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

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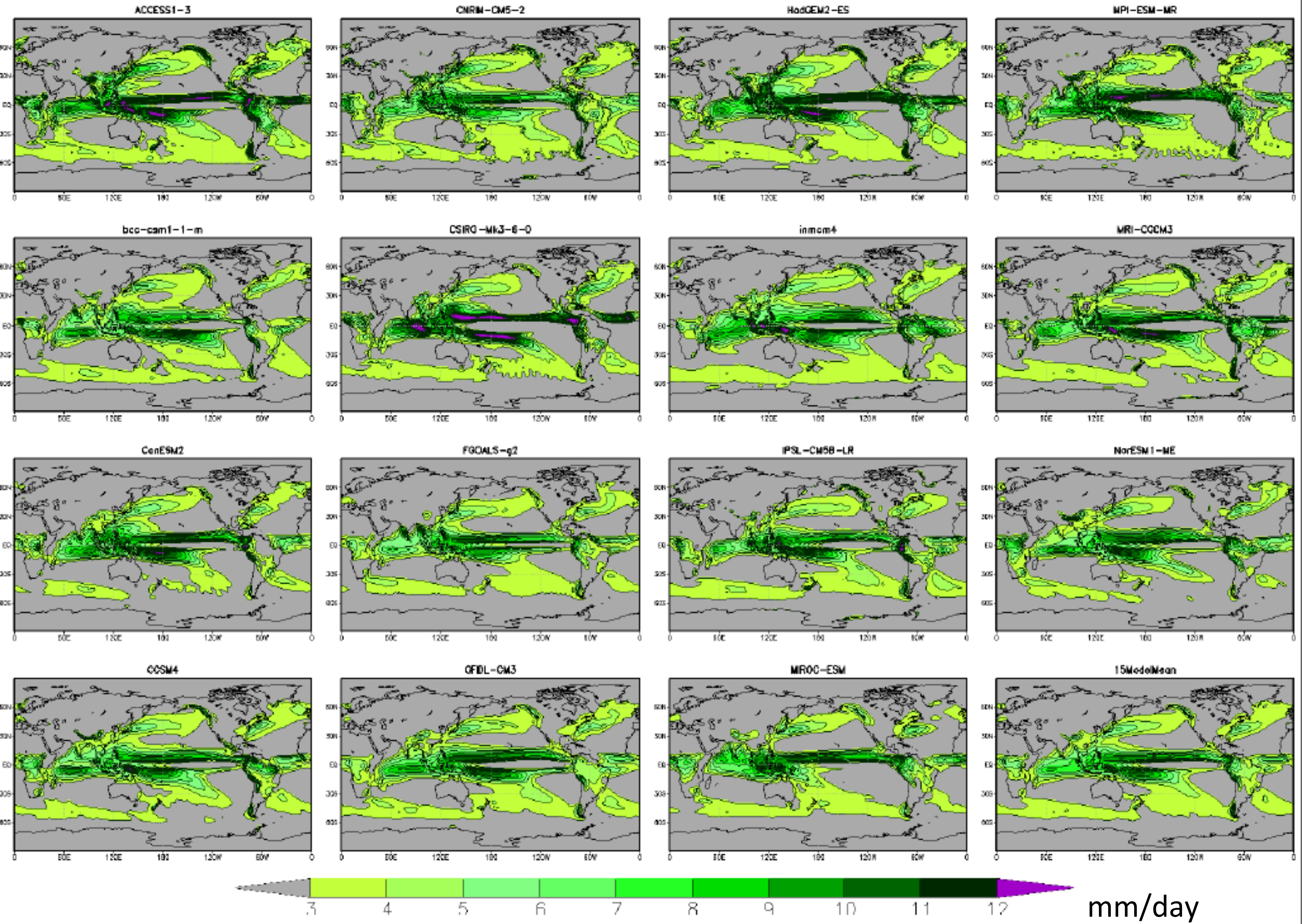
Introduction

- 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(1980–2004Mean): Precip



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 ($c_pT + gz + Lq + k$).
    - 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
- Time Period: January 2001-December 2012.

CMIP5 Models Considered

Model number	Model name	Country/model group	Resolution (Lon × Lat)	Rt-Fs
1	ACCESS1.0	Australia/ACCESS	1.875° × 1.25°	−0.38
2	ACCESS1.3		1.875° × 1.25°	−0.65
3	CCSM4	US/NCAR	1.25° × 0.9375°	−0.35
4	CESM1-BGC		1.25° × 0.9375°	−0.34
5	CESM1-FASTCHEM		1.25° × 0.9375°	−0.35
6	CESM1-WACCM		2.5° × 1.89°	−0.24
7	CSIRO-Mk3.6.0	Australia/CSIRO	1.875° × 1.86°	0.33
8	CanESM2	Canada	2.8125° × 2.79°	0.19
9	GFDL-CM3	US/GFDL	2.5° × 2.0°	−0.36
10	GFDL-ESM2G		2.5° × 2.01°	−0.55
11	GFDL-ESM2 M		2.5° × 2.01°	−0.56
12	GISS-E2-H	US/GISS	2.5° × 2.0°	−0.42
13	GISS-E2-H-CC		2.5° × 2.0°	−0.40
14	GISS-E2-R		2.5° × 2.0°	−0.39
15	GISS-E2-R-CC		2.5° × 2.0°	−0.39
16	HadCM3	UK/Met Office	3.75° × 2.5°	−0.29
17	HadGEM2-CC		1.875° × 1.25°	−0.48
18	HadGEM2-ES		1.875° × 1.25°	−0.46
19	IPSL-CM5A-LR	France/IPSL	3.75° × 1.89°	0.32
20	IPSL-CM5A-MR		2.5° × 1.27°	0.33
21	IPSL-CM5B-LR		3.75° × 1.89°	−0.59
22	MIROC4 h	Japan/MIROC	0.5625° × 0.56°	−0.50
23	MIROC5		1.40625° × 1.40°	0.24
24	MPI-ESM-LR	Germany/MPI	1.875° × 1.86°	0.09
25	MPI-ESM-MR		1.875° × 1.86°	0.21
26	MPI-ESM-P		1.875° × 1.86°	0.12
27	MRI-CGCM3	Japan/MRI	1.125° × 1.12°	−0.19
28	MRI-ESM1		1.125° × 1.12°	−0.20
29	bcc-csm1-1	China/BCC	2.8125° × 2.79°	−0.97
30	bcc-csm1-1-m		1.125° × 1.12°	−0.99

