Bistability of the climate around the habitable zone: a thermodynamic investigation

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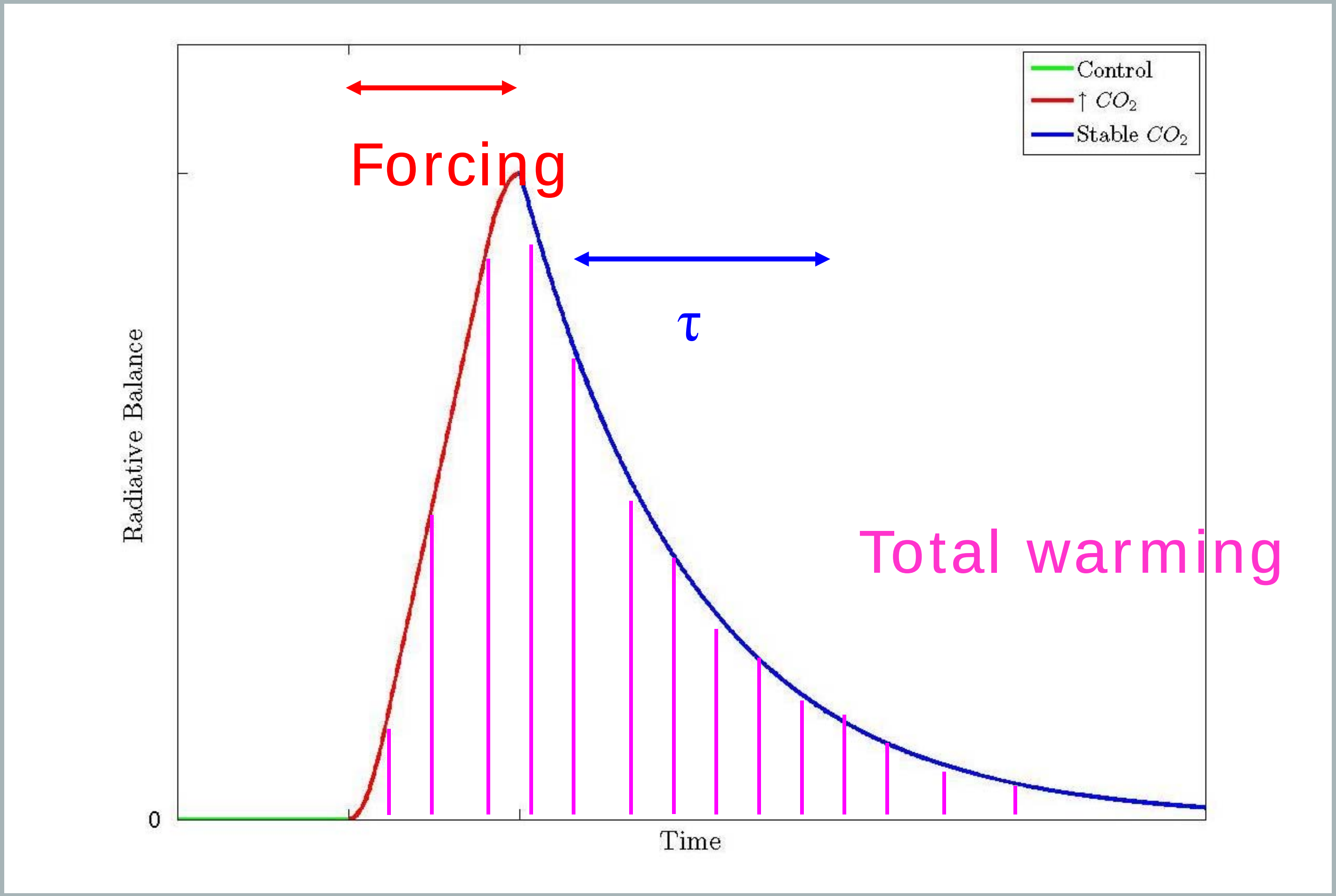
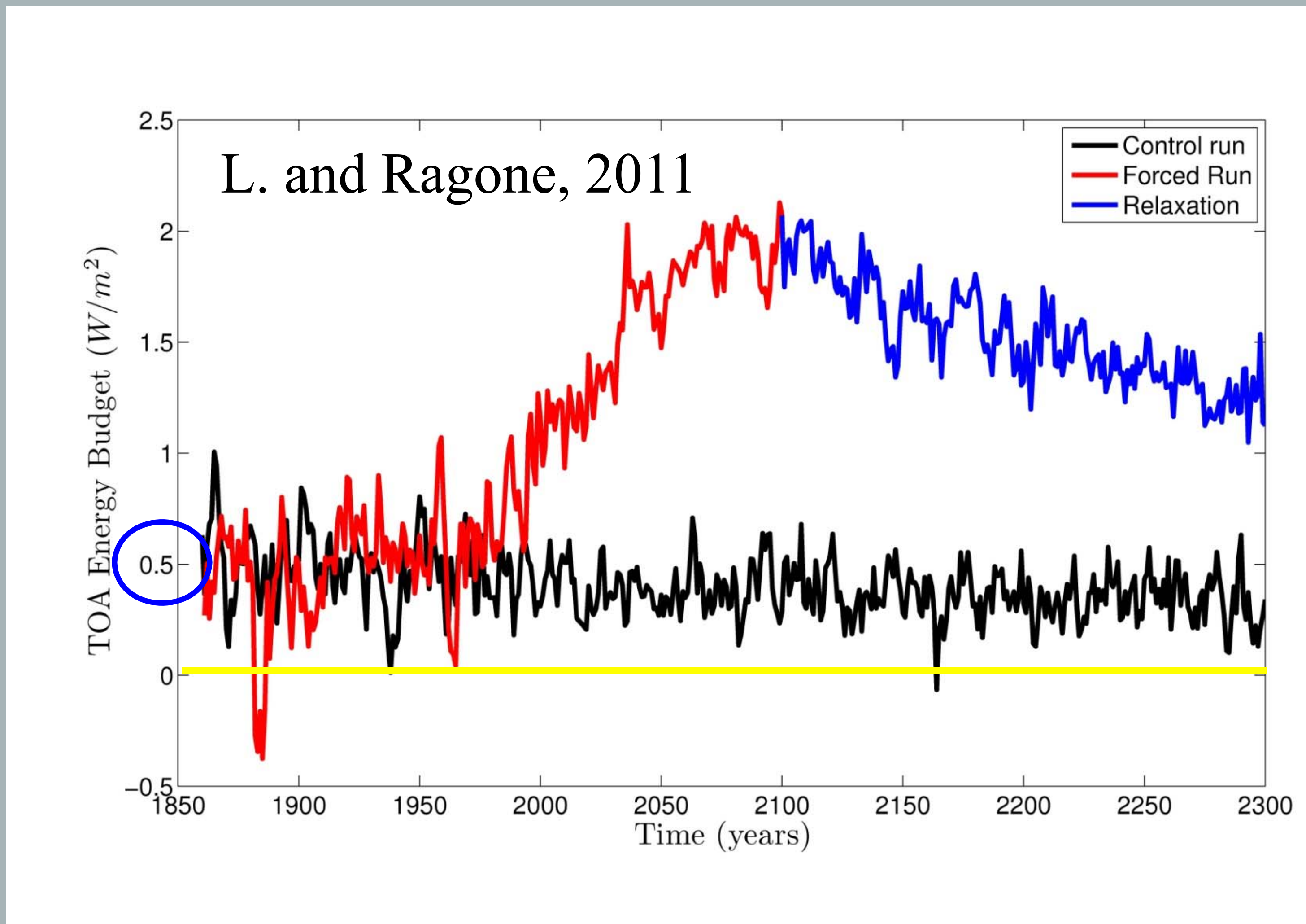
Energy & Forcing – **Perfect Model**



