Bjerknes补偿：海气耦合系统本征模

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LaCOAS

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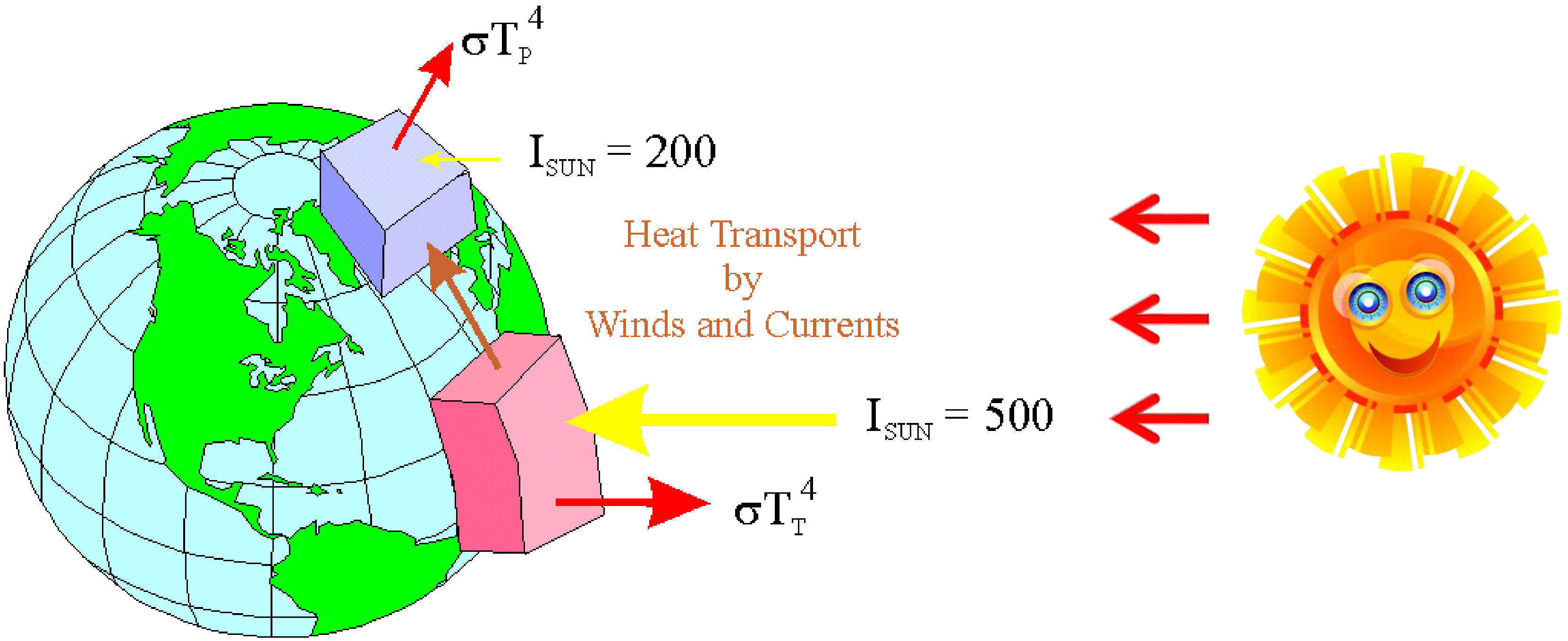
Outline

BJC: Out-of-phase changes in meridional OHT and AHT

- **Fundamentals**
- **Questions**
- **Hypothesis and Theory**
- **CGCM results**
- **Aquaplanet**
- **Summary**

Fundamentals



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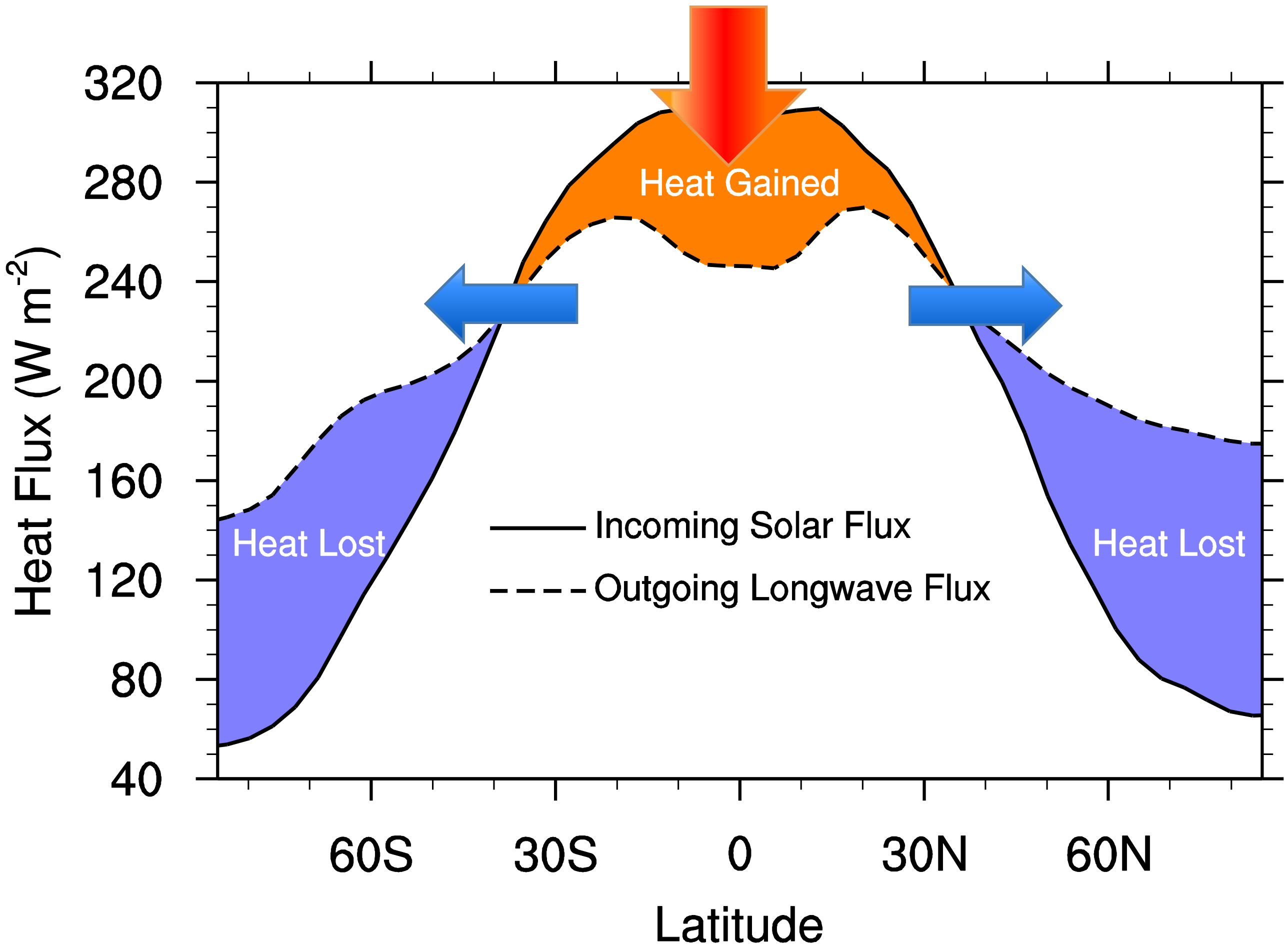
Heat Budget at the TOA



Energy

$$Energy = c_p T + L_v q + gz + \frac{(u^2 + v^2 + w^2)}{2}$$

- **Sensible Heat / Latent heat**
- **Potential energy / Kinetic energy**

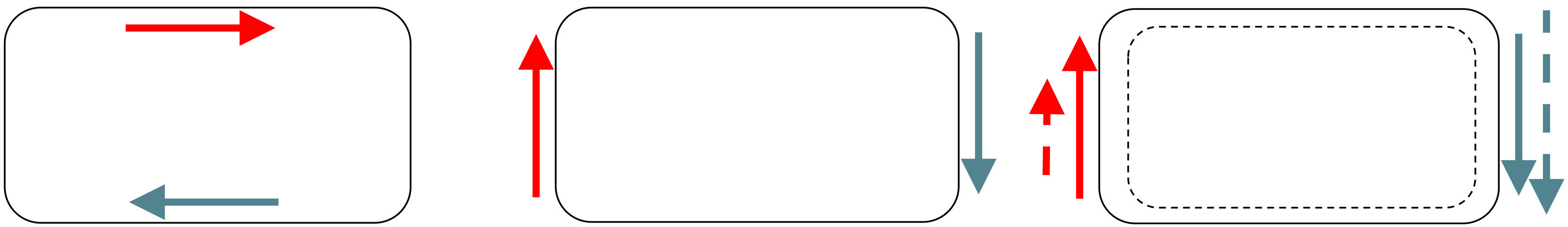
1. **Kinetic energy transport is small**
2. **In the ocean only sensible heat transport**

Fundamental Questions

Energy Transport Mechanisms

Energy multiply by meridional mass transport

$$F_E = \Psi \, C \, \Delta E$$



- Hadley Cell
- Ferrell Cell
- AMOC
- Wind-driven STC

- Monsoon Circulation
- Oceanic Gyres

Eddies:

- Standing Waves
- Transient Storms
- Instability Waves
- Gulf Stream Rings…

Fundamental Questions

Ocean Heat Transport Calculation

Temperature equation

$$\frac{\partial T}{\partial t}+\frac{\partial(u+u^*+u')T}{\partial x}+\frac{\partial(v+v^*+v')T}{\partial y}+\frac{\partial(w+w^*+w')T}{\partial z}=R(T)+D_V(T)+\frac{\partial Q}{\partial z}.$$

Zonal and Vertical Integration

$$\iiint \frac{\partial T}{\partial t}\,dxdydz+\iint (v+v^*+v')T\,dxdz=\iiint R(T)\,dxdydz+\iint Q_0\,dxdy,$$

Storage ↓ OHT_{vT} ↓ OHT_{diff} ↓ OHT_{HF}

OHT_{vT} → $OHT_{eul}+OHT_{bol}+OHT_{sbm}$

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Ocean Heat Transport Calculation

No Submesoscale Eddies — Equilibrium

$$OHT = OHT_{vT} = OHT_{eul} + \cancel{OHT_{bol}} + \cancel{OHT_{sbm}} = OHT_{HF} + \cancel{OHT_{diff}} - \cancel{Storage}$$

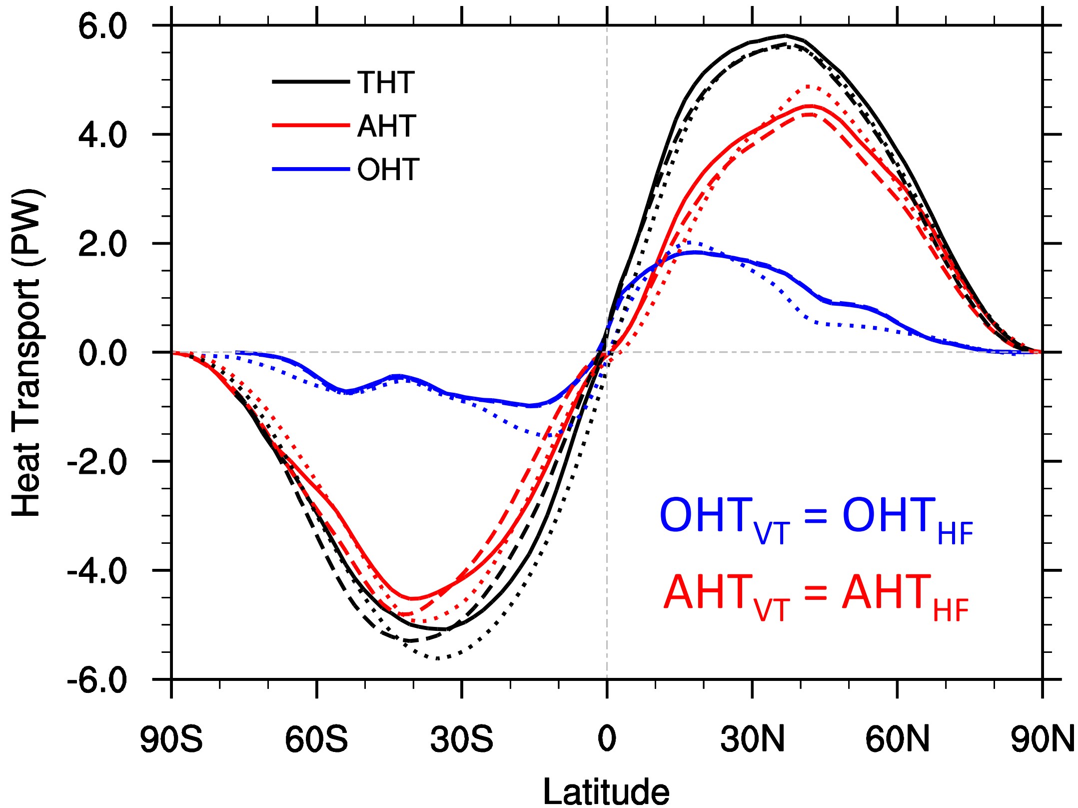
No Mesoscale Eddies — No Mixing

$$OHT_{vT} \approx OHT_{HF} \approx OHT_{eul}$$

Calculation in CGCM

- **Real** heat transport by Atmosphere and Ocean
- OHT components:
  - Basin contribution / Wind-driven / Thermohaline
- AHT components:
  - Dry air VS. Water vapor / Mean VS. Eddies

Meridional Heat Transport



Dotted lines from Obs. Heat Flux (Trenberth and Caron, 2001)

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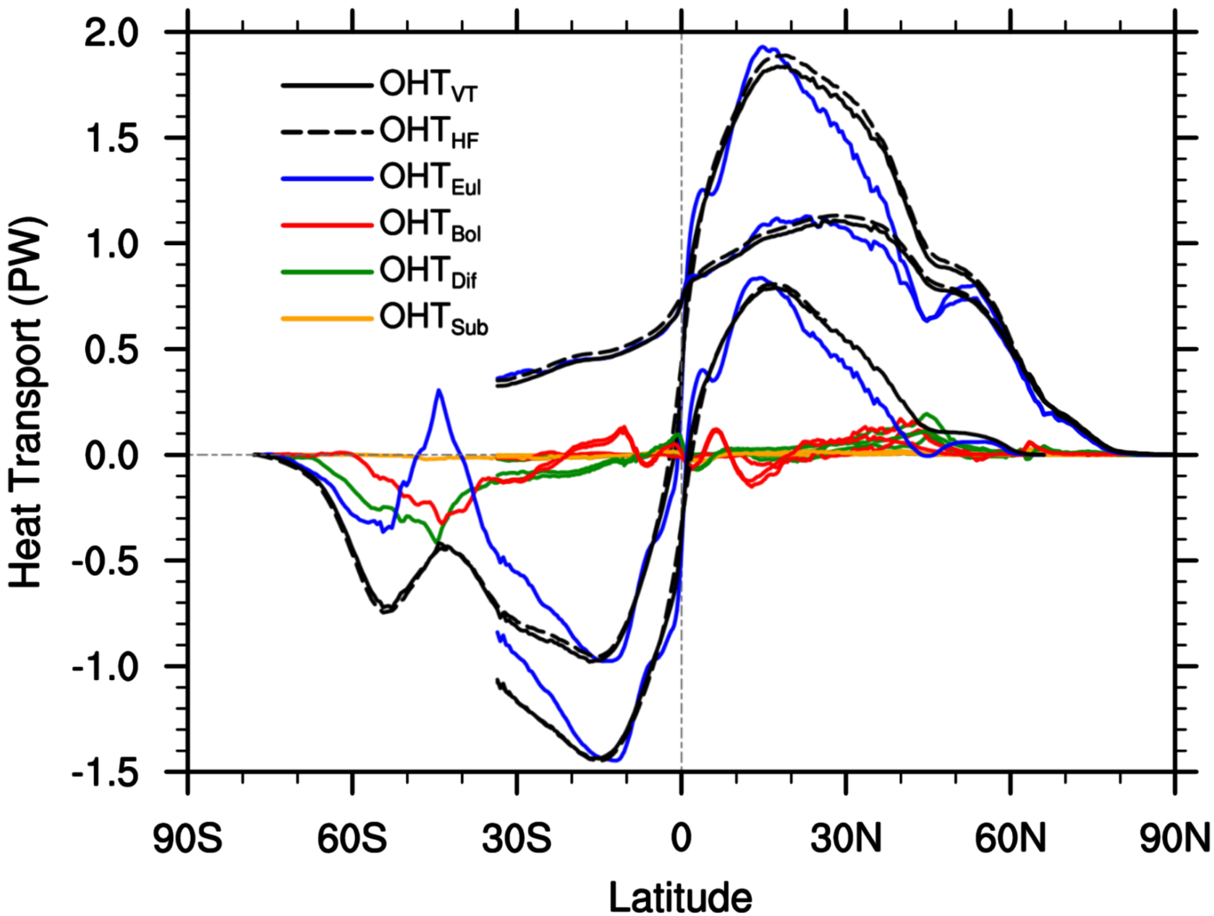
Decomposing OHT_{VT}

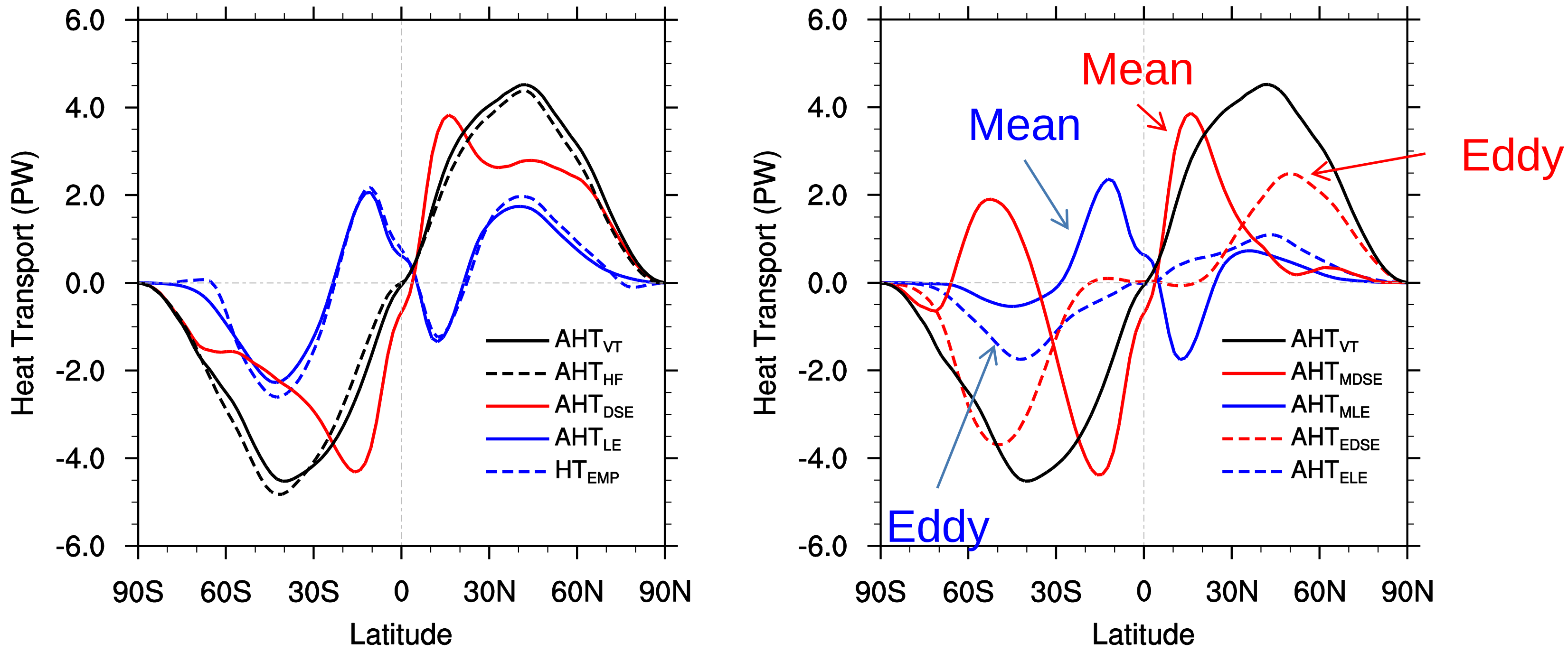


Consistency between OHT_{VT} and OHT_{HF}

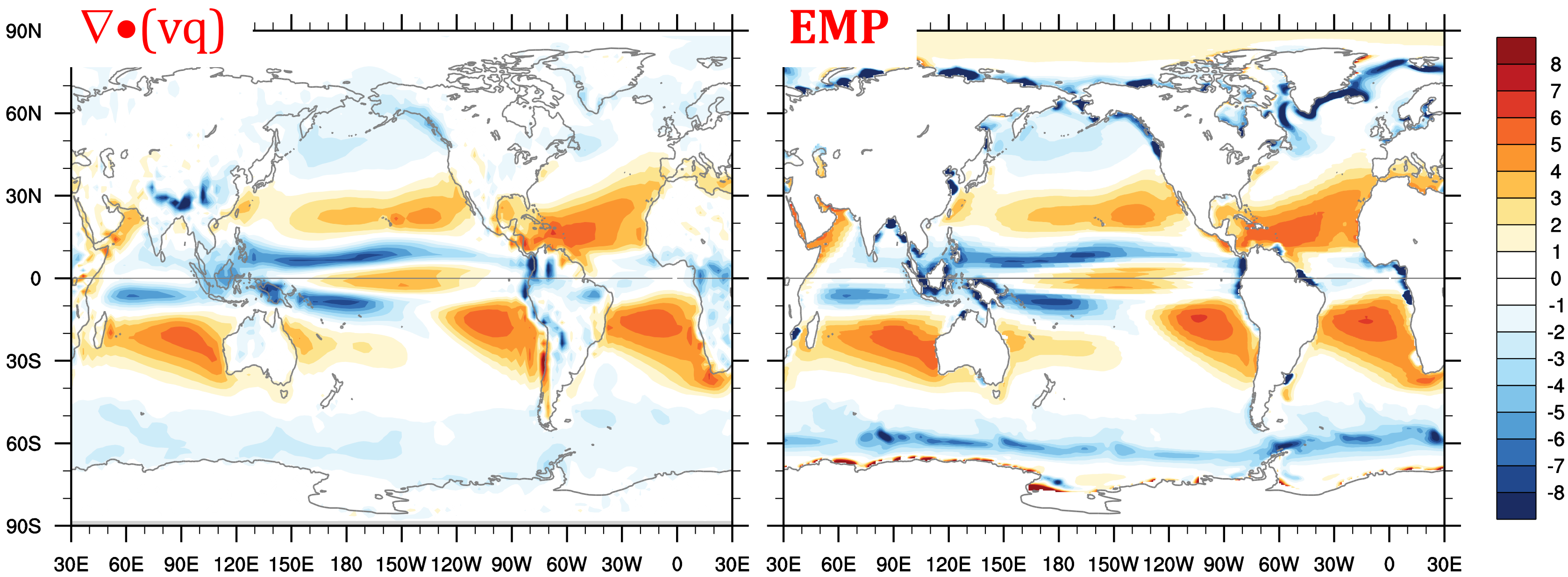
Important role of Bolus and dissipation in ACC

Yang and Li (2015)

Decomposing AHT_{VT}



Divergence of Water Vapor Transport



- Vertically integrated water vapor divergence ∇•(vq)
- Comes from EMP over the global ocean (unit: 10^{-5} $kgm^{-2}s^{-1}$)

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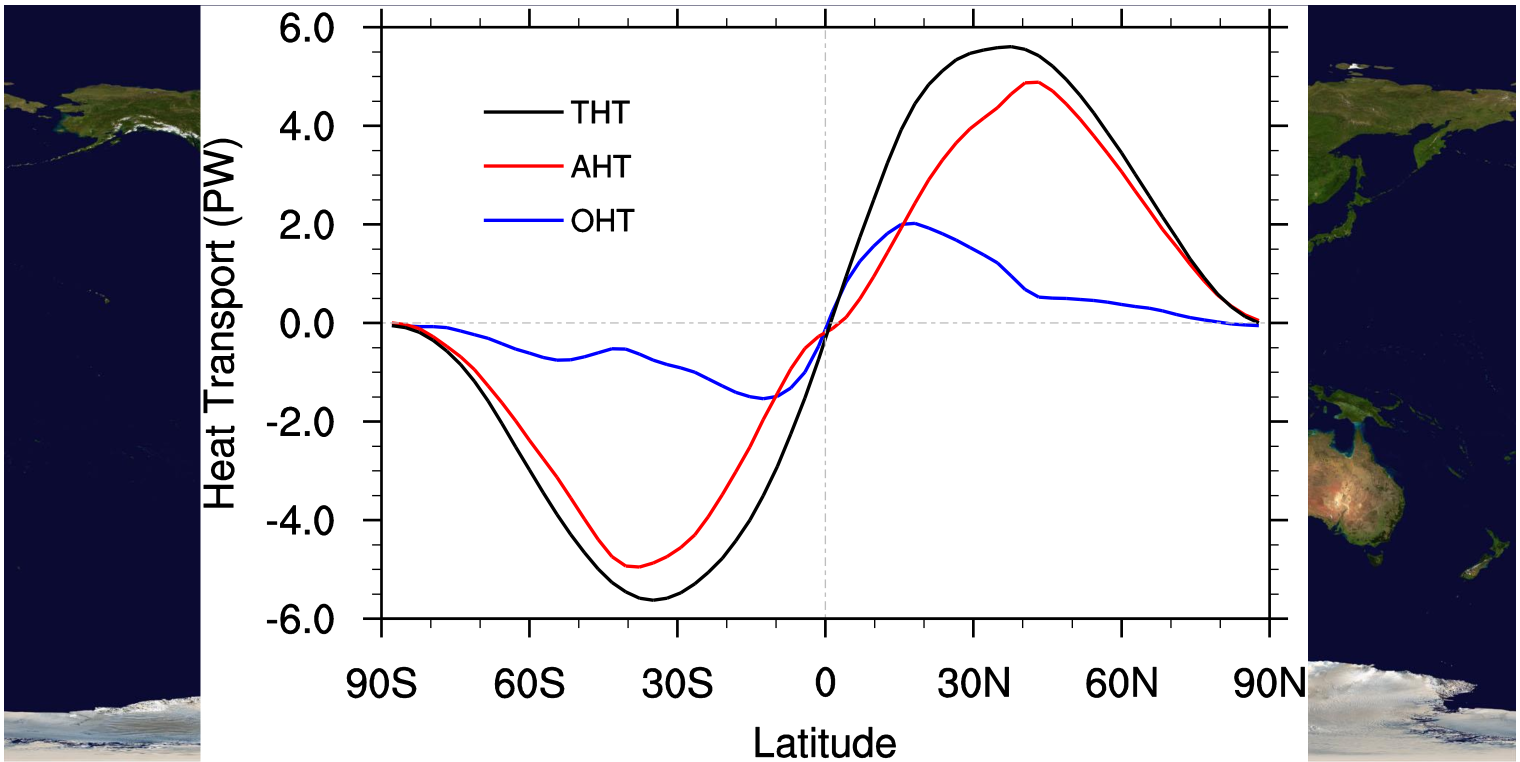
Fundamental Questions

