped or runaway mode

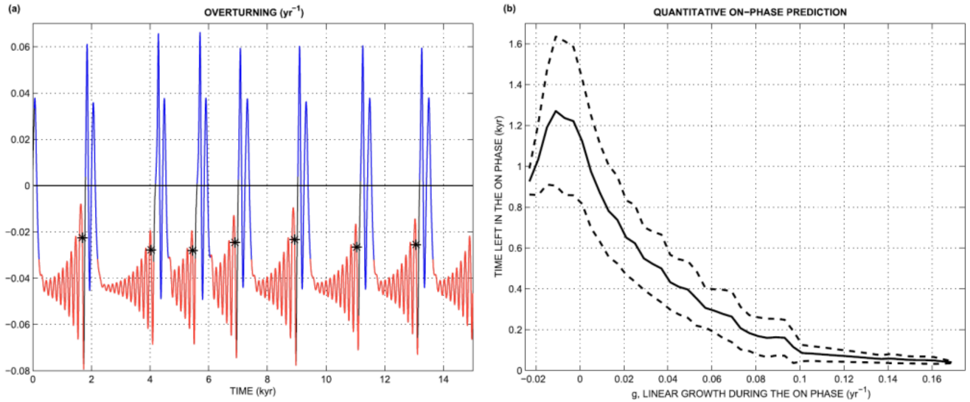
Nonlinear or linear; convection or no convection

Sévellec et al. (2006), On the mechanism of centennial thermohaline oscillations. J. Marine Research

Beyond Box Model

1-D Howard-Malkus loop model, AMOC *Millennial* regime shifts





AMOC *Millennial* shift is predictable in this chaotic model

Two predictive indices are defined

Sévellec & Fedorov (2014), Millennial variability in an idealized model: predicting the AMOC regime shifts

FUDAN UNIVERSITY

Centennial Oscillation in Coupled GCM

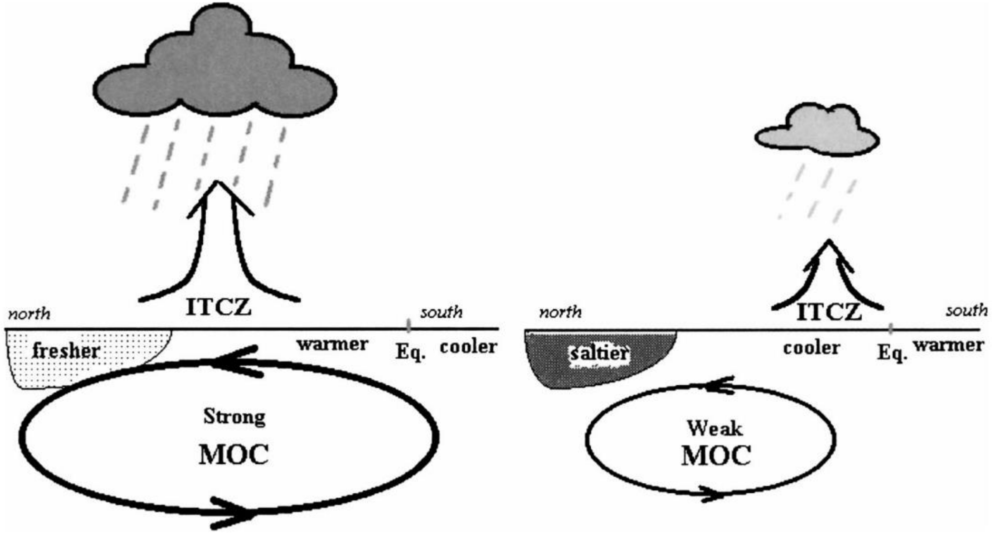


FIG. 16. Schematic of mechanism responsible for centennial THC fluctuation in HadCM3. When the THC is (left) strong ITCZ shifts northward, in response to enhanced SST gradient across equator. Fresh anomalies in the upper-ocean propagate northward and weaken the overturning. This results in the (right) weak phase.

AMOC ⇑ →

→Northward OHT ⇑

→Cross Eq. ΔSST ⇑

→ ITCZ Northward Rain ⇑

→Tropical Salinity⇓

→Northward S-advection ⇓

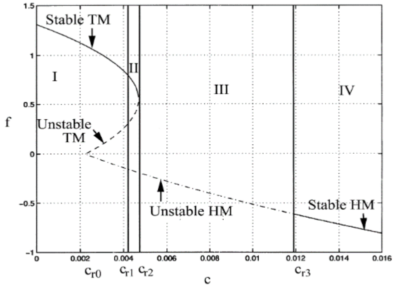
→NADW Salinity ⇓

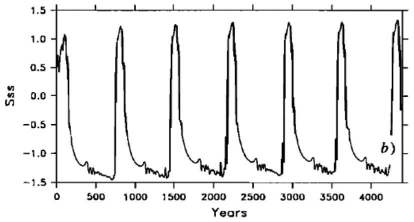
→AMOC ⇓

Vellinga and Wu (2004), Low-latitude freshwater influence on centennial variability of the Atlantic THC. JC

Previous Theoretical Studies: *Summary*

- **THC: stability, bifurcation and regime shift**
- **Forcing: freshwater or/and stochastic**
- **Transition: thermal mode to haline mode**
- **Self-sustained oscillation: δ-function-like**
- **Not particularly on Holocene**





FUDAN UNIVERSITY

Contents

1. Common Knowledge
2. Motivation
3. Observation
4. **Theory: Our Paradigm**
5. Modeling

Climate Variability that *Ocean Matters*

Interannual → Decadal → Multi-decadal → Centennial-Millennial

ENSO
2-7y

PDO
10-30y

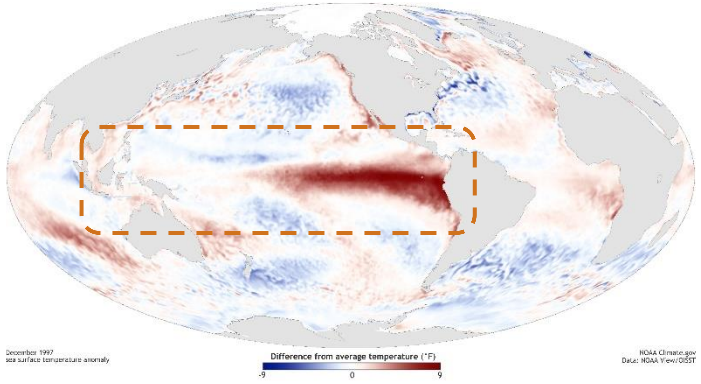
AMO
60-80y

200-300y
BC: 1500y

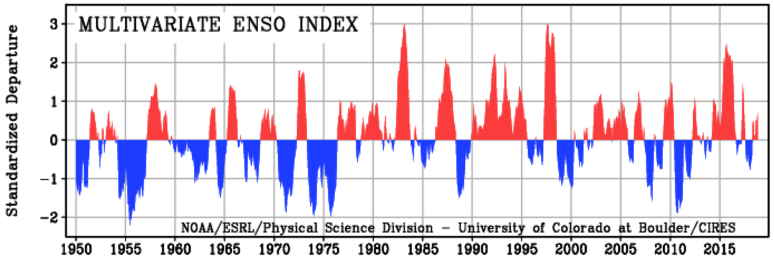
Theory, Observation, Simulation
Comprehensive!

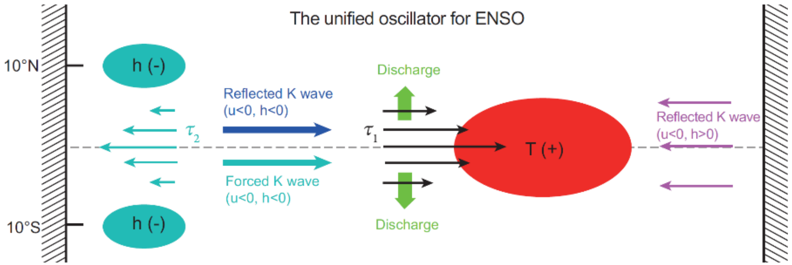
？？？

ENSO Variability: 2-7 Years



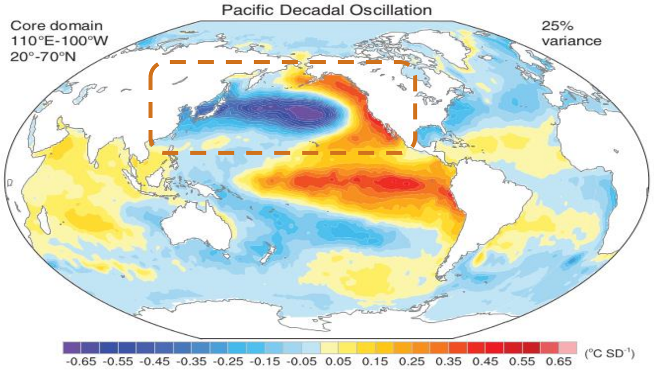
- Eigen Mode : Equatorial Basin Mode, Rossby + Kelvin waves. Cane and Moore (1981)
- Mixed Layer + Thermocline (200m)
- Wang et al. (2018), NSR: A Review of ENSO theories

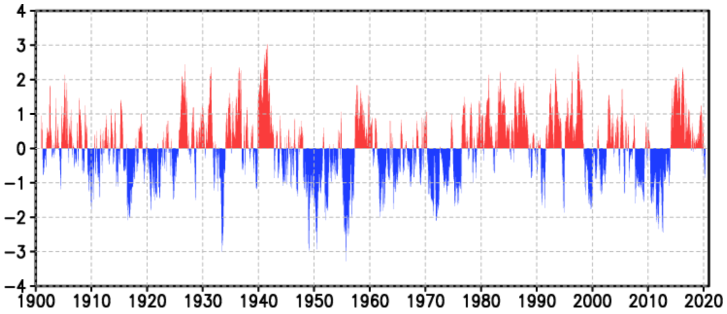




https://www.psl.noaa.gov/enso/mei.old/

Decadal Variability (PDO): *10-30* Years



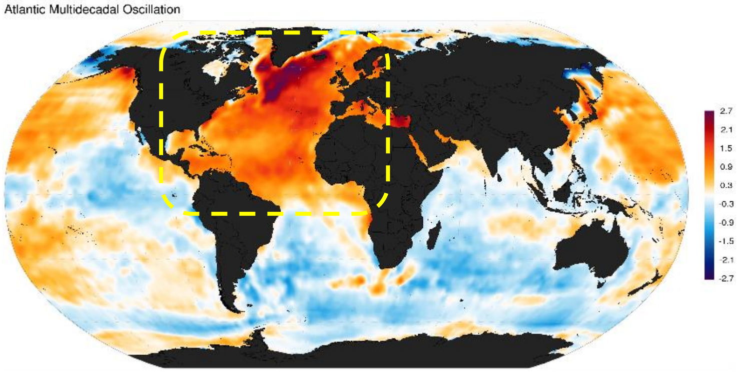


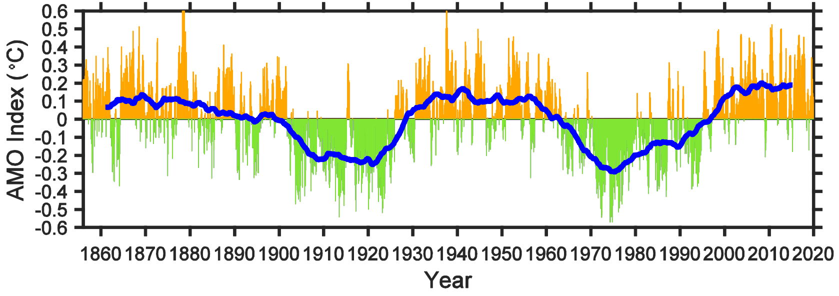
https://www.daculaweather.com/4_pdo_index.php

