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*,
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

Box 1 | Updated energy balance

Figure B1 | The global annual mean energy budget of Earth for the shortwave and infrared fluxes in pink. The four flux quantities in purple-shaded.
Although the hemispheres are structurally different, the reflected flux is identical (~0.1 Wm\(^{-2}\)) – VonderHaar and Suomi, 1969; Voigt et al., 2012; Stephens et al. 2014.
Much of the clear-sky differences (warmer NH) offset by higher (colder) NH cloud tops

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

2003-2010 Hemisphere Average

Reflectance vs. Wavelength (nm)
In a balanced, steady state
\[ N_1 + N_2 = 0 \] (1)

where
\[ N_1 = S_1 - L_1 = X \]
and
\[ N_2 = S_2 - L_2 = -X \]

In the special case of \( X = 0 \) then \( L_1 = L_2 \) otherwise a thermodynamic force is exerted to \( X \neq 0 \) and
\[ N_1 = N_2 = 0 \] (2)
\[ S_1 = S_2 \] (3)

Current Earth conditions:
NH, \( N_1 = -0.04 \pm 0.06 \text{PW} \) (ie \( X \sim 0 \))
SH \( N_2 = 0.44 \pm 0.1 \text{PW} \)

So one hemisphere is balanced, the other not and \( N_1 + N_2 \neq 0 \) (0.4PW or \( \sim 0.8 \text{Wm}^{-2} \))
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.
Key areas affected by monsoonal precipitation

Bias ratio

<table>
<thead>
<tr>
<th>Geographic Region</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Africa</td>
<td>0.64</td>
<td>0.47</td>
<td>0.54</td>
<td>0.17</td>
</tr>
<tr>
<td>South Asia</td>
<td>1.05</td>
<td>2.59</td>
<td>0.67</td>
<td>0.70</td>
</tr>
<tr>
<td>Amazonia</td>
<td>0.86</td>
<td>0.90</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>South East Asia</td>
<td>1.17</td>
<td>0.35</td>
<td>0.80</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Haywood et al., personal communication

Also Haywood et al., 2013
Frierson & Huang, 2012
Voigt et al., 2013
Variability is mostly from clouds and is highly regulated with connected regions of increase and decrease.

Interannual variability of the global-mean reflected flux \( \sim 0.2 \text{ Wm}^{-2} \)
Local (1X1 degree) mean std deviation (deseasonalized \( \sim 9 \text{ Wm}^{-2} \))
Paltridge, 1978
MEP hypothesis & Convection hypothesis

e.g. O'Brien & Stephens, 1993
(both in QJRMS)

CERES Variability Between 2000-2010
In the mean, model interannual variability is ~ 4 times the observed.

Does this matter??
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 asynchronous 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
Each 'box' has five unknowns:

(i) Surface Temperature $T$
(ii) Meridional flux by atmosphere and oceans, $X = X_O + X_A$
(iii) Cloud cover $\theta$
(iv) Latent and sensible heat flux $LE+H$

The Paltridge system has no dynamics (OBrien & Stephens, 1993, QJRMS,)

It is closed and solved using
- Surface and TOA energy balance ($T, \theta, LE+H, surface\ albedo,\ cloud\ albedo ...$)
- Introducing two hypotheses:
  - The introduction of a Maximum Entropy Production (MEP) hypothesis
  - The introduction of a Convection Hypothesis (OBrien and Stephens, 1993)
• MEP - a constraint on $X - X$ is chosen to maximize

$$\text{MEP} = \dot{S}_T = -\dot{S}_e = -\sum_{i=1}^{10} (F_{\downarrow s} - F_{\uparrow L})_i / T_a$$

• Convection Hypothesis – for a given ratio $X_A$ & $X_0$, the cloud cover is such as to maximize $\text{LE+H}$ – constrains ratio $X_A/X_0$ and expresses $\text{LE+H}$ in terms of $T$ and cloud cover $\theta$

• His solutions

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.

