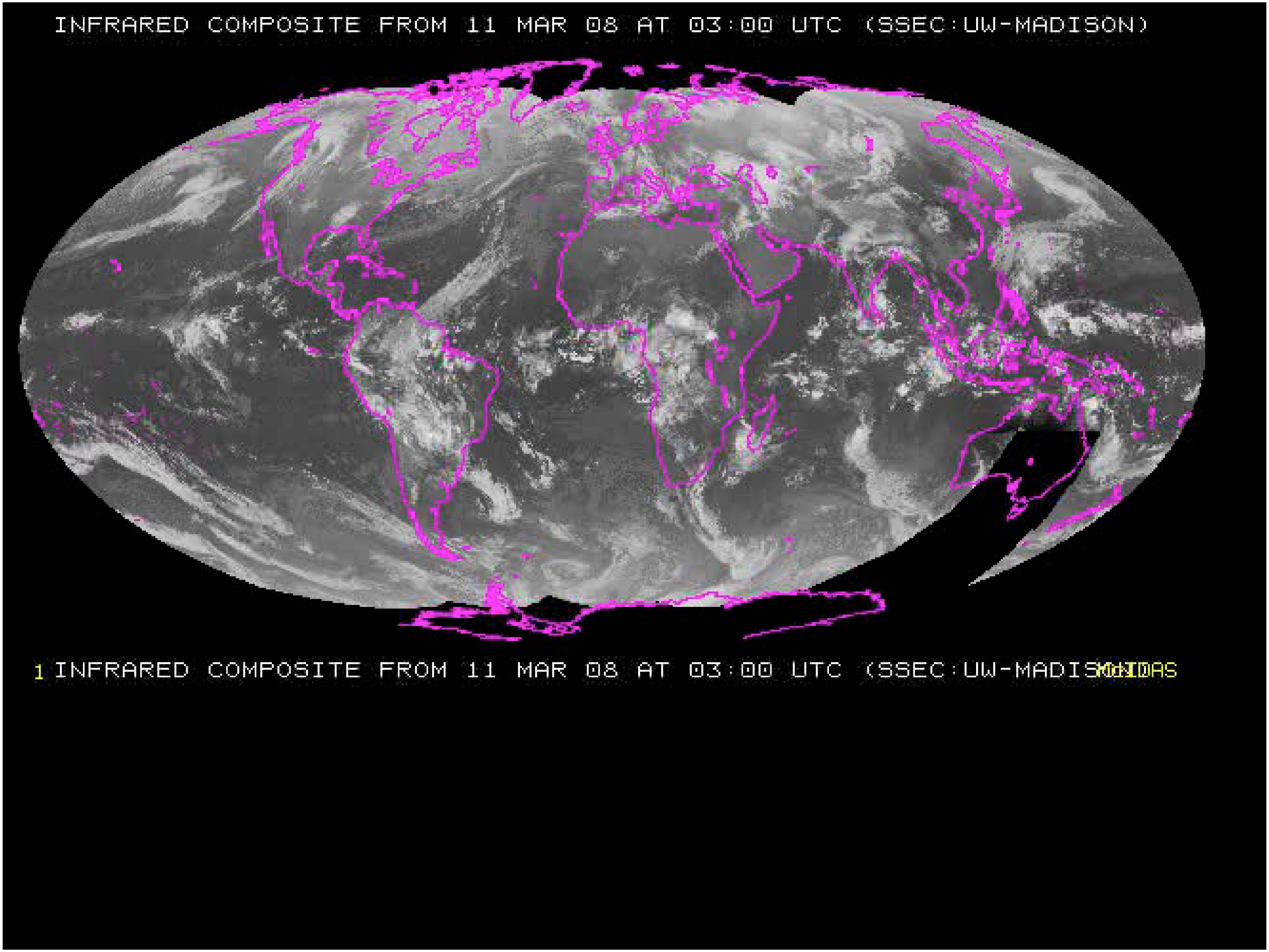
# Entropy Production in the Cloud-Climate System

