Observation-Based Constraints On Atmospheric And Oceanic Cross-Equatorial Heat Transport

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Introduction

- Large-scale tropical circulation and precipitation are constrained by the regional distribution of energy.

- The hemispheric asymmetry in energy determines the cross-equatorial heat transport in the atmosphere and ocean.

- This in turn constrains the mean position of the ITCZ.

- ITCZ and associated precipitation is poorly represented in climate models, likely because they do not correctly represent the regional distribution of energy.
CMIP5 Historical Coupled Simulations (1980-2004 Mean): Precip

mm/day
Objective

- Use CERES EBAF (TOA & SFC) Ed 2.8 and ERA-Interim to determine the implied atmospheric and ocean cross-equatorial heat transports.

- Further decompose the implied cross-equatorial heat transport into radiative and non-radiative contributions.

- Evaluate how climate models (CMIP5) represent the cross-equatorial heat transport.
Observations

- CERES EBAF Ed2.8 (TOA and SFC).
- ERA-Interim total energy tendency and column-integrated divergence of total energy \((c_p T + gz + Lq + k)\).
  - Version of ERA-Interim used obtained from NCAR: The climate data guide: ERA-Interim: Derived components.
  - In this version, a mass flux correction has been applied to the divergence terms.
- GPCP V2.2
## CMIP5 Models Considered

<table>
<thead>
<tr>
<th>Model number</th>
<th>Model name</th>
<th>Country/model group</th>
<th>Resolution (Lon × Lat)</th>
<th>Rt-Fs</th>
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Atmospheric & Surface Energy Budgets from CERES and Reanalysis

\[ \frac{\partial A_E}{\partial t} = R_T - F_S - \nabla . F_A \quad (1) \]

\[ F_S = R_S + LE + S \quad (2) \]

\[ F_A = \frac{1}{g} \int_0^{P_s} (h + k) \bar{u} dp \]

\[ A_E = c_p T + g z + L q + k = h + k \]

\[ \frac{\partial A_E}{\partial t} \& \nabla . F_A \Rightarrow \text{ERA-Interim} \]

\[ R_T \& R_S \Rightarrow \text{CERES EBAF Ed2.8} \]

\[ F_S \& (LE + S) \Rightarrow \text{Residual Terms in (1) \& (2)} \]

Global Mean

- \( R_T = 0.6 \text{ Wm}^{-2} \)
- \( \nabla . F_A = 0 \text{ Wm}^{-2} \)
- \( \frac{\partial A_E}{\partial t} = 0 \text{ Wm}^{-2} \)
- \( F_S = 0.6 \text{ Wm}^{-2} \)
- \( R_S = 109.2 \text{ Wm}^{-2} \)
- \( \text{LE} + S = -108.6 \text{ Wm}^{-2} \)
Implied Cross-Eq. Heat Transports in Atmos. & Ocean from Energetic Constraints

Southern Hemisphere

\[ R_T \]
1.4 Wm\(^{-2}\)

\[ \nabla \cdot F_A \]
-1.0 Wm\(^{-2}\)

\[ \frac{\partial A_E}{\partial t} \]
0.03 Wm\(^{-2}\)

\[ F_S \]
2.3 Wm\(^{-2}\)

0.44 PW

Northern Hemisphere

\[ R_T \]
-0.20 Wm\(^{-2}\)

\[ \nabla \cdot F_A \]
0.90 Wm\(^{-2}\)

\[ \frac{\partial A_E}{\partial t} \]
0.0 Wm\(^{-2}\)

\[ F_S \]
-1.1 Wm\(^{-2}\)

-0.24 PW

0.2 PW
Decomposition of Cross-Equatorial Heat Transport into Radiative and Combined Latent and Sensible Heat Flux Components

\[
\begin{align*}
\text{Atmosphere} & \\
AHT_{EQ} & = \frac{1}{2} \left( \Delta R_T - \Delta F_S - \Delta \frac{\partial A_E}{\partial t} \right) \\
OHT_{EQ} & = \frac{1}{2} \left( \Delta F_S - \Delta \frac{\partial O_E}{\partial t} \right)
\end{align*}
\]

\( \Delta \) denotes the SH minus NH difference.

\[
F_S = R_S + LE + S
\]

\[
AHT_{EQ} = \frac{1}{2} \left( \Delta R_A + \Delta Q_A - \Delta \frac{\partial A_E}{\partial t} \right) \\
OHT_{EQ} = \frac{1}{2} \left( \Delta R_S + \Delta Q_S - \Delta \frac{\partial O_E}{\partial t} \right)
\]

\[
R_A = R_T - R_S \\
Q_S = (LE + S) \\
Q_A = -Q_S
\]
Implied Cross-Eq. Heat Transports in Atmos. & Ocean from Energetic Constraints

**Southern Hemisphere**

- $R_T$: 1.4 Wm$^{-2}$
- $R_A$: -112 Wm$^{-2}$
- $(LE + S)$: 111 Wm$^{-2}$
- $F_S$: 2.3 Wm$^{-2}$

**Northern Hemisphere**

- $R_T$: -0.20 Wm$^{-2}$
- $R_A$: -106 Wm$^{-2}$
- $(LE + S)$: 107 Wm$^{-2}$
- $F_S$: -1.1 Wm$^{-2}$

**Fluxes and Rates**

- $R_T$: 0.2 PW
- $R_A$: -0.75 PW
- $F_S$: 0.51 PW
- $R_S$: 0.95 PW
SH minus NH difference in atmospheric LW Flux

(a) SH minus NH Atm LW Flux Diff (Wm^-2)

- Clear-Sky
- All-Sky
- CRE

SH minus NH difference in cloud fraction

(b) SH minus NH Cloud Fraction Diff

- < 3
- 3 - 5.7
- 5.7 - 10
- > 10

LW ATM cooling in NH dominates
LW ATM cooling in SH dominates
Conclusions

- The large-scale circulation in the tropics and position of the ITCZ are intricately linked with the large-scale distribution of the energy budget.

- CERES EBAF-TOA and SFC combined with ERA-I atmospheric total energy divergence enable a decomposition of cross-equatorial heat transport into radiative and combined latent and sensible heat flux components.

- This decomposition provides a powerful new observational constraint on large-scale energy budget that needs to be satisfied in order to make progress on double ITCZ problem.
Conclusions

- SH has a larger cloud fraction and a greater fraction of low clouds, while the NH has more high clouds. In addition, NH has a higher surface albedo, greater abundance of absorbing aerosols and precipitable water.

⇒ LW radiative cooling is more pronounced in the SH than the NH and SW radiative heating is greater in the NH.

⇒ Net atmospheric radiative effect is more cooling in the SH relative to NH, which implies a NH to SH cross-eq heat transport.

⇒ Surface-to-atmosphere combined latent and sensible heat transport is greater in SH than NH, which compensates somewhat for radiatively driven cross-eq heat transport.
Conclusions

- CMIP5 models that overestimate tropical precipitation in the SH:
  - overestimate net downward surface radiation in SH vs NH
  - overestimate combined latent and sensible heat flux in SH vs NH
  - underestimate atmospheric radiative cooling in the SH vs NH

⇒ Excessive heating of the SH atmosphere and anomalous SH to NH cross-equatorial heat transport

⇒ Ascending branch of Hadley circulation lies too far to the south (necessary to move excess heat from SH to NH).

⇒ Too much SH tropical precipitation.