Bjerknes补偿：海气耦合系统本征模

杨海军　赵莹莹　王坤　戴海晋　温琴　杨千姿

北京大学气候与海-气实验室

北京大学物理学院大气与海洋科学系

Email: hjyang@pku.edu.cn

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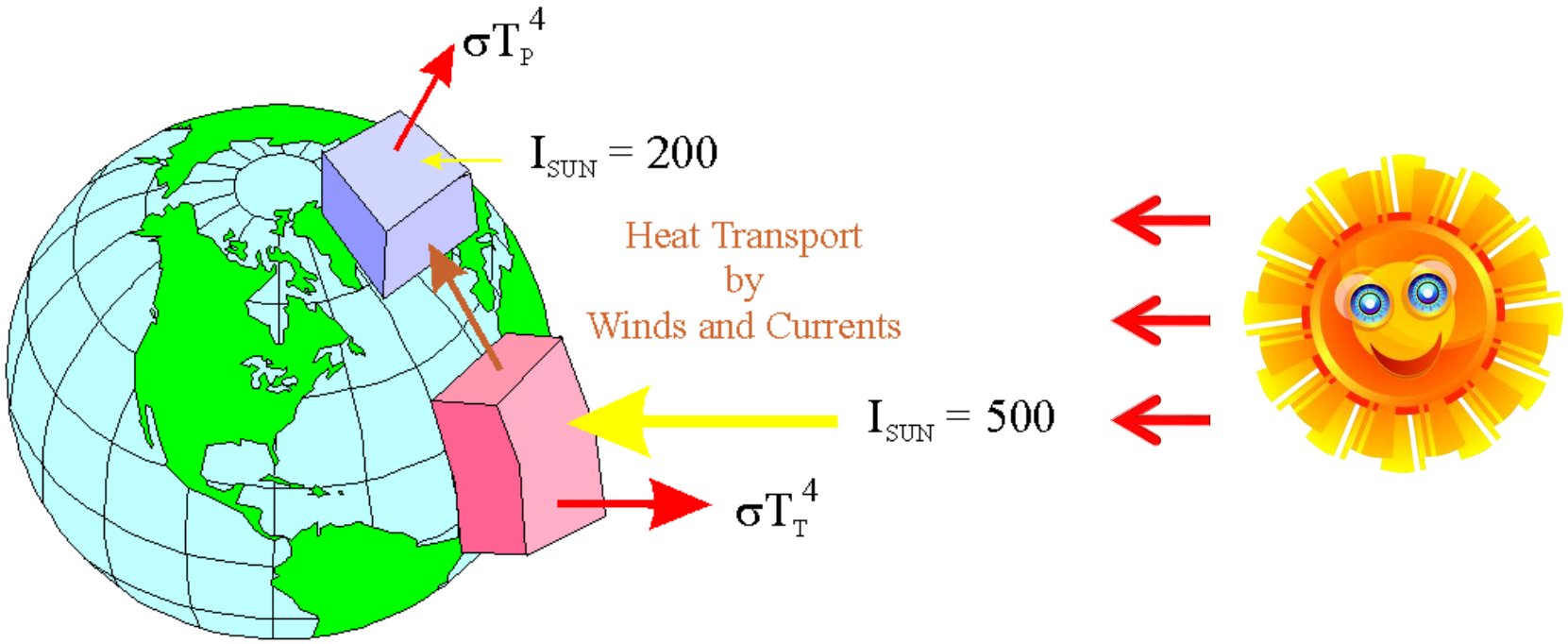
Outline

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

Fundamentals



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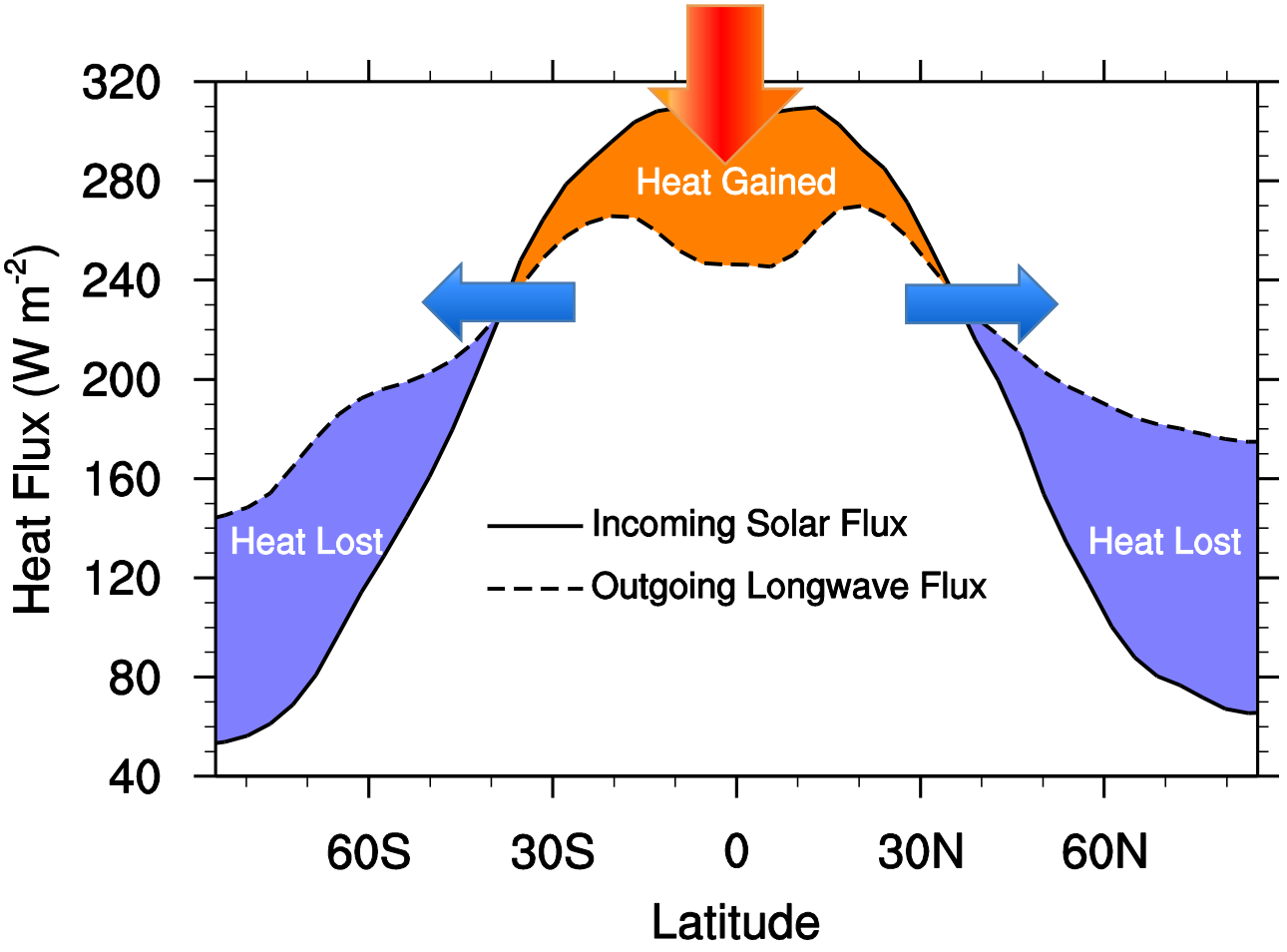
Heat Budget at the TOA



Fundamental Questions

Energy

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

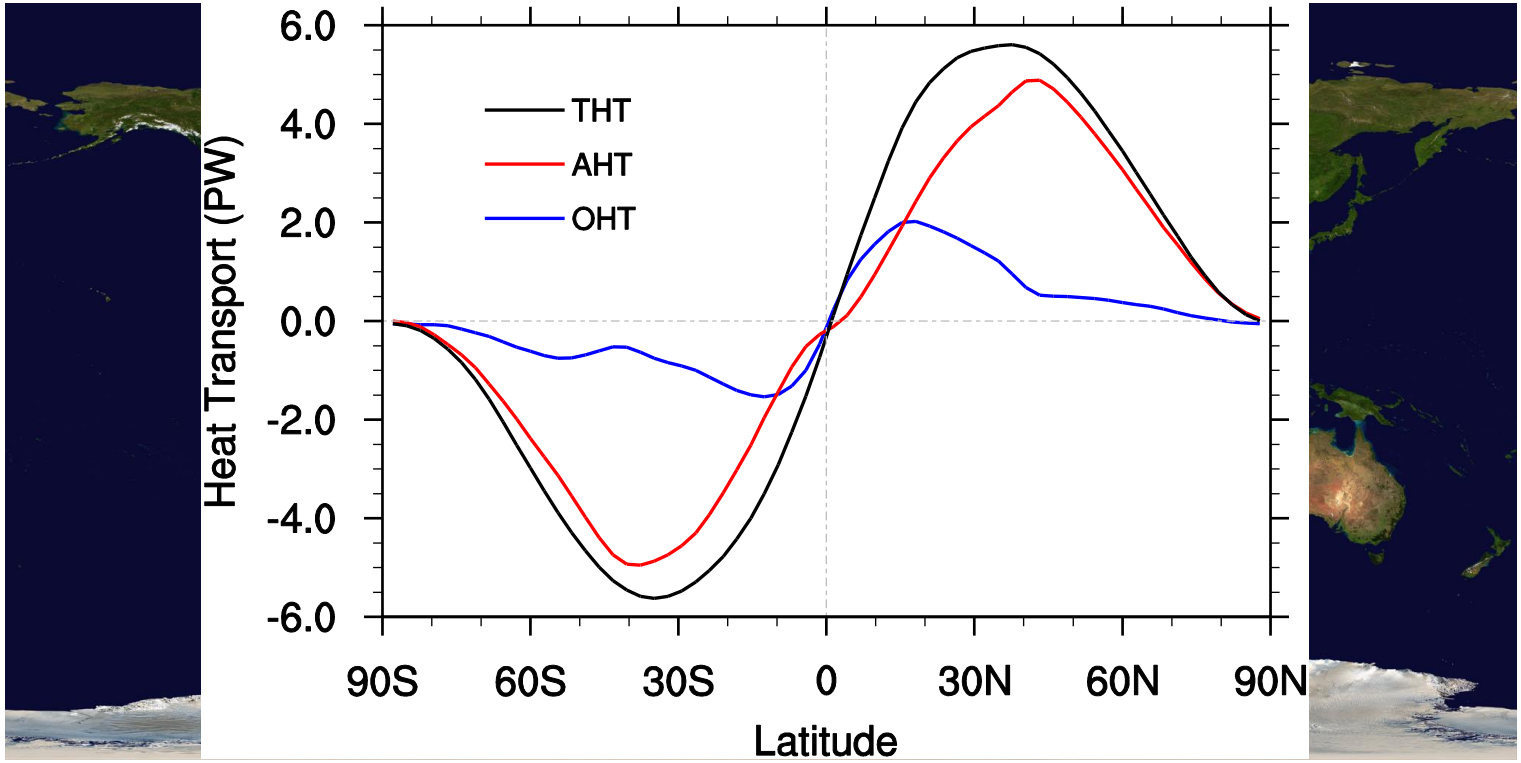
- **Sensible Heat / Latent heat**
- **Potential energy / Kinetic energy**

