Biospheric Theory and Modelling

Max-Planck-Institut für Biogeochemie

An earth system's approach to the sensitivity of the water cycle

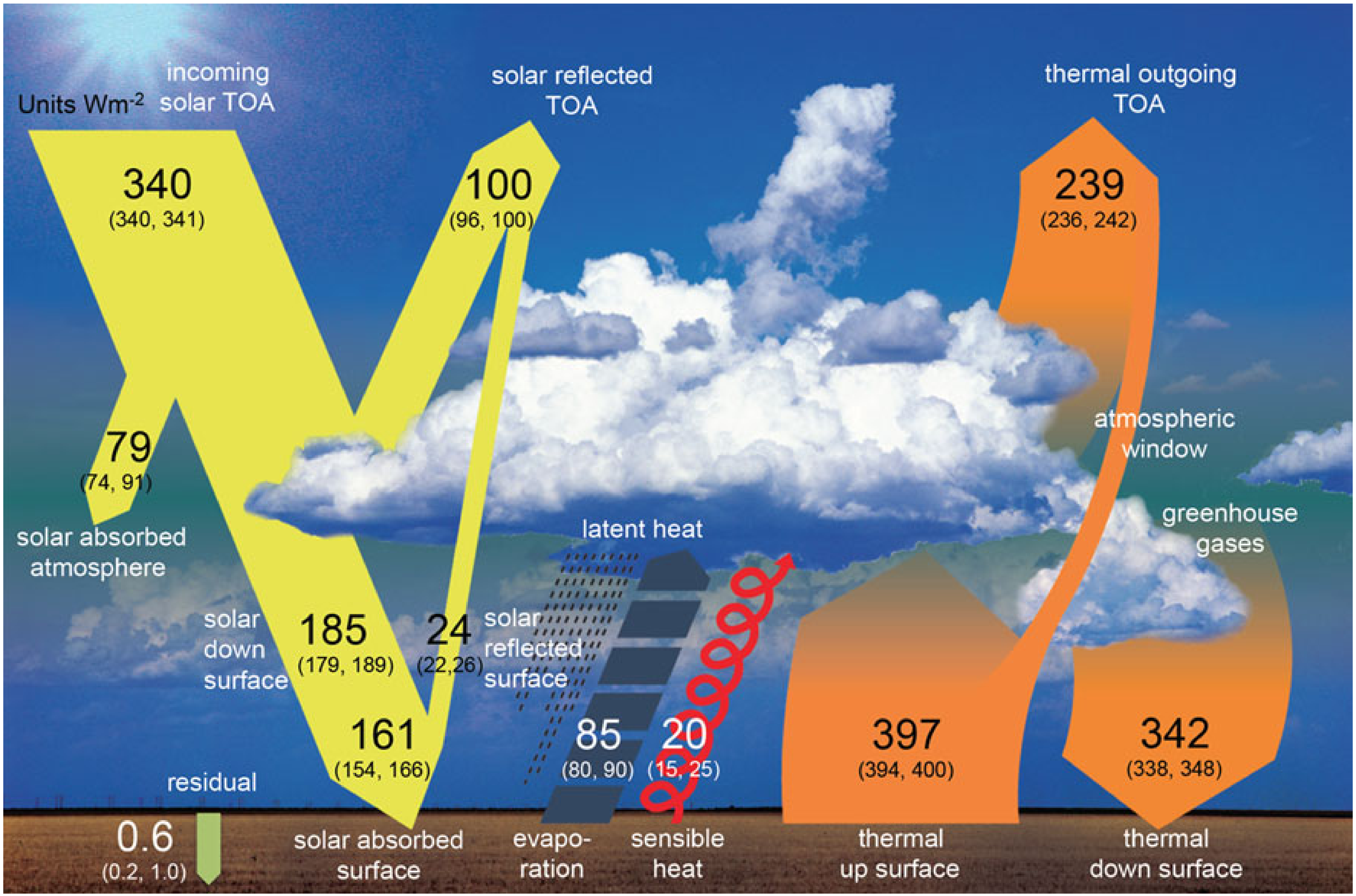
Maik Renner and Axel Kleidon
Max-Planck-Institut für Biogeochemie, Jena, Germany

26. October 2016
EGU-Leonardo conference on the hydrological cycle, Ourense

catchments as organised systems

DFG Deutsche Forschungsgemeinschaft

Water cycle ~ radiation and convection



Wild et al 2013, Clim. Dyn

Systems' perspective on earth

natural system
processes
interacting at
multiple time scales

Global climate model
dynamic state
equations
sub-grid
parameterisations

Systems' perspective on earth

natural system
processes
interacting at
multiple time scales

Global climate model
dynamic state
equations
sub-grid
parameterisations

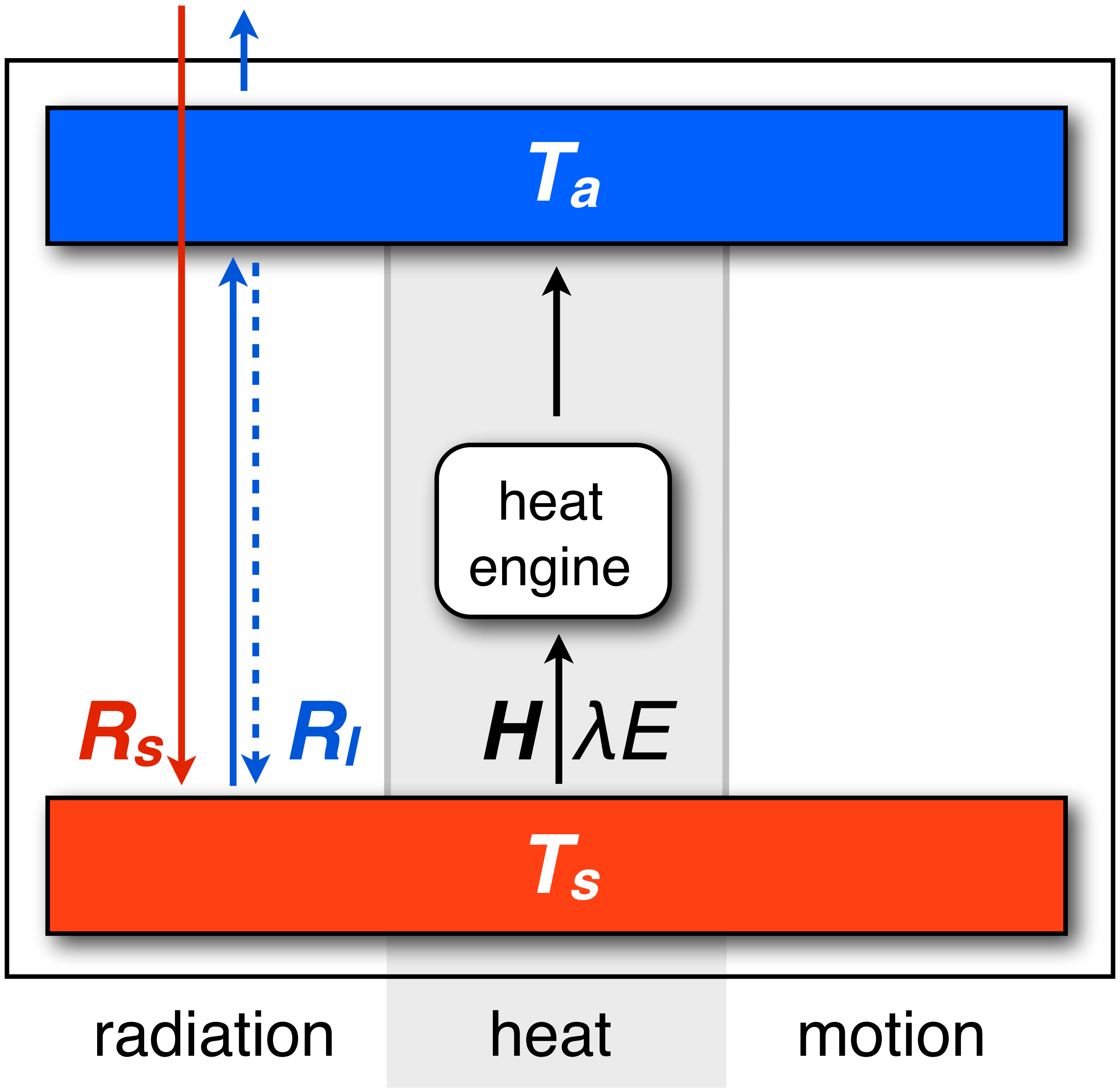
Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away.

Antoine de Saint-Exupery

Can we formulate a simple earth system model which captures the most important (thermo)dynamics to predict the response to radiative changes?

A simple climate model

energy balances as starting points



energy balances:

$$R_s - R_l - H - \lambda E = 0$$

$$R_s - \sigma T_a^4 = 0$$

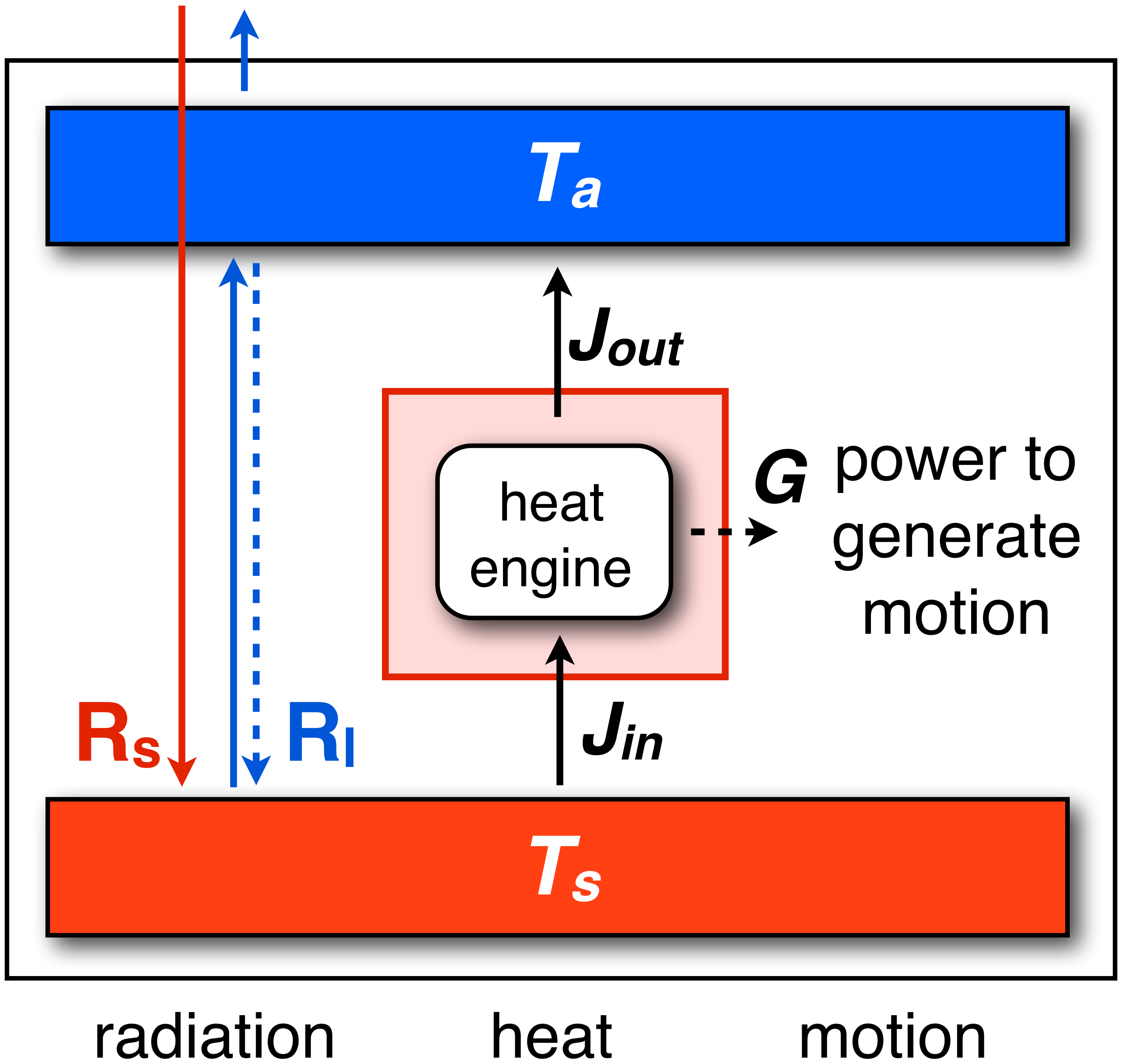
R_s:	absorbed solar radiation
R_l:	net emission of terrestrial radiation
H:	sensible heat flux
λE:	latent heat flux