Goody’s main point - not all parts of the system come under the MEP constraint and thus MEP can’t 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 \( N_1 + N_2 = 0; \; \; N_1 = X, \; N_2 = -X \)

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

\[ X = 0 \rightarrow N_1 = N_2 = 0 \rightarrow L_1 = L_2 \; (T_1 = T_2) \rightarrow S_1 = S_2 \]
Unresolved questions

CMIP5 500 year control
Unchanged 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

<table>
<thead>
<tr>
<th>Scale</th>
<th>Reflected SW Flux (Wm$^{-2}$)</th>
<th>Outgoing LW Flux (Wm$^{-2}$)</th>
<th>Net flux Flux (Wm$^{-2}$)</th>
<th>Heat Accumulated X (PW)</th>
<th>Sea Level Pressure hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma(x)$</td>
<td>$\sigma(x)$</td>
<td>$\sigma(x)$</td>
<td>$\sigma(x)$</td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>99.71</td>
<td>239.73</td>
<td>0.79</td>
<td>0.28</td>
<td>1011.8 (1010.3)</td>
</tr>
<tr>
<td>NH</td>
<td>99.70</td>
<td>240.41</td>
<td>−0.16</td>
<td>0.25</td>
<td>0.06 0.25</td>
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<tr>
<td>SH</td>
<td>99.73</td>
<td>239.05</td>
<td>1.75</td>
<td>0.39</td>
<td>0.44 0.10</td>
</tr>
<tr>
<td>Tropical NH</td>
<td>97.86</td>
<td>256.73</td>
<td>−39.07</td>
<td>0.38</td>
<td>5.72 0.06</td>
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<tr>
<td>Tropical SH</td>
<td>92.00</td>
<td>259.86</td>
<td>−39.82</td>
<td>0.52</td>
<td>6.11 0.08</td>
</tr>
<tr>
<td>Polar NH</td>
<td>102.11</td>
<td>218.45</td>
<td>−52.94</td>
<td>0.23</td>
<td>−5.76 0.03</td>
</tr>
<tr>
<td>Polar SH</td>
<td>111.42</td>
<td>207.58</td>
<td>−55.80</td>
<td>0.44</td>
<td>−5.67 0.05</td>
</tr>
</tbody>
</table>

These are 11 year averages of the EBAF data

1) The NH is balanced, the SH gains heat – i.e. 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
Interannual variability of the global-mean reflected flux $\sim 0.2 \text{ Wm}^{-2}$

Local (1X1 degree) mean std deviation (deseasonalized $\sim 9 \text{ Wm}^{-2}$)

<table>
<thead>
<tr>
<th>Averaging Scale</th>
<th>Total Flux</th>
<th>$\sigma (x)$</th>
<th>Atmosphere Flux</th>
<th>$\sigma (x)$</th>
<th>Surface Flux</th>
<th>$\sigma (x)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>99.7</td>
<td>0.23</td>
<td>86.9</td>
<td>0.29</td>
<td>12.9</td>
<td>0.10</td>
</tr>
<tr>
<td>(30-60S)</td>
<td>103.8</td>
<td>0.52</td>
<td>91.5</td>
<td>0.53</td>
<td>12.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Mid-latitude NH(30-60N)</td>
<td>104.1</td>
<td>0.56</td>
<td>98.9</td>
<td>0.65</td>
<td>5.26</td>
<td>0.10</td>
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<tr>
<td>Mid-latitude SH(30-60S)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polar NH (60-90N)</td>
<td>97.0</td>
<td>0.87</td>
<td>78.7</td>
<td>0.87</td>
<td>19.1</td>
<td>0.47</td>
</tr>
<tr>
<td>Polar SH (60-90N)</td>
<td>118.8</td>
<td>0.68</td>
<td>84.4</td>
<td>1.26</td>
<td>35.5</td>
<td>0.97</td>
</tr>
</tbody>
</table>