Bjerknes Compensation: An Coupled Intrinsic Mode in the Earth System

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Outline

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

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

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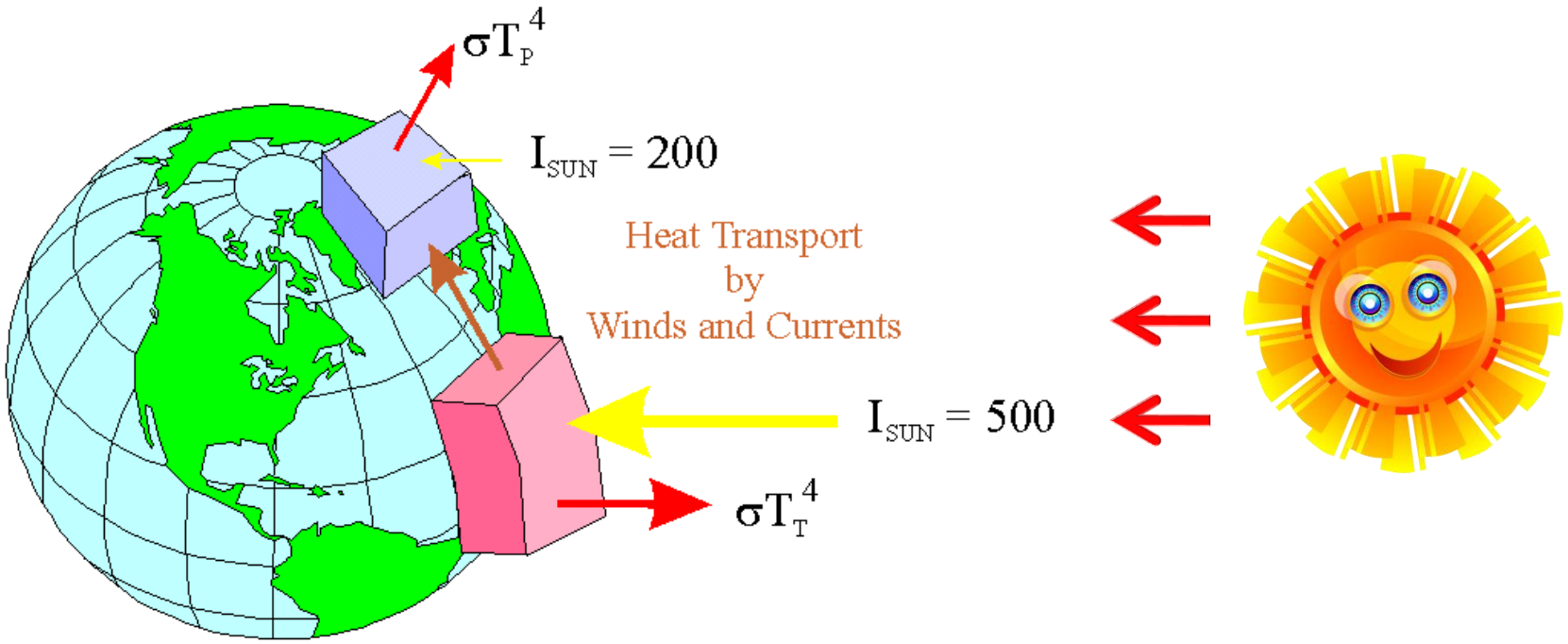
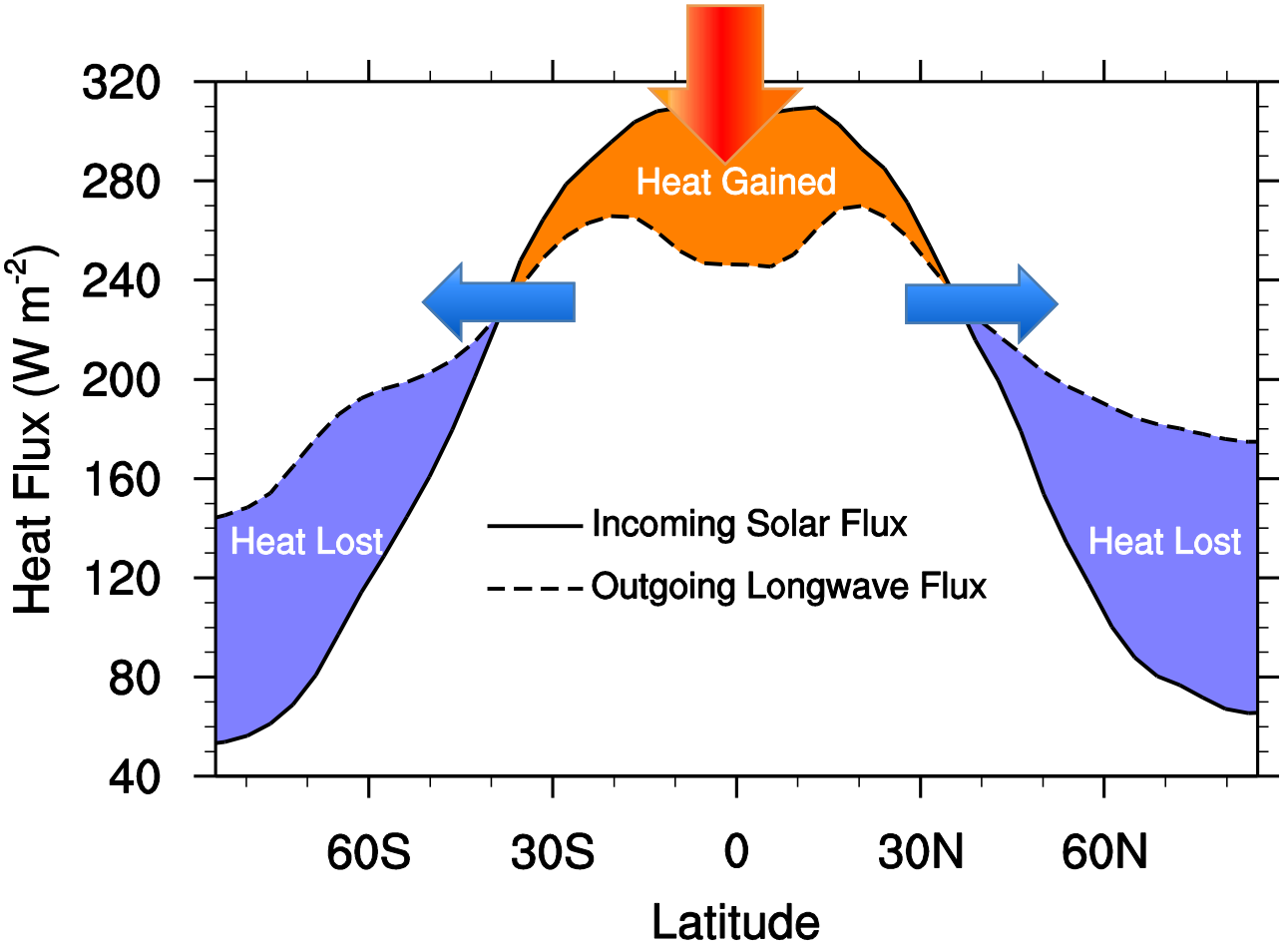
Fundamentals