Tim Garrett

University of Utah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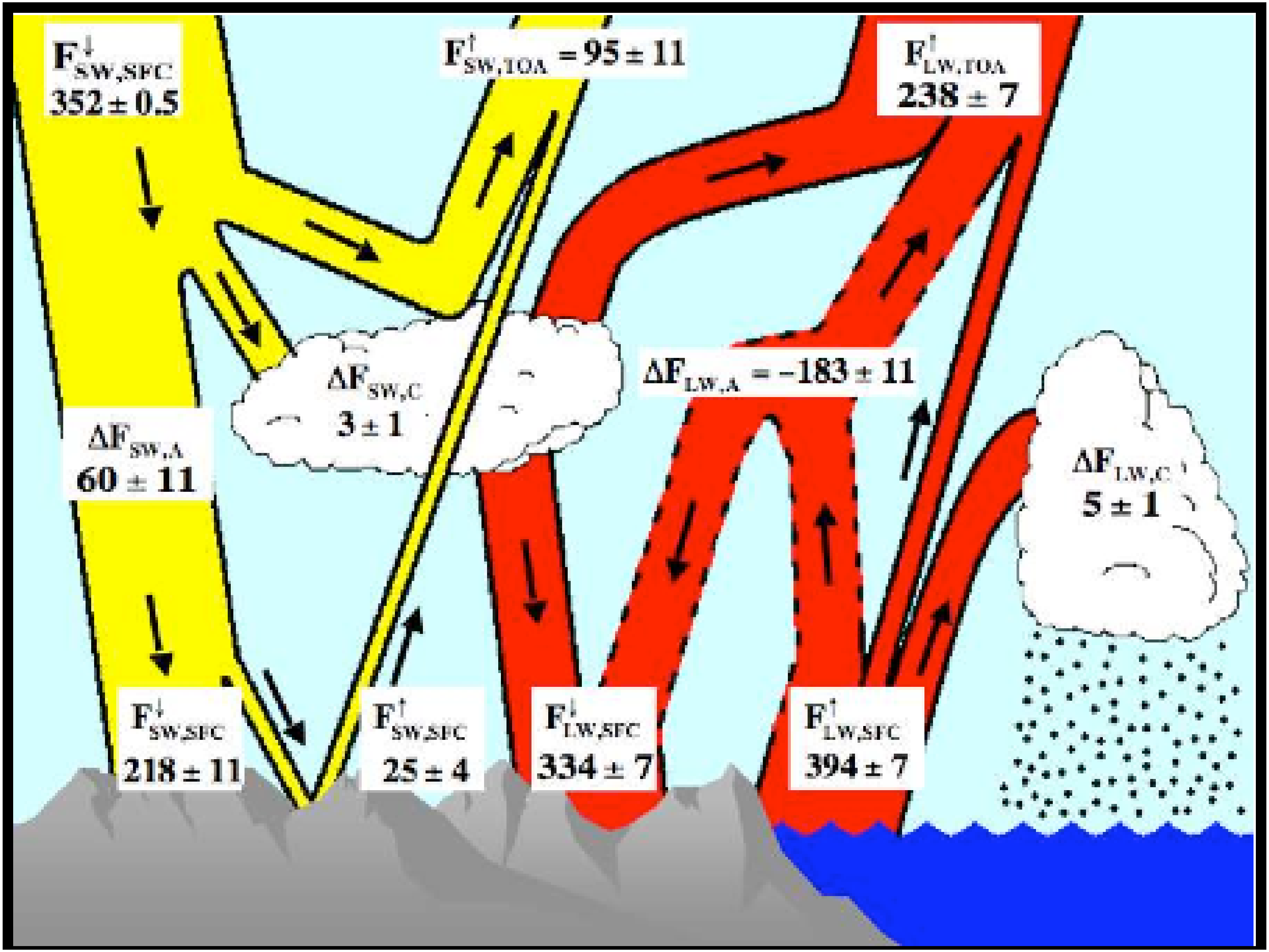
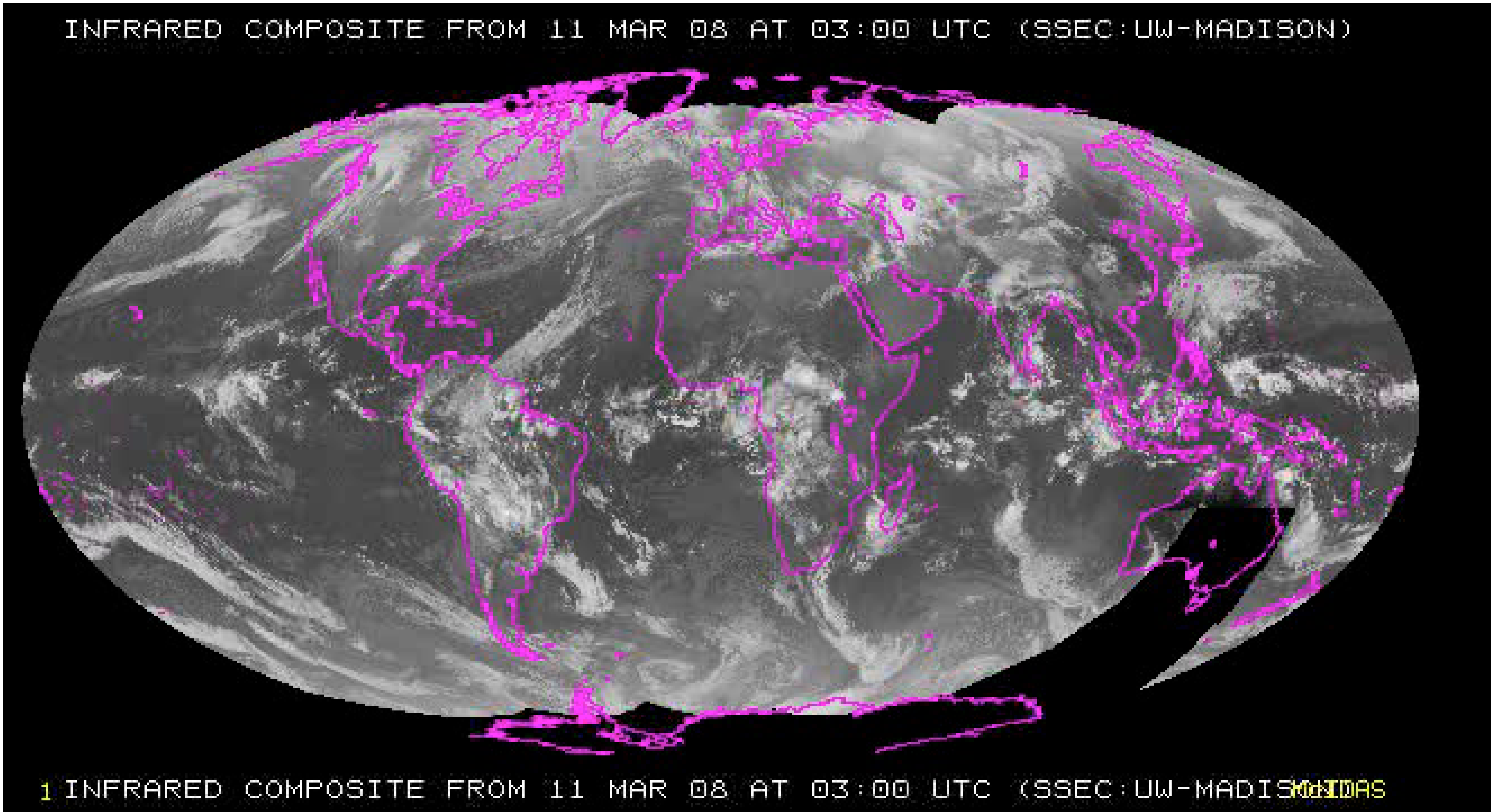
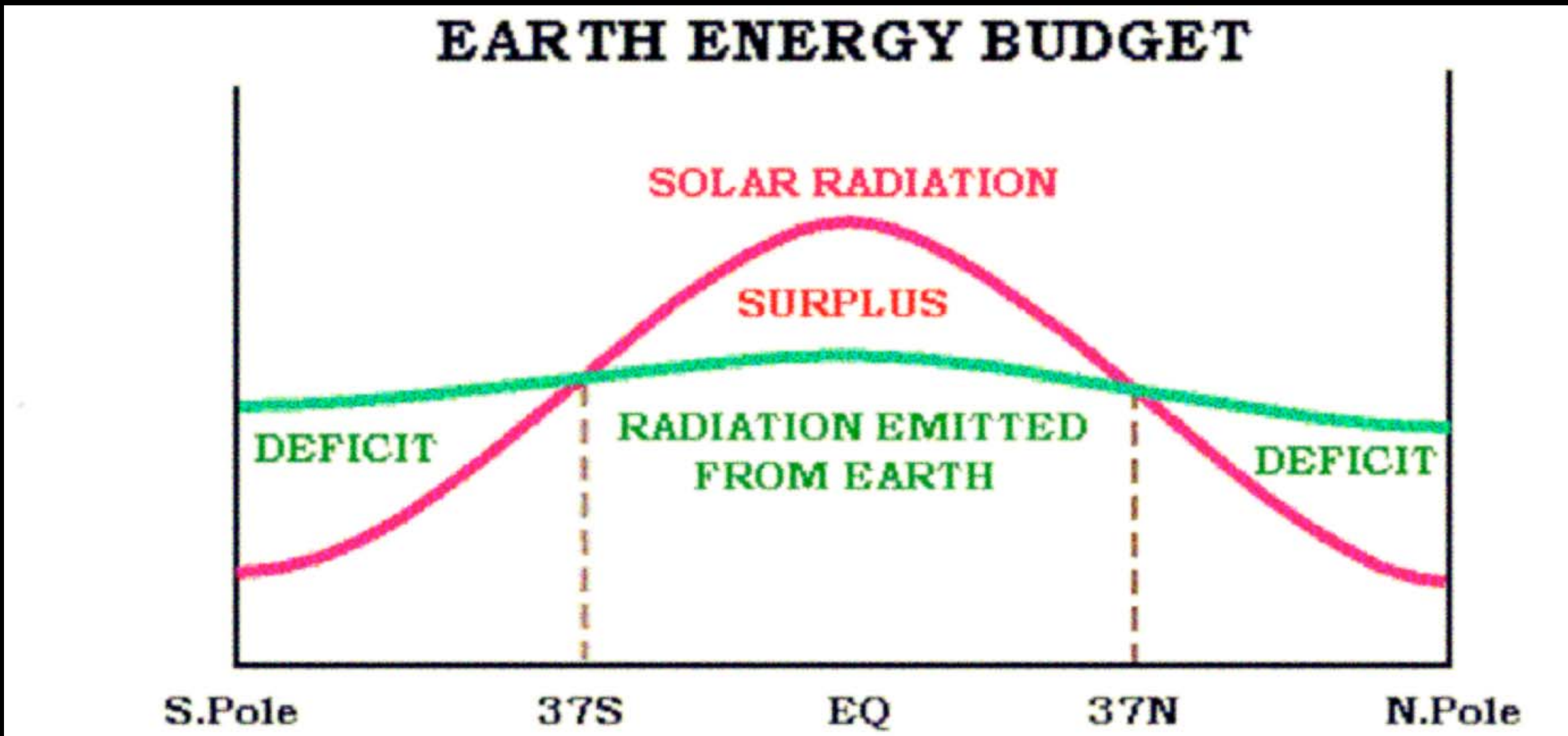


$F^{\downarrow}_{SW,SFC}$ 352 ± 0.5
$F^{\uparrow}_{SW,TOA}$ = 95 ± 11
$F^{\uparrow}_{LW,TOA}$ 238 ± 7
$\Delta F_{SW,C}$ 3 ± 1
$\Delta F_{LW,A}$ = −183 ± 11
$\Delta F_{SW,A}$ 60 ± 11
$\Delta F_{LW,C}$ 5 ± 1
$F^{\downarrow}_{SW,SFC}$ 218 ± 11
$F^{\uparrow}_{SW,SFC}$ 25 ± 4
$F^{\downarrow}_{LW,SFC}$ 334 ± 7
$F^{\uparrow}_{LW,SFC}$ 394 ± 7

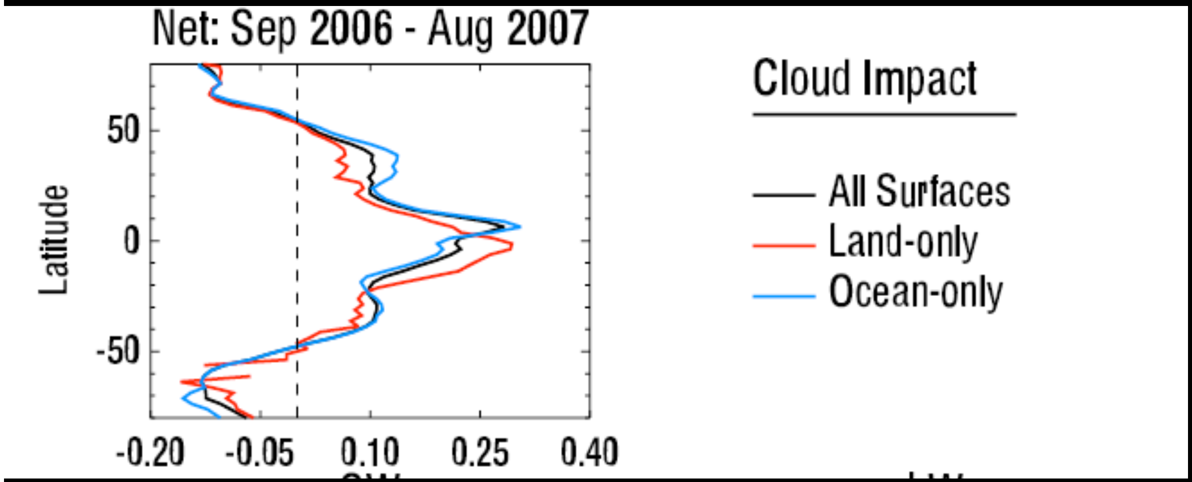



The more things change, the more they stay the same

How do clouds evolve given larger global constraints?


