Exploration of Hemispheric Asymmetry in the Surface Energy Budget using CERES and Reanalysis Data

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Introduction

- The large-scale tropical circulation and precipitation is constrained by the regional distribution of energy.
- The hemispheric asymmetry in energy into the Earth-Atmosphere system determines the cross-equatorial heat transport in the atmosphere and ocean.
- This in turn constrains the mean position of the ITCZ.

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 & MMF) represent the cross-equatorial heat transport.

Observations

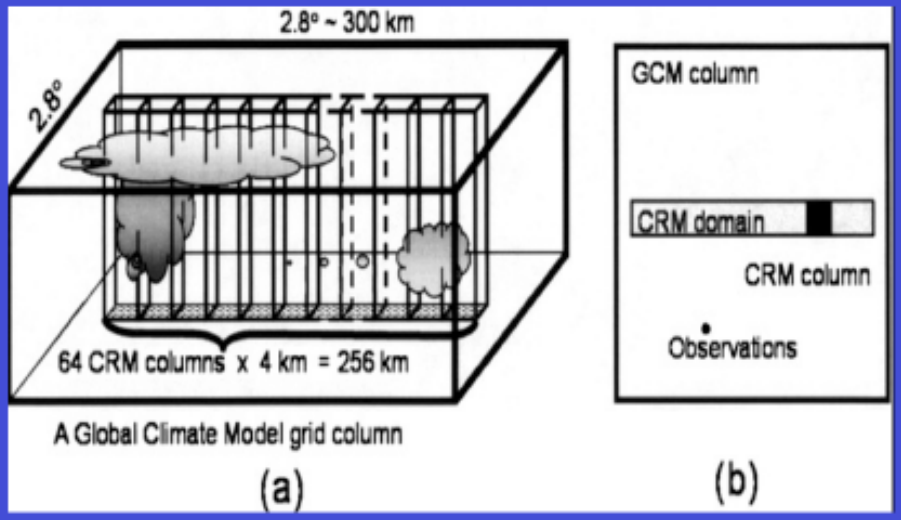
- CERES EBAF Ed2.8 (TOA and SFC).
- ERA-Interim total energy tendency and column-integrated divergence of total energy ($c_pT + gz + Lq + k$).
  - Version of ERA-Interim used obtained from NCAR: The climate data guide: ERA-Interim: Derived components.
  - In this version, a mass flux correction has been applied to the divergence terms.
- GPCP V2.2
- Time Period: January 2001-December 2012.

CMIP5 Models

Model #	Model	Country	Nx*ny	Lon*lat
1	ACCESS1-3	Australia	192x145	1.875x1.25
2	bcc-csm1-1-m	China	320x160	1.125x1.12
3	CanESM2	Canada	128x64	2.8x2.8
4	CCSM4	USA	288x192	1.25x0.94
5	CNRM-CM5-2	France	256x128	1.4x1.4
6	CSIRO-Mk3-6-0	Australia	192x96	1.875x1.86
7	FGOALS-g2	China	128x60	2.8125x3.05
8	GFDL-CM3	USA	144x90	2.5x2.0
9	HadGEM2-ES	UK	192x145	1.875x1.25
10	inmcm4	Russia	180x120	2x1.5
11	IPSL-CM5B-LR	France	96x96	3.75x1.9
12	MIROC-ESM	Japan	128x64	2.8x2.8
13	MPI-ESM-MR	Germany	192x96	1.875x1.86
14	MRI-CGCM3	Japan	320x160	1.125x1.12
15	NorESM1-ME	Norway	144x96	2.5x1.9

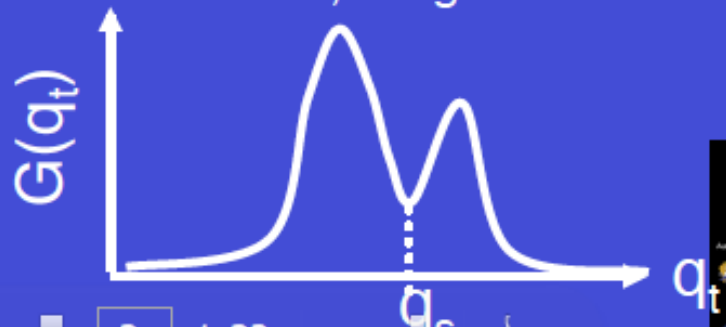
Multiscale Modeling Framework
(Grabowski 2001; Khairoutdinov and Randall 2001)

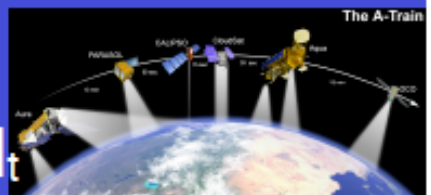
- A CRM is embedded at each grid column (~100s km) of the host GCM to represent cloud physical processes
- The CRM explicitly simulates cloud-scale dynamics (~1s km) and processes
- Periodic lateral boundary condition for CRM (not extend to the edges)



Upgraded CRM with a third-order turbulence closure (IPHOC):

- Double-Gaussian distribution of liquid-water potential temperature, total water mixing ratio and vertical velocity
- Skewnesses, i.e., the three third-order moments, predicted
- All first-, second-, third- and fourth-order moments, subgrid-scale condensation and buoyancy based on the same PDF





Atmospheric & Surface Energy Budgets from CERES and Reanalysis

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

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

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

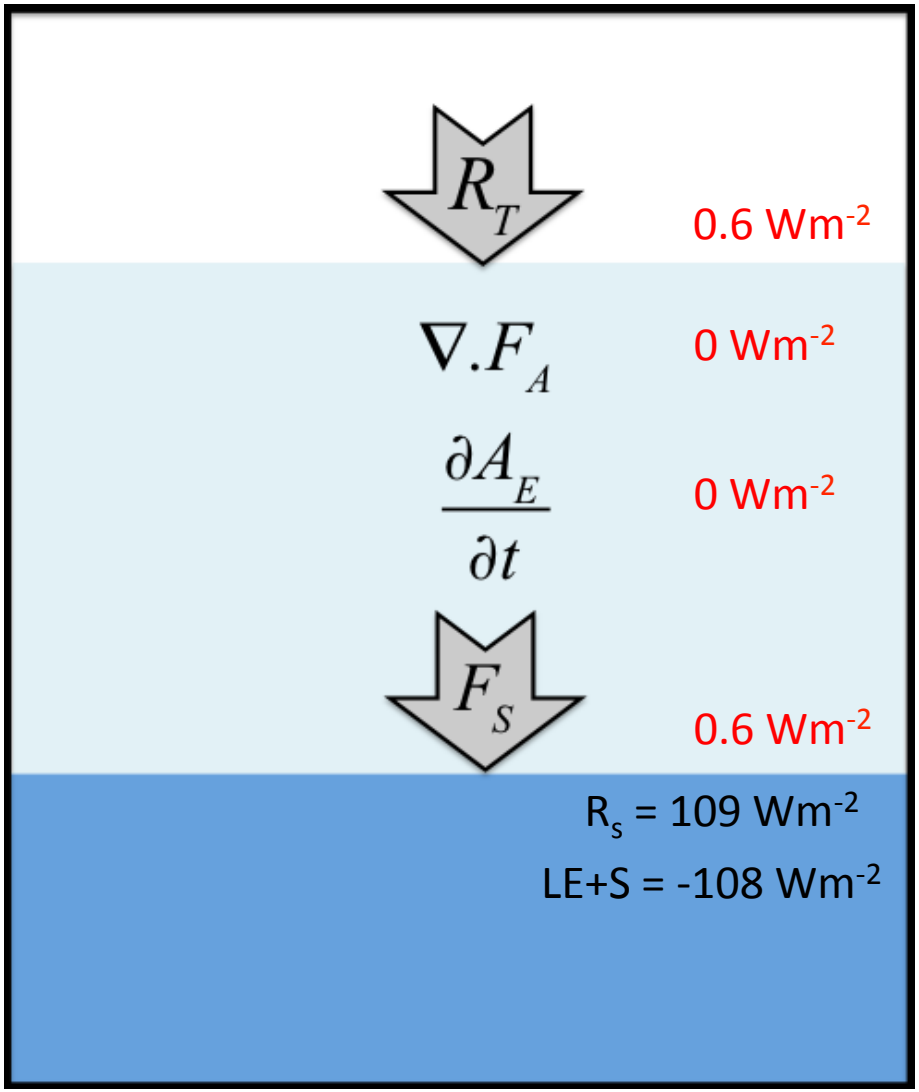
$$A_E = c_p T + gz + Lq + k = h + k$$

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

R_T & R_S => CERES EBAF Ed2.8

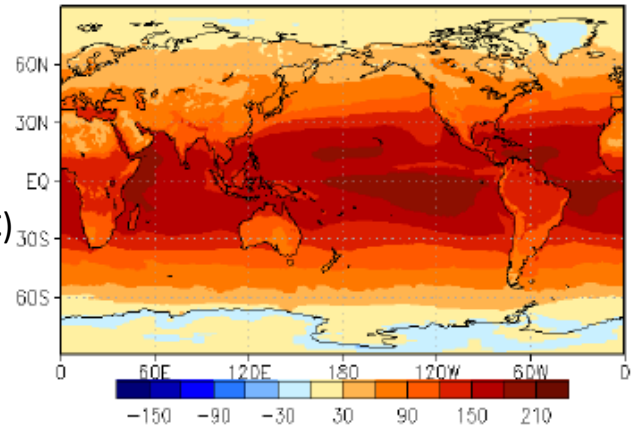
F_S & $(LE+S)$ => Residual Terms in (1) & (2)