Heat Budget at the TOA



Fundamental Questions

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Energy

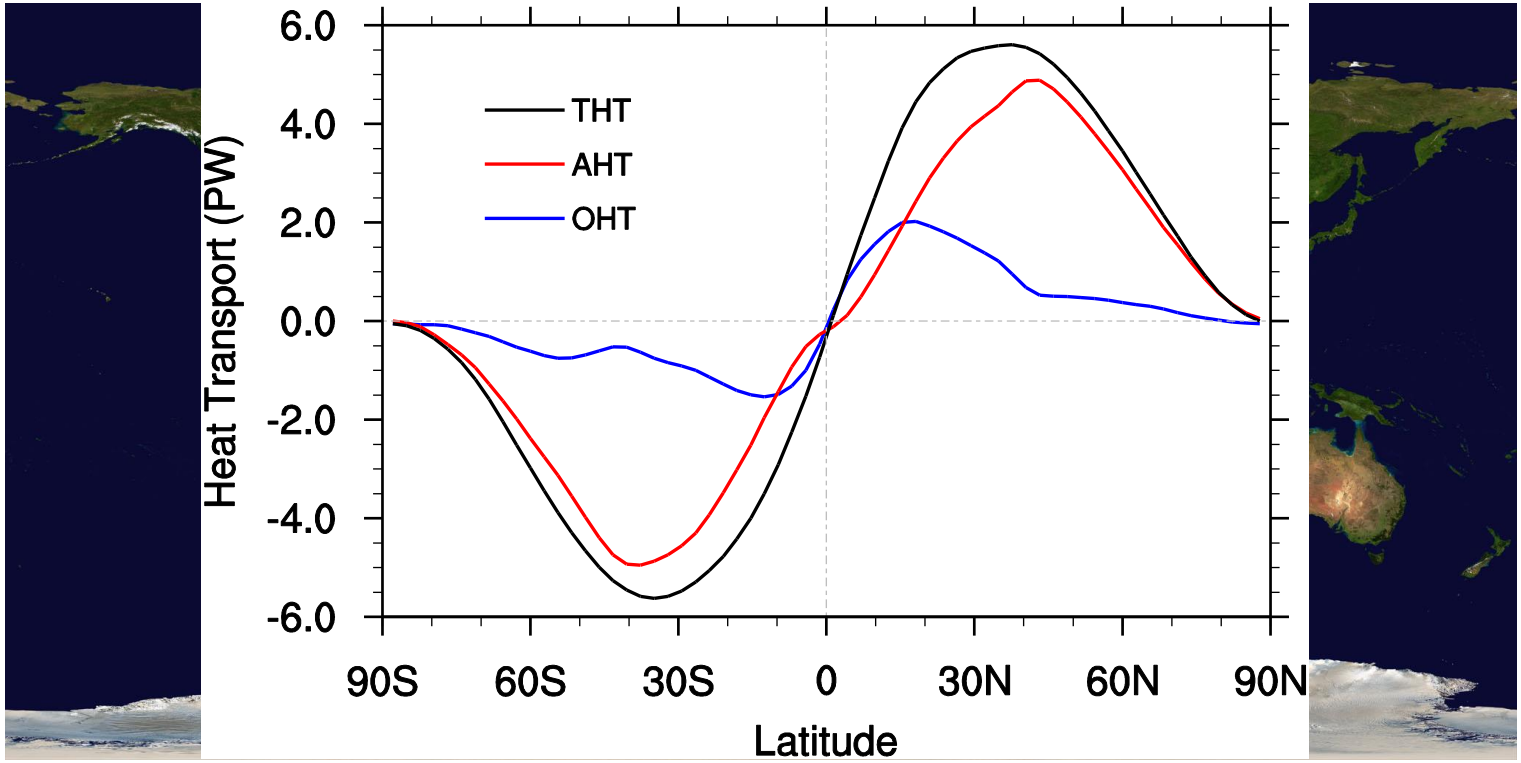
$$Energy = c_p T + L_v q + gz + \frac{(u^2 + v^2 + w^2)}{2}$$