Atmospheric & Surface Energy Budgets from CERES and Reanalysis

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

$$F_S = R_S + LE + S \quad (2)$$

$$F_A = \frac{1}{g}\int_0^{p_s} (h+k)\vec{u}\, dp$$

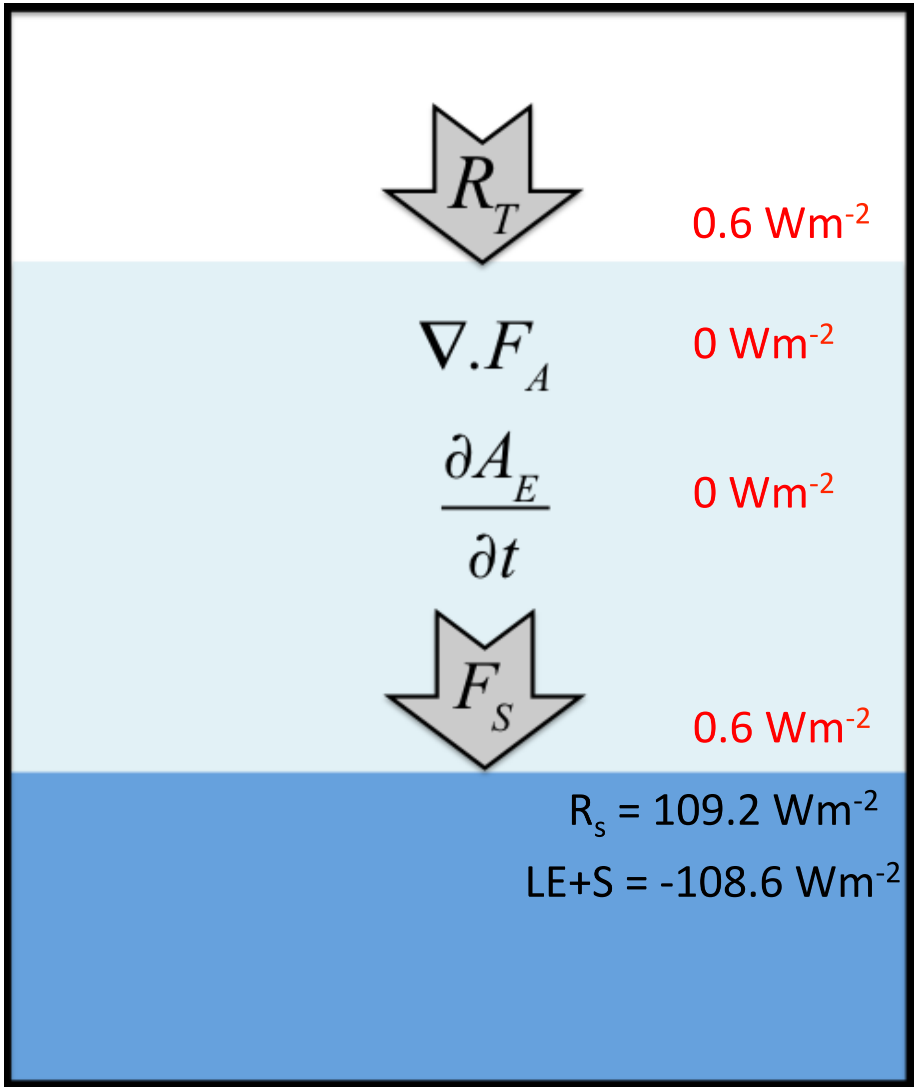