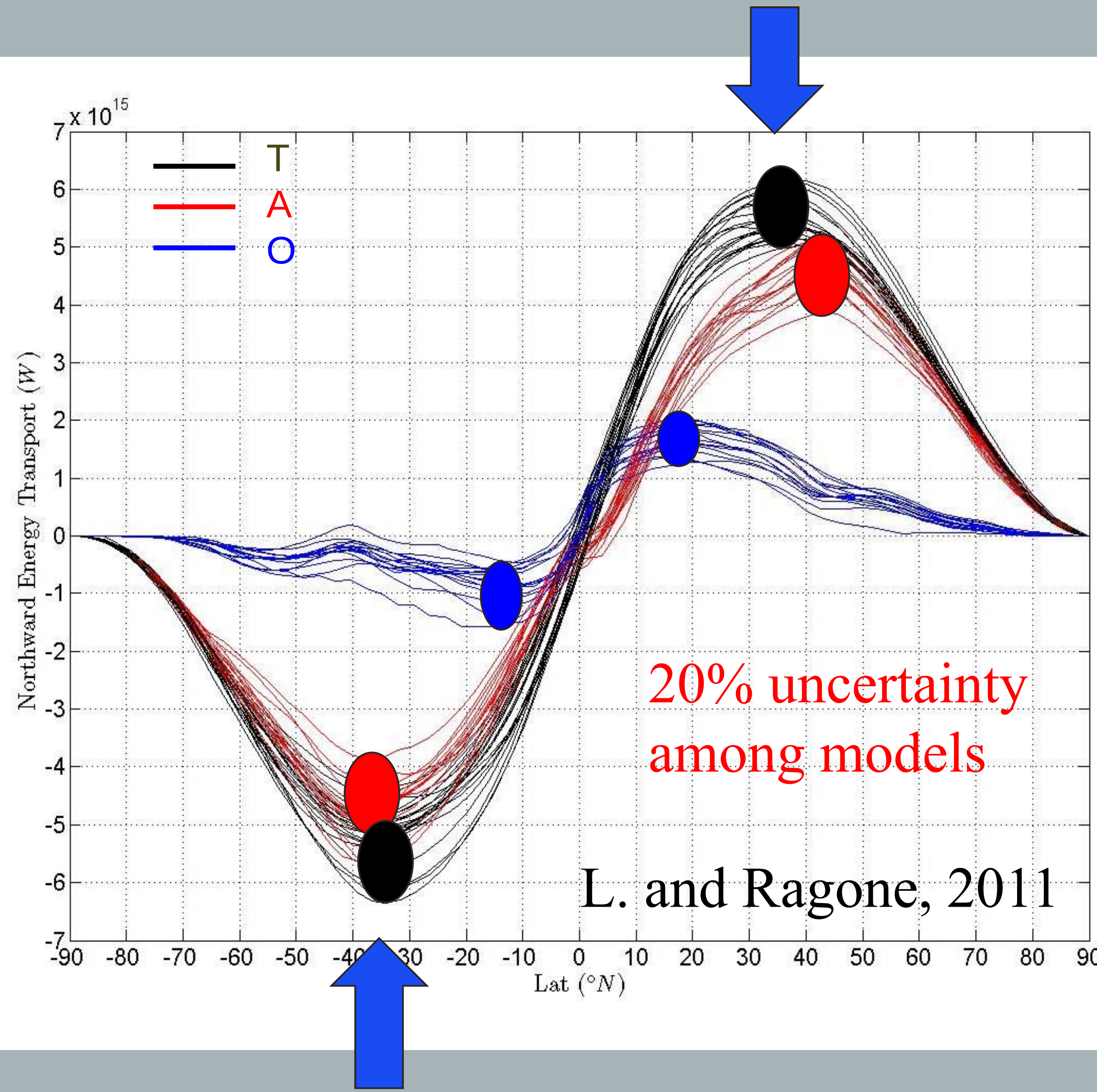
- NESS→Transient → NESS
- Applies to the whole climate and to to all climatic subdomains
  - for atmosphere τ is small, always quasi-equilibrated

Energy and GW – **Actual GCMs**



- Not only bias: bias control ≠ bias final state
  Bias depends on climate state! ➔ Dissipation & Water

Steady State – Meridional Transports



Energies

WORK

$$W = C(P,K)$$

- *Kinetic energy budget*

$$\dot{K}(\Omega) = -\int_{\Omega} dV \varepsilon^2 + C(P,K) = -D + W$$

- *Moist Static Potential Energy budget*

$$\dot{P}(\Omega) = \int_{\Omega} dV \rho \dot{Q} - W \qquad \dot{Q} = 1/\rho\left(\varepsilon^2 - \vec{\nabla}\cdot\vec{H}\right)$$

- *Total Energy Budget*

$$\dot{E}(\Omega) = \int_{\Omega} dV\left(-\vec{\nabla}\cdot\vec{H}\right) = -\int_{\partial\Omega} dS\hat{n}\cdot\vec{H}$$

FLUXES

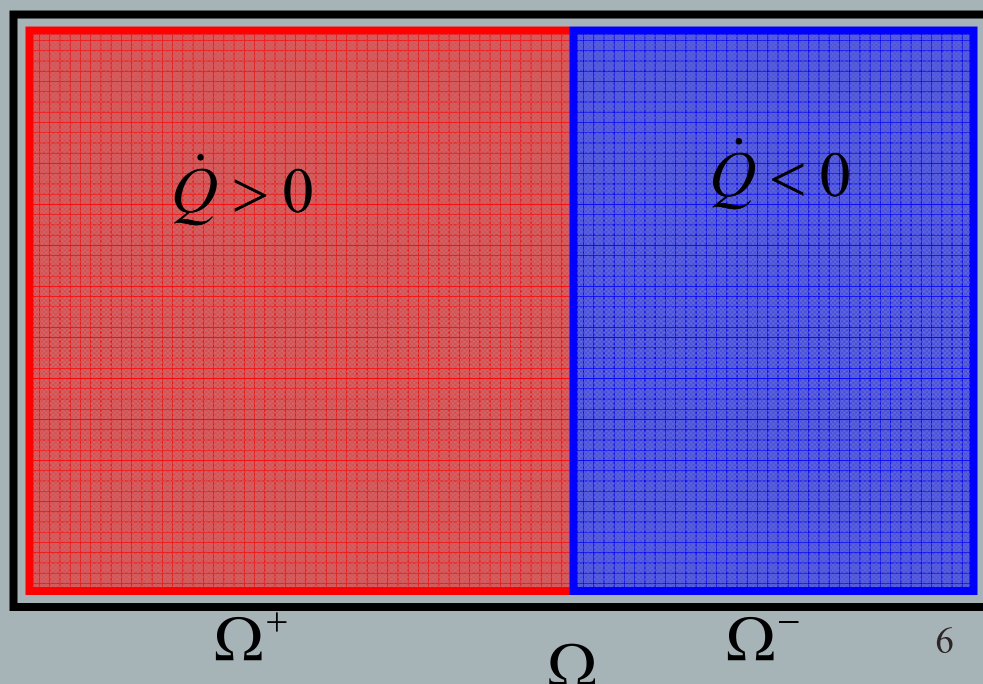
DISSIPATION

Johnson's idea (2000)

- *Partitioning the Domain (Eulerian approach)*

$$\dot{P}(\Omega)+W=\int_{\Omega^+} dV\rho\dot{Q}^+ + \int_{\Omega^-} dV\rho\dot{Q}^- = \dot{\Phi}^+ + \dot{\Phi}^-$$

- *Better than it seems!*

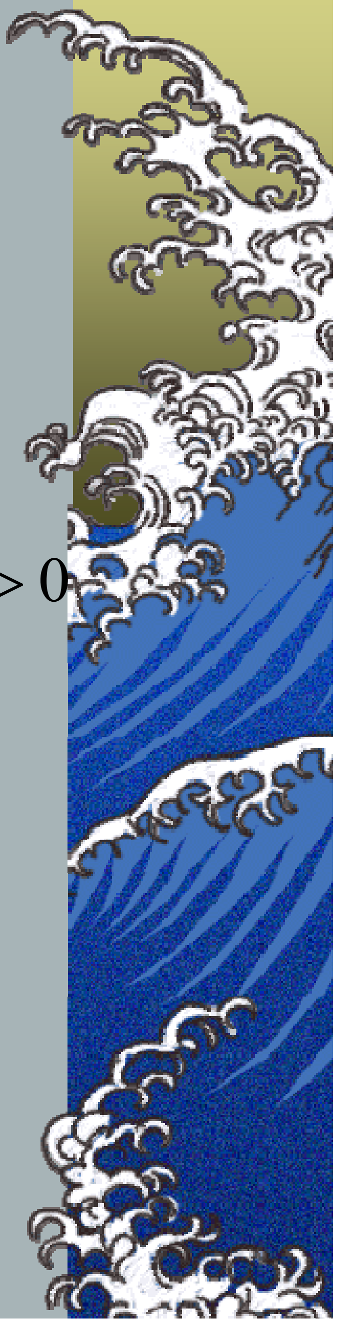


Long-Term averages

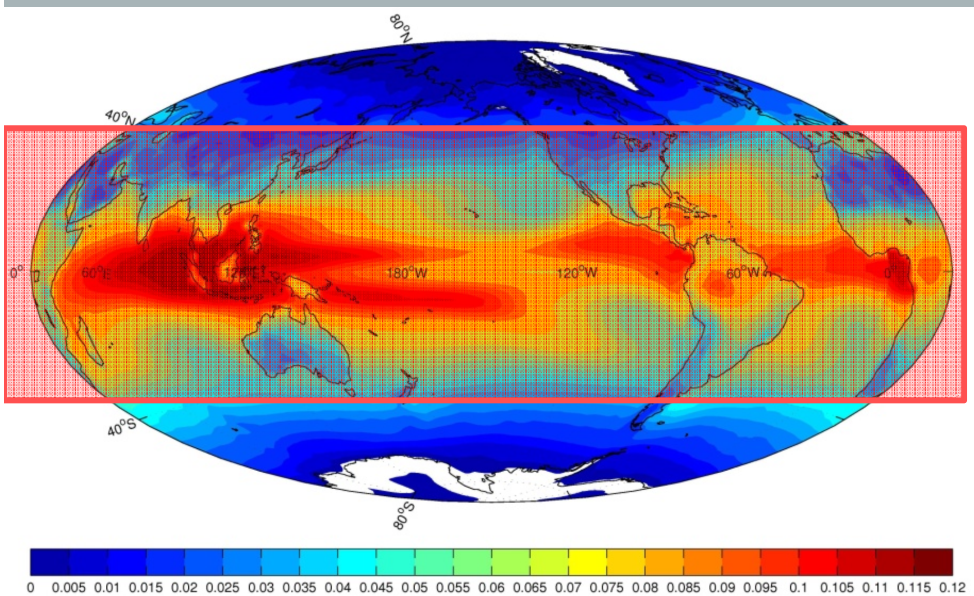
- *Stationarity:* $$\overline{\dot{E}(\Omega)} = \overline{\dot{P}(\Omega)} = \overline{\dot{K}(\Omega)} = 0$$
- *Work = Dissipation* $$-\overline{\dot{K}(\Omega)} + \overline{W} = \overline{W} = \overline{D} > 0$$
- *Work = Input-Output* $$\overline{\dot{P}(\Omega)} + \overline{W} = \overline{W} = \overline{\dot{\Phi}^{+}} + \overline{\dot{\Phi}^{-}} > 0$$
- *A different view on Lorenz Energy cycle*