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

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

Fundamental Questions

1. Antisymmetric MHT?

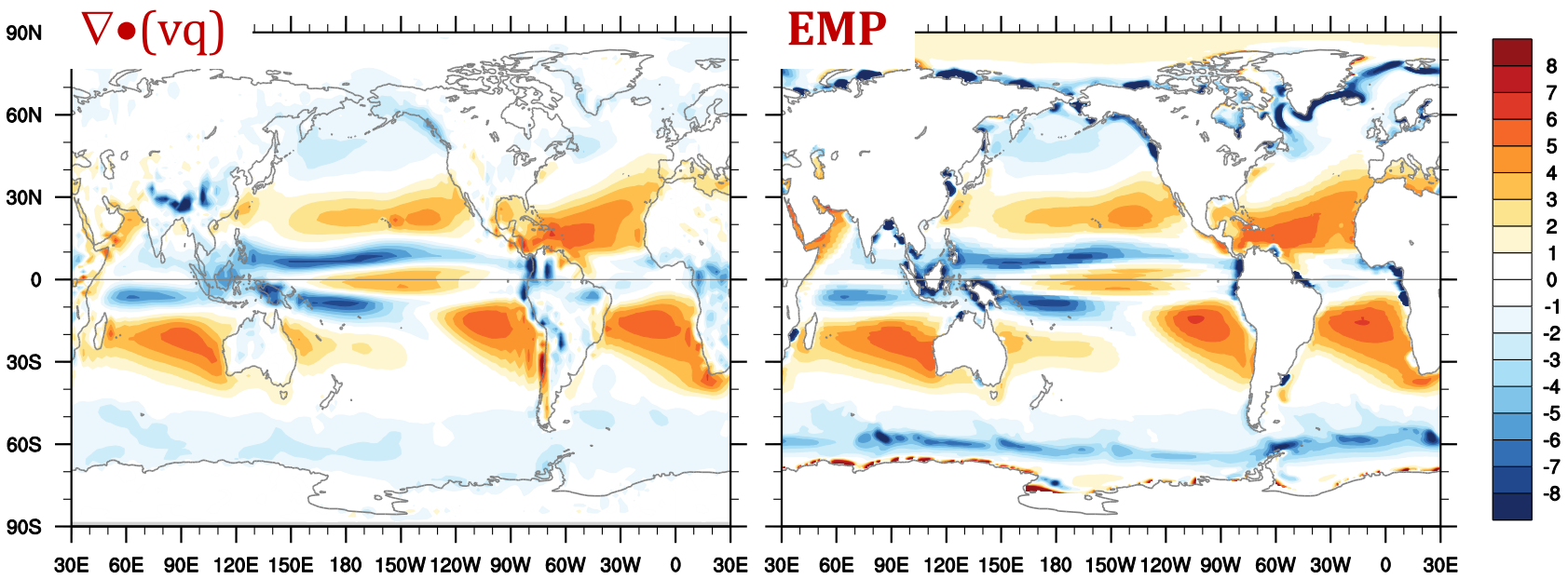


Aquaplanet ➔ Real Earth

Trenberth and Caron (2001)

Fundamental Questions

2. "Real" Oceanic Contribution?



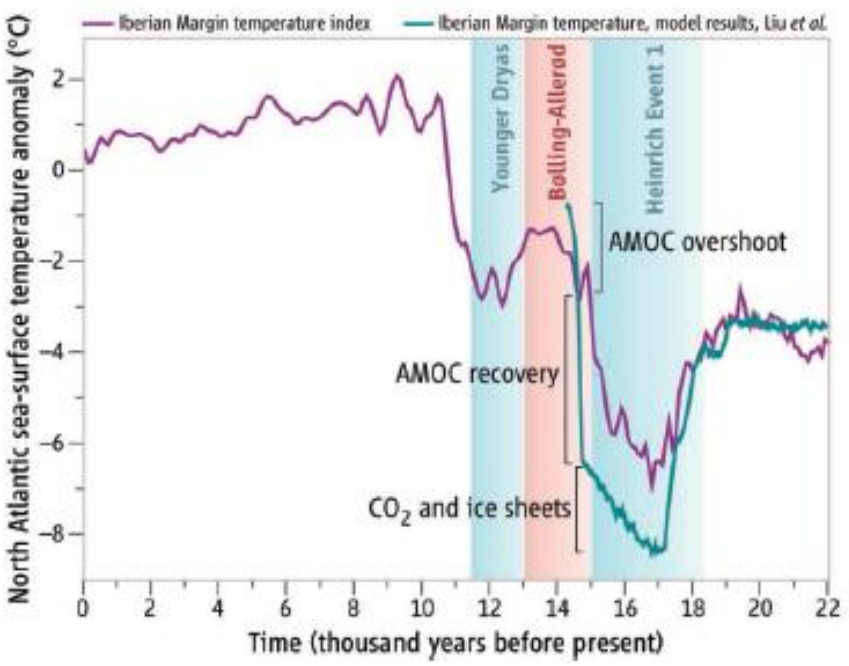
$$Energy = c_p T + L_v q$$

Yang and Li (2015)