1. Antisymmetric MHT?



Aquaplanet ➔ Real Earth

Trenberth and Caron (2001)

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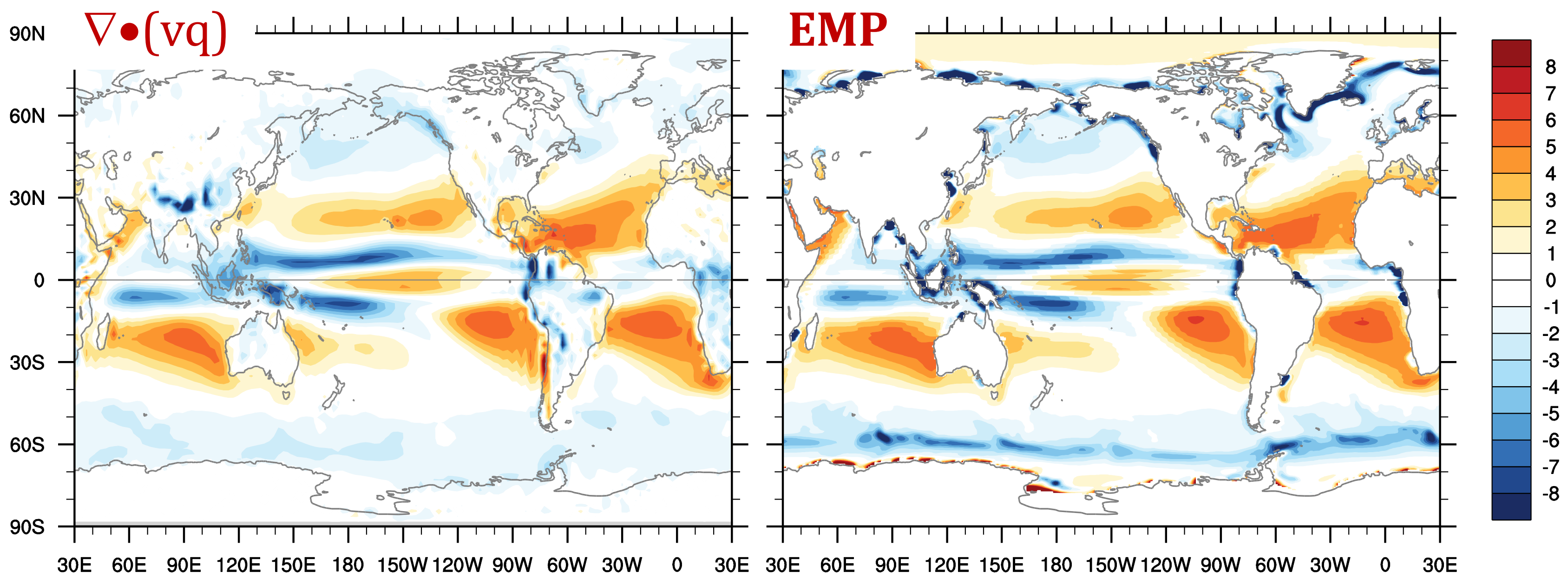
Fundamental Questions

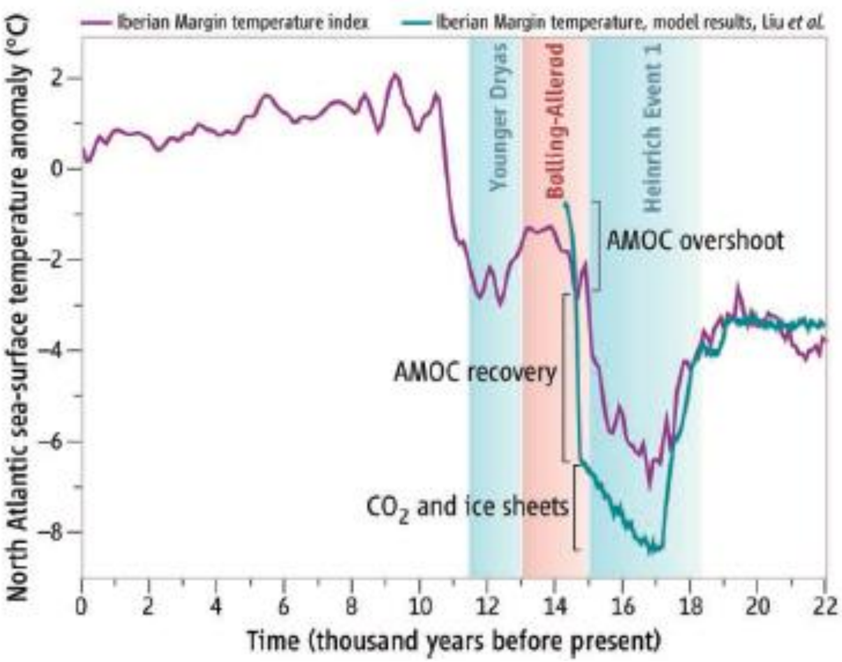
2. "Real" Oceanic Contribution?



Yang and Li (2015)

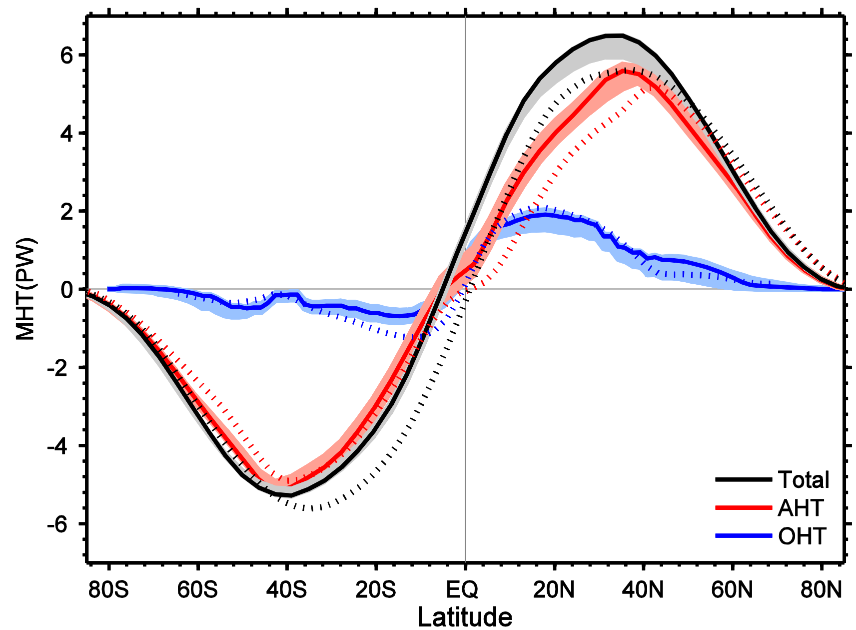
3. Relationship between OHT and AHT Changes?

Earth Climate Stability Mechanism



Climate Change during Past 22 kyr

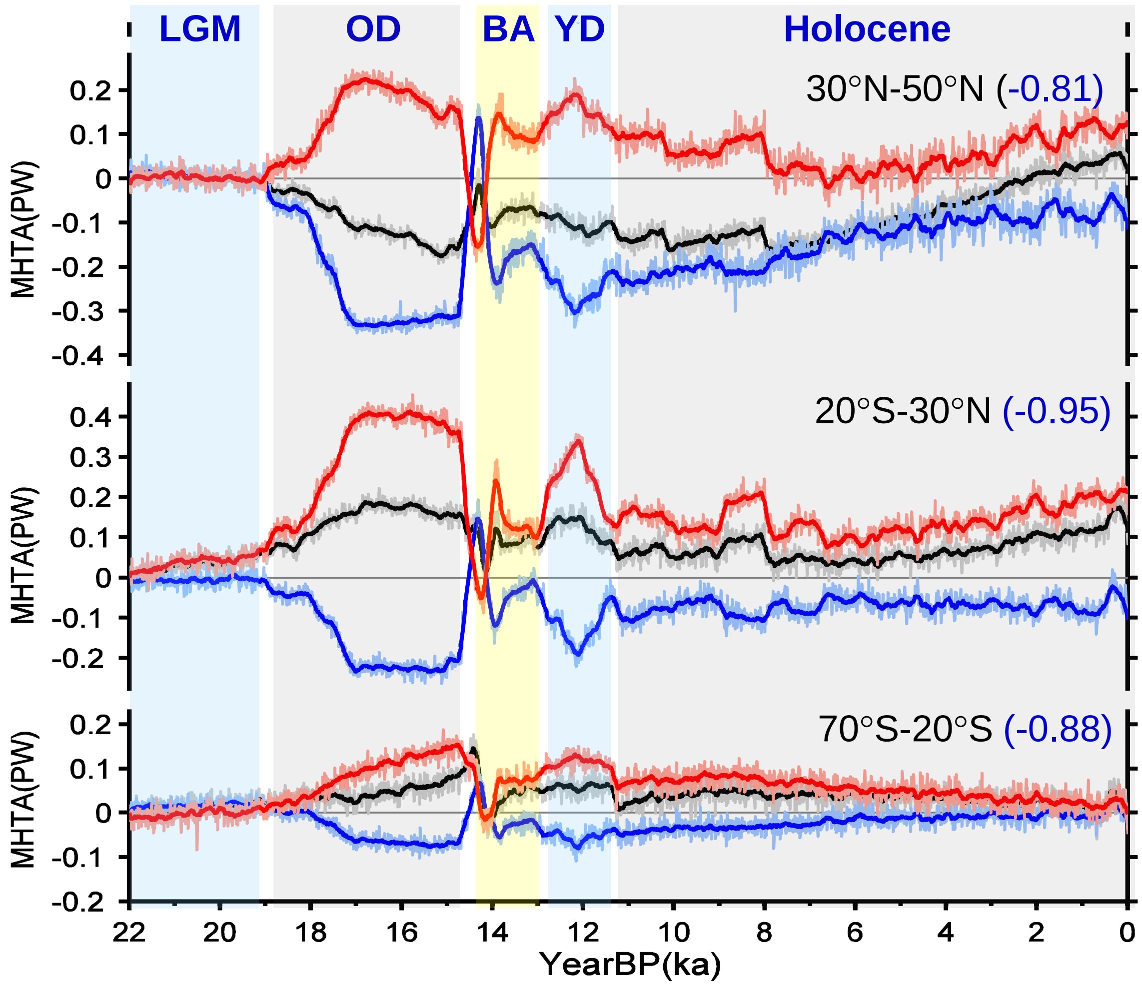
Timmermann (2009), Science



MHT from CCSM3 simulation TraCE-21K, From LGM to present

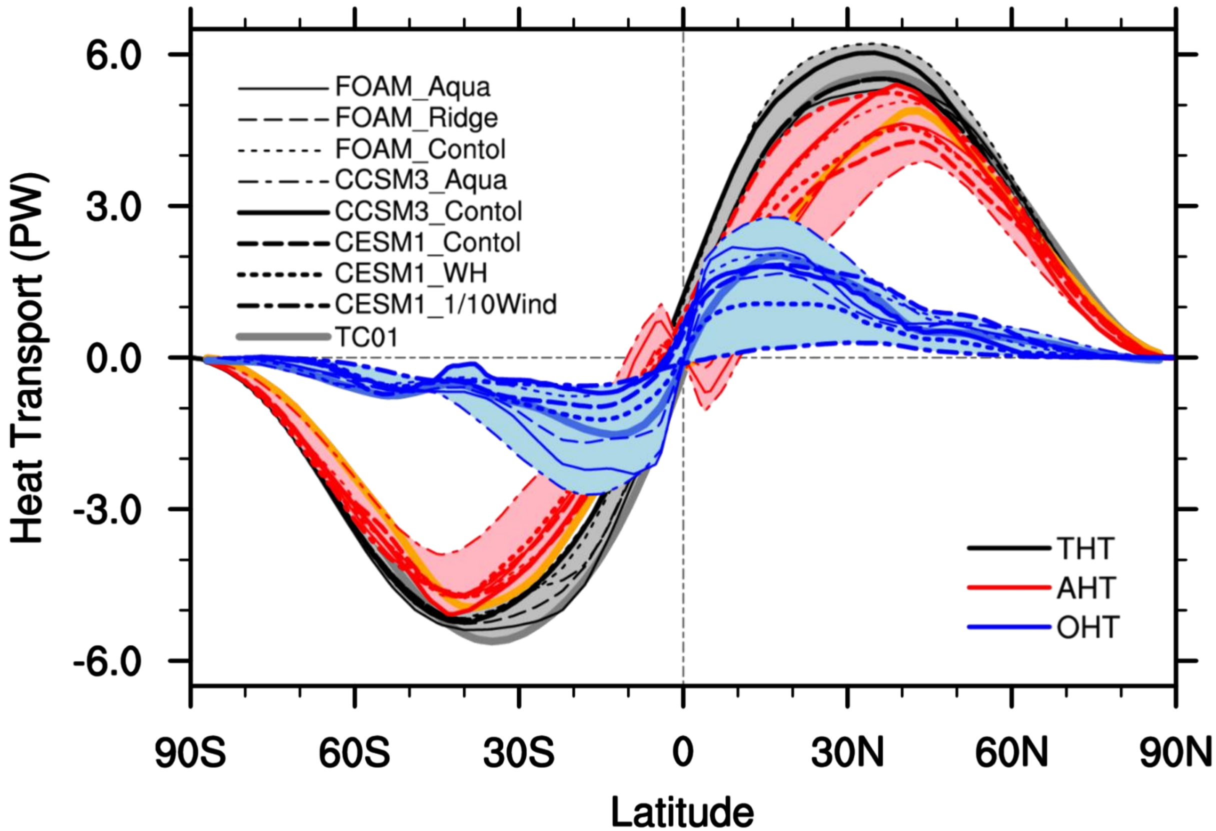
Liu et al. (2009); He (2011)

MHT Change Since LGM



Yang et al. (2015)

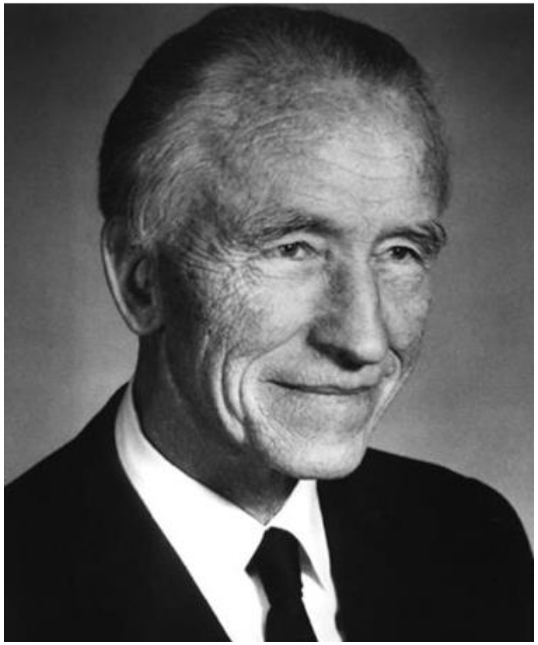
Compensation between AHT and OHT



Note: TC01 is from Trenberth and Caron (2001)

Hypothesis: Bjerknes Compensation

Jacob Aaal Bonnevie Bjerknes
1897-1975



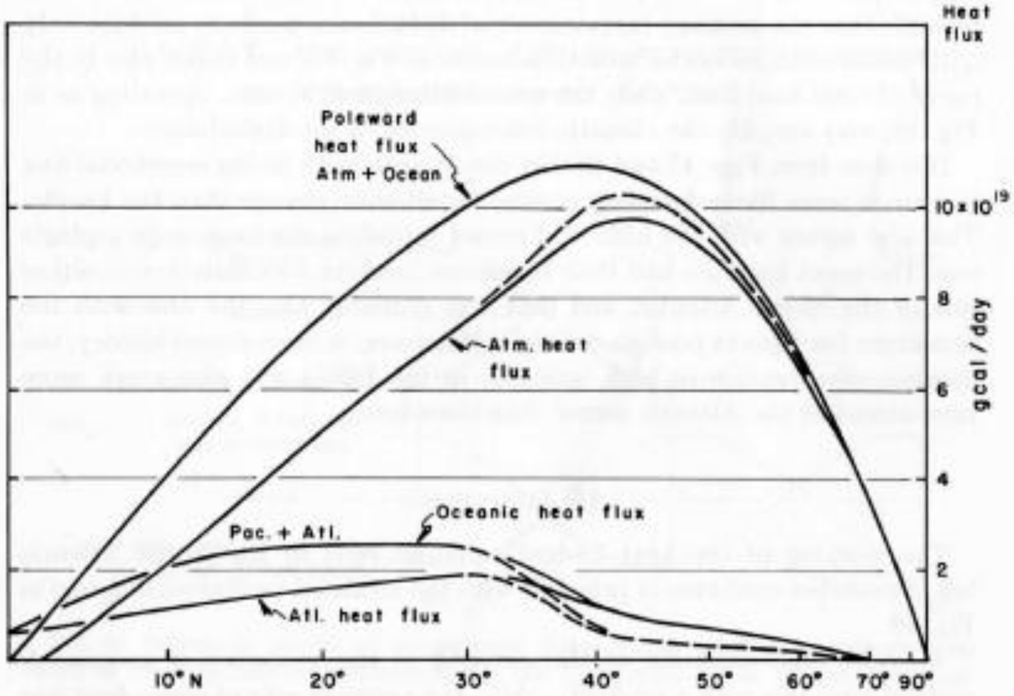
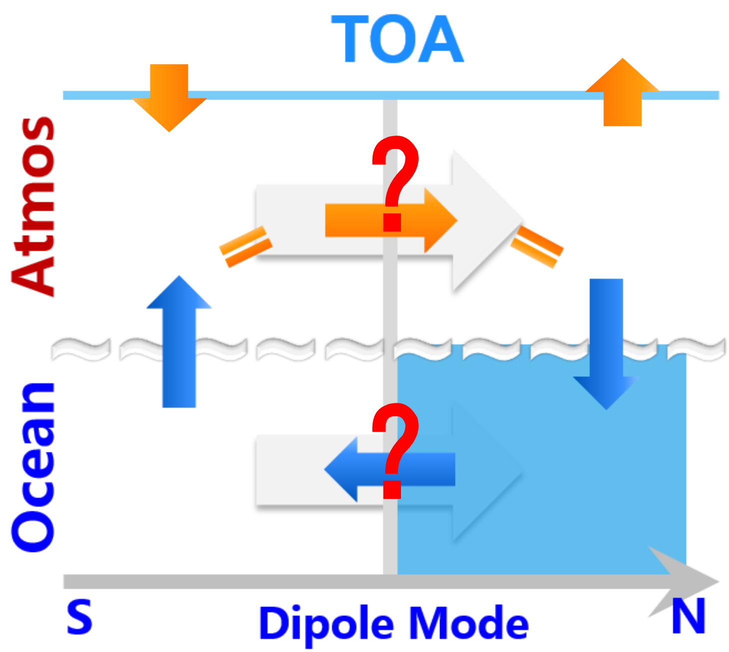


FIG. 48. Solid lines: flux data from Fig. 47 pertaining to present climatic conditions. Dashed lines refer to a sketchy model of the conditions around 1800 A.D. and show qualitative estimate of curtailed Atlantic and total oceanic heat flux as well as increased heat flux by low index atmospheric circulation. The anomalies of heat flux in oceans and atmosphere are assumed to cancel, leaving total heat flux and radiation budget unchanged. Actually, some change in the radiation budget is also likely to have taken place, but it could well have been quite small.

Bjerknes, 1964: Atlantic Air-Sea Interaction, Advances in Geophysics, Vol. 10, P77

Hypothesis: Bjerknes Compensation

Question: How Climate Feedback Determines BJC?



$A + B = 0 \rightarrow A = -B$

but $A + B + C = 0$

C: climate feedback

Then $A = -(B+C)$

Energy Conserved

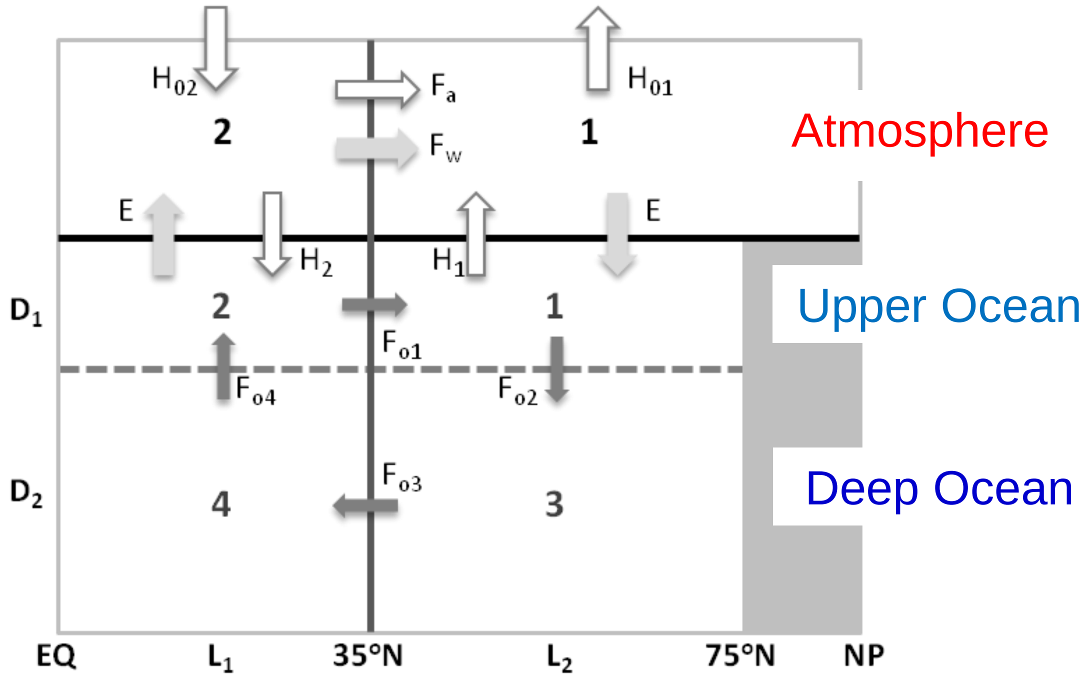
Theory for Equilibrium Change

1. **Coupled Multi-Box Model**
2. **1-D Energy Balance Model (EBM)**

Go to Final Equations

Coupled Multi-Box Model

Yang, Zhao and Liu, 2016: Understanding Bjerknes compensation in atmosphere and ocean heat transports using a coupled box model. J. Climate



Stommel (1961); Nakamura et al. (1994); Marotzke and Stone (1995); Tziperman et al. (1994); Tziperman and Ioannou (2002)

Go to Final Equations

Equations and Dynamics

T 1⋯ 2⋯ 3⋯ 4⋯	S 1⋯ 2⋯ 3⋯ 4⋯

Heat Flux at TOA: $H_{1,2} = A_{1,2} - B_{1,2}T_{1,2}$

Fresh Water Flux : $H_{fw} = \gamma(T_2 - T_1)$

Thermohaline : $q = \kappa[\alpha(T_2 - T_1) - \beta(S_2 - S_1)]$

AHT: $H_d \sim (T_2 - T_1)$	OHT: $O_d \sim q^*(T_2 - T_1)$

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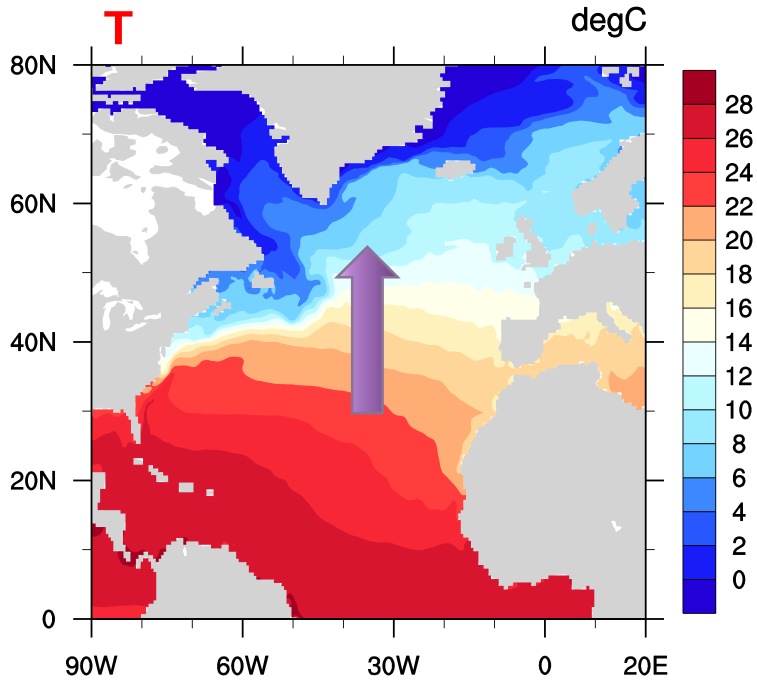
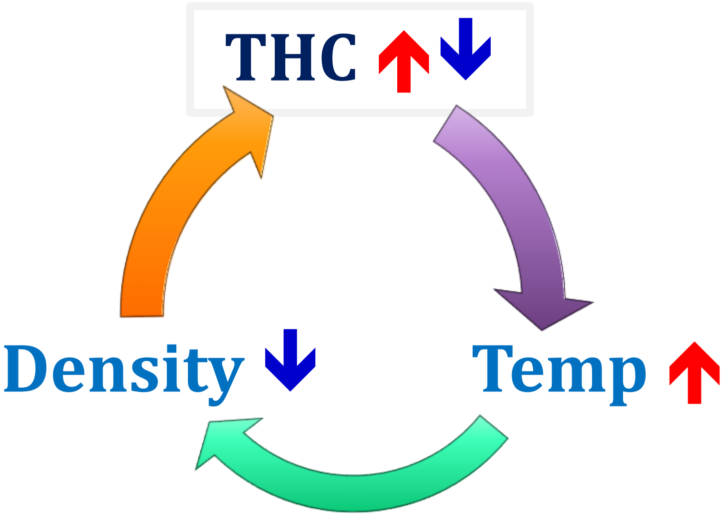
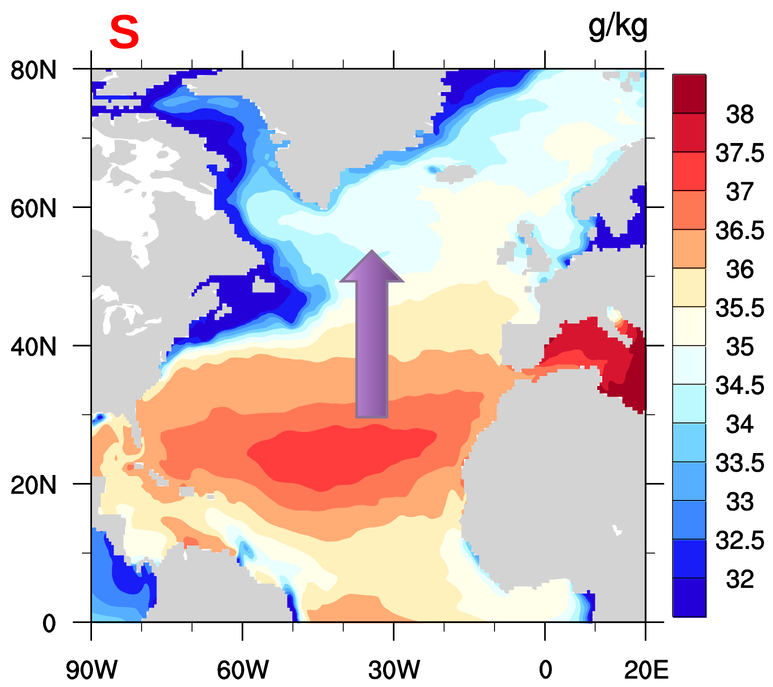
Negative Feedback: *THC* vs *T*