EARTH ENERGY BUDGET
SOLAR RADIATION
SURPLUS
DEFICIT
RADIATION EMITTED FROM EARTH
DEFICIT
S.Pole
37S
EQ
37N
N.Pole

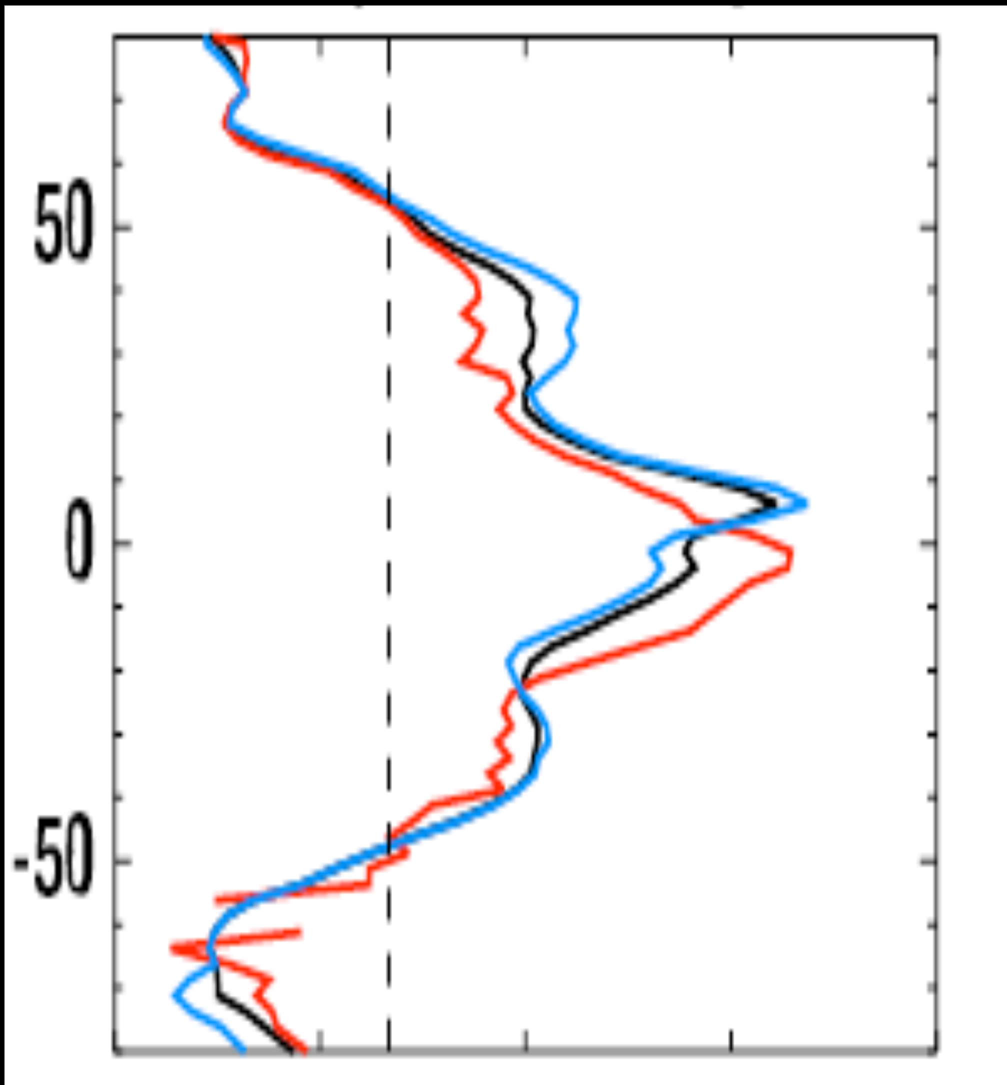
# CloudSat latitudinal heating

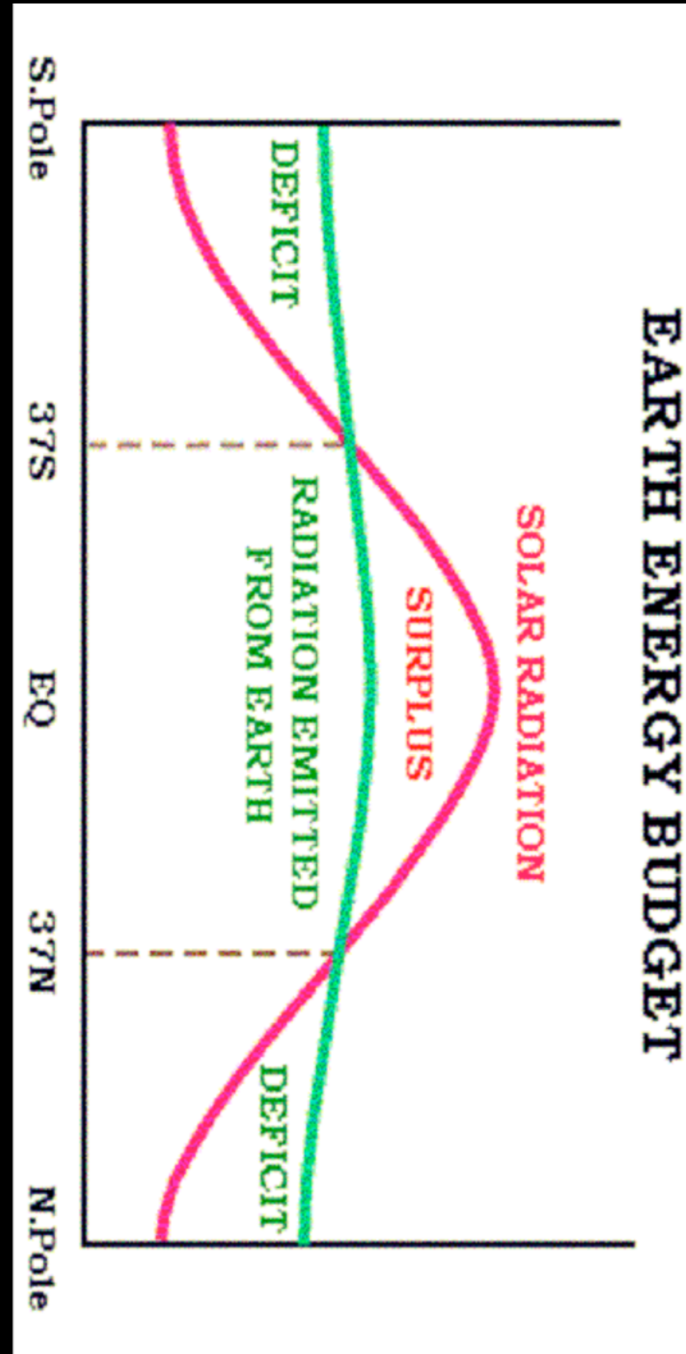



Clouds consume energy

*Courtesy Tristan L'Ecuyer, Colo. State*

Cloud heating or energy consumption



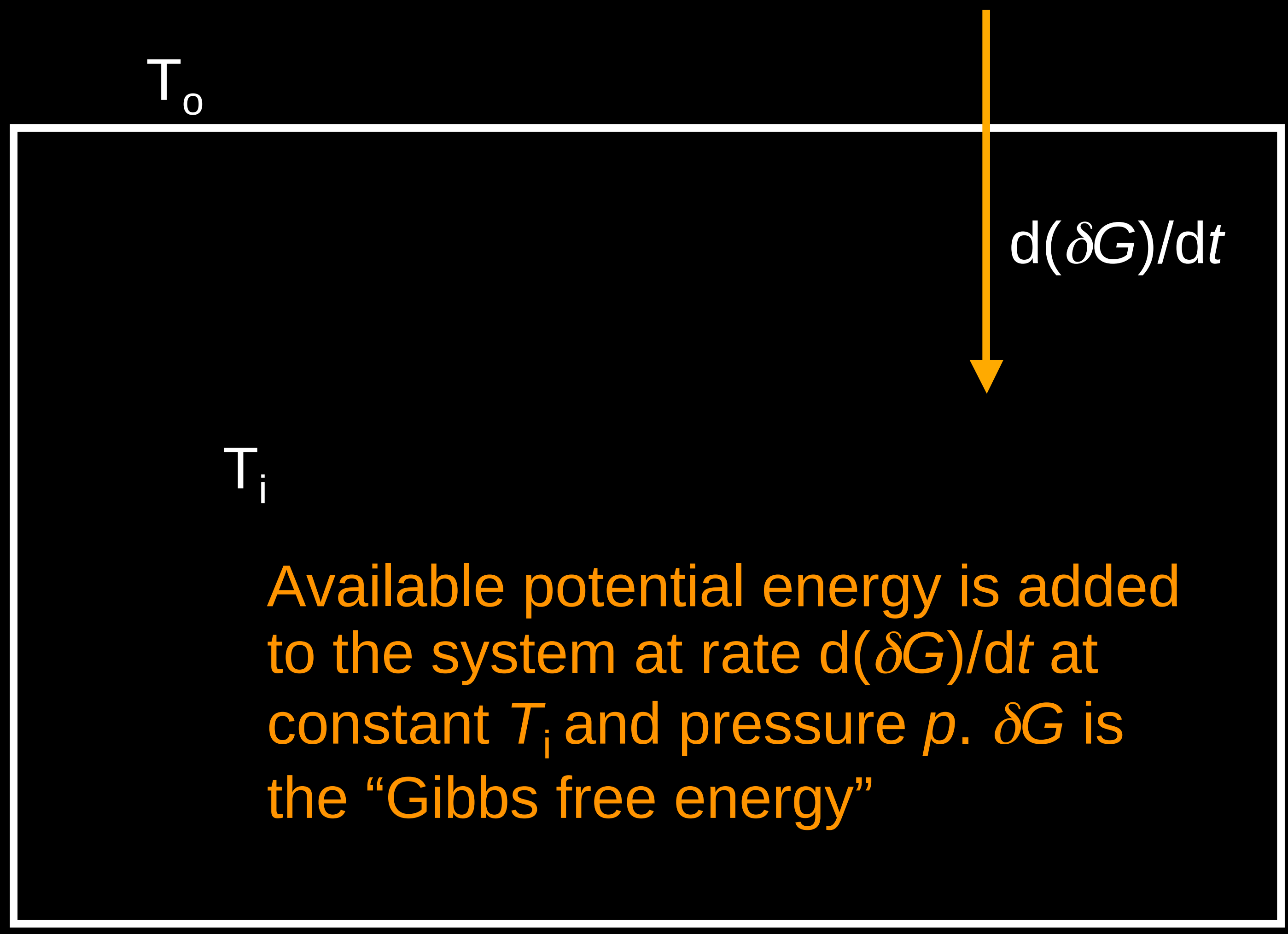



Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you any more.