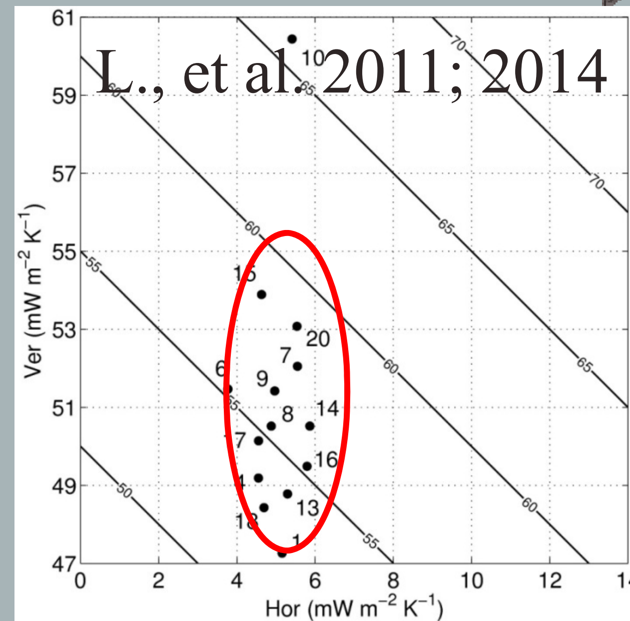
$$\underbrace{\overline{\dot{\Phi}^{+}} + \overline{\dot{\Phi}^{-}}}_{\substack{\textit{differential heating} \\ G(A)}} = \underbrace{\overline{W}}_{\substack{\textit{conversion} \\ C(A,K)}} = \underbrace{\overline{D}}_{\substack{\textit{dissipation} \\ D(K)}} > 0$$

$$\overline{W} = \frac{\overline{\dot{\Phi}^{+}} + \overline{\dot{\Phi}^{-}}}{\overline{\dot{\Phi}^{+}}} \overline{\dot{\Phi}^{+}} = \frac{\Theta^{+} - \Theta^{-}}{\Theta^{+}} \overline{\dot{\Phi}^{+}} = \underbrace{\eta}_{\textit{efficiency}} \overline{\dot{\Phi}^{+}}$$



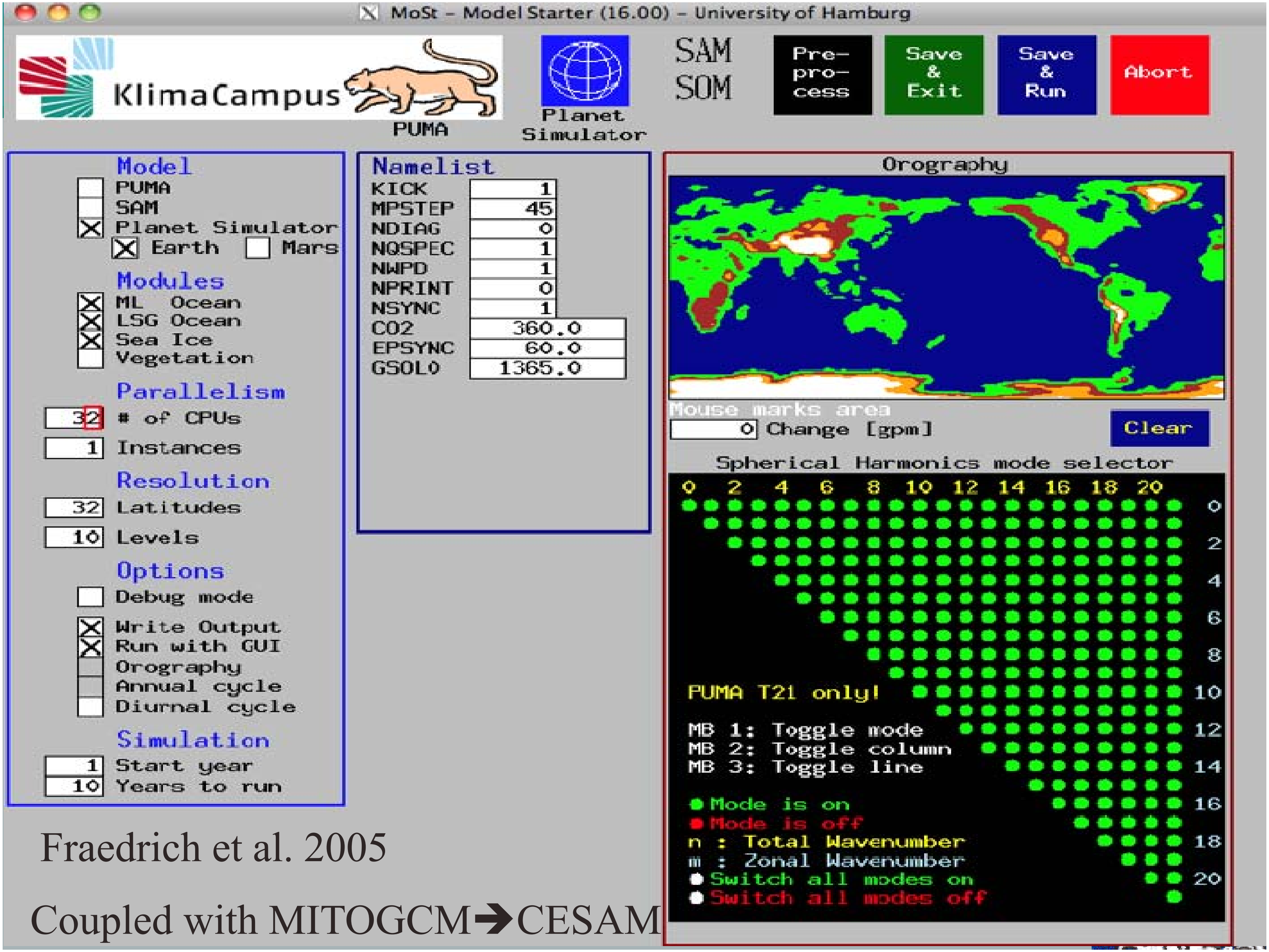
Results on IPCC GCMs





$$\overline{\dot{S}_{mat}(\Omega)} \approx \overbrace{\underbrace{\int_S d\sigma R_{net}^{surf}\left(\frac{1}{T_E}-\frac{1}{T_S}\right)}_{\overline{\dot{S}_{mat}^{vert}(\Omega)}}}^{\overline{\dot{S}_{in}^{vert}(\Omega)}} + \underbrace{\int_S d\sigma R_{net}^{TOA}\frac{1}{T_E}}_{\overline{\dot{S}_{mat}^{hor}(\Omega)}}$$

- *Hor vs Vert EP in IPCC models*
- *Collection of (weak. coup.) vertical columns*
- *Warmer climate: Hor↓ Vert↑*



