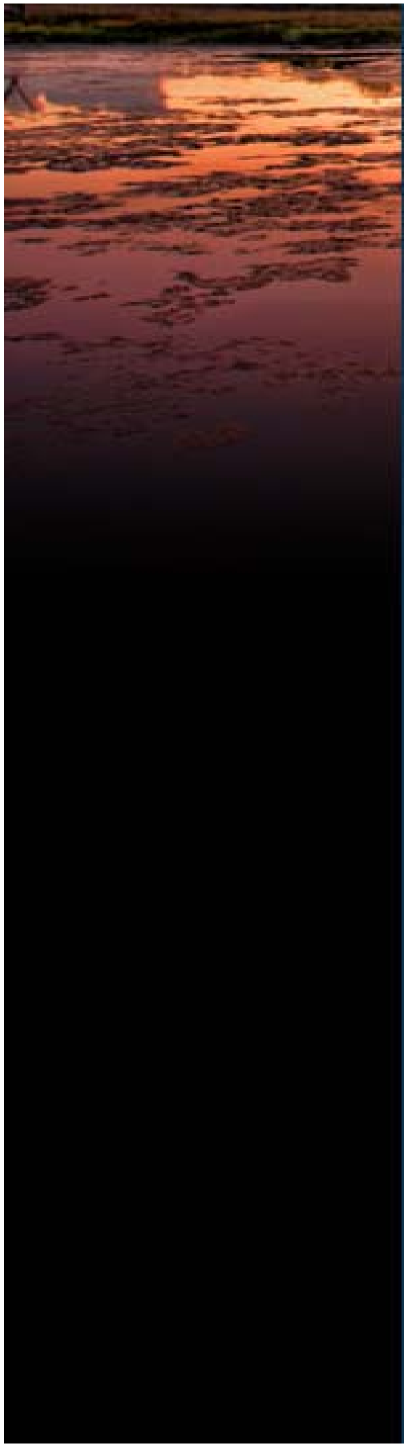
Is the Earth’s climate system constrained?*+

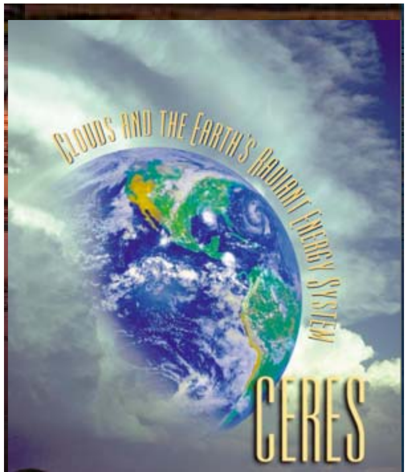
Graeme Stephens, Denis O’Brien, Peter Webster,Peter Pilewskie,Seiji Kato,Juilin Li

*Stephens et al., 2014;The albedo of Earth, *Rev Geophys,*
+ Stephens and L’Ecuyer, 2014;The Earth's Energy Balance ¬ progress, surprises and challenges, J. Atmos Res., (in prep)



I will address the following :

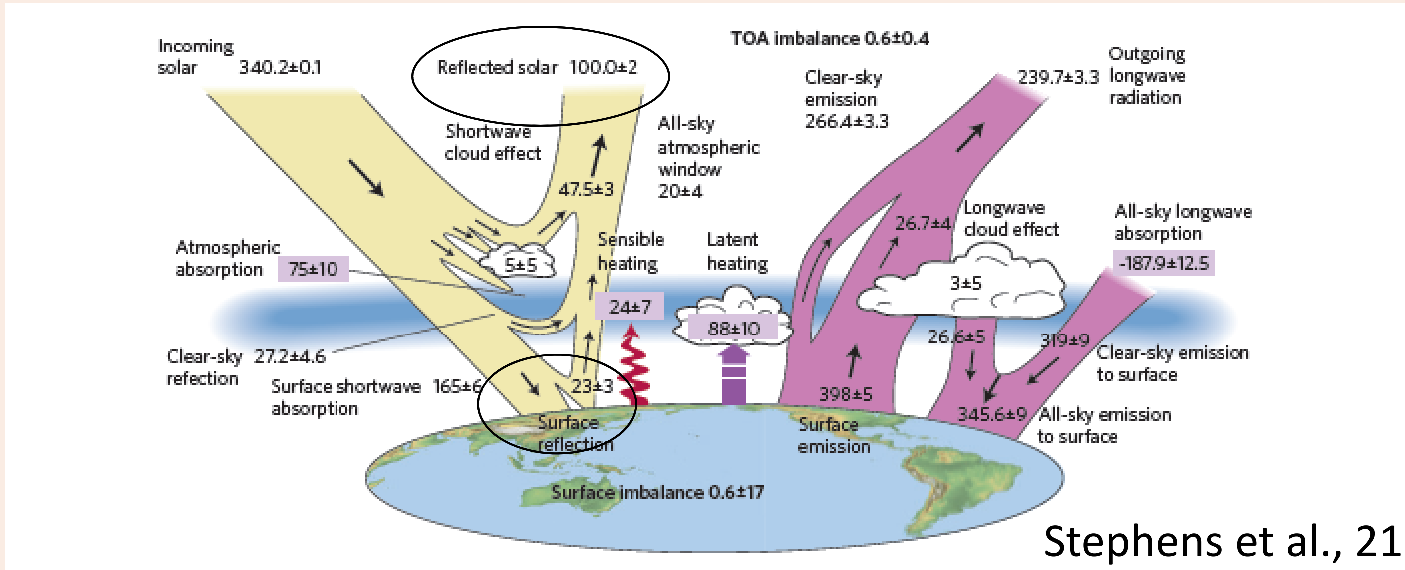
- The energy balance of Earth is highly constrained and mostly by clouds
- That the symmetric energy balance is a fundamental expression of hemispheric thermodynamic steady state under the condition that X=0
- That models energy balance is not similarly constrained.
- Raise man questions including the so what?



Data sources:
CERES EBAF2.6r
Loeb et al., 2009

CERES EBAF
surface fluxes,
Kato et al., 2009

CloudSat/CALIPSO
Geoprof

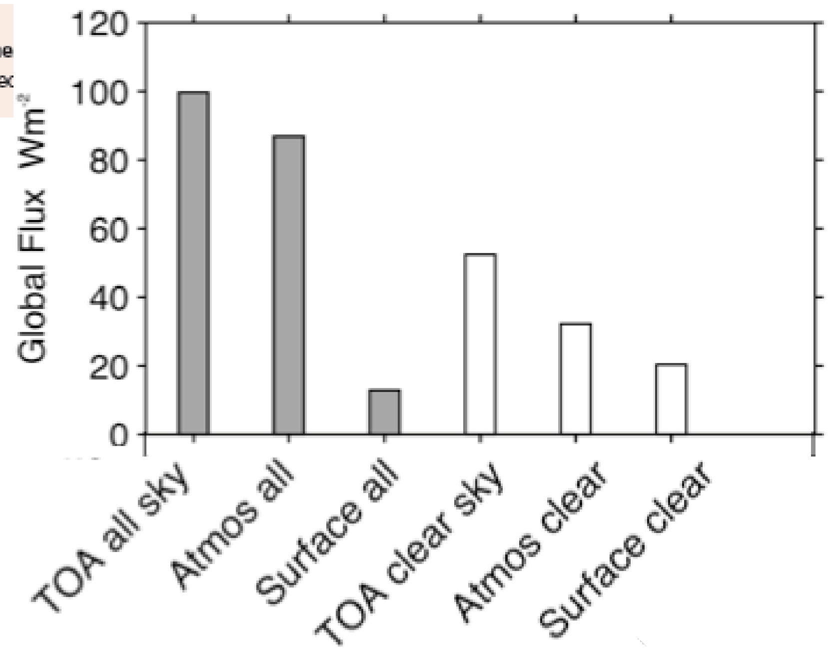

PROGRESS ARTICLE

NATURE GEOSCIENCE DOI: 10.1038/NGEO1580

Box 1 | Updated energy balance

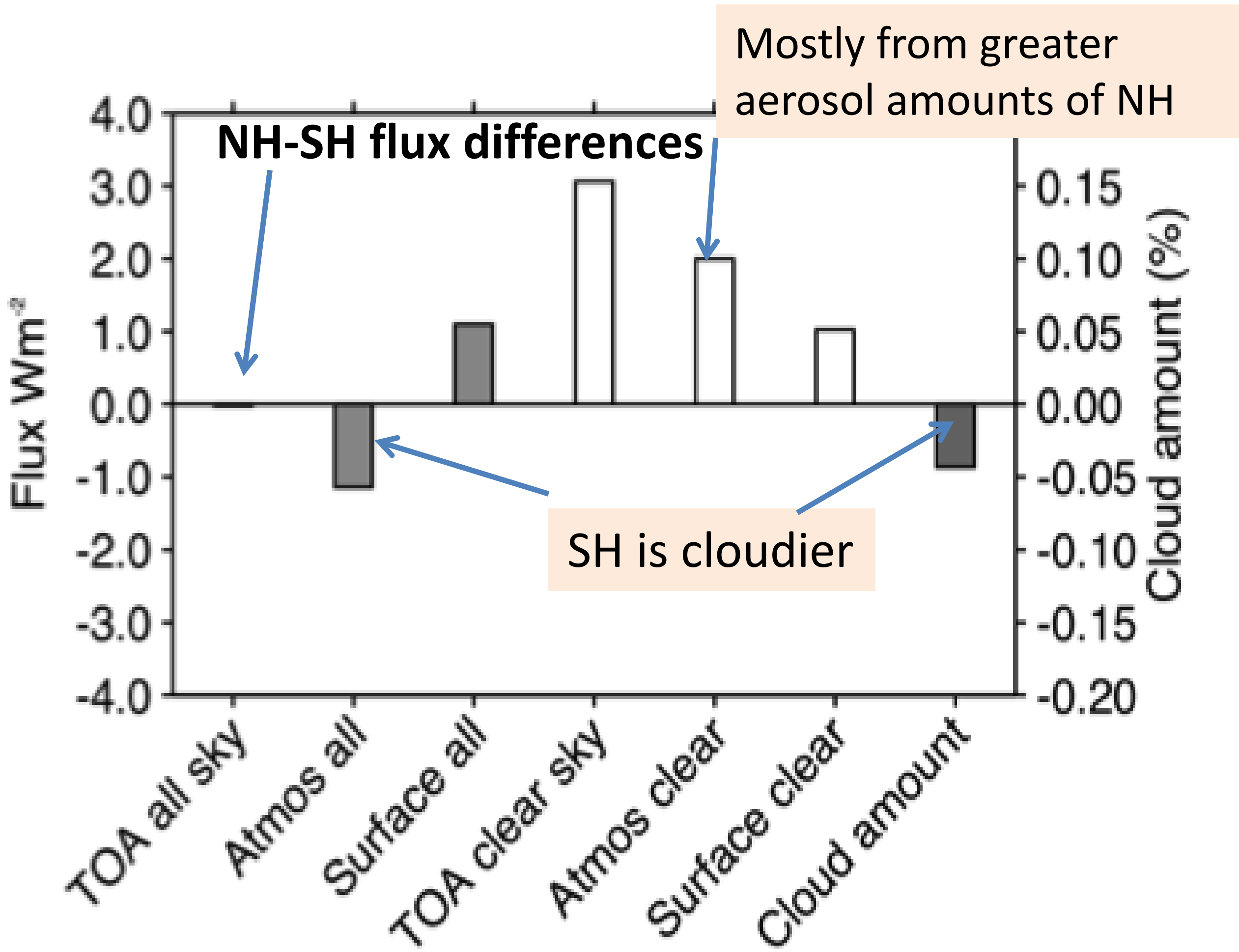
Figure B1 | The global annual mean energy budget of Earth for the
and infrared fluxes in pink. The four flux quantities in purple-shadec