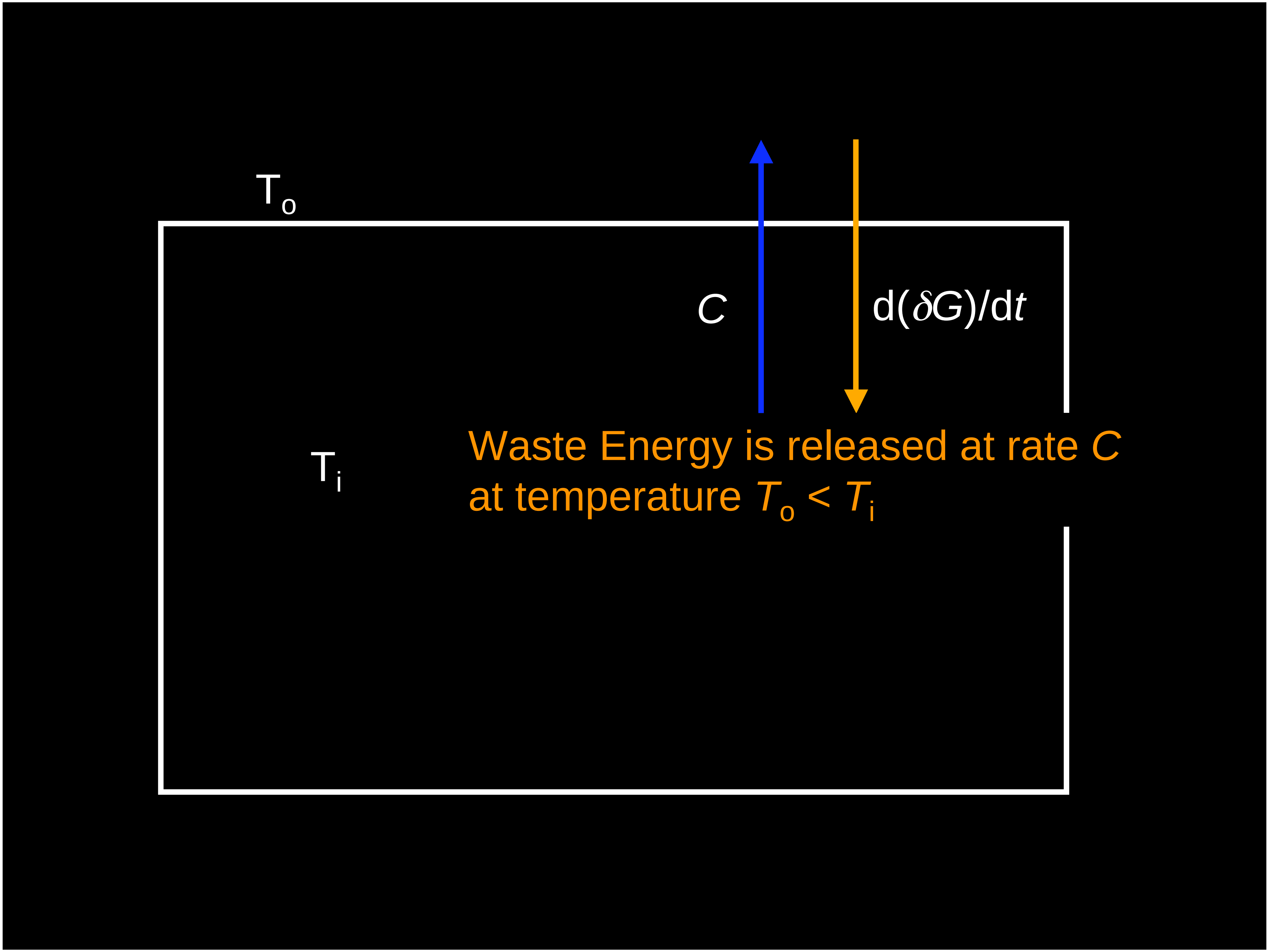
- Arnold Sommerfield (of the fine structure const.)