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

Fundamental Questions

Fundamental Questions

1. Antisymmetric MHT?

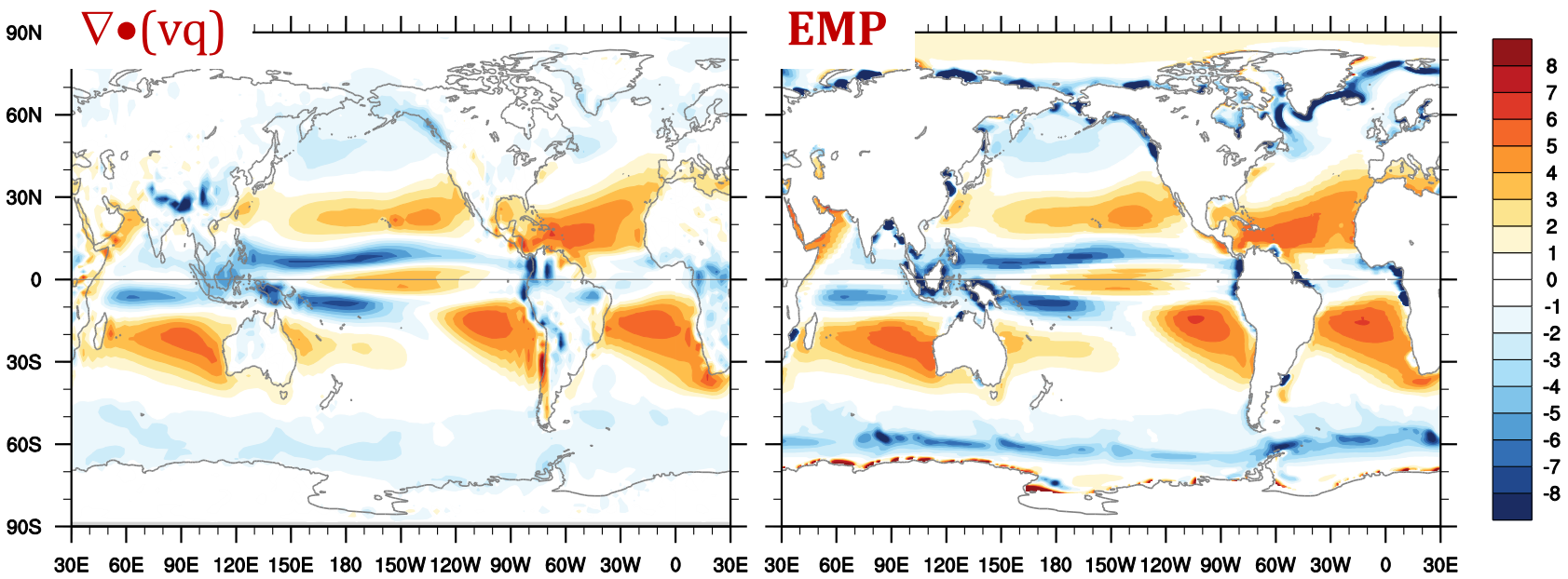


Aquaplanet ➔ Real Earth

Trenberth and Caron (2001)

Fundamental Questions

2. "Real" Oceanic Contribution?

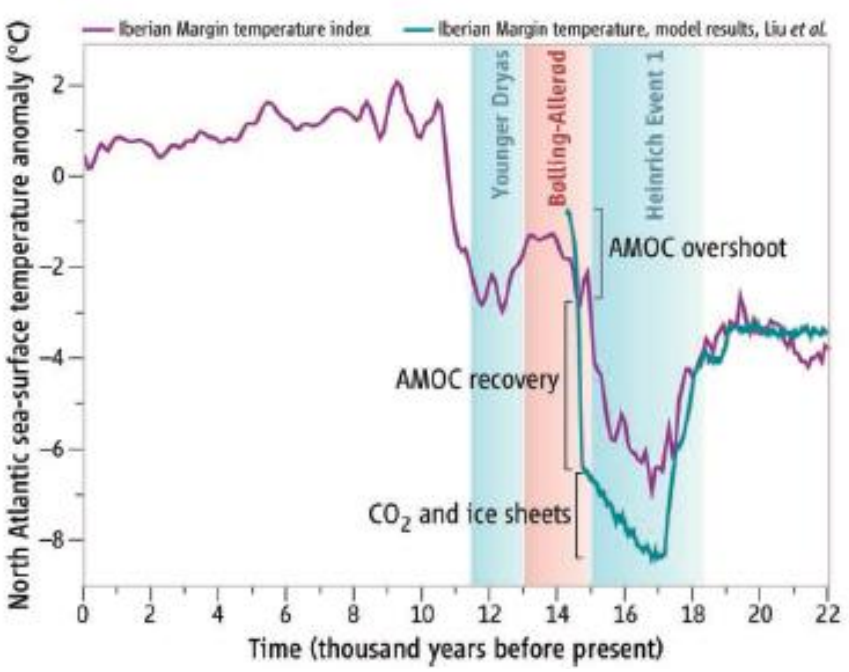


Yang and Li (2015)

Fundamental Questions

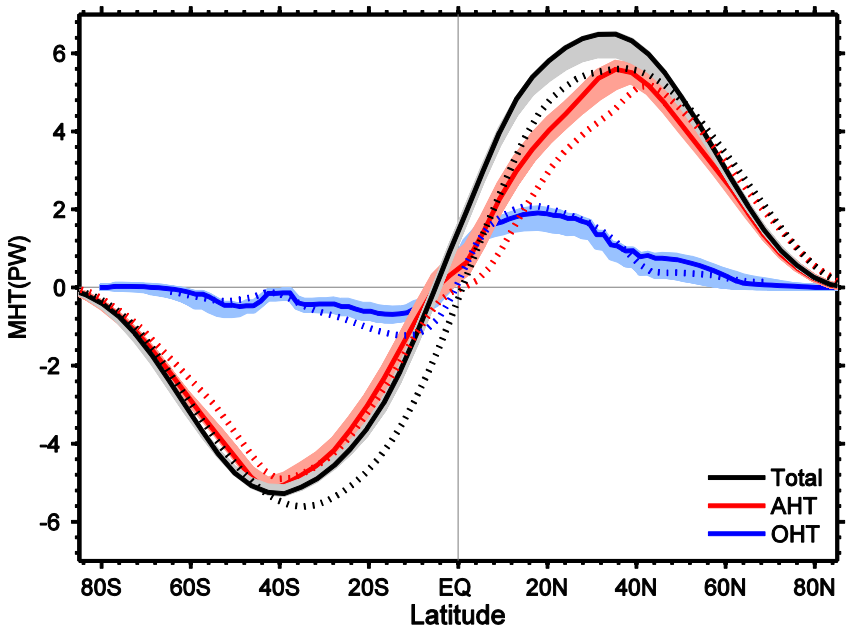
3. Relationship between OHT and AHT Changes?

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)