Fundamental Questions

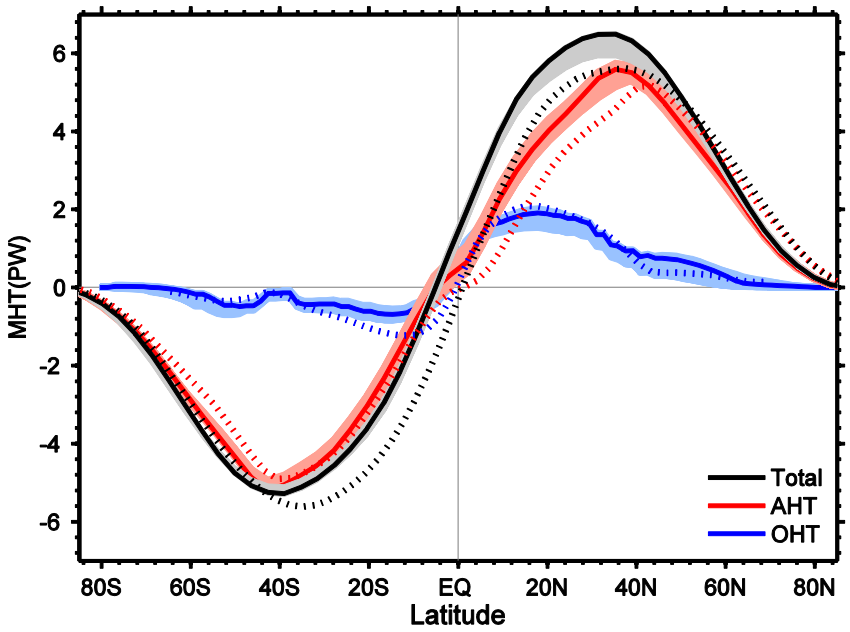
3. Relationship between OHT and AHT Changes?

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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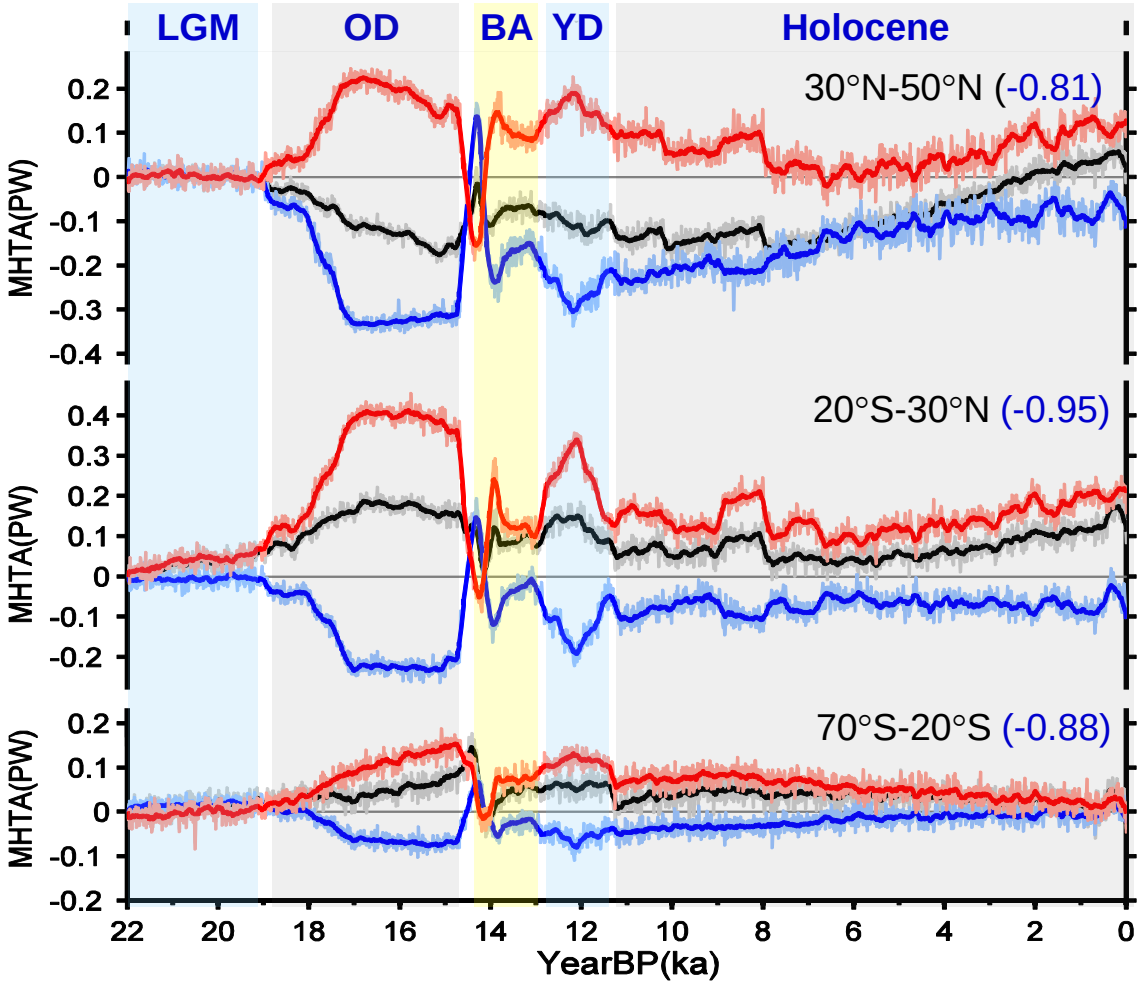
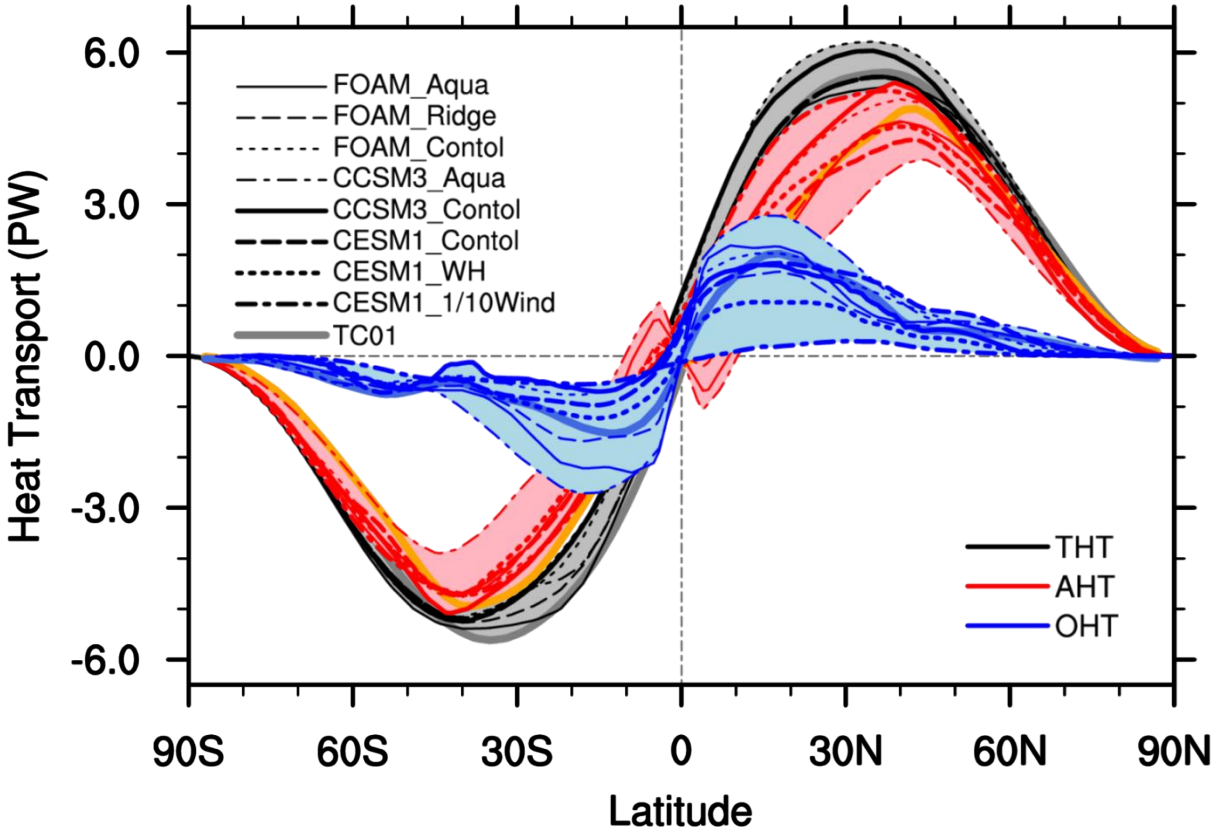
MHT Change Since LGM