given: absorbed solar radiation R_s (= 240 W m^{-2}) and surface temperature T_s (= 288 K)

unknown: partitioning between R_l and $H + \lambda E$?

Atmospheric heat engine

thermodynamic limit on convective motion



first law: energy budget

$$0 = J_{in} - J_{out} - G$$

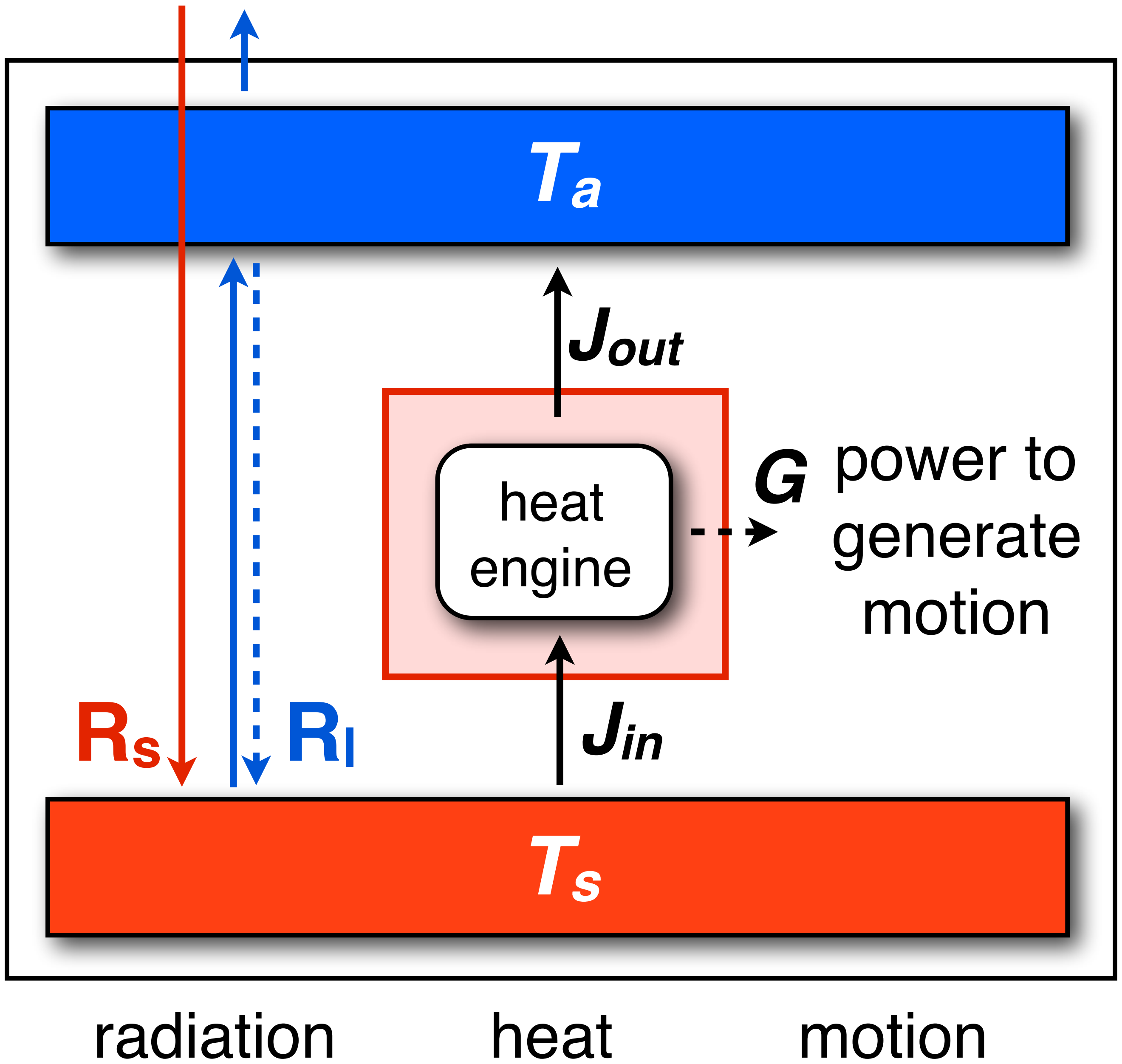
second law: entropy budget

$$\frac{J_{out}}{T_a} - \frac{J_{in}}{T_s} \geq 0$$

best case: $J_{out} = J_{in} \frac{T_a}{T_s}$

Atmospheric heat engine

thermodynamic limit on convective motion



first law: energy budget

$$0 = J_{in} - J_{out} - G$$

second law: entropy budget

$$\frac{J_{out}}{T_a} - \frac{J_{in}}{T_s} \geq 0$$

best case: $$J_{out} = J_{in} \frac{T_a}{T_s}$$

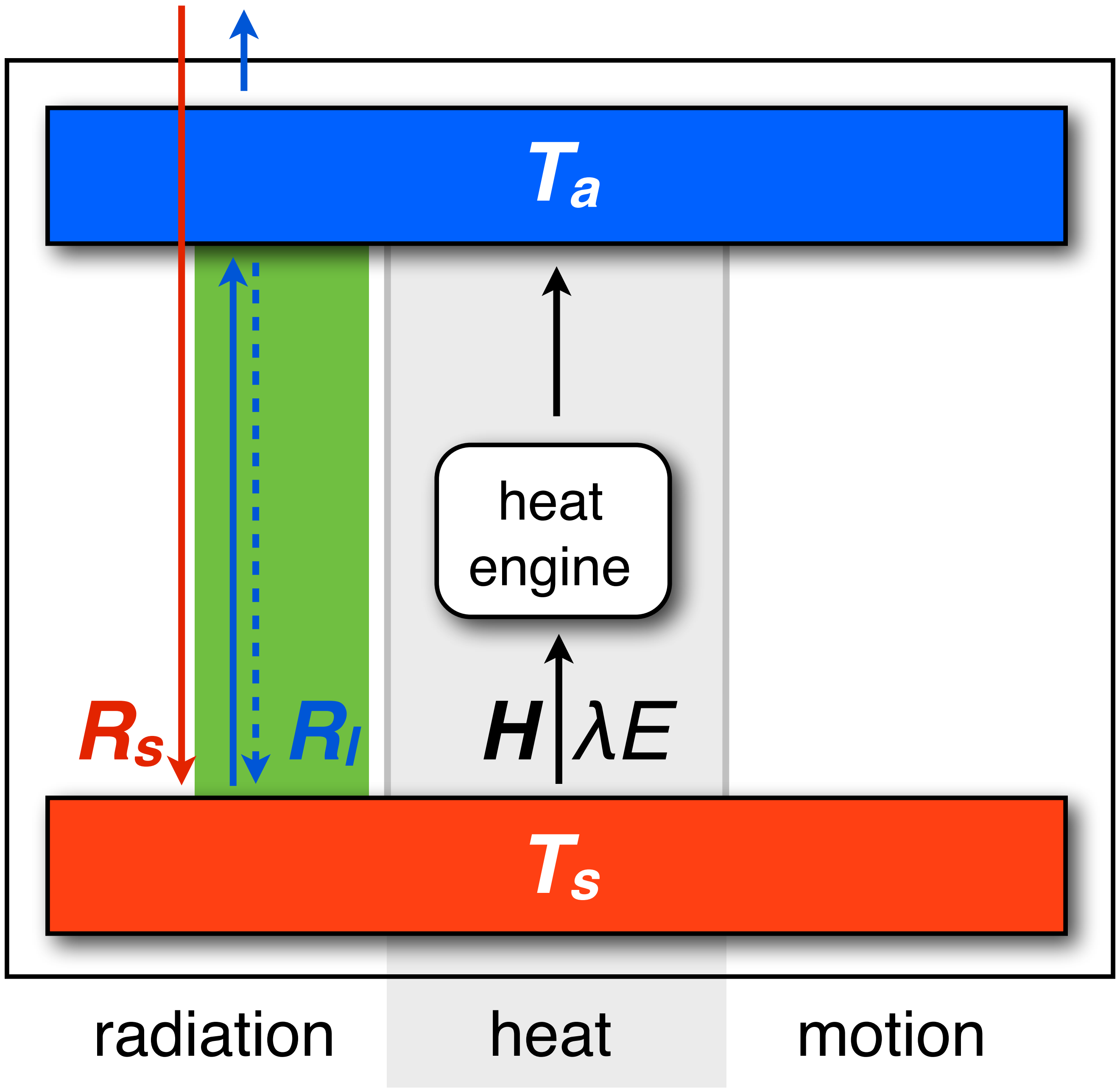
"Carnot" limit for *G*:

$$G = J_{in} \frac{T_s - T_a}{T_s}$$

Kleidon and Renner (2013) *Hydrol. Earth Syst. Sci.*

A simple climate model

exchange of terrestrial radiation



assume **blackbody emission** for surface and atmosphere:

$$R_{l,s} = \sigma T_s^4$$

$$R_{l,a} = \sigma T_a^4$$

linearize emission:

$$\sigma T^4 \approx R_0 + k_r (T - T_0)$$

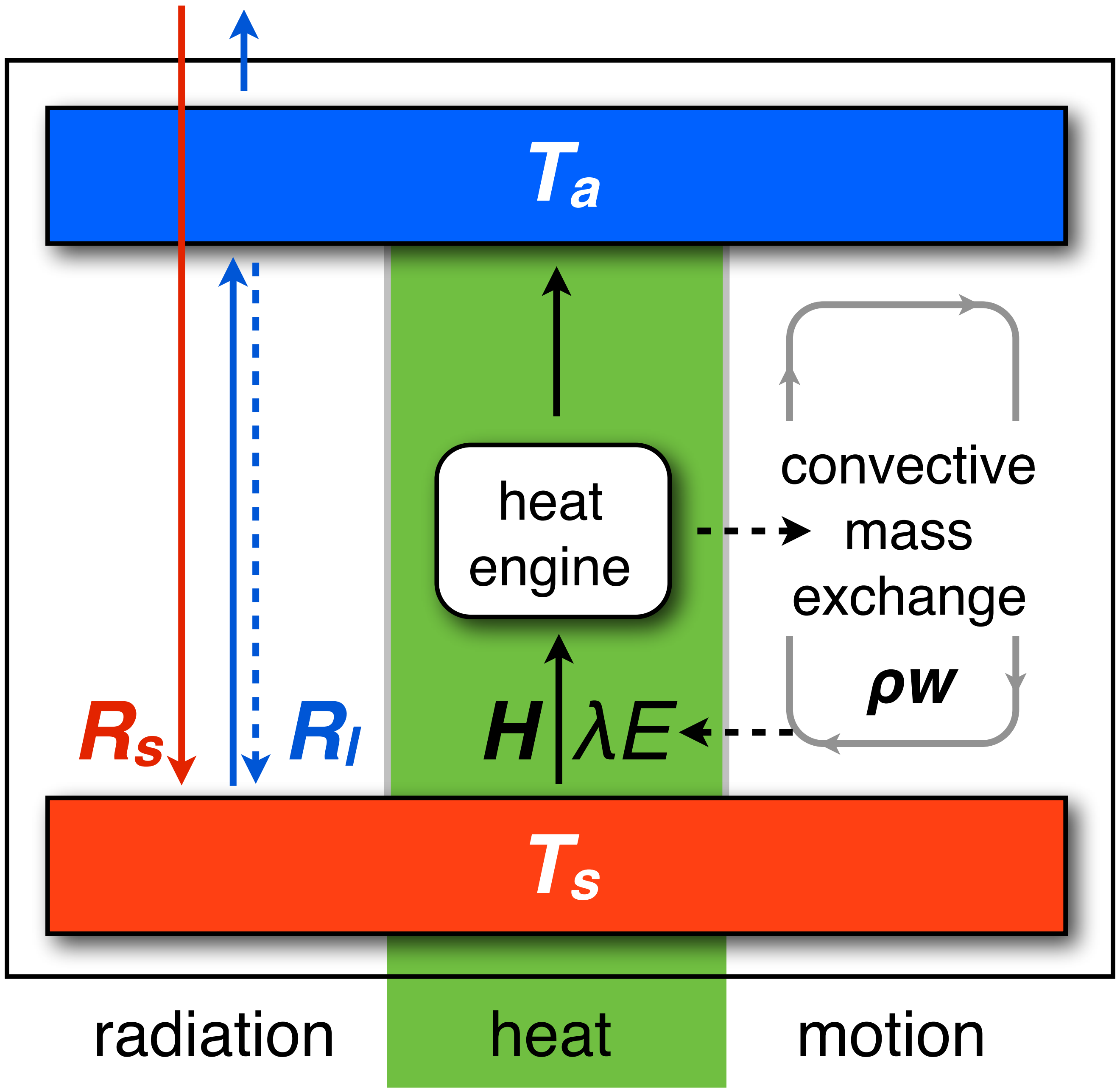
results in simple expression for **net longwave radiative exchange**:

$$R_l = R_{l,s} - R_{l,a}$$
$$= k_r (T_s - T_a)$$

Kleidon and Renner (2013) *Hydrol. Earth Syst. Sci.*

A simple climate model

parameterization of heat fluxes



convective heat fluxes depend on a rate of **mass exchange**, *ρw*:

$$H = c_p \rho w (T_s - T_a)$$

$$\lambda E = \lambda \rho w (q_s - q_a)$$

assume **saturation** for surface and atmosphere and **linearize** saturation vapor pressure curve with slope *s*

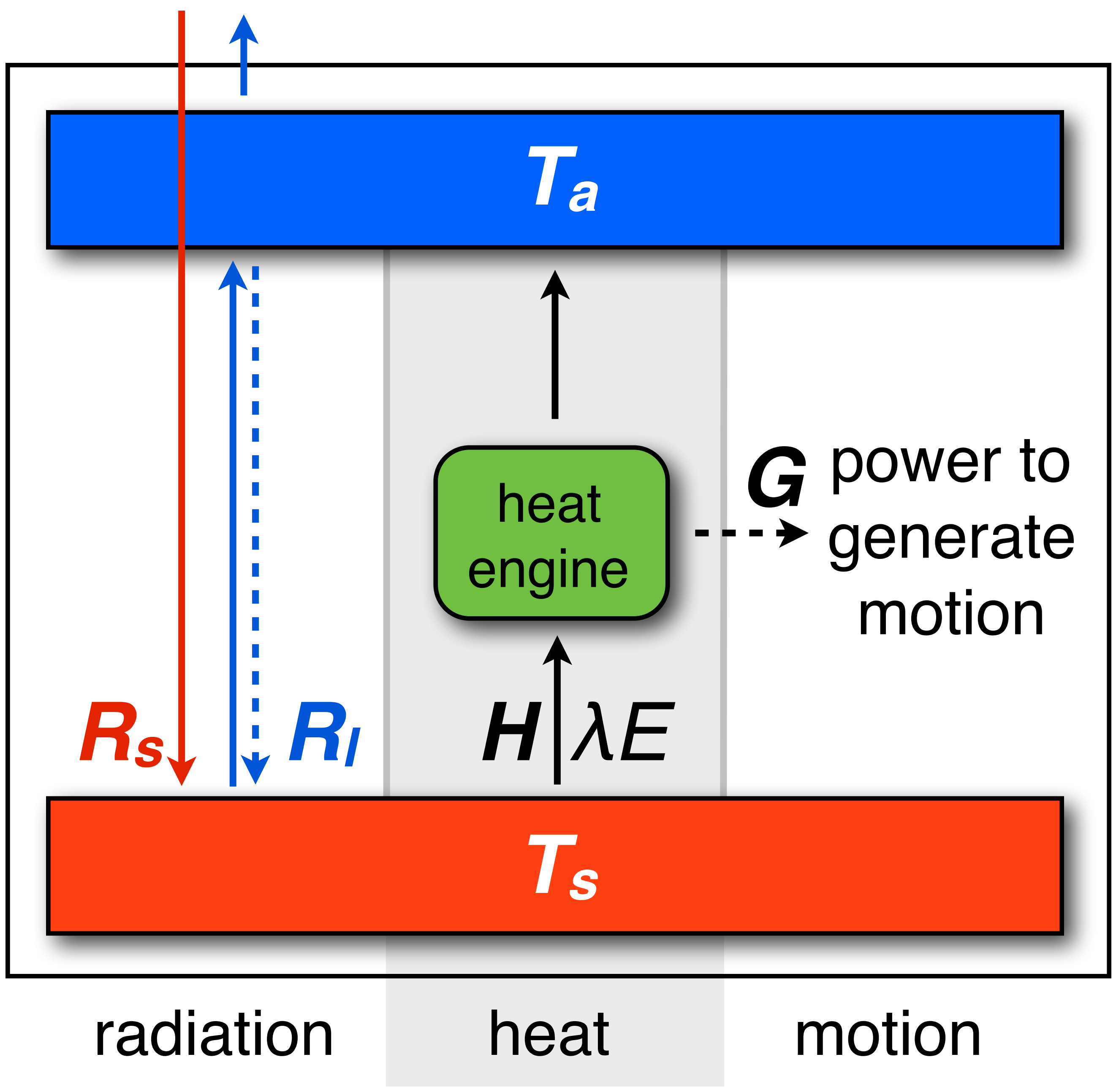
$$\lambda E = c_p \rho w \frac{s}{\gamma} (T_s - T_a)$$

$$\lambda E = \frac{s}{\gamma} H$$

γ: psychrometric constant

Kleidon and Renner (2013) *Hydrol. Earth Syst. Sci.*

Carnot limit for generating convection



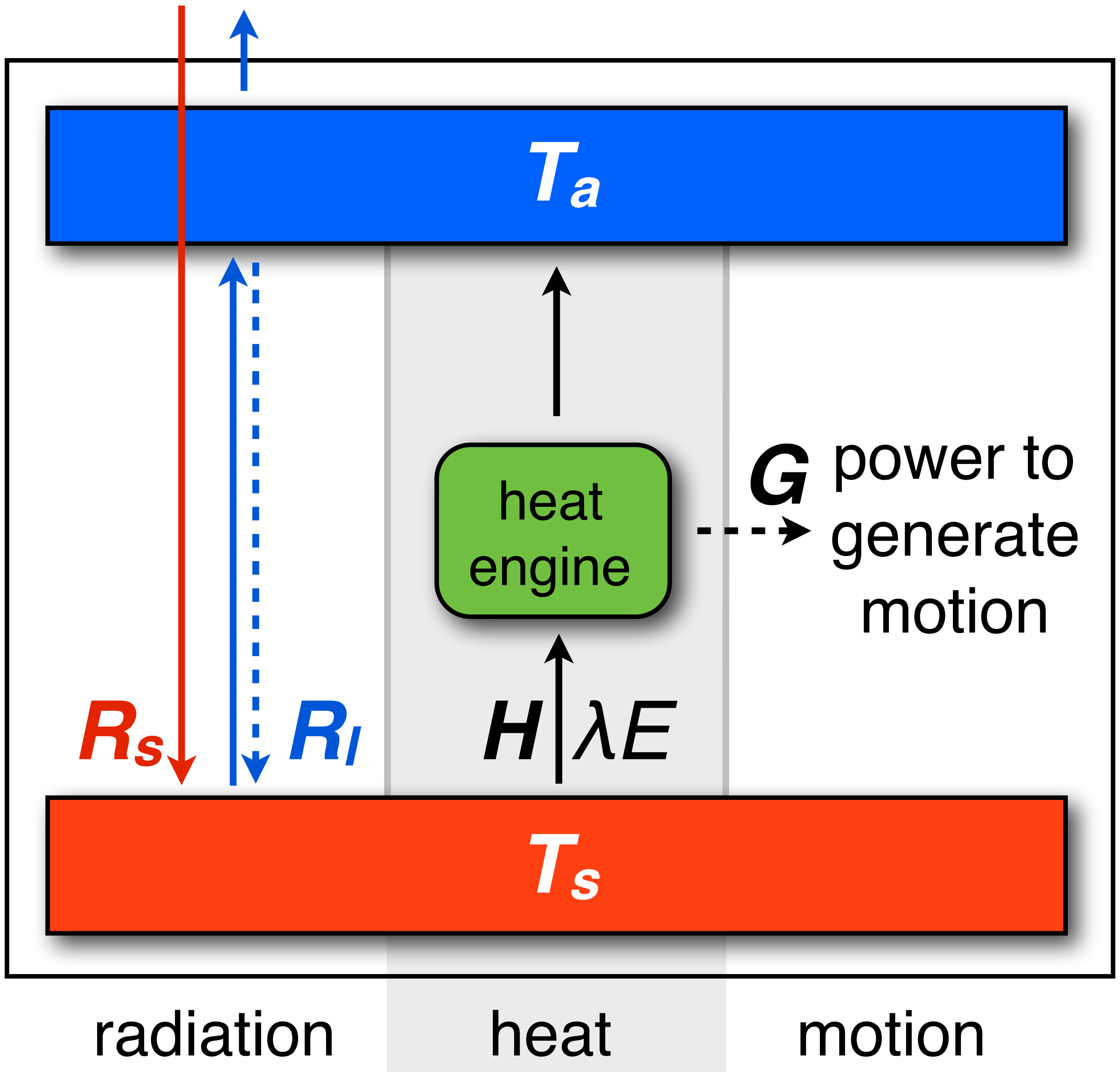
"Carnot" limit for G:

$$G = H \cdot \frac{T_s - T_a}{T_s}$$

use **surface energy balance** to express ΔT:

$$T_s - T_a = \frac{R_s - H - \lambda E}{k_r}$$

Carnot limit for generating convection



"Carnot" limit for *G*:

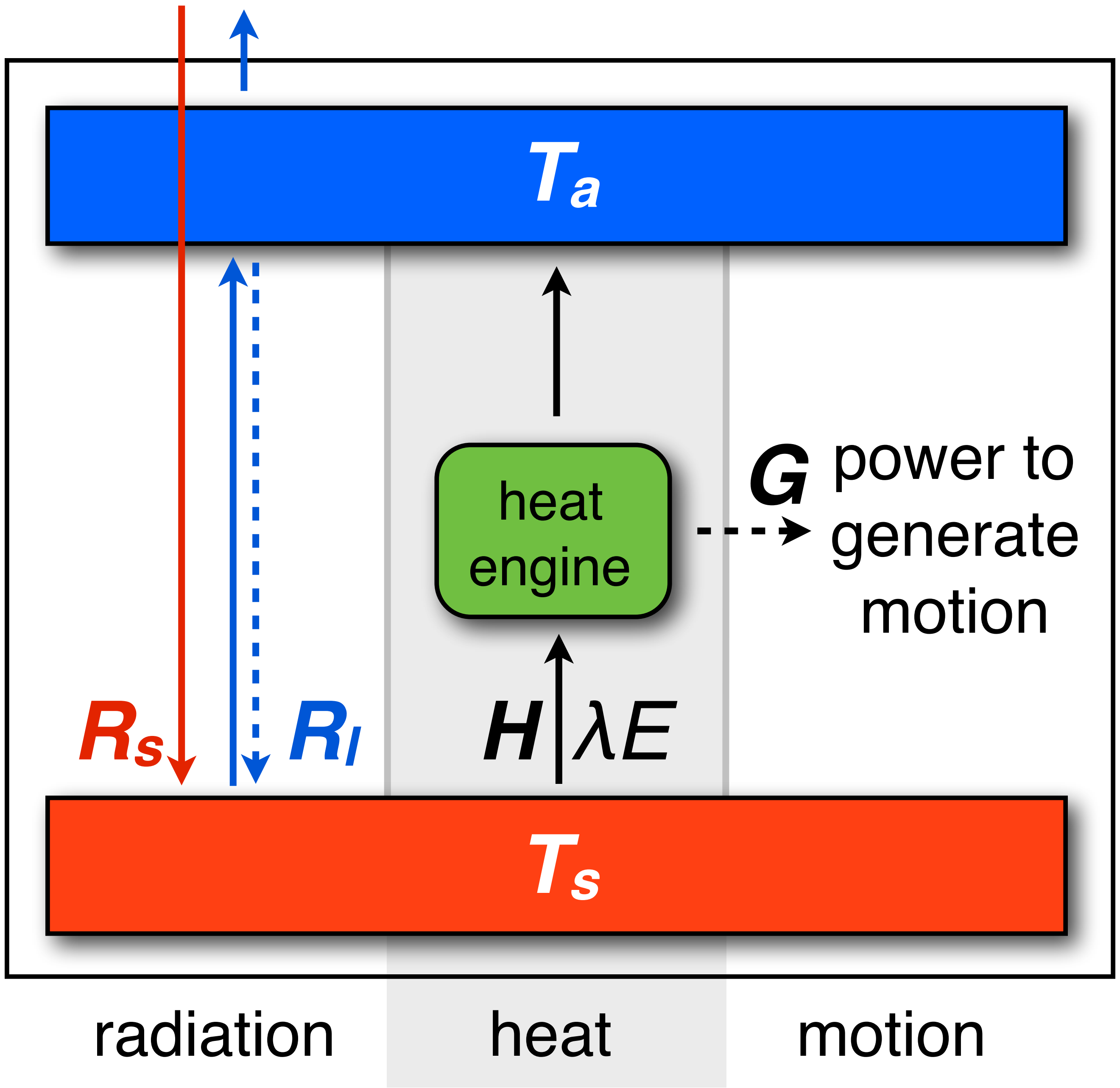
$$G = H \cdot \frac{T_s - T_a}{T_s}$$

use **surface energy balance** to express ΔT:

$$T_s - T_a = \frac{R_s - H - \lambda E}{k_r}$$

maximize power *G*:

Carnot limit for generating convection



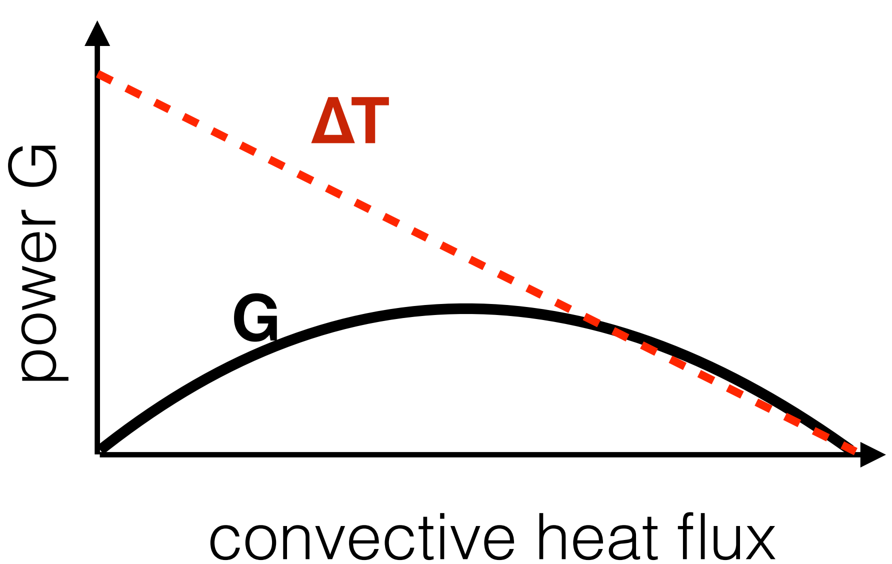
"Carnot" limit for *G*:

$$G = H \cdot \frac{T_s - T_a}{T_s}$$

use **surface energy balance** to express Δ*T*:

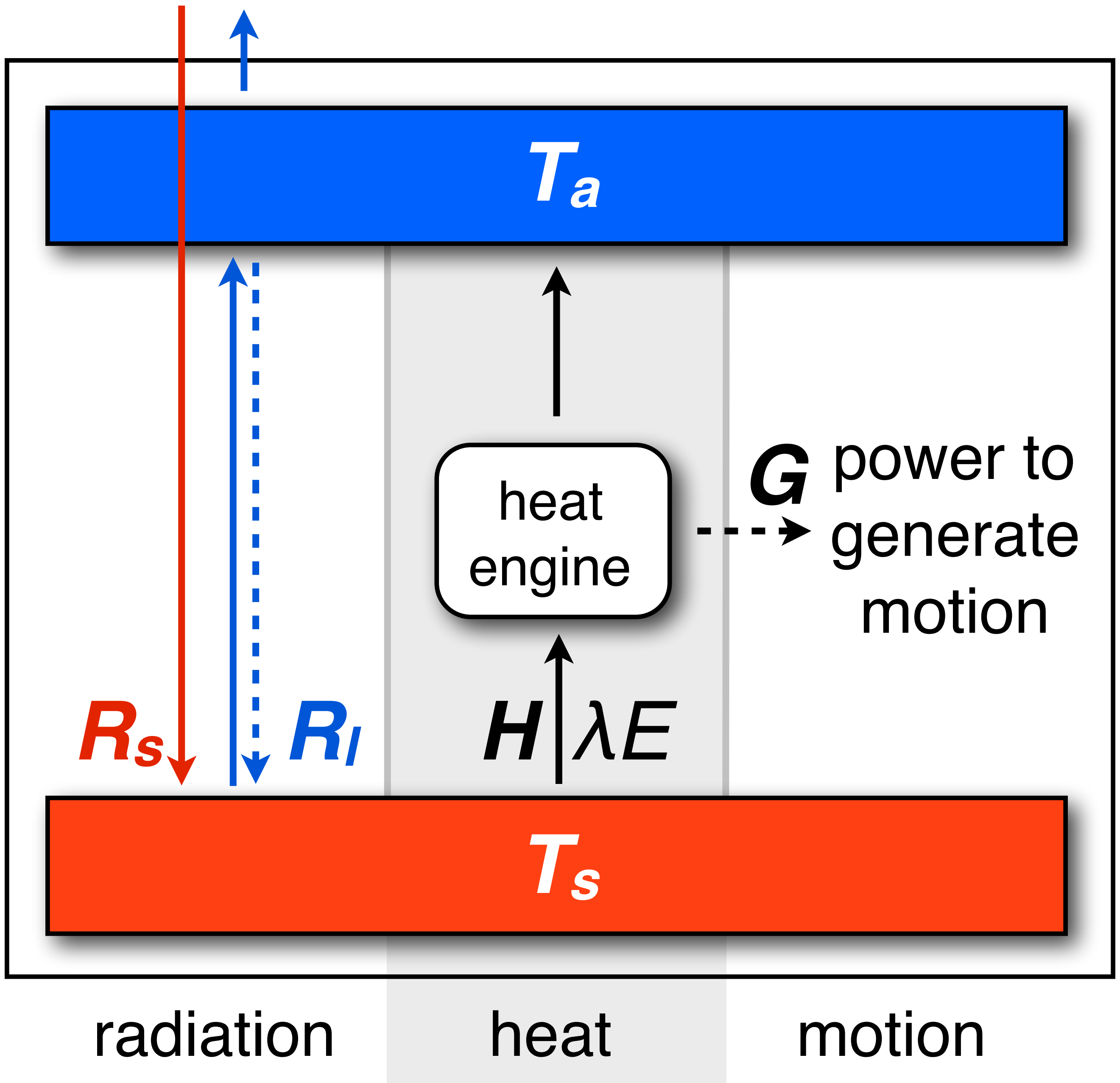
$$T_s - T_a = \frac{R_s - H - \lambda E}{k_r}$$

maximize power *G*:



A simple climate model

flux partitioning at maximum convective power



max. power limit predicts **equal partitioning** among radiative and turbulent fluxes:

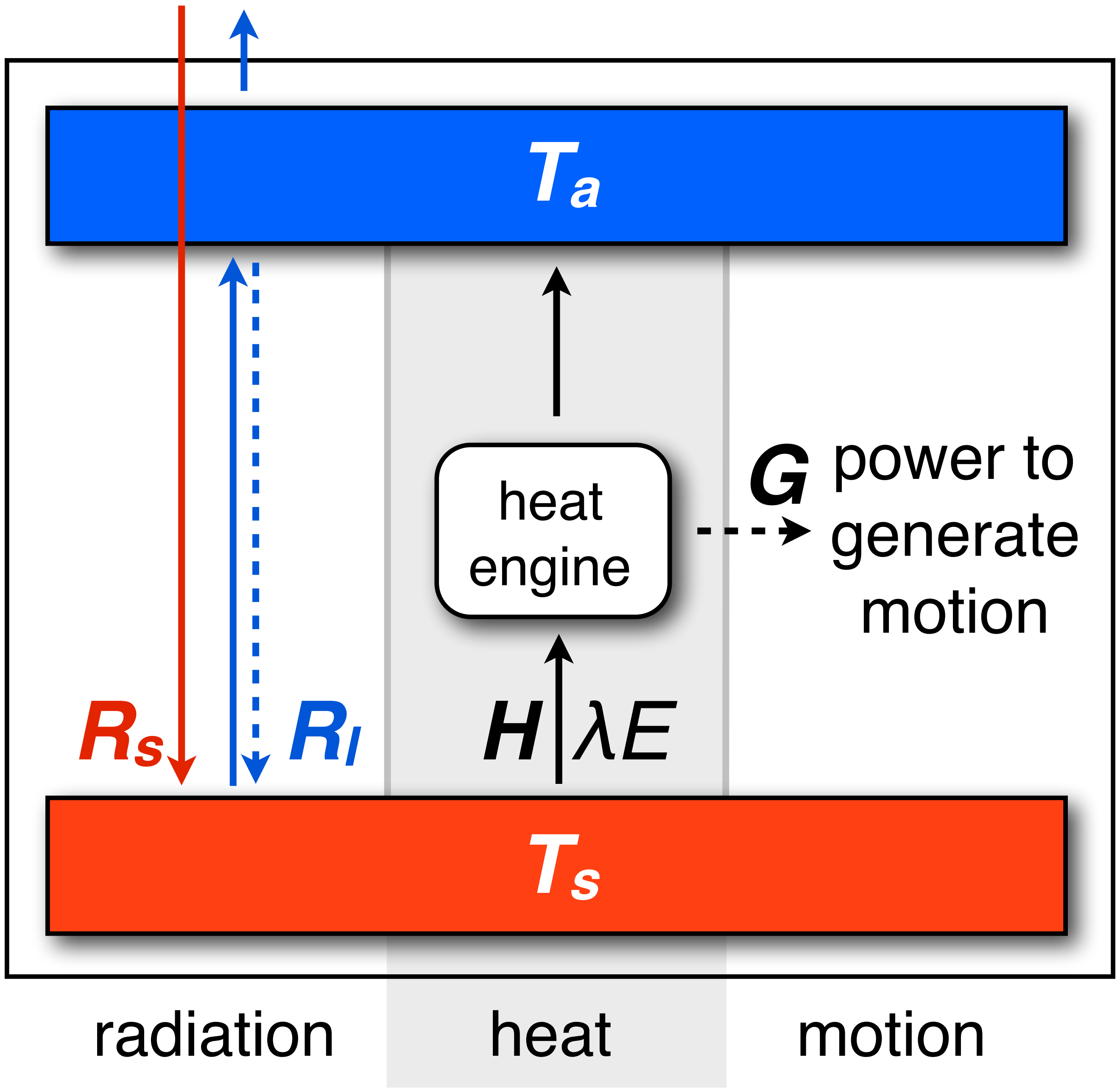
$$R_{l,opt} = \frac{R_s}{2}$$

$$H = \frac{\gamma}{s+\gamma}\frac{R_s}{2}$$

$$\lambda E = \frac{s}{s+\gamma}\frac{R_s}{2}$$

A simple climate model

flux partitioning at maximum convective power



max. power limit predicts **equal partitioning** among radiative and turbulent fluxes:

$$R_{l,opt} = \frac{R_s}{2}$$

$$H = \frac{\gamma}{s+\gamma} \frac{R_s}{2}$$

$$\lambda E = \frac{s}{s+\gamma} \frac{R_s}{2}$$

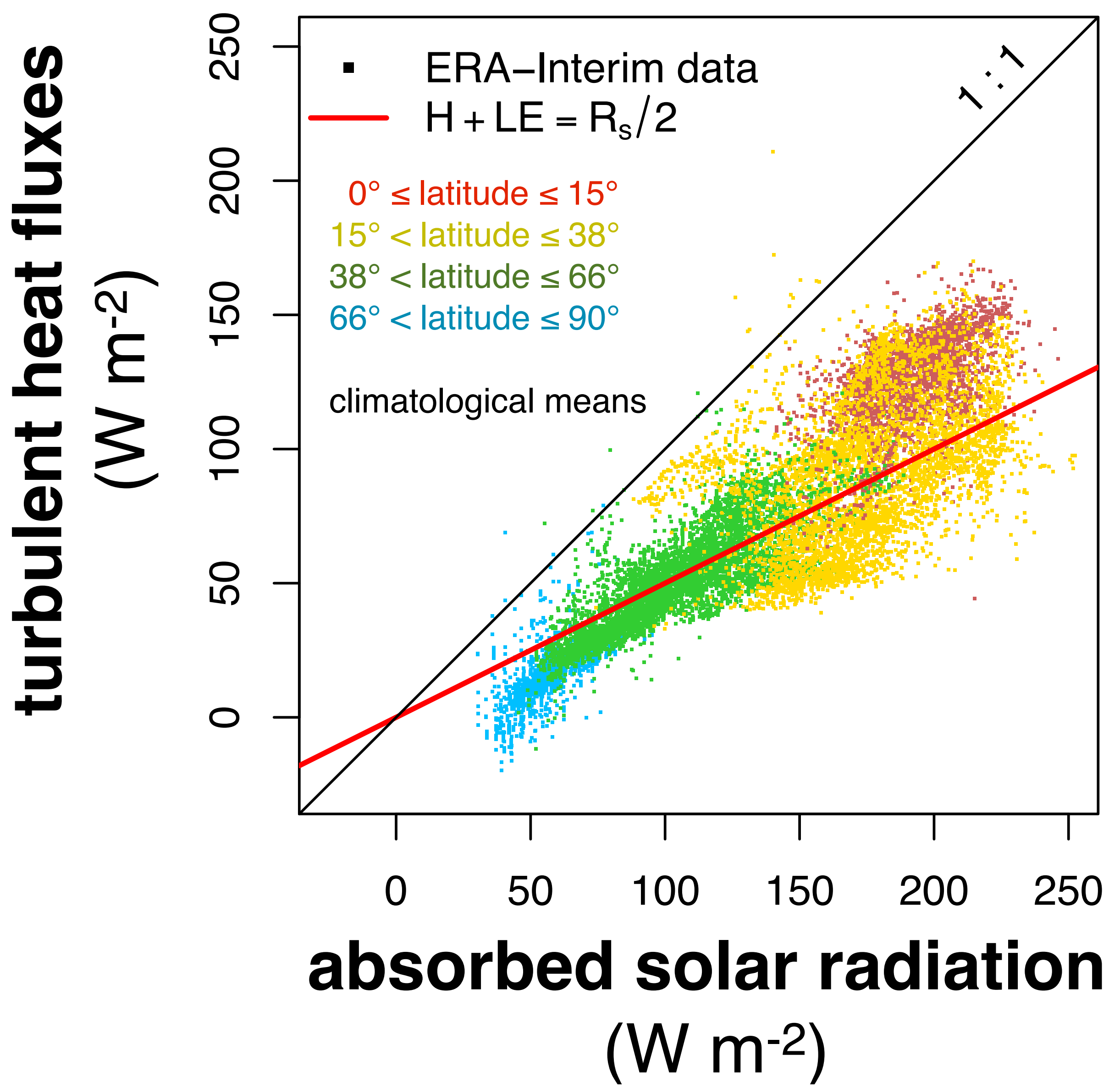
consistent with "equilibrium evaporation" rate of Schmidt (1909) and Slayter & McIlroy (1961), Priestley and Taylor (1971)

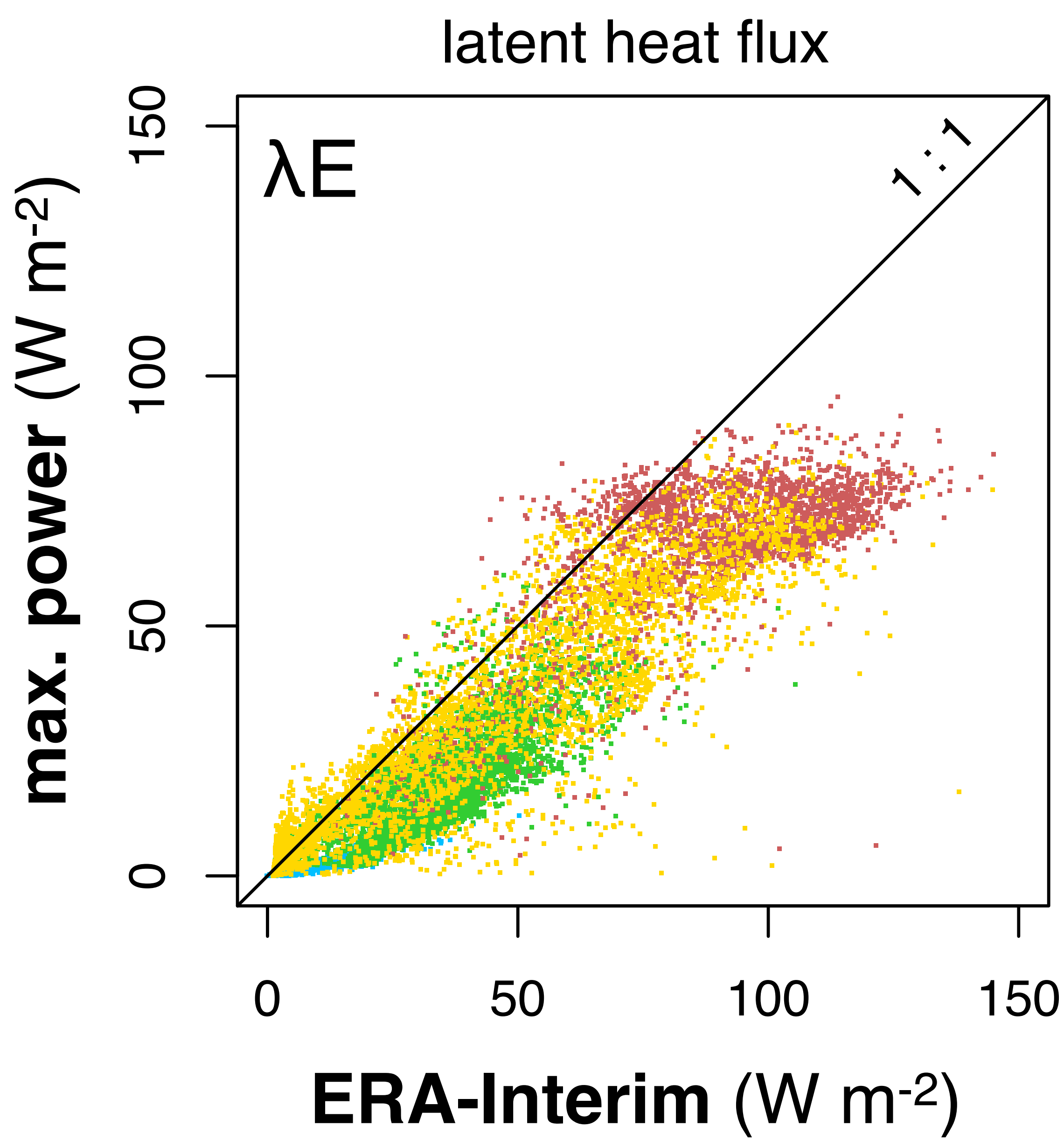
Kleidon and Renner (2013) *Hydrol. Earth Syst. Sci.*