- Eigen Mode:
  1. Planetary Wave Basin Mode, Extratropical Rossby + Coastal Kelvin waves. Yang and Liu (2003)
  2. Subduction mode, 2nd Rossby wave. Gu and Philander (1997); Liu (1999a, b, 2003)
- Mixed Layer + Thermocline (500m)
- Liu (2012), JC: Dynamics of Interdecadal Climate Variability: A Historical Perspective
- Liu and Di Lorenzo (2018), Current Climate Change Reports: Mechanisms and Predictability of Pacific Decadal Variability

FUDAN UNIVERSITY

Multi-Decadal Variability (AMO): 60-80 Years





- Eigen Mode:
  1. Planetary Wave Basin Mode, Extratropical Rossby Waves
  2. Advection mode of AMOC
- Thermohaline dynamics (4000m)
- Vecchi, Delworth and Booth (2018), Nature: Origins of Atlantic Decadal Swings
- Drinkwater et al. (2014), JMS: The Atlantic Multidecadal Oscillation: Its manifestations and impacts with special emphasis on the Atlantic region north of 60N

https://en.wikipedia.org/wiki/Atlantic_multidecadal_oscillation; UK Met Office; HadISST
https://climatedataguide.ucar.edu/climate-data/atlantic-multi-decadal-oscillation-amo

FUDAN UNIVERSITY

Climate Variability that *Ocean Matters*

Interannual → Decadal → Multi-decadal

ENSO
2-7y

PDO
10-30y

AMO
60-80y

Theory: Eigen mode excited by
Air-sea coupling
External (Random) forcing

FUDAN UNIVERSITY

Climate Variability that *Ocean Matters*

We would like to

Searching for Eigen Mode

↓

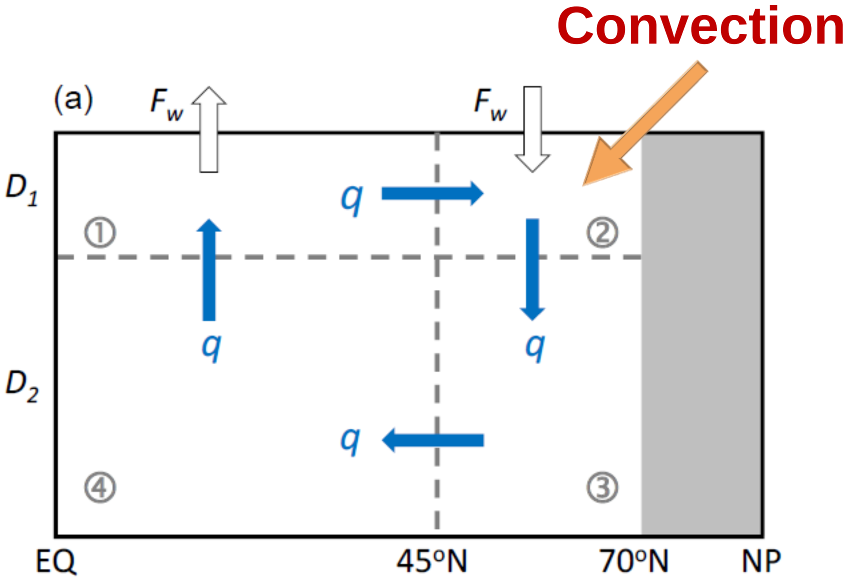
Centennial-Millennial Timescale Climate Variability

↑

? ? ?

FUDAN UNIVERSITY

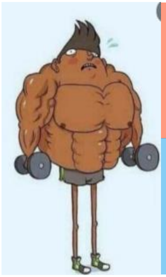
One Hemisphere 4-Box Model



Li and Yang (2021)

Convection

Static instability (头重脚轻)



High Saline → Denser

Fresh

Adiabatic APE

Convective instability (头冷脚热)

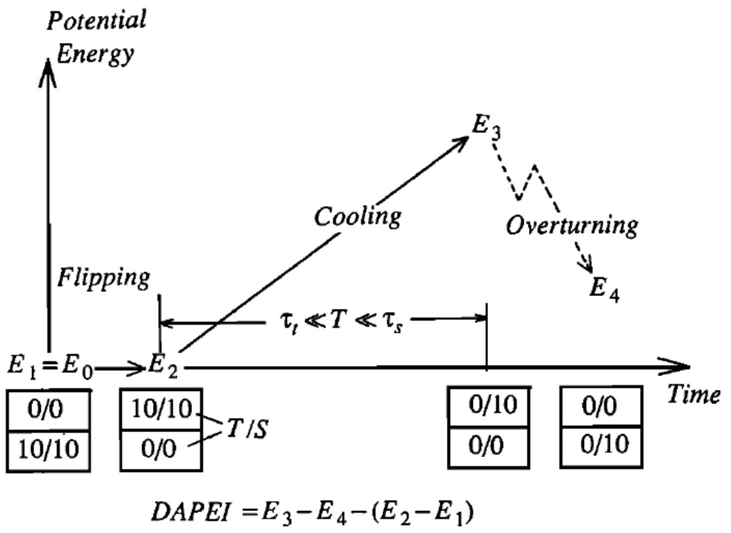
Fresh → Denser

High Saline

Diabatic APE

Li and Yang (2021)

Diabatic Available Potential Energy (DAPE)



Huang (1994)

During the transition from state 3 to 4, a large amount of potential energy is released. The diabatic available potential energy index (DAPEI) is defined as the energy released during the overturning minus the energy required to push the slightly heavy water from the lower box upward to initiate the whole process,

$$DAPEI = E_4 - E_3 - (E_2 - E_1) = \rho_0 g h^2 \alpha (T_2 - T_1)$$

$$DAPEI = \iiint_0^H g\rho_0\alpha\,[T(z) - T_{\rm surf}]\,(H - z)\delta\, dz dx dy$$

where δ is a switch, $\delta = 1$ if $T(z) > T_s$ and $S(z) > S_s$, and $\delta = 0$ otherwise. Thus the switch δ is on only if the stratification is in favor of convective overturning.

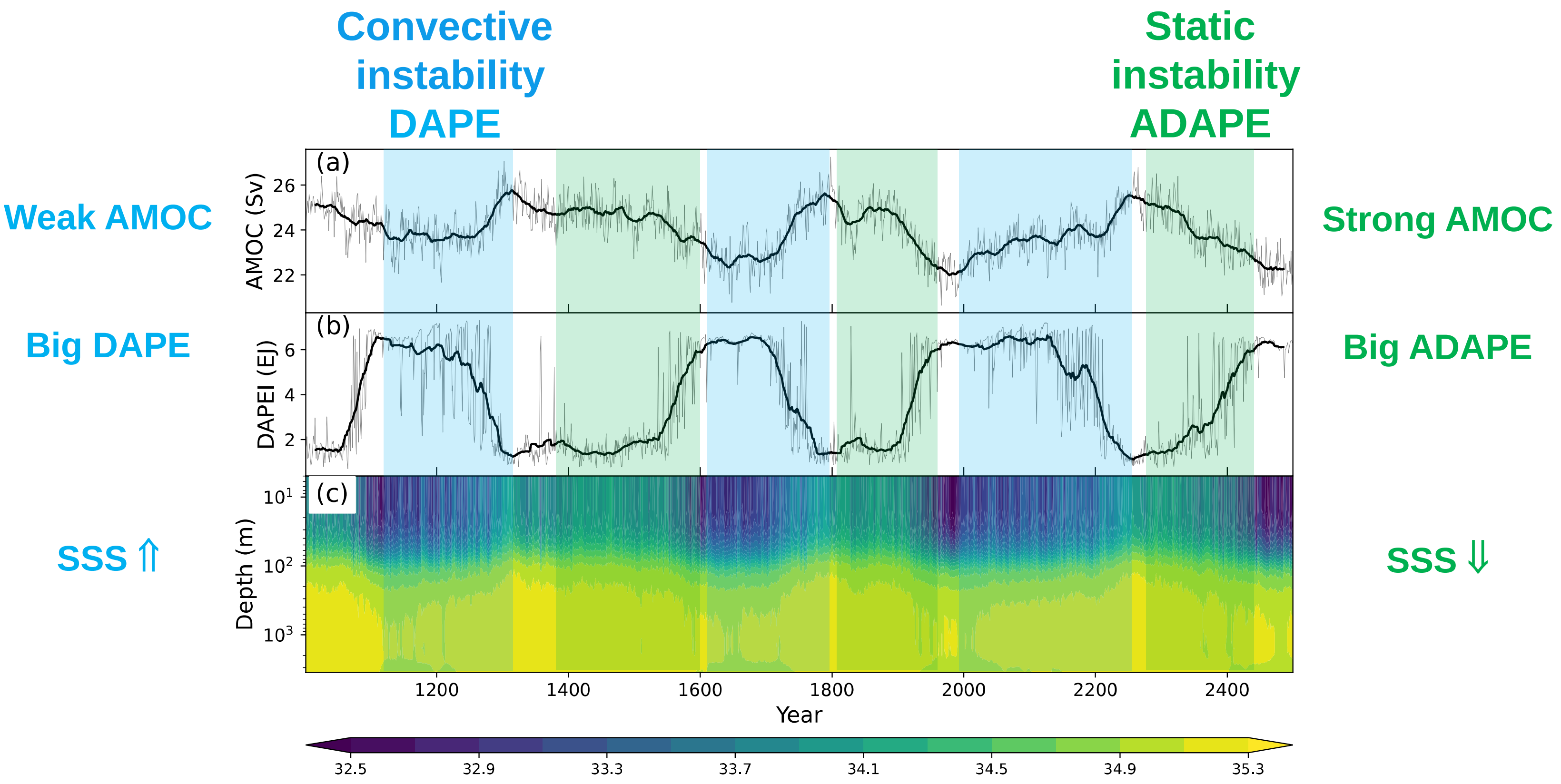
In comparison, the classic APE is defined as

$$APE = \iiint -\frac{g\rho'^2}{2}\left(\frac{\partial\bar{\rho}}{\partial z}\right)^{-1} dx dy dz,$$

where $\partial\bar{\rho}/\partial z$ is the horizontal mean of the vertical density gradient.