Yang et al. (2015)

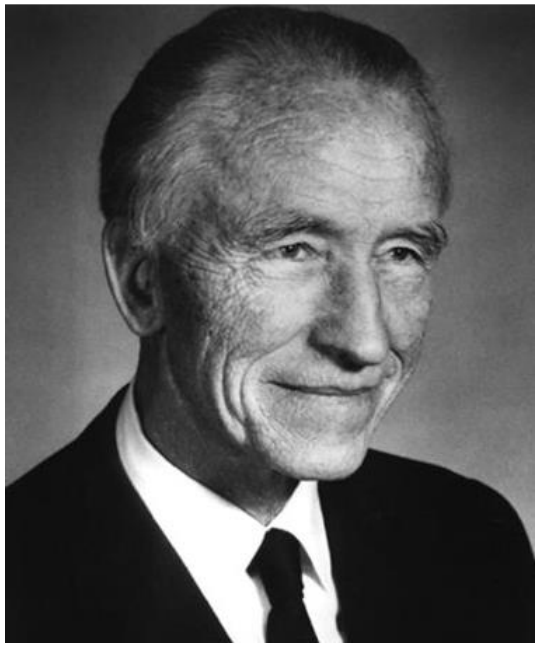
Compensation between AHT and OHT



Note: TC01 is from Trenberth and Caron (2001)