A simple climate model

surface energy partitioning on land

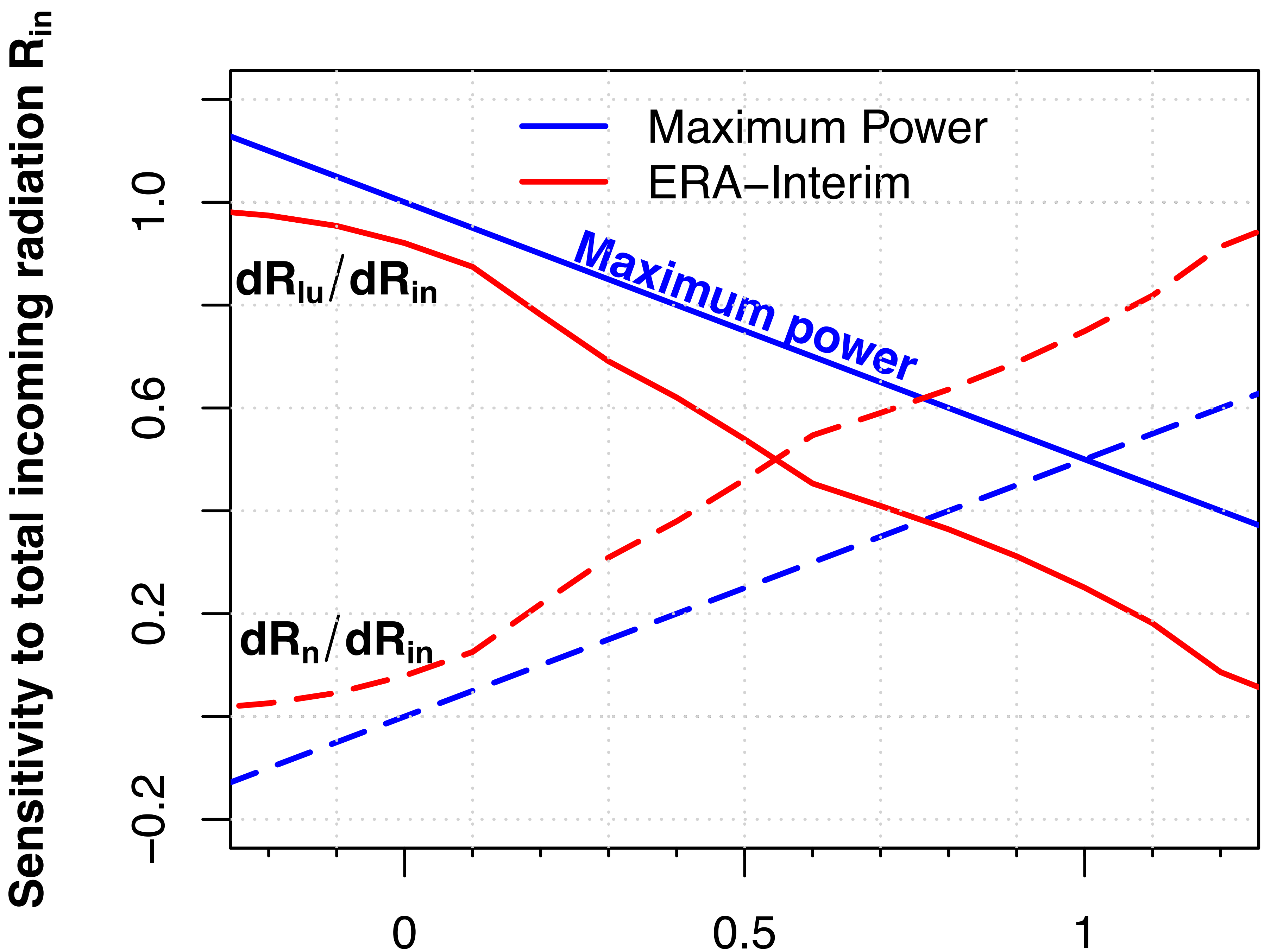
(with added water balance constraint)





Kleidon, Renner, Porada (2014) *Hydrol. Earth Syst. Sci.*

Sensitivity to type of radiative forcing



longwave change dominates

shortwave change dominates

$$
\begin{aligned}
R_{ln} &= R_{sn}/2 \\
&= R_{lu}(T_s) - R_{ld} \\
\partial R_{lu}/\partial R_{ld} &= 1 \\
\partial R_{lu}/\partial R_{sn} &= 1/2
\end{aligned}
$$

Renner, Dhara and Kleidon, in prep.

Hydrologic Cycling and Surface Warming

Evaporation rate: $$\lambda E_{opt} = \frac{s}{\gamma + s}\frac{R_s}{2}$$

Kleidon and Renner (2013) *ESD*
Kleidon, Kravitz, Renner (2015) *GRL*

Hydrologic Cycling and Surface Warming

Evaporation rate:

$$\lambda E_{opt} = \frac{s}{\gamma + s} \frac{R_s}{2}$$

Relative sensitivity:

$$\frac{1}{E}\Delta E = \frac{1}{E}\frac{\partial E}{\partial s}\frac{ds}{dT_s}\Delta T_s + \frac{1}{E}\frac{\partial E}{\partial R_s}\Delta R_s$$

Kleidon and Renner (2013) *ESD*
Kleidon, Kravitz, Renner (2015) *GRL*

Hydrologic Cycling and Surface Warming

Evaporation rate: $$\lambda E_{opt} = \frac{s}{\gamma + s} \frac{R_s}{2}$$

Relative sensitivity: $$\frac{1}{E} \Delta E = \frac{1}{E} \frac{\partial E}{\partial s} \frac{ds}{dT_s} \Delta T_s + \frac{1}{E} \frac{\partial E}{\partial R_s} \Delta R_s$$

≈ 2.2 % K^{-1} ≈ 1 % K^{-1}

greenhouse-induced warming: 2.2 % K^{-1}

solar-induced warming: 3.2 % K^{-1}

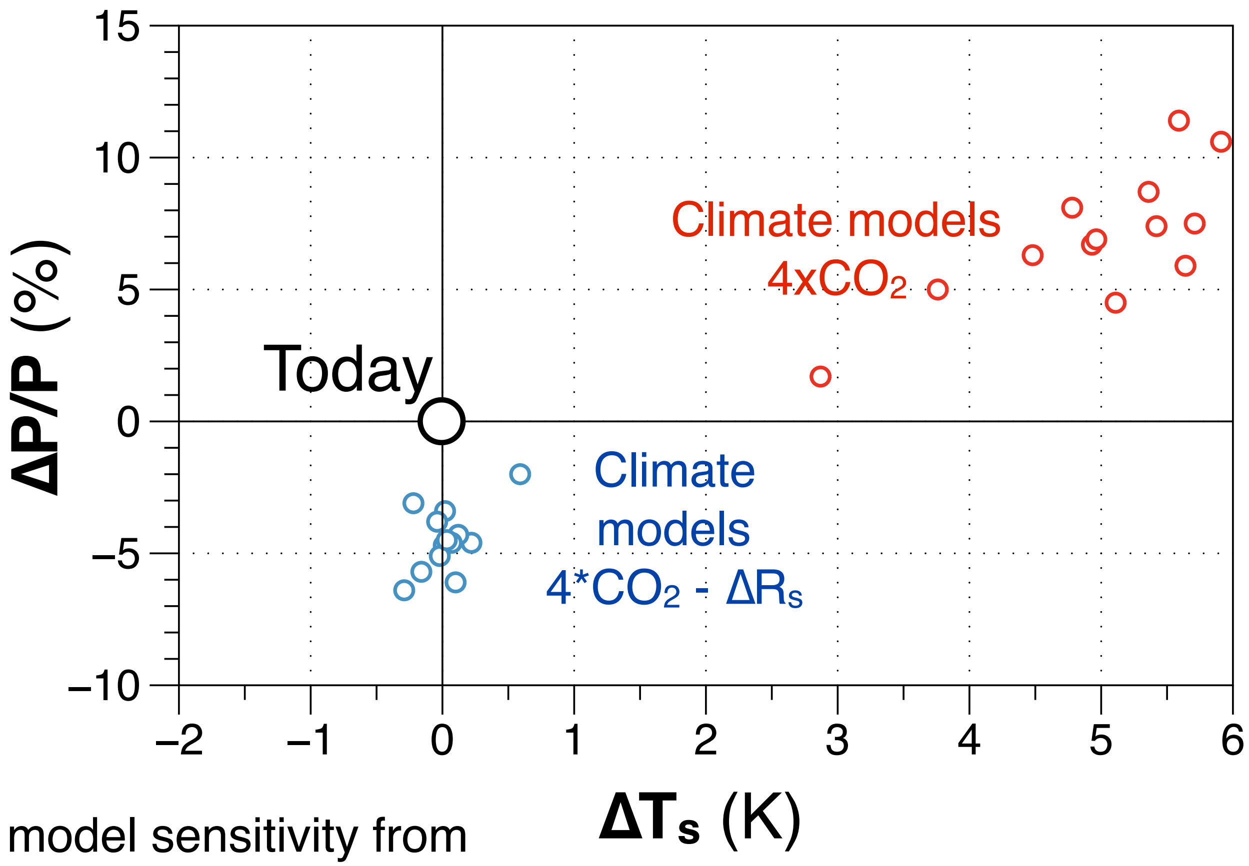
Kleidon and Renner (2013) *ESD*
Kleidon, Kravitz, Renner (2015) *GRL*

Hydrologic Cycling and Surface Warming

Evaporation rate: $$\lambda E_{opt} = \frac{s}{\gamma + s} \frac{R_s}{2}$$

Relative sensitivity: $$\frac{1}{E} \Delta E = \frac{1}{E} \frac{\partial E}{\partial s} \frac{ds}{dT_s} \Delta T_s + \frac{1}{E} \frac{\partial E}{\partial R_s} \Delta R_s$$