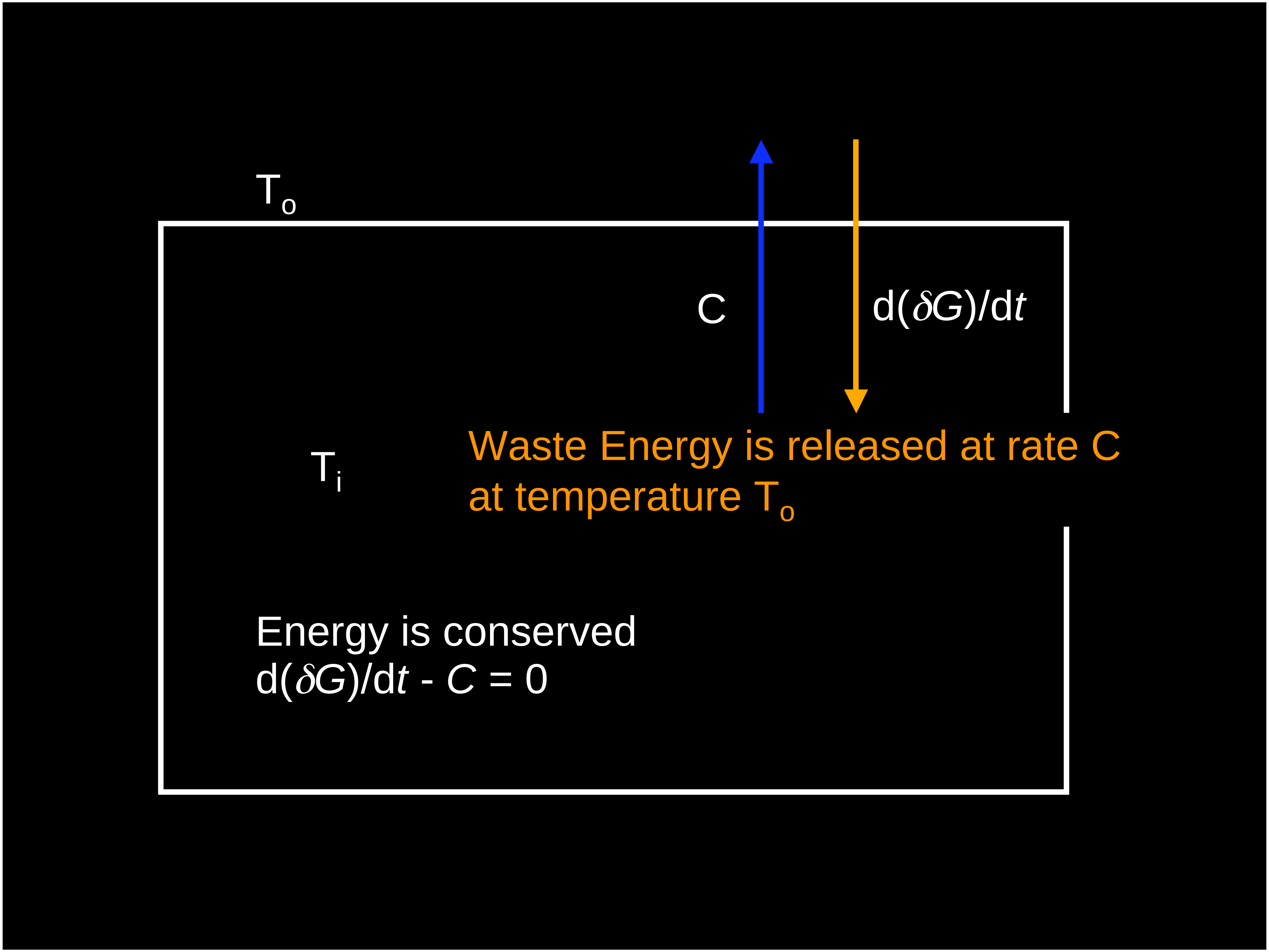
Outside at temperature $T_o$

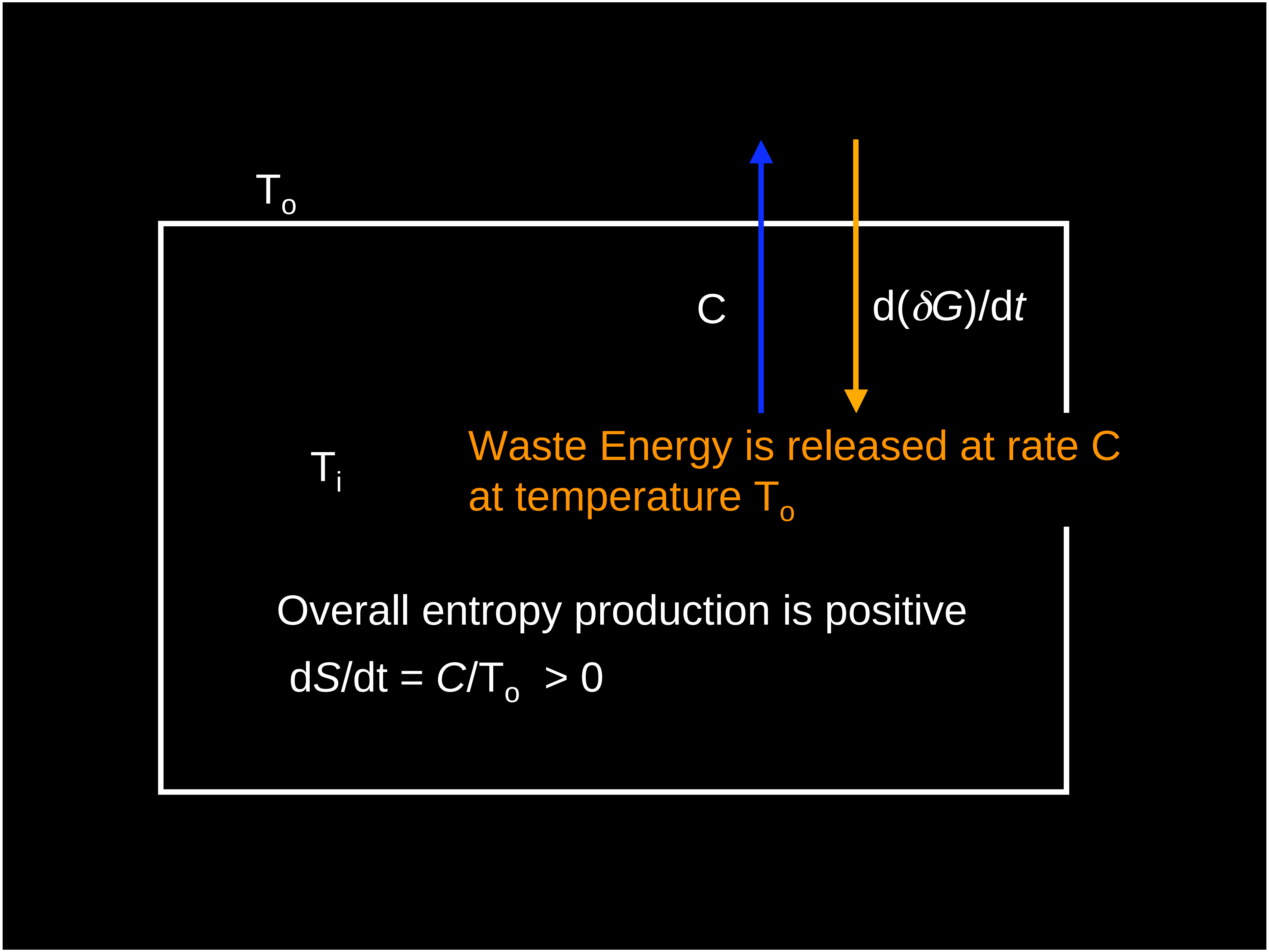
System with internal temperature $T_i$



$T_o$
$d(\delta G)/dt$
$T_i$
Available potential energy is added to the system at rate $d(\delta G)/dt$ at constant $T_i$ and pressure $p$. $\delta G$ is the “Gibbs free energy”


$T_o$
$C$
$d(\delta G)/dt$
Waste Energy is released at rate $C$
at temperature $T_o < T_i$
$T_i$


$T_o$
C
$d(\delta G)/dt$
Waste Energy is released at rate C
at temperature $T_o$
$T_i$
Energy is conserved
$d(\delta G)/dt - C = 0$



$T_o$
C
$d(\delta G)/dt$
$T_i$
Waste Energy is released at rate C
at temperature $T_o$
Overall entropy production is positive
$dS/dt = C/T_o > 0$

Suppose $T_o$ is the temperature of the coldest reservoir at hand through conduction or radiation then

"*Whenever an irreversible process takes place, the effect on the universe is the same as that which would be produced if a certain quantity of energy were converted from a form in which it is completely available for work into a form in which it is completely unavailable for work. The amount of energy $\delta G$ is $T_o$ times the entropy change of the universe brought about by the irreversible process…$\delta G$ is the energy that is rendered unavailable for work*"

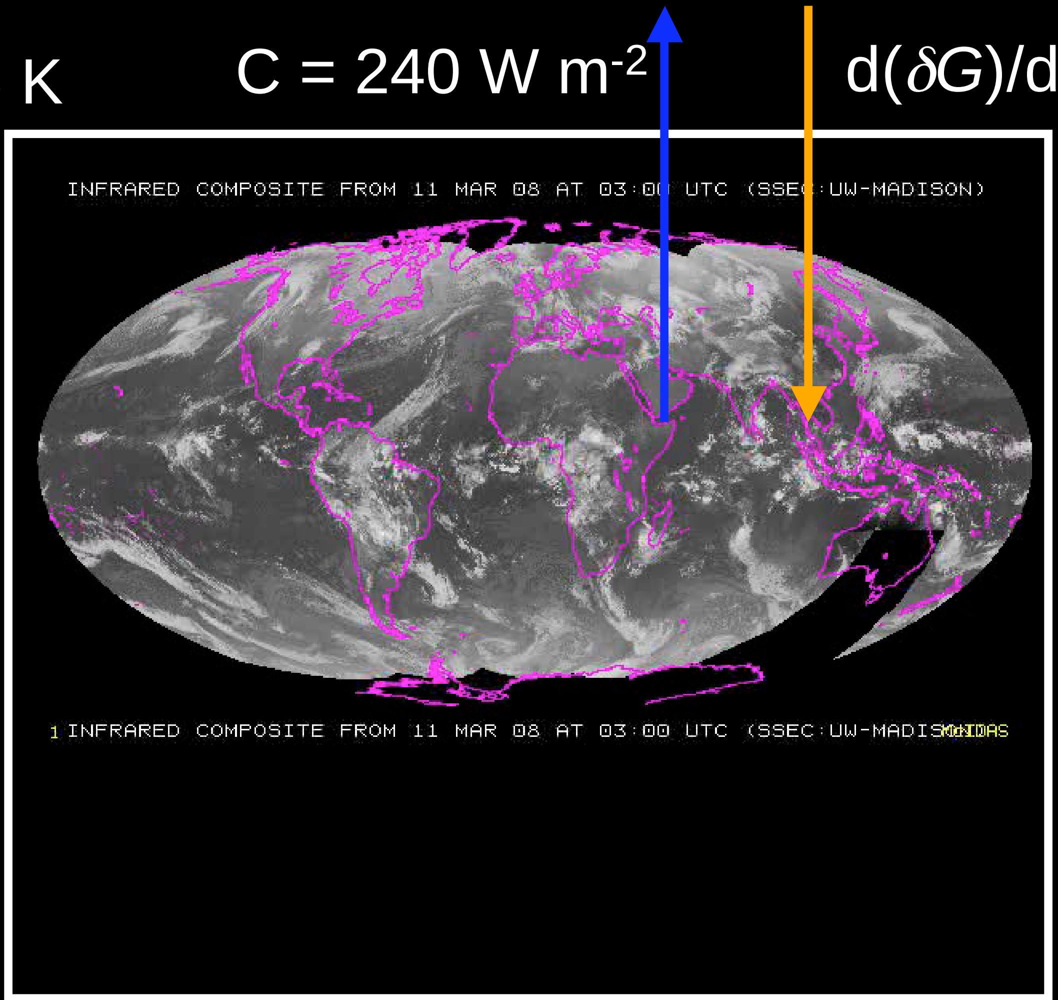
$$C = \mathrm{d}(\delta G)/\mathrm{d}t = T_o \mathrm{d}S/\mathrm{d}t$$

Energy consumption = Entropy production (times $T_o$ )

255 K

$C = 240$ W m$^{-2}$

$d(\delta G)/dt = 240$ W m$^{-2}$




$$\frac{dS}{dt}\Big|_{\theta} = \frac{C}{T_o} = \frac{d\left(\delta G\right)/dt}{T_o}\Big|_{\theta} \geq 0$$

Entropy production is about 1 W K$^{-1}$ m$^{-2}$

What about the non-equilibrium consumption case?