Stephens et al., 2102

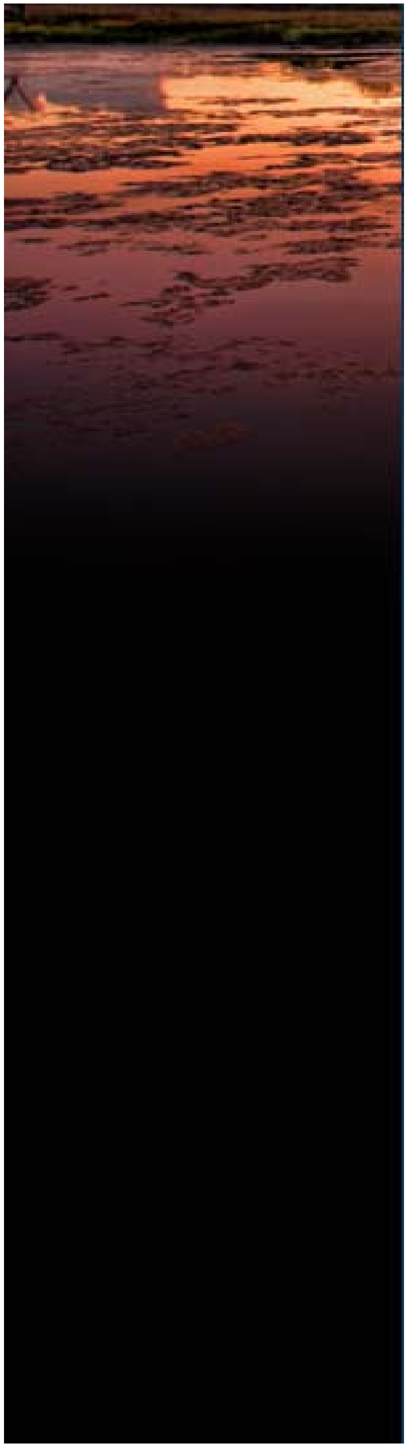


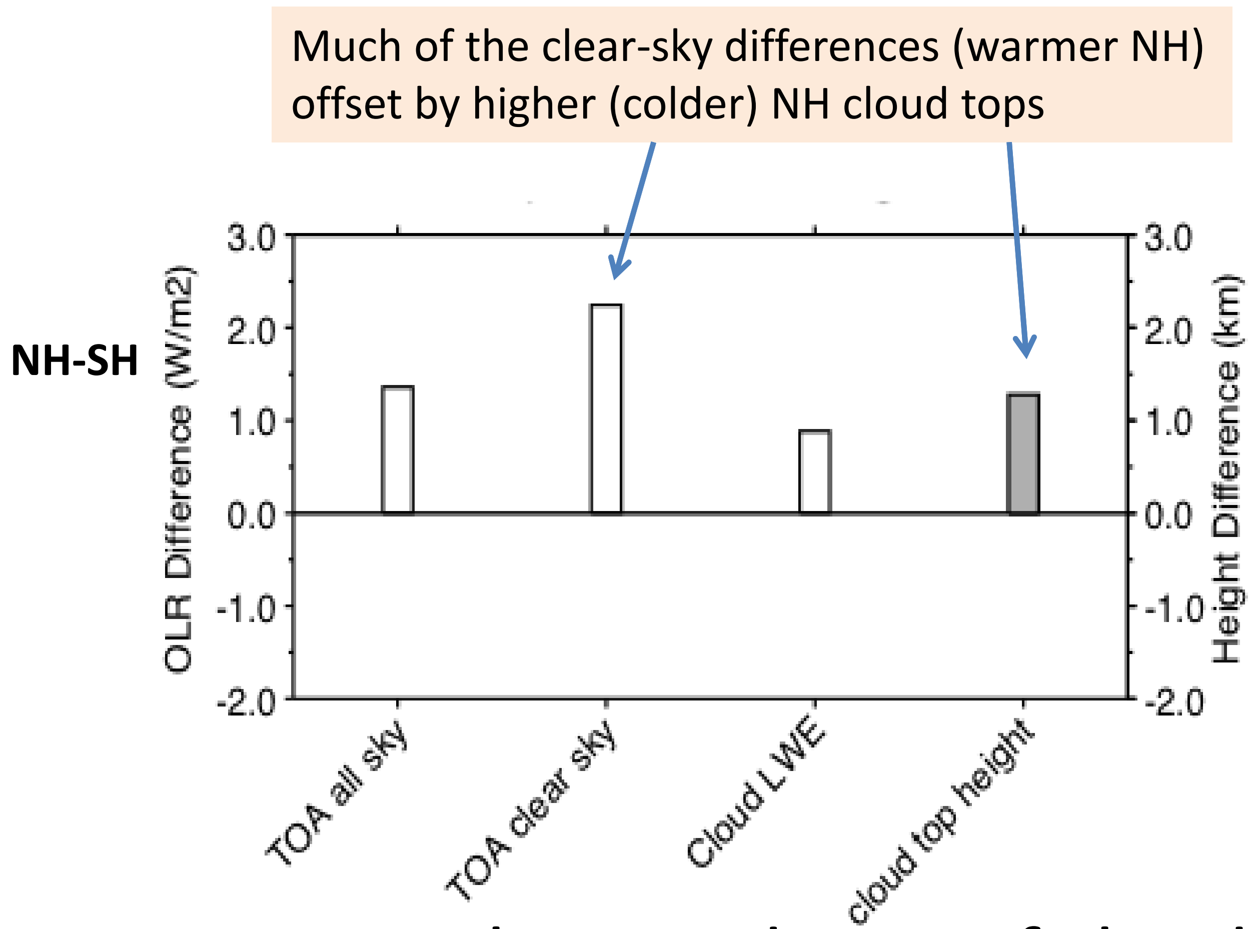
For the mean annual case, the measured global planetary albedo is 29 percent and the entire earth-plus-atmosphere system is in near radiative equilibrium since the infrared emission averages 0.33 cal cm^{-2} min^{-1}. No significant differences between the total radiation budgets of the Northern and Southern hemispheres are noted on a mean annual scale. This points out the overriding influence of cloudiness on the energy exchange between earth and space, since the surface features

VonderHaar & Suomi, 1969



Although the hemispheres are structurally different, the reflected flux is identical (~0.1Wm^{-2}) – VonderHaar and Suomi, 1969; Voigt et al., 2012; Stephens et al 2014