$\approx 2.2\ \%\ K^{-1}$ $\approx 1\ \%\ K^{-1}$



greenhouse-induced warming: $2.2\ \%\ K^{-1}$

solar-induced warming: $3.2\ \%\ K^{-1}$

model sensitivity from
Tilmes et al. (2013) *JGR*

Kleidon and Renner (2013) *ESD*
Kleidon, Kravitz, Renner (2015) *GRL*

Hydrologic Cycling and Surface Warming

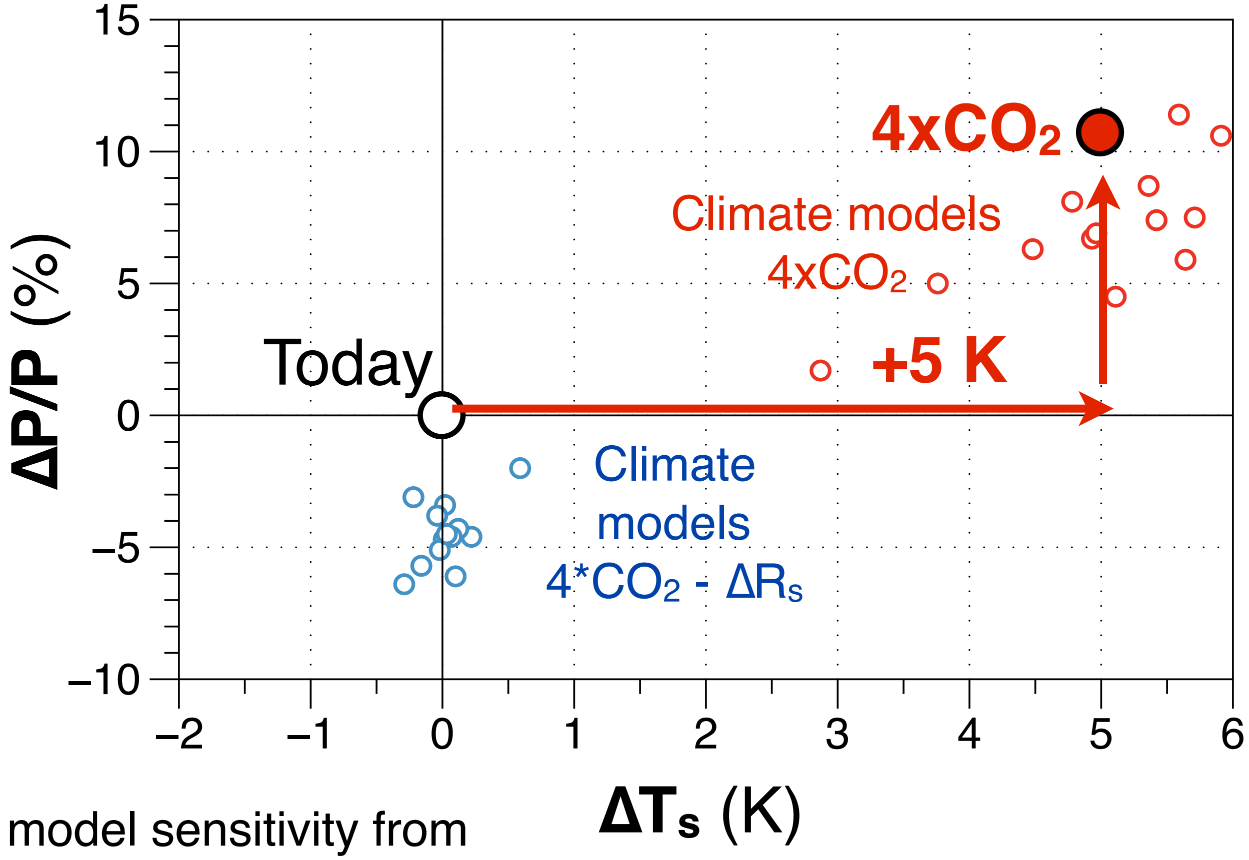
Evaporation rate: $$\lambda E_{opt} = \frac{s}{\gamma + s} \frac{R_s}{2}$$

Relative sensitivity: $$\frac{1}{E}\Delta E = \frac{1}{E}\frac{\partial E}{\partial s}\frac{ds}{dT_s}\Delta T_s + \frac{1}{E}\frac{\partial E}{\partial R_s}\Delta R_s$$

$\approx 2.2~\%~K^{-1}$ $\approx 1~\%~K^{-1}$

greenhouse-induced warming: 2.2 % K^{-1}

solar-induced warming: 3.2 % K^{-1}



model sensitivity from Tilmes et al. (2013) *JGR*

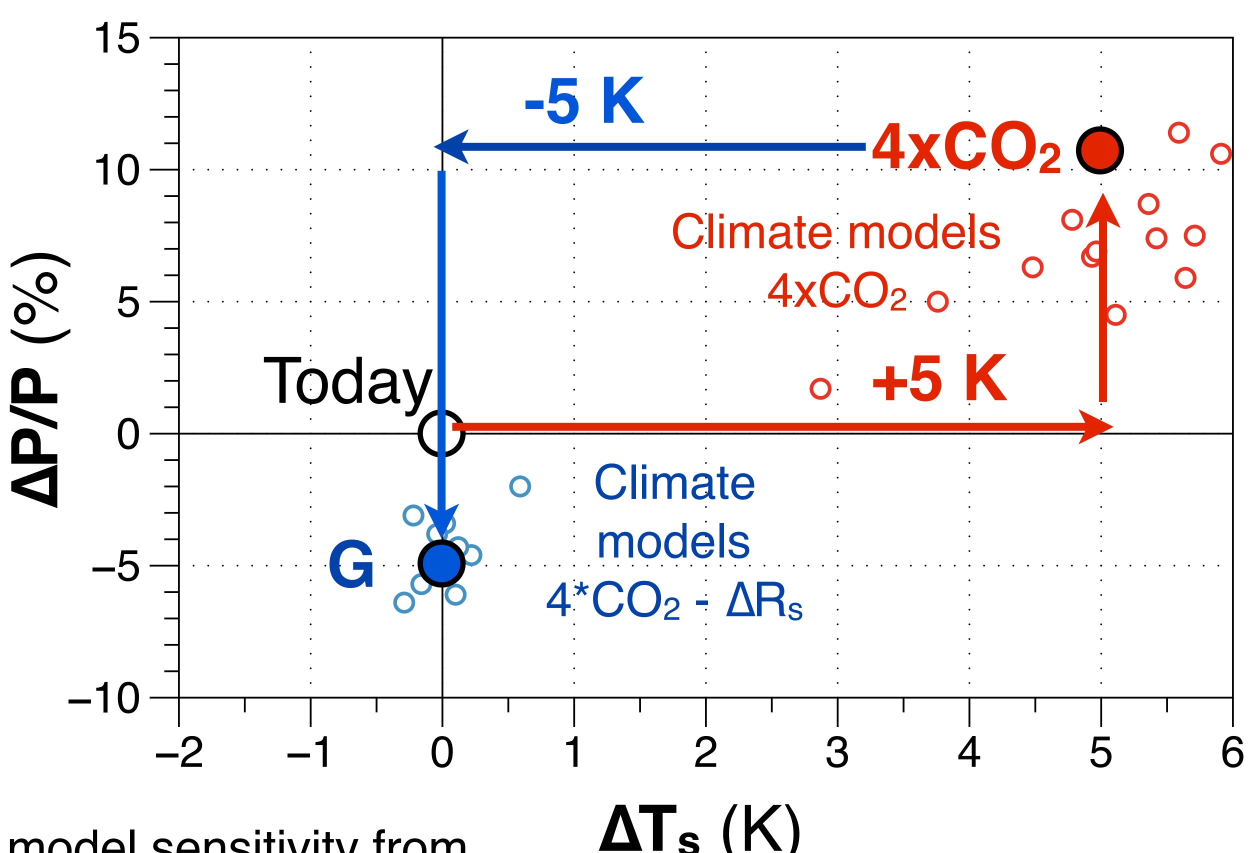
Kleidon and Renner (2013) *ESD*
Kleidon, Kravitz, Renner (2015) *GRL*

Hydrologic Cycling and Surface Warming

Evaporation rate: $$\lambda E_{opt} = \frac{s}{\gamma + s} \frac{R_s}{2}$$

Relative sensitivity: $$\frac{1}{E}\Delta E = \frac{1}{E}\frac{\partial E}{\partial s}\frac{ds}{dT_s}\Delta T_s + \frac{1}{E}\frac{\partial E}{\partial R_s}\Delta R_s$$

≈ 2.2 % K^{-1} ≈ 1 % K^{-1}



model sensitivity from Tilmes et al. (2013) *JGR*

greenhouse-induced warming: 2.2 % K^{-1}

solar-induced warming: 3.2 % K^{-1}

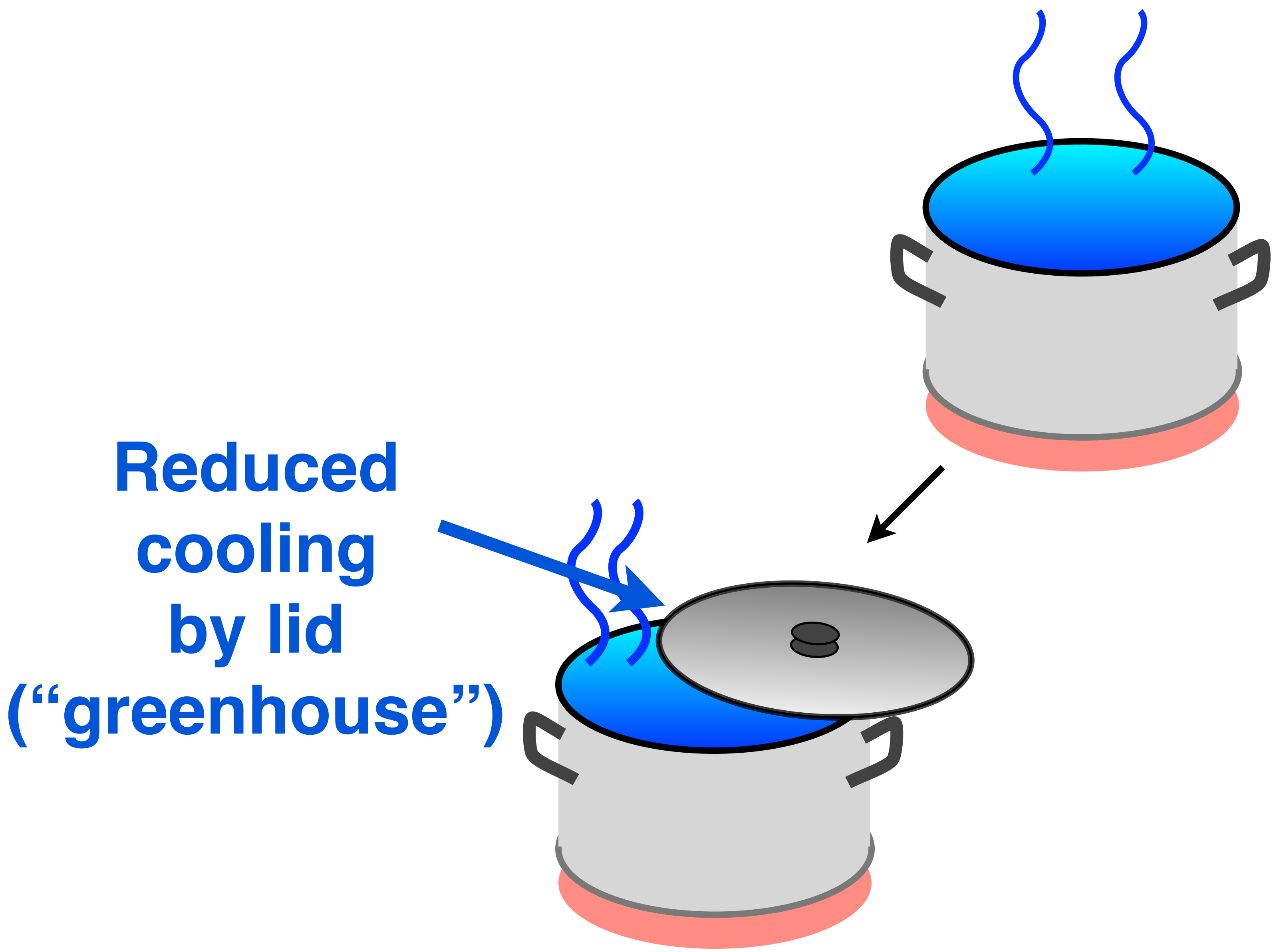
Kleidon and Renner (2013) *ESD*
Kleidon, Kravitz, Renner (2015) *GRL*