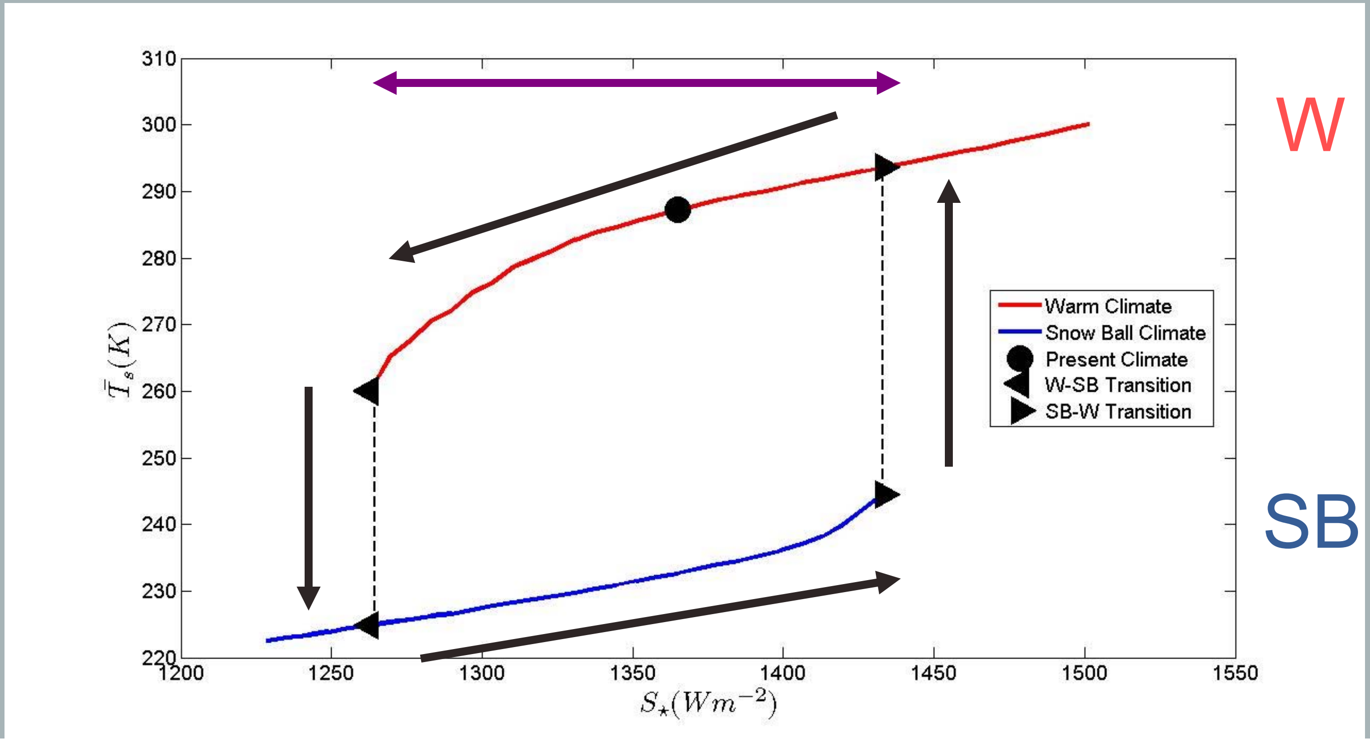
Fraedrich et al. 2005

Coupled with MITOGCM➔CESAM

Snowball Hysteresis

- *Swing of S^* by $\pm$10% starting from present climate*
  - *→ hysteresis experiment!*
- ***Global average surface temperature T_S***
  - *Wide (~ 10%) range of S^* bistable regime -ΔT_S ~ 50 K*
  - d T_S/d S_* >0 *everywhere, almost linear*

L., Lunkeit, Fraedrich, 2010



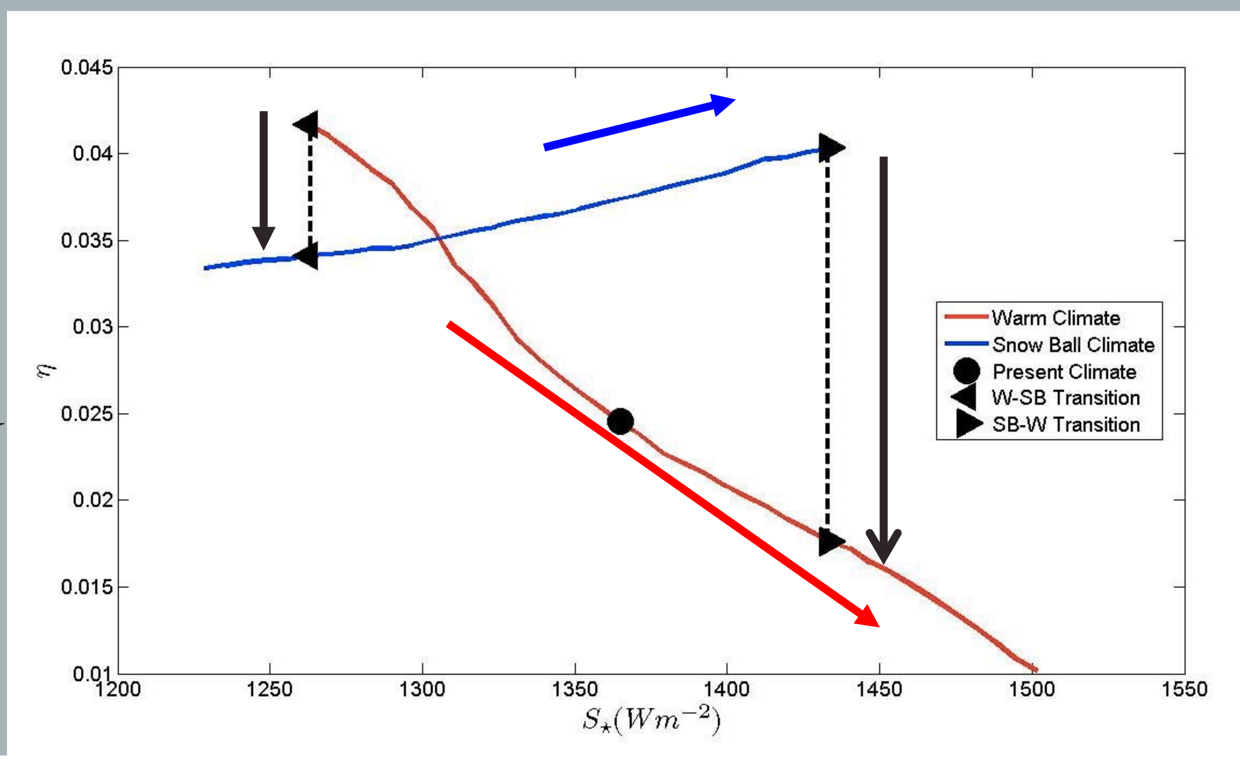
Thermodynamic Efficiency

- d η/d S_* >0 *in SB regime*
  - *Effect of decreased static stability*
- d η/d S_* <0 *in W regime*
  - *System thermalized by efficient LH fluxes*
- η *decreases at transitions* $\rightarrow$ *System more stable*

$\eta=0.04$

$\leftrightarrow$

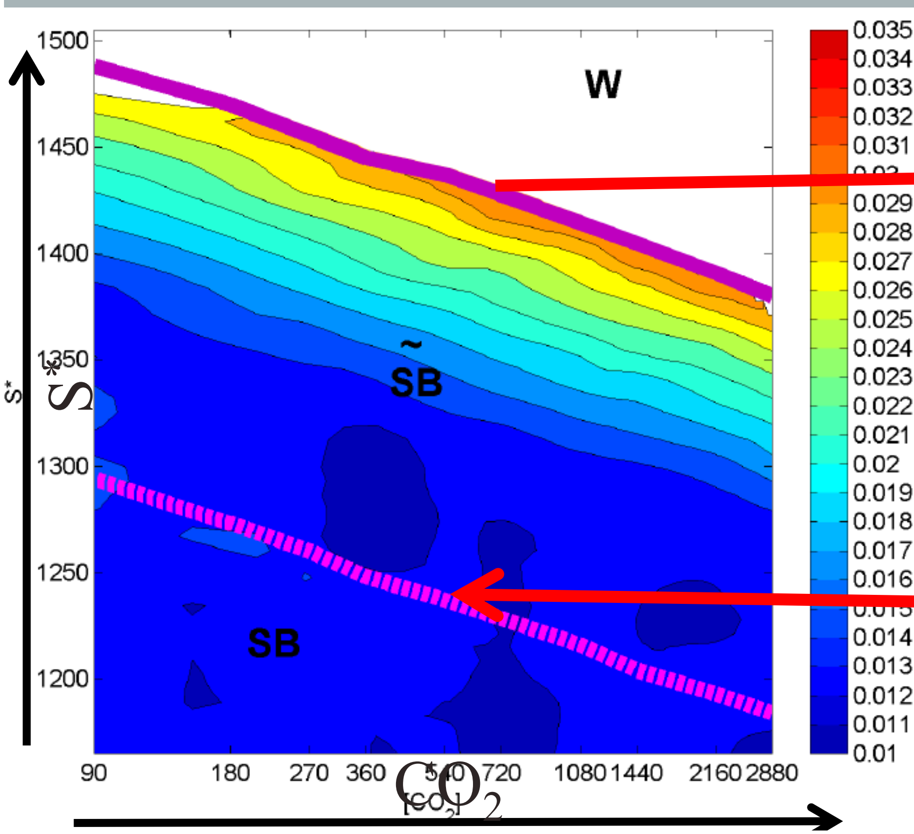
$\Delta\theta=10K$

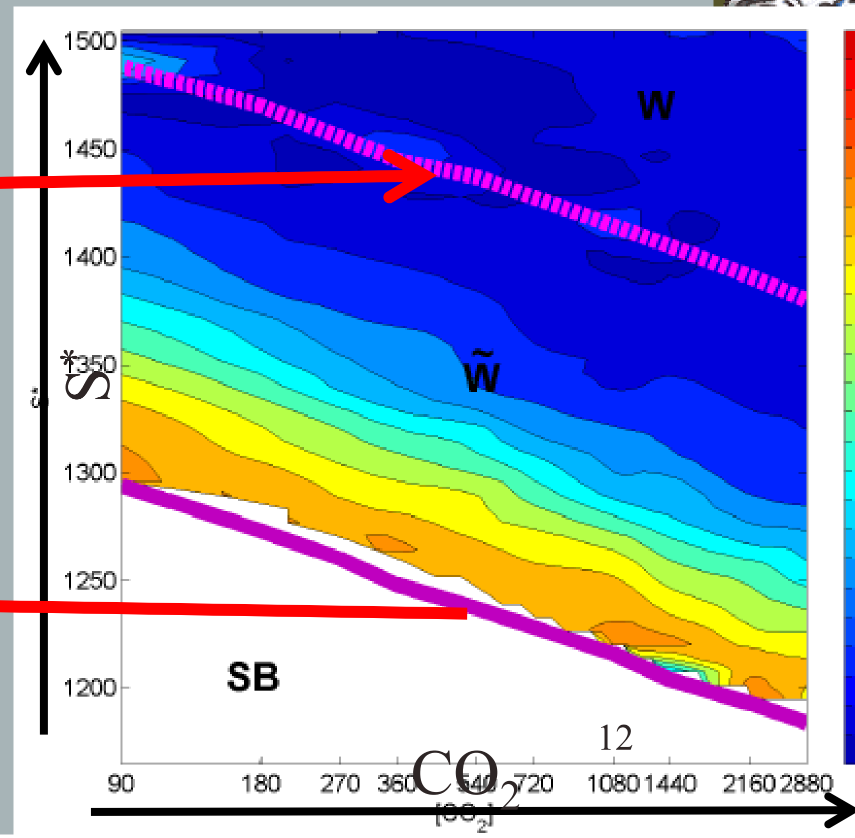


Let's alter also $[CO_2]$

- *Parametric Analysis of Climate Change*
- *Structural Properties of the system (Boschi, et al. 2013)*