FUDAN UNIVERSITY

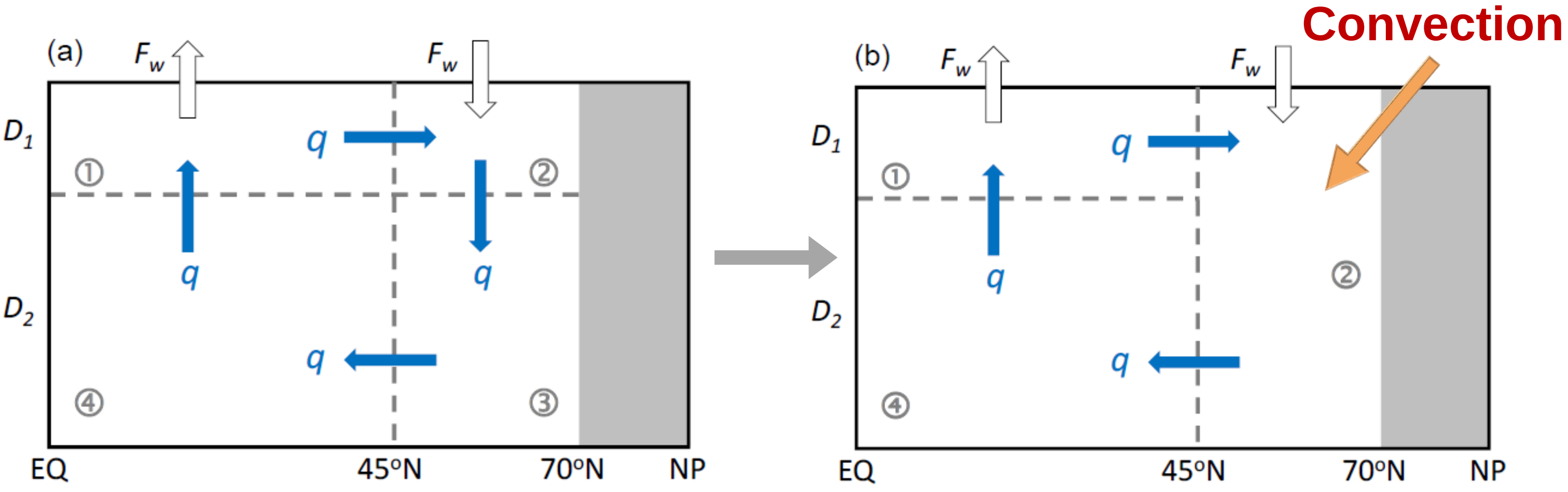
AMOC, DAPE and Upper Salinity in CESM



Li and Yang (2021)

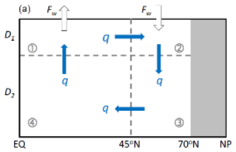
One Hemisphere Box Model

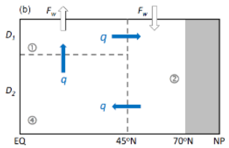
$$|S_2 - S_3| > S_b \Rightarrow \begin{cases} S_2 - S_3 > S_b^+ , & \textit{Static instability} \\ S_2 - S_3 < S_b^- , & \textit{Convective instability} \end{cases}$$



Li and Yang (2021)

One Hemisphere Box Model





$$V_1\dot{S}'_1 = q'(\bar{S}_4 - \bar{S}_1) + \bar{q}(S'_4 - S'_1)$$

$$V_2\dot{S}'_2 = q'(\bar{S}_1 - \bar{S}_2) + \bar{q}(S'_1 - S'_2)$$

$$V_3\dot{S}'_3 = q'(\bar{S}_2 - \bar{S}_3) + \bar{q}(S'_2 - S'_3)$$

$$V_4\dot{S}'_4 = q'(\bar{S}_3 - \bar{S}_4) + \bar{q}(S'_3 - S'_4)$$

$$\Delta\rho' = \rho_0\beta[\delta(S'_2 - S'_1) + (1-\delta)(S'_3 - S'_4)], \text{ and } \delta = \frac{V_1}{V_1+V_4} = \frac{V_2}{V_2+V_3} = \frac{D_1}{D}$$

$$V_1\dot{S}'_1 = q'(\bar{S}_4 - \bar{S}_1) + \bar{q}(S'_4 - S'_1)$$

$$V_2\dot{S}'_2 = q'(\bar{S}_1 - \bar{S}_2) + \bar{q}(S'_1 - S'_2)$$

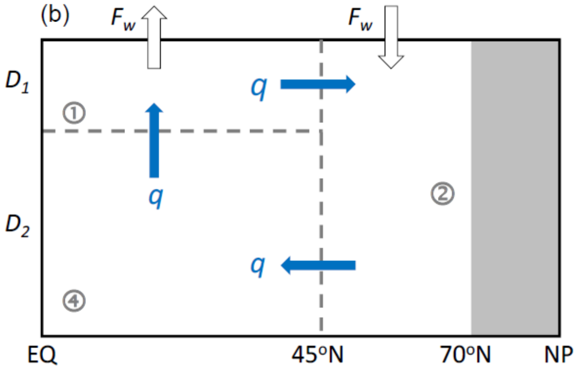
$$V_4\dot{S}'_4 = q'(\bar{S}_2 - \bar{S}_4) + \bar{q}(S'_2 - S'_4)$$

$$V_1S'_1 + V_2S'_2 + V_4S'_4 = constant$$

$$q' = \lambda\Delta\rho' = \lambda\rho_0\beta[S'_2 - \delta S'_1 - (1-\delta)S'_4], \text{ and } \delta = \frac{V_1}{V_1+V_4} = \frac{D_1}{D}$$

Li and Yang (2021)

Theorical Solution to 3-Box Model



Li and Yang (2021)

$$\omega = \frac{1}{2}\left[(C_2M - C_3) \pm \sqrt{(C_2M - C_3)^2 - 4C_2C_4(1-M)}\right]$$

where $C_1 = \frac{1}{\delta_1} + \frac{1}{\delta_2}$, $C_2 = \frac{1}{\delta_1\delta_2}$, $C_3 = \frac{1}{\delta_1} + \frac{1}{\delta_2} + \frac{1}{\delta_4}$, and $C_4 = \frac{1}{\delta_4}$.

Based on (A5), the essential stability condition for the system is

$$M \le \min\left(\frac{C_3}{C_2},\ 1\right)$$

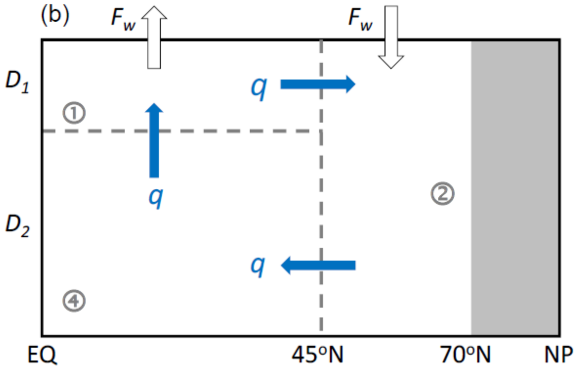
and the oscillation condition of the system is

$$M_1 < M < \min(M_2,\ 1)$$

where $M_{1,2} = \frac{C_3 - 2C_4}{C_2} \pm \frac{2}{C_2}\sqrt{C_4^2 + C_4(C_2 - C_3)}$. Thus, $\lambda_{1,2} = \overline{q}M_{1,2}/\rho_n$.

FUDAN UNIVERSITY

Stability Condition for 3-Box Model

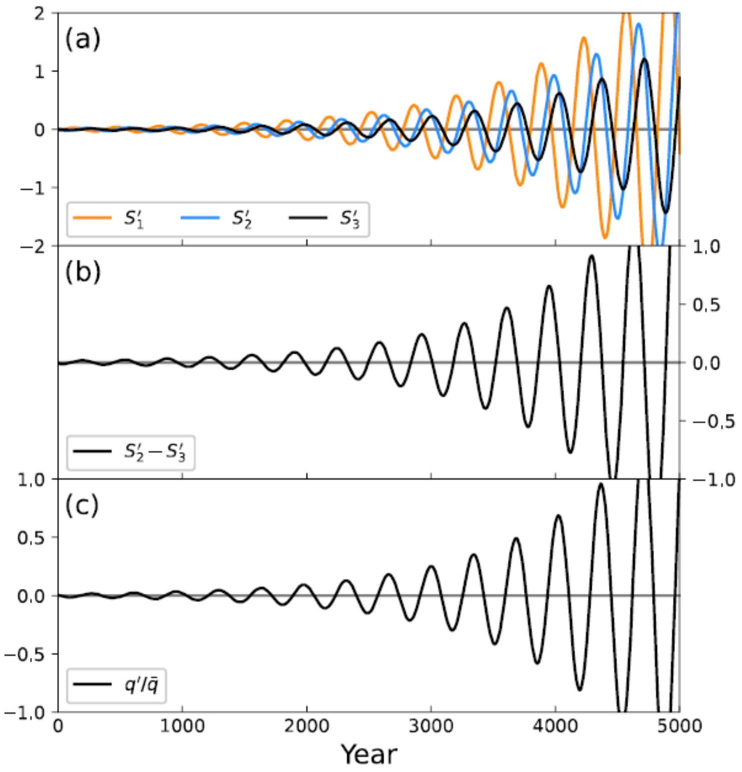


$$\lambda \leq \lambda_C \equiv \frac{\bar{q}^2}{\rho_0 \beta F_w} \frac{(V_1+V_4)(V_1V_2+V_2V_4+V_1V_4)}{V_1V_4(V_1+V_2+V_4)}$$

Here, λ_C is defined as the critical value to the linear closure parameter λ, which is determined by mean THC strength $\bar{q}$, the atmosphere moisture flux F_w as well as the basin geometry V_i. This parameter implies the complexity of oscillation behaviors in reality: at the multi-centennial timescale, whether an oscillation mode can be identified from paleoclimatic proxy data is full of uncertainty.

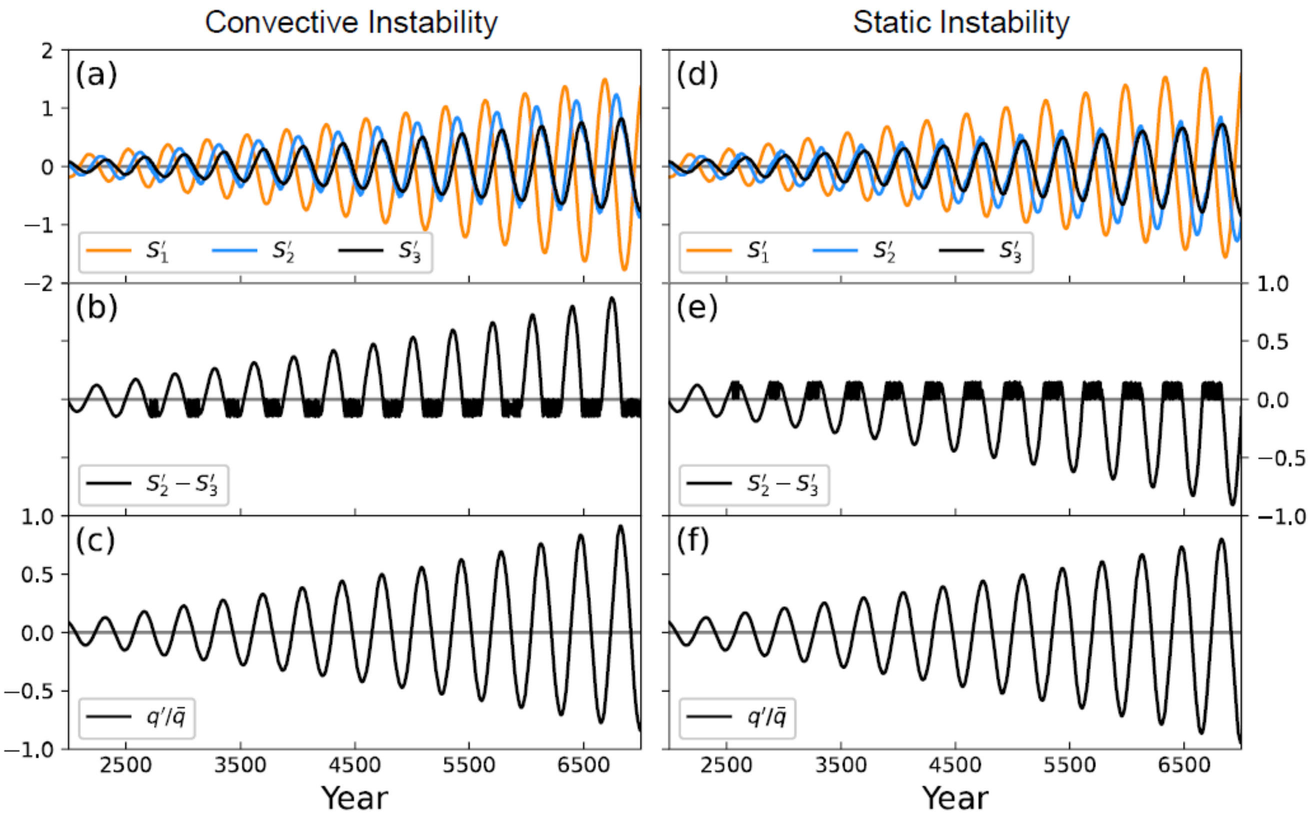
Li and Yang (2021)