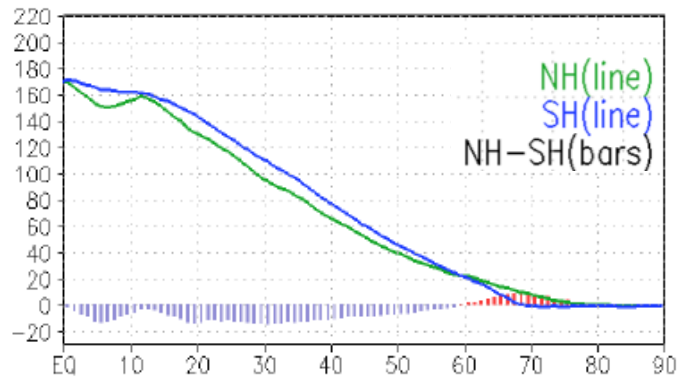
Global Mean



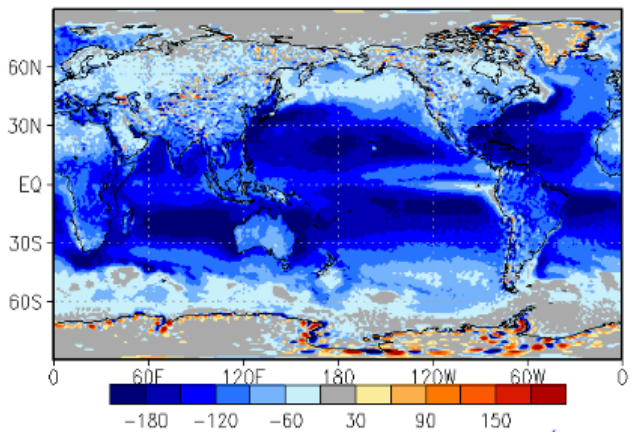
Surface Fluxes Inferred from CERES EBAF R_T and R_S & ERA-Interim Div(F_A)

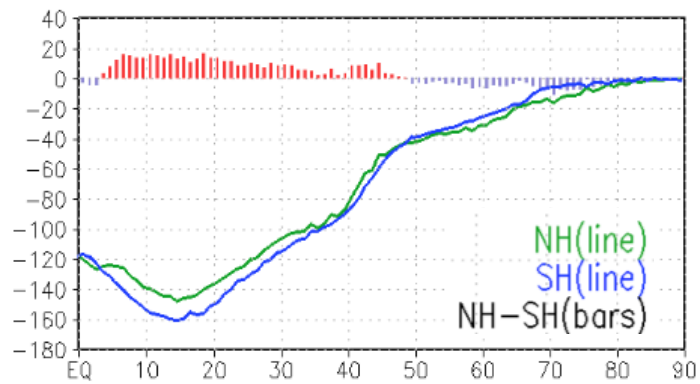
R_s
(CERES SFC)



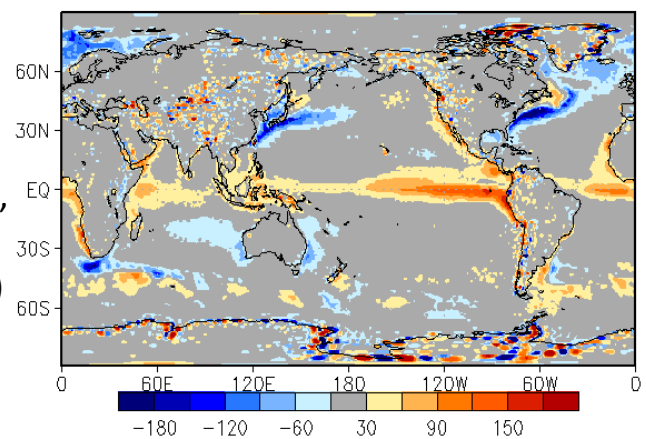


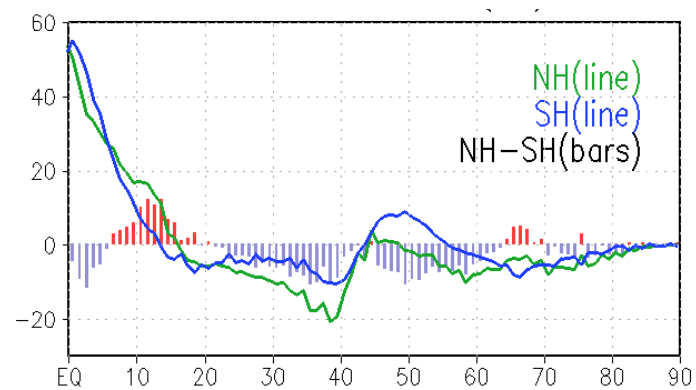
LE + S
($F_s - R_s$)





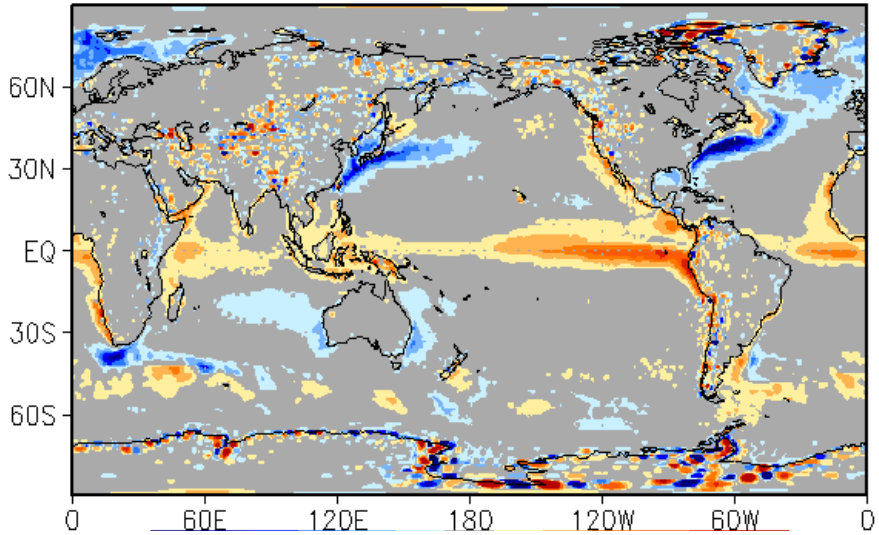
F_S
(CERES TOA,
ERA-Int.
TETEN, Div)



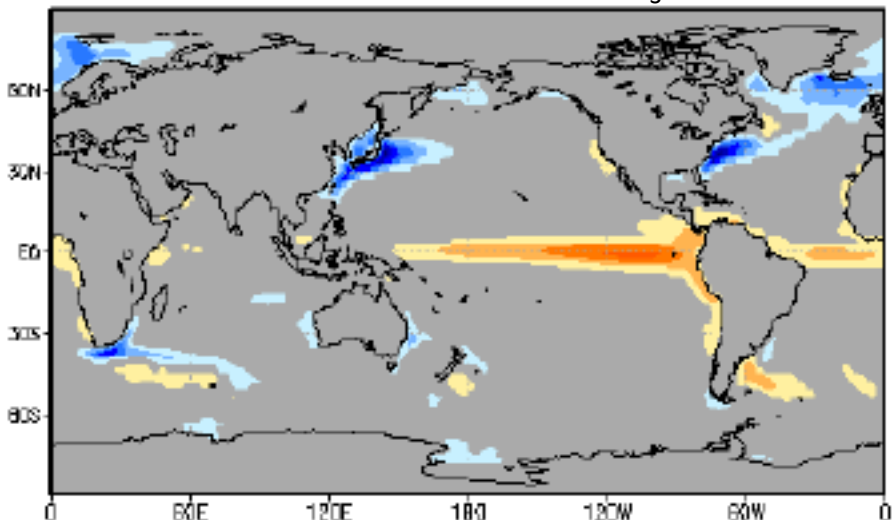


Comparison of Surface Flux ($F_s = R_s + LE + S$)