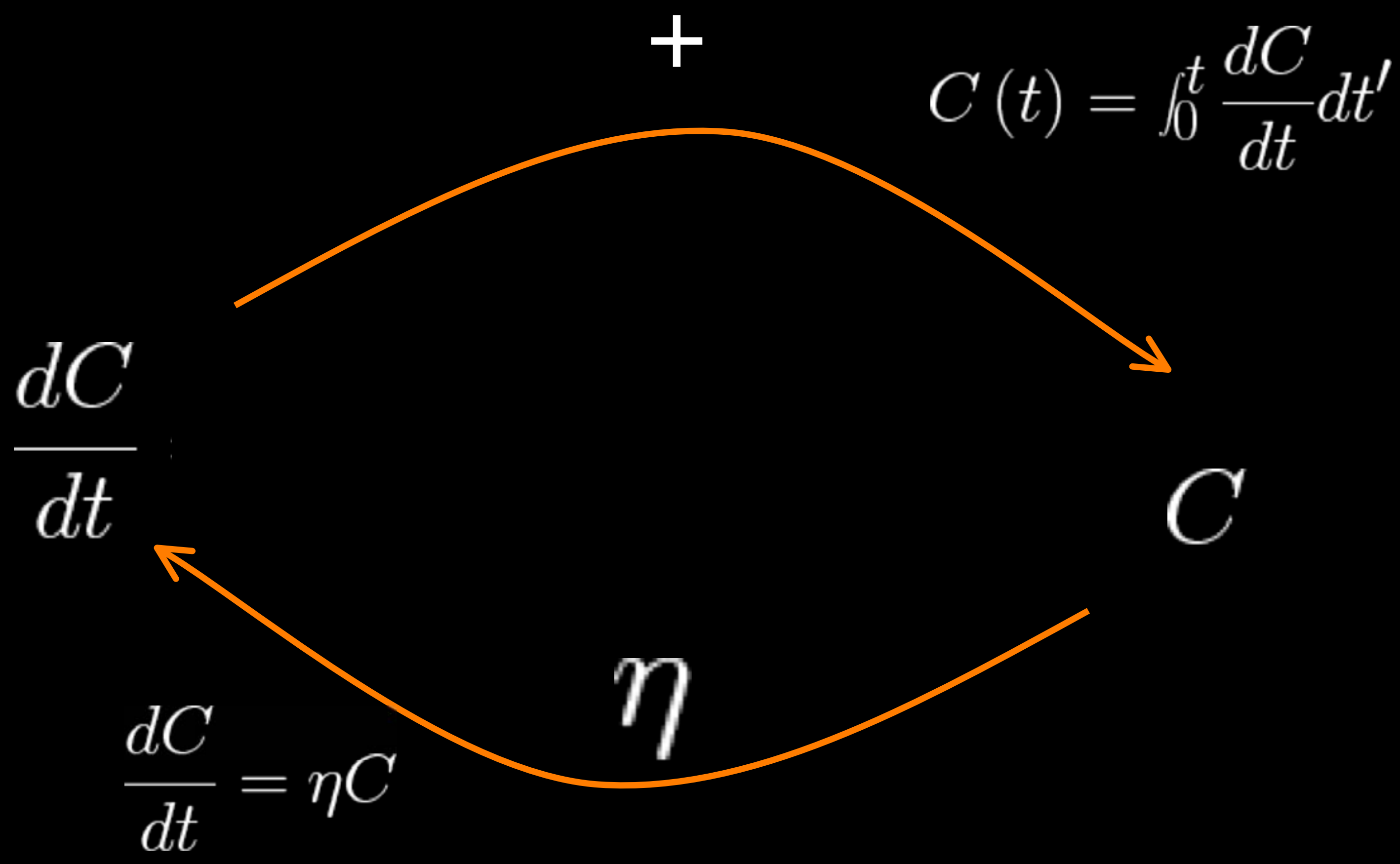
This system evolves as energy consumption and entropy production increases

$T_o = 255$ K

C

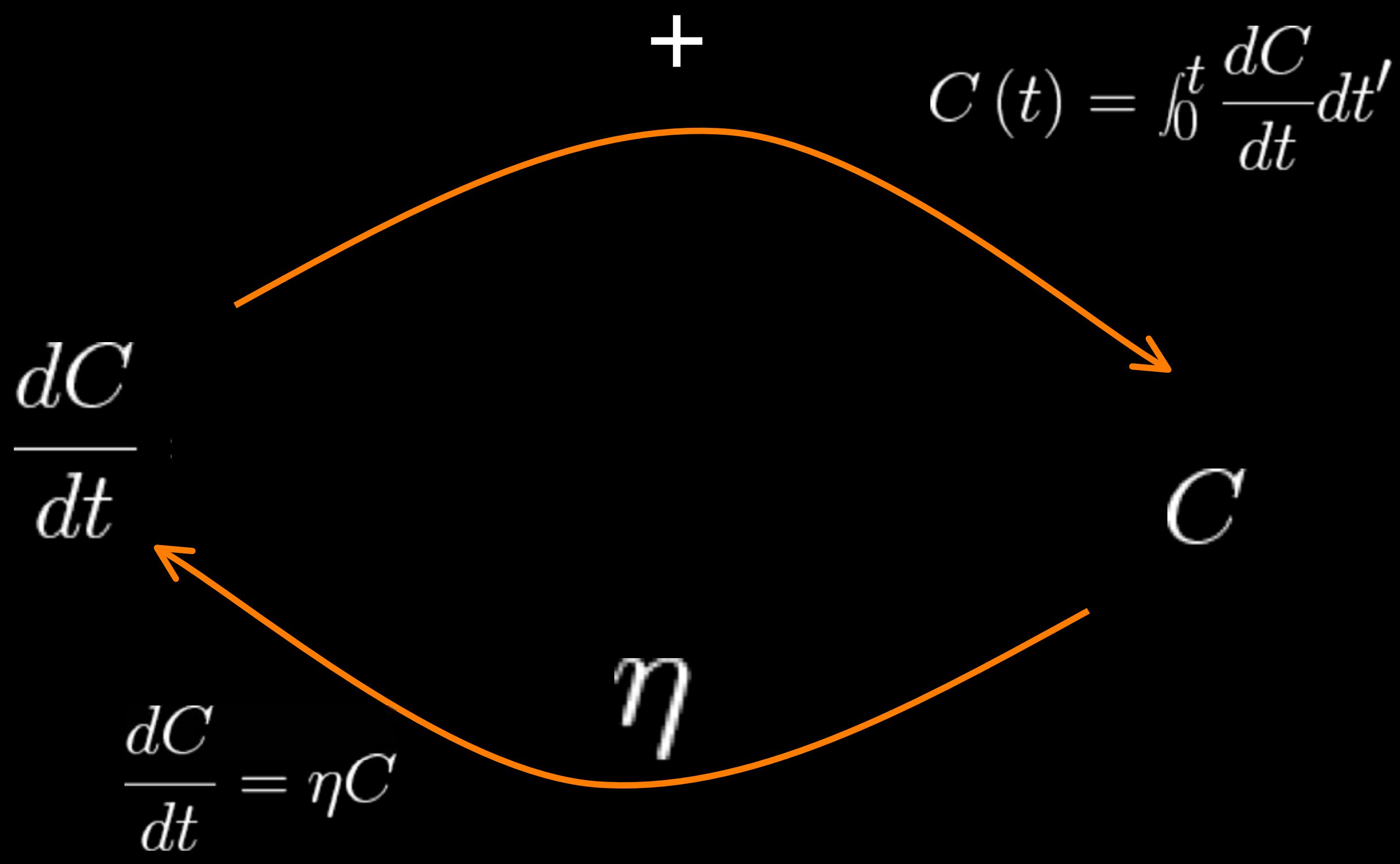
$d(\delta G)/dt = 50\ W$


$dS/dt = C/255 = 0.2$ W/K *and growing!*




$\eta$ Feedback parameter. Units per time

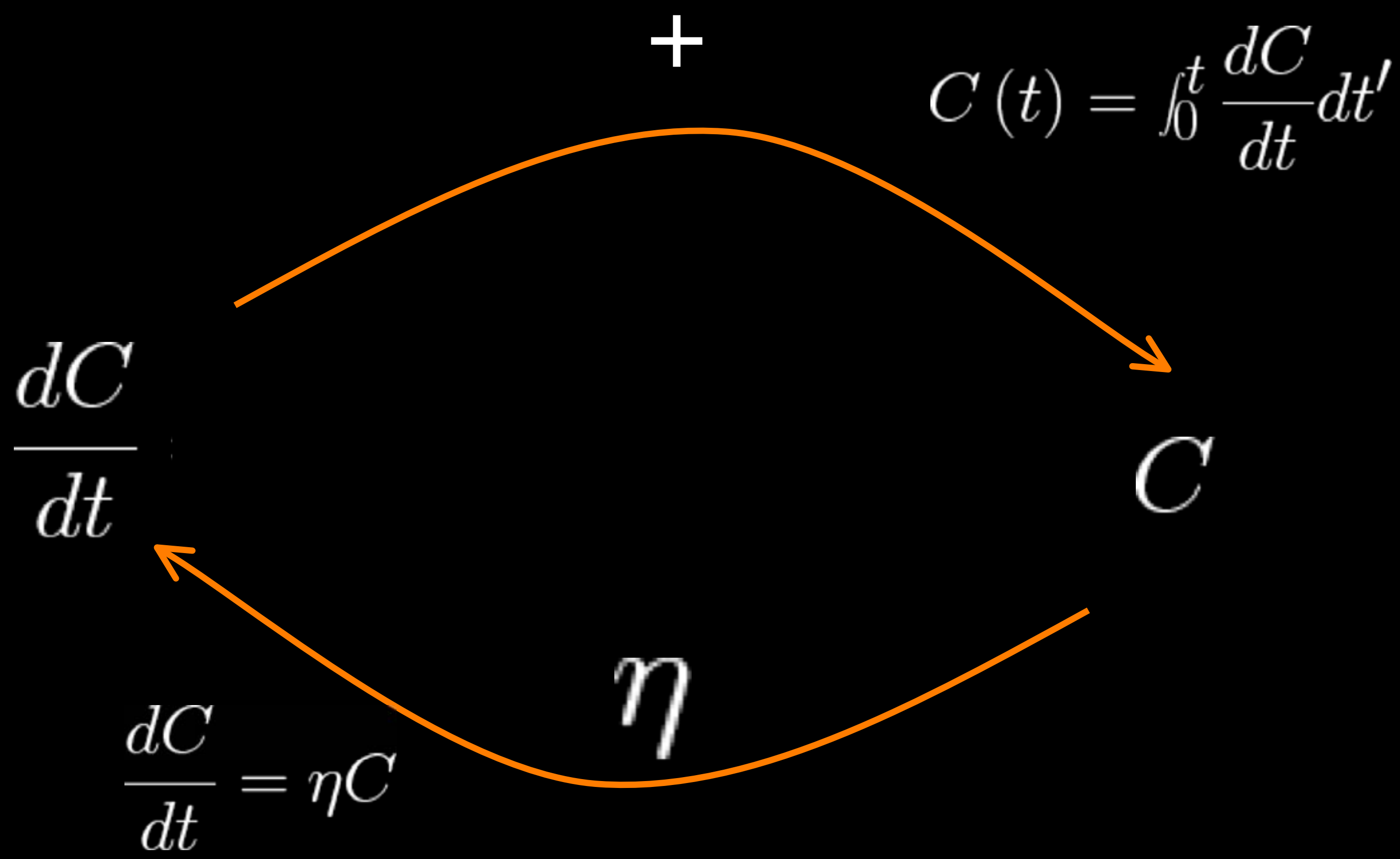
$C$ Energy consumption rate. Units power