Lower Manifold η Upper Manifold

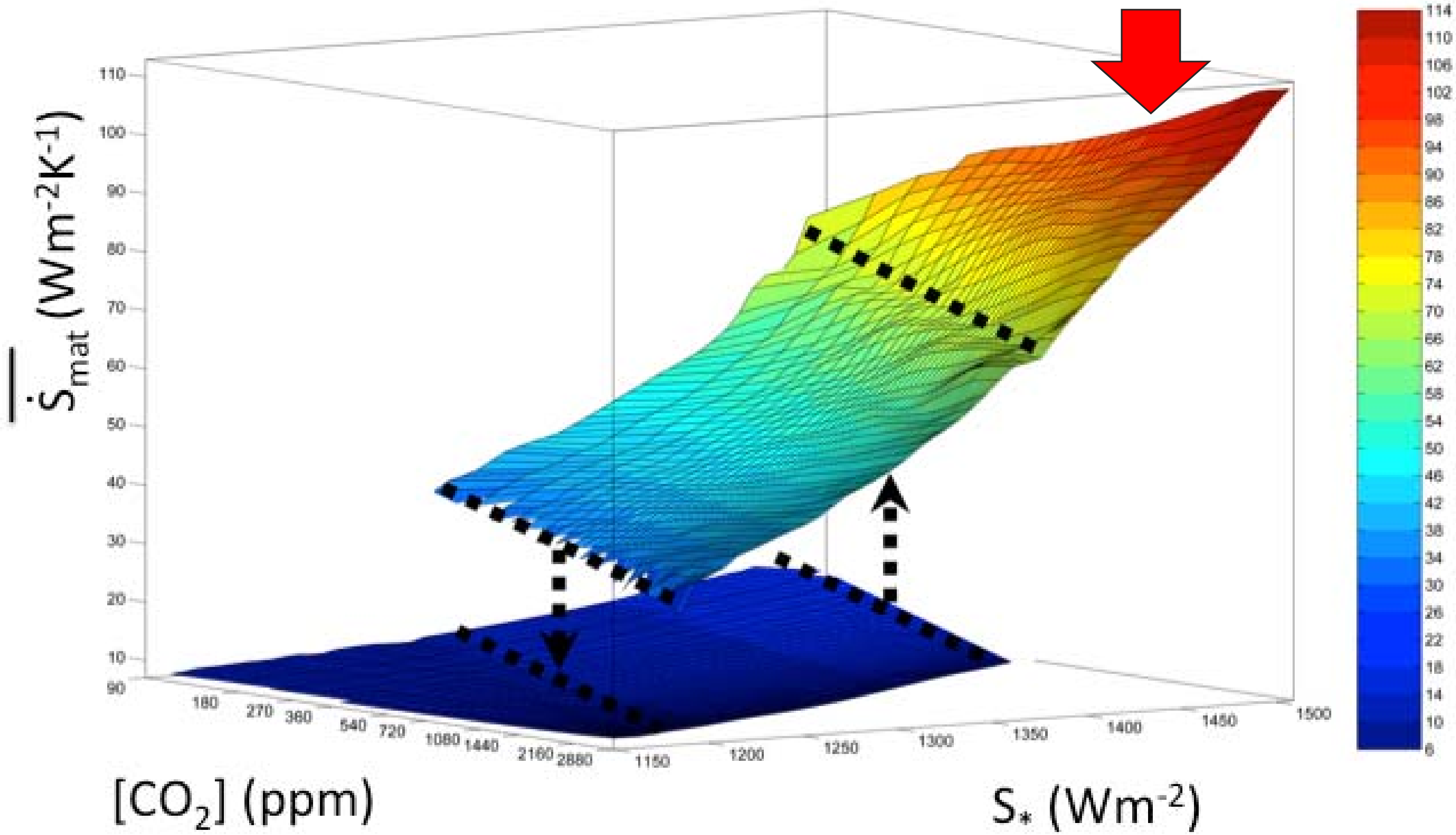




A 3D picture - EP

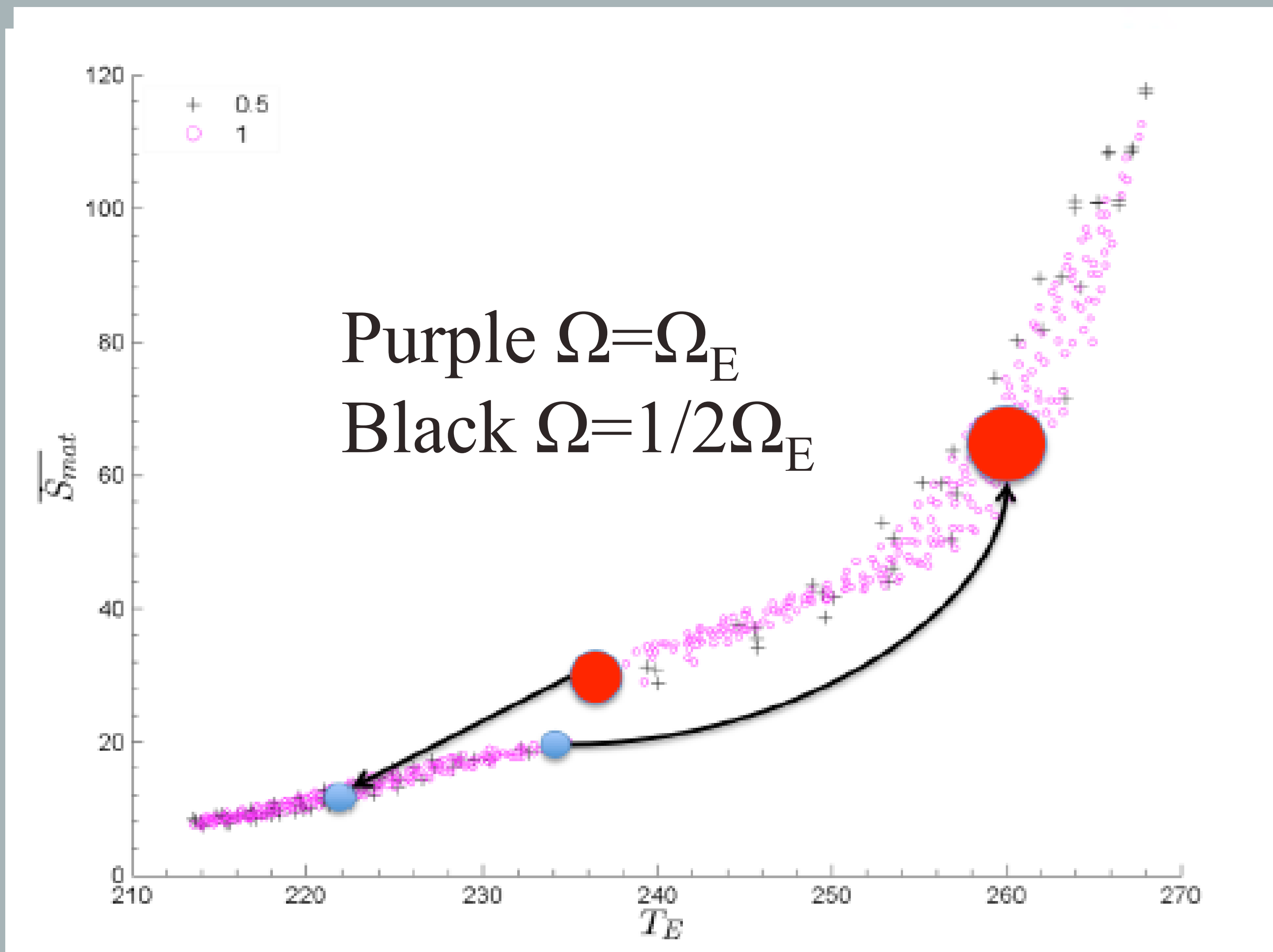
$$\overline{\dot{S}_{mat}(\Omega)} = \int_{\Omega} dV\, \overline{\vec{H}\cdot\vec{\nabla}\left(\frac{1}{T}\right)} + \int_{\Omega} dV\, \overline{\frac{\varepsilon^2}{T}}$$

$$Be = \overline{\dot{S}_{mat}(\Omega)} \Big/ \overline{\dot{S}_{\min}(\Omega)} = \overline{\dot{S}_{mat}(\Omega)}\langle\Theta\rangle \Big/ \overline{W}$$