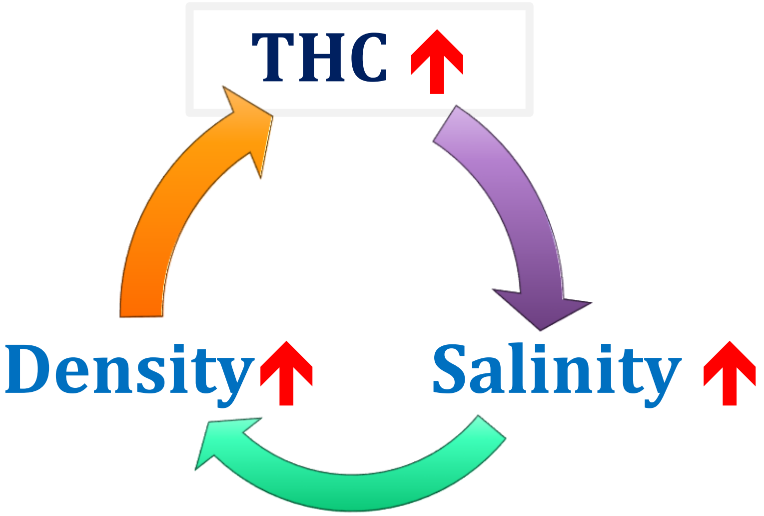




Willebrand (1993)

Positive Feedback: *THC* vs *S*

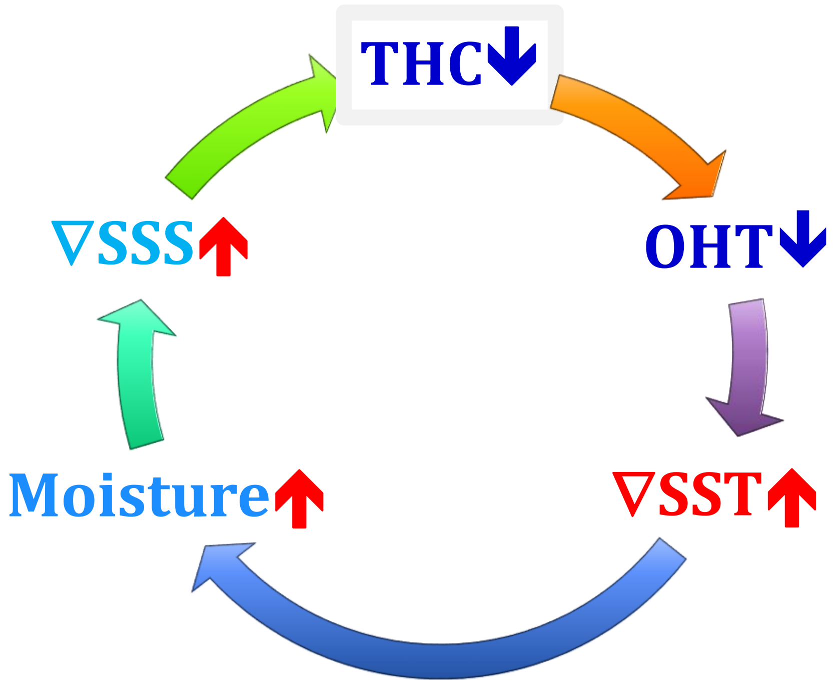




Willebrand (1993)

Positive Feedback: *THC* vs *EMT*

EMT: Atmosphere Eddy Moisture Transport



Nakamura et al. (1994)

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Analytical Solution: BJC Rate

$$C_R \equiv \Delta H_a / \Delta H_o = -(B_1+B_2)\chi / [B_1 B_2 + (B_1+B_2)\chi]$$

↓

if $B_1 = B_2$

↓

$$C_R = -1/[1+B/2\chi] < 0 \quad \sim \quad \text{Intrinsic Rate}$$

Intrinsic parameters:

- $B_{1,2}$ ~ **Local feedback between *T* and *HF* at TOA**
- χ ~ **Atmospheric heat transport efficiency.**

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Intrinsic Rate

$|C_R|$

$|C_R|$	$<1,\ \ if\ -B_1, -B_2 < 0,$ **Undercompensation**
	$=1,\ \ if\ B_1 B_2 = 0,$ **Full Compensation**
	$>1,\ \ if\ either\ -B_1$ or $-B_2 > 0,$ **Overcompensation**

$B_{1,2}$ ~ **Local climate feedback VITAL!**

1-D Slab-Ocean Energy Balance Model

Liu, Yang, He and Zhao, 2016: A theory for Bjerknes compensation: the role of climate feedback. J. Climate

Non-dimensional Equation

$$\partial_{xx}[M(x)T] - b(x)T + f(x) = 0, \qquad for \;\; 0 < x < 1$$

With Non-dimensional OHT and AHT

$$f(x) = -\partial_x H_O,$$

$$H_A = -\partial_x [M(x)T].$$

Stommel (1961); North, (1975)

Analytical Solution: BJC Rate

Intrinsic Rate

$$C_R \equiv \Delta H_a/\Delta H_o = -1/\left[1+B/(n\pi)^2\right] < 0,\ n=1,2,\ \ldots$$

- ***B*** ~ Intrinsic parameter, Local feedback between *T* and *HF* at TOA
- ***n*** ~ Forcing scale.

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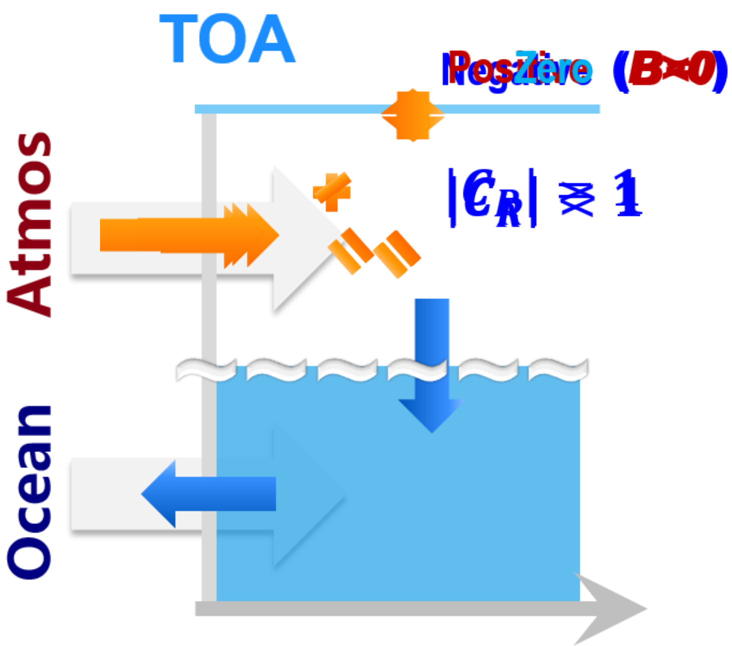
Coupled Intrinsic Mode

Thermohaline-Climate Feedback-Energy Balance



$$C_R \equiv \frac{\Delta F_a}{\Delta F_o} = -\frac{1}{1-B} < 0$$

Local climate feedback $B(y)$

Yang, Zhao and Liu (2016)
Zhao, Yang and Liu (2016)

Climate Feedback + MHT ➔ Earth Energy Balance

Coupled Intrinsic Mode

能量补偿 ⇔ 体重保持

饮食
(海洋)

新陈代谢
(气候反馈)

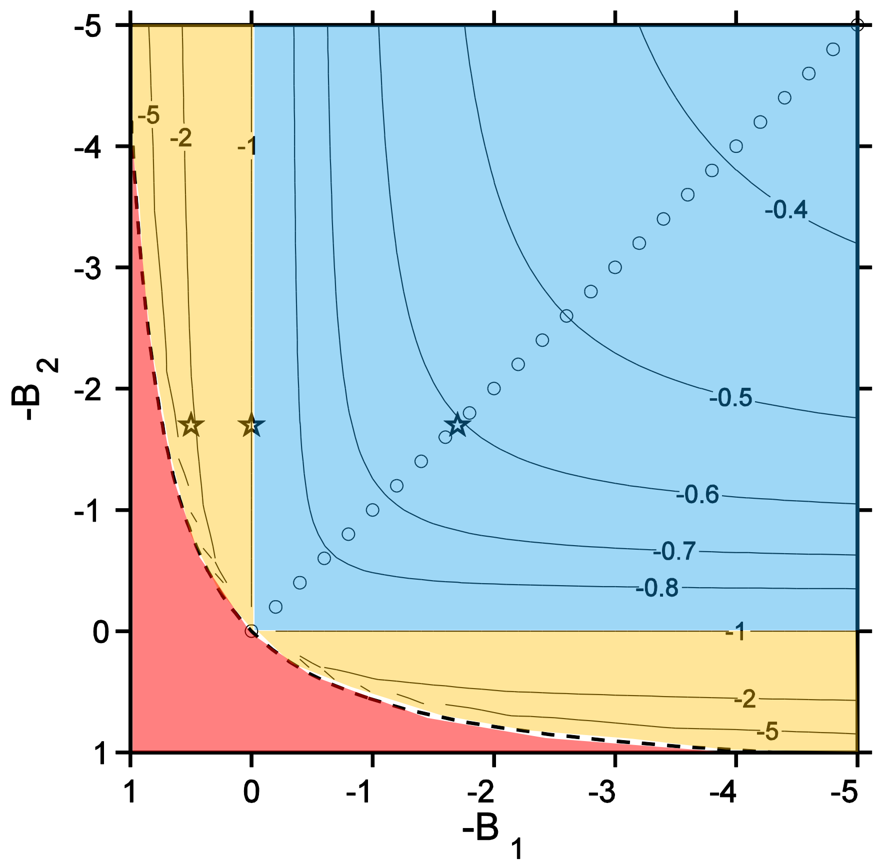
运动
(大气)

$$C_R = -\frac{1}{1-B}$$

Go to BJC for Climate Variability

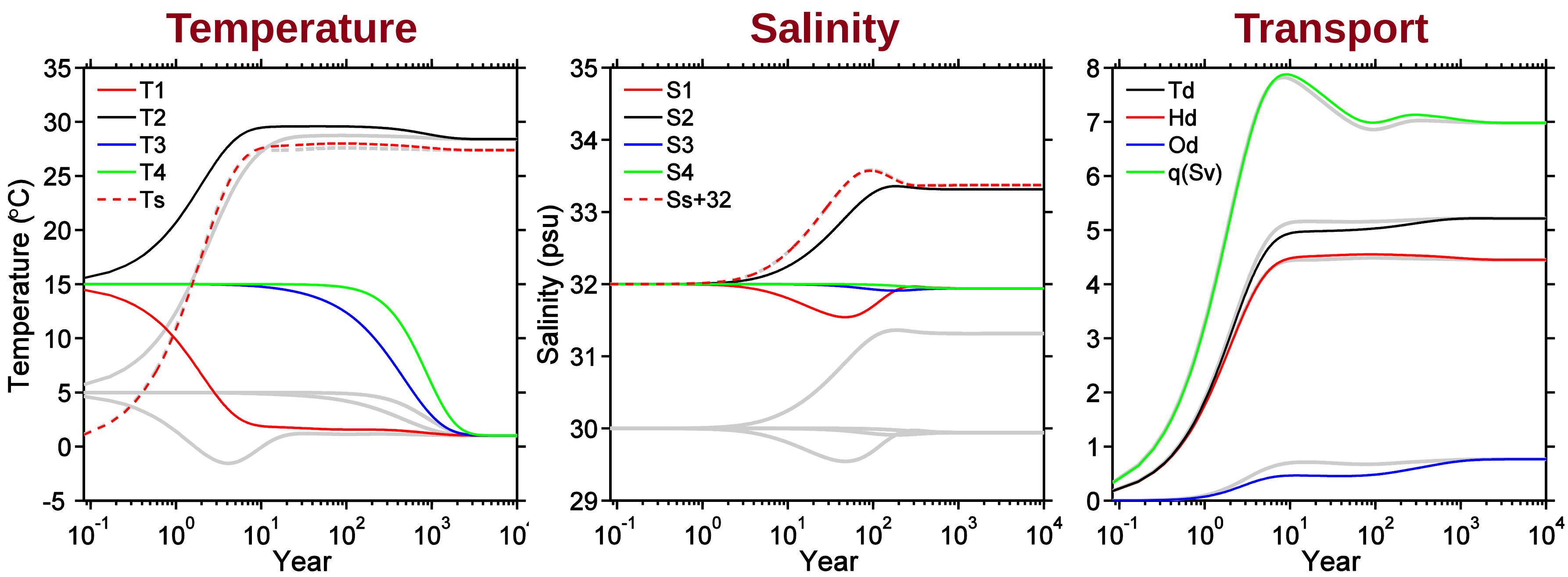
Go to Outline

Intrinsic Rate

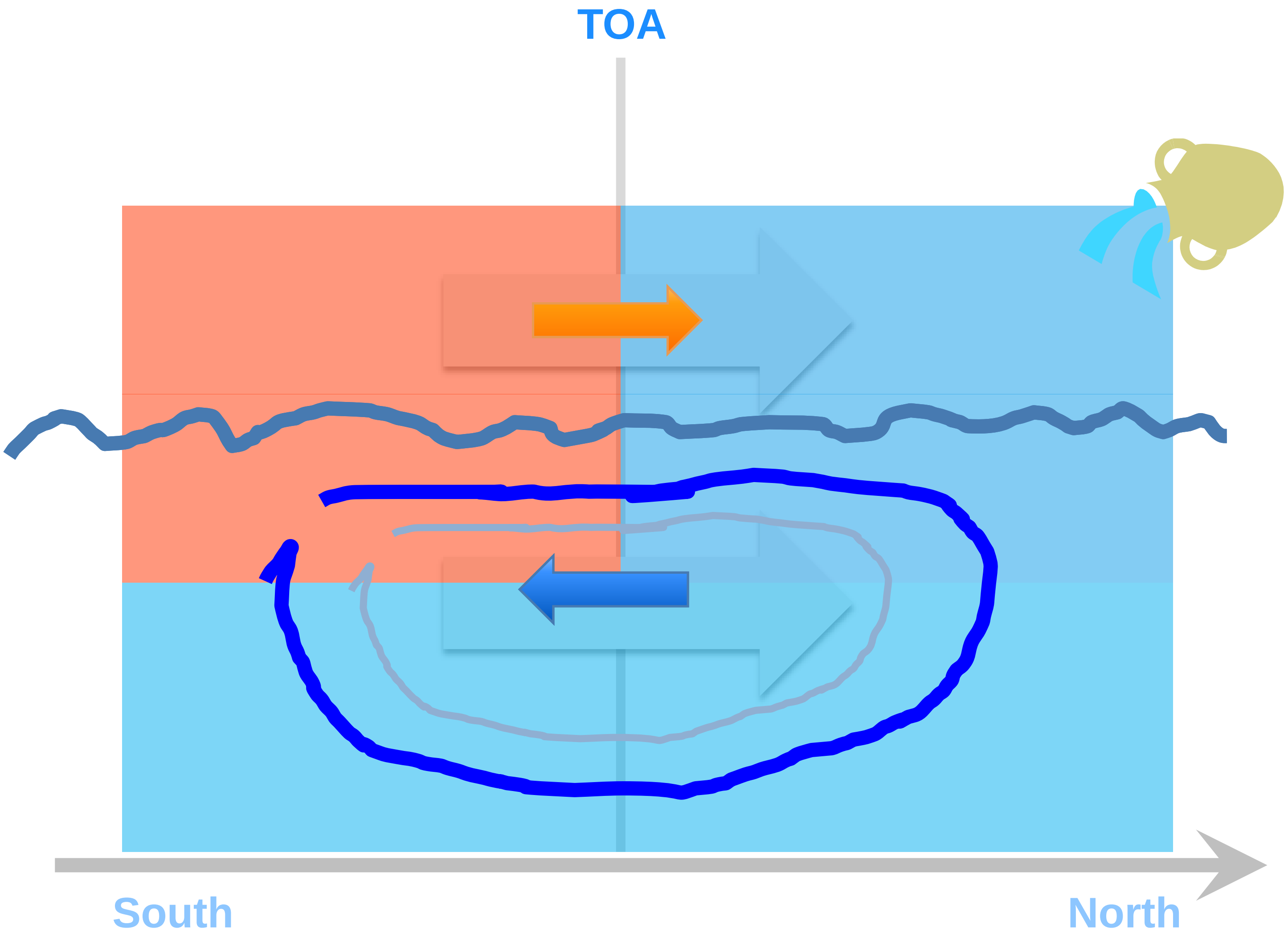


$$C_R = -(B_1+B_2)\chi/[B_1B_2+(B_1+B_2)\chi]$$

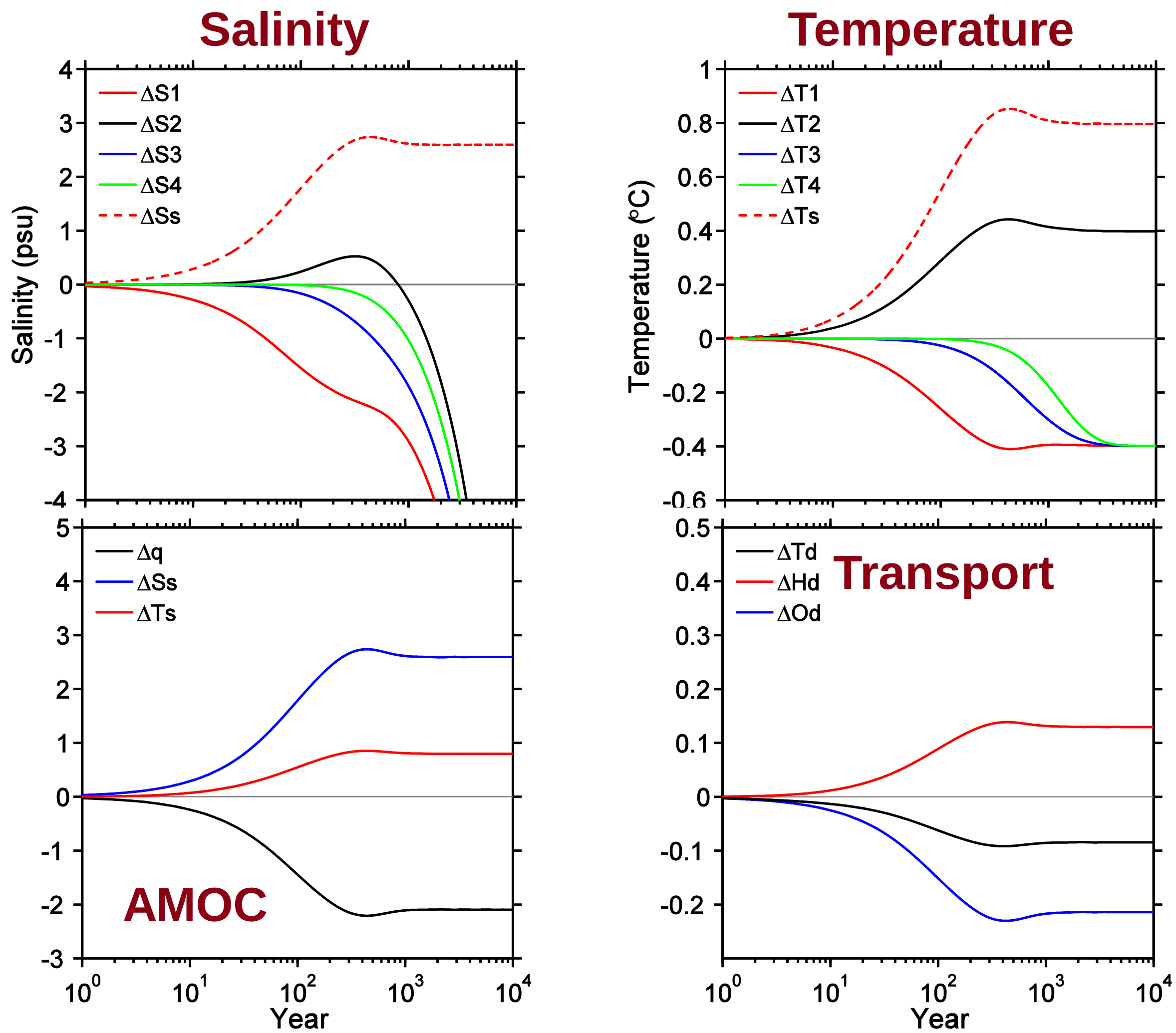
Mean Climate



How BJC Occurs: Fresh Water



Climate Change under Fresh Water



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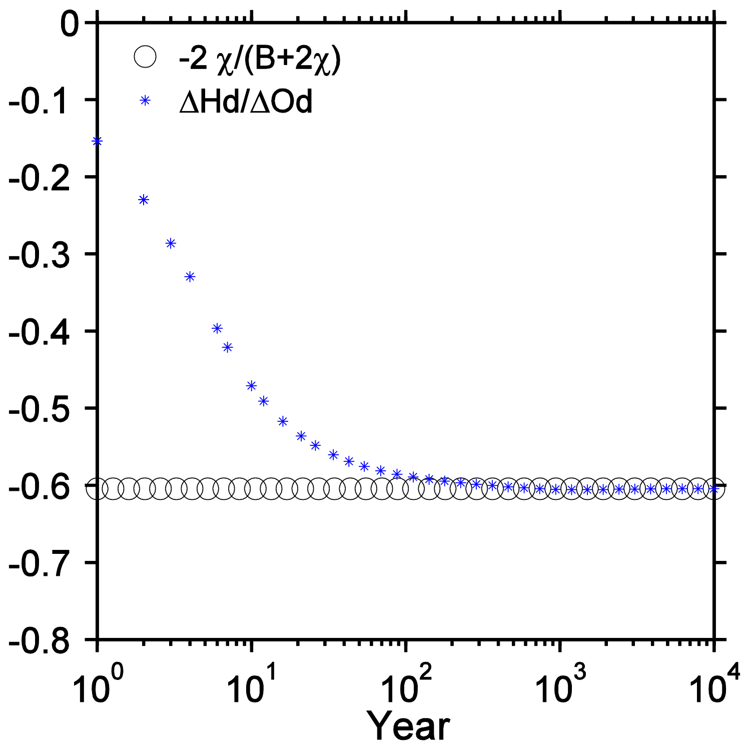
BJC under Negative Feedback

Compensation Rate: Constant!