CERES TOA & ERA-I TETEN, Div(TOT)



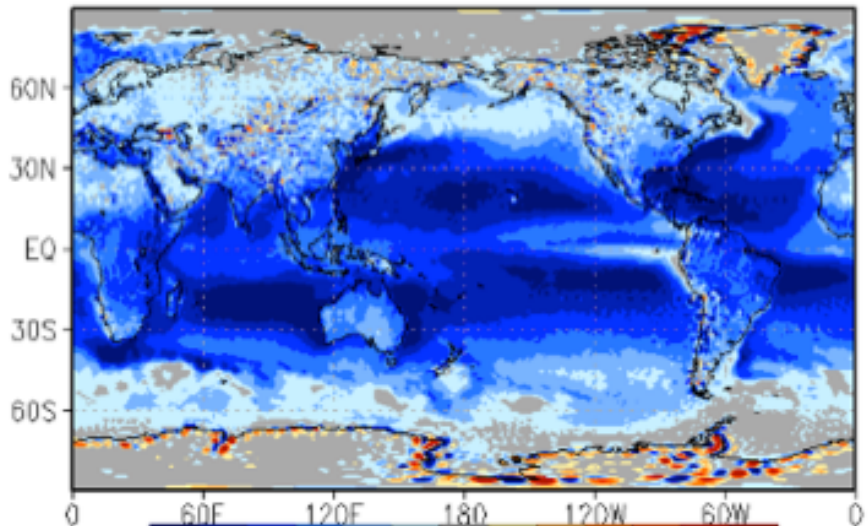
CMIP5 (15 Model Mean; $R_s + LE + S$)



(Wm^{-2})

Comparison of Turbulent Heat Fluxes (LE + S)

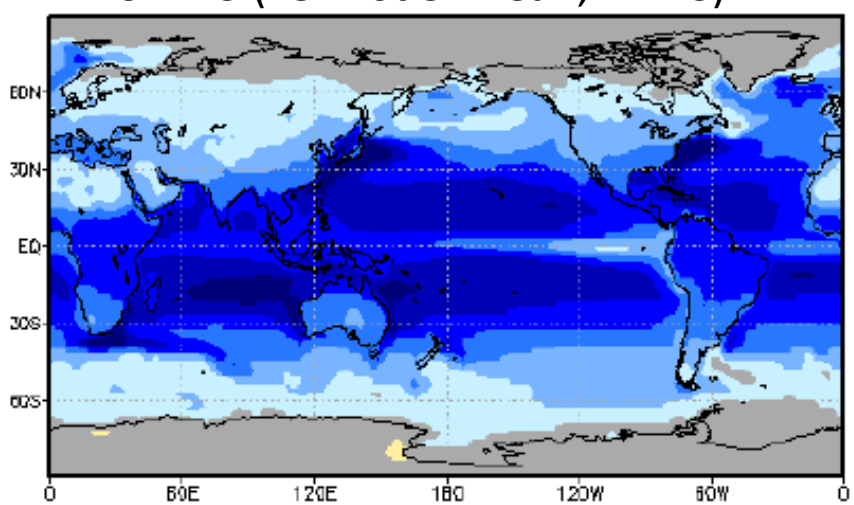
CERES TOA, SFC, & ERA-I TETEN, Div(TOT)



Global Mean

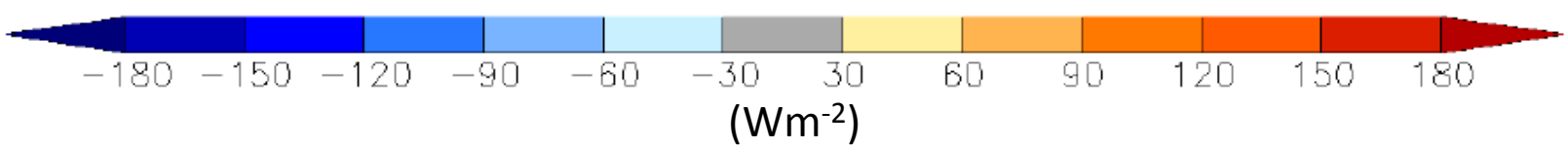
-108 Wm^{-2}

CMIP5 (15 Model Mean; LE + S)