Hypothesis: Bjerknes Compensation

Jacob Aaal Bonnevie Bjerknes
1897-1975



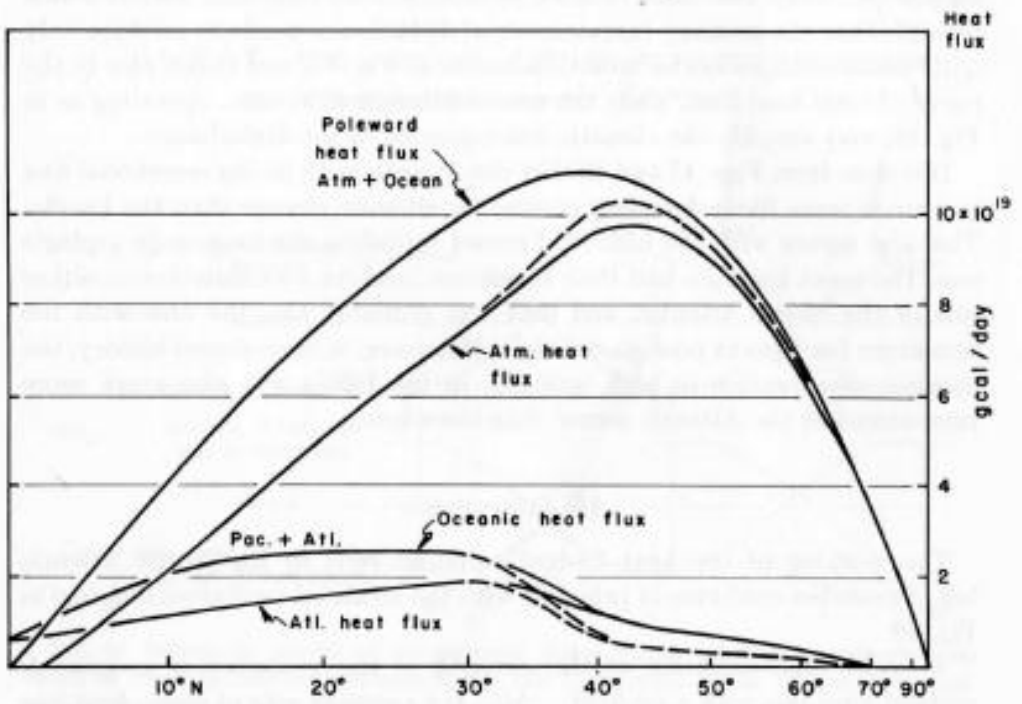


FIG. 48. Solid lines: flux data from Fig. 47 pertaining to present climatic conditions. Dashed lines refer to a sketchy model of the conditions around 1800 A.D. and show qualitative estimate of curtailed Atlantic and total oceanic heat flux as well as increased heat flux by low index atmospheric circulation.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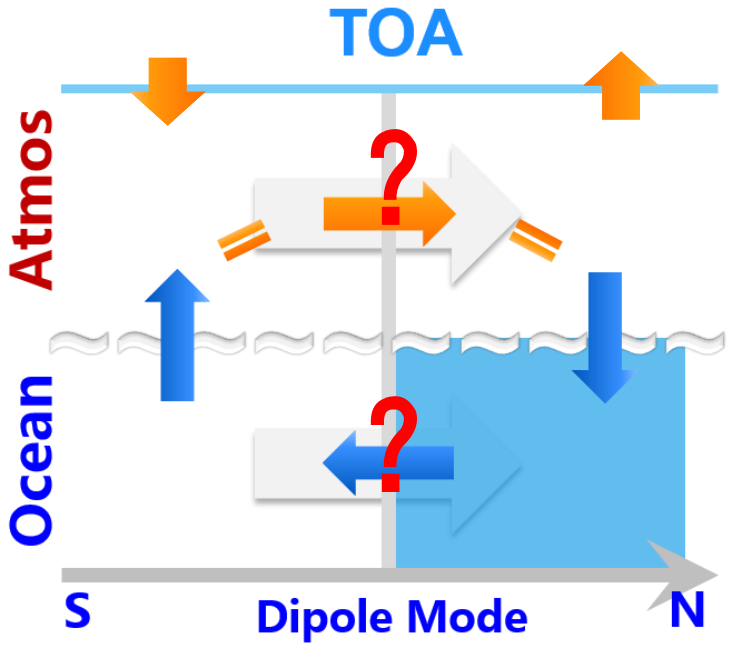
Hypothesis: Bjerknes Compensation

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

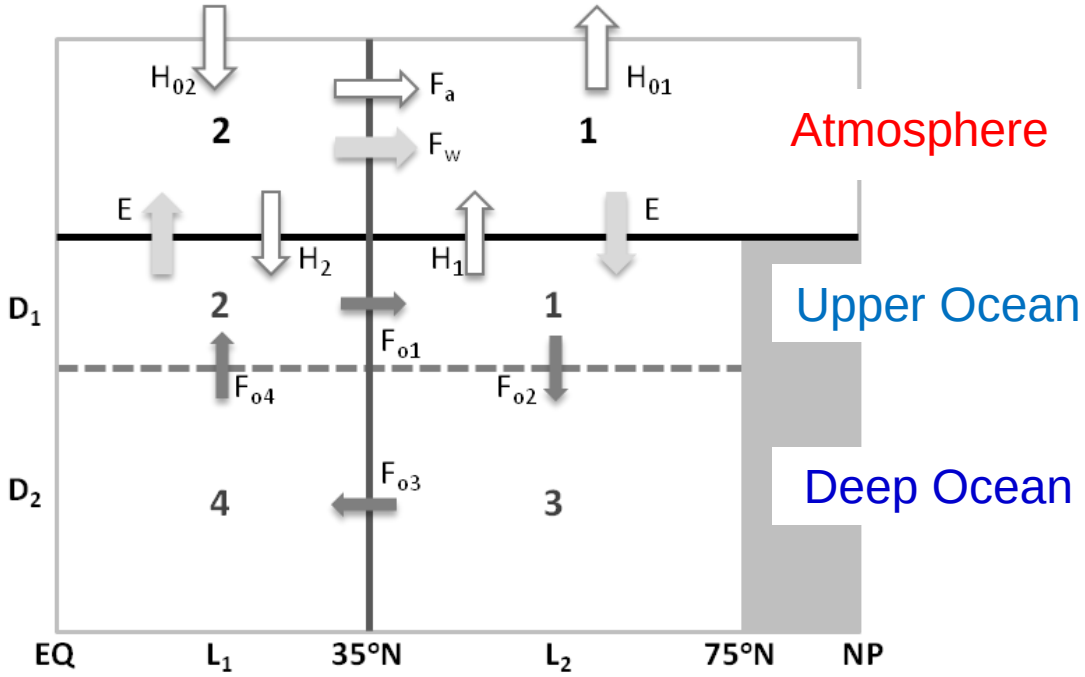
Theory for Equilibrium Change

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

Equations and Dynamics

T $1\cdots$ $2\cdots$ $3\cdots$ $4\cdots$	S $1\cdots$ $2\cdots$ $3\cdots$ $4\cdots$