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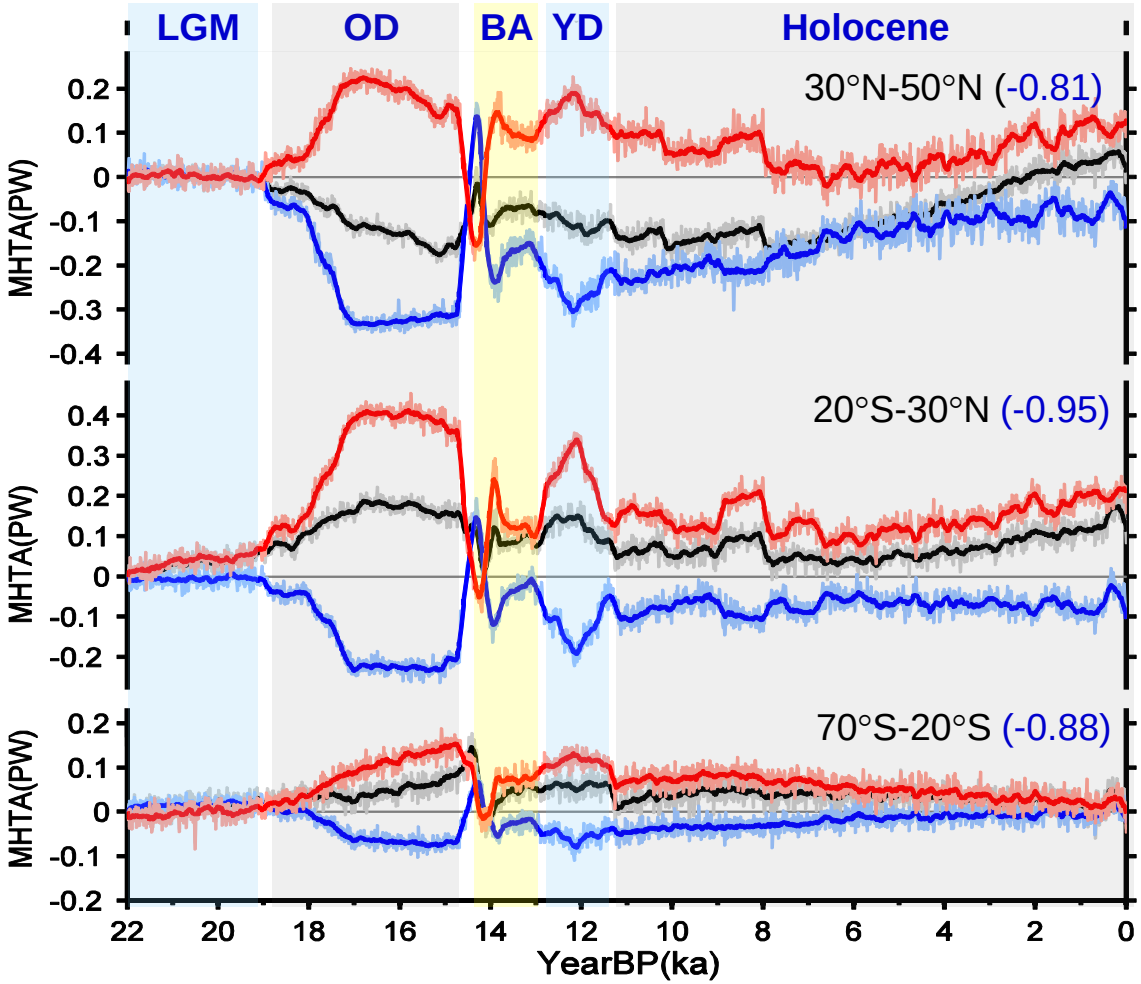
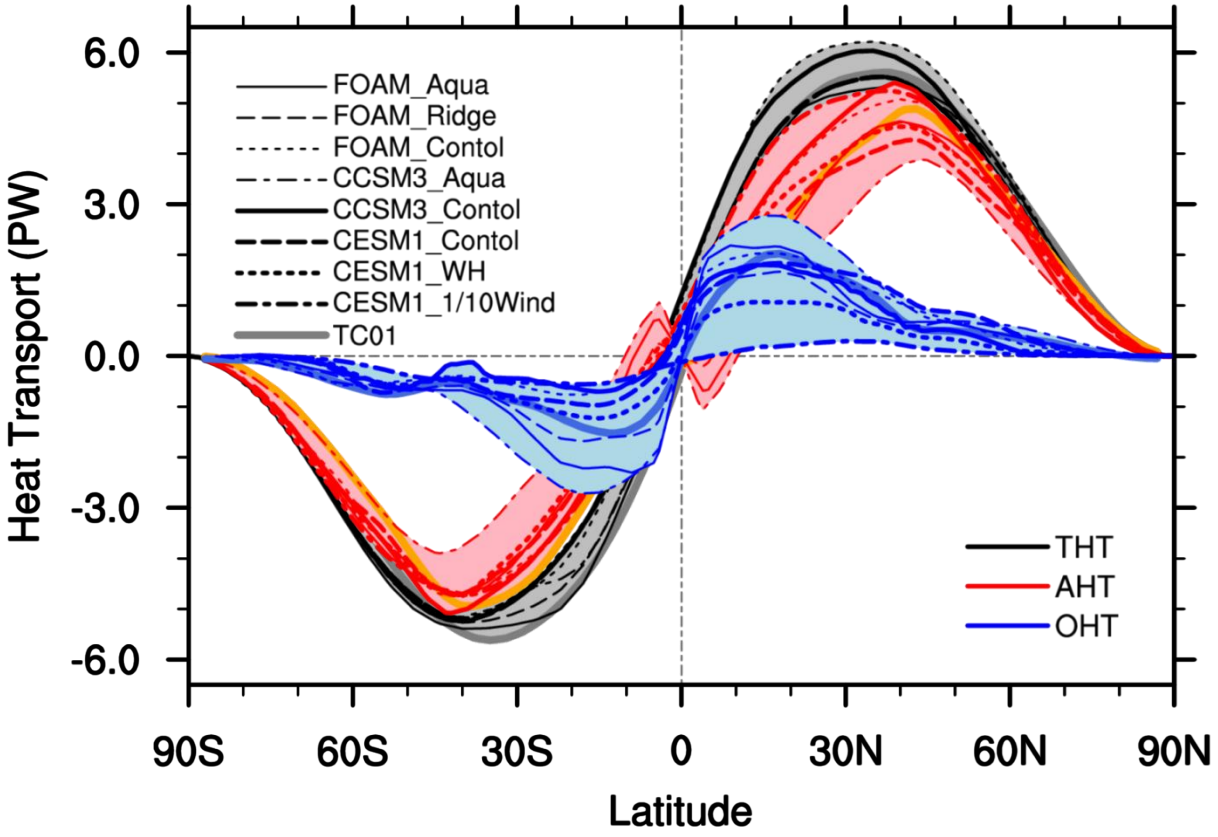
MHT Change Since LGM



Yang et al. (2015)

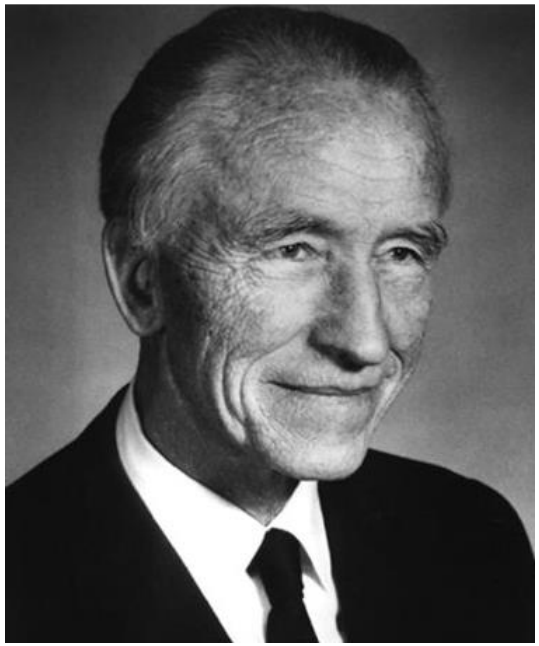
Compensation between AHT and OHT



Note: TC01 is from Trenberth and Caron (2001)

Hypothesis: Bjerknes Compensation

Jacob Aaal Bonnevie Bjerknes
1897-1975



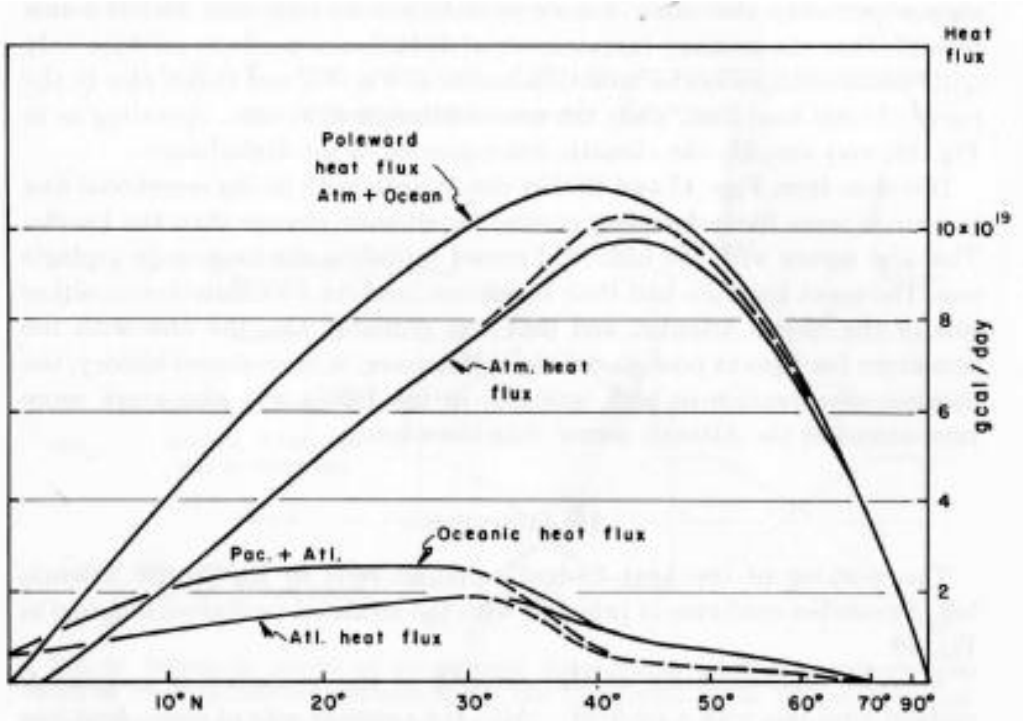


FIG. 48. Solid lines: flux data from Fig. 47 pertaining to present climatic conditions. Dashed lines refer to a sketchy model of the conditions around 1800 A.D. and show qualitative estimate of curtailed Atlantic and total oceanic heat flux as well as increased heat flux by low index atmospheric circulation. 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

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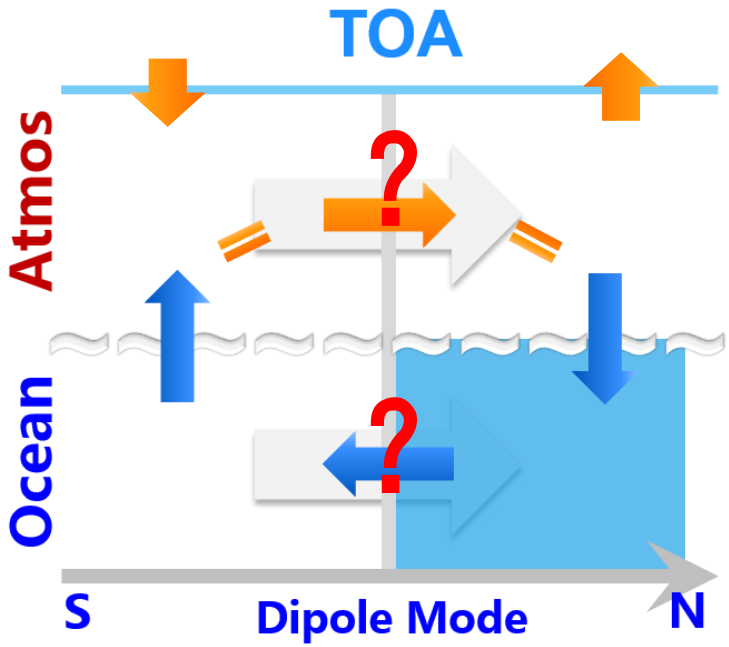
Hypothesis: Bjerknes Compensation