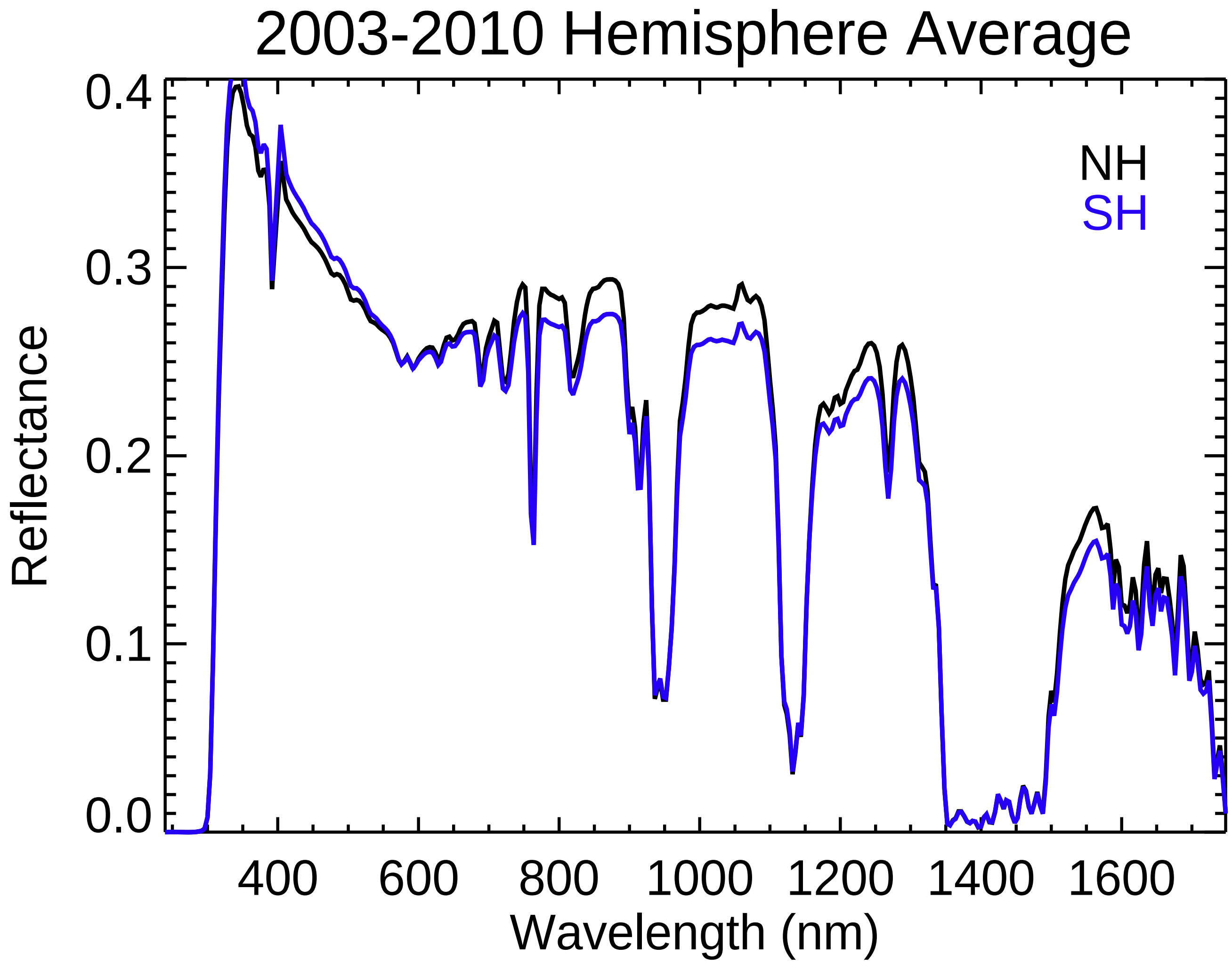


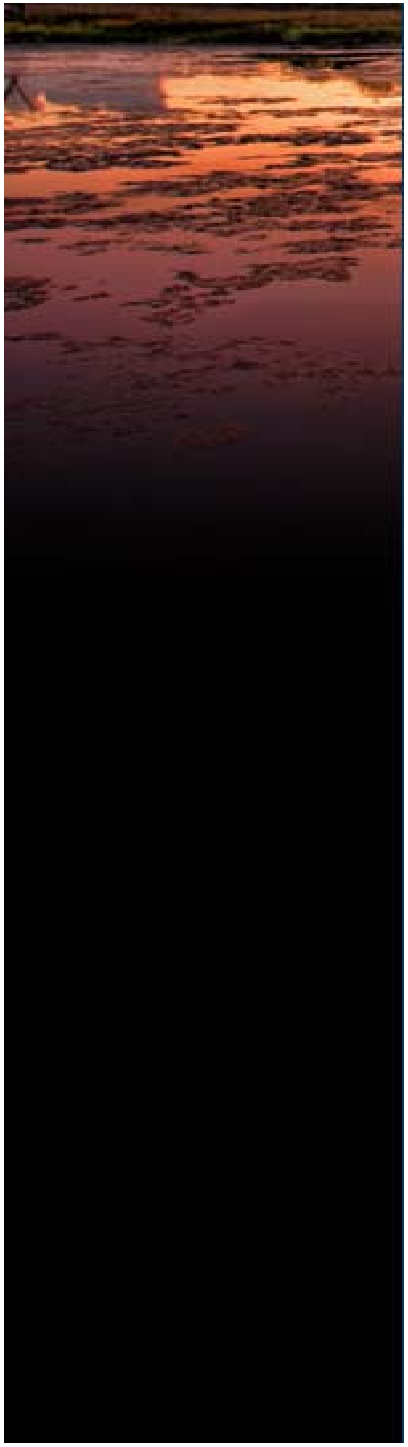
We see very clear evidence of cloud regulation of the hemispheric energy balances towards symmetry both in reflected sunlight and OLR

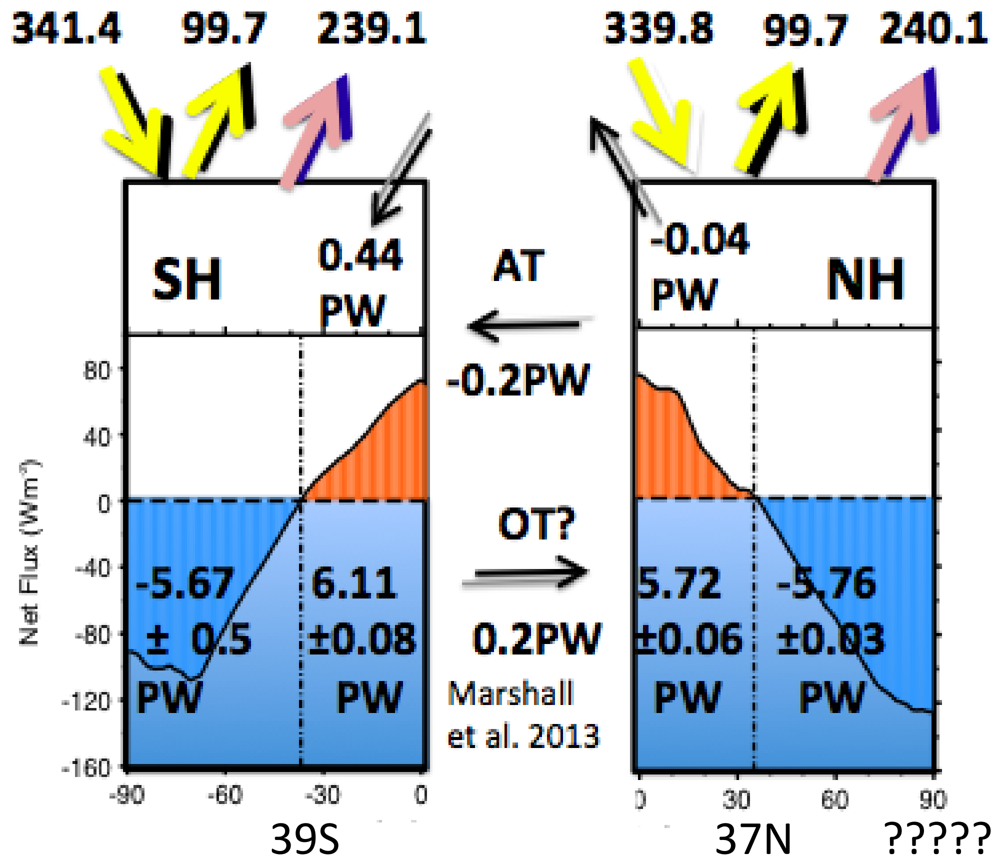
Is this accidental (Voigt et al., 2012)?

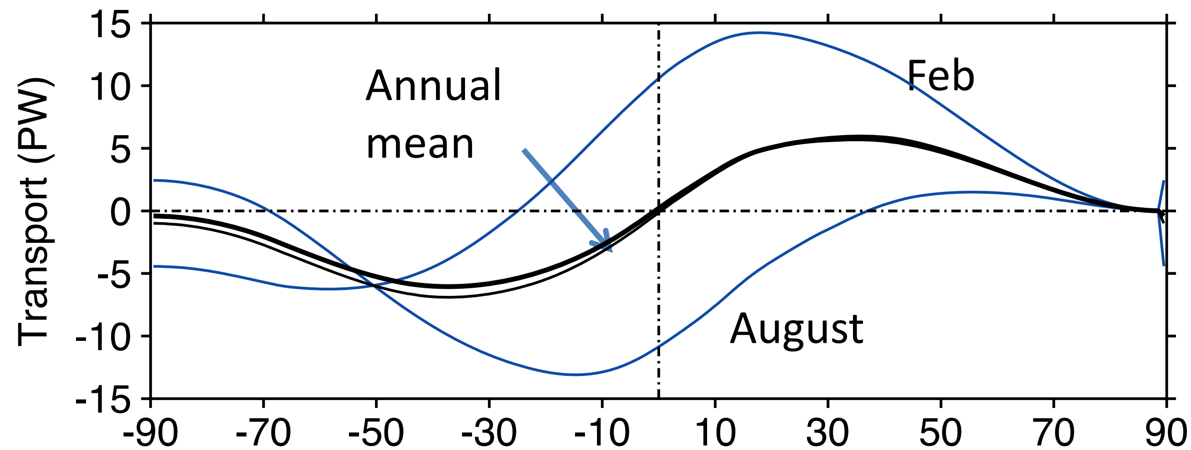
A little ore more anecdotal evidence

SCHIAMARCHY DATA



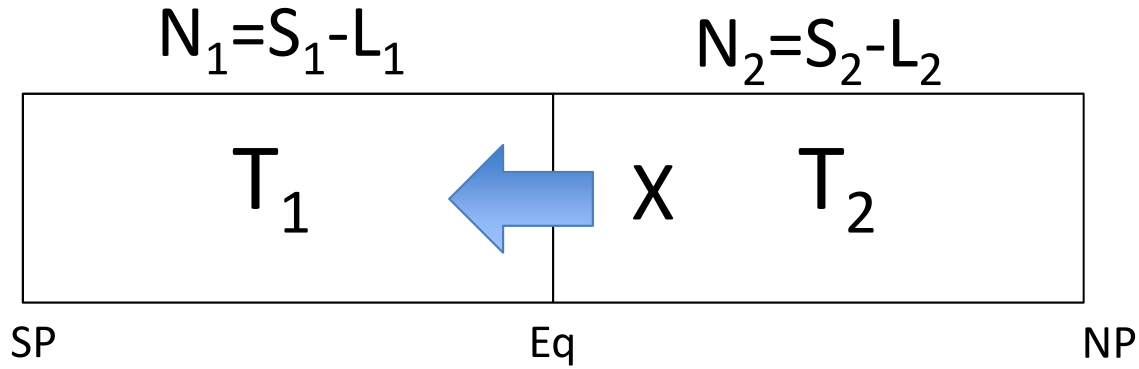






Stephens & L'Ecuyer, 2014

A symmetric balance is the balance of a steady unforced climate system with X=0.