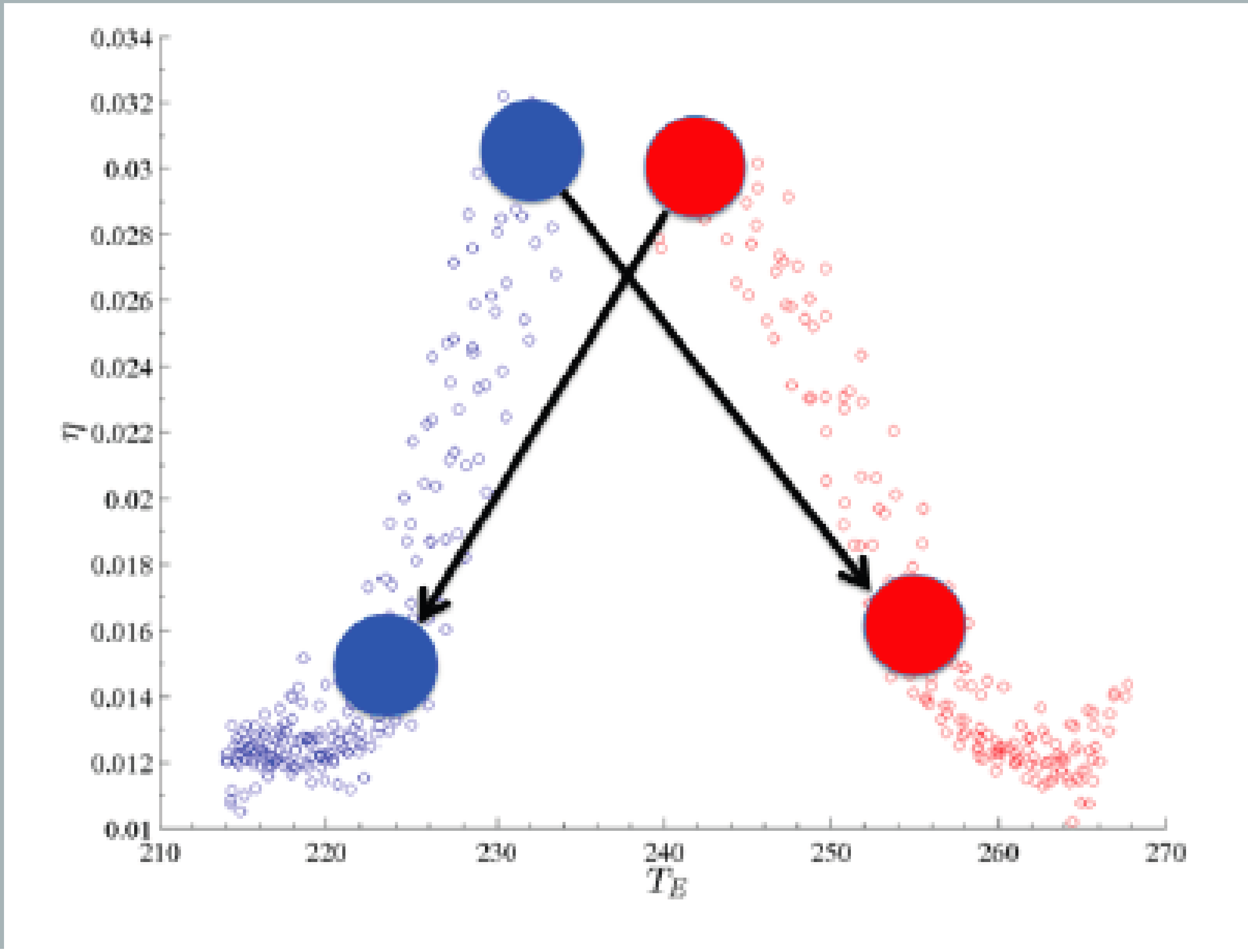
Parametrizations

- *EP vs Emission Temperature*



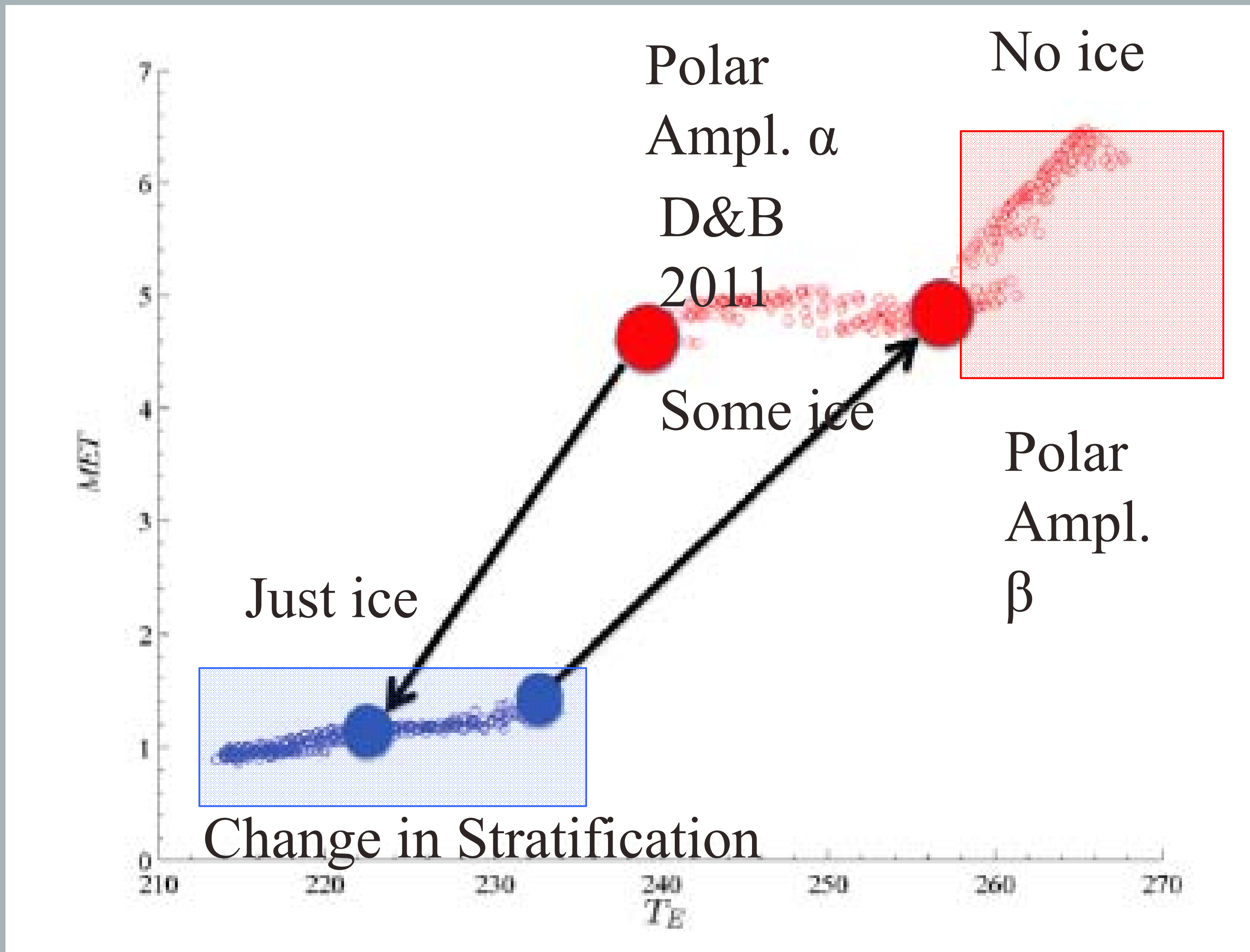
Parametrizations

- *Efficiency vs Emission Temperature*

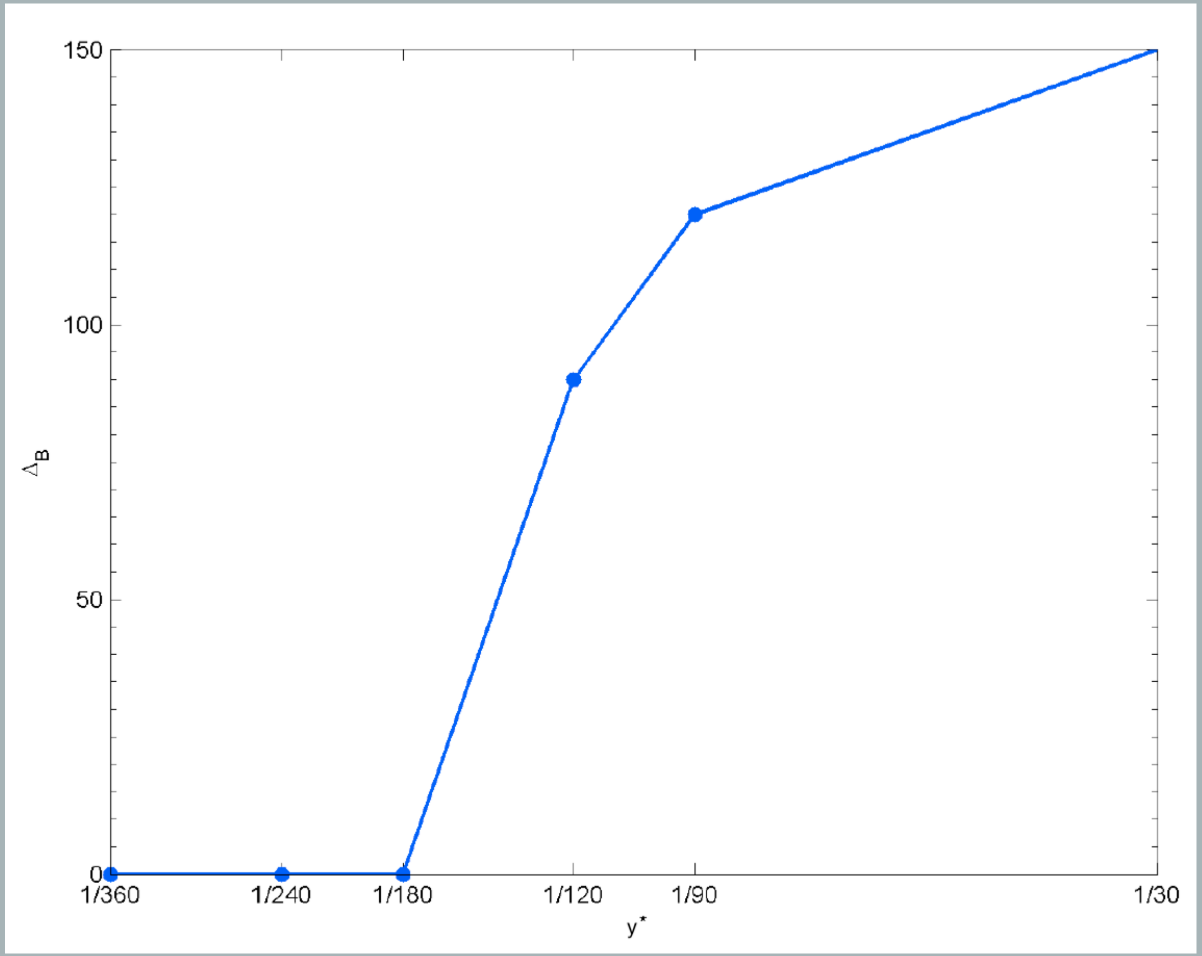


Parametrizations

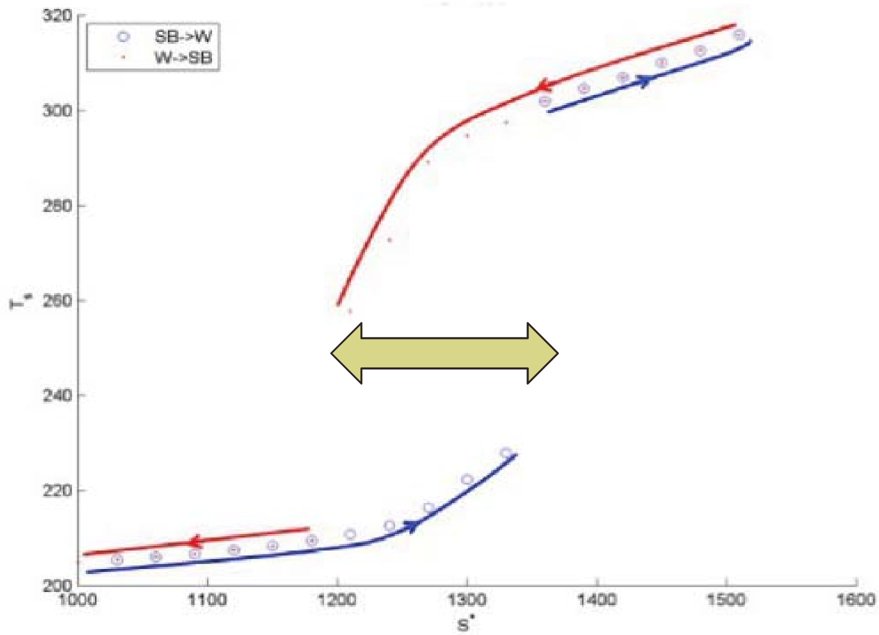
- *Heat Transport vs Emission Temperature*



Shorter year - Phase Transition



- *Width bistability vs length year (L. et al. 2013)*