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

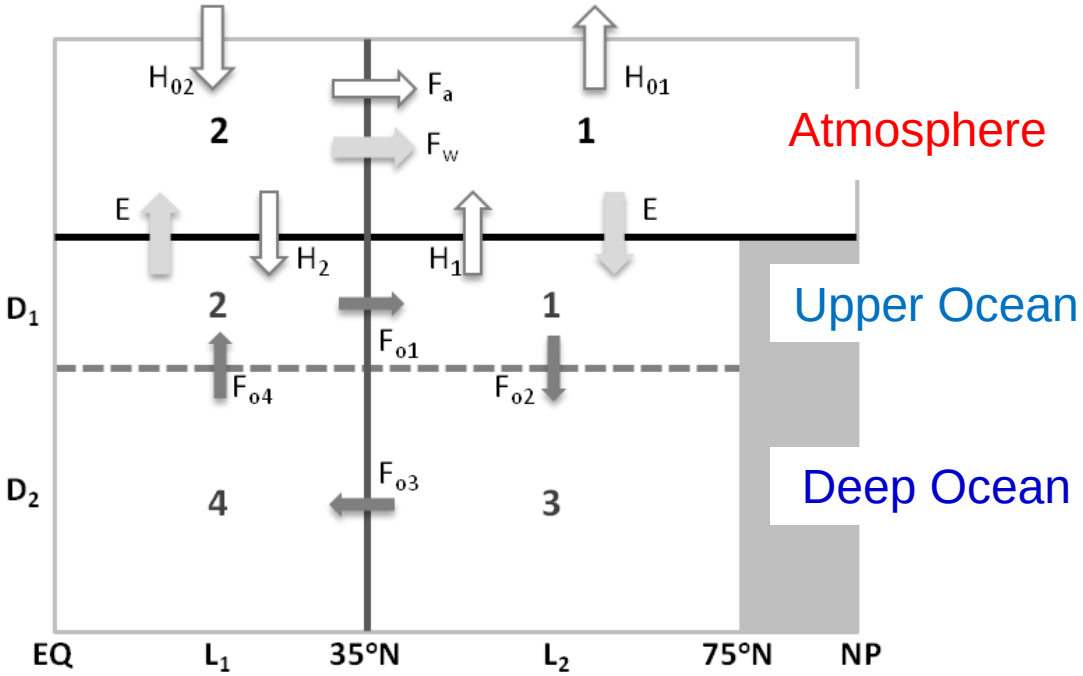
Theory for Equilibrium Change

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

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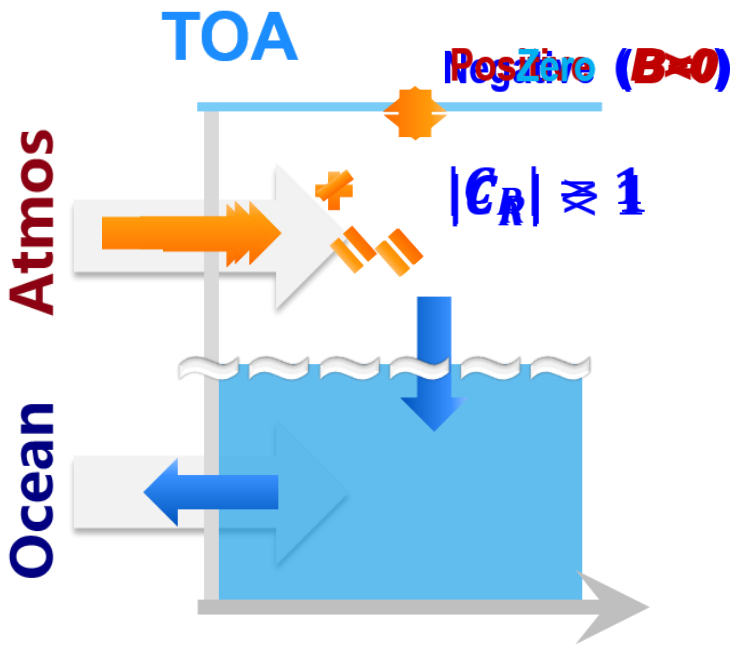
Coupled Intrinsic Mode

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

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

Go to BJC for Climate Variability

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)**

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BJC for Climate Variability

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

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

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

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

$$\omega \to 0$$

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

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

BJC for Climate Variability

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

No correlation and No BJC

$$\omega \to 0 \;\Rightarrow\; r_\delta \to -1;\; C_R(1) \asymp C_{R0}(2) \asymp C_{Rp}(3)$$

Full correlation and equilibrium BJC

Go to Climate Variability Validation

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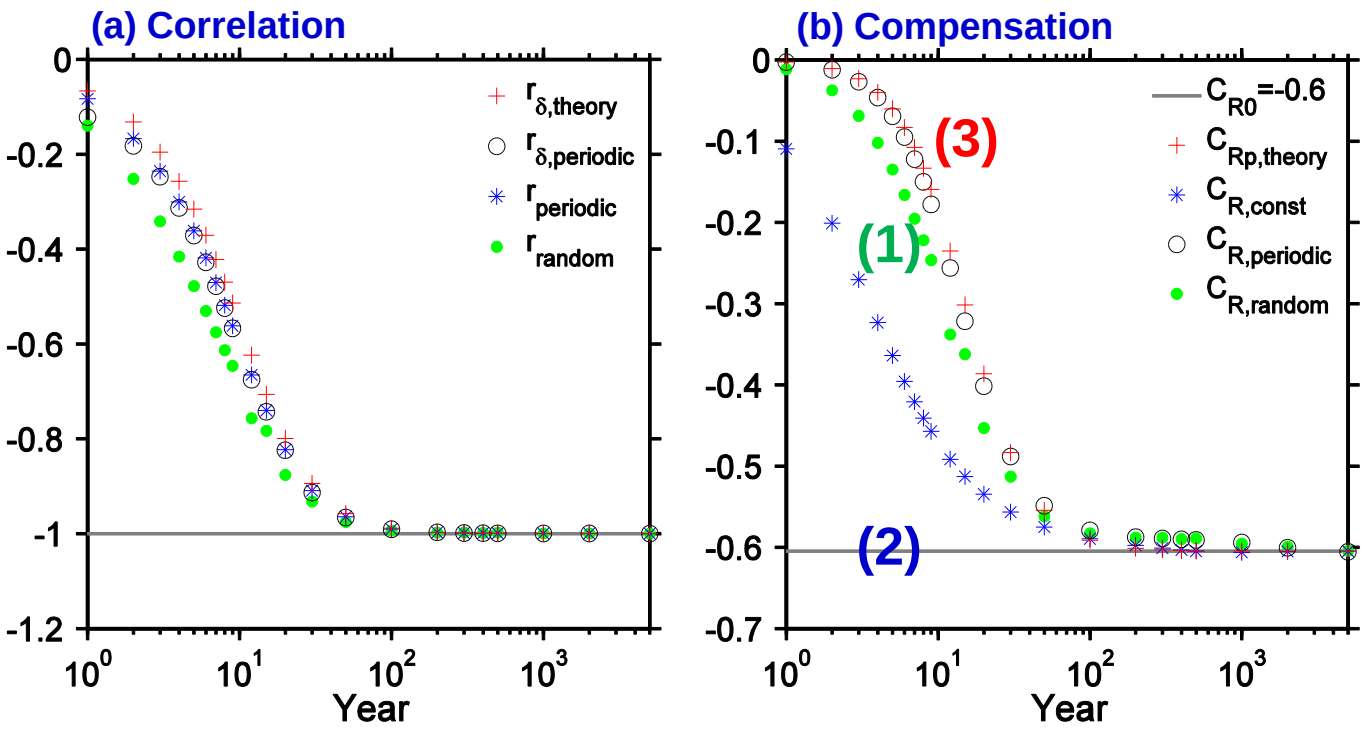
BJC Theory Valid for Climate Variability



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

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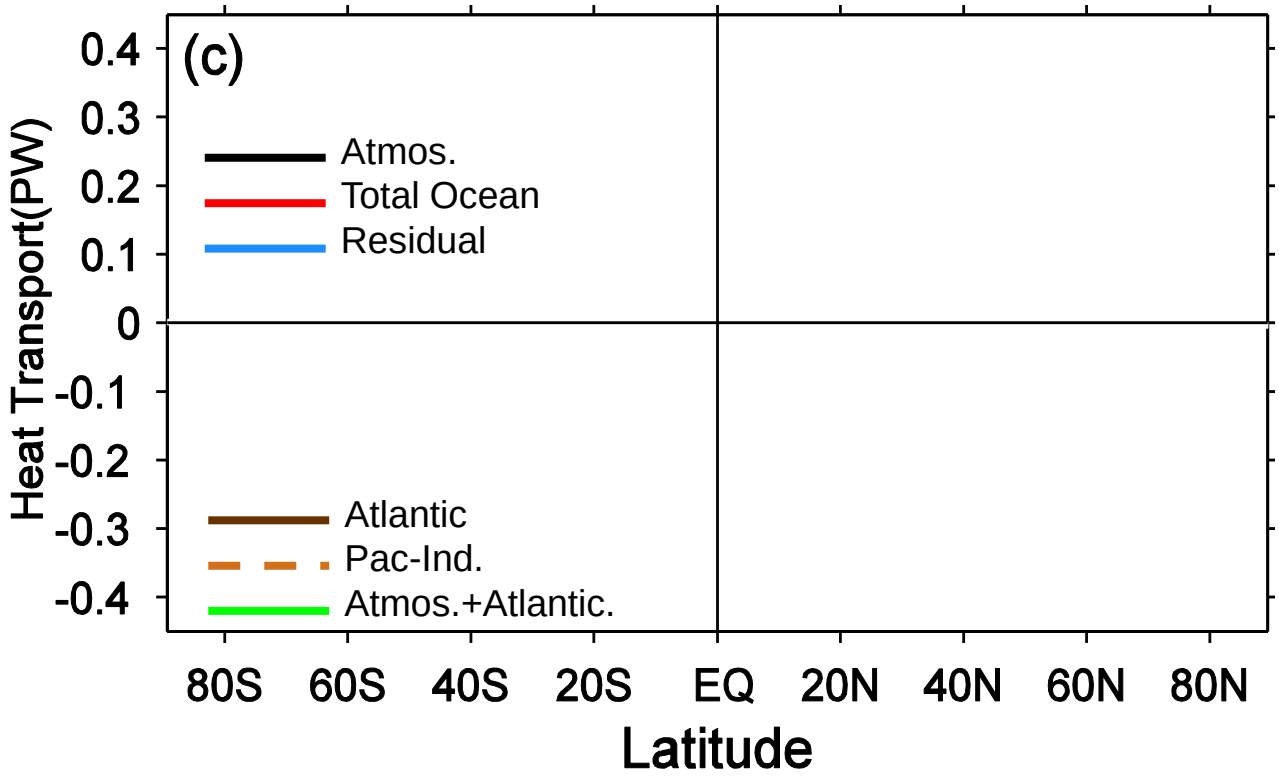
CESM Experiment and Mechanism