In a balanced, steady state

$$N1+N2=0 \qquad (1)$$

where $N1=S1-L1=X$

and $N2=S2-L2=-X$

In the special case of X=0 then L1=L2 otherwise a thermodynamic force is exerted to $X \neq 0$ and

$$N1=N2=0 \qquad (2)$$

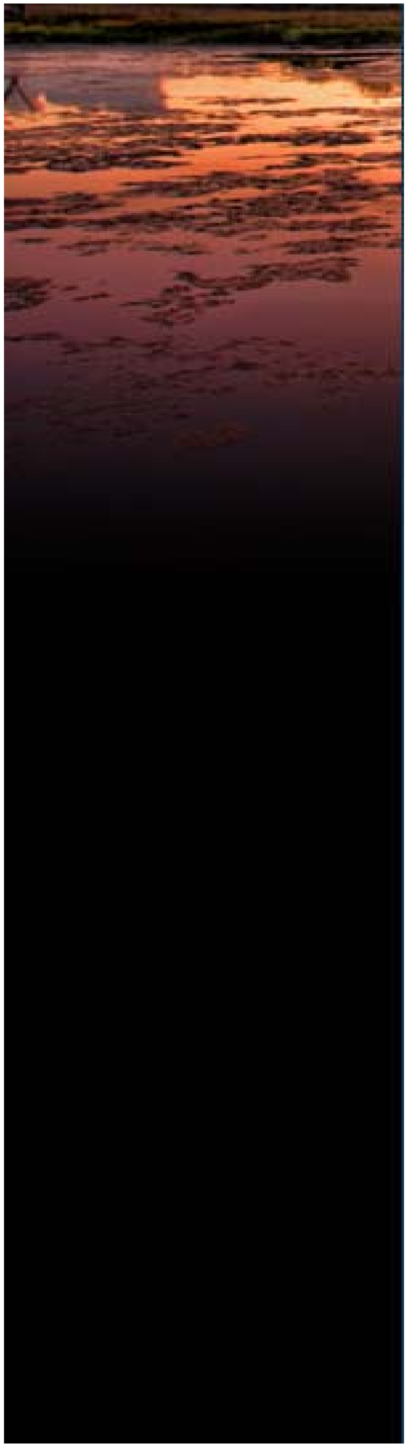
$$S1=S2 \qquad (3)$$

Current Earth conditions:

NH, $N1=-0.04\pm0.06$PW (ie X~0)

SH $N2=0.44\pm0.1$PW

So one hemisphere is balanced, the other not and N1+N2 $\neq 0$ (0.4PW or ~0.8Wm^{-2})

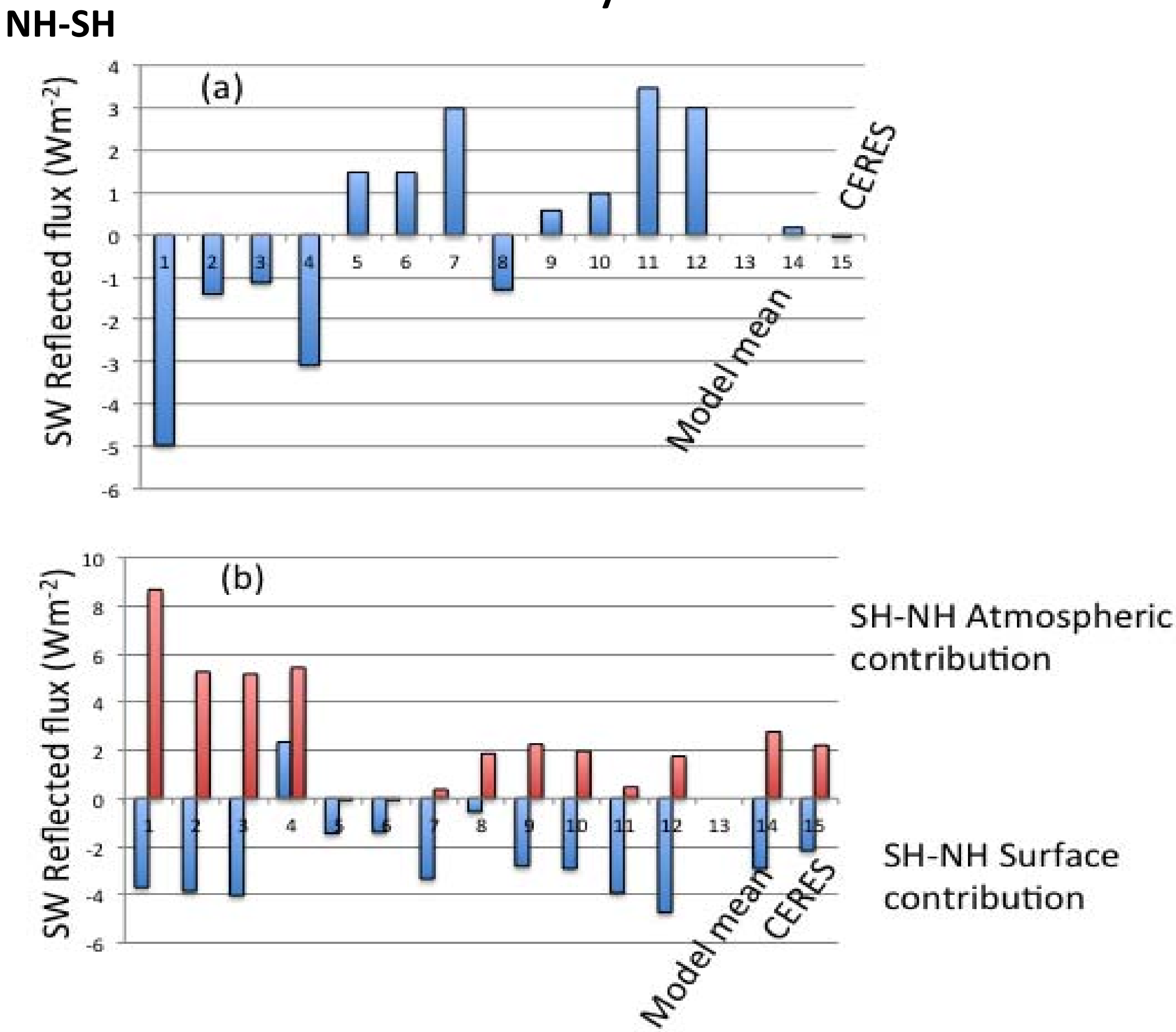


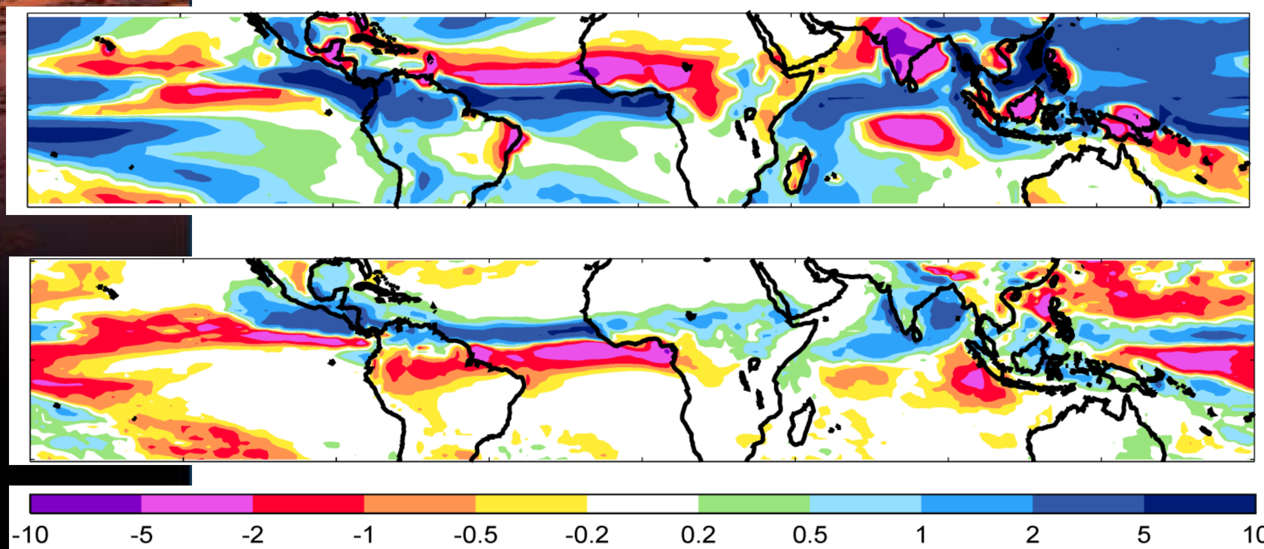
Earth system models?