Under-Compensation (-B1,2<0)

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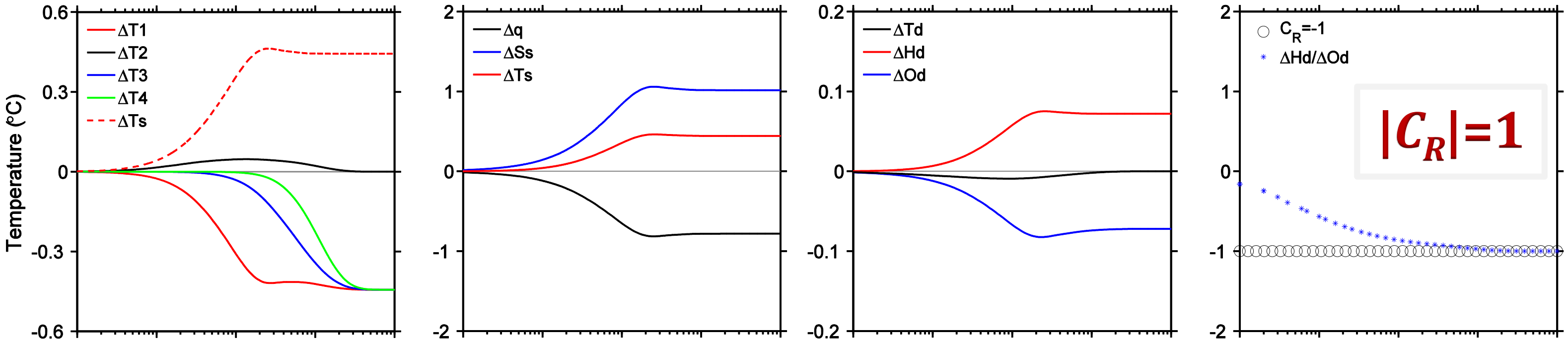
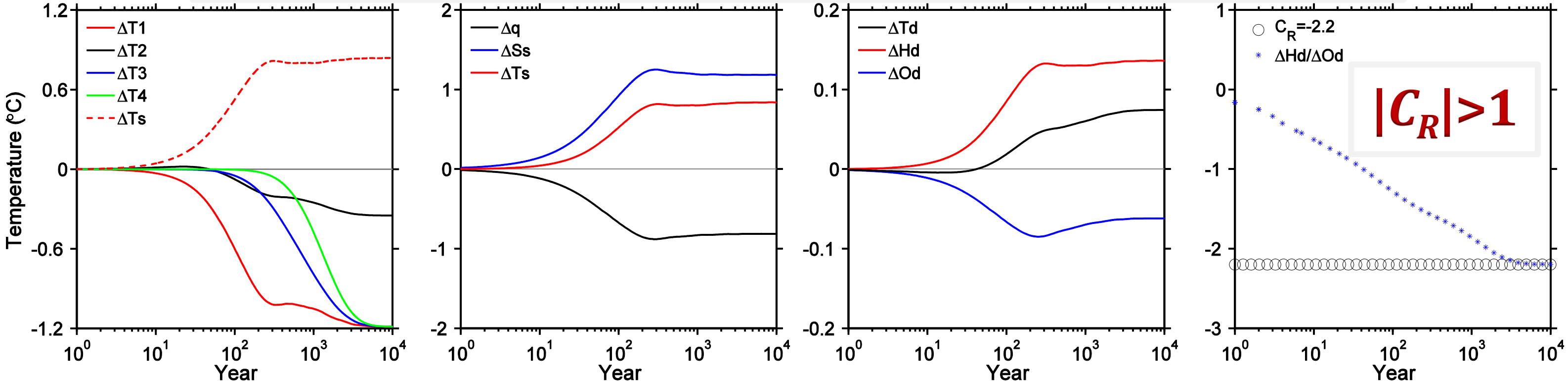
Climate Change under Fresh Water

Full Compensation (-B1=0, Zero Feedback)



Overcompensation (-B1=0.5, Positive Feedback)



Modeling MHT and OHT in Past 22ka

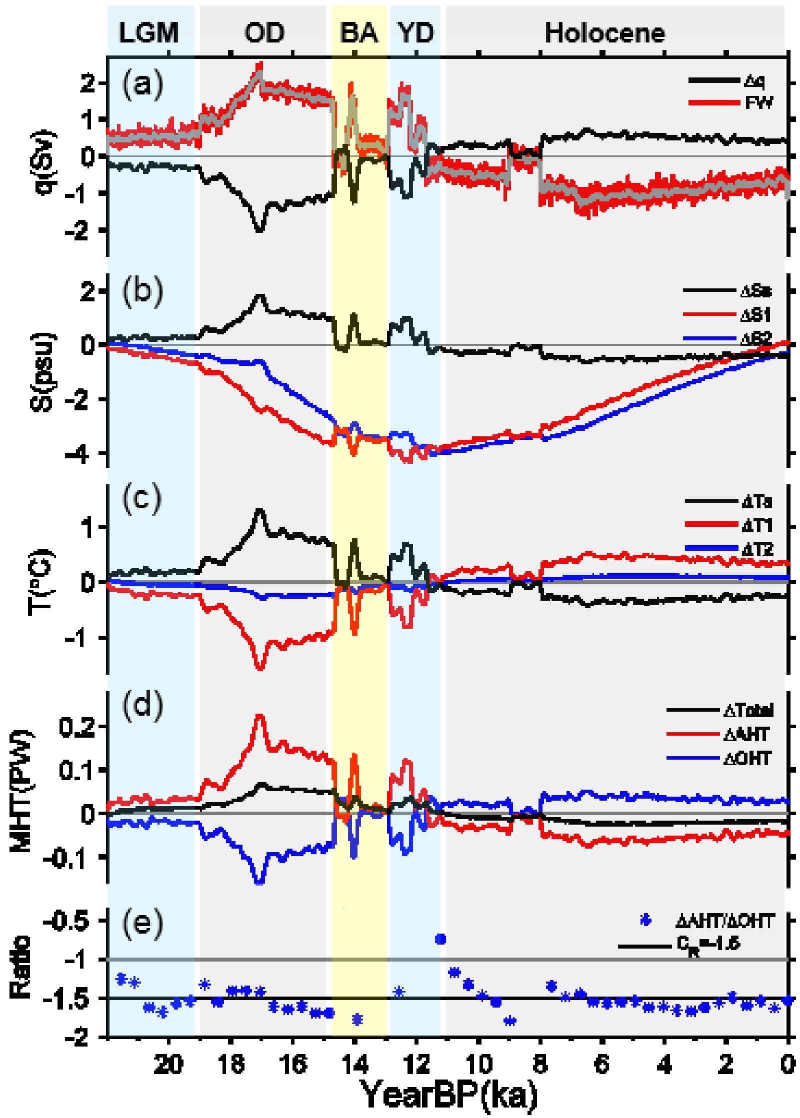
Freshwater Forcing

Salinity Change

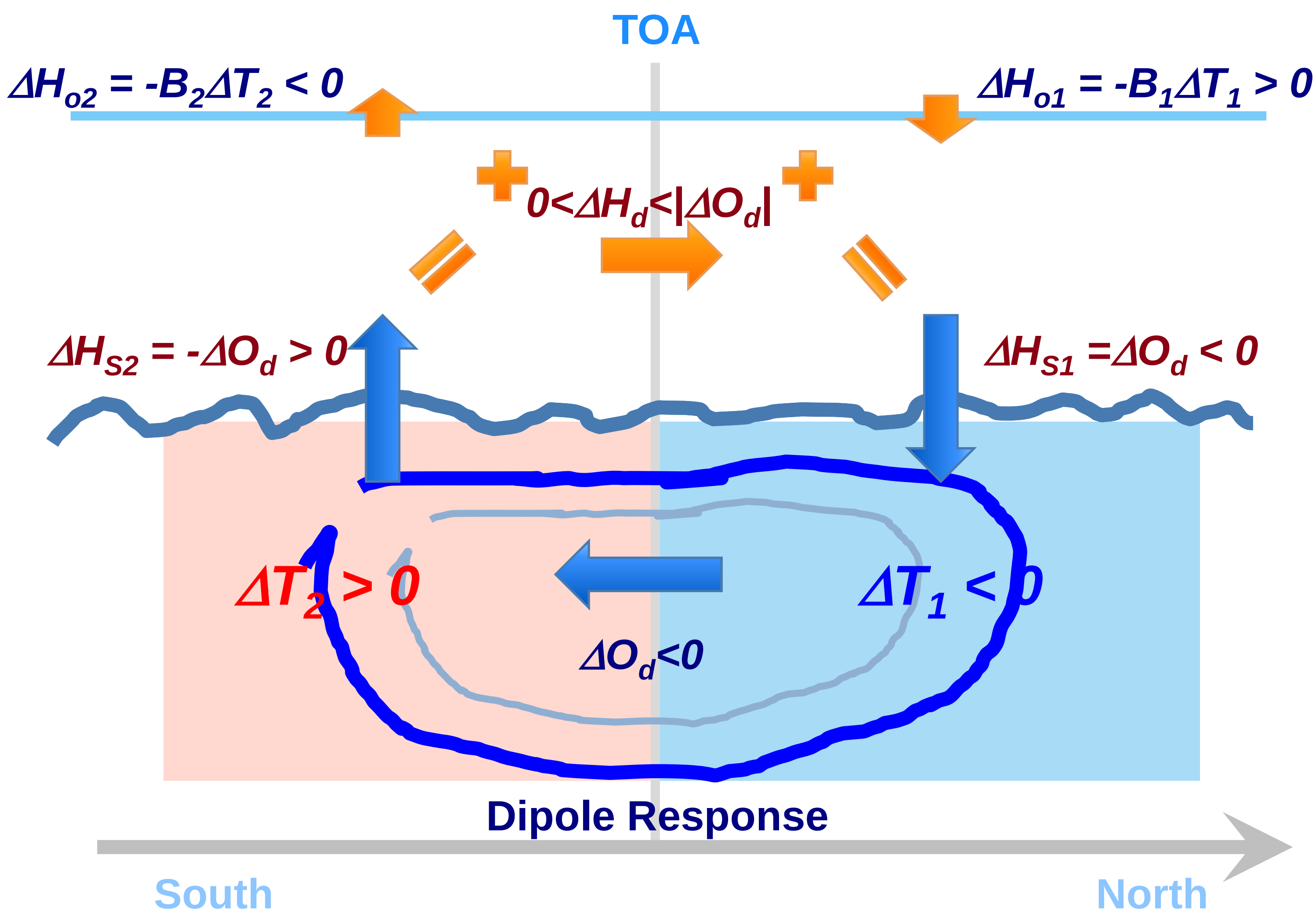
Temperature Change

AHT and OHT

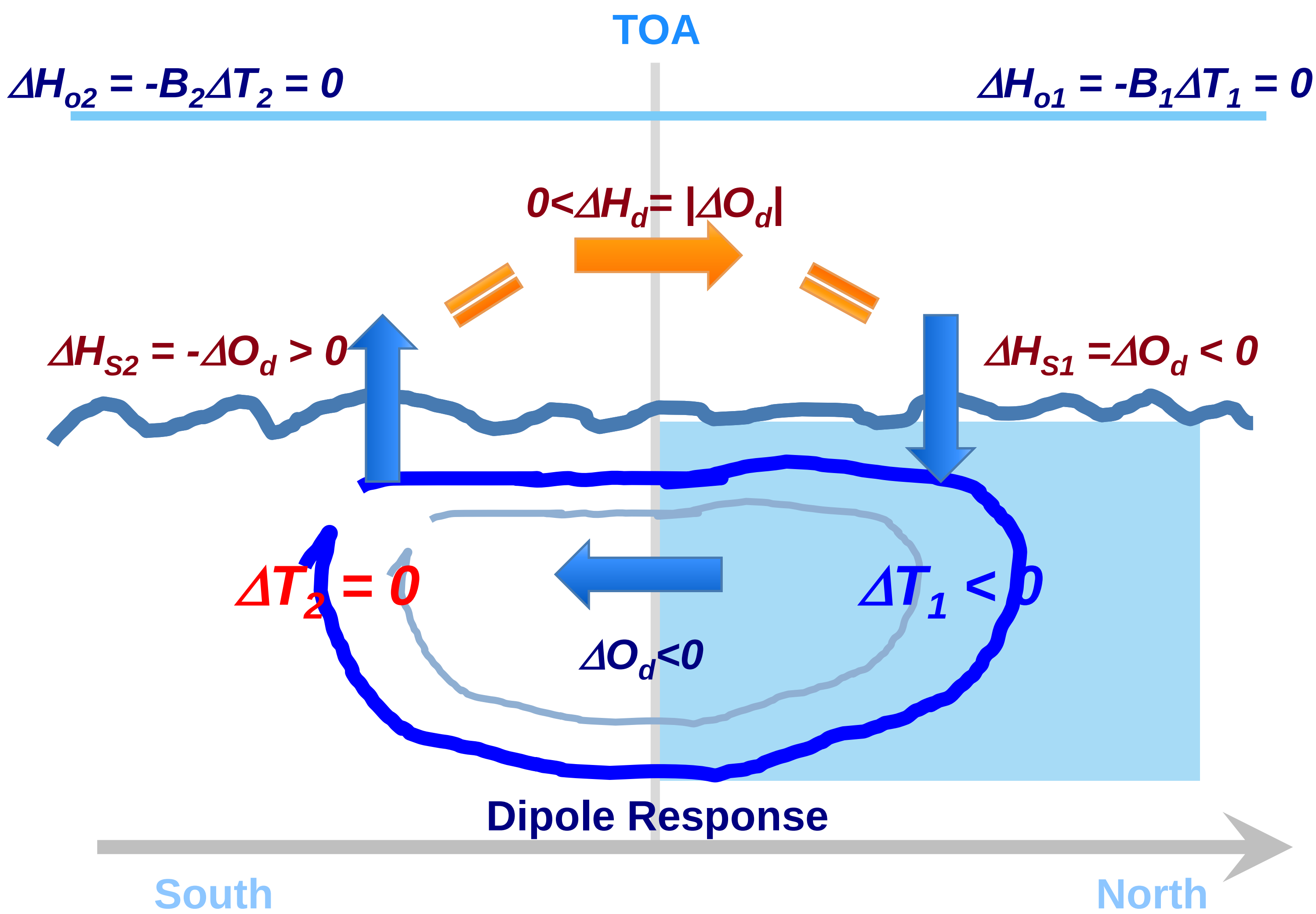
BJC = -1.5



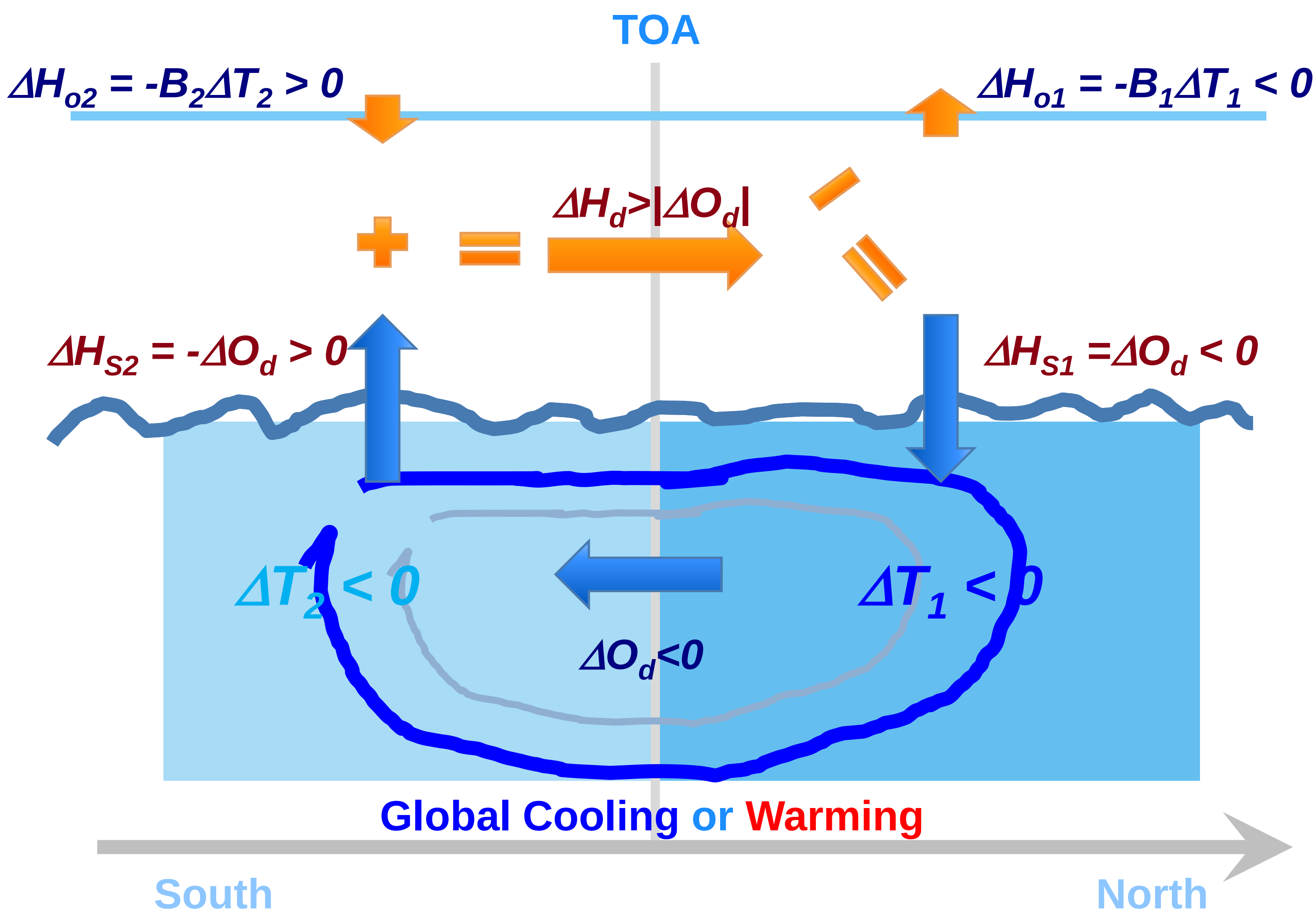
Mechanism for Undercompensation



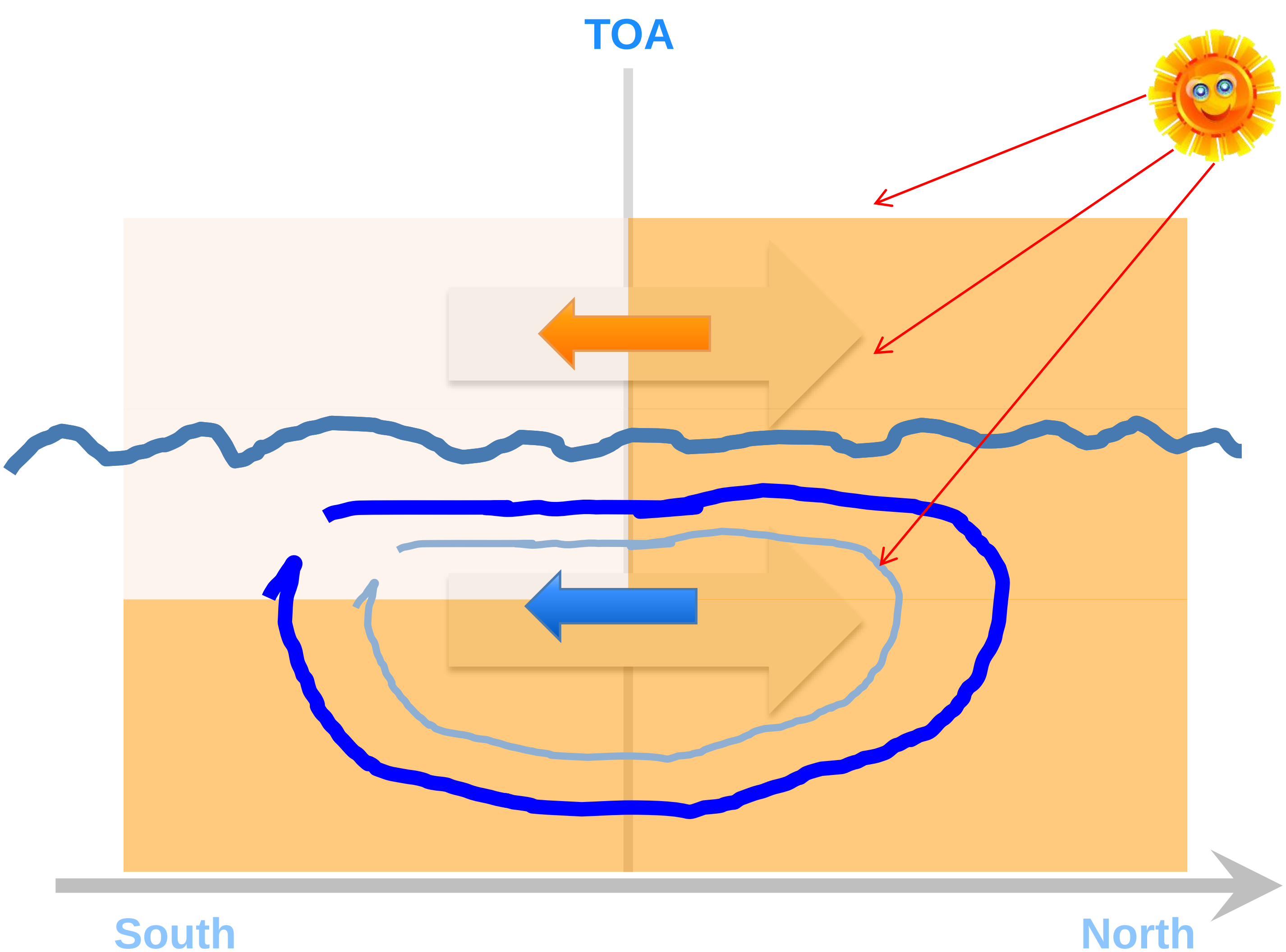
Mechanism for Full compensation



Mechanism for Overcompensation



Will BJC Occur under Heating?



Analytical Solution: BJC Rate under Heating

$$C_h \equiv \Delta H_a/\Delta H_o = \{1/[1+(B_2-B_1)\ \Delta A/\Delta T_S\ [B_1B_2+(B_1+B_2)\chi]]\}\ C_R$$

↓

if $B_1=B_2$ global uniform feedback

↓

$$C_h = C_R < 0$$

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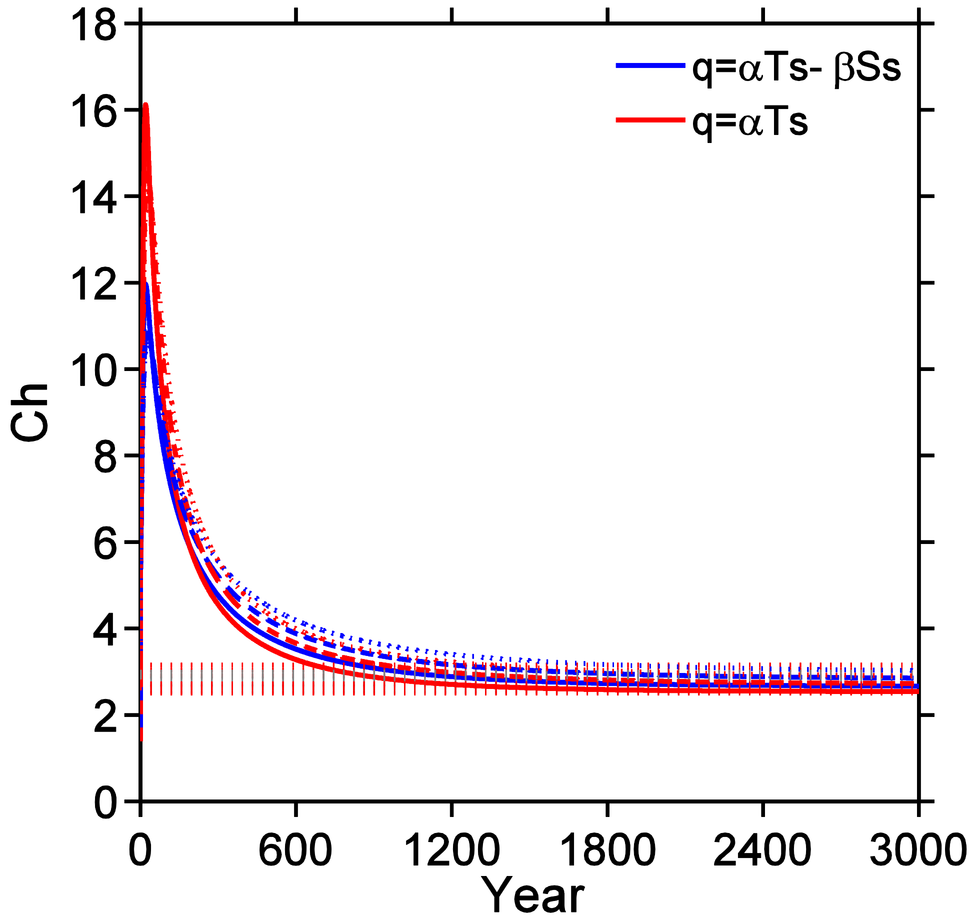
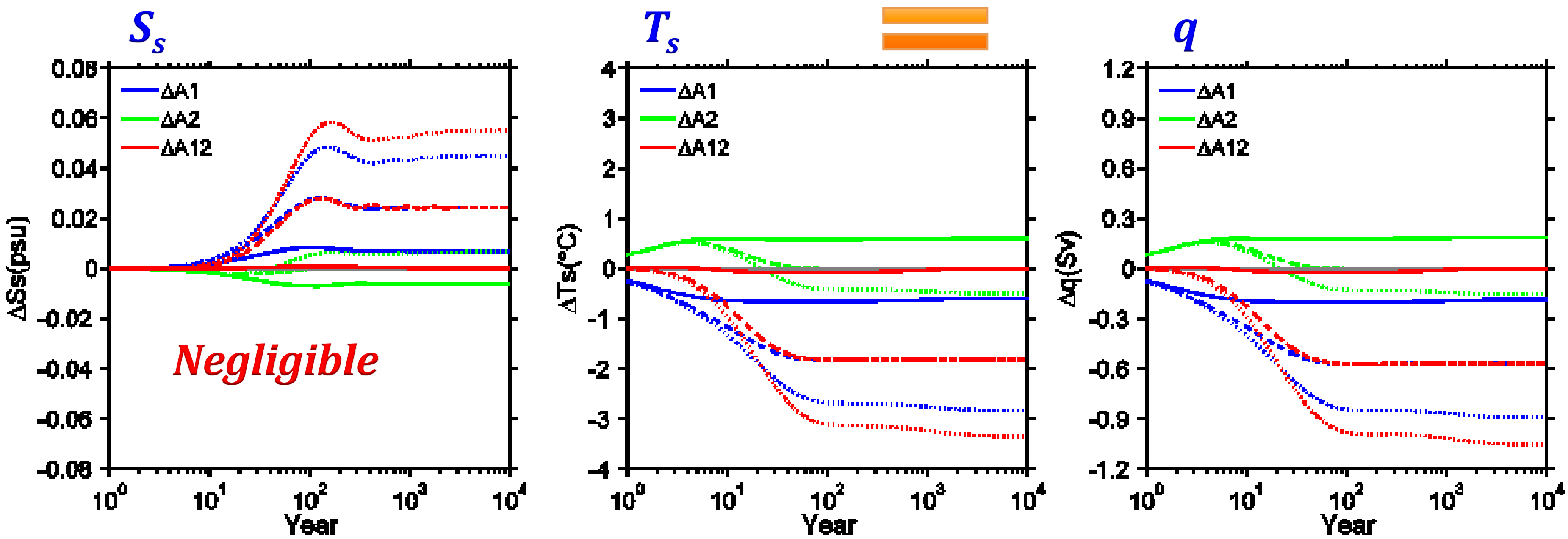
“BJC Rate” under **Heating**

No thermohaline dynamics ➔ No Compensation!



Why *No* BJC under Heating?



$$q \sim T_s \Rightarrow O_d \sim q^*T_s \sim T_s{}^*T_s$$

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Why *No* BJC under Heating?

$q \sim T_s \rightarrow O_d \sim q{*}T_s \sim T_s{*}T_s$

↓

$C_q \equiv \Delta H_a/\Delta H_o = H_a/2H_o$

↓

No Compensation! $C_q > 0$ **&** $C_q \sim$**Constant**

↑

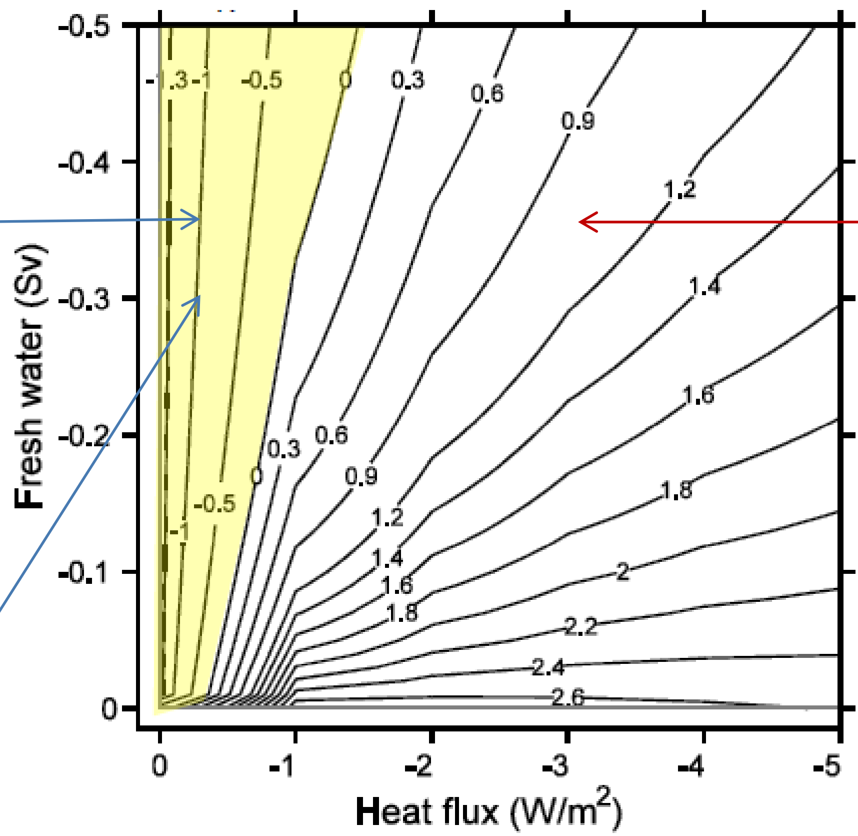
No thermohaline dynamics

BJC Possible under Freshwater + Heating?