- **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)

BJC under Freshwater in CESM

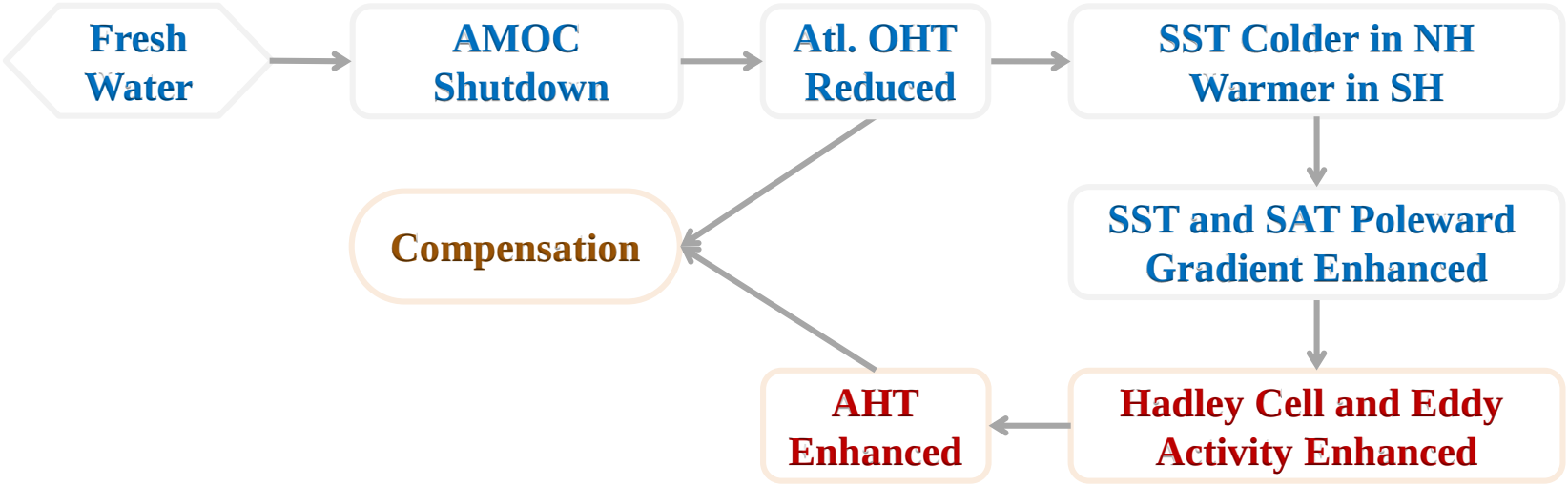


80-90%

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

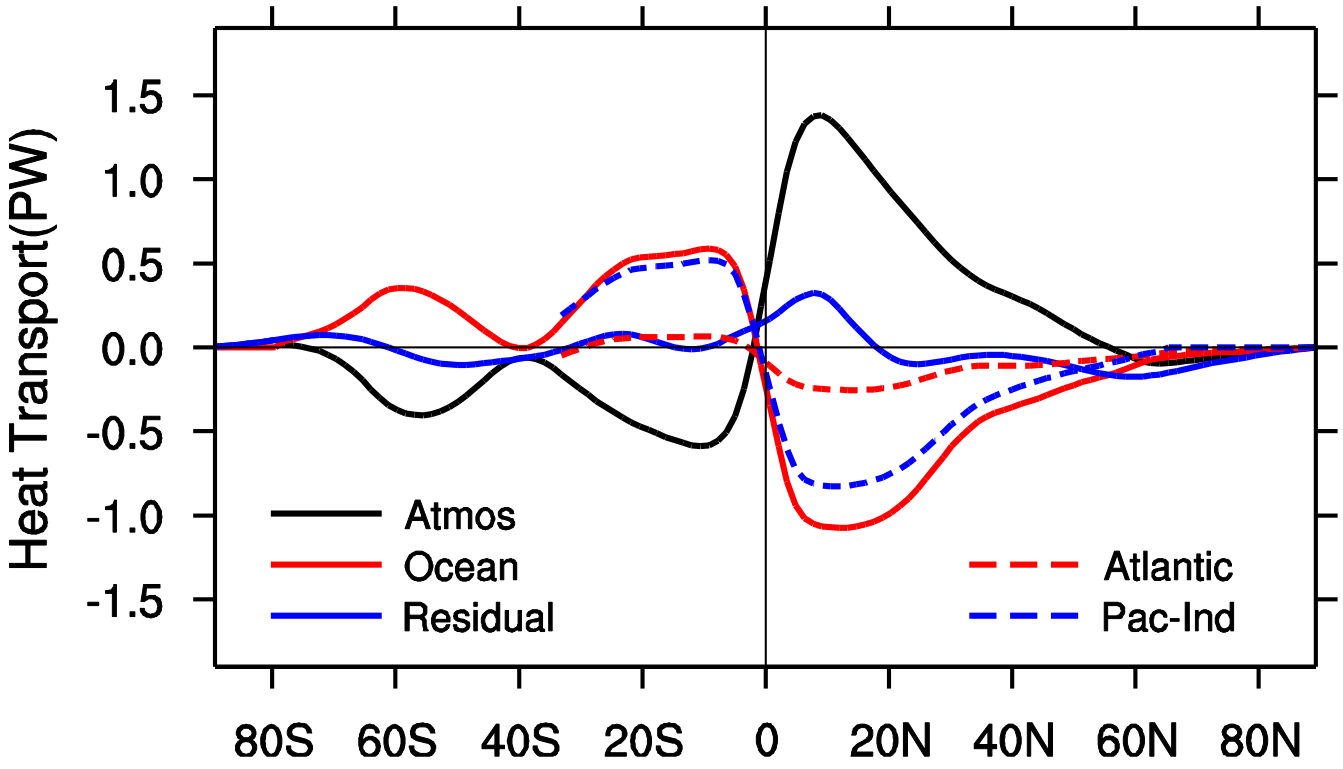
Atlantic OHT ≈ AHT; Pac-Ind. OHT ≈ Overcompensation

“Mechanism”



Yang et al. (2013, 2017)