If equilibrium consumption $\eta = 0$ $\quad C \neq 0$

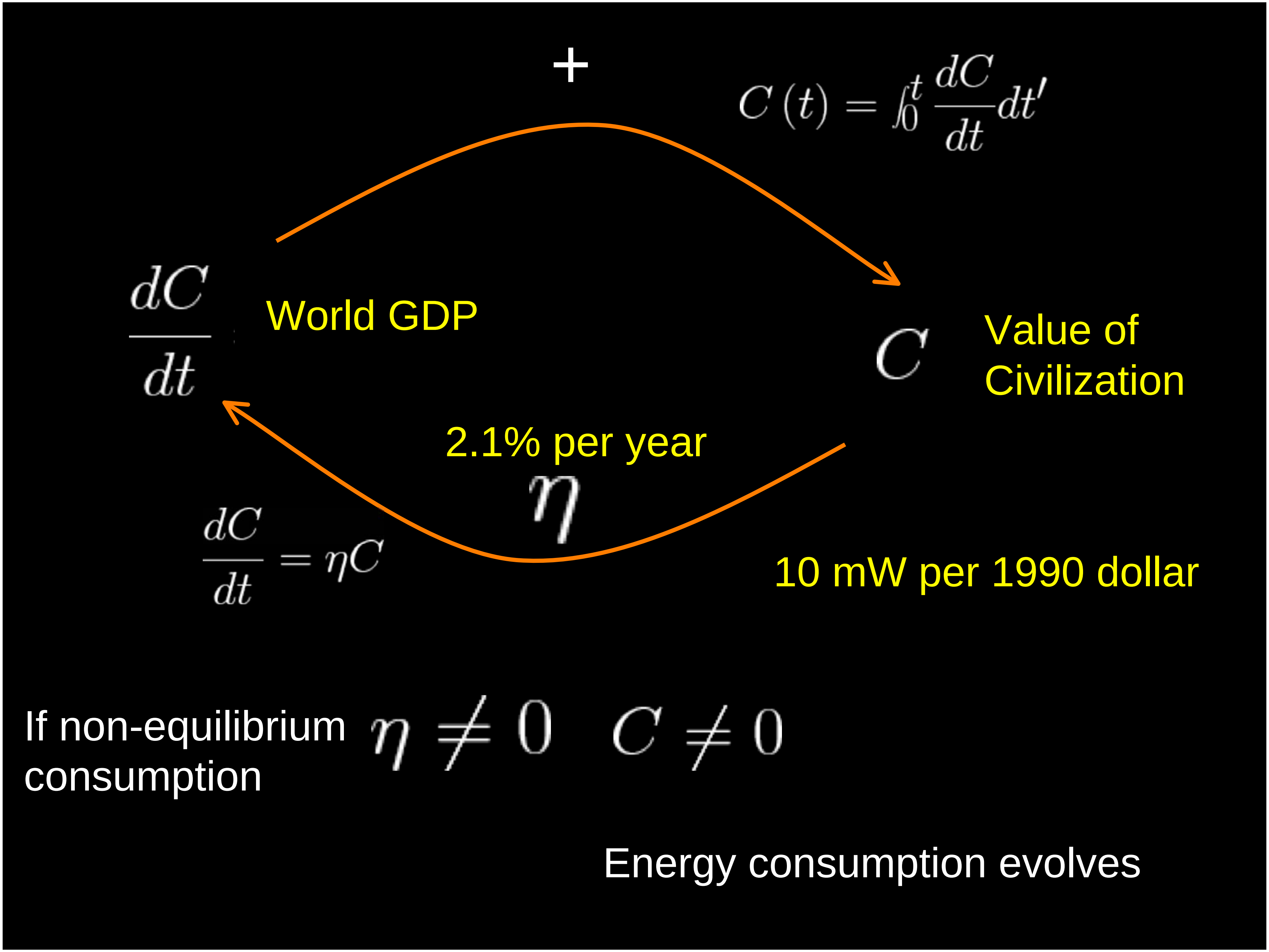
$$\frac{dC}{dt} = 0$$

Energy consumption is constant




If non-equilibrium consumption $\eta \neq 0$ $C \neq 0$

Energy consumption evolves


+
$C(t) = \int_0^t \frac{dC}{dt} dt'$
$\frac{dC}{dt}$
World GDP
$C$
Value of Civilization
2.1% per year
$\eta$
$\frac{dC}{dt} = \eta C$
10 mW per 1990 dollar
If non-equilibrium consumption
$\eta \neq 0$
$C \neq 0$
Energy consumption evolves

# First hypothesis

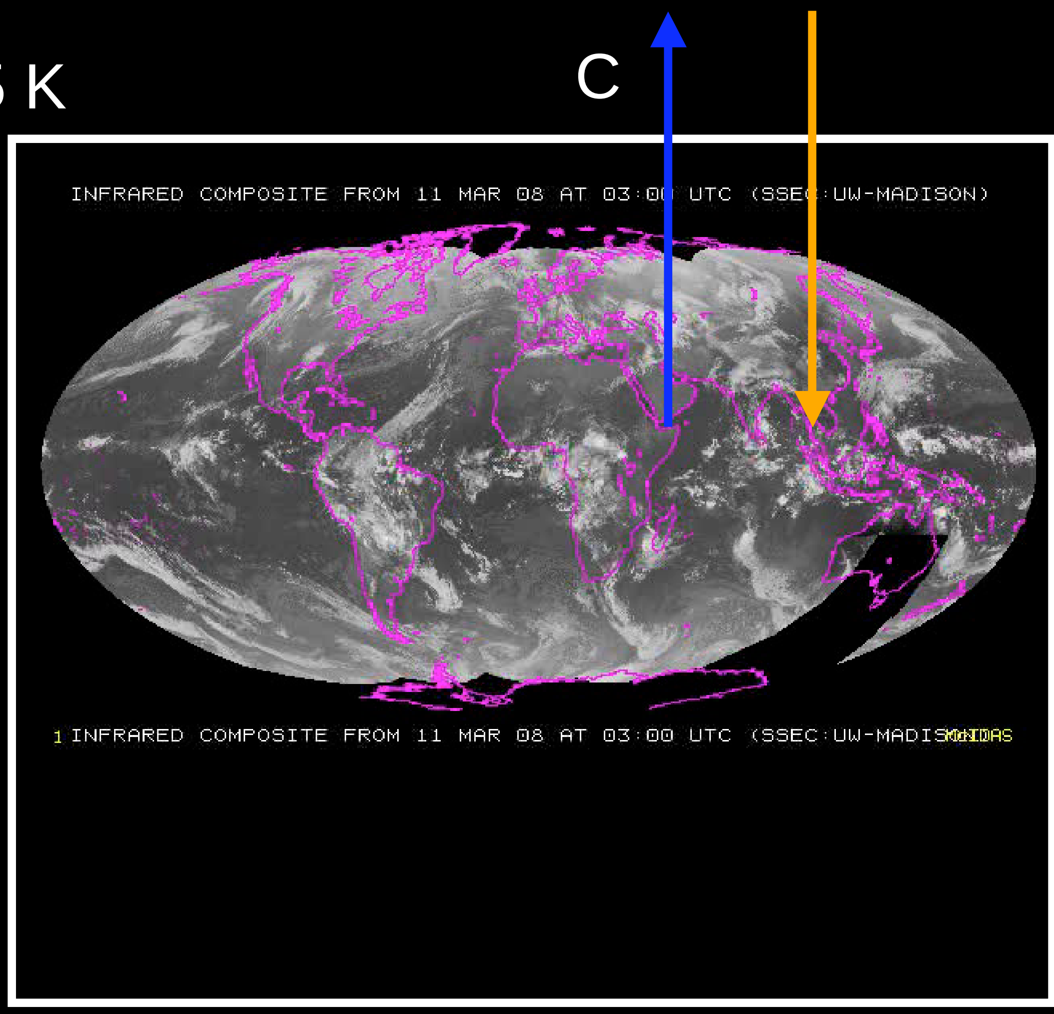
Non-equilibrium consumption:
System evolution is defined by the most efficient departures from equilibrium consumption. These transitions are characterized by processes whose values of the feedback parameter $\eta$ is large