Valid for weak heating

BJC

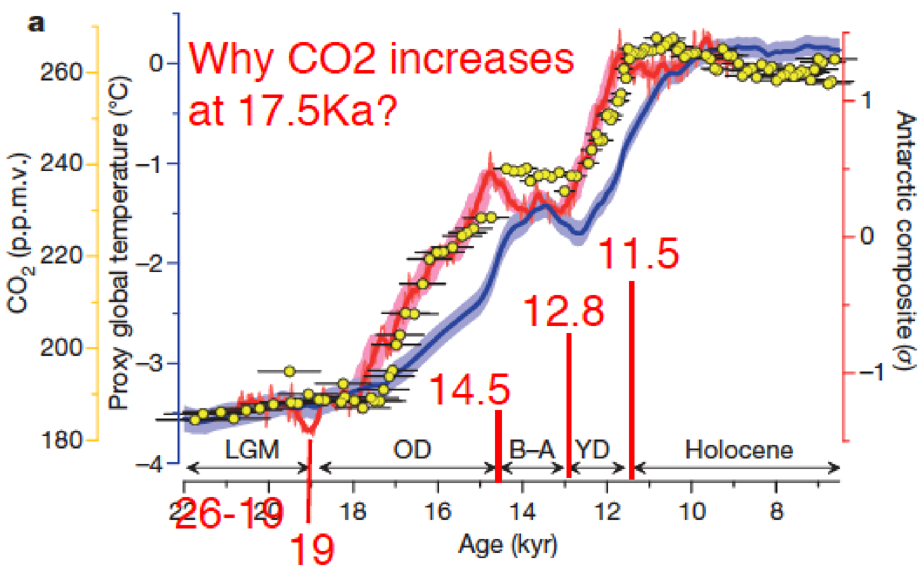
No BJC

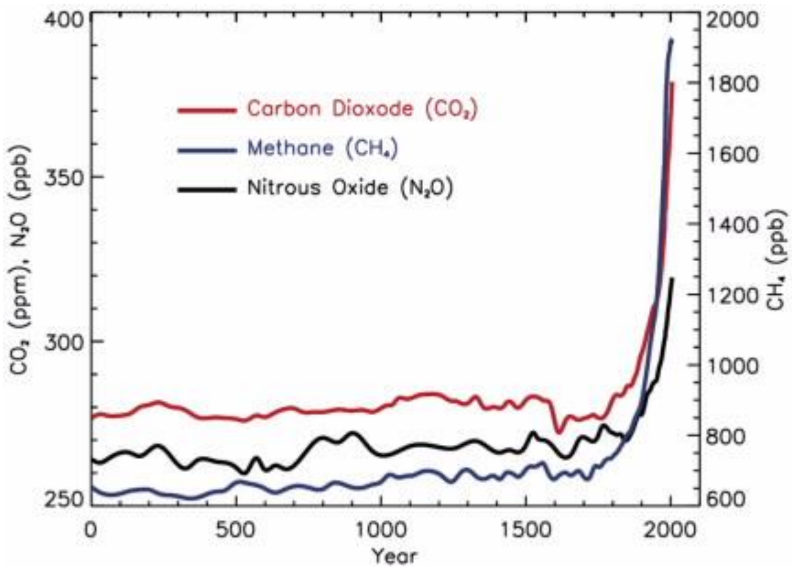


Positive Feedback: S1⇑ ➔ THC⇑ ➔ S1⇑ ➔ THC⇑ ➔ Ts⇓

CO2 since the LGM

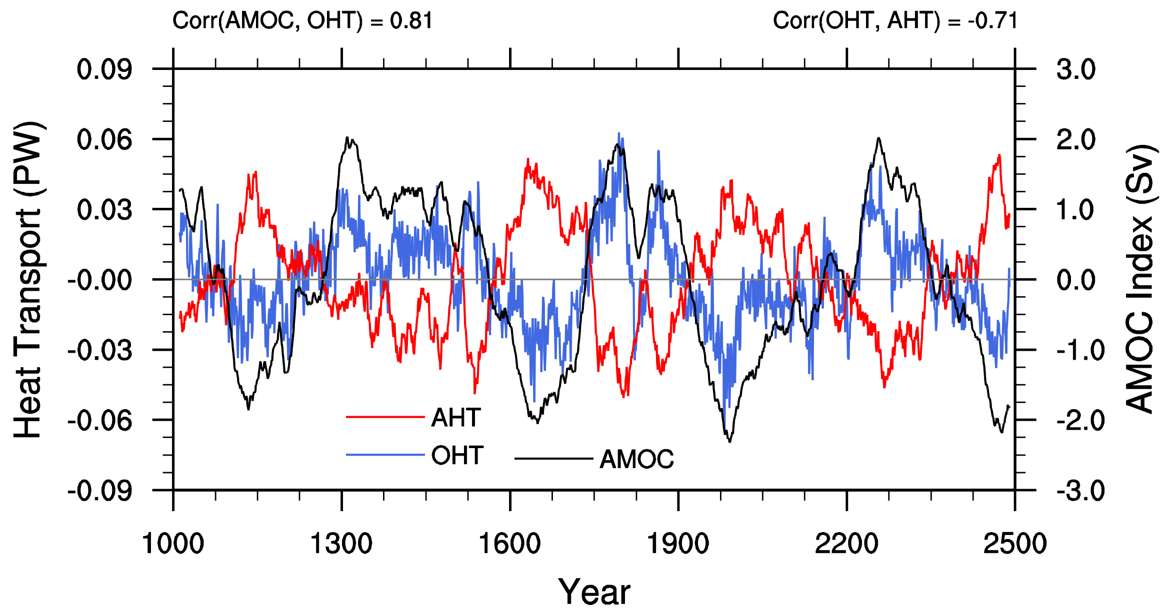
Since LGM: 1.5×10^{-4} W/m^2/year (Shakun et al., 2012)

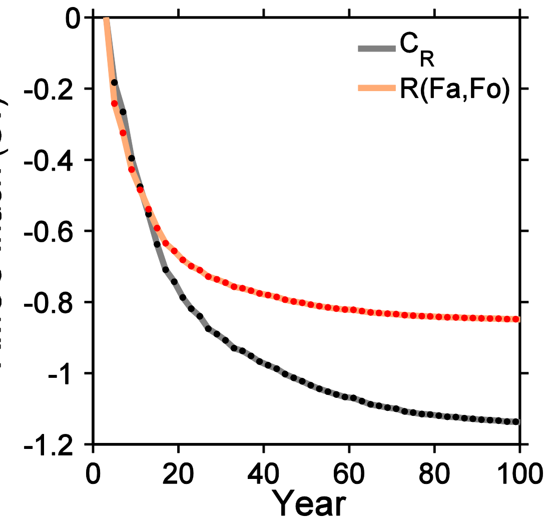




Since 1770: 1×10^{-2}W/m^2/year (IPCC, 2007)

Climate Variability and BJC in CESM





Define: $$C_R \equiv r \frac{\sigma_{F_a}}{\sigma_{F_o}} \qquad (1)$$

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Theory for Transient Climate Variability

$$\dot{T}_s = \frac{1}{\epsilon c \rho_0 D_1}[(A_2 - A_1 - BT_s) - 2\chi T_s] - 2qT_s,$$
$$\dot{S}_s = \frac{2S_0}{\epsilon_w D_1}\gamma T_s - 2qS_s + h_{fw}.$$

Linearization: $T = \bar{T} + T'$ and $S = \bar{S} + S'$

$$\frac{\partial}{\partial t}\begin{pmatrix} T'_s \\ S'_s \end{pmatrix} = M\begin{pmatrix} T'_s \\ S'_s \end{pmatrix} + \begin{pmatrix} 0 \\ h_0 e^{i\omega t} \end{pmatrix}$$

If $h_{fw} = const.$ → $C_{R0} = -\frac{1}{1+B/2\chi}$ **(2)**

BJC for Climate Variability

Zhao, Yang and Liu, 2016: Assessing Bjerknes compensation for climate variability and its timescale dependence. J. Climate

$$C_{Rp} \equiv \frac{F'_a}{F'_o} = Re\left(C_{R0}e^{i\delta}\right) = r_\delta * C_{R\omega}$$

$$r_\delta \equiv cos\delta = -\frac{F}{\sqrt{\omega^2 + F^2}}$$

$$C_{R\omega} = \frac{2\chi}{\epsilon c \rho_0 D_1 \sqrt{\omega^2 + F^2}}$$

=

$$C_R \equiv r\frac{\sigma_{F_a}}{\sigma_{F_o}}$$

$\omega \to 0$

$$C_{R0} = -\frac{1}{1 + B/2\chi}$$

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BJC for Climate Variability

$$\omega \to \infty \;\; \Rightarrow \; r_\delta \to \mathbf{0}; \;\; C_{R0} \to \mathbf{0}; \; C_{Rp} \to \mathbf{0}$$

No correlation and No BJC

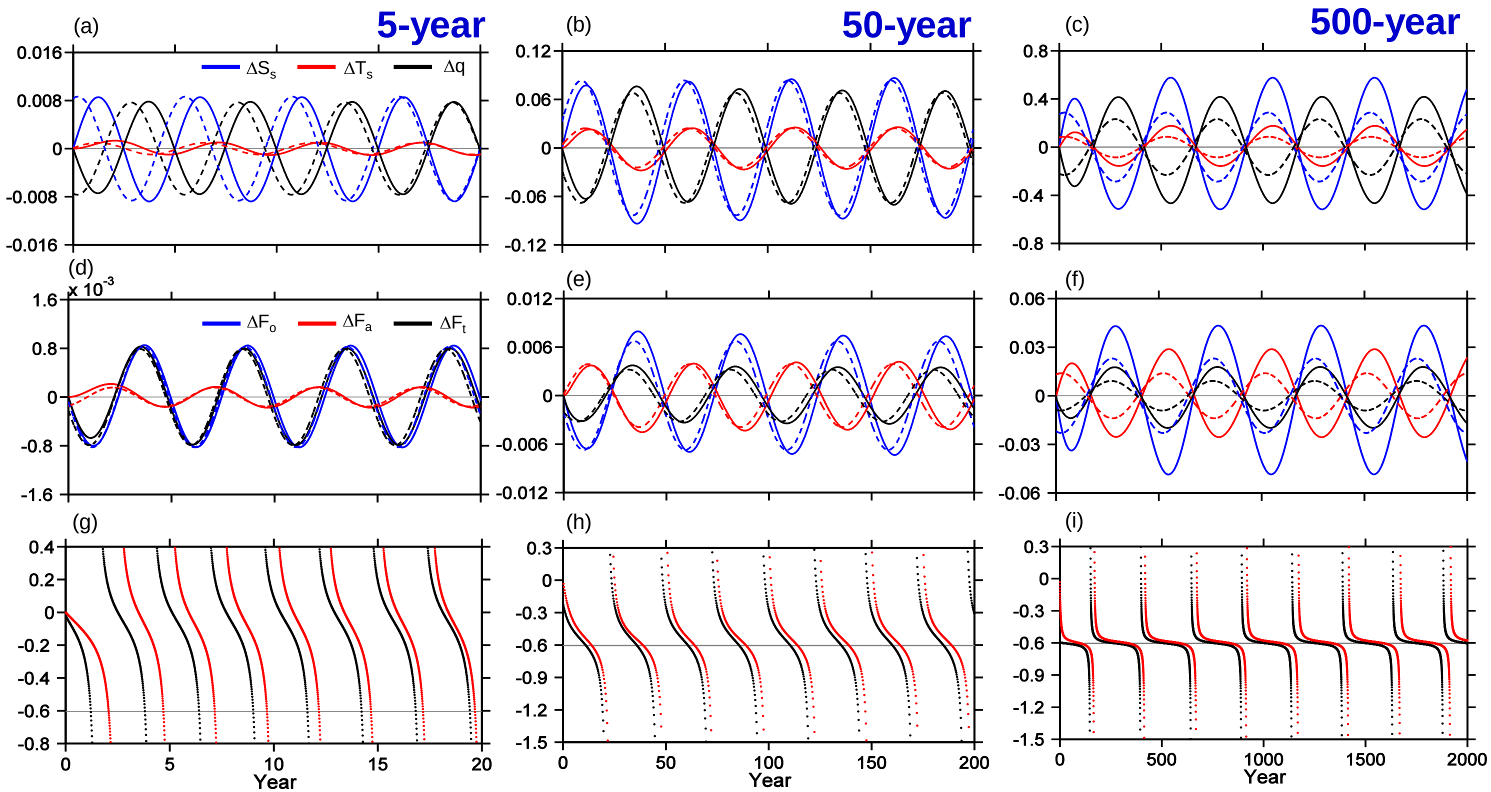
$$\omega \to \mathbf{0} \;\; \Rightarrow \; r_\delta \to -\mathbf{1}; \;\; C_R(\mathbf{1}) \asymp C_{R\mathbf{0}}(\mathbf{2}) \asymp C_{R\mathbf{p}}(\mathbf{3})$$

Full correlation and equilibrium BJC

Go to Climate Variability Validation

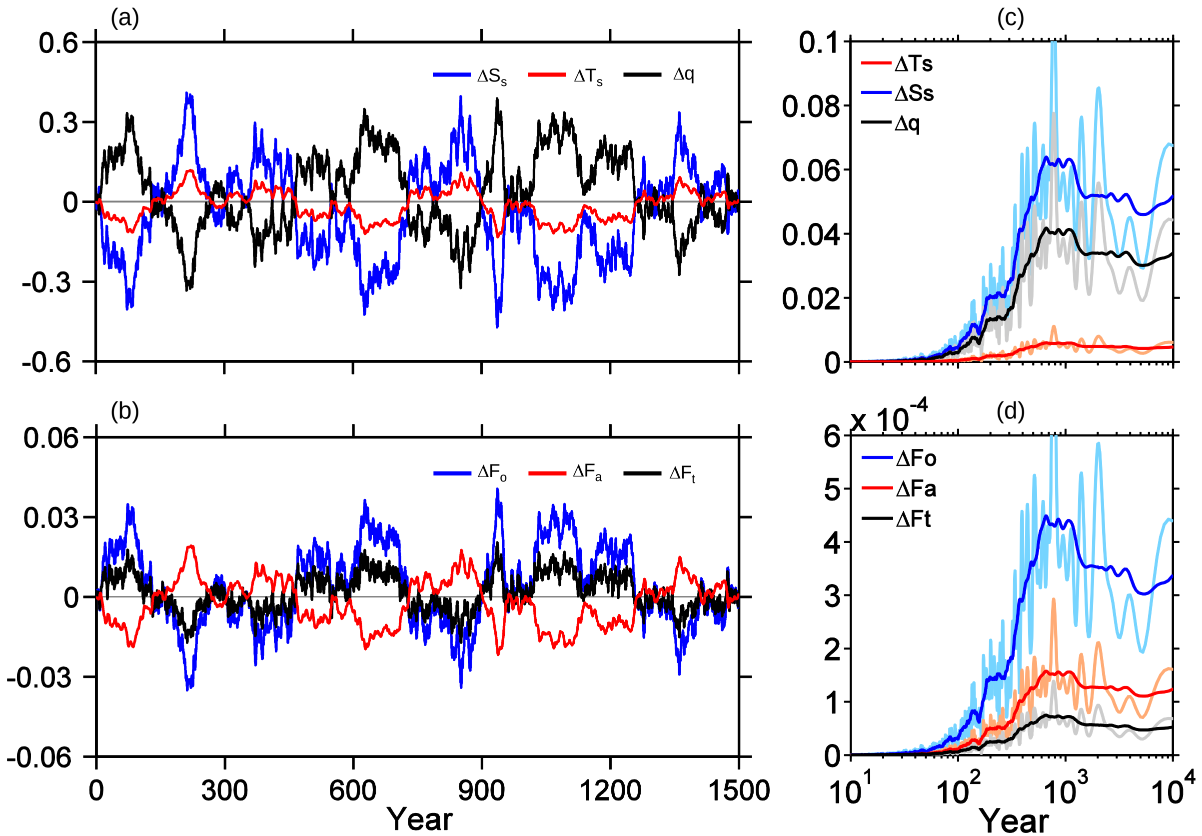
BJC for Climate Variability

Under periodic forcing: $h_{fw} = Re(h_0 e^{i\omega t})$



BJC for Climate Variability

Under stochastic forcing: $h_{fw} = h_0 \int_{\omega=0}^{\omega=\infty} e^{i\omega t}\, d\omega$



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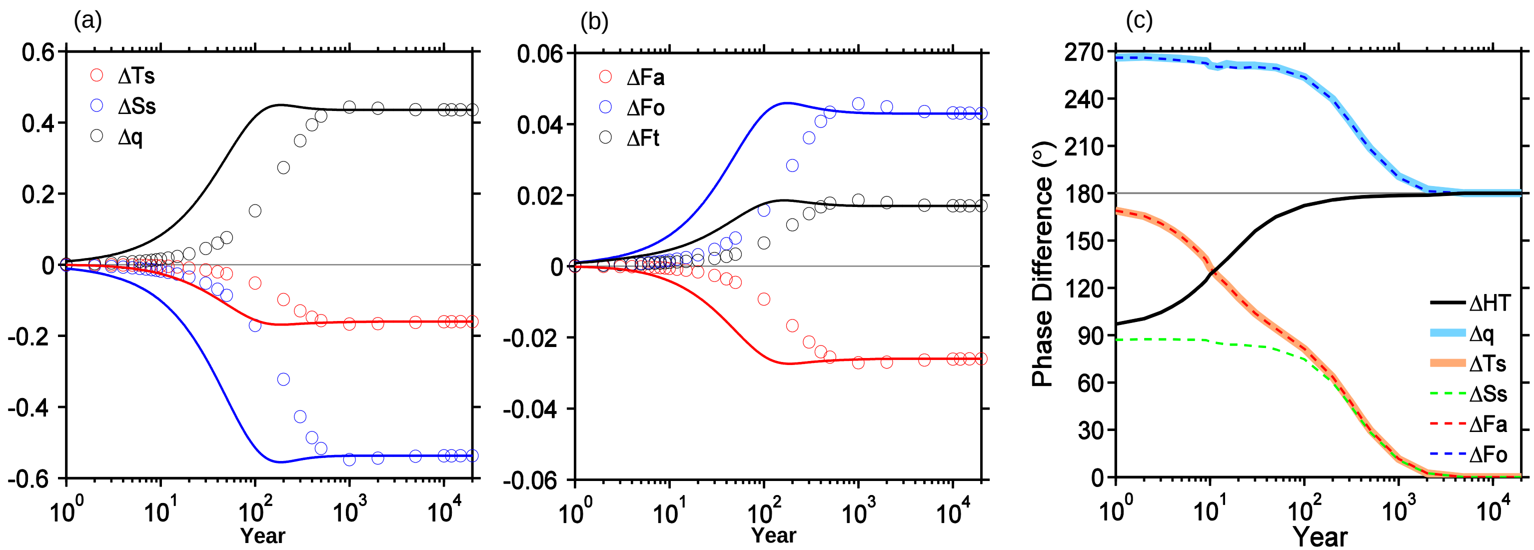
BJC for Climate Variability



Forcing frequency $\omega \rightarrow 0$ $\Rightarrow$ Equilibrium solution

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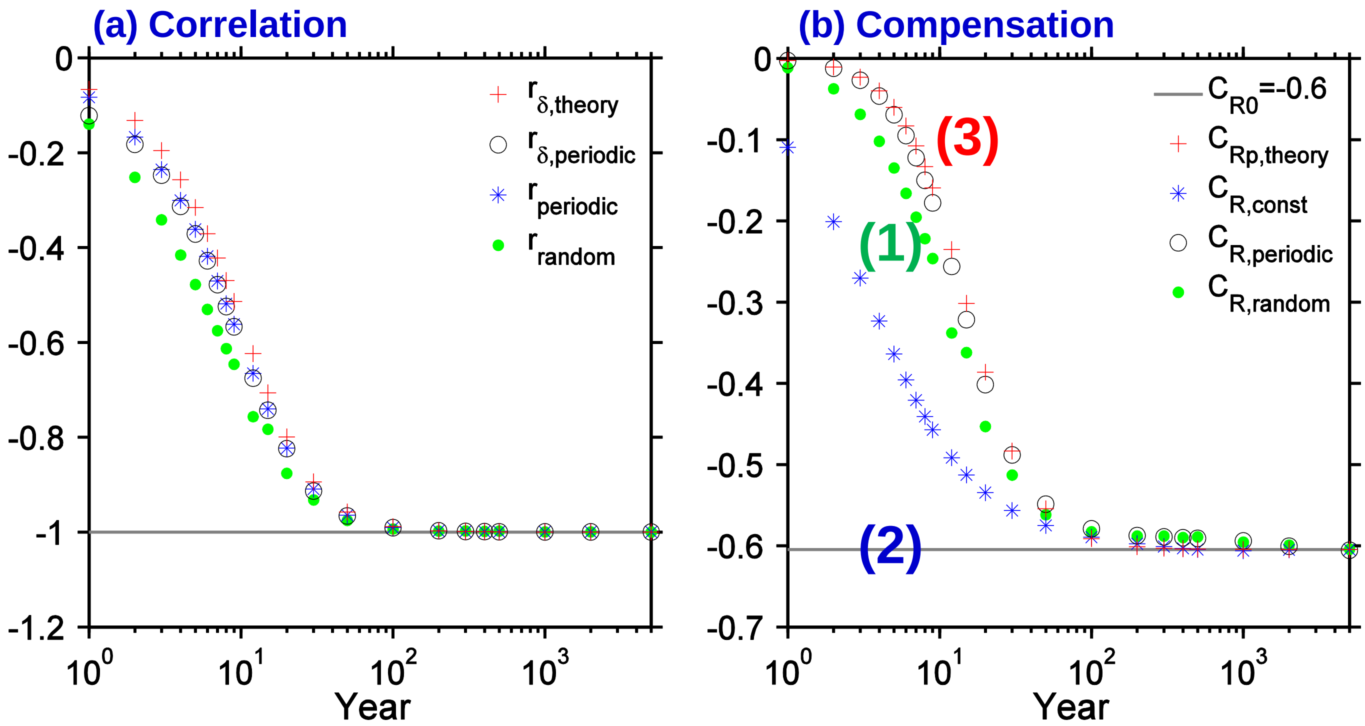
BJC Theory Valid for Climate Variability



Beyond *decadal* timescale, AHT and OHT out of phase, BJC established

Outline

- Fundamentals
- Questions
- Hypothesis and Theory
- CGCM results
- Aquaplanet
- Summary

CESM Experiment and Mechanism

- **Fresh-water experiments**
- **Wind-perturbation experiments**
- **Global warming experiments**
- **Internal variability from a long control run**

Yang and Dai (2015), Yang et al. (2013, 2016, 2017)

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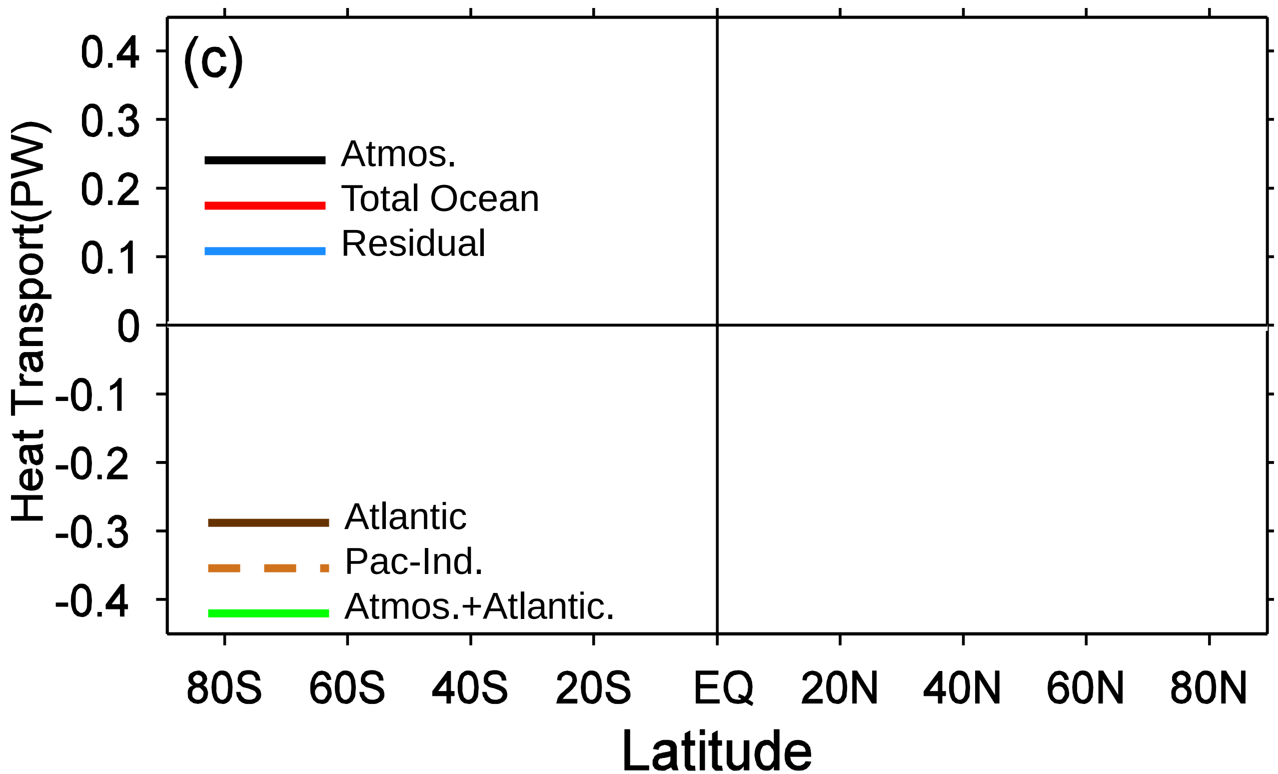
BJC under Freshwater in CESM



