Climate Thermodynamics 2010

Wed 21 April

12:15 Arrival

12:30 Lunch

13:30 Workshop starts in **1L61**

13:30 Maarten Ambaum: Welcome, introduction; global heat flows in the atmosphere.

14:00 Tim Palmer: Climate Model Bias and the Fluctuation-Dissipation Theorem.

14:30 TBA.

15:00 Break.

15:30 Jonathan Gregory: Energetic analysis of changes in the AMOC under increasing CO2.

16:00 Kevin Oliver: An approximation for the structure of global meridional overturning in the ocean,

as a function of the gravitational potential energy generation and surface density fields.

16:30 Valerio Lucarini: Efficiency and Entropy Production in the Climate System.

Drinks and dinner.

Thu 22 April

9:00 Workshop reconvenes in **1L43**.

9:00 Peter Jan van Leeuwen: Information transfer and entropy in large-dimensional systems. 9:30 Salvatore Pascale: Entropy production in HadCM3 model and MEP conjecture for objective tuning.

10:00 Richard Allan: Thermodynamic and Energy Constraints on Precipitation.

10:30 Break.

11:00 Bob Plant: Self-organized criticality in tropical convection.

11:30 Christopher Dancel: The sensitivity of an Ocean Model's Architecture to the latent heat transport in the Atmosphere.

12:00: Remi Tailleux: Dynamics/Thermodynamics coupling in the incompressible Boussinesq model. Close: short discussion on the way forward (future workshops, publications, consortium bids, etc.)

Global Heat Flows in the Atmosphere

Maarten Ambaum *Department of Meteorology University of Reading*

1 The global energy budget 2 The global entropy budget 3 Closing thoughts

The global energy budget

Earth system at equilibrium:

energy in = energy out ≈ 120 PW (120×10¹⁵ W)

The global energy budget

Earth system at equilibrium:

energy in = energy out \approx 120 PW

= 1500×Hiroshima *each second*

The energy in $= 120$ PW $= 240$ W/m² on average

For Reading area (55 km²): Energy in $= 10$ GW $= 3 \times$ Didcot power station

The energy in $= 120$ PW = insolated − reflected = 170 PW − 50 PW

Reflected fraction (albedo)

Absorbed short-wave

(units W/m2)

Of the energy in $= 120$ PW,

80 PW go to the tropics, 40 PW go to the extratropics. Of the energy in $= 120$ PW,

80 PW go to the tropics, 40 PW go to the extratropics.

Of the energy out $= 120$ PW,

70 PW come from the tropics, 50 PW come from the extratropics, 10 PW is transported from tropics to extratropics.

(units PW)

The global entropy budget

The entropy budget for a body of fluid d*U/*d*t* = *Q*˙ + *W*˙ (10.43) with \mathbf{U} the total internal energy, and \mathbf{U} and opy budget for ϵ *F^q* · *n*ˆ d*A* and *W*˙ = − f *p*_U *n***u** *d*_{*n*}

The first law: $dU/dt = Q + W$ ϵ first lease $\frac{3\pi i}{4}$, for a volume that only exchanges the set of ϵ \mathbf{e} is respectively. $\mathbf{u} \circ \mathbf{u} = \mathbf{v} + \mathbf{v}$ *A* $\frac{d}{dx}$, $\frac{d}{dx}$ is $\frac{d}{dx}$ is the unit norm-

F^q · *n*^ª d^A and *W*[−] d^A and *W*[−]

$$
\dot{Q} = -\int_A \mathbf{F}_q \cdot \hat{\mathbf{n}} \, dA \qquad \qquad \dot{W} = -\int_A p \mathbf{U} \cdot \hat{\mathbf{n}} \, dA.
$$

pU · *n*ˆ d*A.* (10.44)

Here *F^q* is the heat flux, *U* is the local flow velocity, and *n*ˆ the unit nor-Now define: A surrounding the volume of volume. An outward directed flux, defined as follows: A surrounding the volume of We now write the normal heat flux *F^q* · *n*ˆ as the sum of an inward directed

$$
F_{\text{in}} = \begin{cases} 0 & \text{if } \mathbf{F}_q \cdot \hat{\mathbf{n}} > 0 \\ -\mathbf{F}_q \cdot \hat{\mathbf{n}} & \text{if } \mathbf{F}_q \cdot \hat{\mathbf{n}} < 0 \end{cases} \quad F_{\text{out}} = \begin{cases} \mathbf{F}_q \cdot \hat{\mathbf{n}} & \text{if } \mathbf{F}_q \cdot \hat{\mathbf{n}} > 0 \\ 0 & \text{if } \mathbf{F}_q \cdot \hat{\mathbf{n}} < 0 \end{cases}
$$

$$
\Rightarrow \qquad \dot{Q} = \int_A F_{\text{in}} \, dA - \int_A F_{\text{out}} \, dA.
$$

The entropy budget: $dS/dt = d_eS/dt + d_iS/dt$

$$
\frac{\mathrm{d}_e S}{\mathrm{d} t} = -\int_A \frac{F_q \cdot \hat{n}}{T} \, \mathrm{d}A \quad \text{and} \quad \frac{\mathrm{d}_i S}{\mathrm{d} t} \geq 0.
$$

then: change
change

$$
\frac{\mathrm{d}_e S}{\mathrm{d} t} = \frac{1}{T_{\text{in}}} \int_A F_{\text{in}} \, \mathrm{d}A - \frac{1}{T_{\text{out}}} \int_A F_{\text{out}} \, \mathrm{d}A,
$$

where we have defined the temperatures *T*in and *T*out as where above definitions for *F*in and *F*out we can write for the reversible entropy

$$
\frac{1}{T_{\text{in}}} = \left(\int_A F_{\text{in}} \, \mathrm{d}A\right)^{-1} \int_A \frac{F_{\text{in}}}{T} \, \mathrm{d}A,
$$