1) There is a general lack of hemispheric symmetry in models

2) The reasons for this vary – in some models the SH clouds are too bright, for others clouds aren't bright enough & yet in others the surface is too bright

CMIP5 analysis





Also Haywood et al., 2013
Frierson & Huang, 2012
Voigt et al., 2013

Bias ratio

Key areas affected by monsoonal precipitation

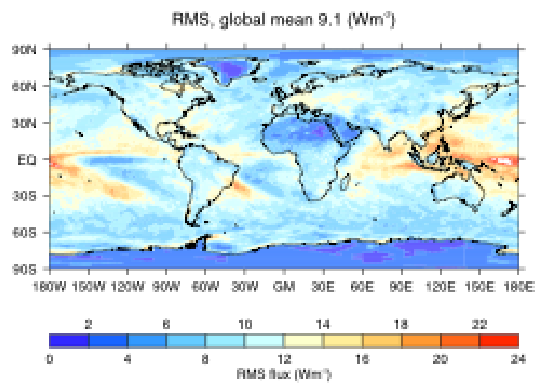
Wet season Precip

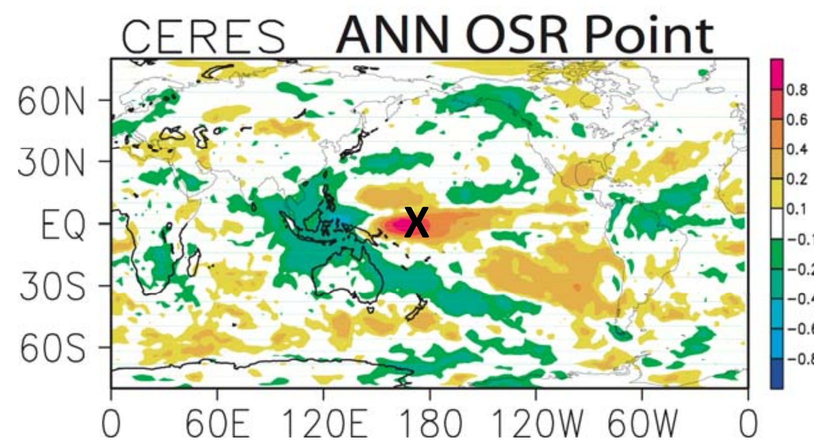
Geographic Region	DJF	MAM	JJA	SON
North Africa	0.64	0.47	0.54	0.17
South Asia	1.05	2.59	0.67	0.70
Amazonia	0.86	0.90	0.73	0.72
South East Asia	1.17	0.35	0.80	0.96

Haywood et al., personal communication

Averaging Scale	Total Flux	Total σ (x)	Atmosphere Flux	Atmosphere σ (x)	Surface Flux	Surface σ (x)
Global	99.7	0.23	86.9	0.29	12.9	0.10
Mid-latitude NH(30-60N)	103.8	0.52	91.5	0.53	12.3	0.15
Mid-latitude SH(30-60S)	104.1	0.56	98.9	0.65	5.26	0.10
Polar NH (60-90N)	97.0	0.87	78.7	0.87	19.1	0.47
Polar SH (60-90N)	118.8	0.68	84.4	1.26	35.5	0.97

Variability is mostly from clouds and is highly regulated with connected regions of increase and decrease





(also Smith et al. 1990)

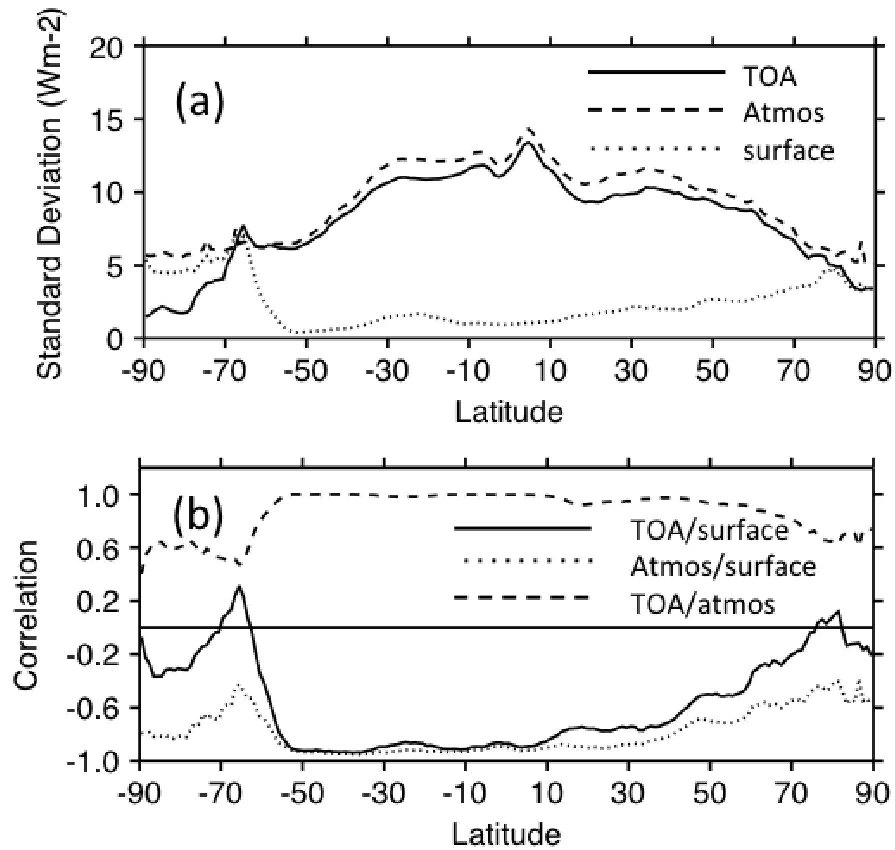
Interannual variability of the global-mean reflected flux ~0.2 Wm^{-2}
Local (1X1 degree) mean std deviation (deasonalized ~ 9 Wm^{-2})

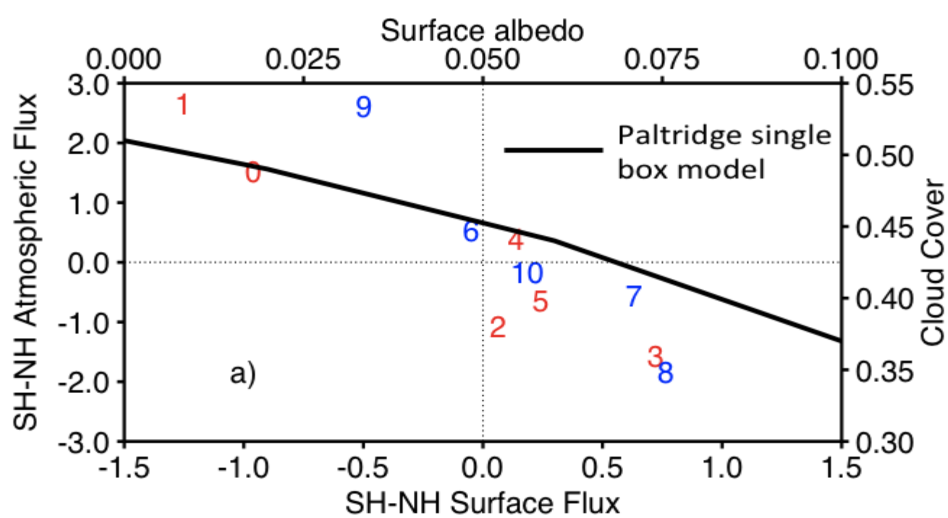
Paltridge, 1978
MEP hypothesis
& Convection
hypothesis

e.g. OBrien &
Stephens,1993

(both in QJRMS)

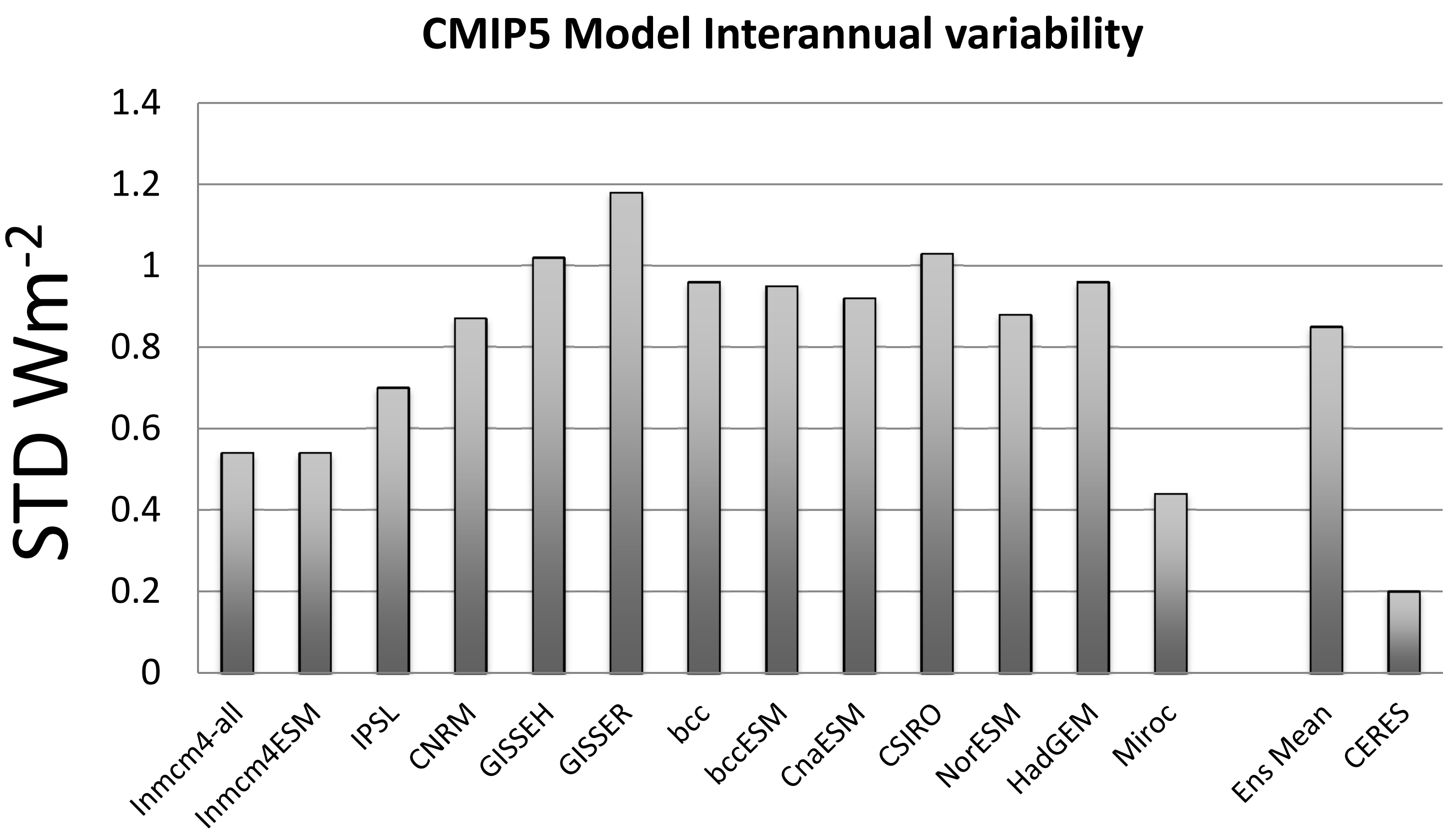
CERES Variability
Between 2000-2010





In the mean, model interannual variability is ~ 4 times the observed.