$$A_E = c_p T + gz + Lq + k = h + k$$

$\frac{\partial A_E}{\partial t}$ & $\nabla . F_A$ => ERA-Interim

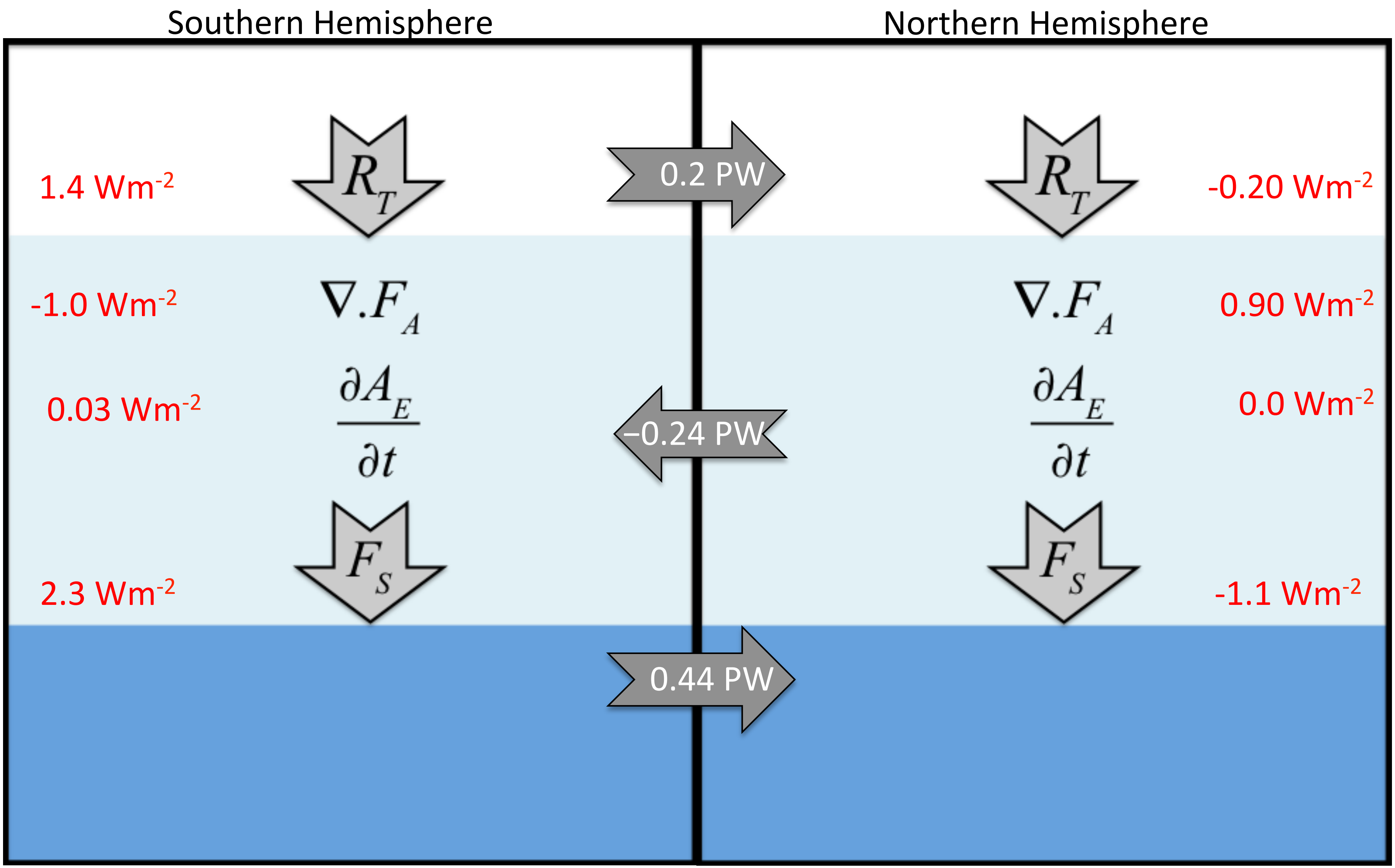
R_T & R_S => CERES EBAF Ed2.8

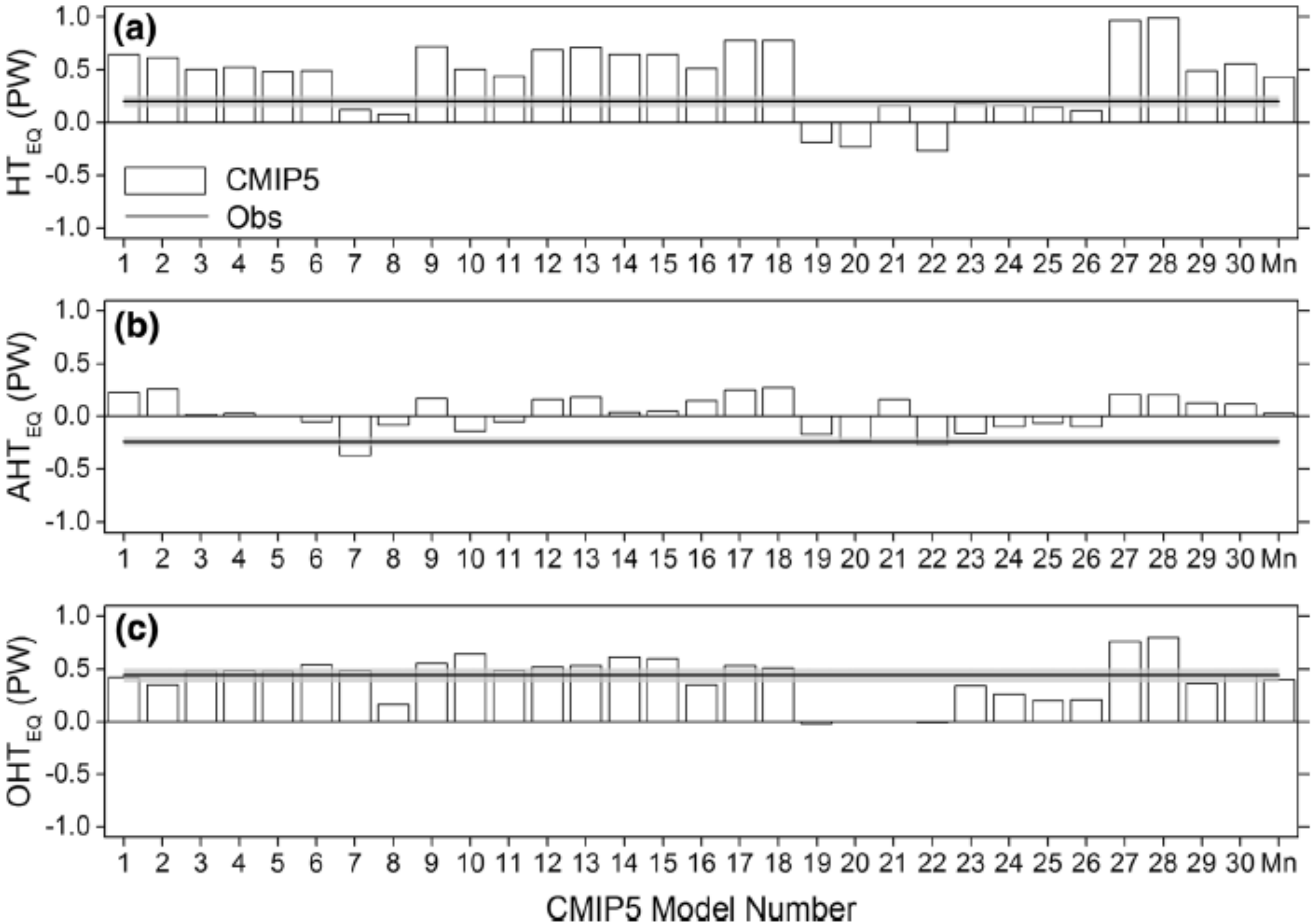
F_S & $(LE + S)$ => Residual Terms in (1) & (2)