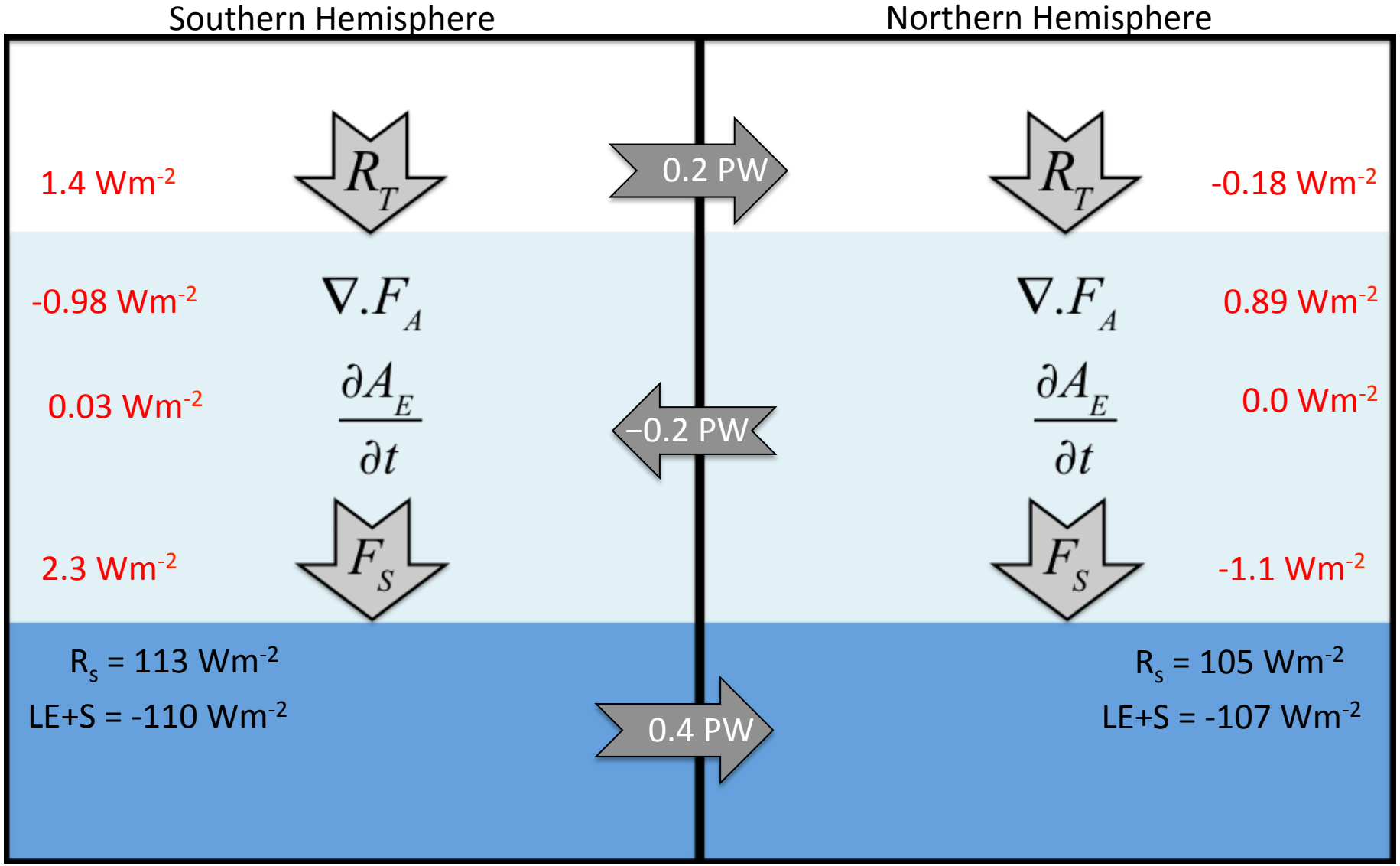
Global Mean

-104 Wm^{-2}

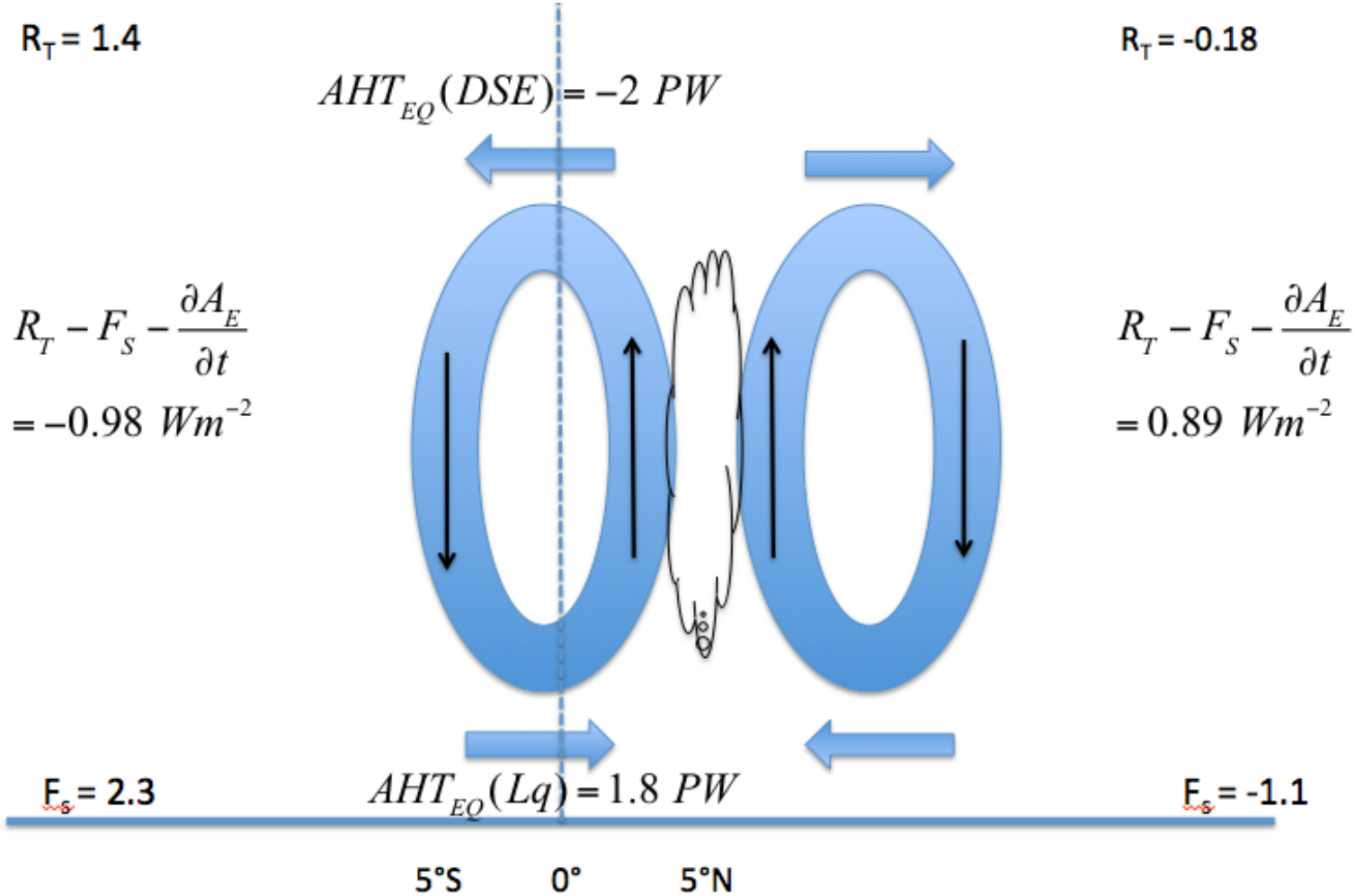


Implied Cross-Eq. Heat Transports in Atmos. & Ocean from Energetic Constraints

- Determine cross-equatorial heat transports in atmosphere and ocean from hemispheric contrast in energy fluxes.