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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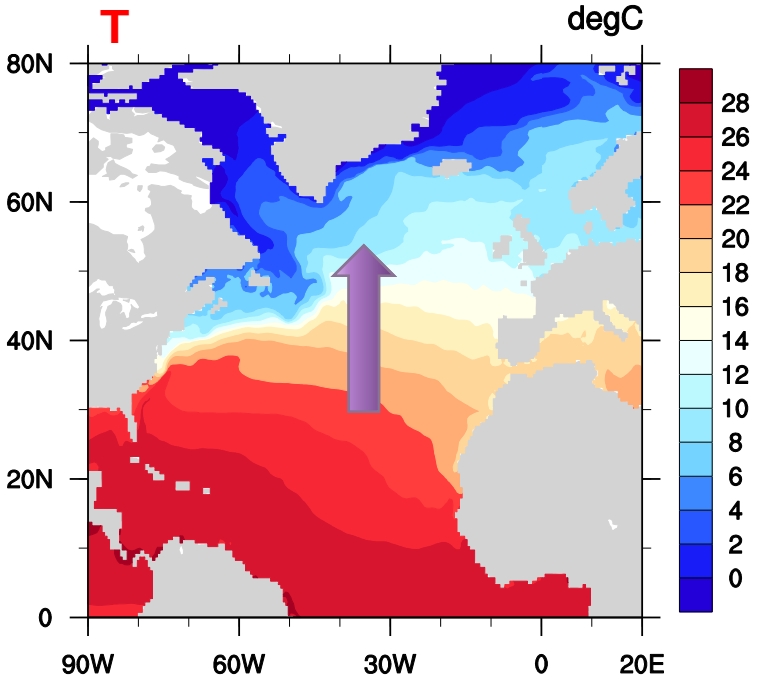
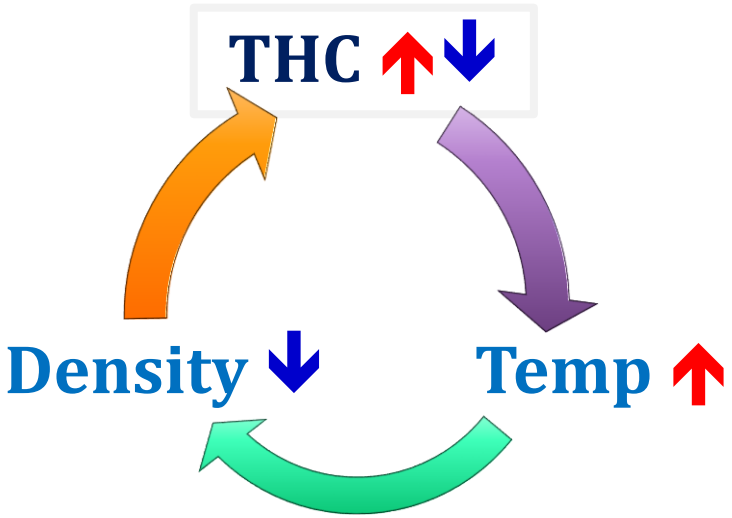
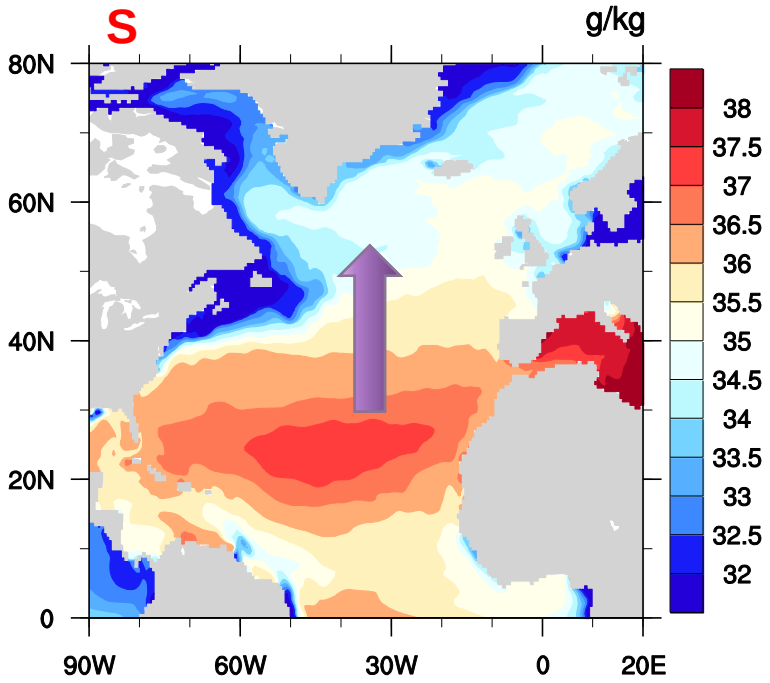
Negative Feedback: *THC* vs *T*