Global Mean



Implied Cross-Eq. Heat Transports in Atmos. & Ocean from Energetic Constraints





(a)
(b)
(c)
HT_{EQ} (PW)
AHT_{EQ} (PW)
OHT_{EQ} (PW)
1.0
0.5
0.0
-0.5
-1.0
CMIP5
Obs
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 Mn
CMIP5 Model Number

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

Atmosphere

$$AHT_{EQ} = \frac{1}{2}\left(\Delta R_T - \Delta F_S - \Delta \frac{\partial A_E}{\partial t}\right)$$

Ocean

$$OHT_{EQ} = \frac{1}{2}\left(\Delta F_S - \Delta \frac{\partial O_E}{\partial t}\right)$$

Δ denotes the SH minus NH difference.

$$F_S = R_S + LE + S$$

$$AHT_{EQ} = \frac{1}{2}\left(\Delta R_A + \Delta Q_A - \Delta \frac{\partial A_E}{\partial t}\right)$$

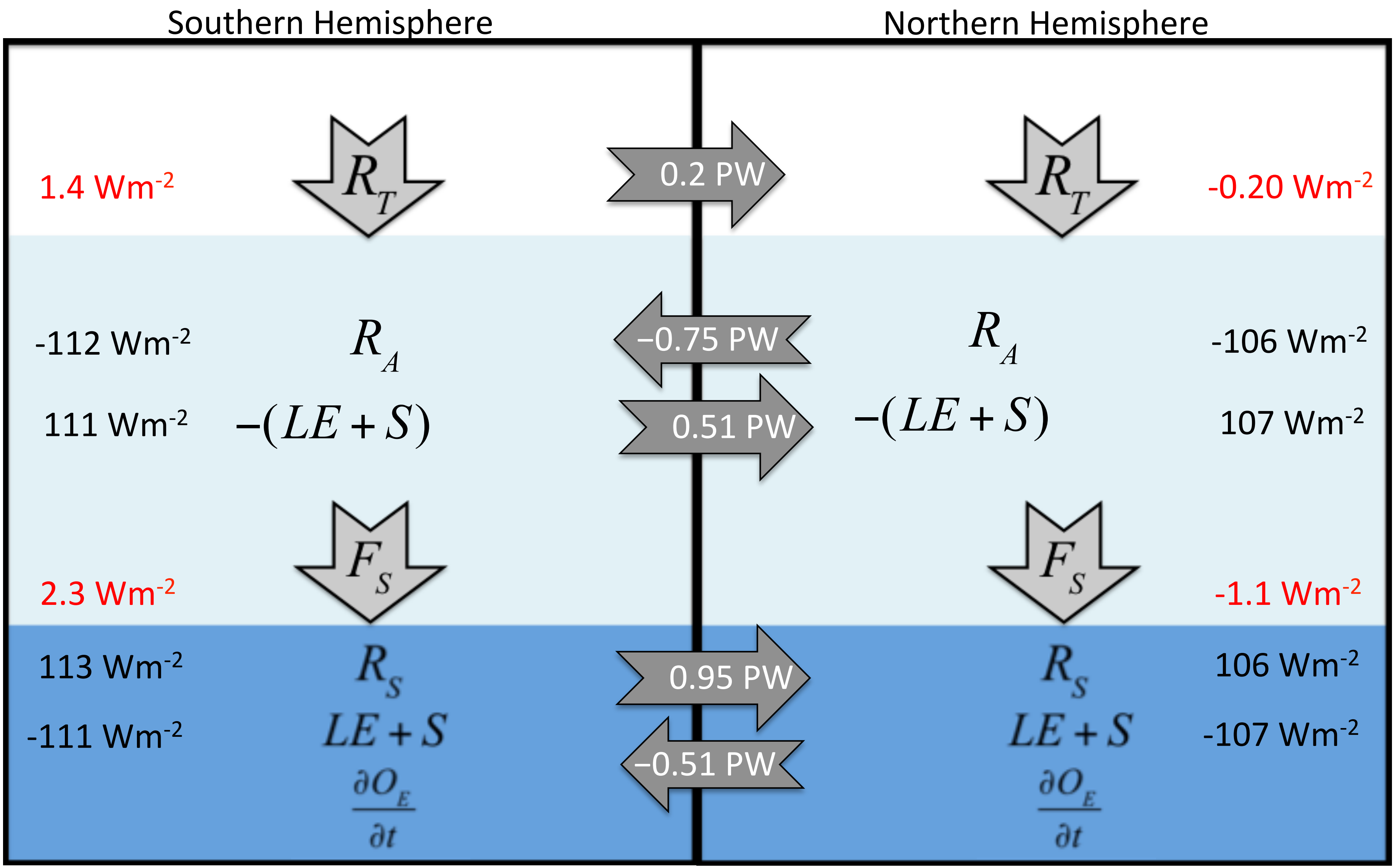
$$OHT_{EQ} = \frac{1}{2}\left(\Delta R_S + \Delta Q_S - \Delta \frac{\partial O_E}{\partial t}\right)$$