Unstable Oscillation without Convection



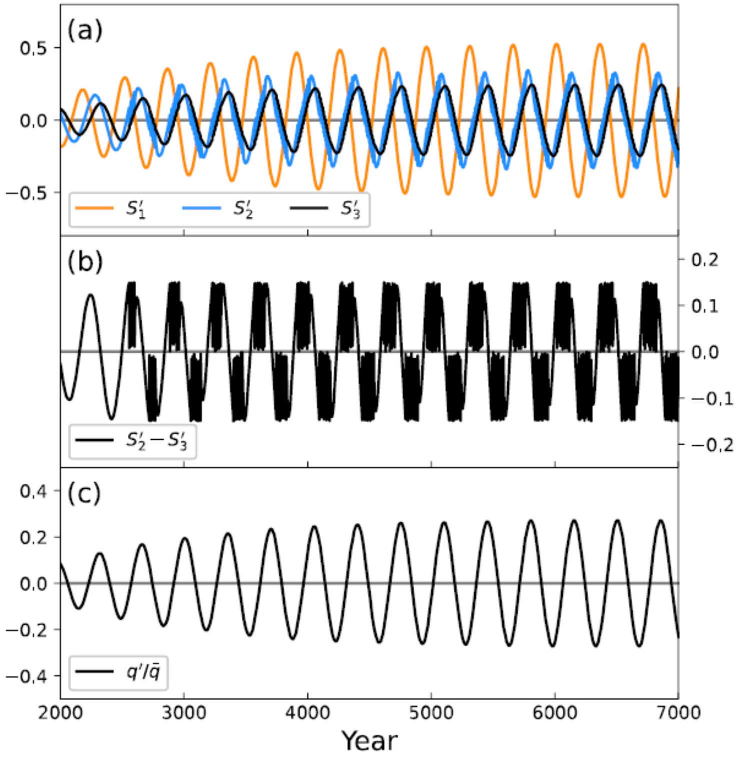
Li and Yang (2021)

Unstable Oscillation with *One* Convection



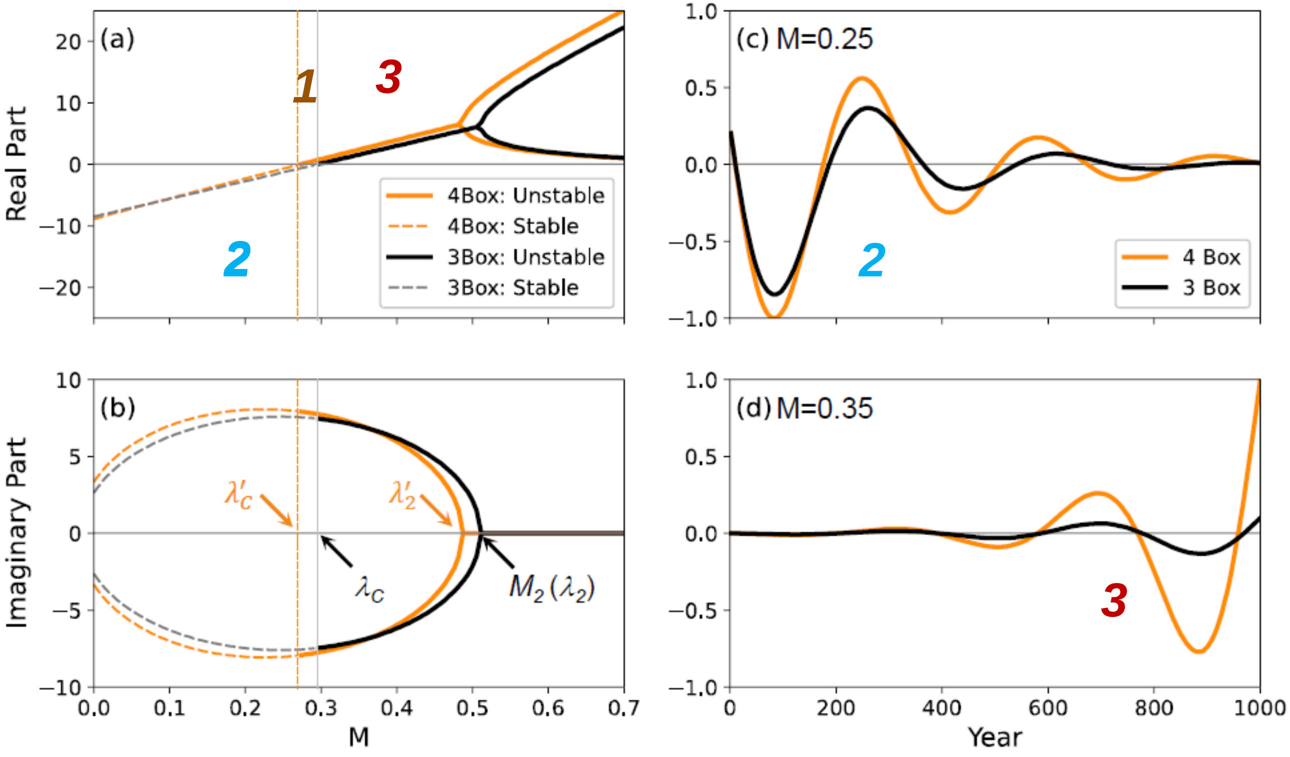
Li and Yang (2021)

Self-Sustained Oscillation with Convection



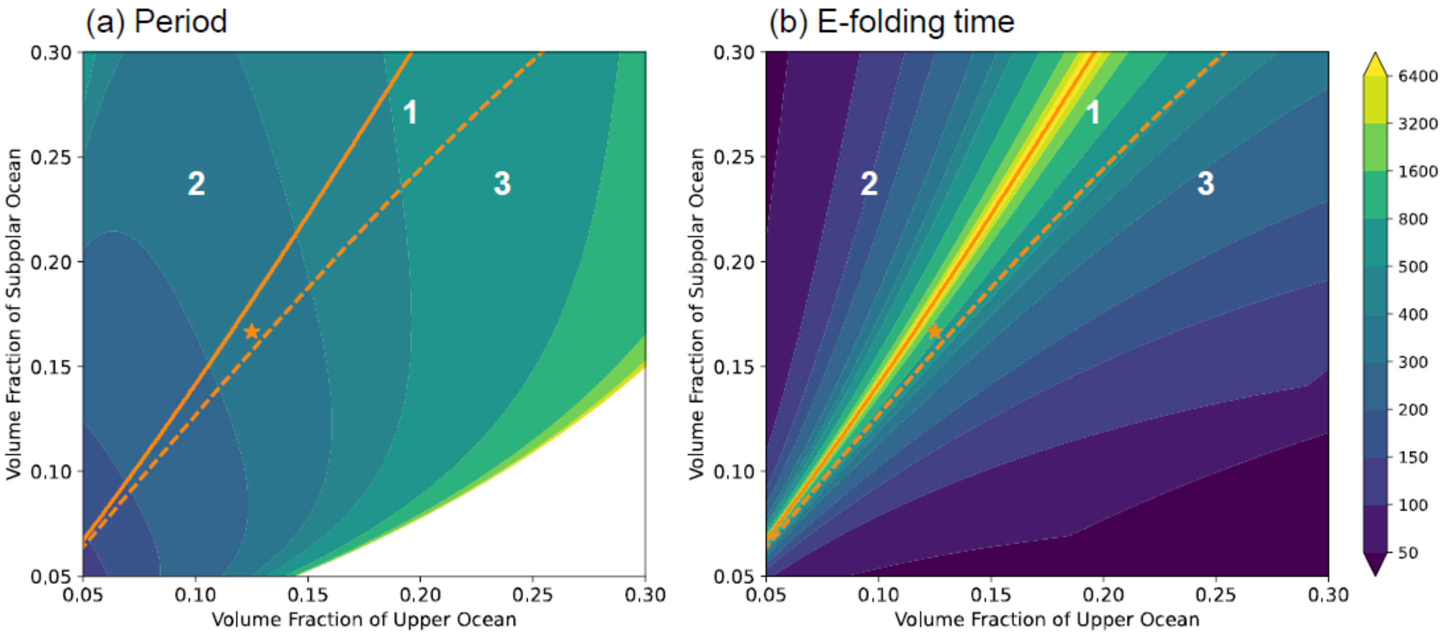
Li and Yang (2021)

Self-Sustained Oscillation with Convection



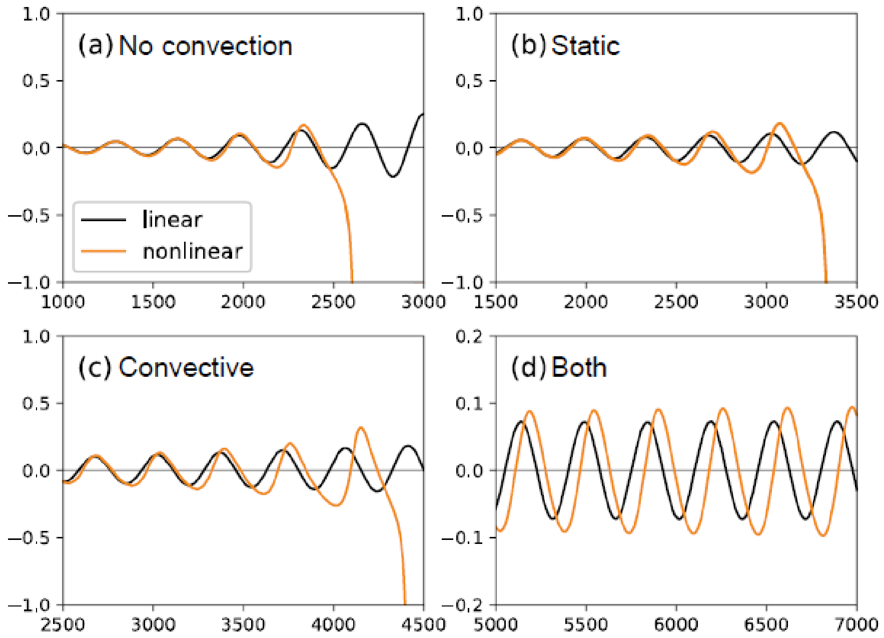
Li and Yang (2021)