Hydrologic Cycling and Surface Warming

Analogy: Increasing the temperature of a pot on a stove

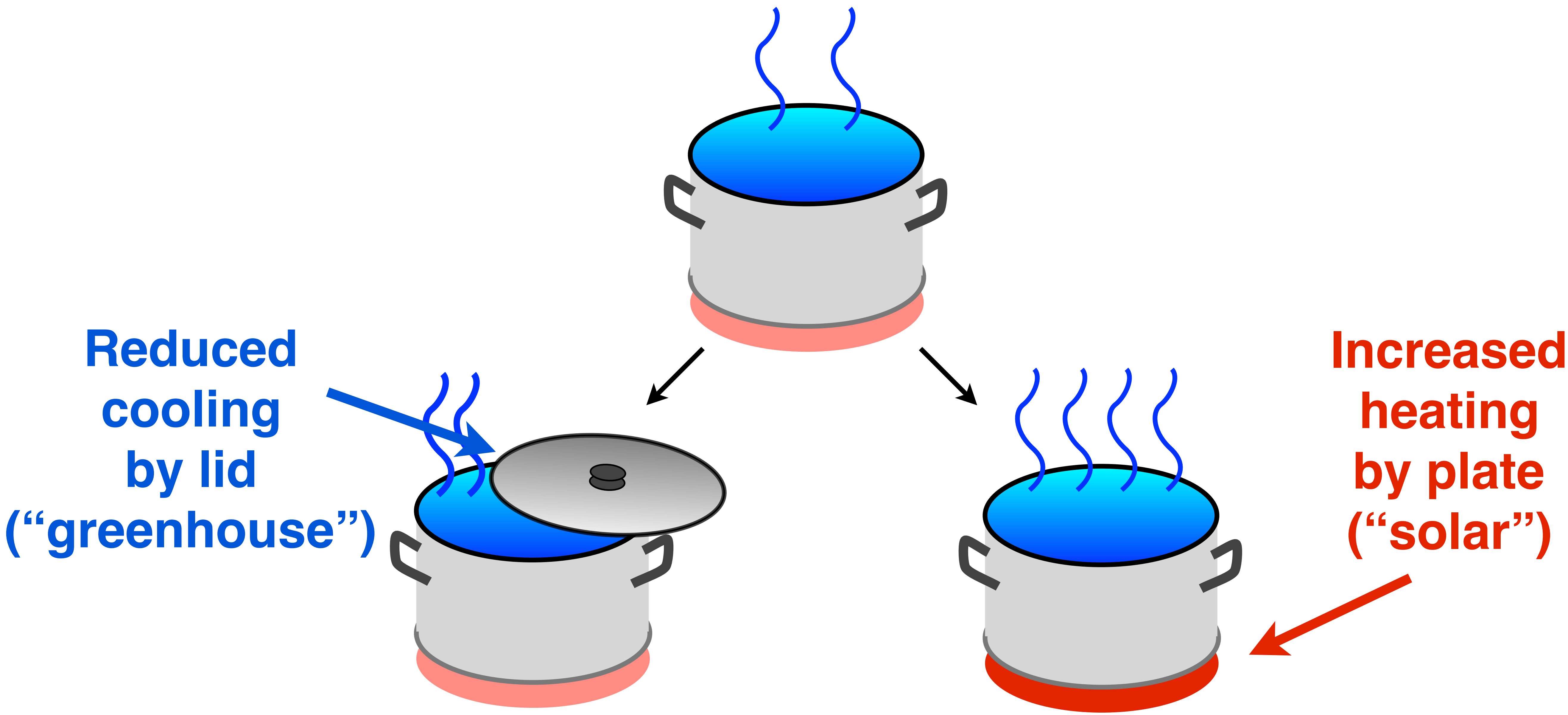
Hydrologic Cycling and Surface Warming

Analogy: Increasing the temperature of a pot on a stove



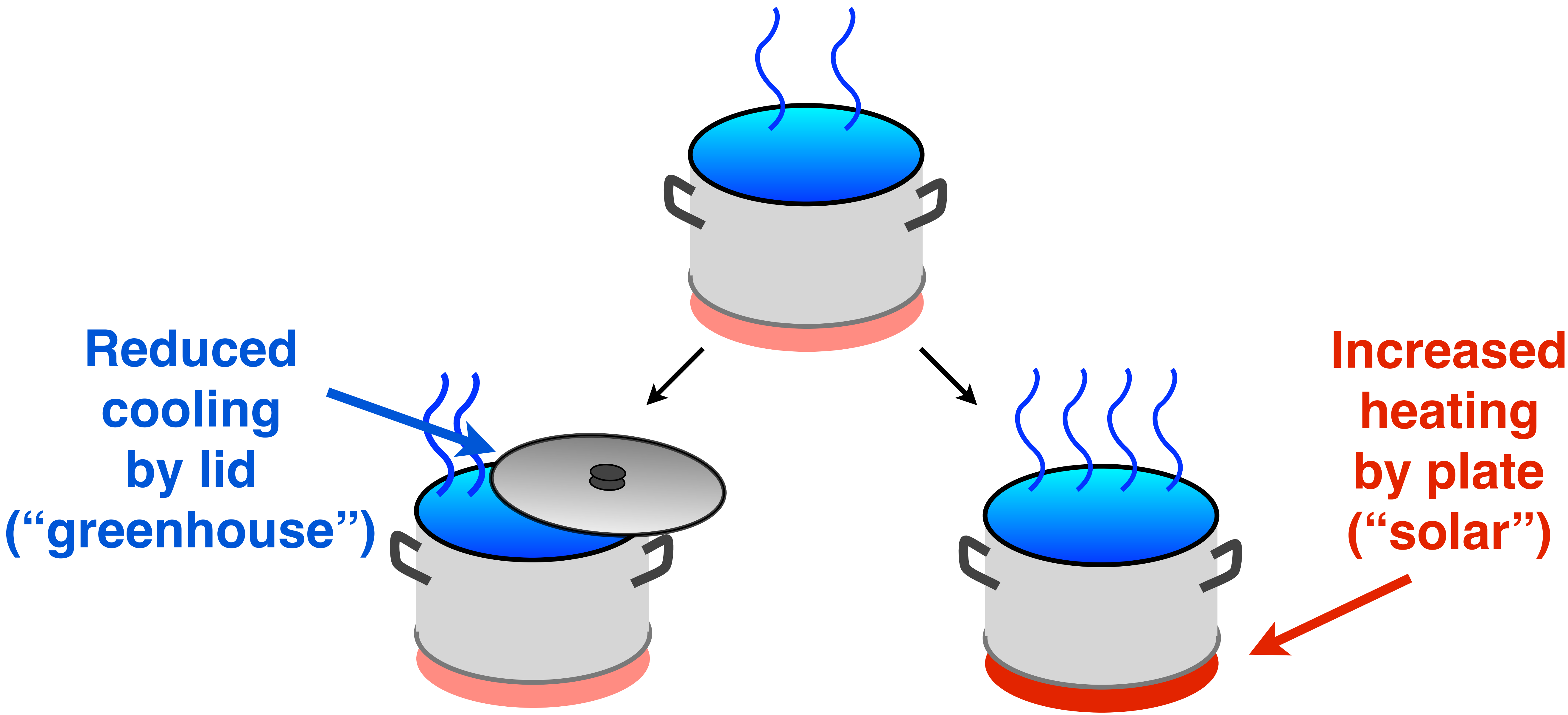
Hydrologic Cycling and Surface Warming

Analogy: Increasing the temperature of a pot on a stove



Hydrologic Cycling and Surface Warming

Analogy: Increasing the temperature of a pot on a stove



Solar geoengineering:
Compensate temperature increase by lid by reducing the heating

Summary and Conclusions

Earth systems' approach

- atmosphere as a heat engine
- trade-off between temperature gradient and the turbulent heat flux
- thermodynamic optimality - state of maximum power
- allows first order predictions on earth system

Conclusion:

- type of radiative change (SW <-> LW) is key to predict response of temperature and water cycle
- 2.2% / K increase of water cycle by greenhouse warming understood by saturation vapour pressure constrained by surface energy balance

References

Dhara, C., Renner, M., & Kleidon, A. (2016). Broad climatological variation of surface energy balance partitioning across land and ocean predicted from the maximum power limit. Geophysical Research Letters, 43(14), 2016GL070323. https://doi.org/10.1002/2016GL070323

Kleidon, A., Kravitz, B., & Renner, M. (2014). The hydrological sensitivity to global warming and solar geoengineering derived from thermodynamic constraints. Geophysical Research Letters, 2014GL062589. https://doi.org/10.1002/2014GL062589

Kleidon, A., & Renner, M. (2013a). A simple explanation for the sensitivity of the hydrologic cycle to surface temperature and solar radiation and its implications for global climate change. Earth System Dynamics, 4(2), 455–465. https://doi.org/10.5194/esd-4-455-2013

Kleidon, A., & Renner, M. (2013b). Thermodynamic limits of hydrologic cycling within the Earth system: concepts, estimates and implications. Hydrol. Earth Syst. Sci., 17(7), 2873–2892. https://doi.org/10.5194/hess-17-2873-2013

Kleidon, A., Renner, M., & Porada, P. (2014). Estimates of the climatological land surface energy and water balance derived from maximum convective power. Hydrology and Earth System Sciences, 18(6), 2201–2218. https://doi.org/10.5194/hess-18-2201-2014

Tilmes, S., Fasullo, J., Lamarque, J.-F., Marsh, D. R., Mills, M., Alterskjær, K., … Watanabe, S. (2013). The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres, 118(19), 11,036-11,058. https://doi.org/10.1002/jgrd.50868

Wild, M., Folini, D., Schär, C., Loeb, N., Dutton, E. G., & König-Langlo, G. (2013). The global energy balance from a surface perspective. Climate Dynamics, 1–28. https://doi.org/10.1007/s00382-012-1569-8

Thank you!