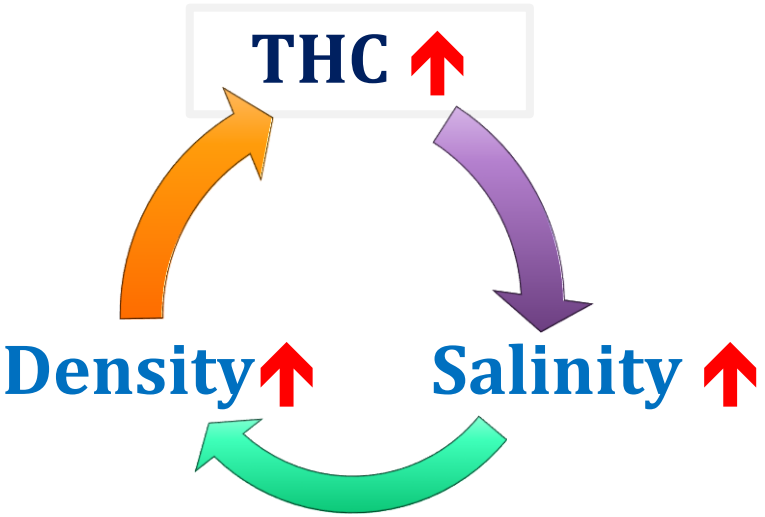




Willebrand (1993)

Positive Feedback: *THC* vs *S*

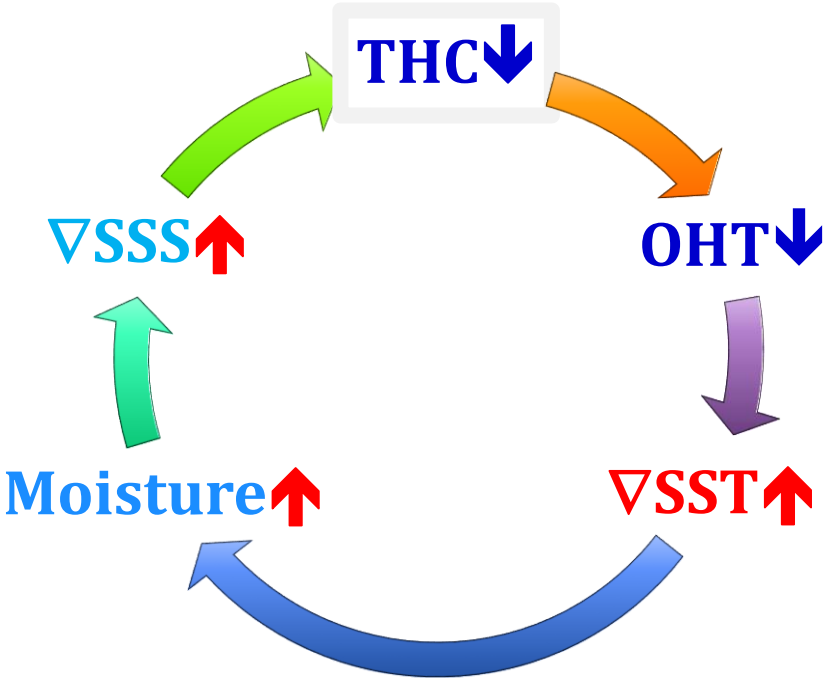




Willebrand (1993)

Positive Feedback: *THC* vs *EMT*

EMT: Atmosphere Eddy Moisture Transport



Nakamura et al. (1994)

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

<1, *if* $-B_1, -B_2 < 0$, **Undercompensation**

$|C_R| = 1$, *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!**

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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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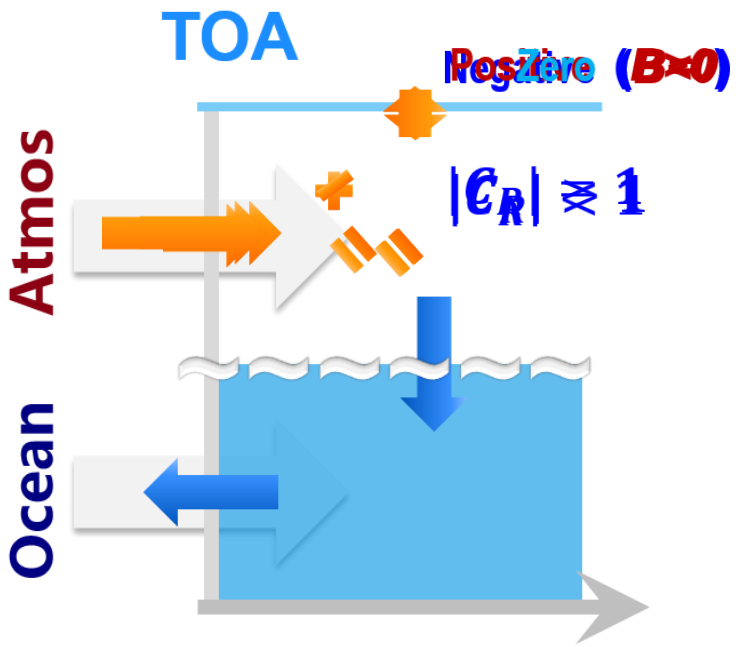
Coupled Intrinsic Mode

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

Energy Compensation ⇔ Weight Management

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

Go to Aqua

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

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

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

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

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

$\omega \to 0$

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

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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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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