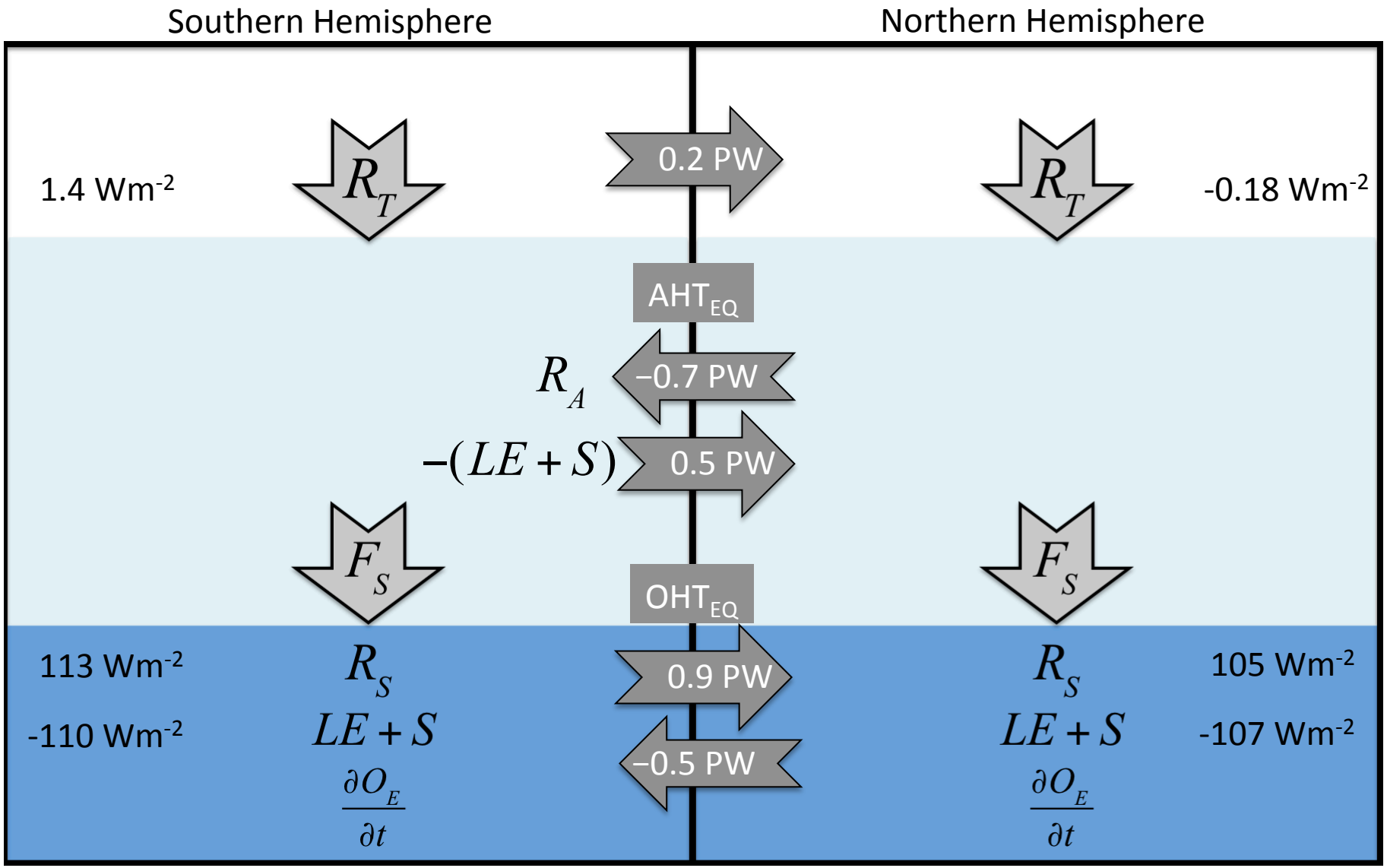


Atmospheric Cross-Equatorial Heat Transport & Mean Position of ITCZ



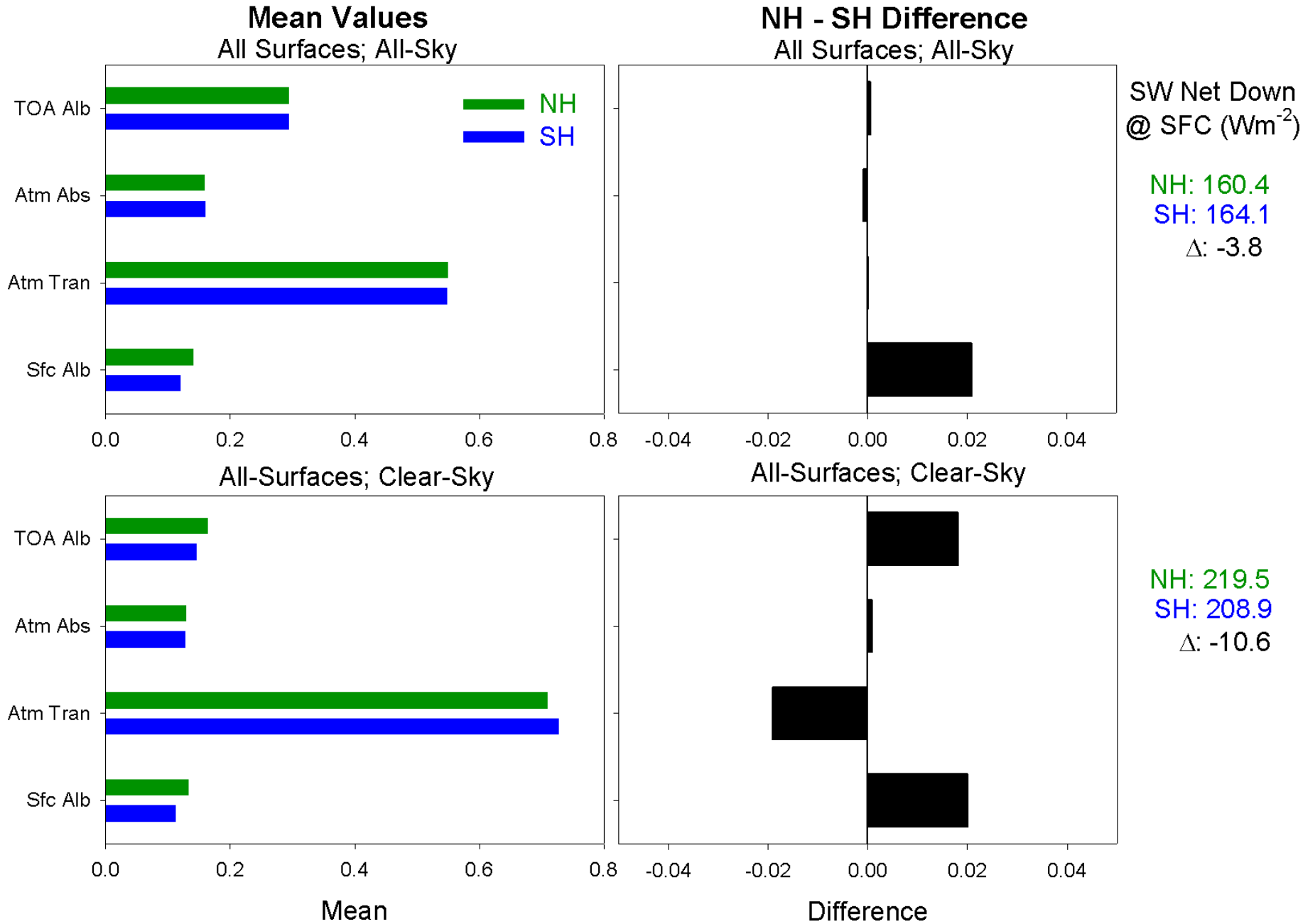
- In order to transport energy from warmer atmosphere in NH to cooler atmosphere in SH, mean position of ITCZ needs to be in NH (Frierson et al. 2013; Marshall et al. 2013).
- Transport of DSE in upper branch of Hadley circulation exceeds latent heat transport in lower branch by 0.2 PW.

Radiative & Non-Radiative Contributions to Cross-Equatorial Heat Transports

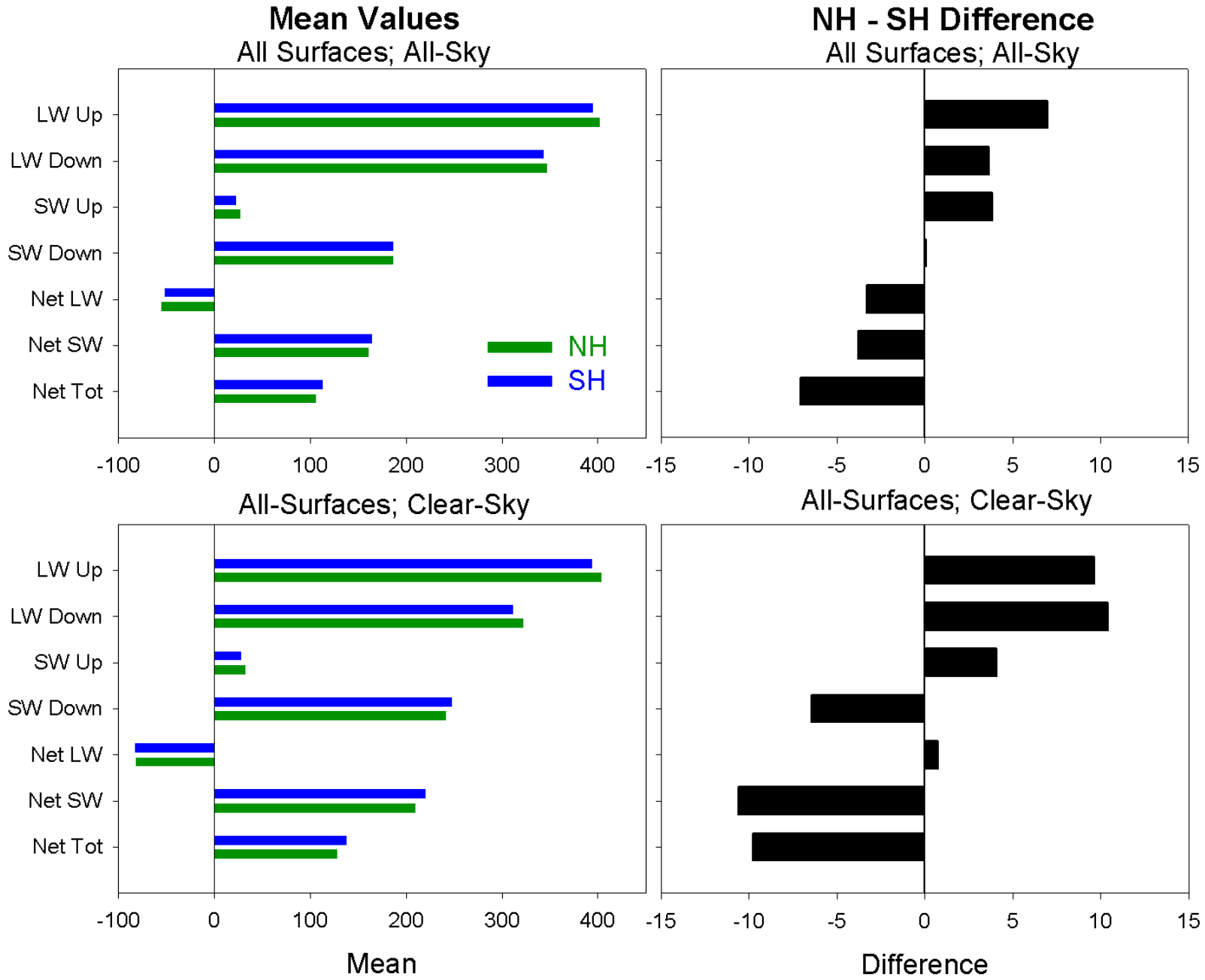


- Hemis. contrasts in SFC & ATM radiation determine direction of atm. & ocean heat transports.
- Hemis. contrast in turbulent heat fluxes imply heat transport in opposite direction.
- Assumes hemis. symmetry in ocean heat storage.

Hemispheric Asymmetry

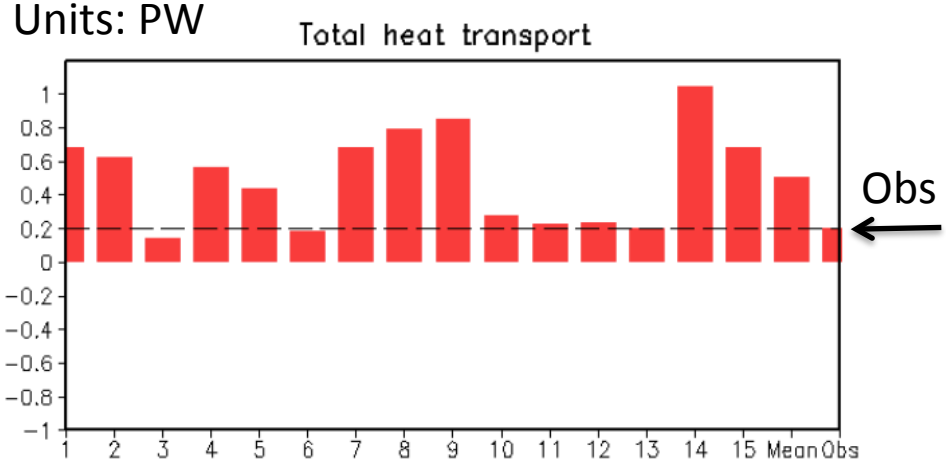


Hemispheric Asymmetry (Surface)