BJC under Wind Perturbation in CESM

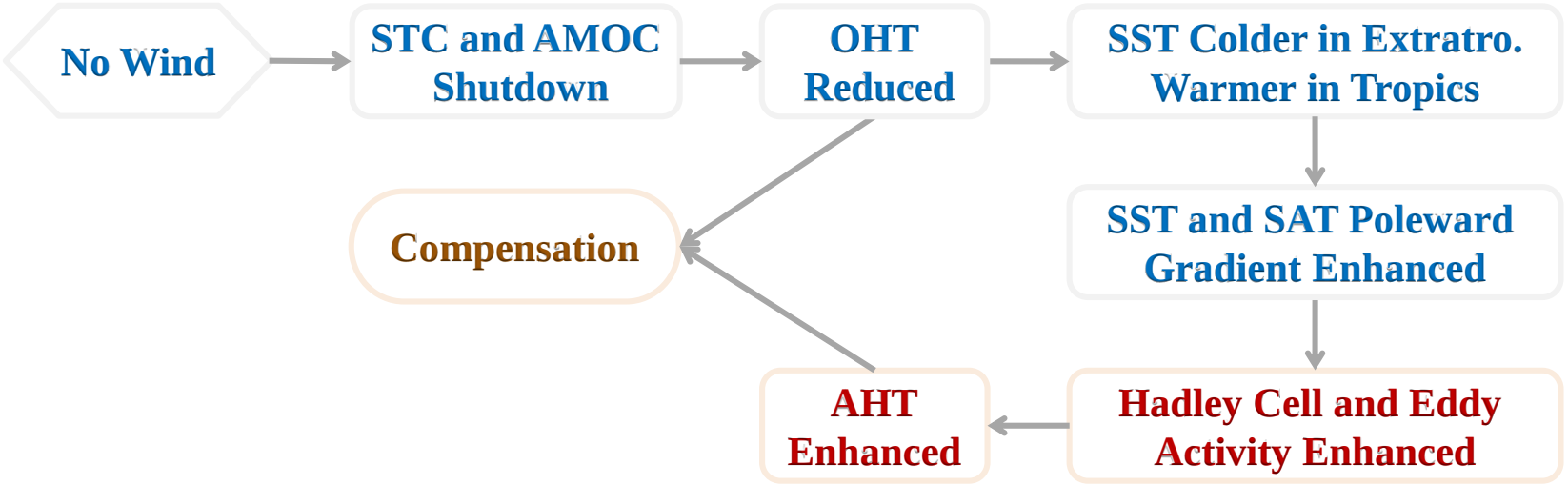


80-90%

Pacific-Indian OHT ↓ ⇒ Ty ↑ ⇒ HC ↑ ⇒ AHT ↑

Nearly Compensation

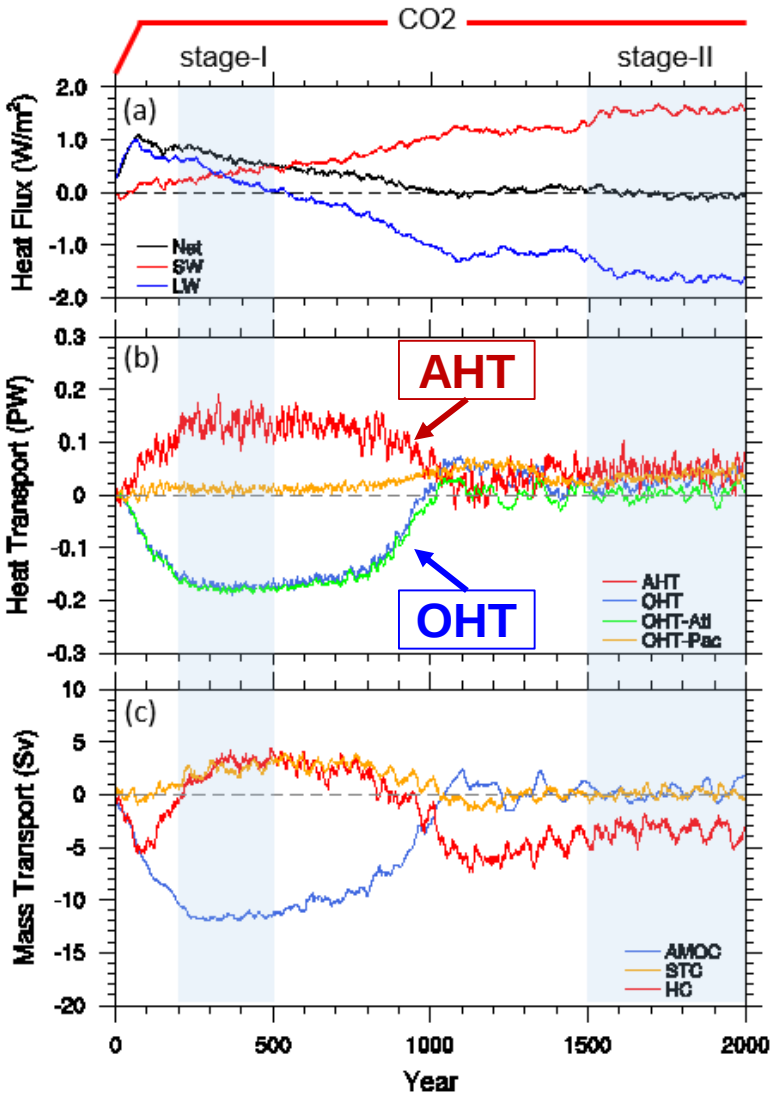
“Mechanism”



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

BJC under Global Warming in CESM

85%



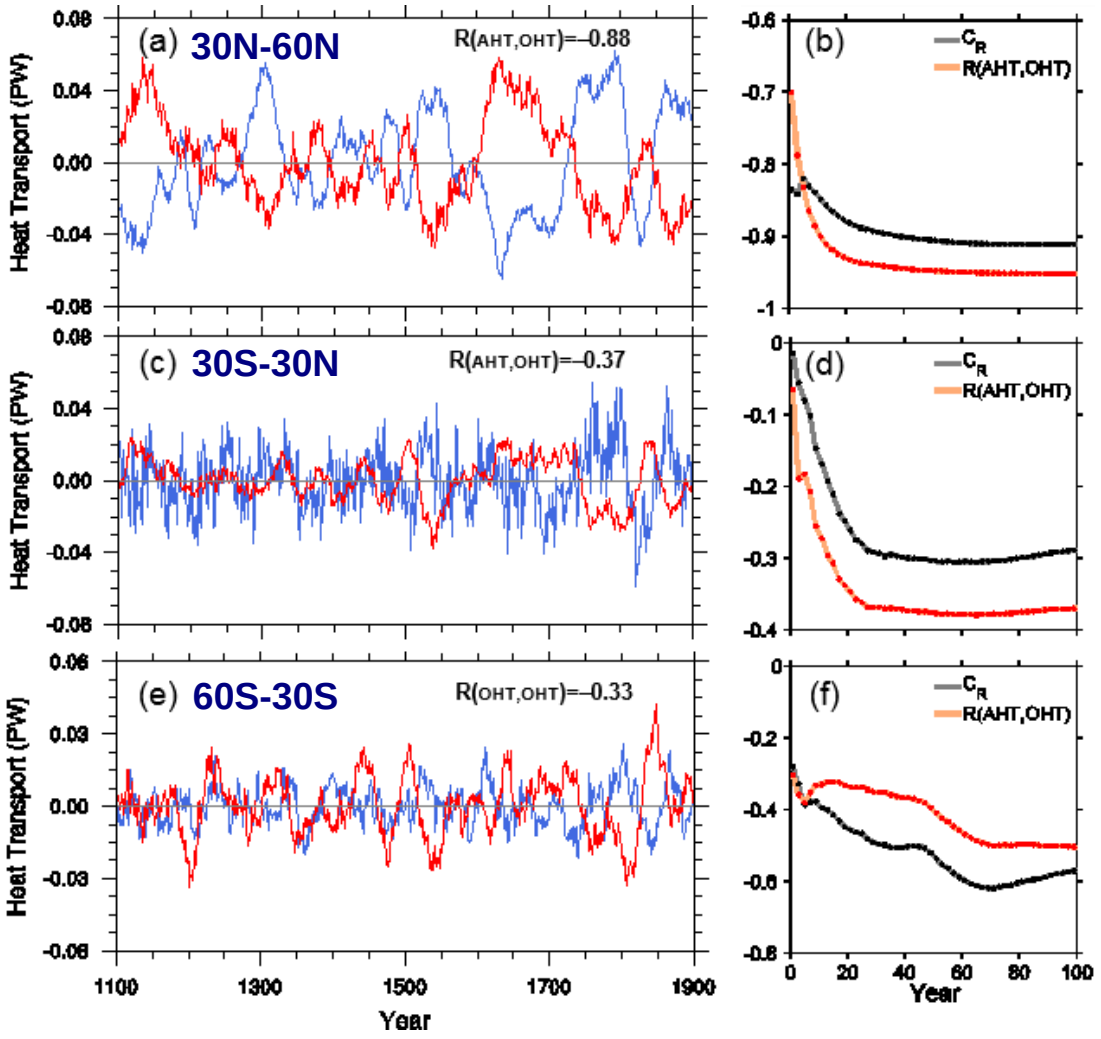
Yang et al. (2017)

Under 2 X CO2 forcing

BJC valid due to *thermohaline dynamics*!

BJC in Natural Variability in CESM

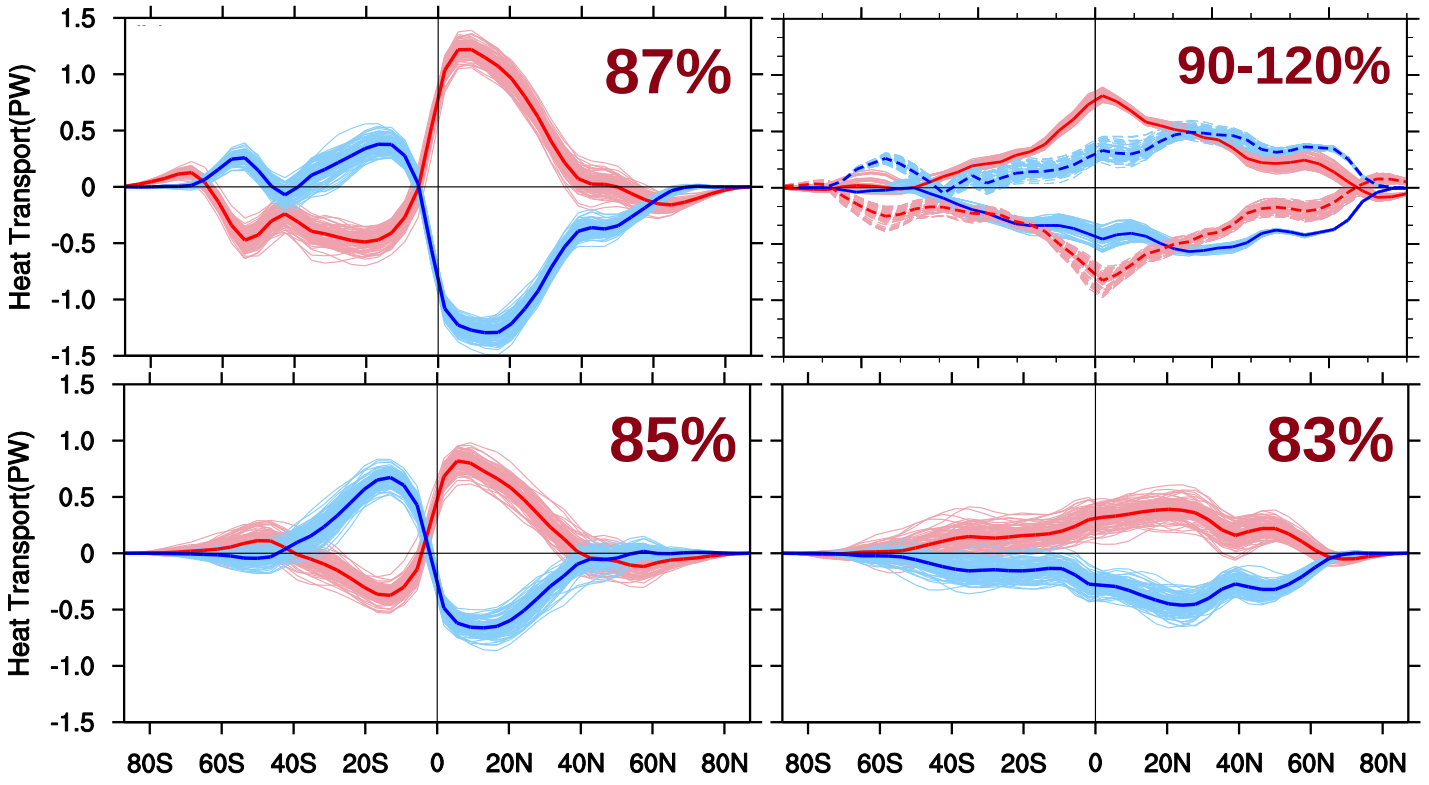
2000-year CESM control run



Zhao and Yang (2017)