  - *Fast orbiting planets cannot be in Snowball Earth*
  - *Habitability*


SB->W
W->SB
T_s
s*
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300
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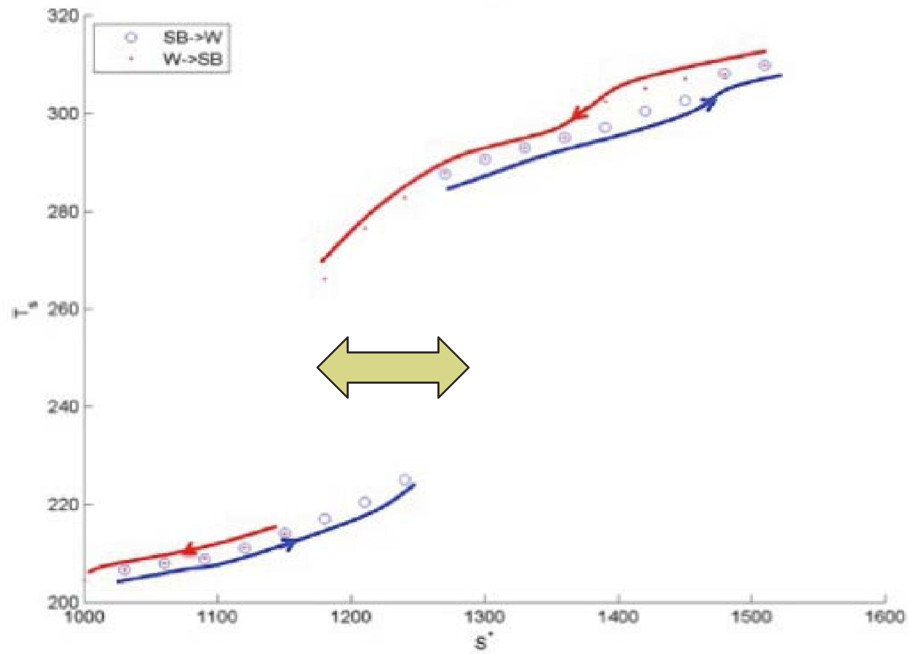
1600

(a)


SB->W
W->SB
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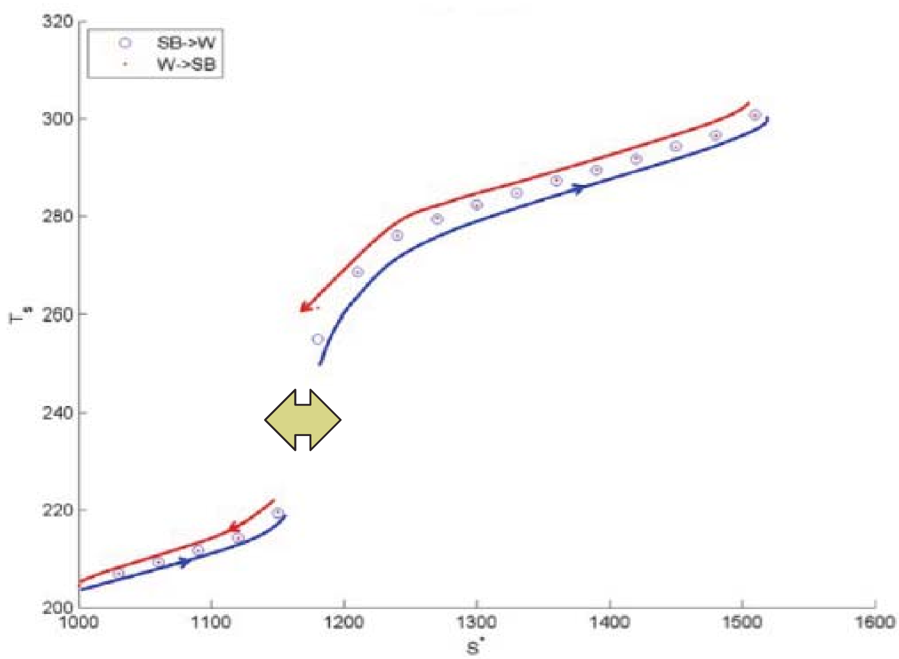
(b)


SB->W
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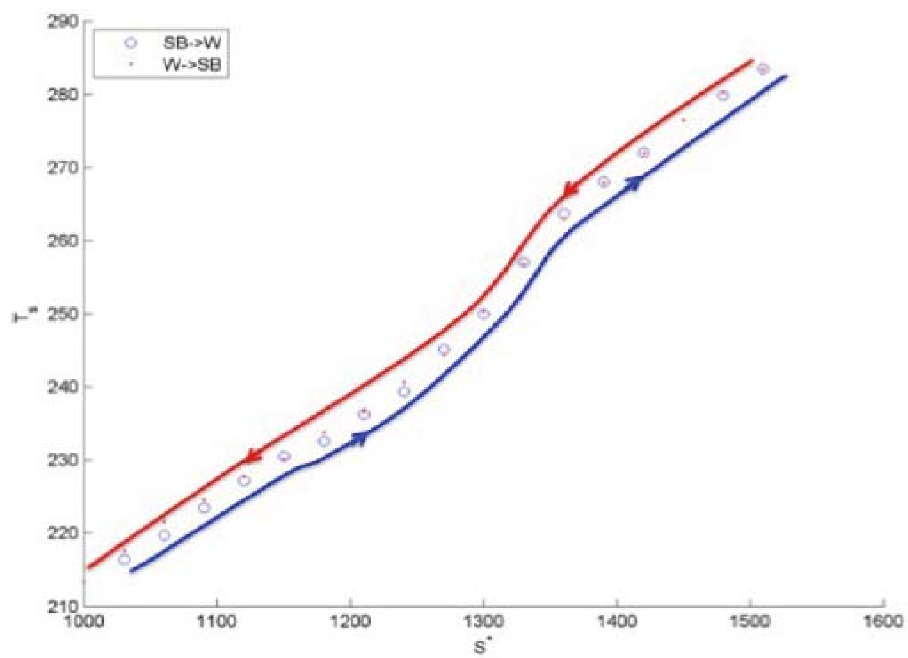
(c)