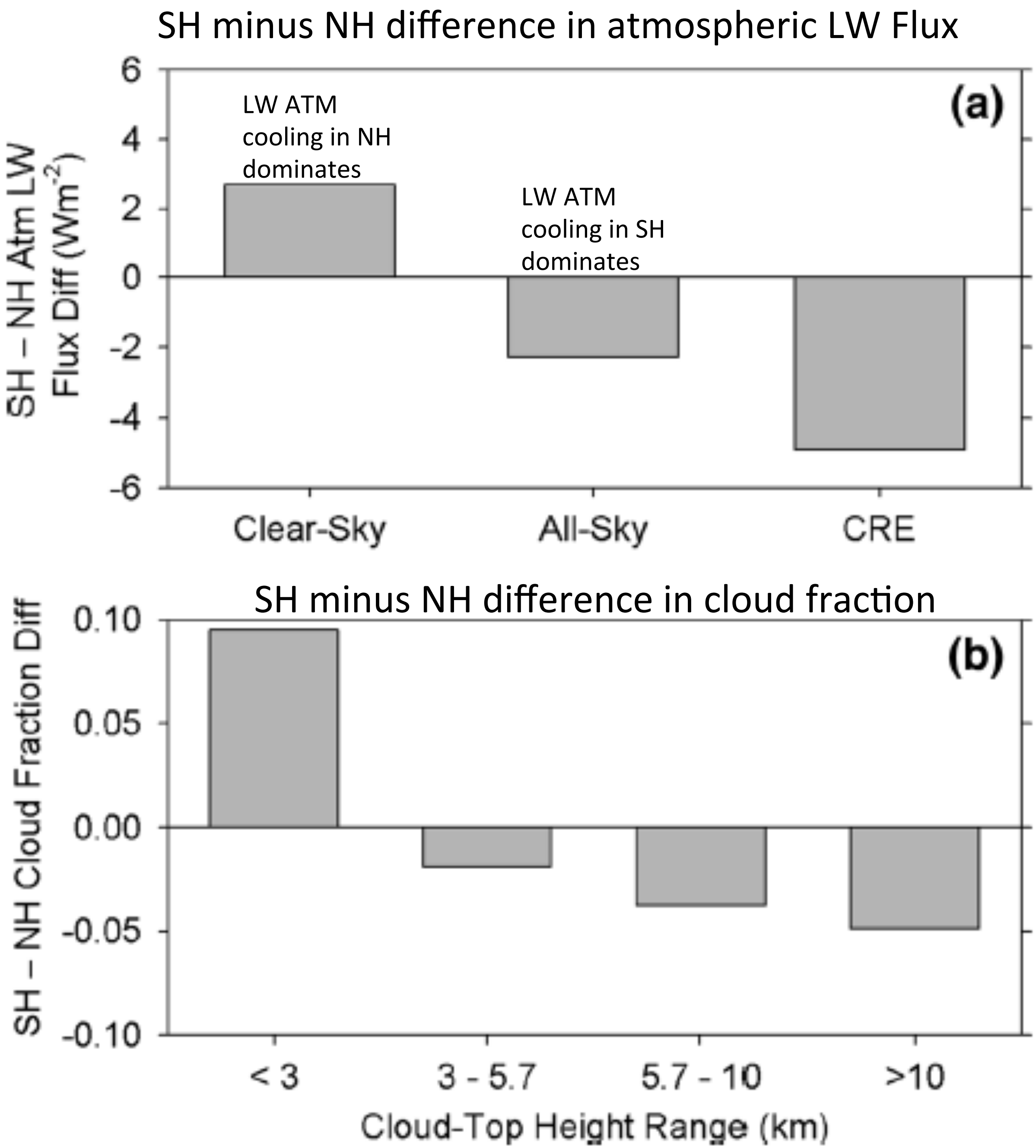
$R_A = R_T - R_S$

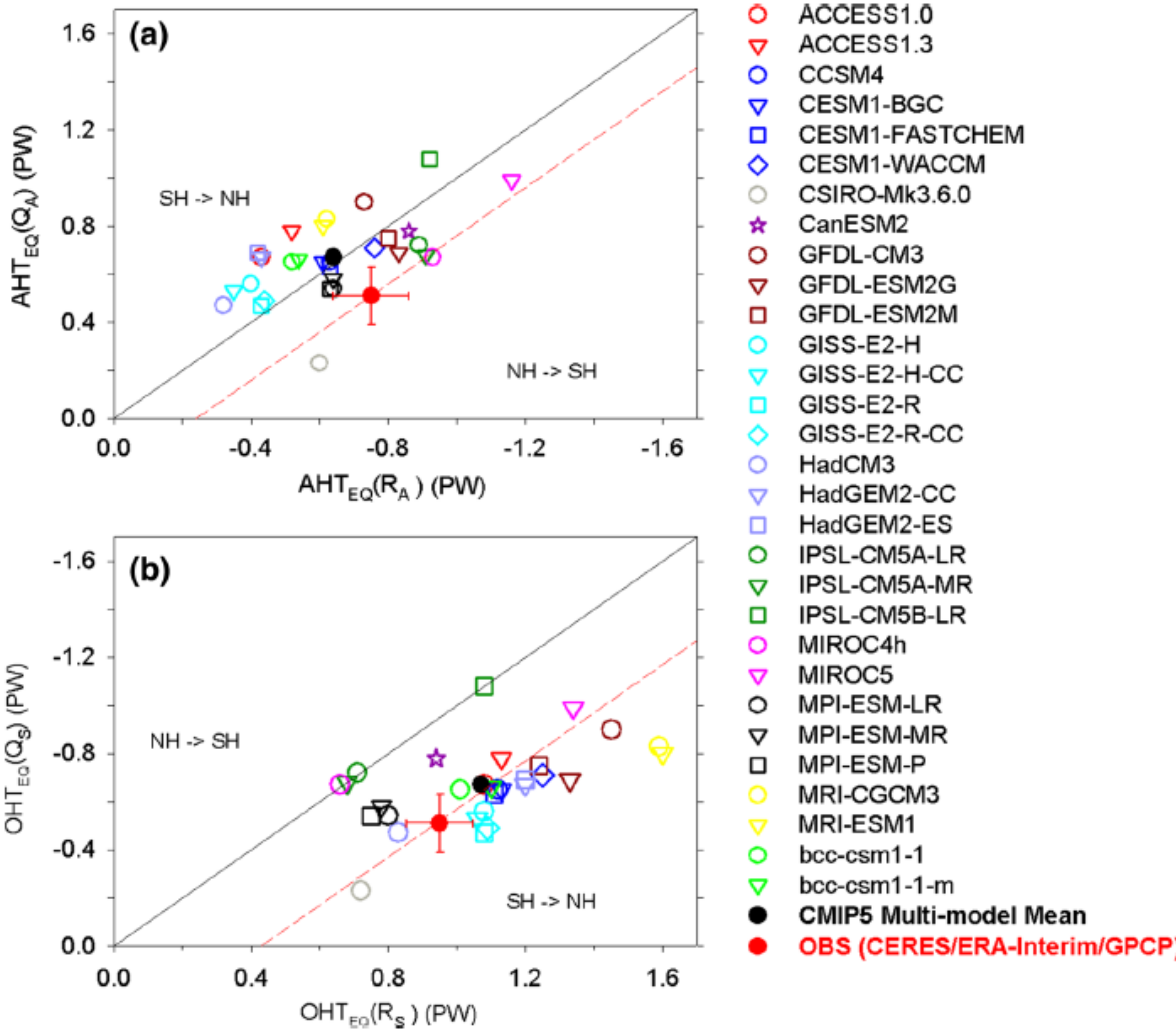
$Q_S = (LE + S)$

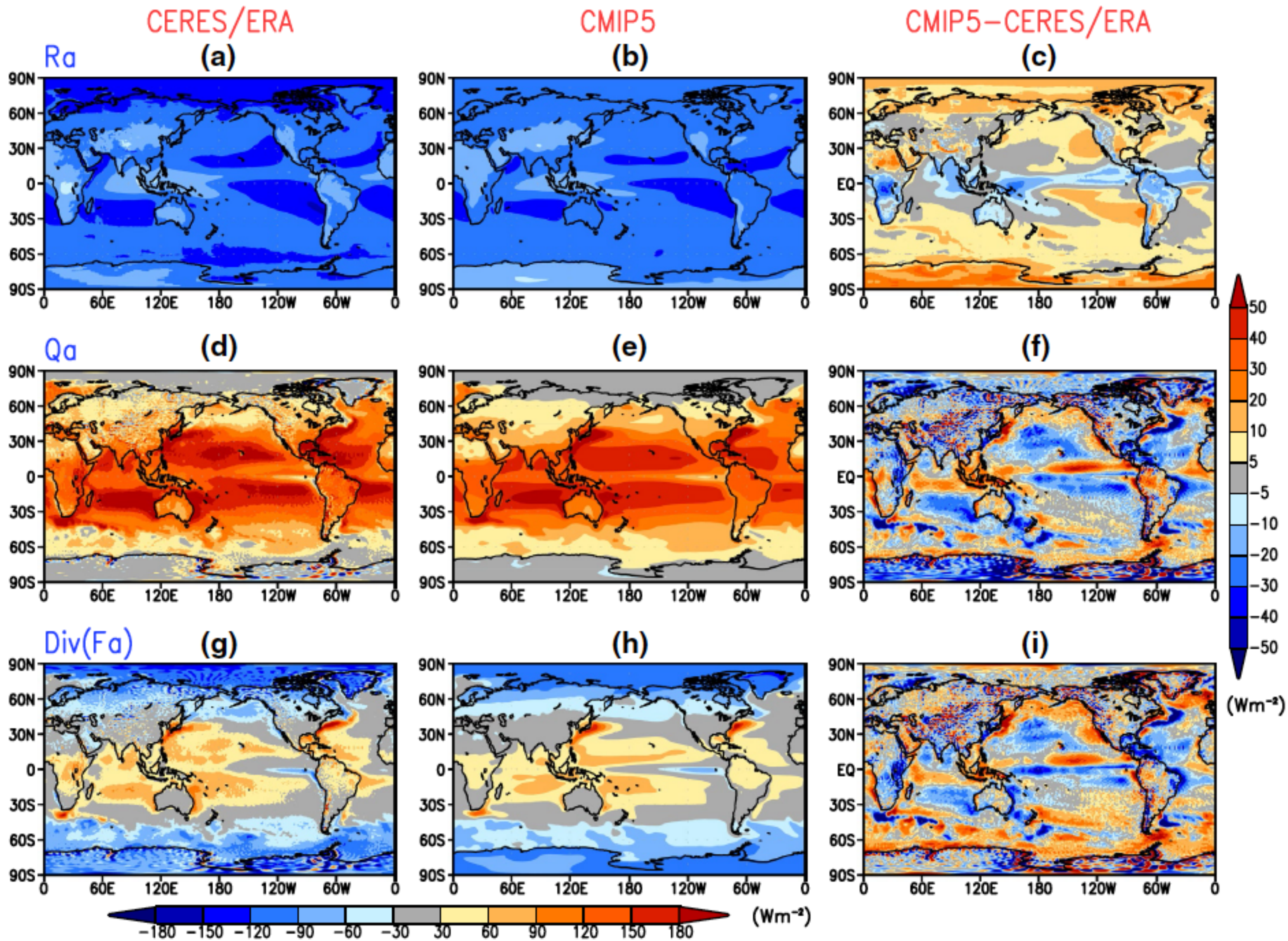
$Q_A = -Q_S$

Implied Cross-Eq. Heat Transports in Atmos. & Ocean from Energetic Constraints

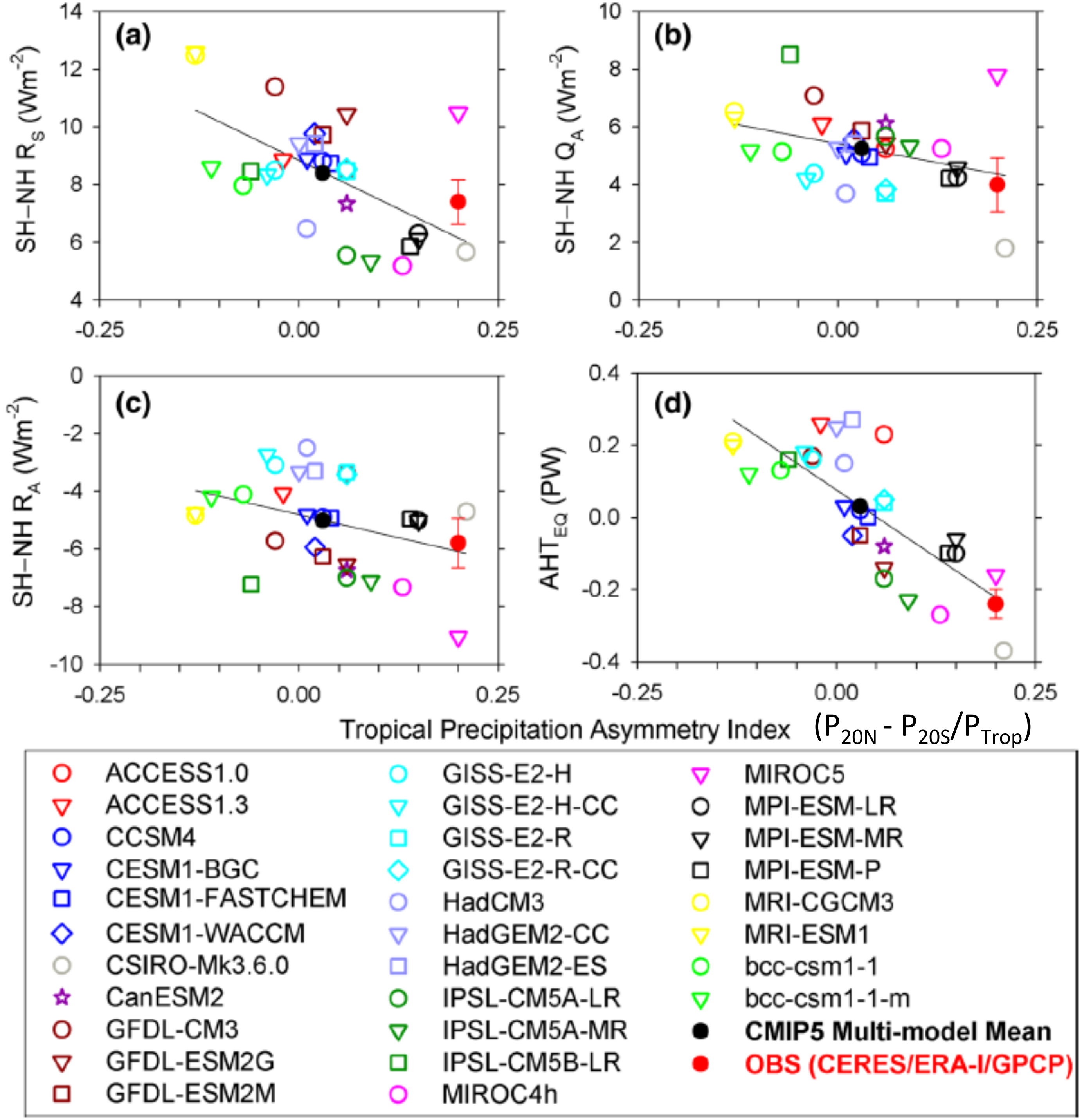


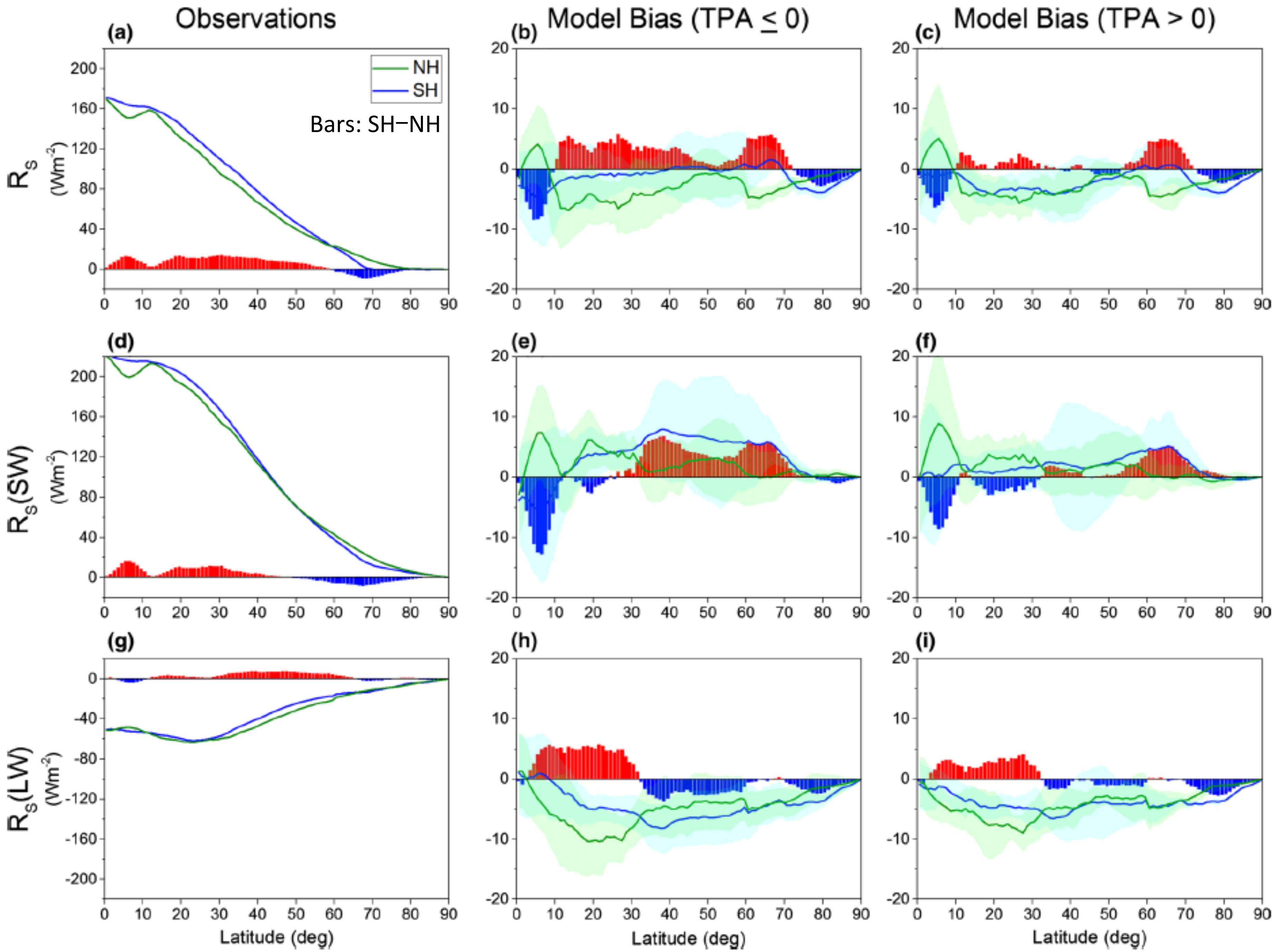

SH minus NH difference in atmospheric LW Flux
(a)
LW ATM cooling in NH dominates
LW ATM cooling in SH dominates
SH – NH Atm LW Flux Diff (Wm-2)
6
4
2
0
-2
-4
-6
Clear-Sky
All-Sky
CRE
SH minus NH difference in cloud fraction
(b)
SH – NH Cloud Fraction Diff
0.10
0.05
0.00
-0.05
-0.10
< 3
3 - 5.7
5.7 - 10
>10