80-90%

Atlantic OHT ↓ ⇒ AHT ↑ ⇒ Pac-Ind. OHT ↑

Atlantic OHT ≈ AHT; Pac-Ind. OHT ≈ Overcompensation

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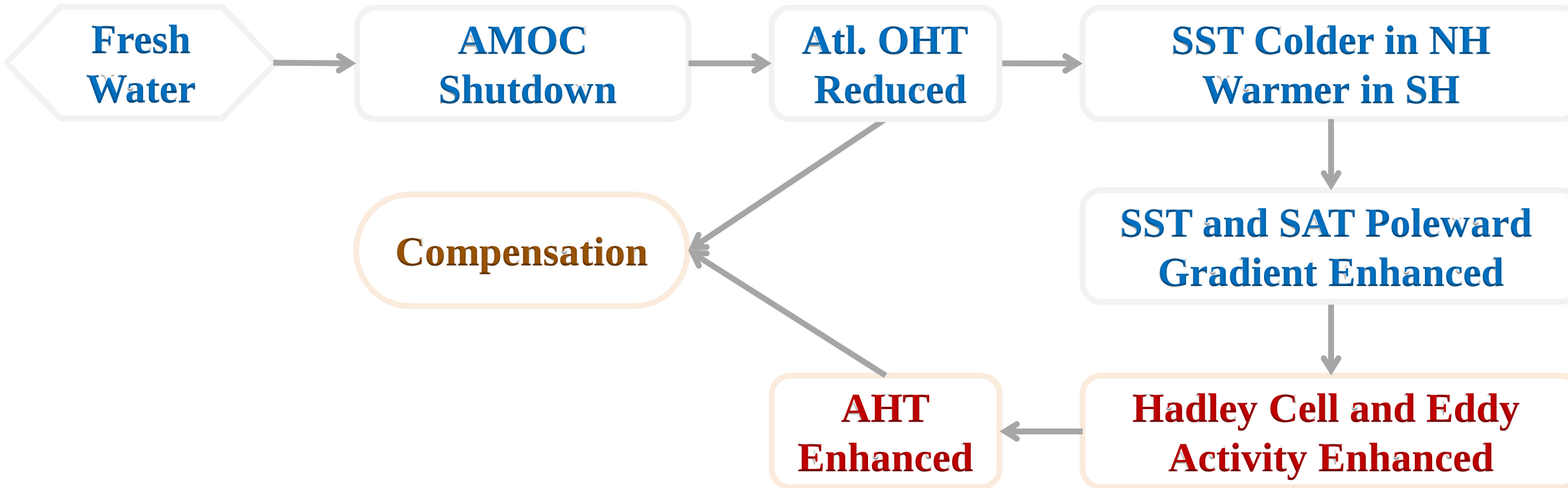
“Mechanism”



Yang et al. (2013, 2017)

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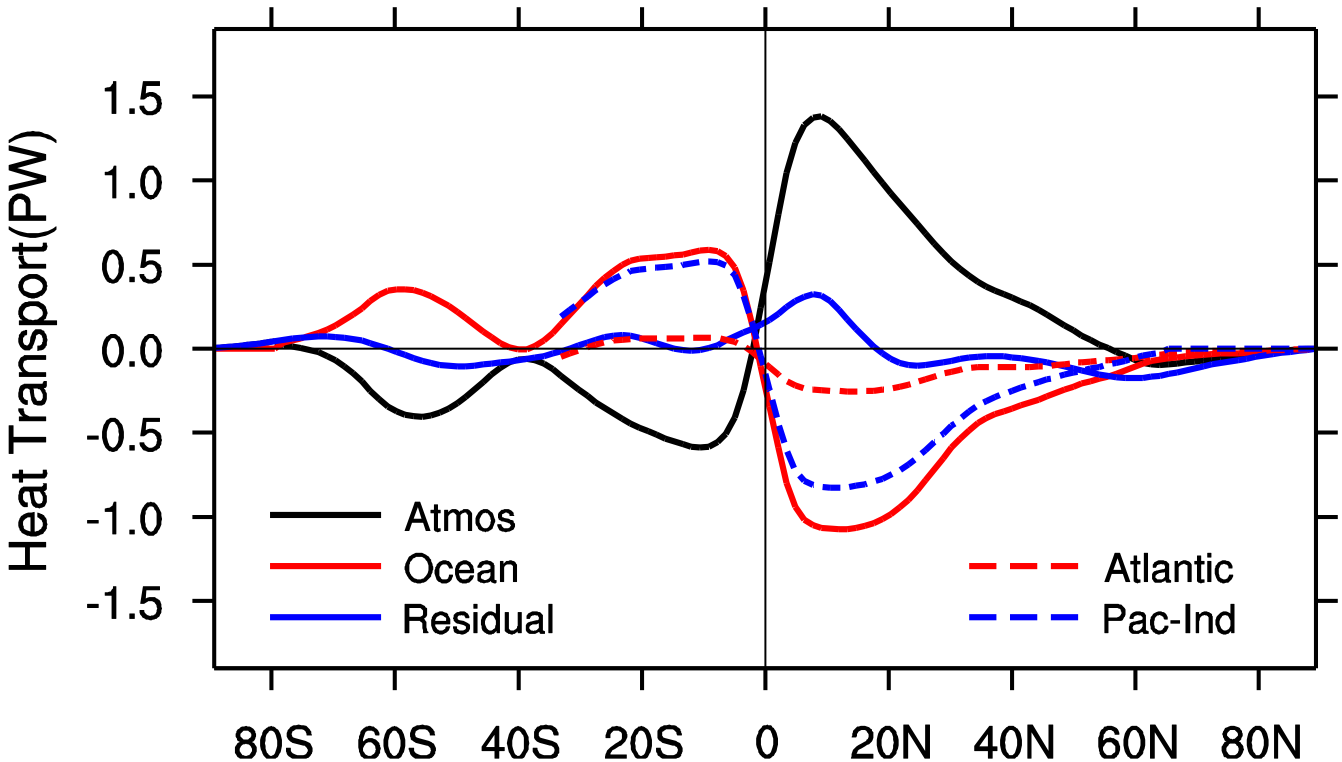
BJC under Wind Perturbation in CESM

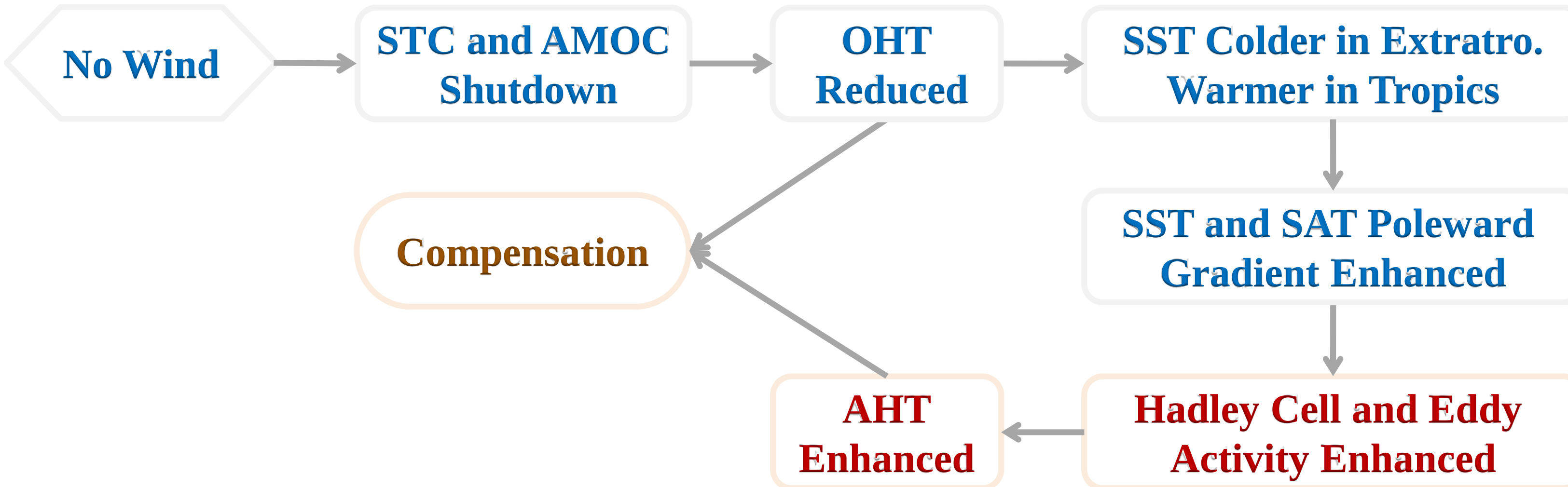


80-90%

Pacific-Indian OHT ⬇ ⇒ Ty ⬆ ⇒ HC ⬆ ⇒ AHT ⬆

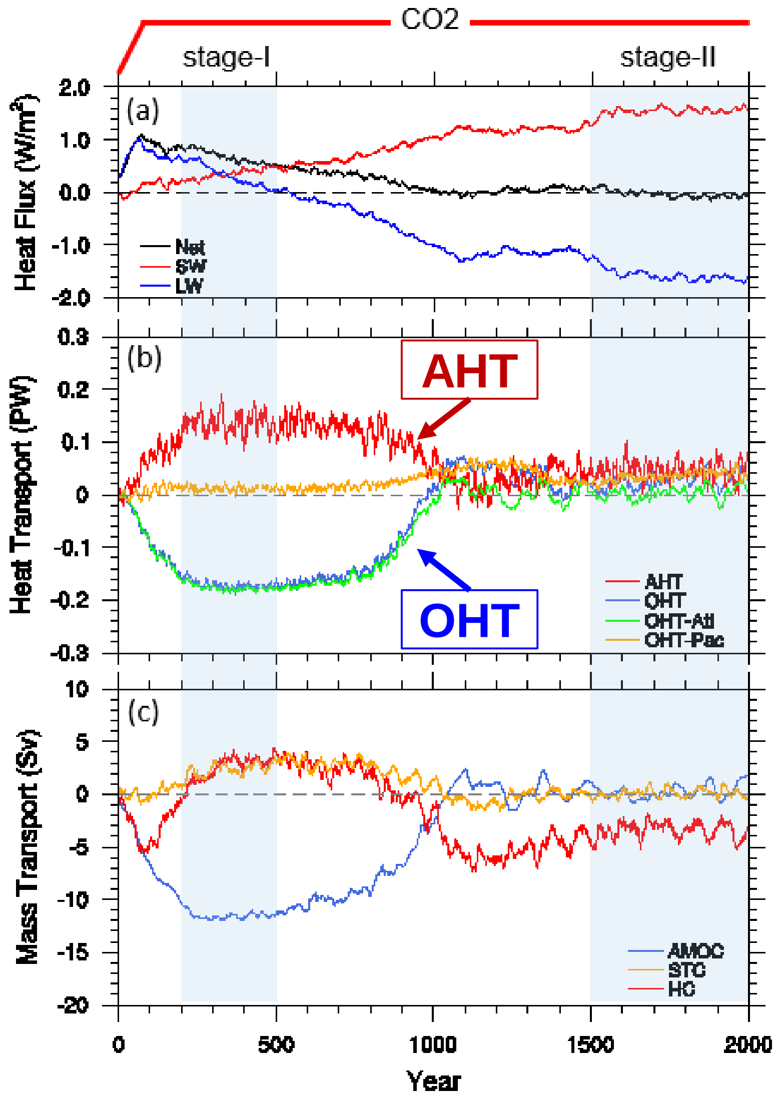
Nearly Compensation

“Mechanism”



Yang and Dai (2015), Dai et al. (2017)

BJC under Global Warming in CESM



Yang et al. (2017)

85%

Under 2 X CO2 forcing

BJC valid due to *thermohaline dynamics*!

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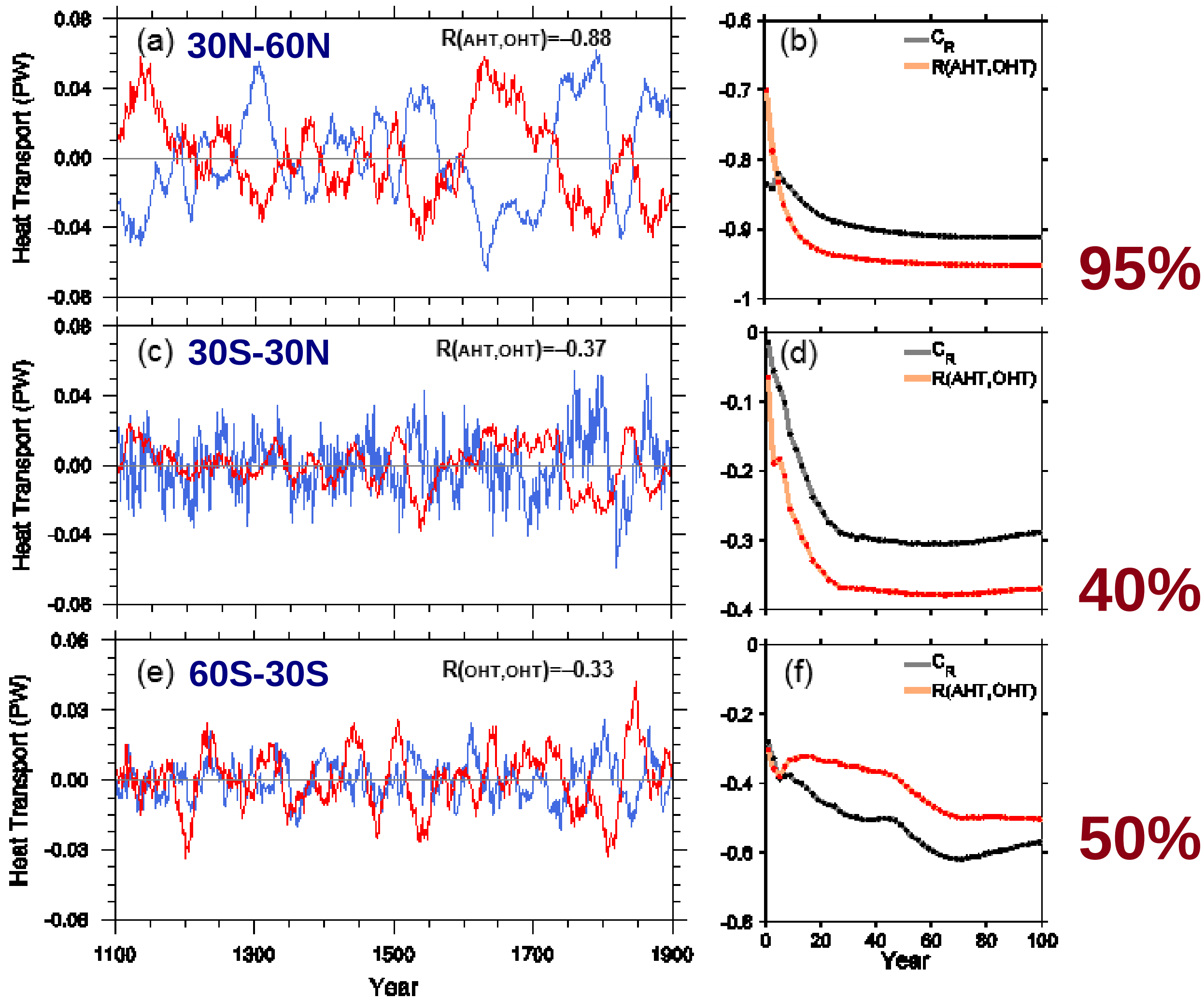
BJC in Natural Variability in CESM

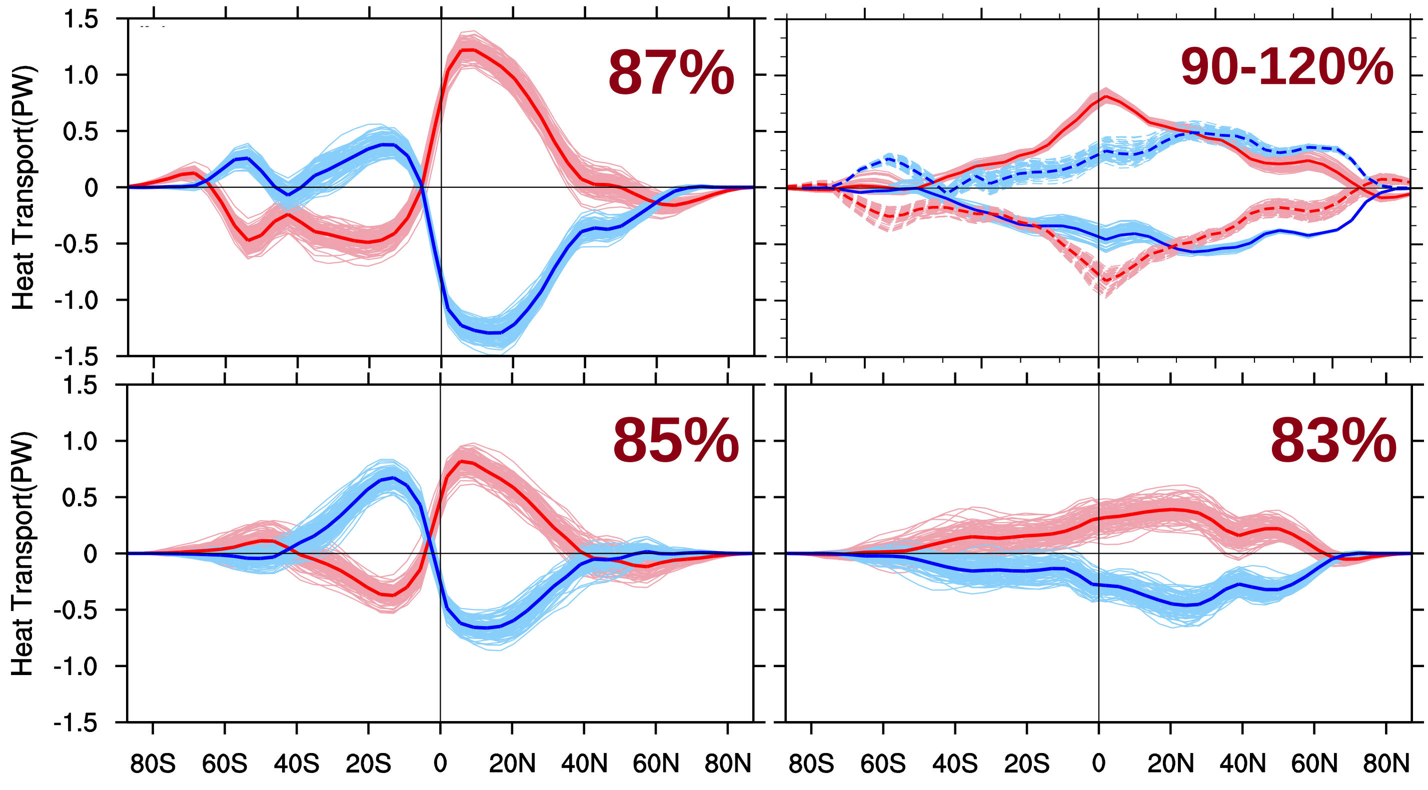
2000-year CESM control run



Zhao and Yang (2017)

Summary: BJC in CESM

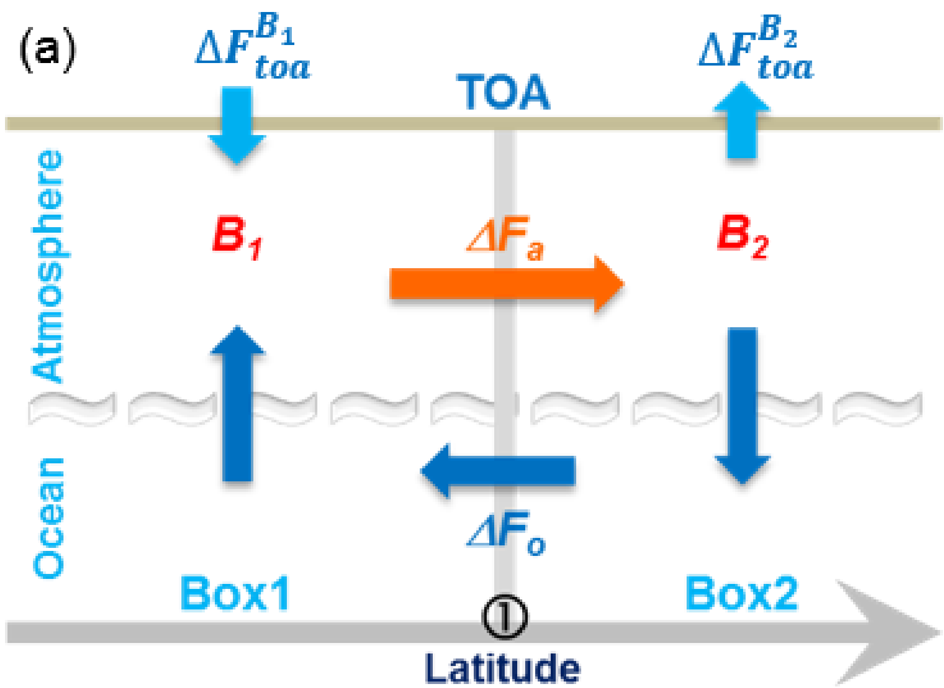
Surface Reason: *Out-of-phase* changes in Atmos-Ocean MOC → BJC



Yang and Dai (2015), Yang et al. (2013, 2016, 2017)

BJC Mechanism

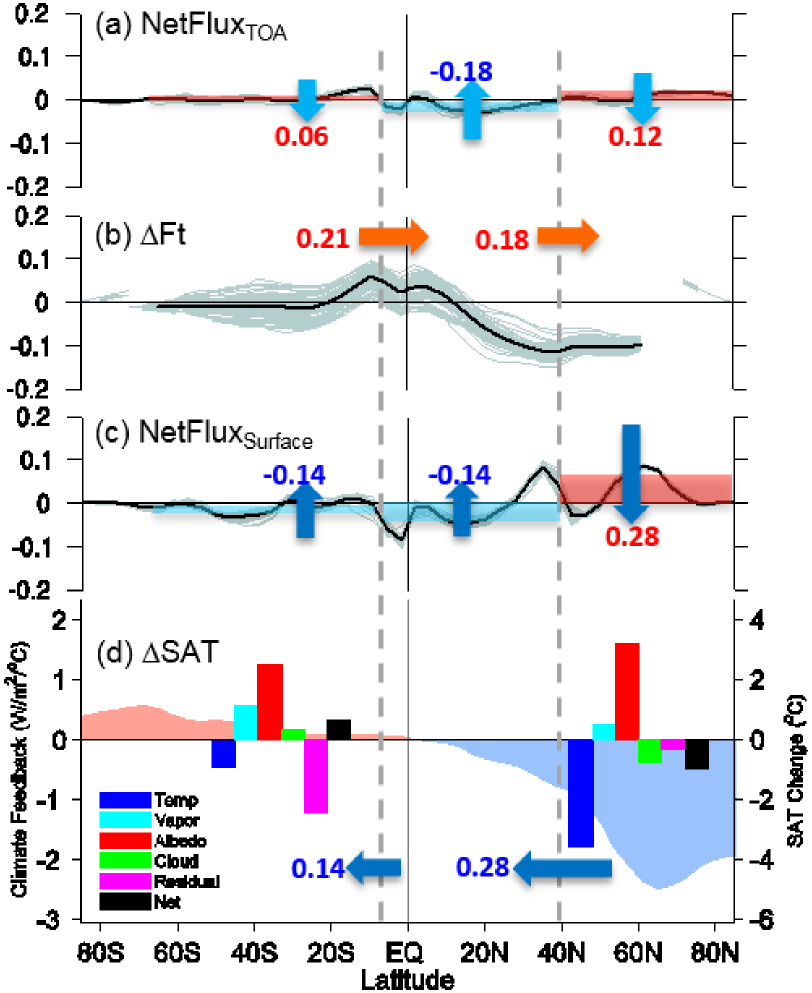
Fundamental Reason: Climate feedback + Energy constrain ➔ BJC



$$C_R = -(B_1+B_2)\chi/[B_1B_2+(B_1+B_2)\chi]$$

BJC: *Theory* vs *CGCM*

CESM Wind Perturbation experiments



Wind		Temp	Albedo	Cloud	C_{Rmodel}	$C_{Rtheory}$
0.1A	NH	-1.80	1.30	-0.23	-1.10	-1.09
	SH	-0.44	1.16	-0.07		
	Global	-2.20	1.34	-0.28	-0.83	-0.71
0.1P	NH	-1.87	1.30	0.34	-1.85	-1.61
	SH	-2.14	0.39	0.57		
	Global	-1.88	0.95	0.27	-0.85	-0.77
0.1G	NH	-1.84	1.05	-0.08	-0.95	-0.91
	SH	-1.70	1.96	-0.29		
	Global	-1.77	1.51	-0.18	-0.87	-0.81

$$C_{Rmodel} \approx C_{Rtheory}$$

Dai et al. (2017)

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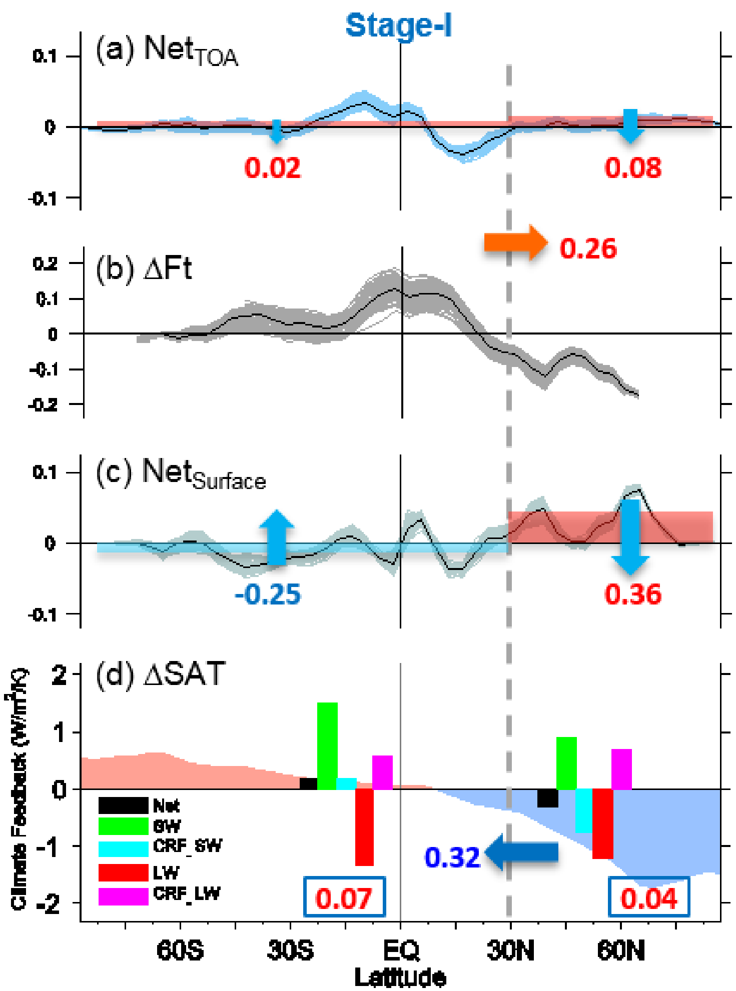
BJC: *Theory* vs *CGCM*

CESM Freshwater experiments



	Freshwater	Global	SH	NH	90°S-30°N	30°N-90°N
Stage-I	Net CF	-0.63	0.89	0.08	0.18	-0.30
	C_{Rmodel}	-0.97	-1.36		-0.88	
	$C_{Rtheory}$	-0.83	-1.05		-1.43	
Stage-II	Net CF	1.96	0.66	0.35	0.16	-0.28
	C_{Rmodel}	-1.11	-1.90		-0.90	
	$C_{Rtheory}$	-2.88	-1.18		-1.33	

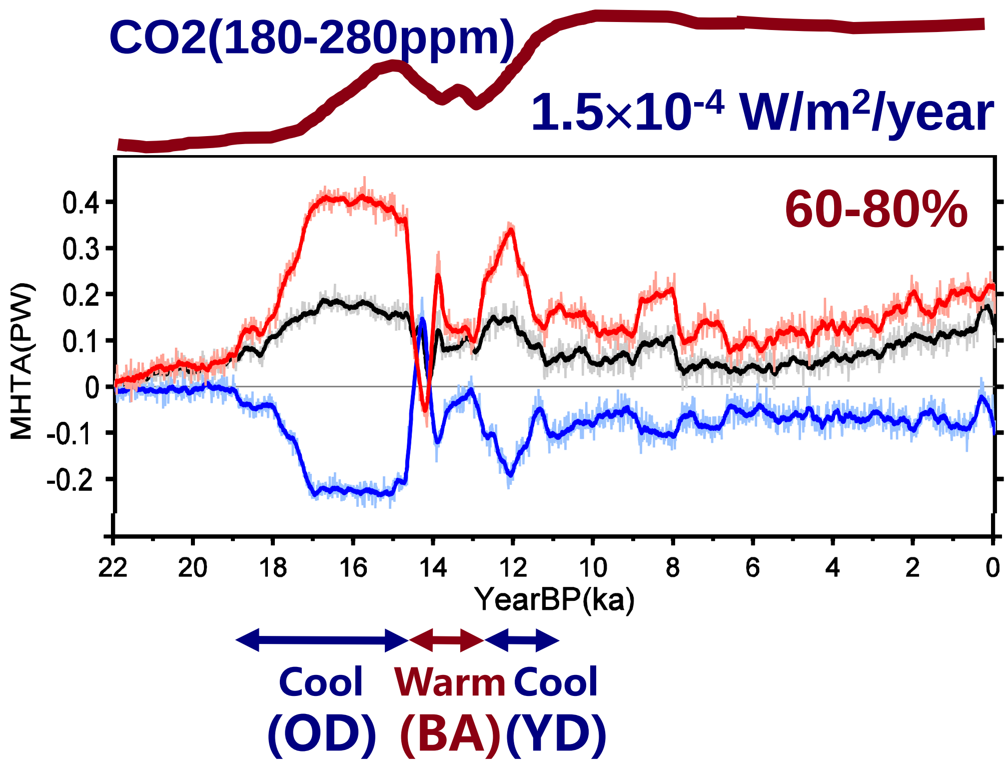
$$C_{Rmodel} \approx C_{Rtheory}$$

Yang et al. (2017)

BJC: Coupled *Intrinsic* Mode

3. Relationship between OHT and AHT Changes? **Answered!**

All-in-One **Simulation since LGM**



BJC helps to maintain overall Earth climate stability

Yang et al. (2015), Sci. Rep.