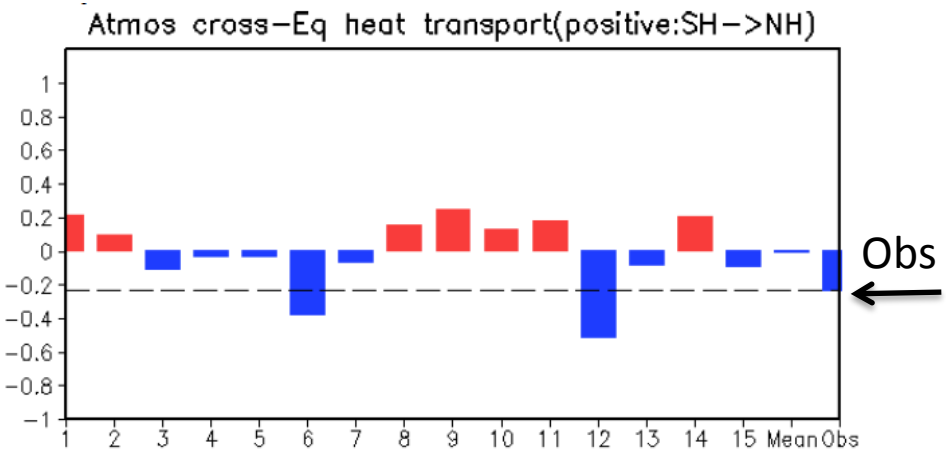


Comparisons with CMIP5 Models

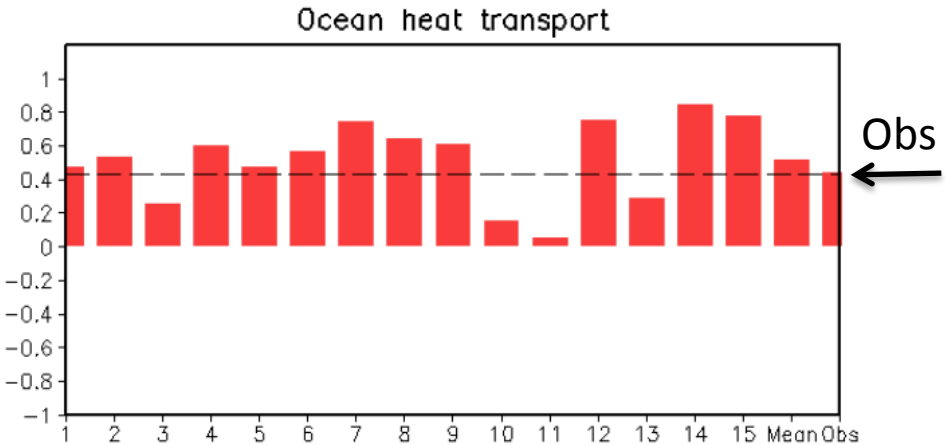
Units: PW



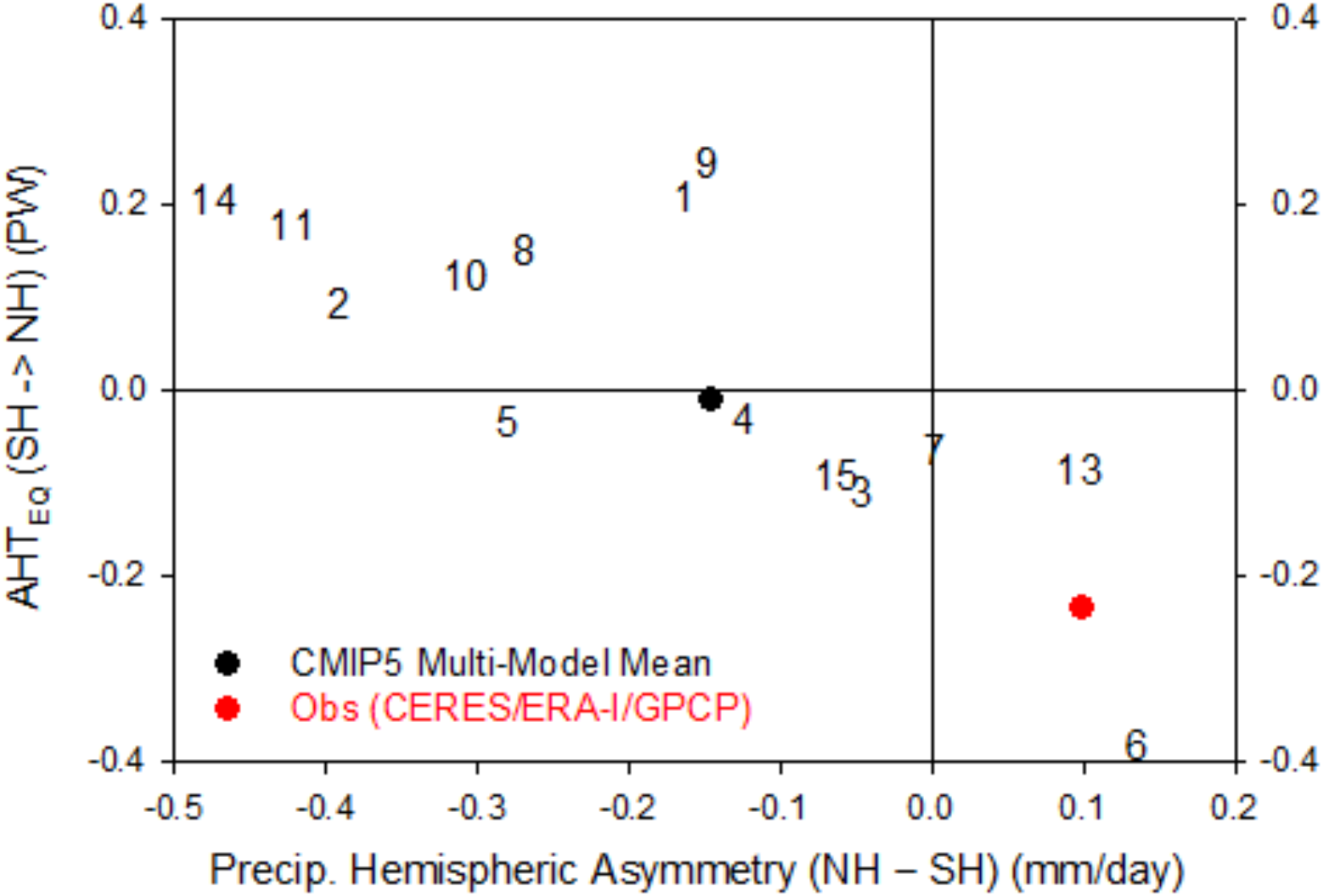
- All models show SH -> NH Cross-Eq. Heat Transport.
- Large spread amongst models.