Self-Sustained Oscillation in Depth Space



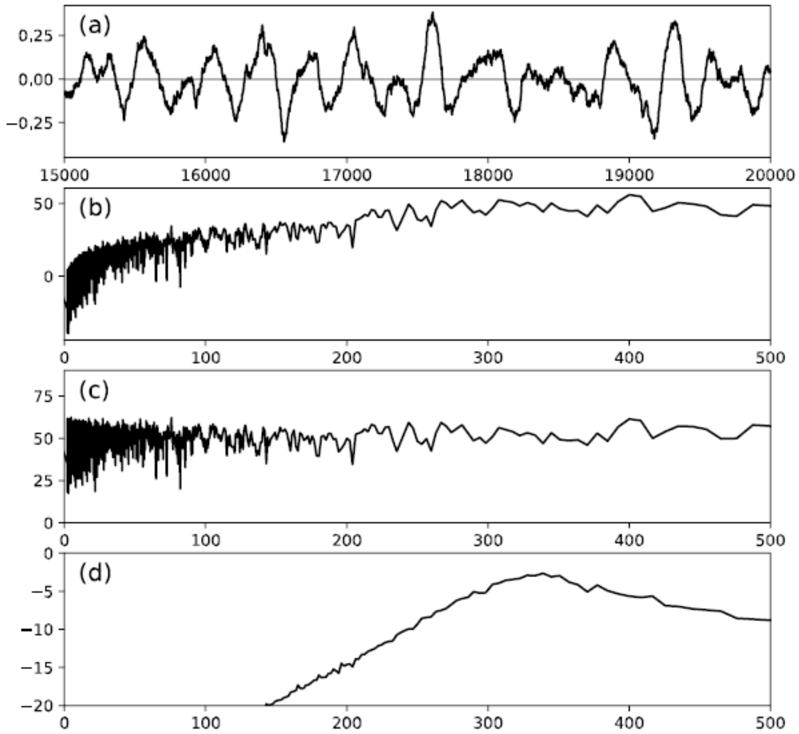
Li and Yang (2021)

Nonlinearity: Self-Sustained Oscillation



Li and Yang (2021)

Self-Sustained Oscillation under Stochastic Forcing

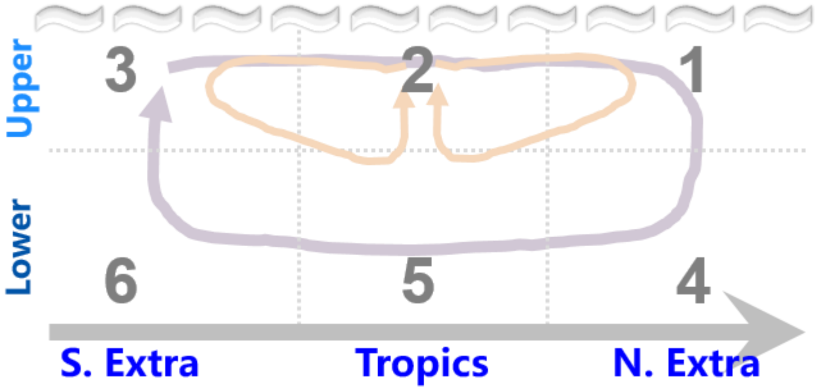


Li and Yang (2021)

FUDAN UNIVERSITY

6-Box Model for Two Hemispheres

Symmetric WDC and Global THC



6 temperature + 6 salinity = 12 equations

Shi and Yang (2020)

Eigen Modes in a 6-Box Model

$$\frac{\partial}{\partial t}\begin{pmatrix}T\\S\end{pmatrix} = M\begin{pmatrix}T\\S\end{pmatrix}$$

M: 12x12 matrix ➔

12 Eigen modes

Two oscillation modes

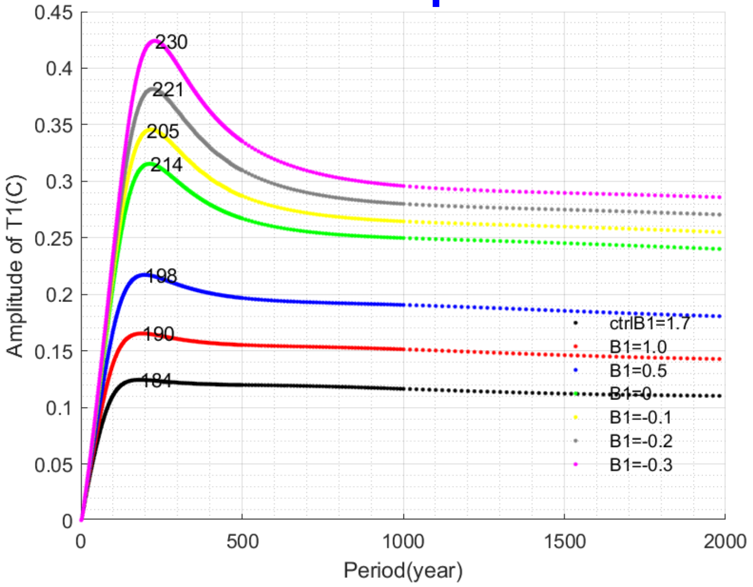
CTRL	B1=0.5	B1=0	B1=-0.3
0.6530	0.8406	1.0160	1.1994
183年	193年	205年	221年
-6.5 -14.3 -35.1 -131.4+202.0i -131.4-202.0i -261.9 -3281.3 Nan -1187+7341i -1187-7341i -1044+1543i -1044-1543i	-8 -14 -42 -187+224i -187-224i -376 -4522 Nan -1685+11791i -1685-11791i -1473+2183i -1473-2183i	-10 -13 -46 -246+242i -246-242i -508 -5819 Nan -2242+18925i -2242-18925i -1948+2892i -1948-2892i	-12+92i -12-92i -50 -310+258i -310-258i -674 Nan -7353 -2916+31770i -2916-31770i -2522+3745i -2522-3745i
0.6789	0.6756	0.6754	0.6722

Shi and Yang (2021)

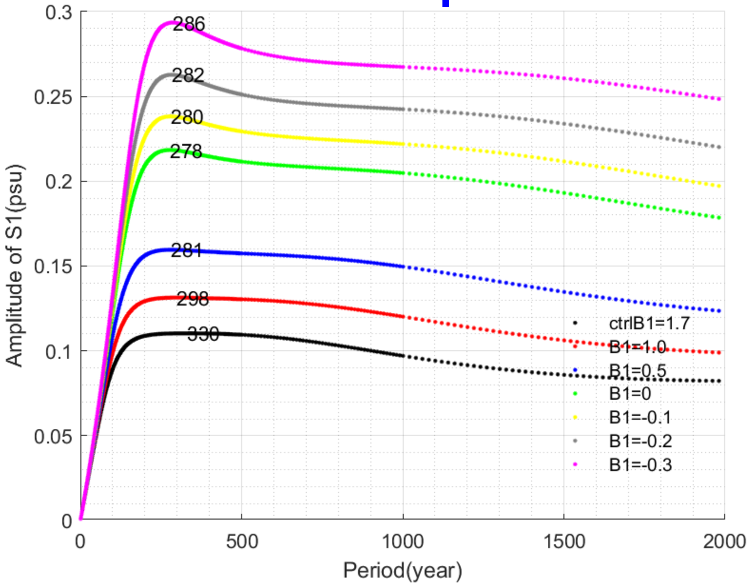
FUDAN UNIVERSITY

Can be easily excited by random forcing!

N. Extratropical T1



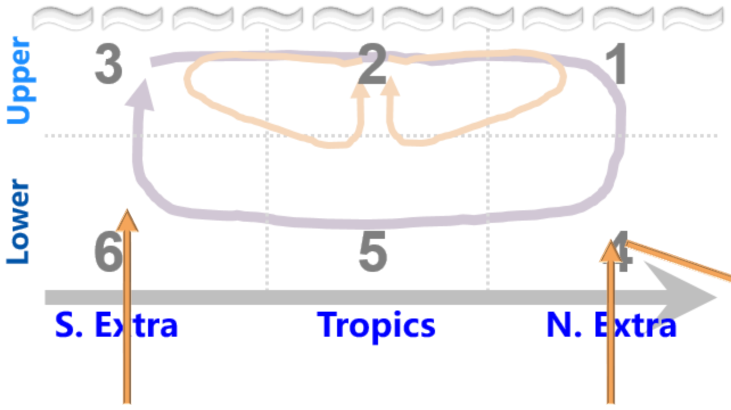
N. Extratropical S1



Shi and Yang (2021)

Millennial Mode in 6-Box Model

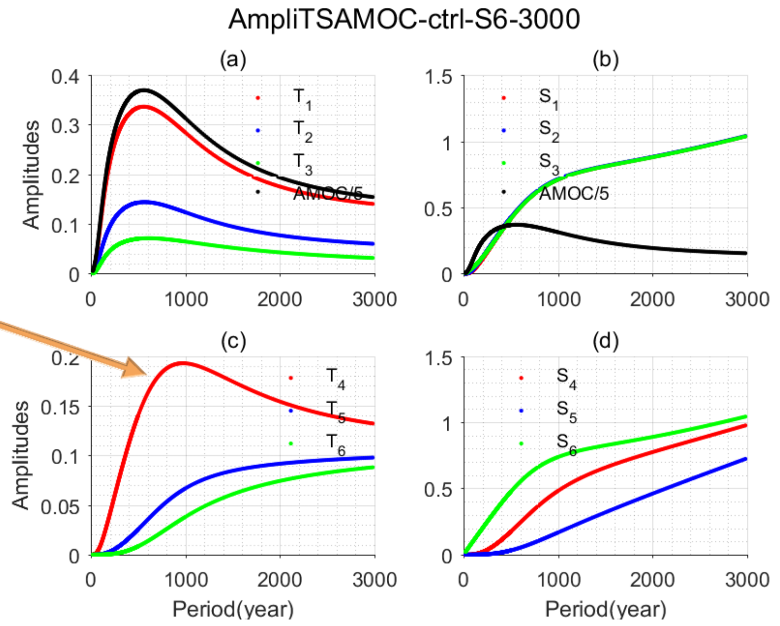
Can be *only* excited by *deep SO* perturbation *(??)*



Perturbation here

Response here

T6 ➔ S4; S6➔T4



Shi and Yang (2021)