SB->W
W->SB
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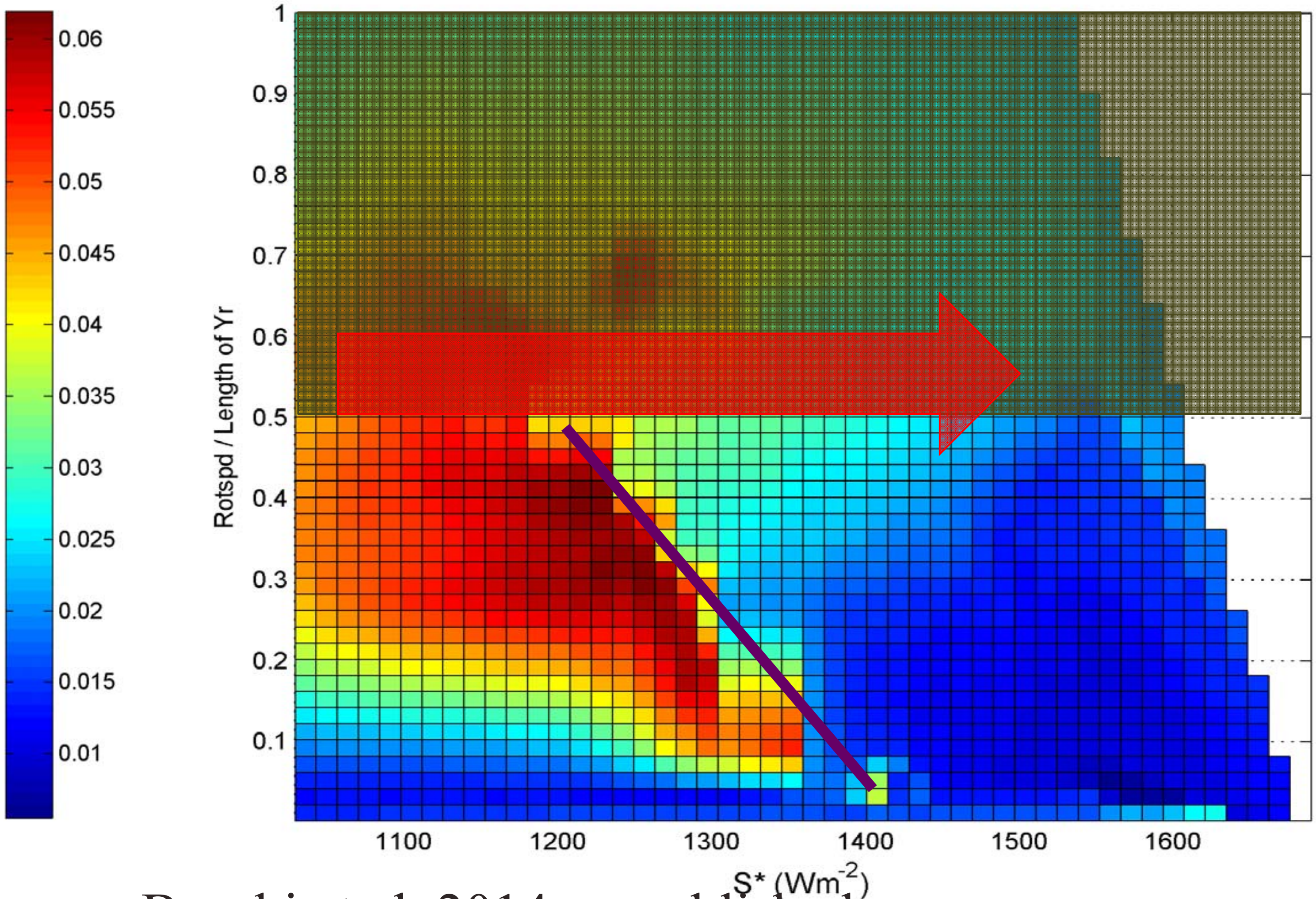
(d)

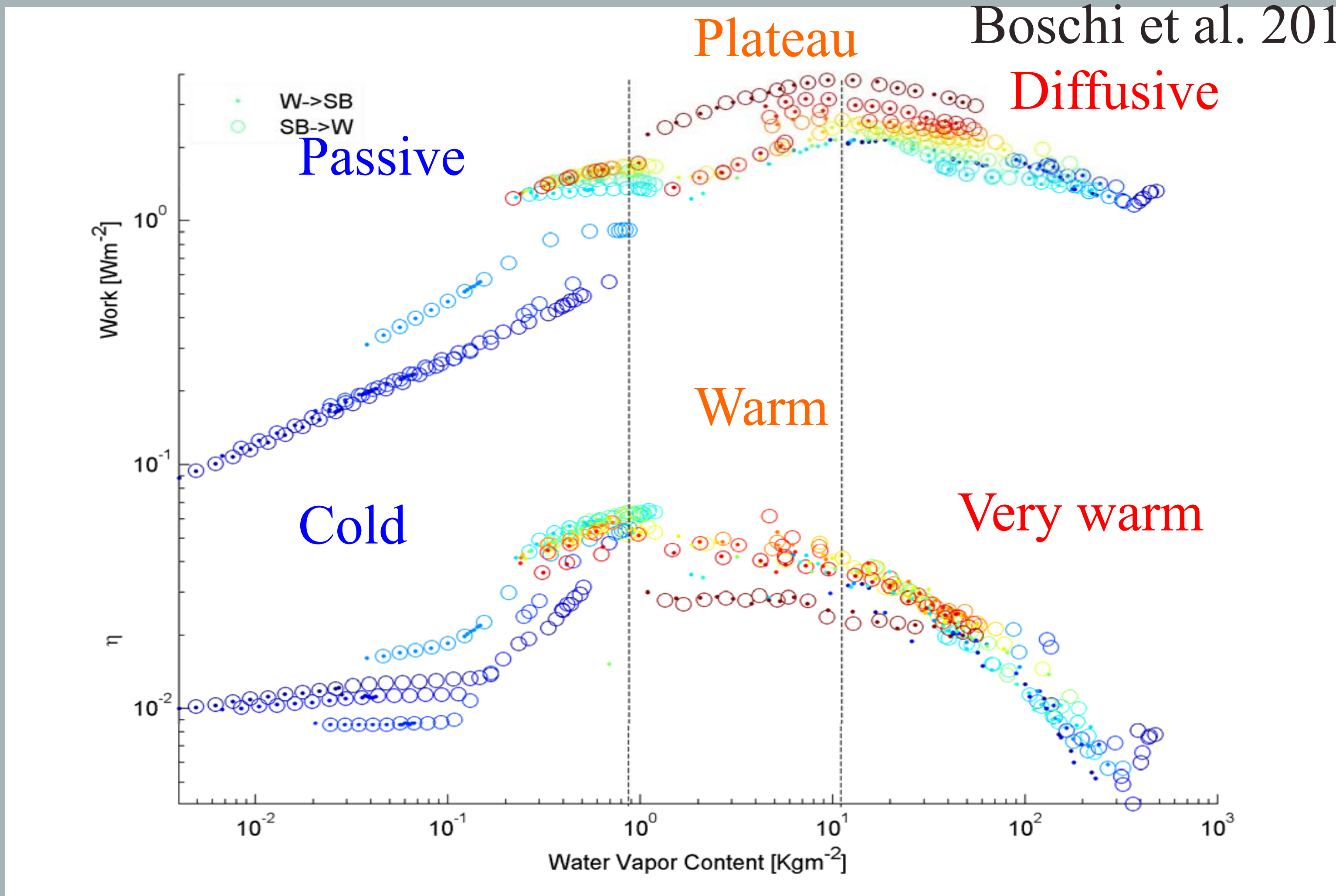
Bistability, Efficiency, Etc.



Boschi et al. 2014, unpublished

Water Vapour and Thermodynamics

Boschi et al. 2014, unpublish



Conclusions

- *Unifying picture connecting Energy cycle to EP;*
- *Simplified 2D formula for studying GCMs*
- *Snowball hysteresis experiment*
  - *Mechanisms involved in climate transitions;*
  - *Analysis of the impact of [CO_2] increase*
  - *Generalized set of climate sensitivities*
  - *Analysis of impact of change on l.o.y.*

- ***Many challenges ahead:***
  - *Analysis of GCMs performance*
  - *Melancholia/Edge States*
  - *Multiscale, coarse graining effects*

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