 θ $\log_{\rm OUS}$ for $T_{\rm out}$ from receives heat from receivers heat from receivers heat from receives heat from receivers heat (analogous for T_{out}) We can now derive for the work output $\dot{L} = -\dot{W}$:

$$
\dot{L} = \left(1 - \frac{T_{\text{out}}}{T_{\text{in}}}\right) \int_A F_{\text{in}} \, dA - T_{\text{out}} \frac{d_i S}{dt}
$$

*^T*in # ! $Carnot$ theorem and the Guoy-Stodola theorem) $\frac{1}{\sqrt{2}}$, and its heat engine as a fraction of its heat input has an upper has an uppe (This general expression for the second law includes the Carnot theorem and the Guoy-Stodola theorem)

Back to the Earth system Rack to the Farth system *S*0, the mean albedo *˛,* and the area of the Earth disk *!R*² **Fack to the** !
! arth system *F*in d*A* and *R*˙ out = $\overline{\mathbf{C}}$ *ICK to the Earth system .*

where the total radiative heat in put and output $\mathbf r$ radiative heat in put and output $\mathbf r$ First write: **The total short-wave radiative rate in** put rate R ^{in is set by the solar constant} The total short-wave radiative radiative rate R^2 **in is set by the solar constant rate in put rate** R^2 **constant** R^2 **constant**

$$
\dot{R}_{\rm in} = \int_A F_{\rm in} \, dA \quad \text{and} \quad \dot{R}_{\rm out} = \int_A F_{\rm out} \, dA
$$

Both are equal to 120 PW. long-wave radiative heat output rate *R*˙ out has the same value, on average. T_{total} is in the Earth system can be estimated in the Earth system can *R*₂ *R*² *Both are equal to 120 PW,* $\frac{120}{2}$ *PW,* (10.58)

*S*0, the mean albedo *˛,* and the area of the Earth disk *!R*² At equilibrium<mark>:</mark> from the expression for d*eS/*d*t,* Eq. 10.49. In this case this expression reduces (1 PW endianal per unit area on Earth) who earthq to 239 W monach area on Earth (1 PW monach area on Earth) was long-wave radiative heat output rate *R*˙ out has the same value, on average. long-wave radiative heat output rate *R*˙ out has the same value, on average.

$$
\frac{\mathrm{d}_{i}S}{\mathrm{d}t} = -\frac{\mathrm{d}_{e}S}{\mathrm{d}t} = \dot{R}_{\mathrm{in}} \left(\frac{1}{T_{\mathrm{out}}} - \frac{1}{T_{\mathrm{in}}} \right)
$$

Make T_{in} and T_{out} a weighted average of surface and mean metric temperature **designed** *examplement netric temperature* bolometric temperature ⁼ [−]d*eS* $\frac{1}{2}$ \overline{R} and \overline{T} . *T*out a weig *Make T_{in}* and T_{out} a weighted average of surface and me *A*ak **e** *T*_{in} a \overline{r} cucidated overage of

from Trenberth, Fasullo & Kiehl, *Bull. Am. Met. Soc.*, 2009

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$$
T_{\text{in}} \approx 276 \text{ K}
$$
 and $T_{\text{out}} \approx 260 \text{ K}$.

The total independent only production. ... substitute to find the *material entropy production:*

 $d_iS/dt \approx 53$ mW m⁻² K⁻¹

onfused discussions about entropy in the radiation entropy production of 896 mW m−² K−1*.* The vast majority of this entropy pro-(Beware confused discussions about entropy in the radiation field!)

 $T_{\text{in}} \approx 276 \text{ K}$ and $T_{\text{out}} \approx 260 \text{ K}$.

Let's assume these temperatures are the effective mean Let's assume these temperatures are the enective mea
temperatures between which the atmosphere operates

max efficiency:
$$
\eta_{\text{Carnot}} = 1 - \frac{T_{\text{out}}}{T_{\text{in}}} \approx 0.06
$$

max power:
$$
\eta_{\text{endoreversible}} = 1 - \sqrt{\frac{T_{\text{out}}}{T_{\text{in}}}} \approx 0.03
$$

perature $2 \cdot 4 \cdot 10^{10}$ $\frac{2}{\pi}$ and $\frac{7}{\pi}$ $\frac{10}{\pi}$ and $\frac{2}{\pi}$ and $\frac{1}{\pi}$ This corresponds to 14 Wm⁻² and 7 Wm⁻²; compare to "observed" dissipation rate of 3.5 Wm $^{-2}$.

Closing thoughts

Back to our general formula:

$$
\dot{L} = \left(1 - \frac{T_{\text{out}}}{T_{\text{in}}}\right) \int_A F_{\text{in}} \, \text{d}A - T_{\text{out}} \frac{\text{d}_i S}{\text{d}t}
$$

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$$

This equation defines a relevant efficiency.

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$$

This equation defines a relevant efficiency.

This equation implies the Sandström "theorem".

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Thermal Physics of the Atmosphere

Maarten H. P. Ambaum

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