Outline

- Fundamentals
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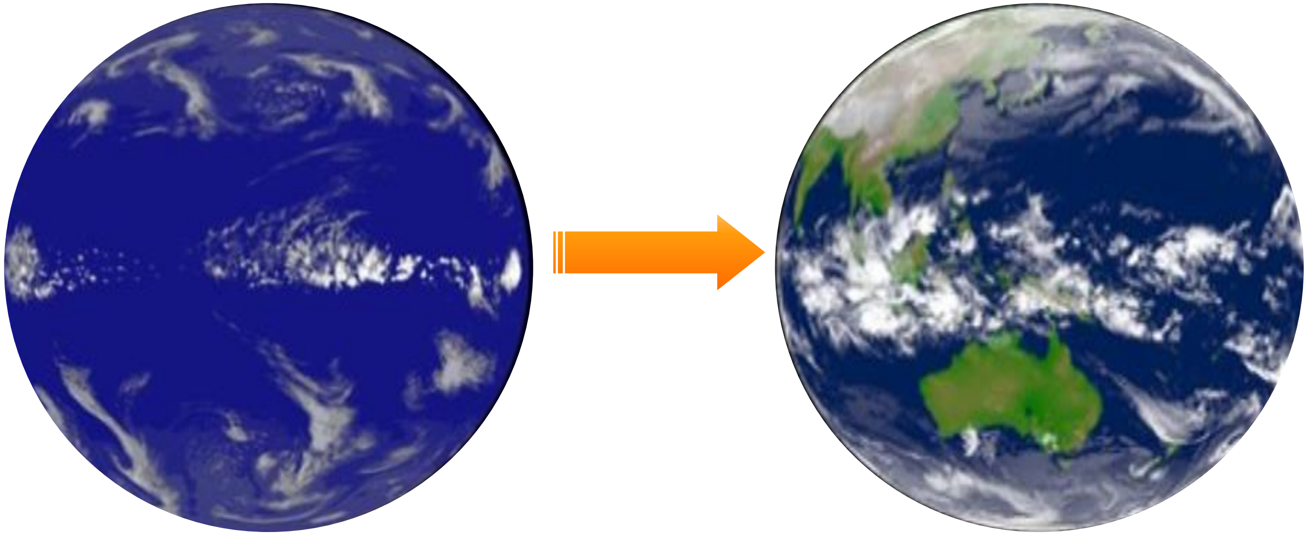
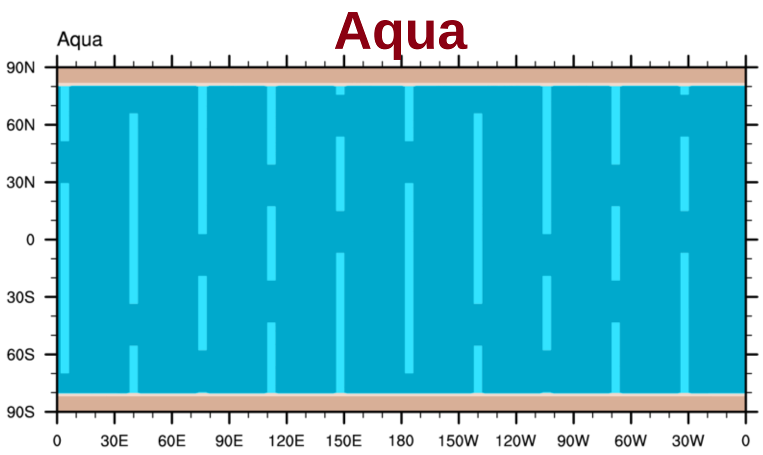
Why anti-symmetric MHT?

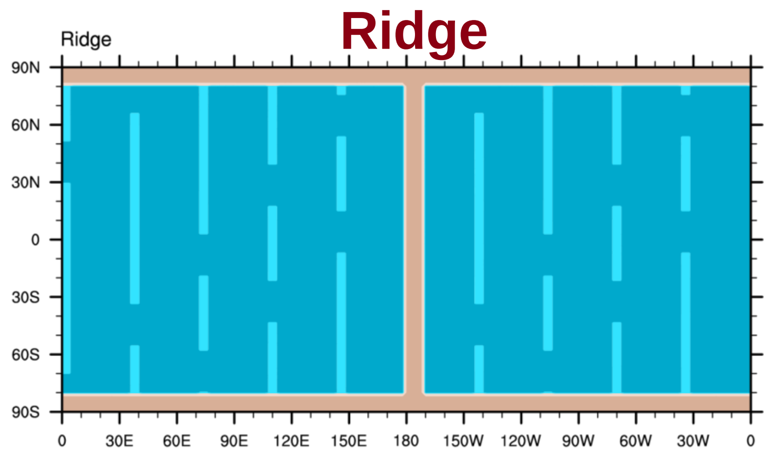


Try to answer this fundamental question

Topo for Aqua and Ridge

Land: 10 m; Ocean: 5000 m; Bottom random ridge: 500 m



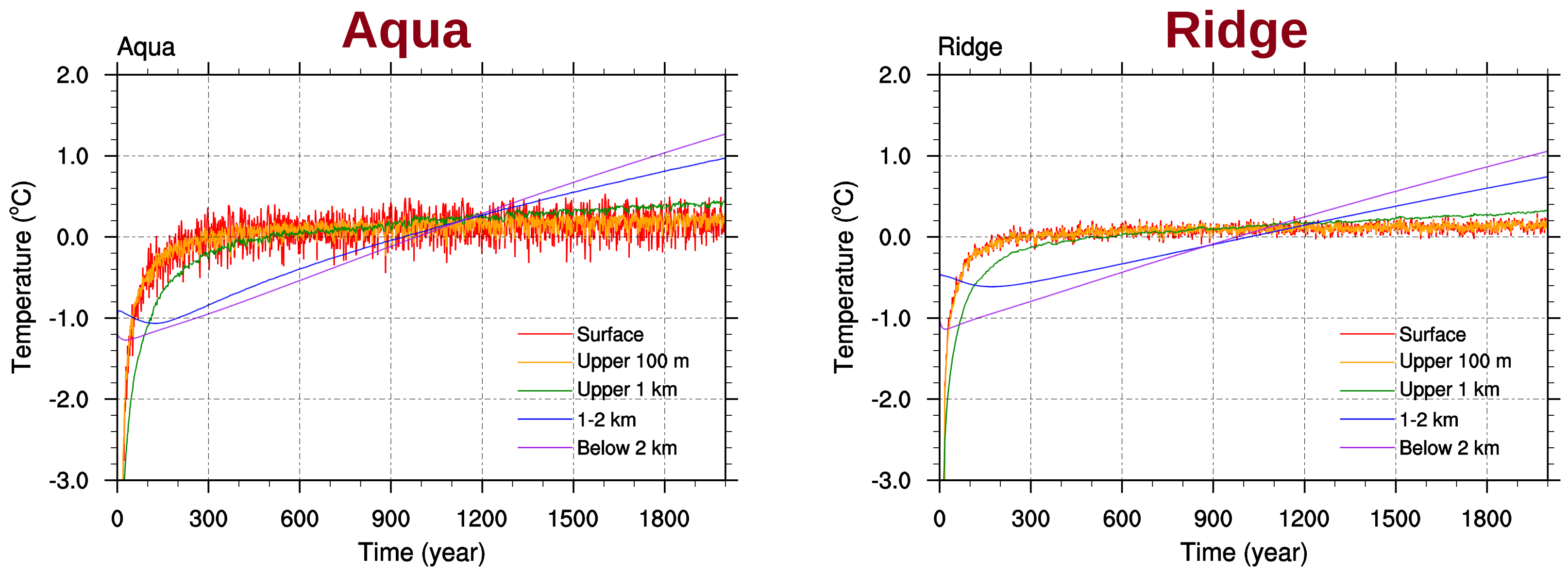


Li and Yang (2018)

Go to Summary

Hard to Reach Equilibrium

2000-year Simulation using CESM



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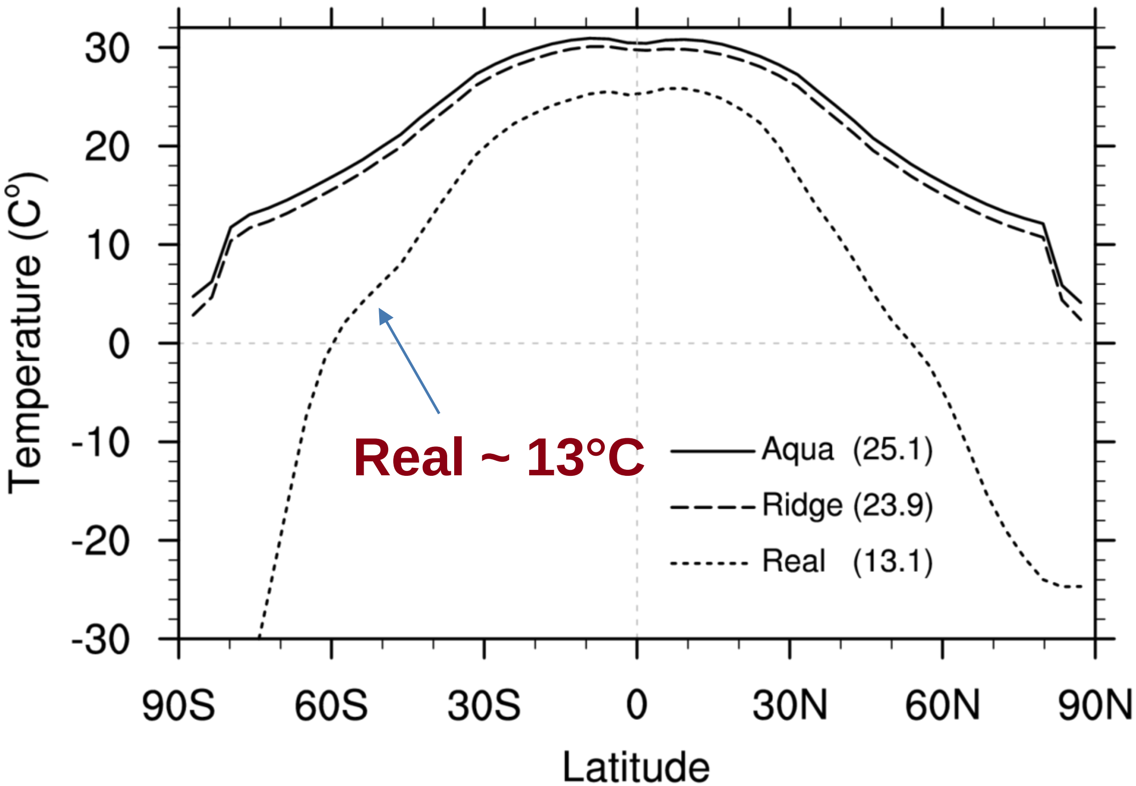
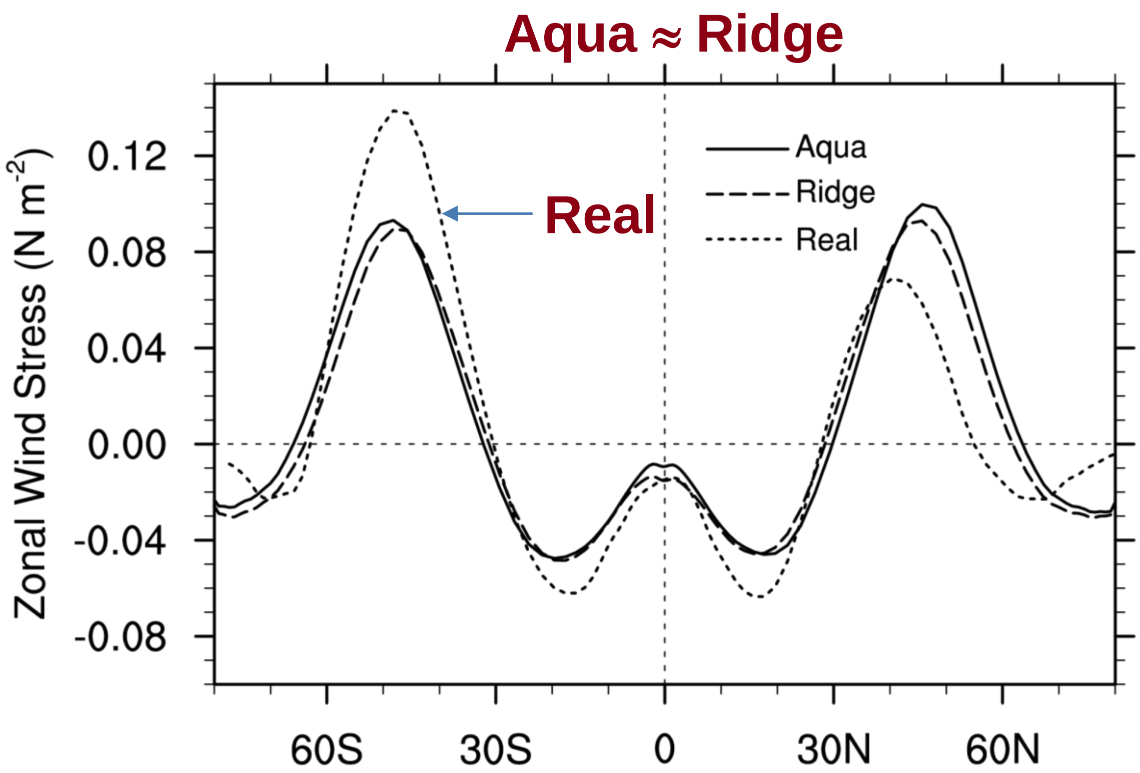
SAT: Warmer Climate

Aqua ≈ Ridge ≈ 24 ~ 25°C



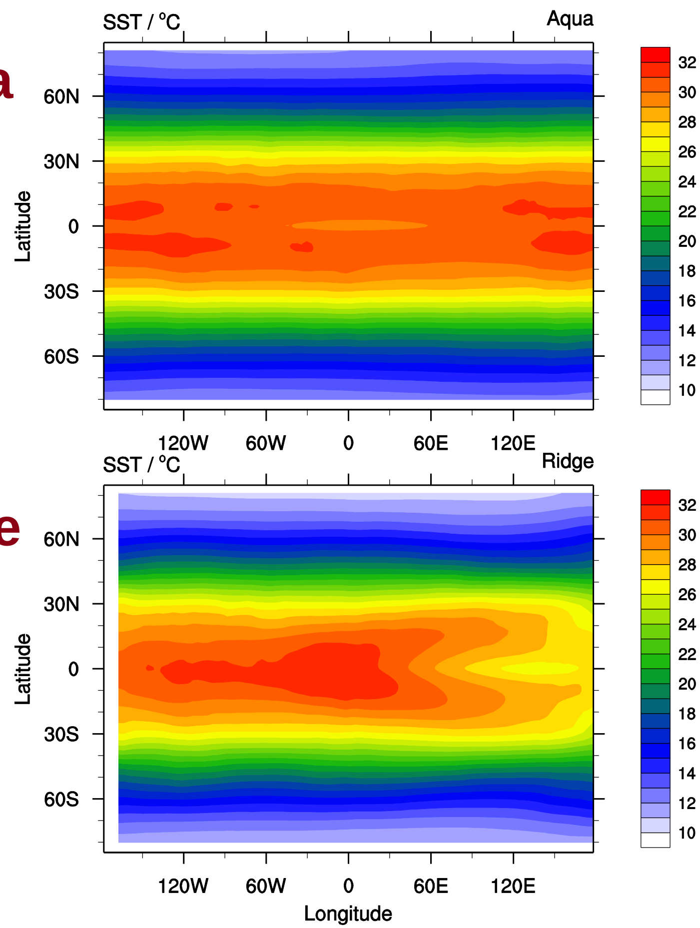
Symmetric Zonal Surface Wind Stress

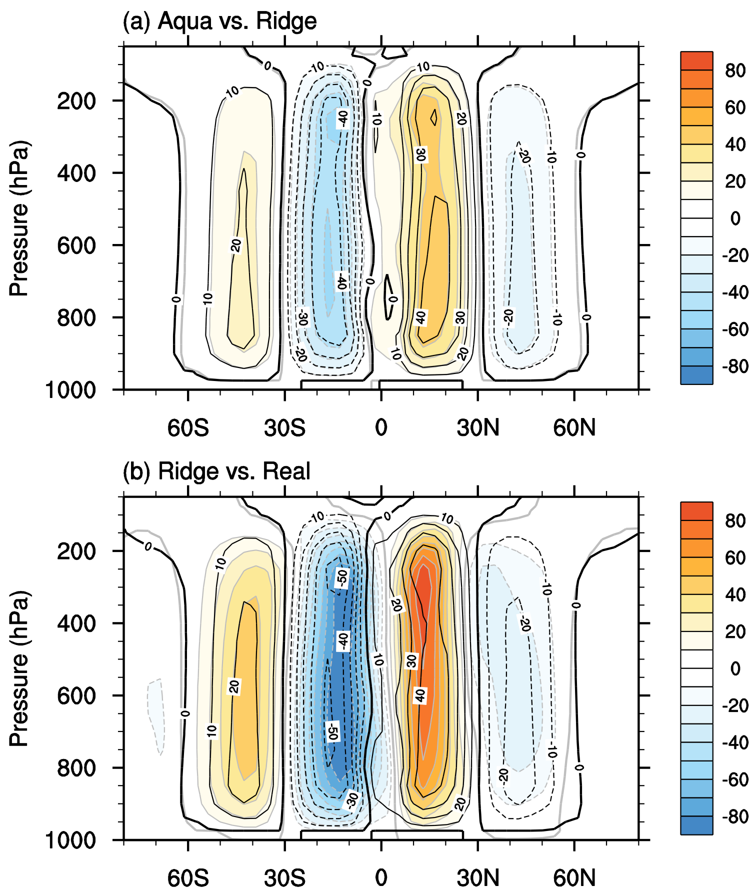


Symmetric SST and Hadley Cell

Aqua

Ridge





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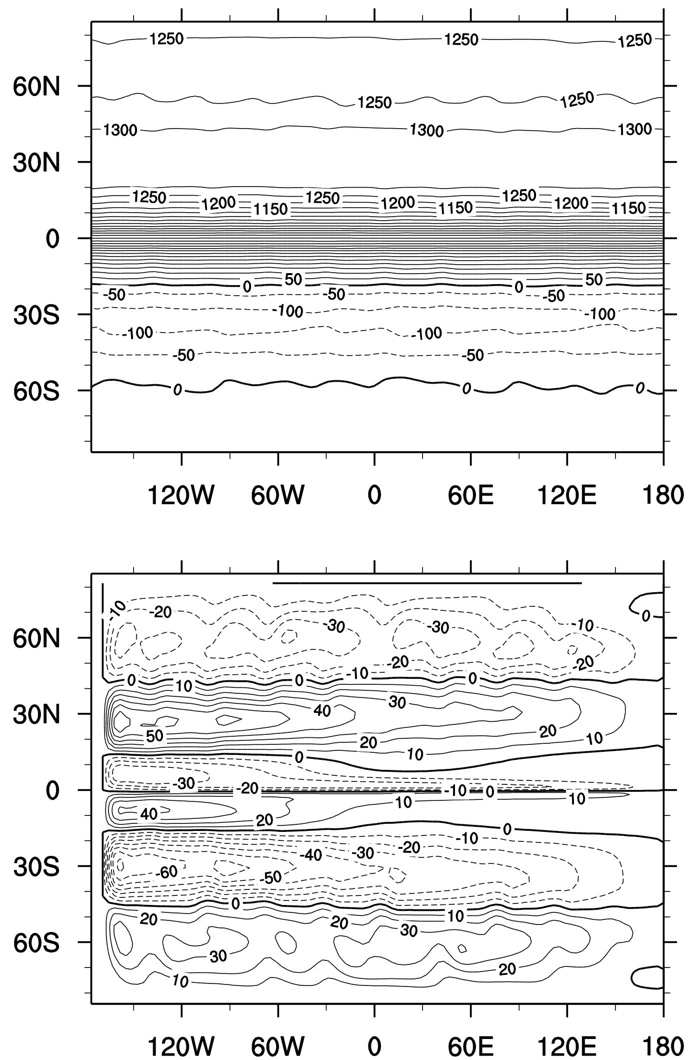
Symmetric Ocean Circulation