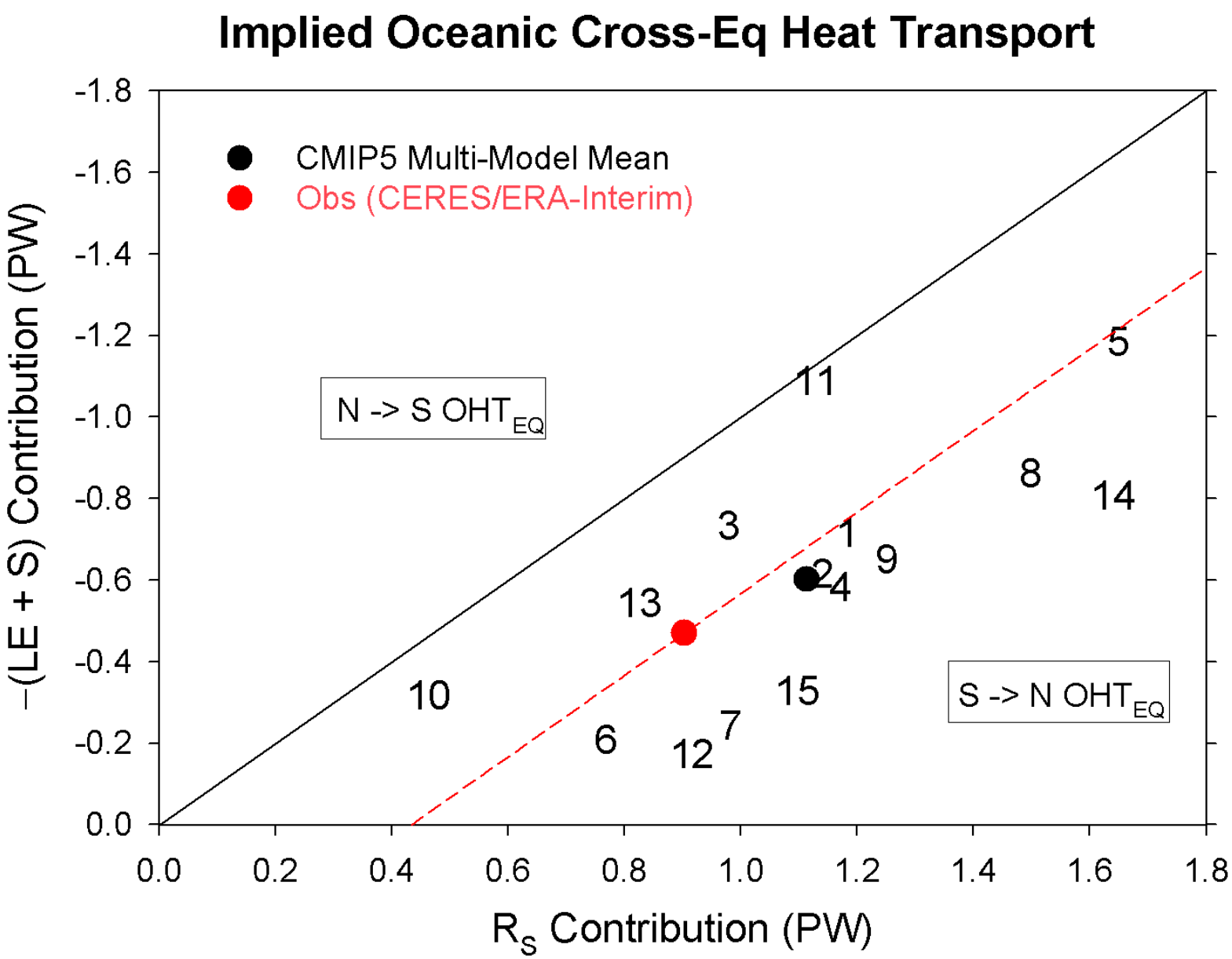
- Only half the models show NH -> SH AHT_{EQ} seen in obs.



AHT_{EQ} vs Precipitation Asymmetry



- Models with strong SH -> NH AHT_{EQ} show more precip in SH (double ITCZ).
- Only 2 models provide correct sign of precip. asymmetry.


Implied Oceanic Cross-Eq Heat Transport
CMIP5 Multi-Model Mean
Obs (CERES/ERA-Interim)
N -> S OHT$_{EQ}$
S -> N OHT$_{EQ}$
-(LE + S) Contribution (PW)
R_S Contribution (PW)
-1.8
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
1
2
3
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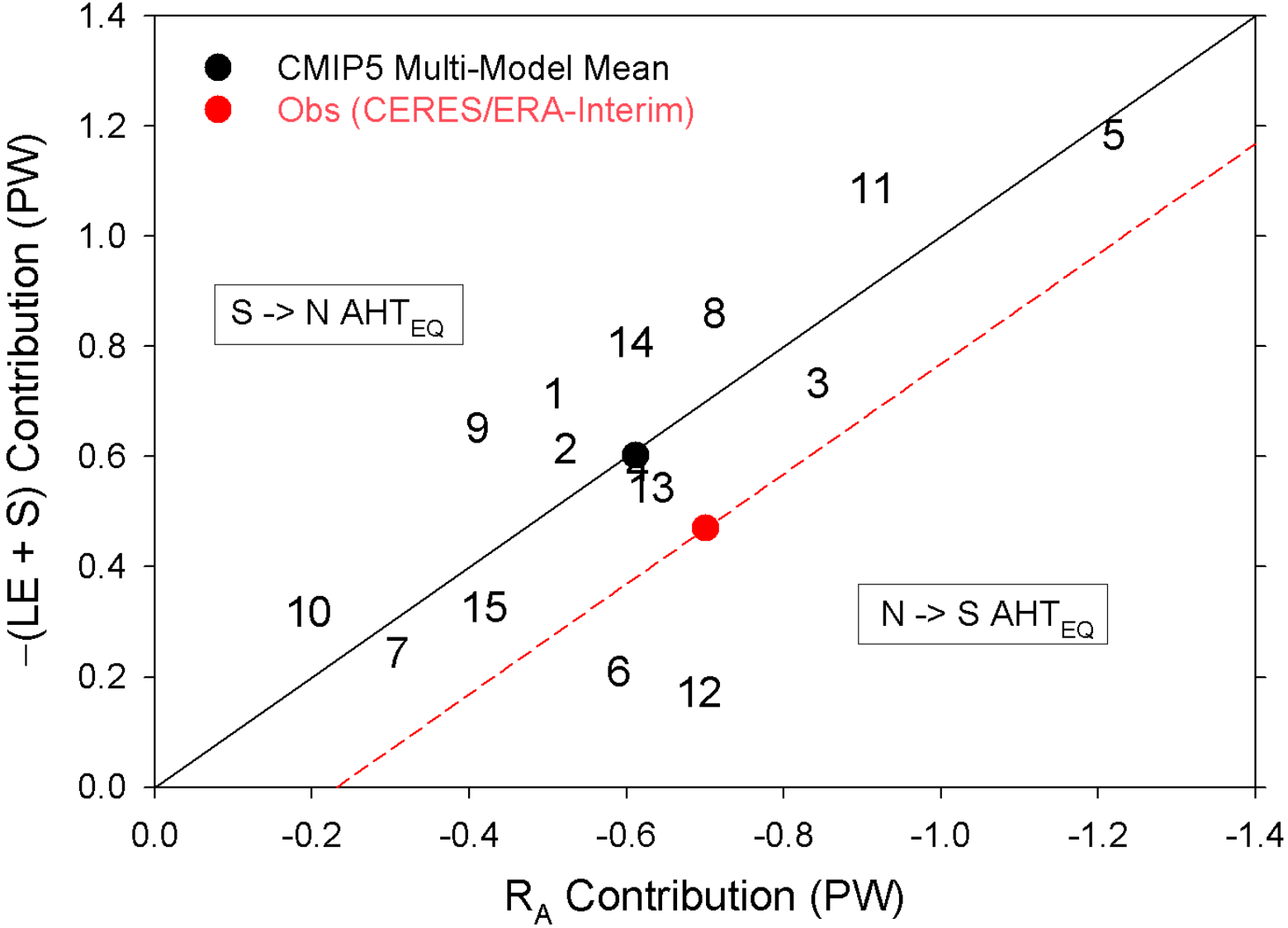
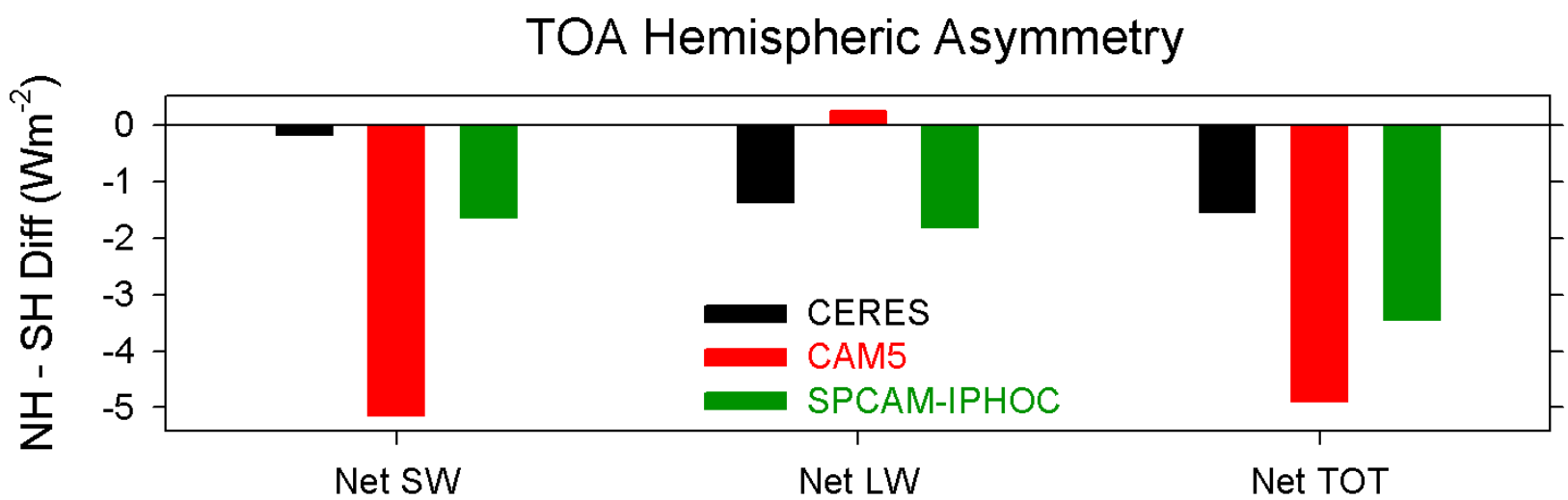
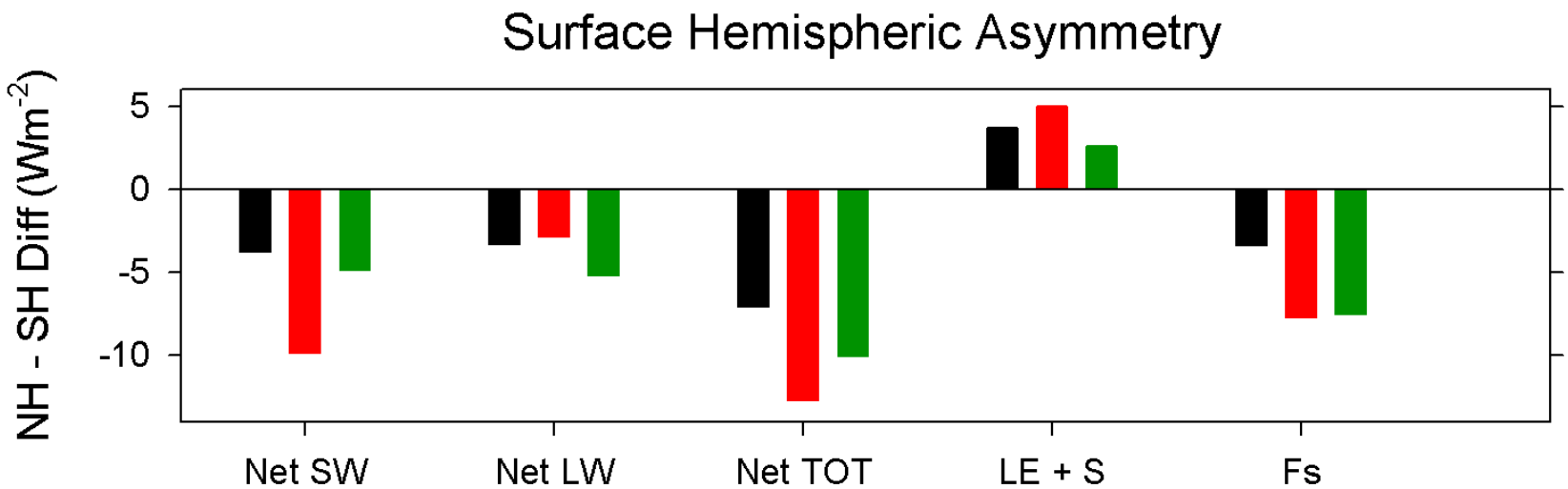
15