Does this matter??

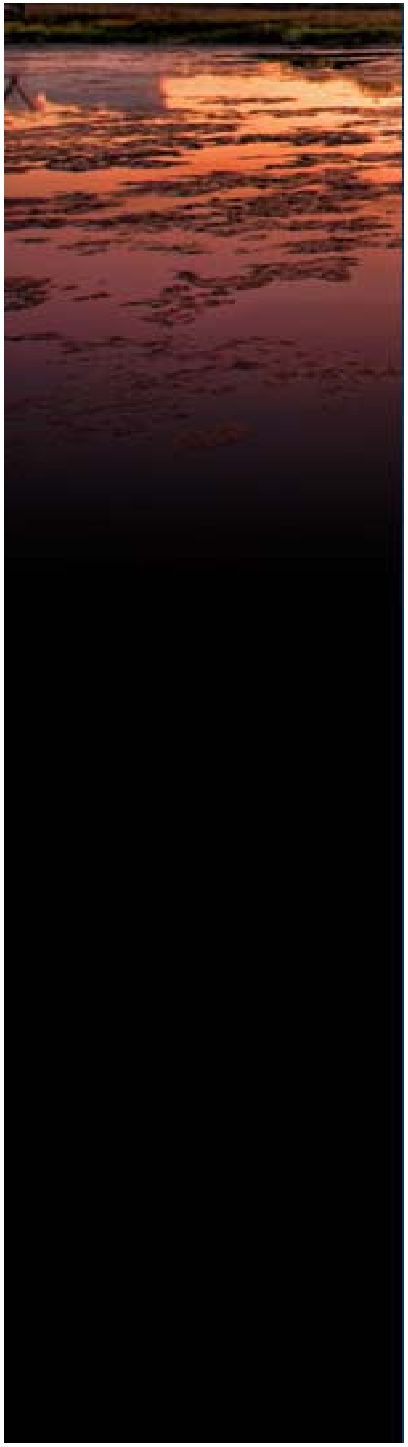


Many unresolved questions remain

- **Timescale?**
- **CERES data precision?**
- **Is there a fundamental theory for why X=0?**
- **How might we further test of steady state?**

Summary:

- Is the Earth's Climate system constrained?
  - The reflected energy from Earth is highly regulated & this regulation by clouds. The most dramatic example of this appears in hemispheric symmetry of reflected solar radiation
  - Hemispheric OLR also appears regulated by clouds
  - The symmetry is not accidental?? but is a condition required for a steady state with X=0
- If some overriding symmetric steady state constraint exist, what is its significance?
  - synchronized planetary response to asynchronized hemispheric or more local forcings (e.g solar, aerosol..).
  - Insight on global feedbacks (e.g clouds) - fundamentally negative?
- Are models similarly constrained?
  - Models don't have the same behavior as the observed Earth – they lack the same degree of regulation and symmetry. Does this really matter? It seems so.



Supporting material

The Paltridge Model

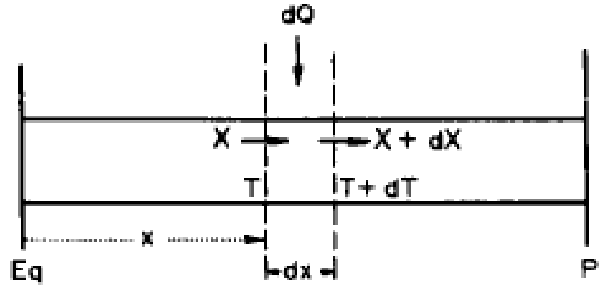


Figure 1. Schematic version of the thermodynamics of a one-dimensional hemisphere from equator (Eq) to pole (P). *T* is temperature, *X* is meridional flux of energy, *dQ* is net radiative input – all functions of distance or latitude, *x*.

[redacted] five unknowns

[redacted]mperature T

[redacted]l flux by atmosphere and oceans, $X=X_O+X_A$

[redacted]er θ

[redacted]l sensible heat flux LE+H

[redacted]ystem has no dynamics (OBrien & Stephens, 1993, QJRMS,)

[redacted]l solved using

[redacted]l TOA energy balance (T, θ, LE+H, surface albedo, cloud albedo ……)

[redacted]g two hypotheses

[redacted]ction of a Maximum Entropy Production (MEP) hypothesis

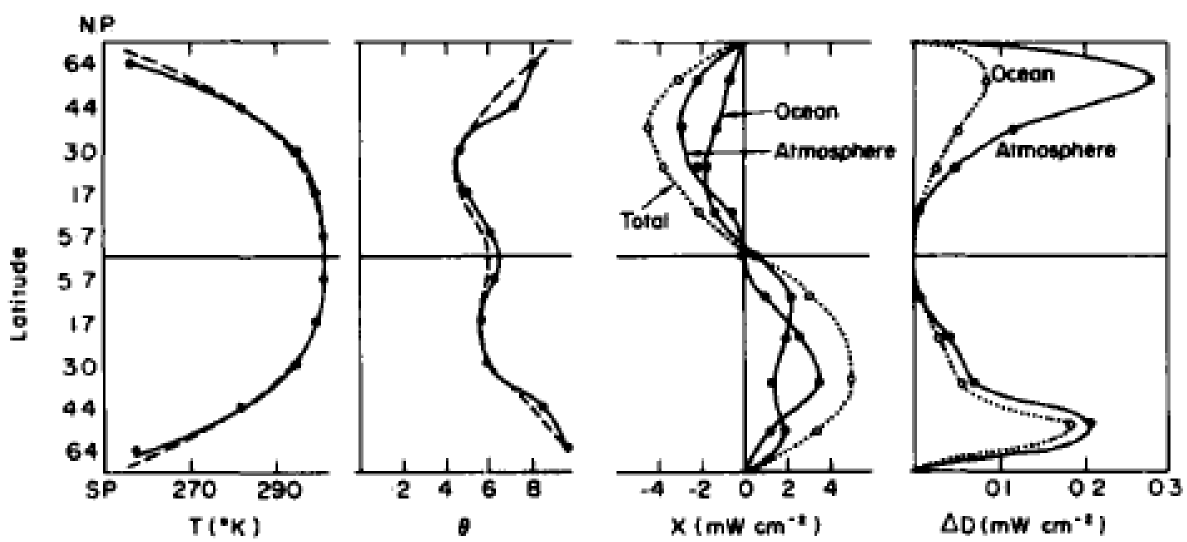
[redacted]ction of a Convection Hypothesis (OBrien and Stephens, 1993)

- MEP – a constraint on X – X is chosen to maximize

MEP= $$\dot{S}_I = -\dot{S}_e = -\sum_{i=1}^{10}(F{\downarrow}_S - F{\uparrow}_L)_i/T_{ai}$$

- Convection Hypothesis – for a given ratio X_A & X_0, cover is such as to maximize LE+H – s ratio X_A/X_0 and expresses LE+H in T and cloud cover θ

ons

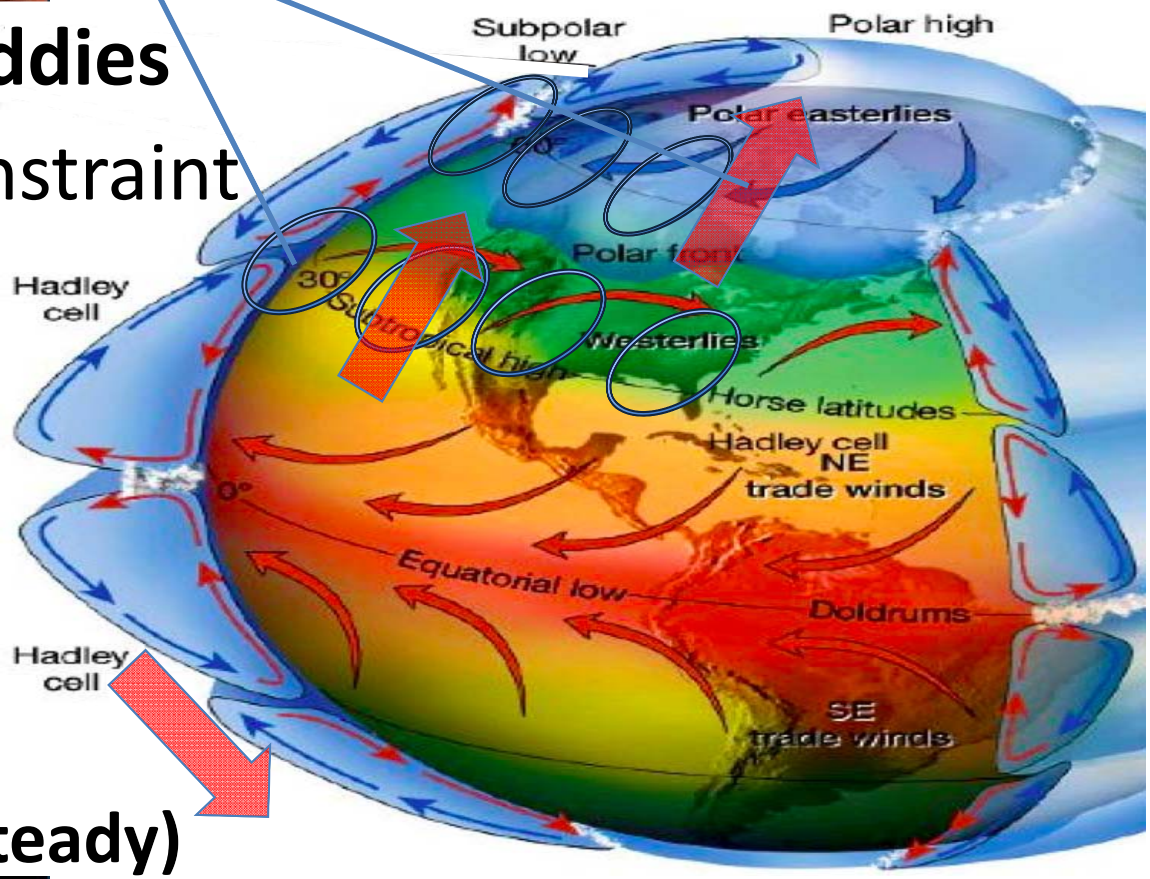


A 'remarkable' result & even today (35 yrs later) MEP still has followers and conjures interest. But .....