Summary: BJC in CESM

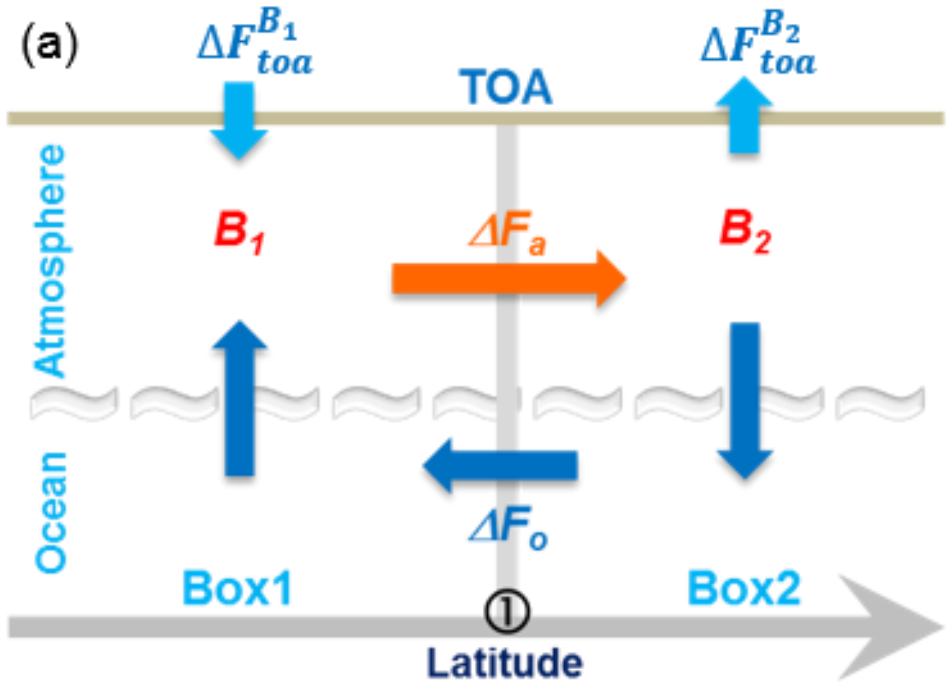
Surface Reason: *Out-of-phase* changes in Atmos-Ocean MOC ➔ BJC



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

BJC Mechanism

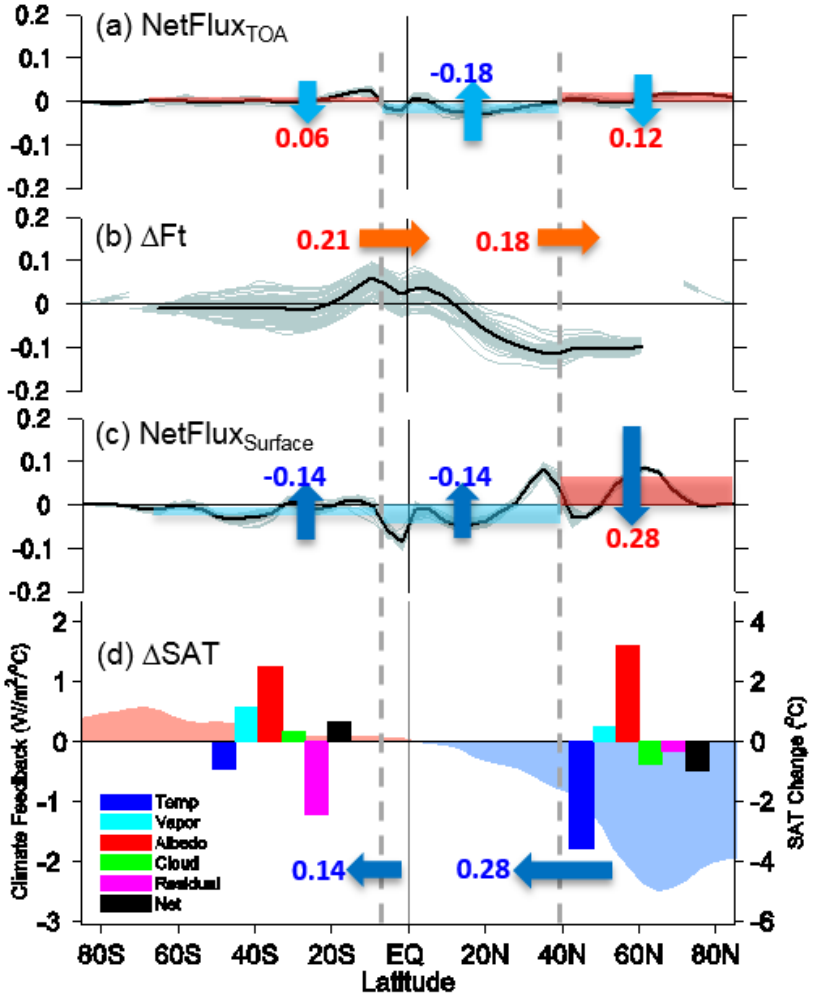
Fundamental Reason: Climate feedback + Energy constrain ➔ BJC



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

BJC: *Theory* vs *CGCM*

CESM Wind Perturbation experiments



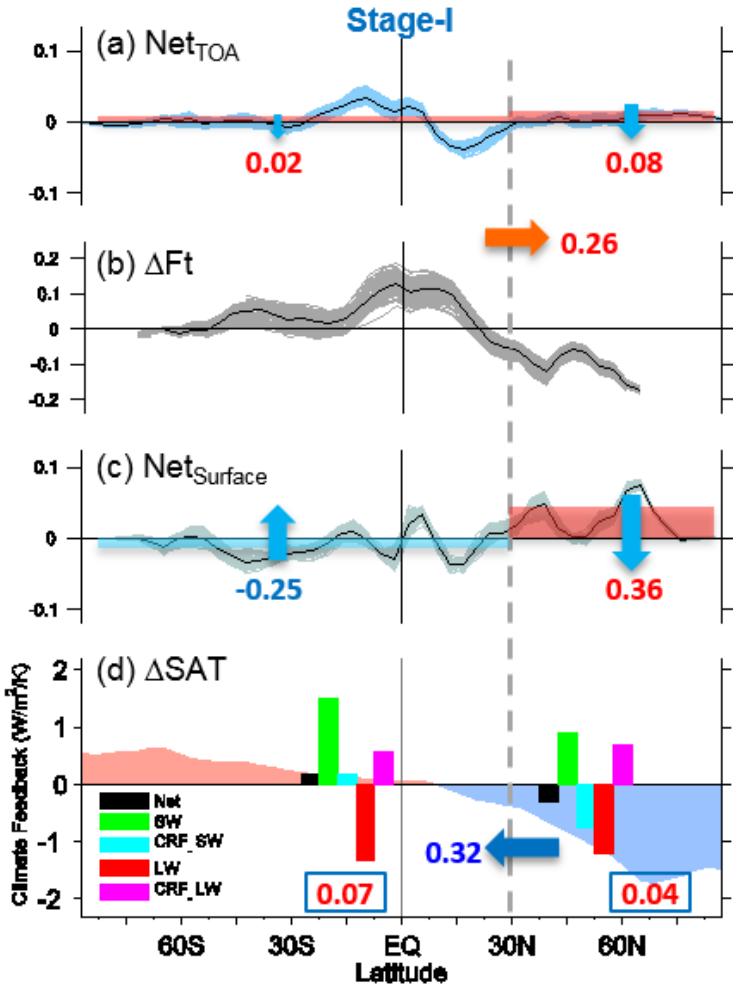
Wind		Temp	Albedo	Cloud	C_{Rmodel}	C_{Rtheor}
0.1A	NH	-1.80	1.30	-0.23	-1.10	-1.09
	SH	-0.44	1.16	-0.07		
	Global	-2.20	1.34	-0.28	-0.83	-0.71
0.1P	NH	-1.87	1.30	0.34	-1.85	-1.61
	SH	-2.14	0.39	0.57		
	Global	-1.88	0.95	0.27	-0.85	-0.77
0.1G	NH	-1.84	1.05	-0.08	-0.95	-0.91
	SH	-1.70	1.96	-0.29		
	Global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

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

Dai et al. (2017)

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	

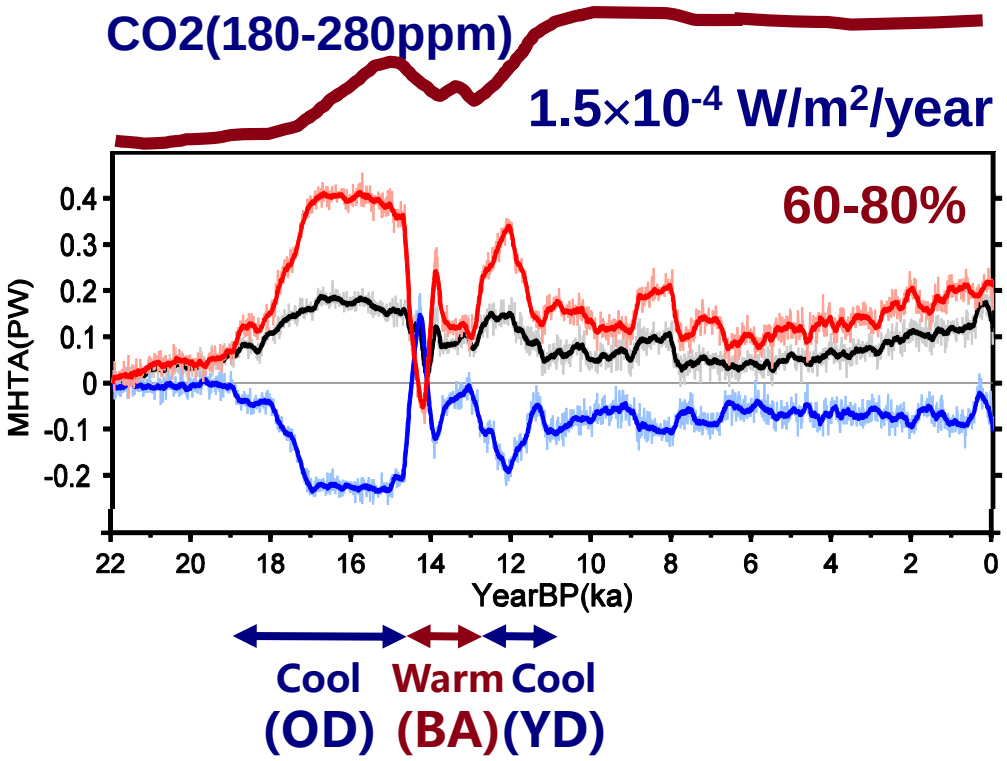
$$C_{Rmodel} \approx C_{Rtheory}$$

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.