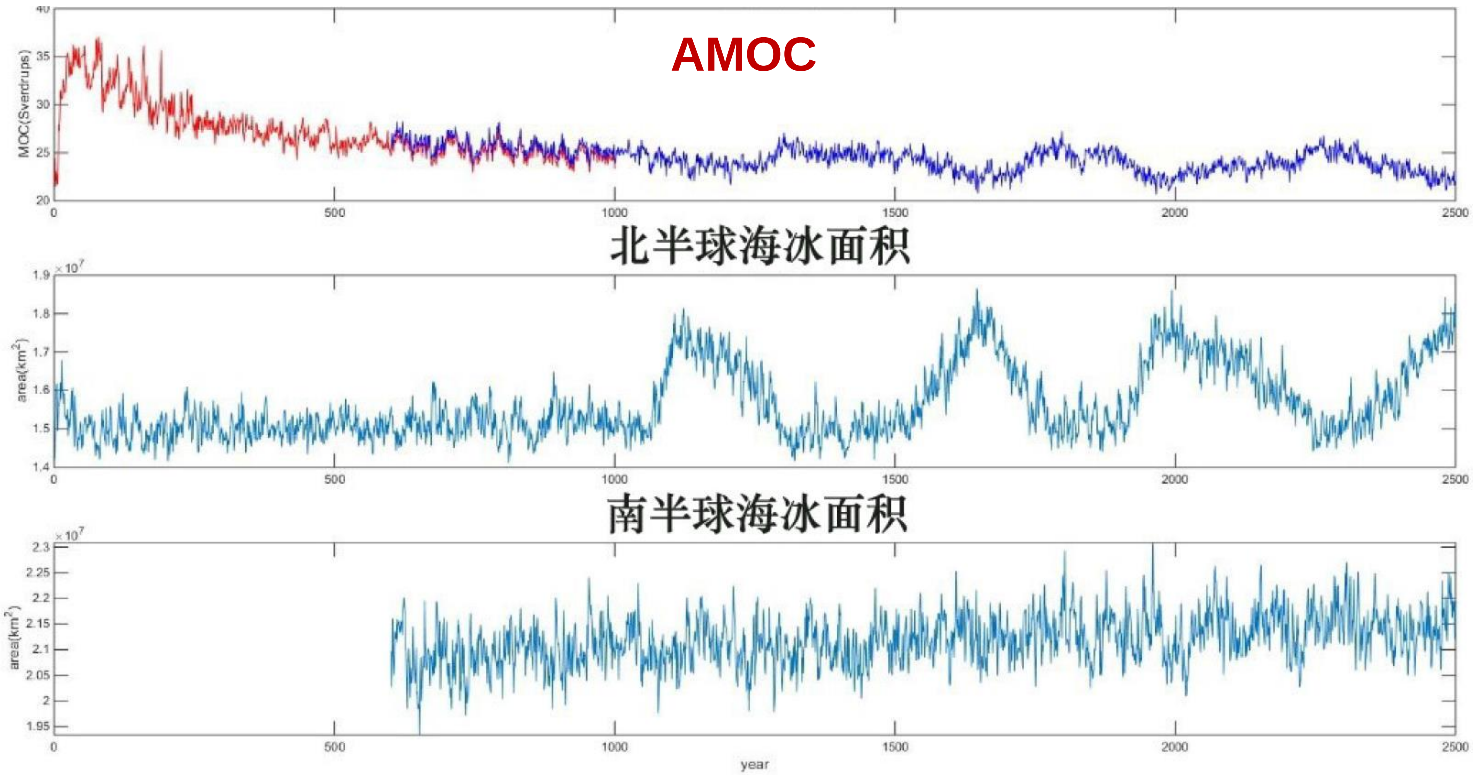
FUDAN UNIVERSITY

Contents

1. Common Knowledge
2. Motivation
3. Observation
4. Theory
5. **Modeling**

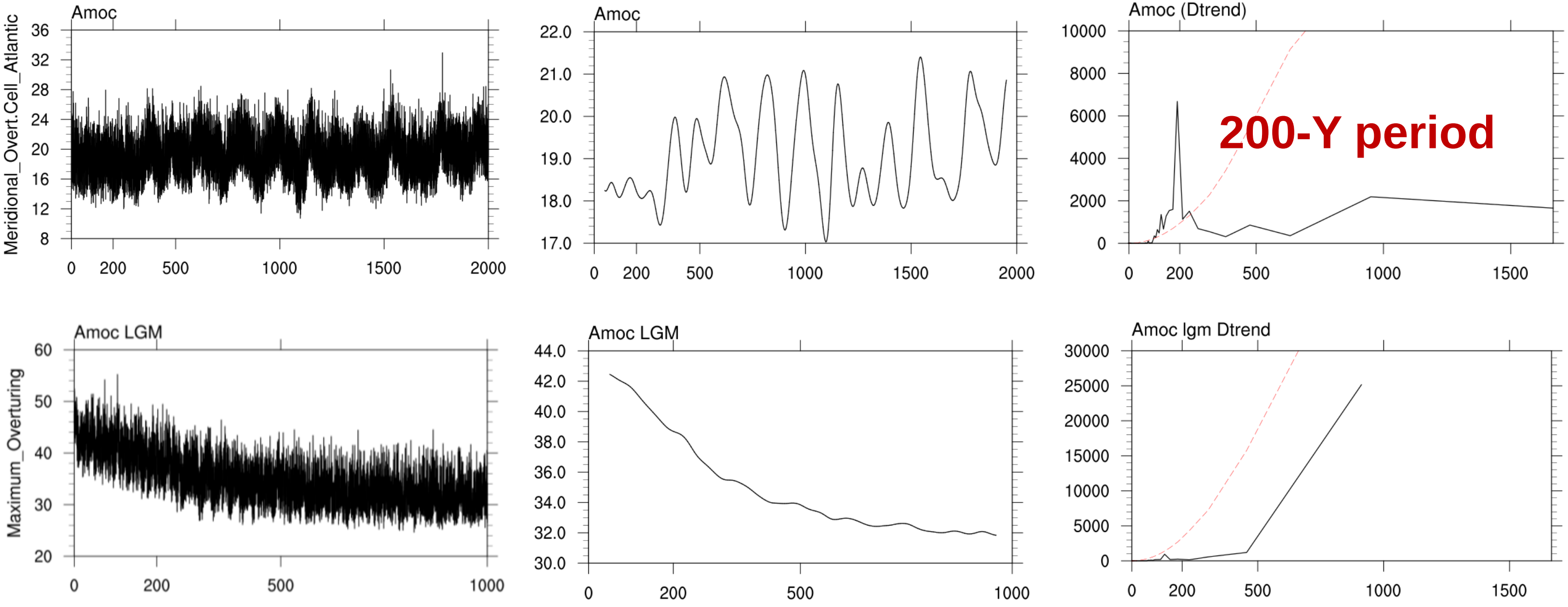
Centennial Oscillation in CESM2.0

2500 Years period PI control experiment



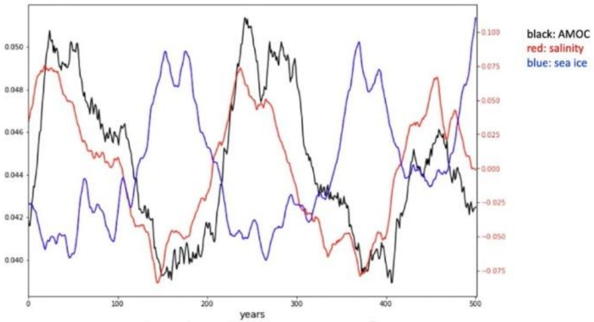
Centennial Oscillation in EC-Earth3 Model

2000 Years period PI control experiment

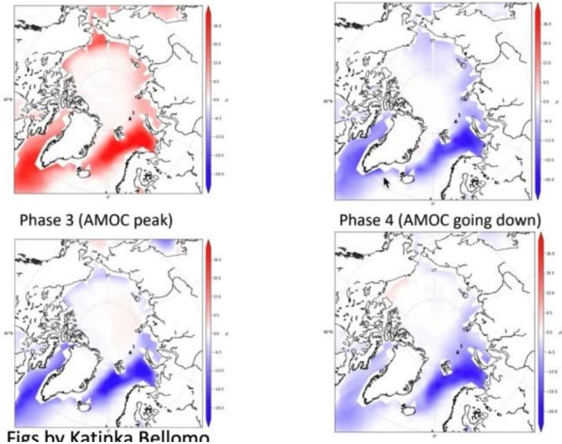


Zhang et al. (2021)

Exists also in Other Models …



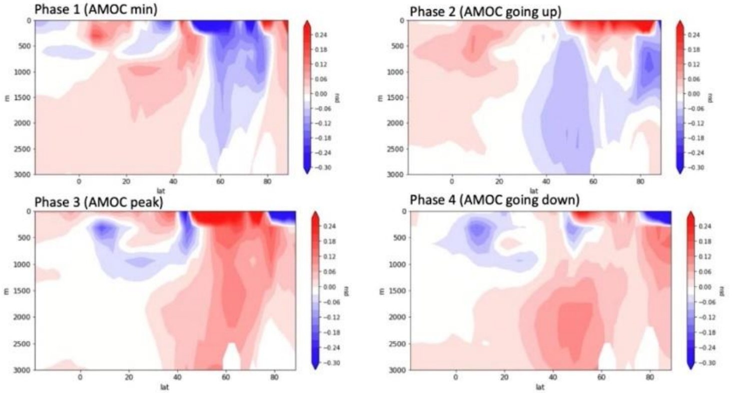
Sea Ice Conc. anomaly



Figs by Katinka Bellomo

An example of topic of possibly broader interest: Oscillations in PI EC-Earth simulations

Salinity anomaly



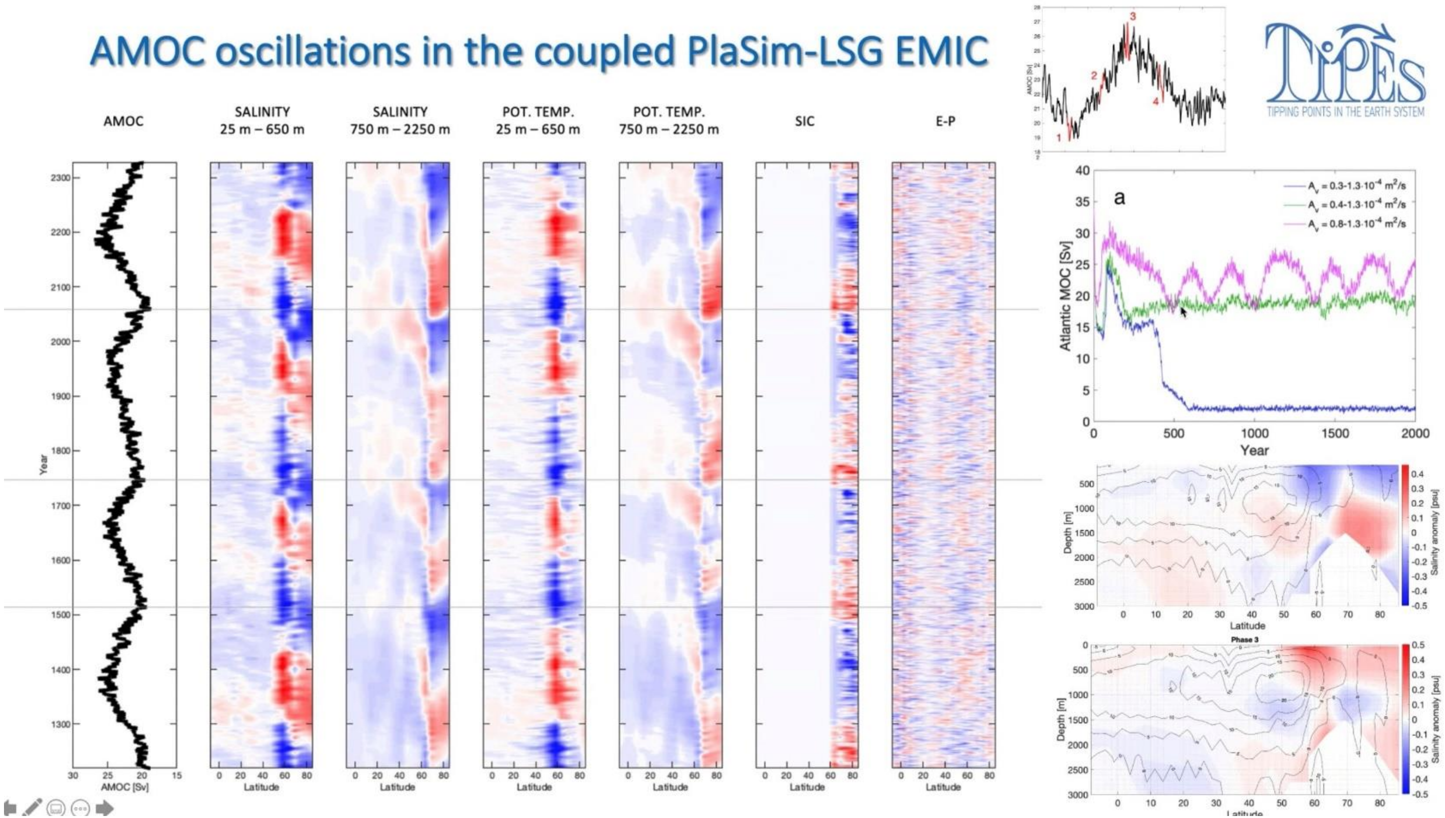
An understanding of these oscillations has implications for:

- better tuning and creation of equilibrated ICs of the model
- Interdecadal variability in EC-Earth
- Paleoclimate and tipping points
- A better understanding of mechanisms associated with AMOC decrease in projections

Jost von Hardenberg (2021) Personal communication

FUDAN UNIVERSITY

Exists also in Other Models …



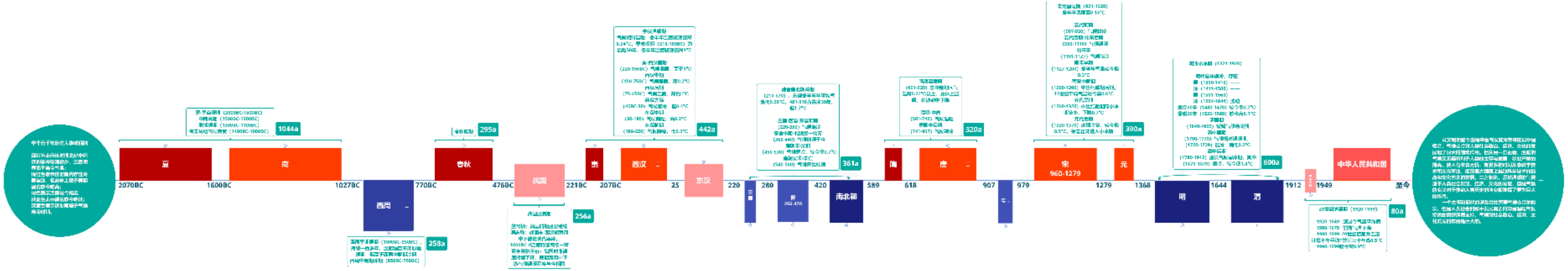
Angeloni et al. (2021)

Centennial-Millennial Variabilities

Observations → **Theory** ↔ **Modeling**

Confirmed

Internal Eigen Mode 200-1000y ↔ **Ocean-alone Or Coupled**



Centennial-Millennial Climate Variability

A 10-year long way …

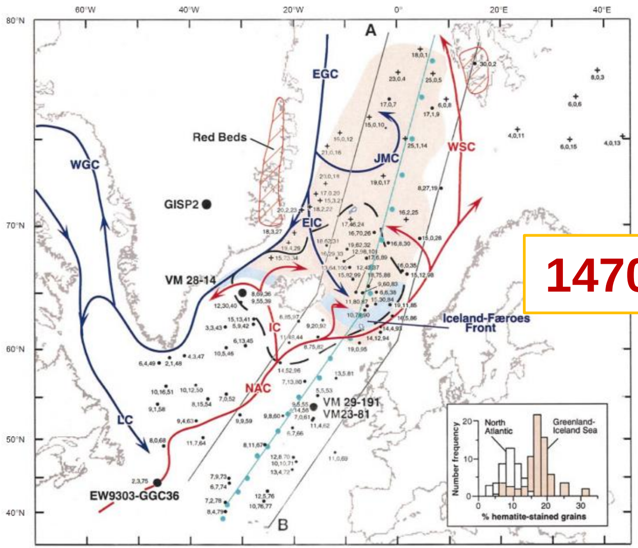
- Eigen Mode: likely
- Physics: can be disclosed
- Southern ocean matters for millennial
- Salinity change (freshwater) matters
- Advection-feedback process dominates

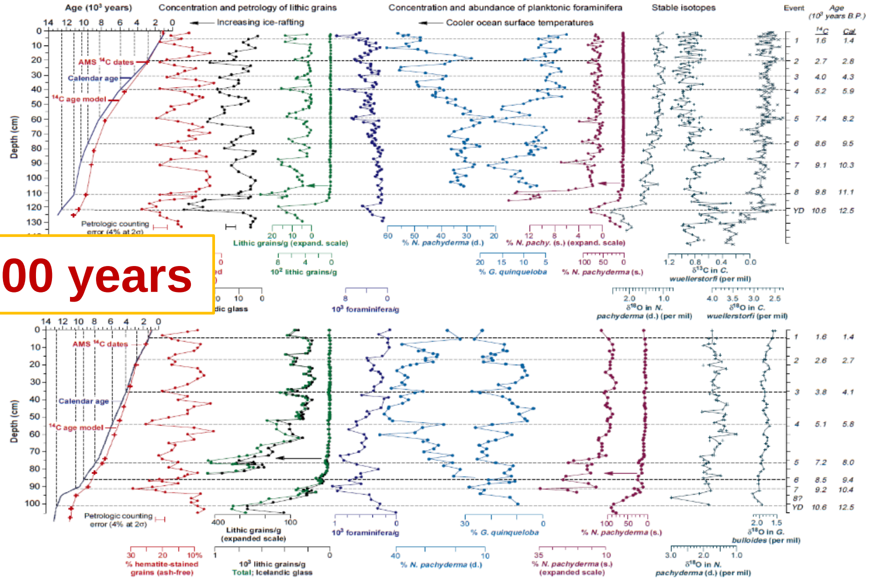
LaCOAS
北京大学气候与海-气实验室

谢 谢

Millennial Variability- Bond Cycle: ~1500 (?) Years

Bond and Lotti (1995), Science; **Bond** et al. (1997), Science; **Bond** et al. (1999) …



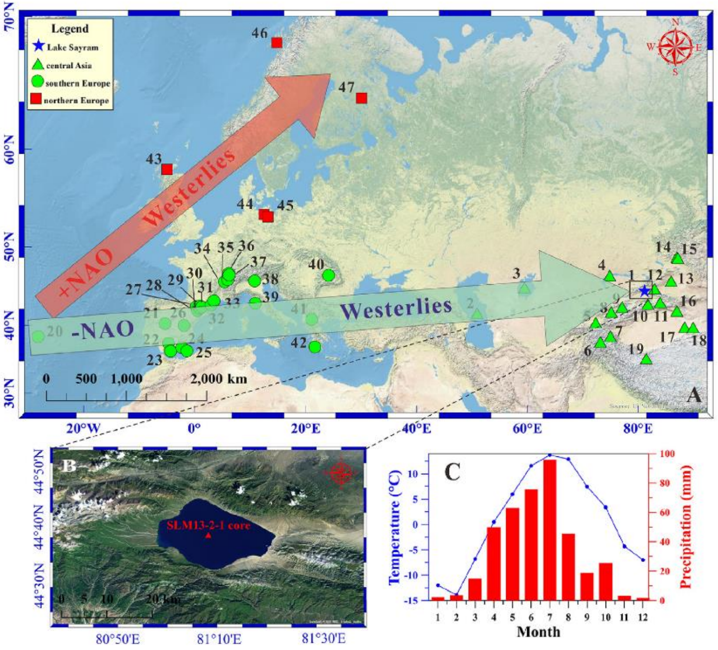


1470±500 years

Pacings of the Holocene events and of abrupt climate shifts during the last glaciation statistically the same; The Holocene events the most recent manifestation of a pervasive millennial-scale climate cycle, independent on the glacial-interglacial climate state. Amplification of the cycle during the last glaciation linked to the North Atlantic's thermohaline circulation.

FUDAN UNIVERSITY

Millennial Variability- Bond Cycle: *~1500 (?)* Years



Lan et al. (2020)

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Late Holocene hydroclimatic variation in central Asia and its response to mid-latitude Westerlies and solar irradiance

Jianghu Lan [a, b, **], Jin Zhang [c, *], Peng Cheng [a, b], Xiaolin Ma [a, b], Li Ai [a, b], Sakonvan Chawchai [d], Kang'en Zhou [a, e], Tianli Wang [a, e], Keke Yu [f], Enguo Sheng [g], Shugang Kang [a, b], Jingjie Zang [a], Dongna Yan [a, e], Yaqin Wang [a], Liangcheng Tan [a, b, h], Hai Xu [c, b]

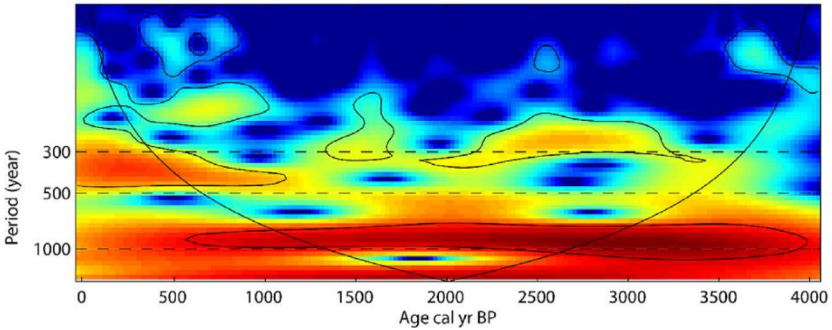
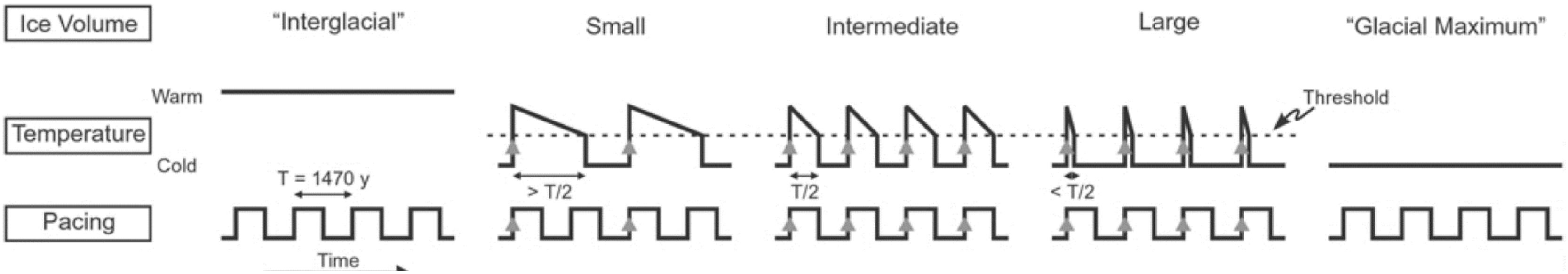


Fig. 7. Evolutive spectral analysis of hydroclimatic variations recorded by $\delta^{13}C_{carb}$ from Lake Sayram over the past 4000 years. Black lines indicate >90% significance levels.

Millennial Variability- Bond Cycle: *~1500 (?)* Years

Dansgaard-Oeschger interstadials ➔ 1470-year climate cycle



1470-y pacing cycle as function of continental ice volume.