Perhaps the clearest analysis of the relevance of MEP to climate is that of Goody, 2004

Eddies

MEP constraint



[redacted]eady)

[redacted]l transport

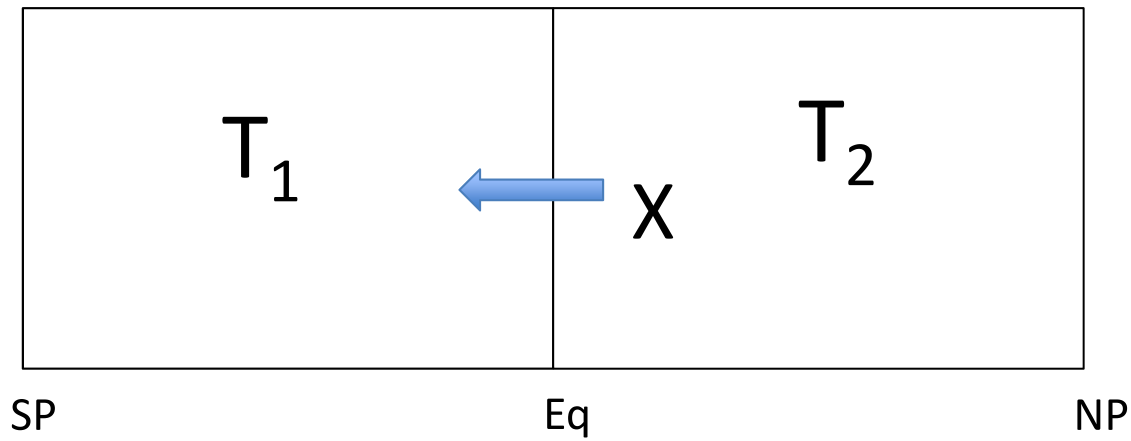
[redacted]d by linear

[redacted]r momentum

Goody's main point - not all parts of the system come under the MEP constraint and thus MEP cant be a powerful global system constraint.

Suppose a steady state exists

$N_1=S_1-L_1$ $N_2=S_2-L_2$

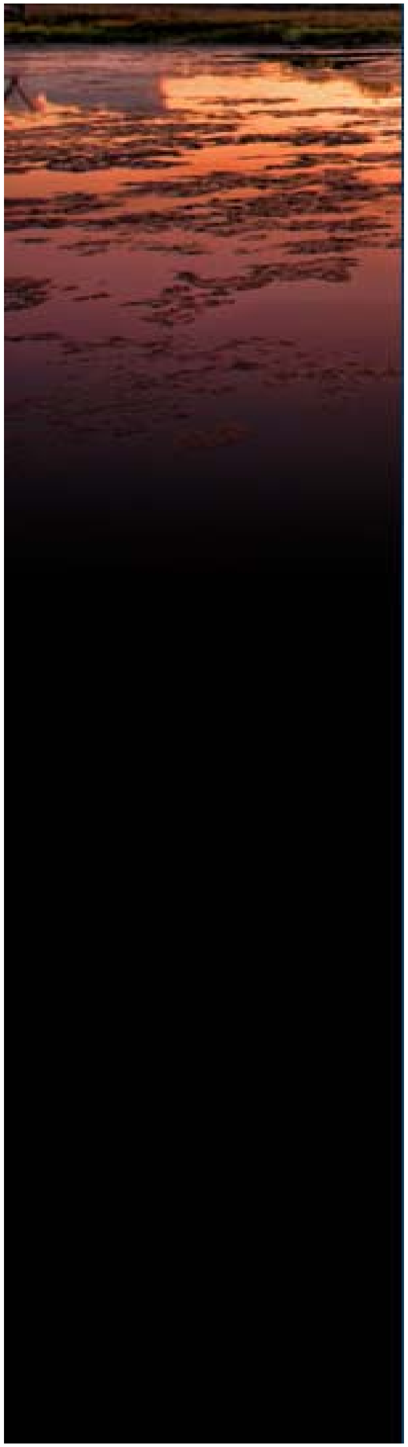


On some time scale, steady state requires

N1+N2=0; N1=X, N2=-X

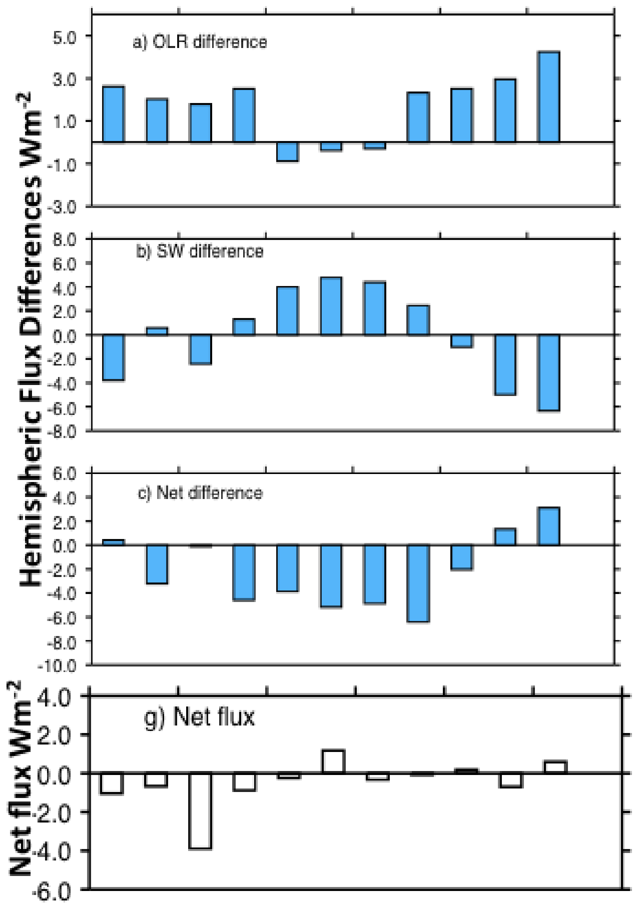
Suppose $T_1 \neq T_2$ then a thermodynamic force $-\nabla T$ is produced driving a circulation between hemispheres Fluxes of momentum and angular momentum across the equator must be zero implying the net mass flux is zero across the equator and the flux of heat too is zero (as observed). Thus

X=0 → N1=N2=0 → L1=L2 (T1=T2) → S1=S2

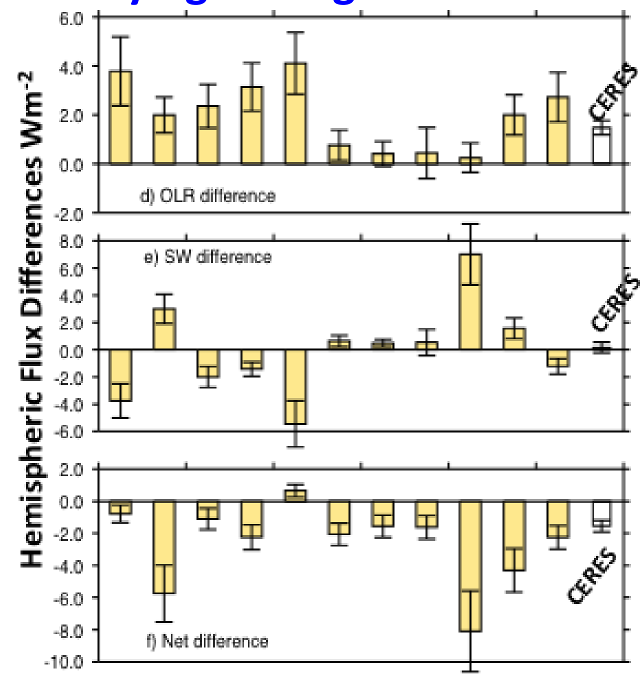


Unresolved questions

CMIP5 500 year control
Unchanged forcings, ….

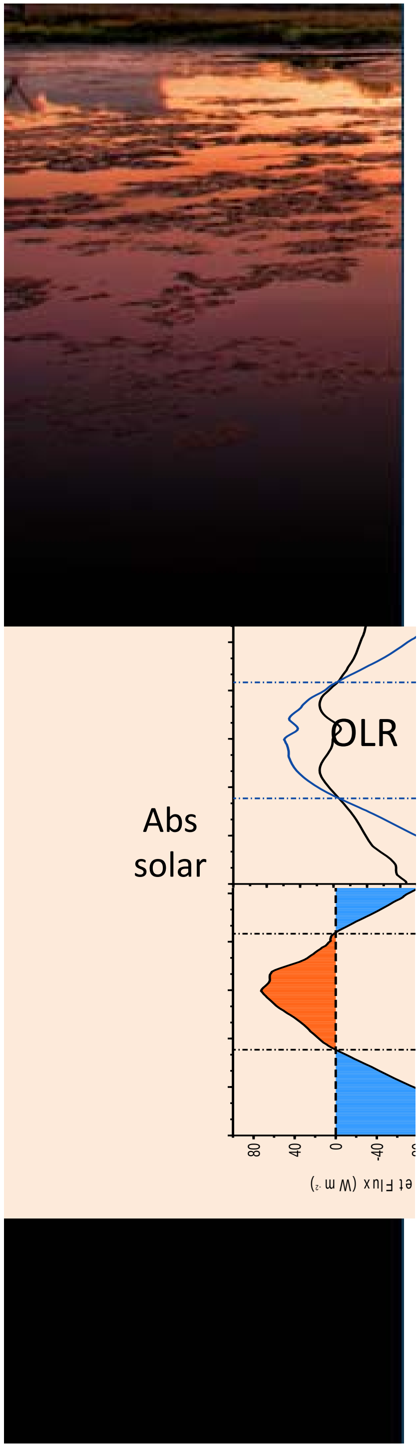


CMIP5 historical - time varying forcings



We can't use present models to test ideas because they are neither balanced nor in steady state (eg as in control). The hemispheric differences of models (historical) exceed that observed.