Implied Atmospheric Cross-Eq Heat Transport

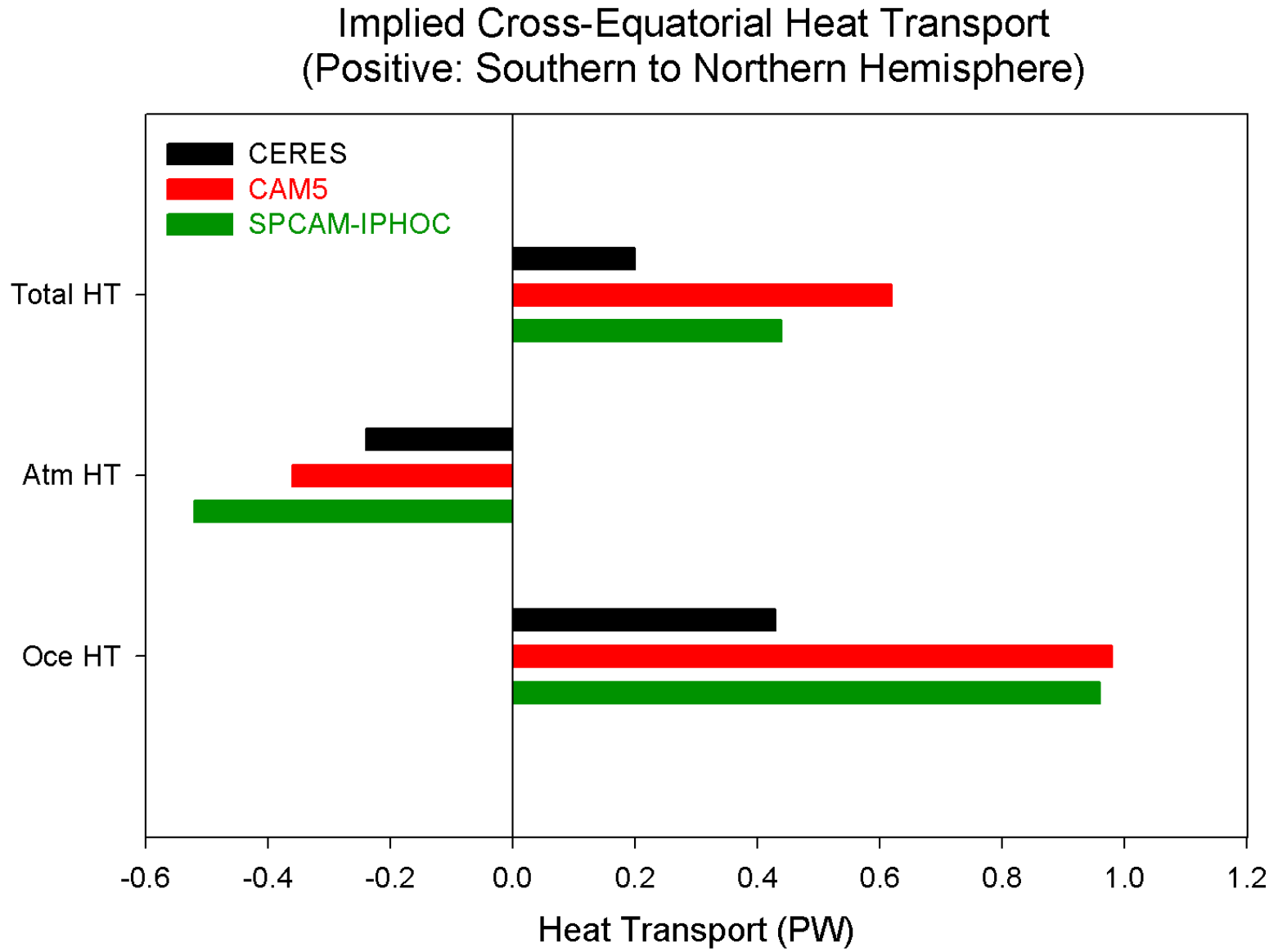


Comparisons with High-Resolution Multi-Model Framework Results (Xu and A.Cheng, 2013)





- Models overestimate SH TOA and surface energy gain relative to NH.
- SPCAM-IPHOC provides better representation of net SW asymmetry (TOA & SFC).



- Models yield SH -> NH OHT_{EQ} and NH -> NH AHT_{EQ}, consistent with obs.
- However, Implied cross-equatorial heat transport in models is factor of 2 larger than observations, both in atmosphere and ocean.

Conclusions (1/3)

- Mean position of ITCZ north of the equator is a direct consequence of hemispheric asymmetry in surface heating.
- Observations imply 0.4 PW SH -> NH OHT_{EQ} and 0.2 PW NH -> SH AHT_{EQ}.
- Clouds reduce hemispheric asymmetry in radiative fluxes both at TOA and SFC.

Conclusions (2/3)

- CERES EBAF-TOA and SFC combined with ERA-I TETEN enable decomposition of cross-equatorial heat transport into radiative and non-radiative (turbulent heat flux) components.
- Regional patterns of surface fluxes (radiation + turbulent) inferred as residual of CERES EBAF TOA minus ERA-Interim TETEN appear quite reasonable.
- Hemispheric contrasts in SFC & ATM radiation determine direction of atmospheric & oceanic heat transports, while turbulent heat fluxes act to transport heat in opposite direction.

Conclusions (3/3)

- All CMIP5 models show SH -> NH OHT_{EQ} (consistent with obs), but only half show the observed NH -> SH AHT_{EQ}.
- Models with stronger SH -> NH AHT_{EQ} show more precip in SH (double ITCZ).
- Only 2 CMIP5 models provide consistent sign of precip. asymmetry compared to GPCP.
- MMF models capture direction of cross-equatorial heat transports but magnitude is twice as large as observations.