Cloud-Top Height Range (km)


(a)
SH -> NH
NH -> SH
AHT$_{EQ}$(Q$_A$) (PW)
AHT$_{EQ}$(R$_A$) (PW)
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
(b)
NH -> SH
SH -> NH
OHT$_{EQ}$(Q$_S$) (PW)
OHT$_{EQ}$(R$_S$) (PW)
-1.6
-1.2
-0.8
-0.4
0.0
0.4
0.8
1.2
1.6
ACCESS1.0
ACCESS1.3
CCSM4
CESM1-BGC
CESM1-FASTCHEM
CESM1-WACCM
CSIRO-Mk3.6.0
CanESM2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-H-CC
GISS-E2-R
GISS-E2-R-CC
HadCM3
HadGEM2-CC
HadGEM2-ES
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC4h
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MPI-ESM-P
MRI-CGCM3
MRI-ESM1
bcc-csm1-1
bcc-csm1-1-m
CMIP5 Multi-model Mean
OBS (CERES/ERA-Interim/GPCP)



CERES/ERA
CMIP5
CMIP5−CERES/ERA
Ra
(a)
(b)
(c)
Qa
(d)
(e)
(f)
Div(Fa)
(g)
(h)
(i)
90N
60N
30N
0
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
50
40
30
20
10
5
−5
−10
−20
−30
−40
−50
(Wm⁻²)
−180
−150
−120
−90
−60
−30
30
60
90
120
150
180
(Wm⁻²)


(a)
(b)
(c)
(d)
SH–NH R$_S$ (Wm^{-2})
SH–NH Q$_A$ (Wm^{-2})
SH–NH R$_A$ (Wm^{-2})
AHT$_{EQ}$ (PW)
Tropical Precipitation Asymmetry Index (P$_{20N}$ - P$_{20S}$/P$_{Trop}$)
ACCESS1.0
ACCESS1.3
CCSM4
CESM1-BGC
CESM1-FASTCHEM
CESM1-WACCM
CSIRO-Mk3.6.0
CanESM2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-H-CC
GISS-E2-R
GISS-E2-R-CC
HadCM3
HadGEM2-CC
HadGEM2-ES
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC4h
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MPI-ESM-P
MRI-CGCM3
MRI-ESM1
bcc-csm1-1
bcc-csm1-1-m
CMIP5 Multi-model Mean
OBS (CERES/ERA-I/GPCP)



Observations
Model Bias (TPA ≤ 0)
Model Bias (TPA > 0)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
NH
SH
Bars: SH−NH
R_S (Wm^-2)
R_S(SW) (Wm^-2)
R_S(LW) (Wm^-2)
Latitude (deg)

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

$\Rightarrow$ Excessive heating of the SH atmosphere and anomalous SH to NH cross-equatorial heat transport

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

$\Rightarrow$ Too much SH tropical precipitation.