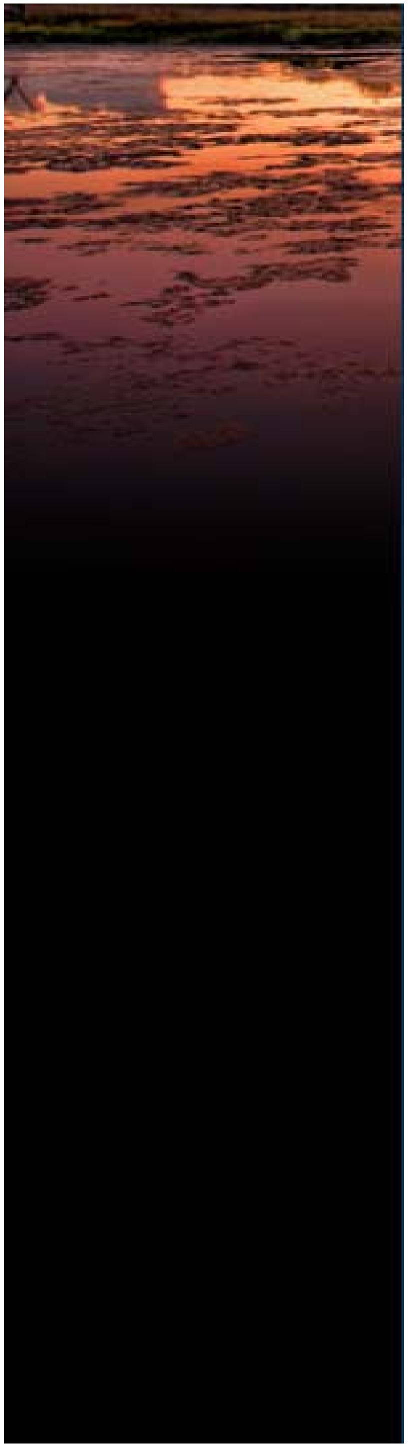
The (near) symmetry

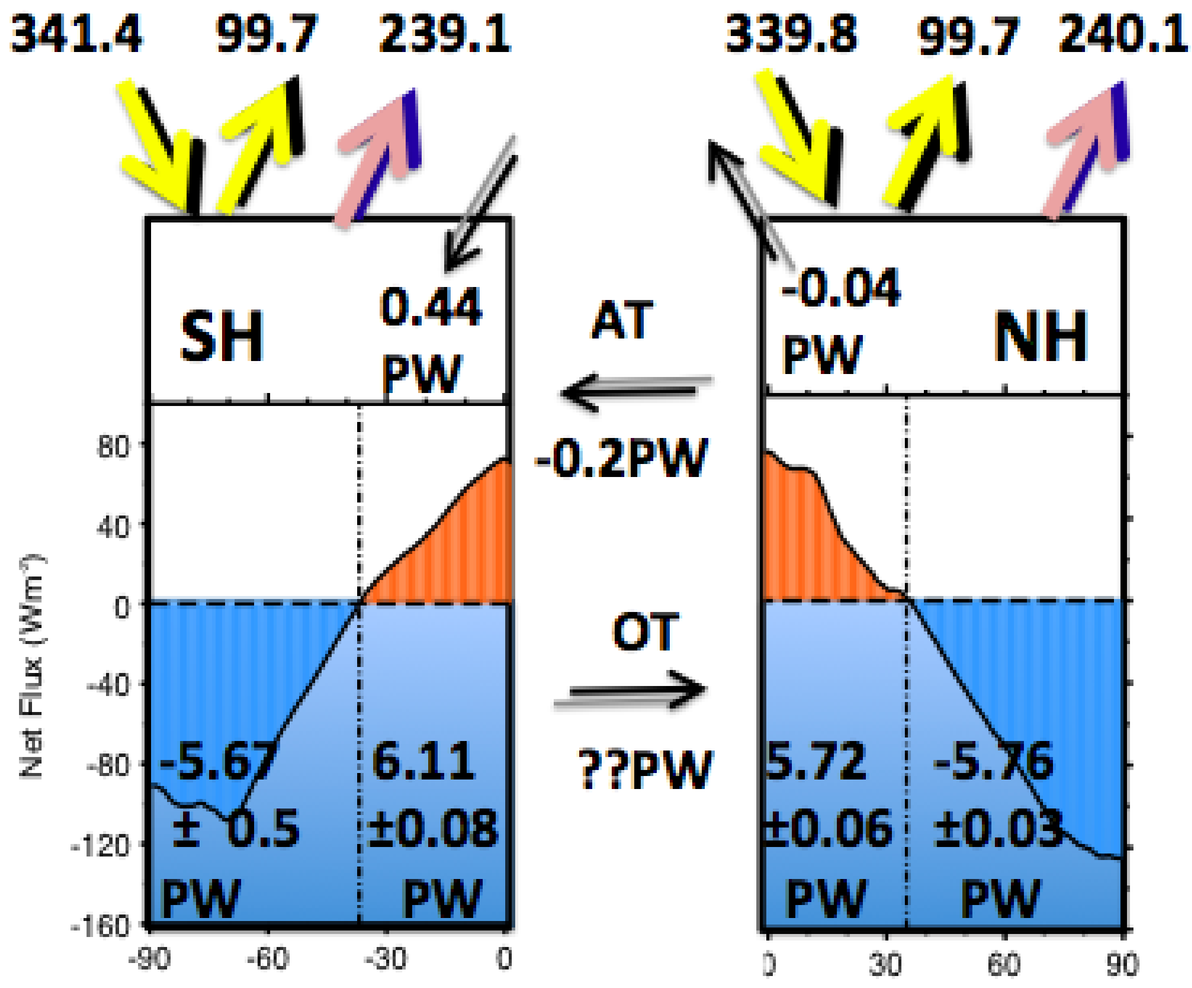


Scale	Reflected SW (Wm^{-2})		Outgoing LW (Wm^{-2})		Net flux (Wm^{-2})		Heat Accumulated (PW)		Sea Level Pressure (hPa)	
(x)	Flux	$\sigma(x)$	Flux	$\sigma(x)$	Flux	$\sigma(x)$	X	$\sigma(x)$	P	$\sigma(x)$
Global	99.71	0.24	239.73	0.25	0.79	0.28				
NH	99.70	0.24	240.41	0.19	−0.16	0.25	−0.04	0.06	1011.8 (1010.3)	0.25
SH	99.73	0.39	239.05	0.41	1.75	0.39	0.44	0.10	1011.0 (1010.8)	0.27
Tropical NH	97.86	0.50	256.73	0.44	39.07	0.38	5.72	0.06		
Tropical SH	92.00	0.48	259.86	0.55	39.82	0.52	6.11	0.08		
Polar NH	102.11	0.54	218.45	0.49	−52.94	0.23	−5.76	0.03		
Polar SH	111.42	0.44	207.58	0.42	−55.80	0.44	−5.67	0.05		

These are 11 year averages of the EBAF data

1) The NH is balanced , the SH gains heat – ie the ocean uptake occurs in southern oceans
2) This slight imbalance occurs through a slight OLR asymmetry
3) Less obvious is the also near symmetry in meridional heat transport





Stephens & L'Ecuyer, 2014

Averaging Scale	Total		Atmosphere		Surface	
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(30N-30S)						
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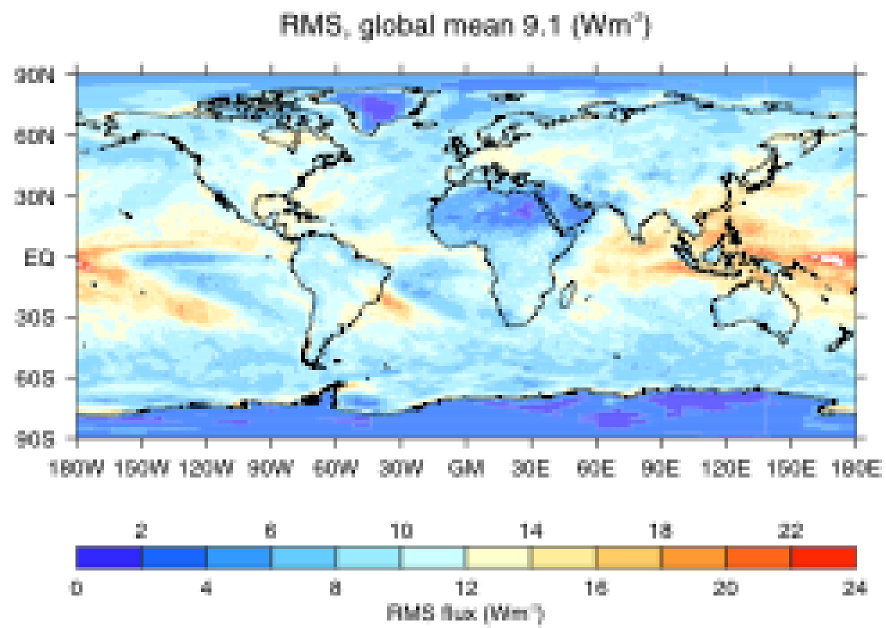

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