Actual shape of the pacing cycle (bottom row) is unimportant because this signal acts only as trigger (vertical arrowheads) for Dansgaard-Oeschger type temperature fluctuations (center row)

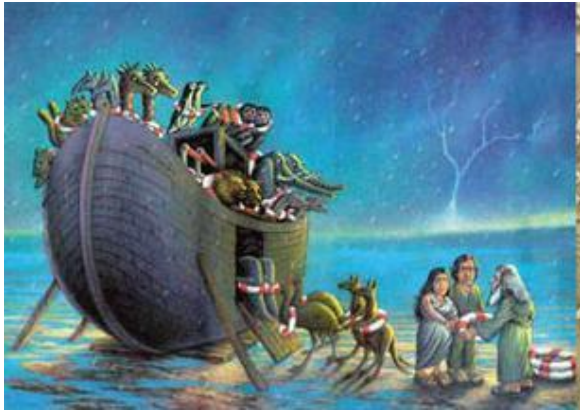
Michael Schulz (2002), GRL

FUDAN UNIVERSITY

Centennial-Millennial Variability: *Human Civilization (?)*

人类文明的兴衰史也与百年-千年的气候振荡有密切关系

诺亚方舟



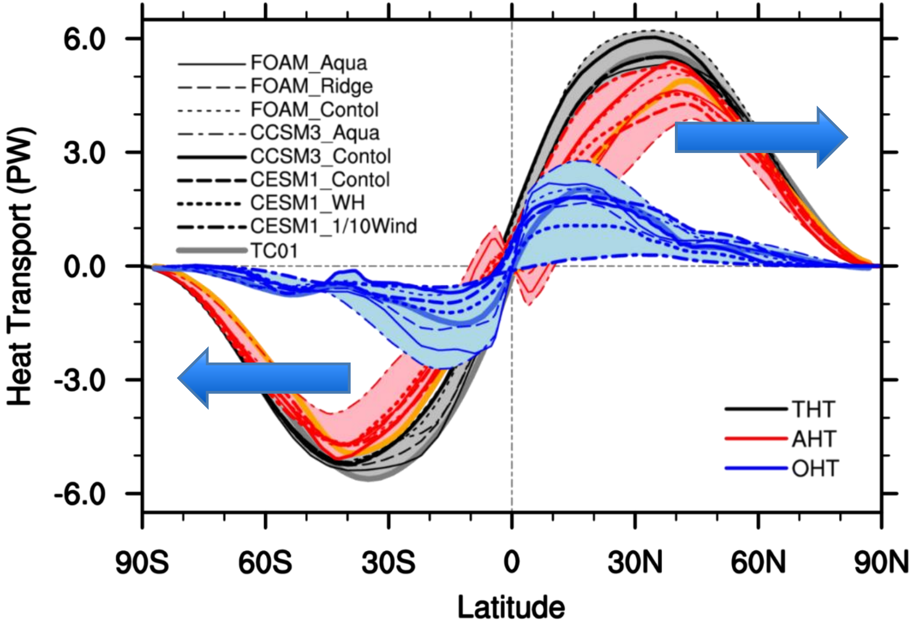
大禹治水

- 王绍武（2005a）：公元前2.2-2千年尼罗河文明、两河流域文明及印度河文明等等突然衰落发生在中纬度普遍变冷的气候背景中，是全新世进入大暖期以来的一次强冷事件
- 王绍武（2005b）：洪水➔干旱➔中华文明的诞生➔公元前2070年夏朝建立
- 王绍武和黄建斌（2006）：夏朝建立的基础“大禹治水”，气候干旱可能对“治水”成功产生了影响
- 王绍武等（2011）：距今6-4千年的五帝时代：湿润➔干旱；可能与热盐环流的突然减弱有关

FUDAN UNIVERSITY

Bjerknes Compensation (BJC)

A *Eigen Mode* of Coupled Ocean-Atmosphere System



Yang et al. (2015, 2016, 2017, 2018); Liu et al. (2016, 2019)

Bjerknes Compensation (BJC)

A *Eigen Mode* of Coupled Ocean-Atmosphere System

Robust and theoretically derived!

Climate Shift:

$$C_{R0} \equiv \frac{F_a'}{F_o'} = -\frac{1}{1+B/2\chi}$$

↕

Climate Variability:

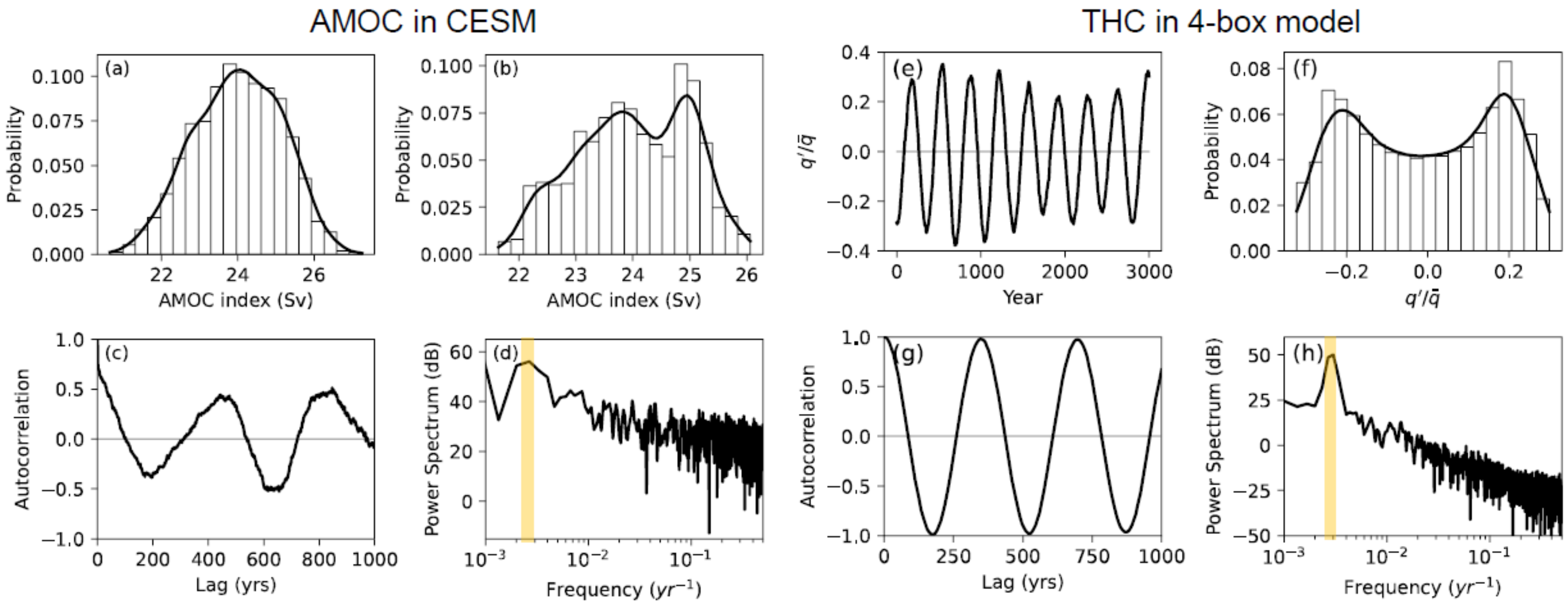
$$C_{Rp} \equiv \frac{F_a'}{F_o'} = r_\delta * C_{R0};\ r_\delta \equiv cos\delta = -\frac{F}{\sqrt{\omega^2+F^2}}$$

$$\boldsymbol{\omega \to 0 \ \Rightarrow\ r_\delta \to -1;\ C_{Rp} \asymp C_{R0}}$$

Yang et al. (2015, 2016, 2017, 2018); Liu et al. (2016, 2019)

FUDAN UNIVERSITY

Self-Sustained Oscillation in CESM?

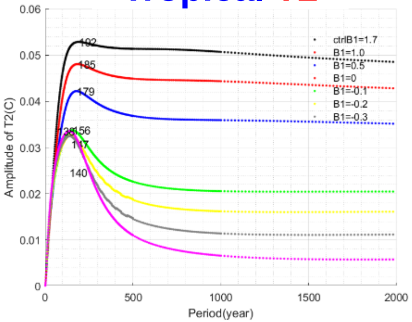


Li and Yang (2021)

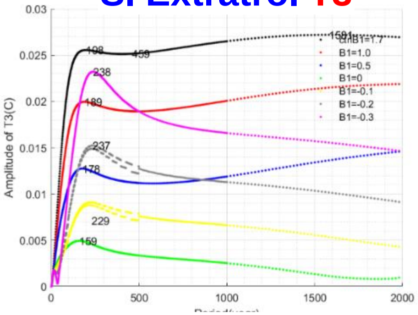
Multi-Centennial Mode

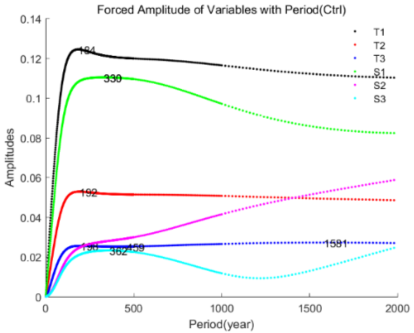
Can be easily excited by random forcing!

Tropical T2

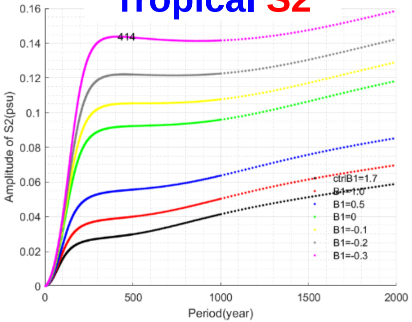


S. Extratro. T3

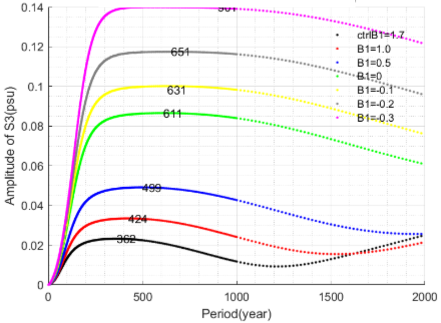


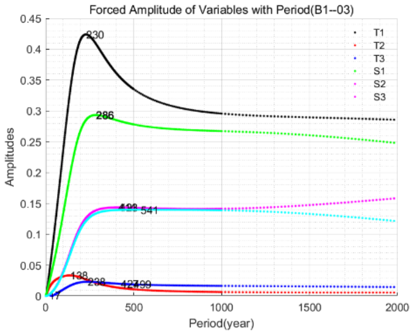


Tropical S2



S. Extratro. S3





Shi and Yang (2021)

FUDAN UNIVERSITY

Multi-Centennial Mode

Features:

- **Significant signal in *upper* ocean, *Northern* Hemisphere**
- **Also in *Tropics***
- **Self-sustained / Random forcing**

Shi and Yang (2021); Li and Yang (2021)

FUDAN UNIVERSITY

Millennial Mode in 6-Box Model

Determined by the *lower ocean depth*

D2=5000	CTRL	D2=3000	D2=2000	D2=1000
0.65	0.65	0.65	0.65	0.70
-6.53 -14.26 -35.07 -131.39+ 202.08i -131.39- 202.08i -264.70 -4101.71 nan -1484.22 + 9179.53i -1484.22 - 9179.53i -1283.99+ 2027.32i -1283.99 - 2027.32i	-6.5 -14.3 -35.1 -131.4+202.0i -131.4-202.0i -261.9 -3281.3 Nan -1187+7341i -1187-7341i -1044+1543i -1044-1543i	-6.53 -14.26 -35.07 -131.45+ 201.87i -131.45 - 201.87i -253.28 -2461.00 Nan -890.56 + 5500.67i -890.56 - 5500.67i -814.87 + 1075.65i -814.87 - 1075.65i	-6.53 -14.2 -35.07 -131.59 + 201.06i -131.59 - 201.06i -223.25 -1640.72 nan -593.74 + 3656.27i -593.74- 3656.27i -612.35 + 658.49i -612.35 - 658.49i	-6.53 -14.26 -35.07 -131.27+ 190.70i -131.27 - 190.70i -140.48 -820.67 nan -296.93 + 1797.81i -296.93 - 1797.81i -437.72+ 335.90i -437.72- 335.90i
0.6333	0.6789	0.7568	0.9299	1.3031

Shi and Yang (2021)