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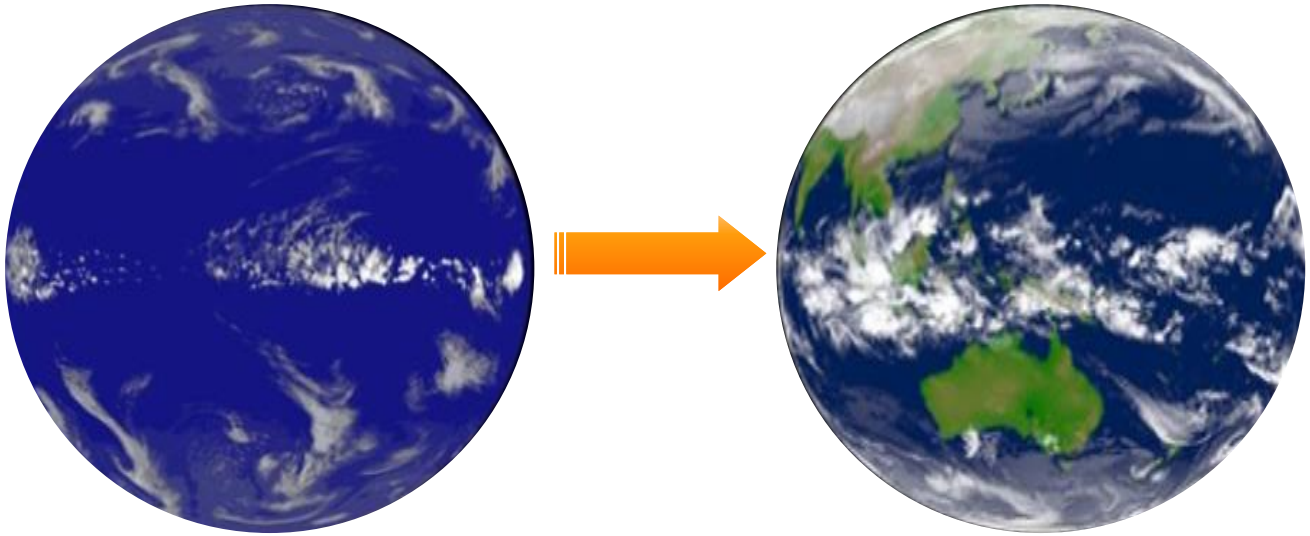
Aquaplanet → Real Earth

Why anti-symmetric MHT?



Try to answer this fundamental question

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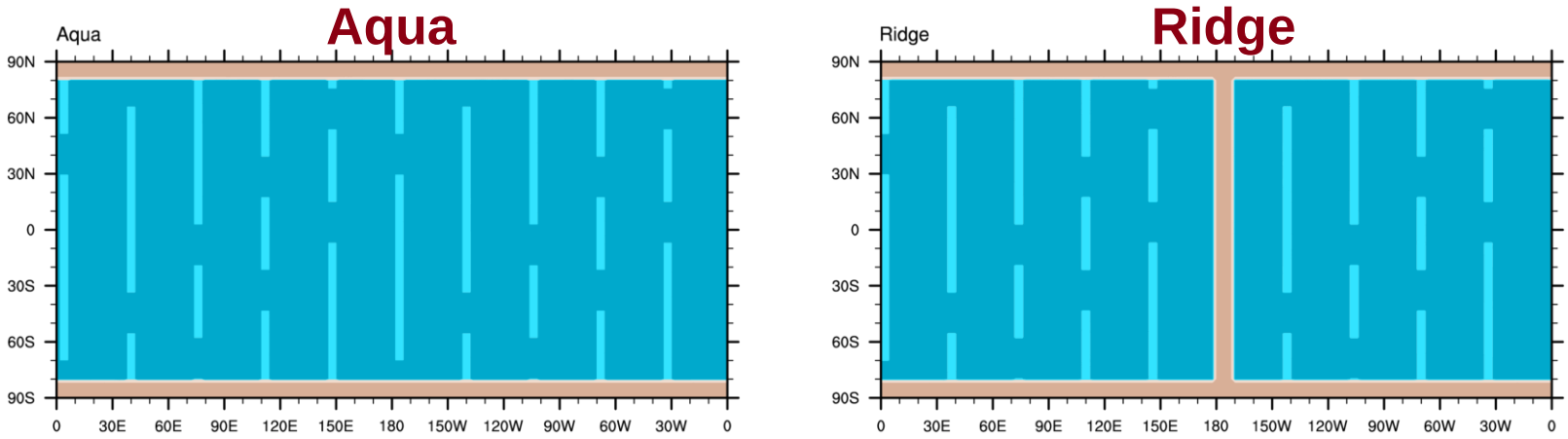
Topo for Aqua and Ridge

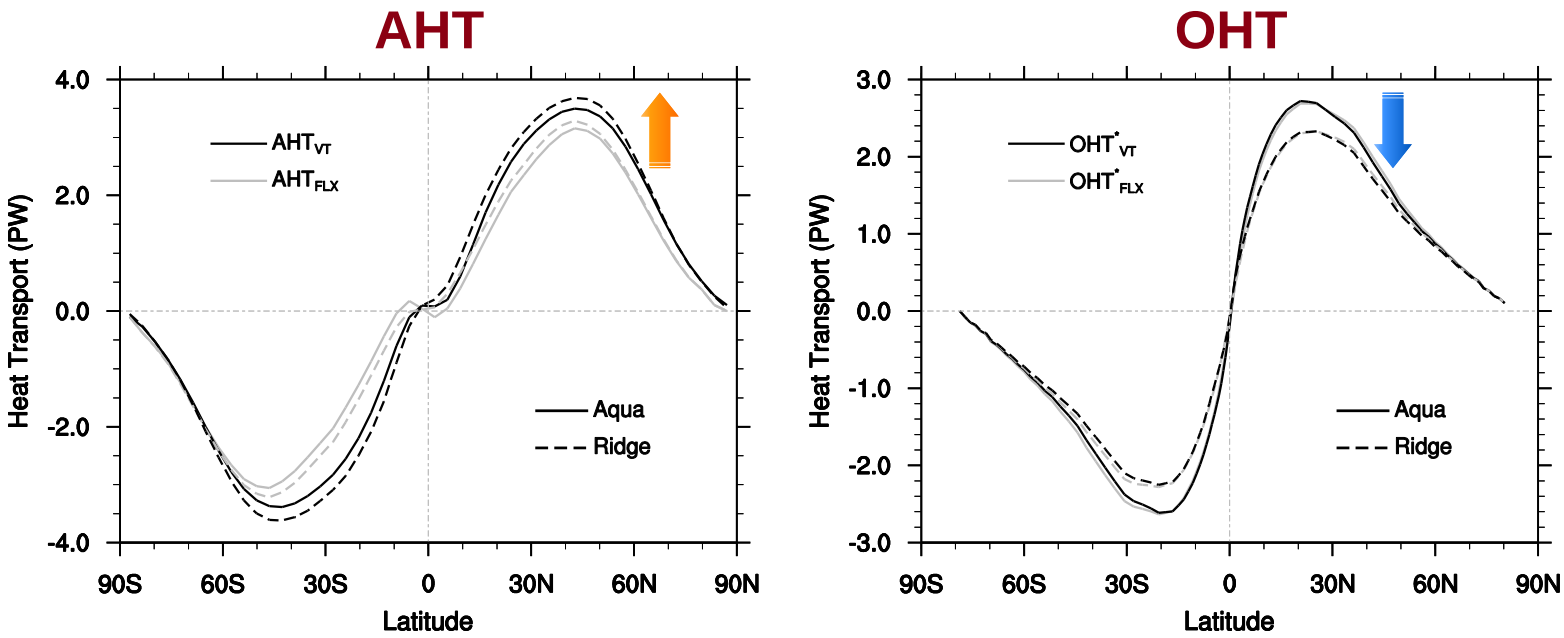
Land: 10 m; Ocean: 5000 m; Bottom random ridge: 500 m



Li and Yang (2018)

Go to Summary

Symmetric AHT and OHT



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

Bjerknes Compensation

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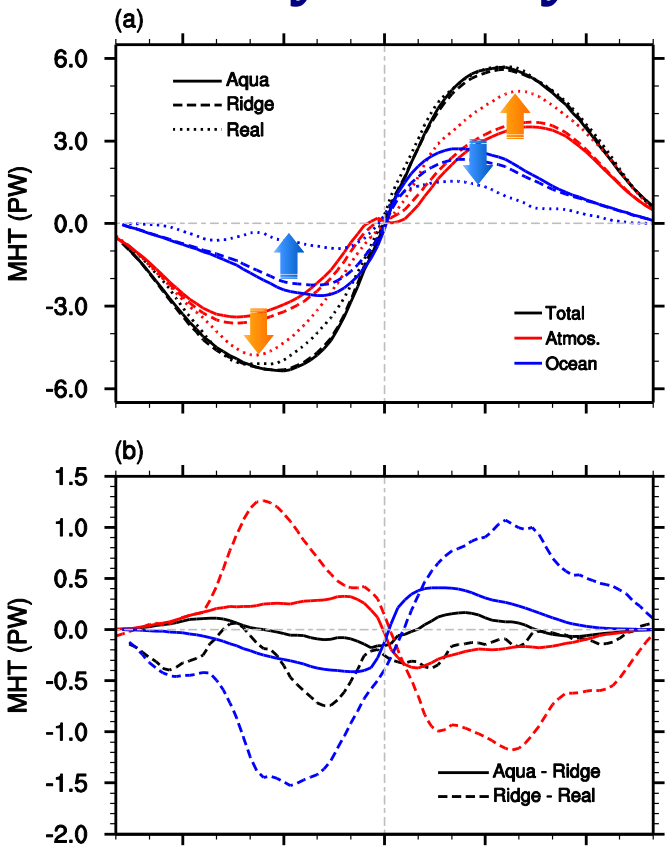
Aquaplanet → Real Earth

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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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 (?)

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