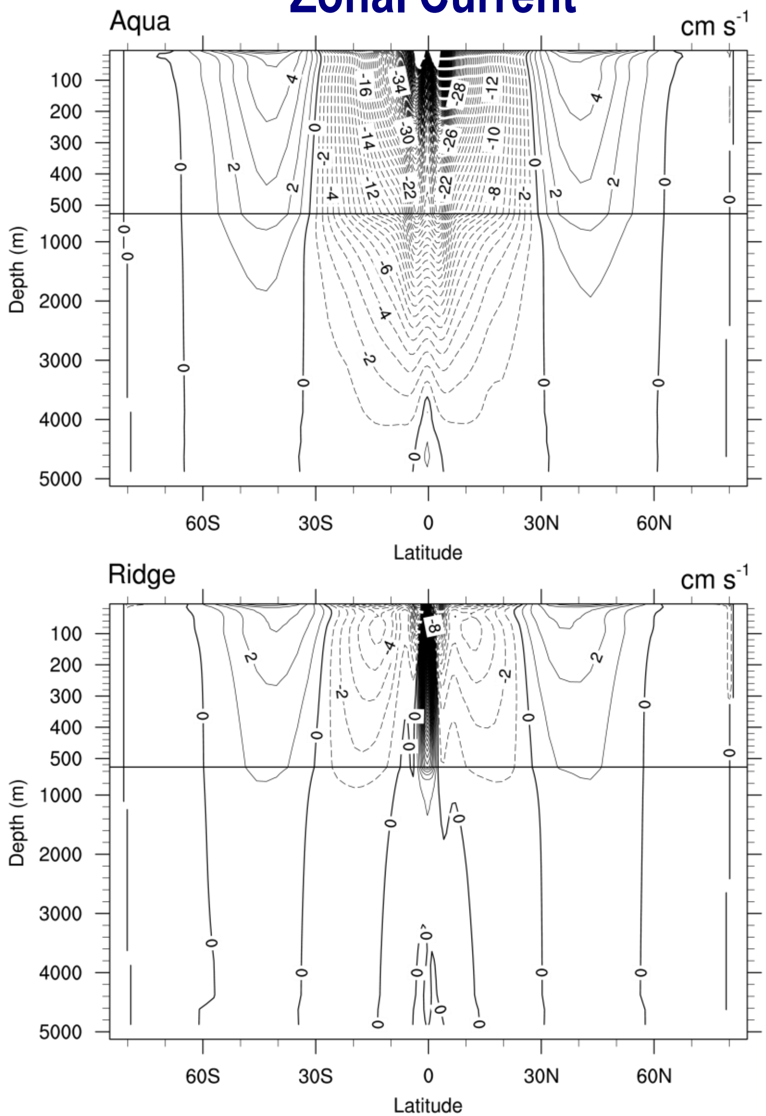
Barotropic Streamfunction

Aqua

Ridge



Zonal Current



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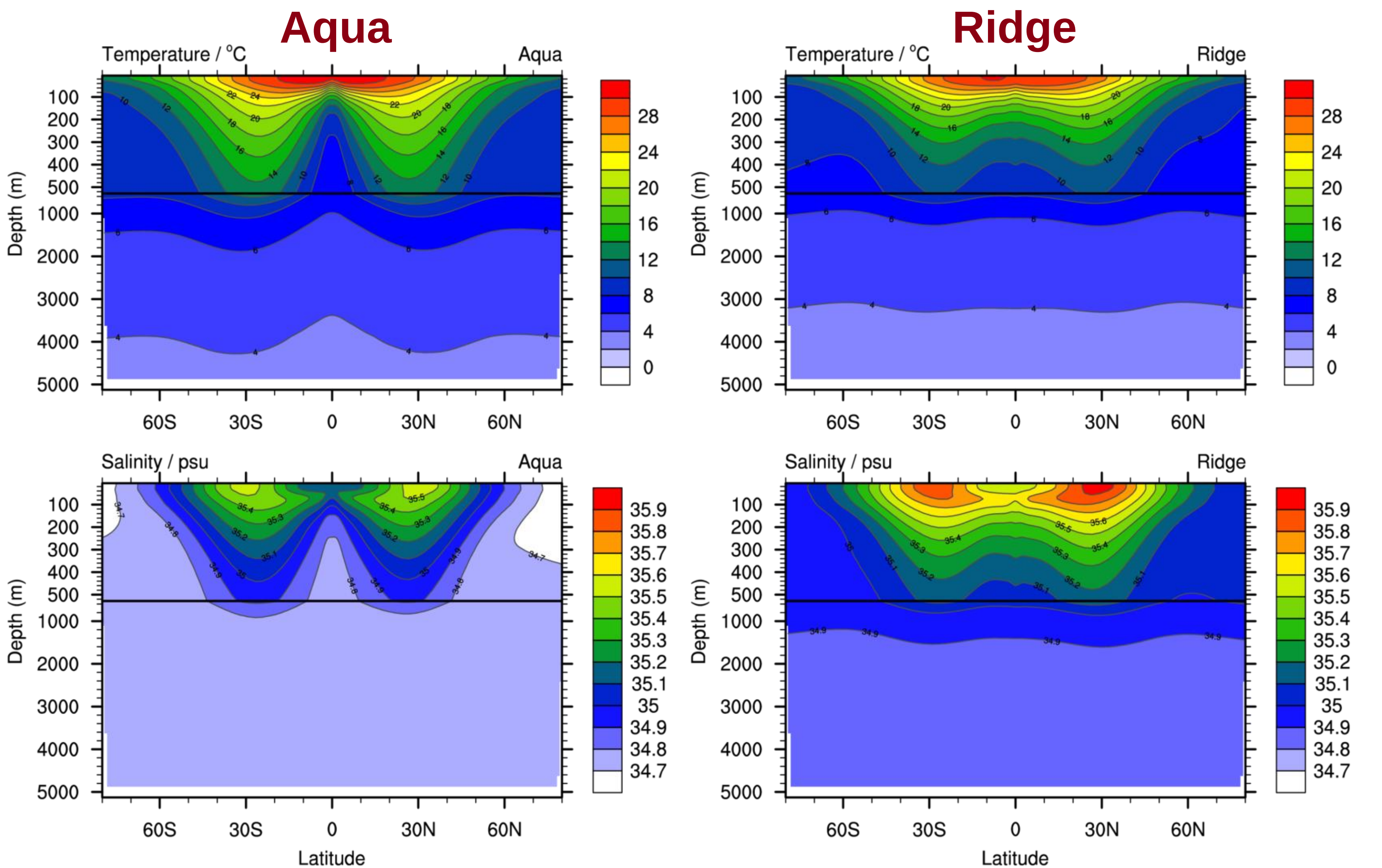
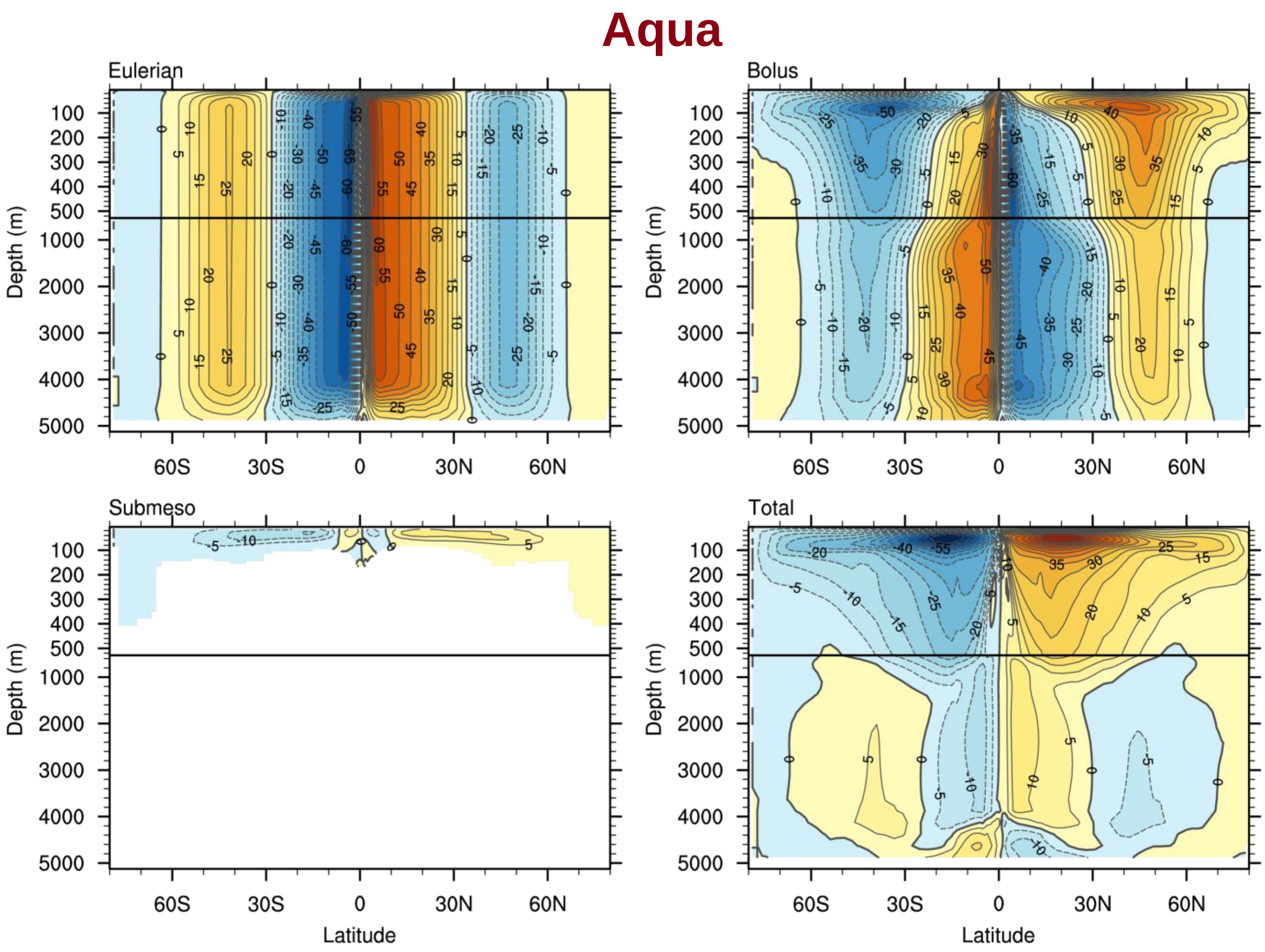
Symmetric Ocean Buoyancy

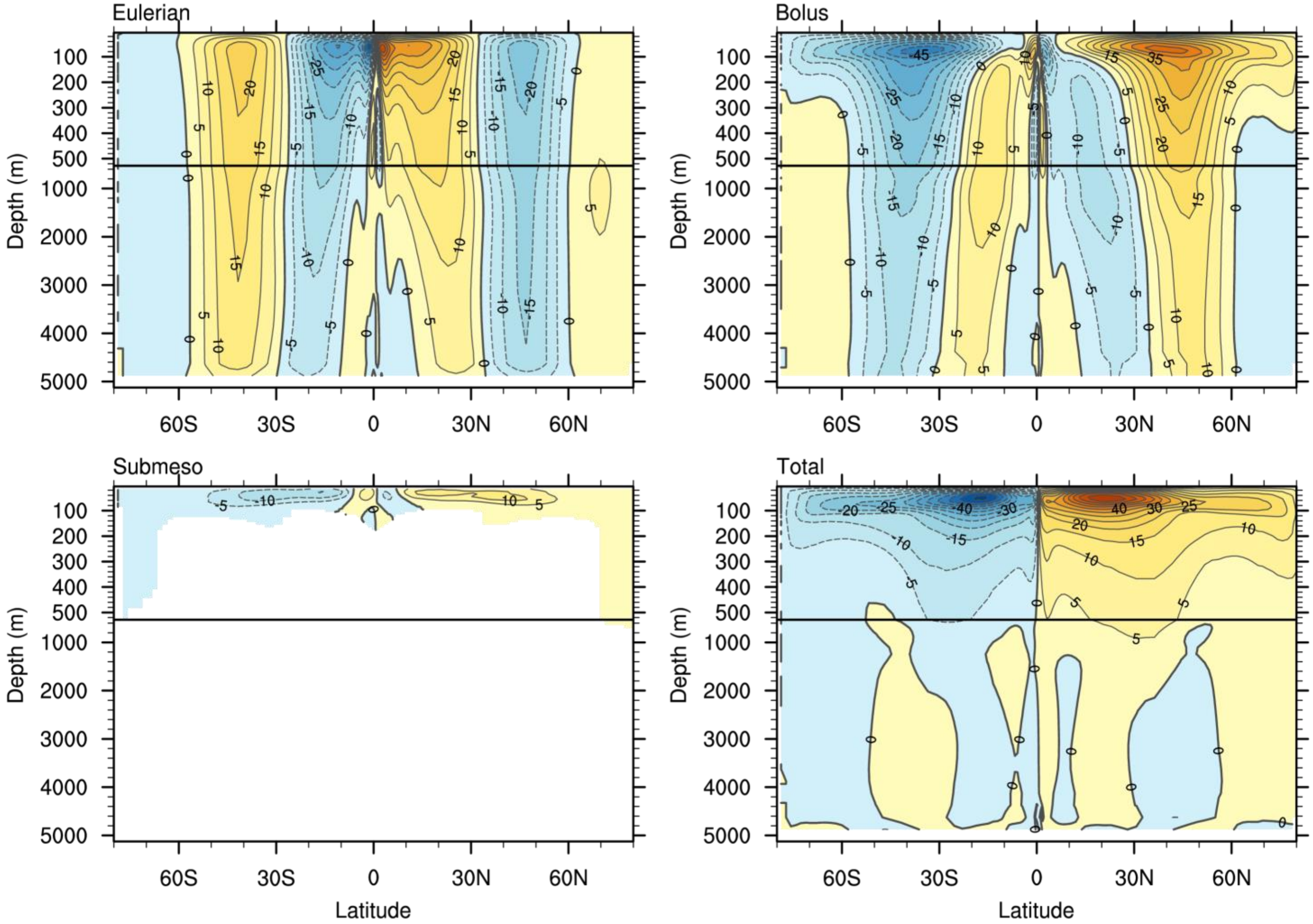


Symmetric Overturning Circulation



Symmetric Overturning Circulation

Ridge



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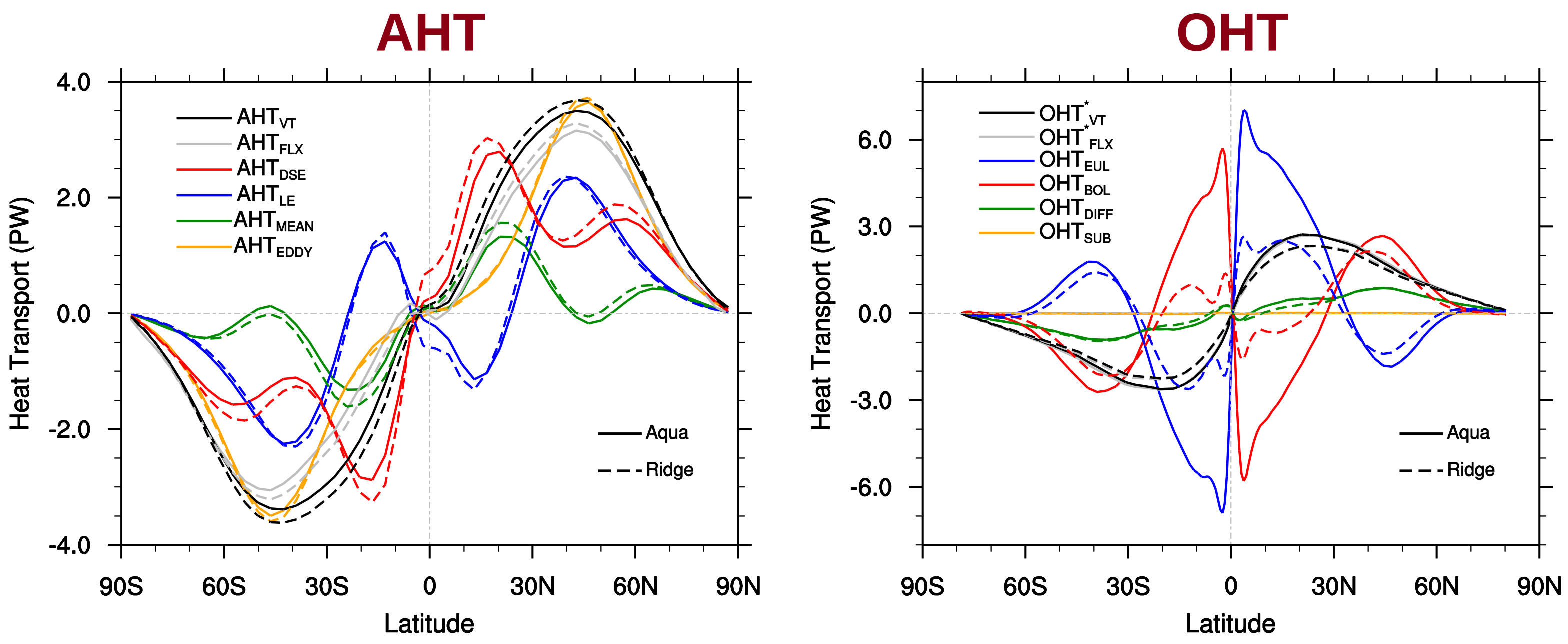
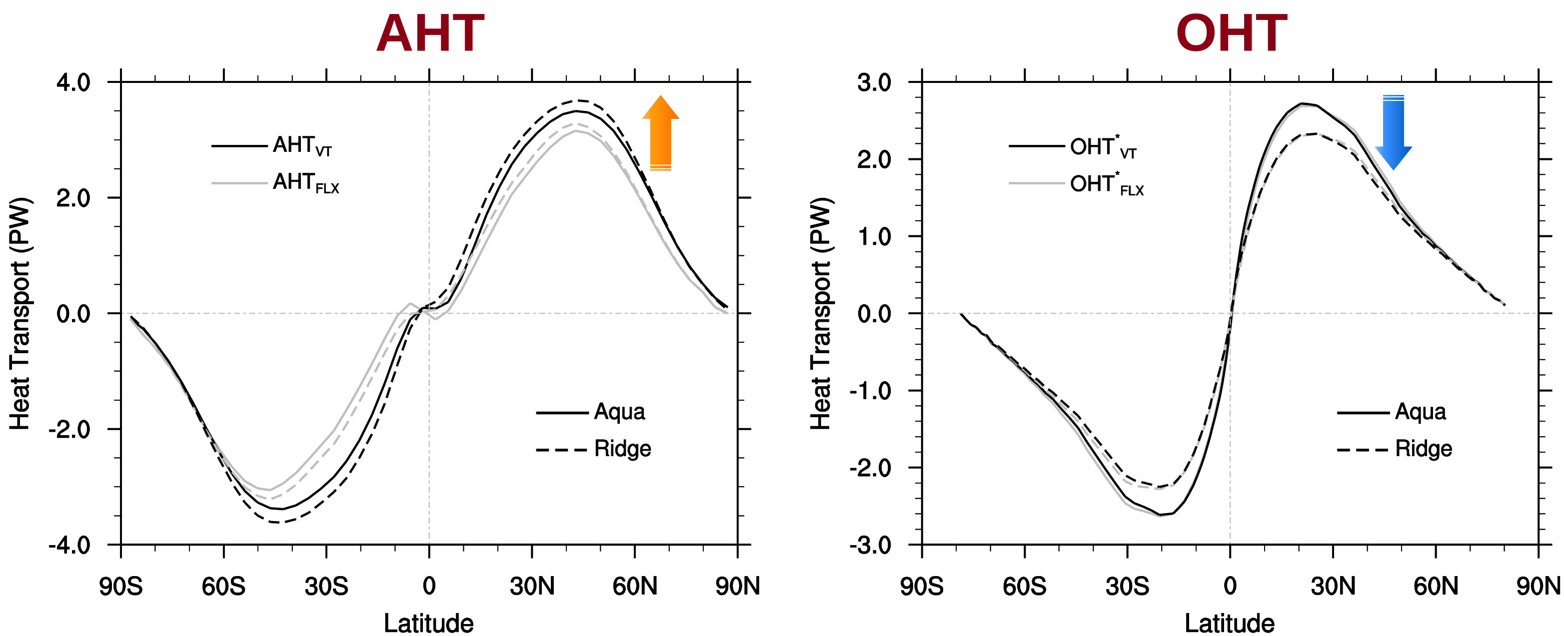
Symmetric AHT and OHT



Symmetric AHT and OHT



From *Aqua* to *Ridge* ➔ OHT ⇓ and AHT ⇑

Bjerknes Compensation

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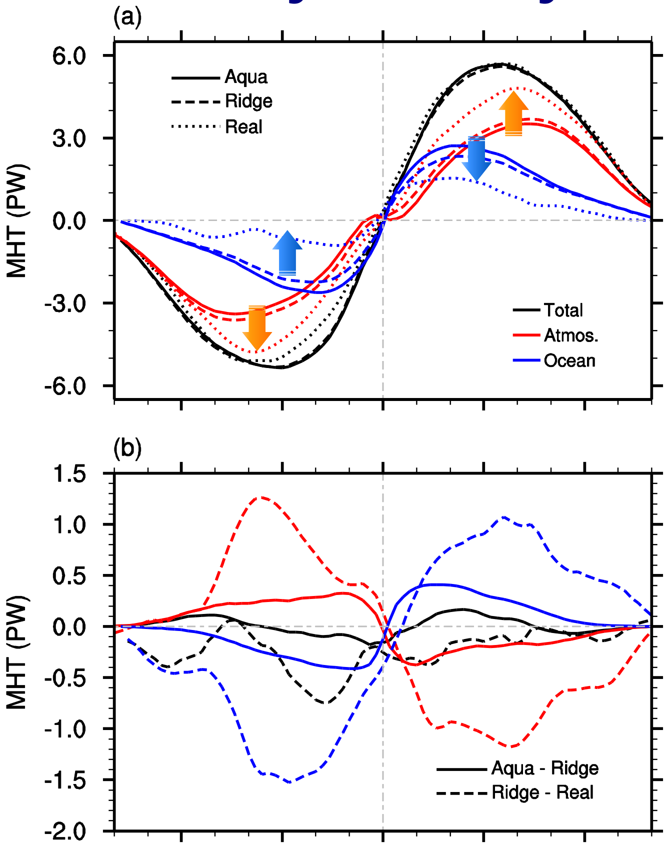
Aquaplanet → Real Earth

Why anti-symmetric MHT? Answered



From *Aqua* to *Real*

1. OHT ⇓ and AHT ⇑
2. OHT → asymmetric, NH>SH, AMOC + Weaker baroclinic
3. AHT → asymmetric, SH>NH, Stronger baroclinic dT/dy ⇑

→ Total MHT *unchanged*

BJC maintains antisymmetric MHT!

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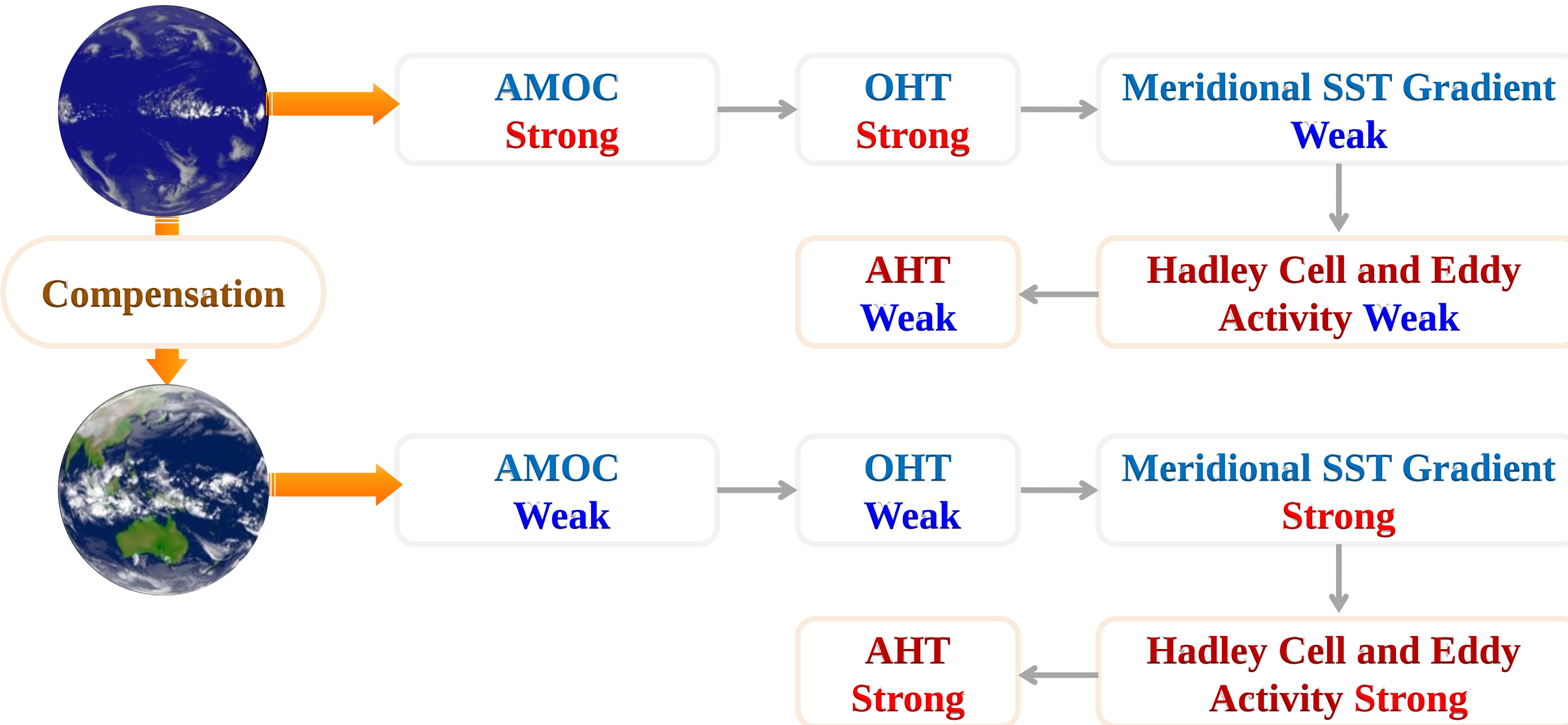
“Mechanism”



BJC maintains antisymmetric MHT!

Yang et al. (2018)

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Summary and Discussion

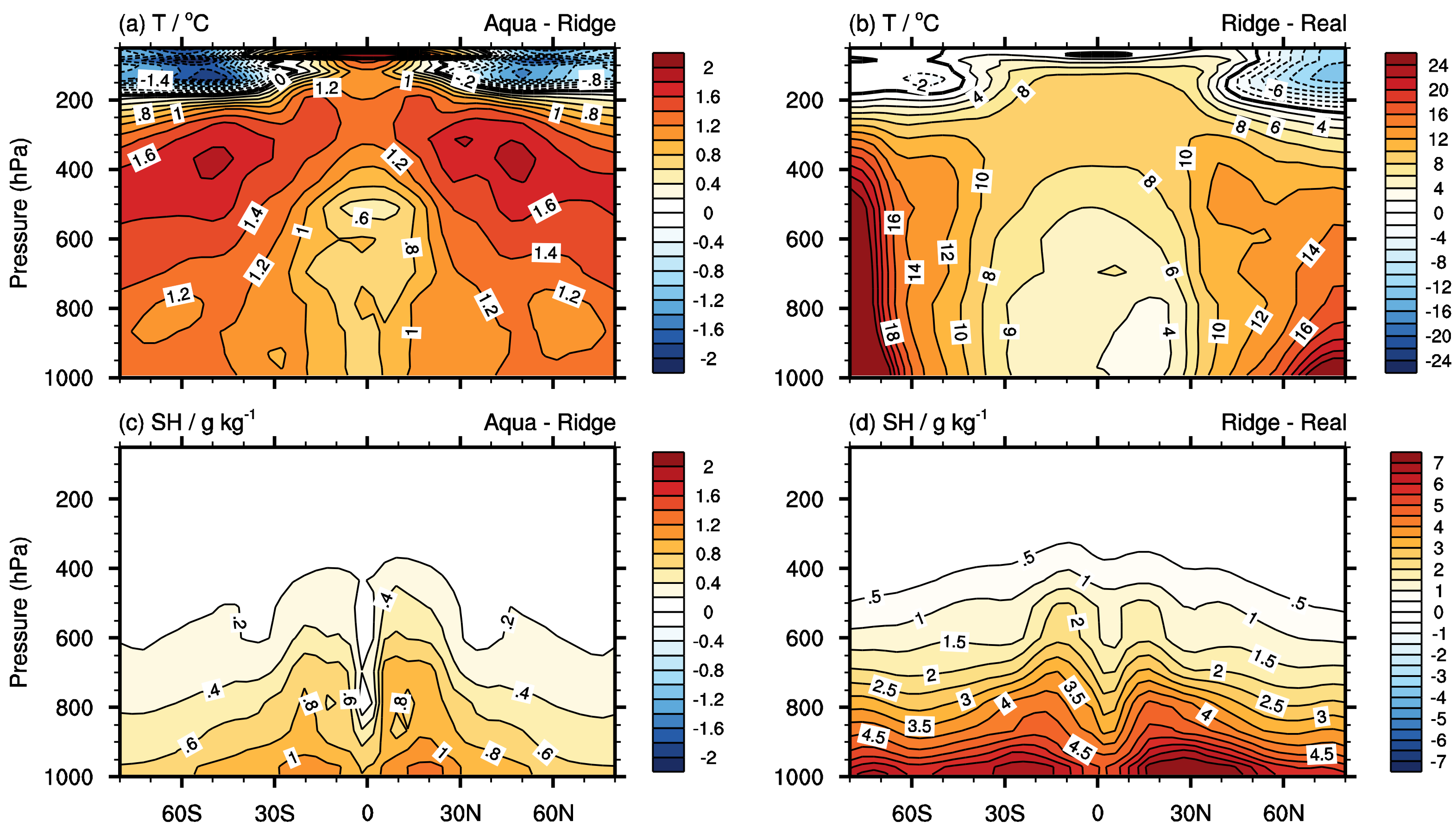
- **Bjerknes compensation**
  - **Intrinsic mode**
  - **Atmospheric physics ⇔ Physical oceanography**
    - **Climate feedback ⇔ Thermohaline circulation**
- **Self-constraint mechanism**
  - **Climate didn't drift too much**
- **If feedback ➔ Reversibility of climate**
  - **Invisible hand (?)**

LaCOAS
北京大学气候与海-气实验室

谢 谢

Aquaplanet → Real Earth

Weaker Baroclinic and More Moisture



Coupled Intrinsic Mode

Energy Compensation ⇔ Weight Management

Diet
Ocean

Metabolism
Climate
Feedback

Motion
Atmos

$$C_R = -\frac{1}{1-B}$$

Go to BJC for Climate Variability

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