$$\frac{dC}{dt} = \eta C$$

$d(\delta G)/dt = 240 \text{ W m}^{-2}$

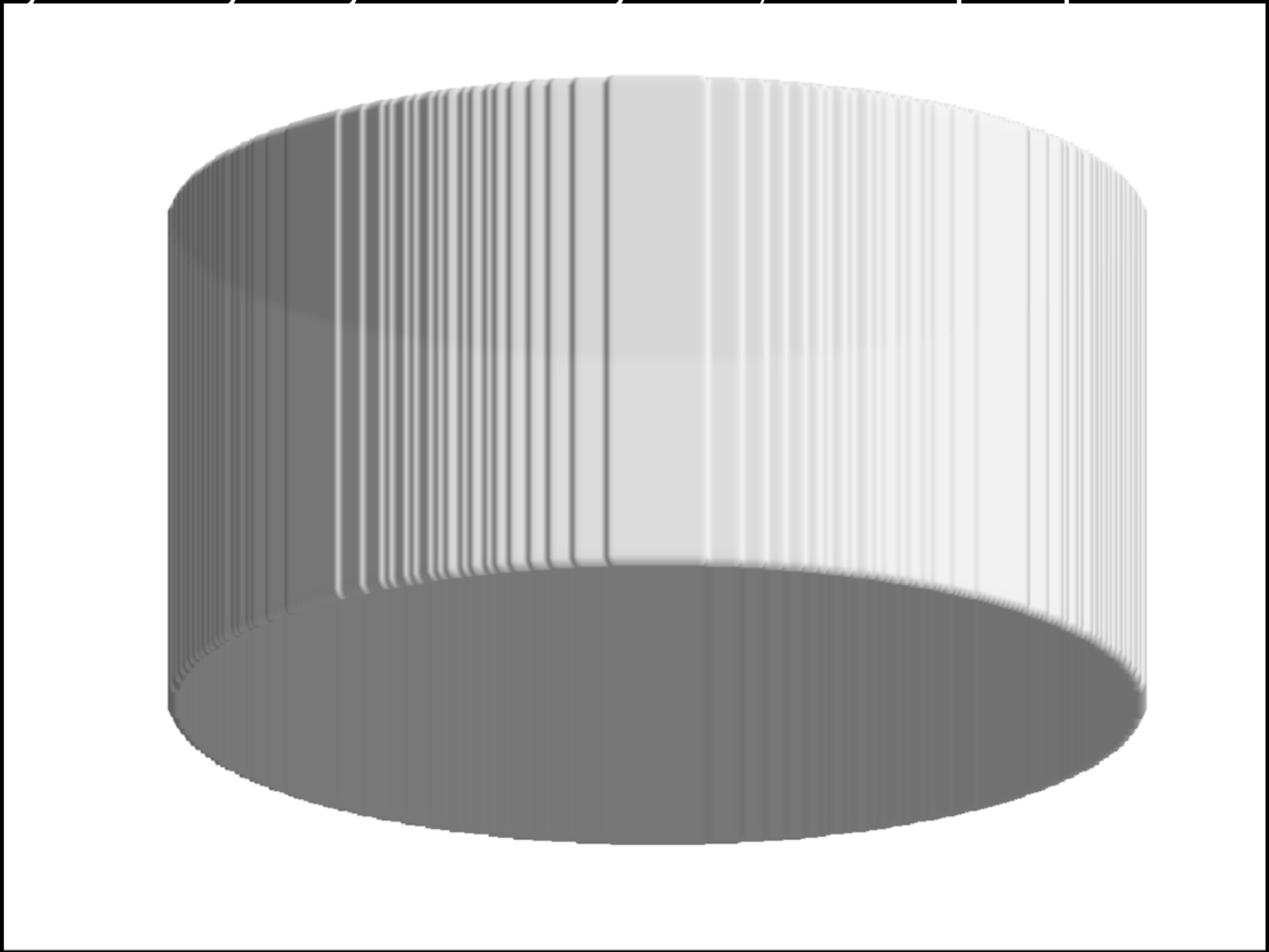
255 K

C

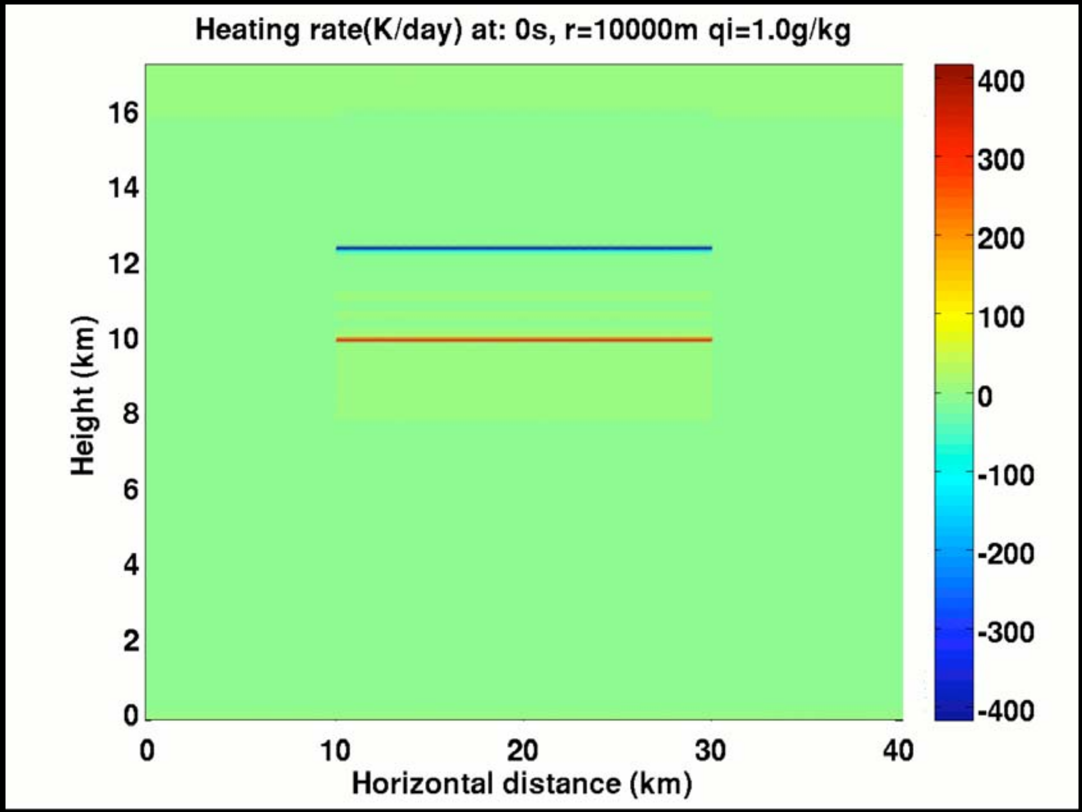



$dS/dt = C/255$

Initially neutrally buoyant cirrus cylinder, with no precip and no sun



Cloud evolves due to IR interactions only




Cross-section of heating rates in the cylindrical cloud

$$C = \frac{d\left(\delta G\right)}{dt}|_{\theta} = |\Delta F| A$$

Energy creation or consumption = IR flux deposition times Area

$$\frac{dC_i}{dt} = \eta_i C_i$$

$$\frac{d \ln C_i}{dt} = \eta_i$$ Feedback parameter

$$C = \frac{d\left(\delta G\right)}{dt}|_{\theta} = |\Delta F| A$$ Total consumption = flux dep. x area

$$\frac{d \ln C}{dt} = \frac{1}{\theta}\frac{d\theta}{dt}|_{\theta, A} + \frac{1}{L}\frac{dL}{dt}|_{\theta, \Delta F}$$ Specific feedbacks

Cloud Evolution = Rate of change in cloud potential temperature + Rate of change of cloud radius

Evolution of energy consumption is determined by three feedback parameters: convective mixing, isentropic adjustment, and horizontal spreading

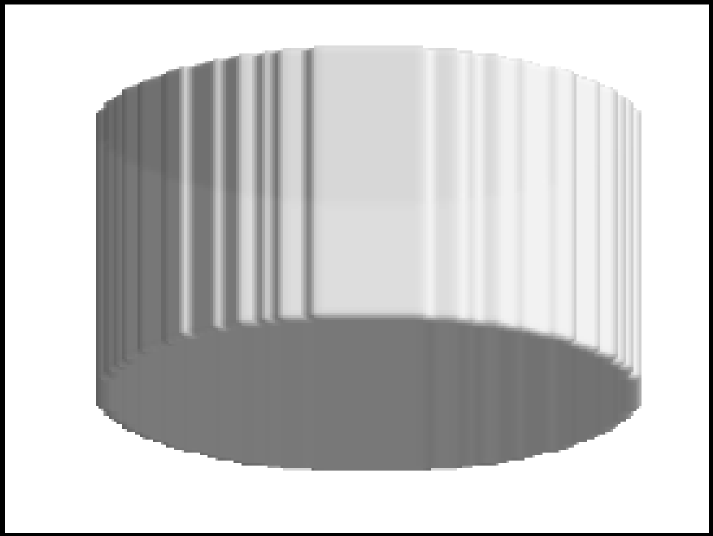
$$\frac{dC}{dt} = \sum_i \eta_i C_i = \Big(\overbrace{\eta_{mix} C_{mix} + \eta_{adj} C_{adj}}^{\text{Temperature/ Flux dep. change}} + \overbrace{\eta_{spread} C_{spread}}^{\text{Area change}}\Big)$$

Change in consumption = sum of all possible feedbacks

$$\frac{dC}{dt} = \left(N C_{mix} + \frac{\mathcal{H} g}{\theta N^2 h} C_{adj} + \frac{N h}{L} C_{spread}\right)$$

# Case 1

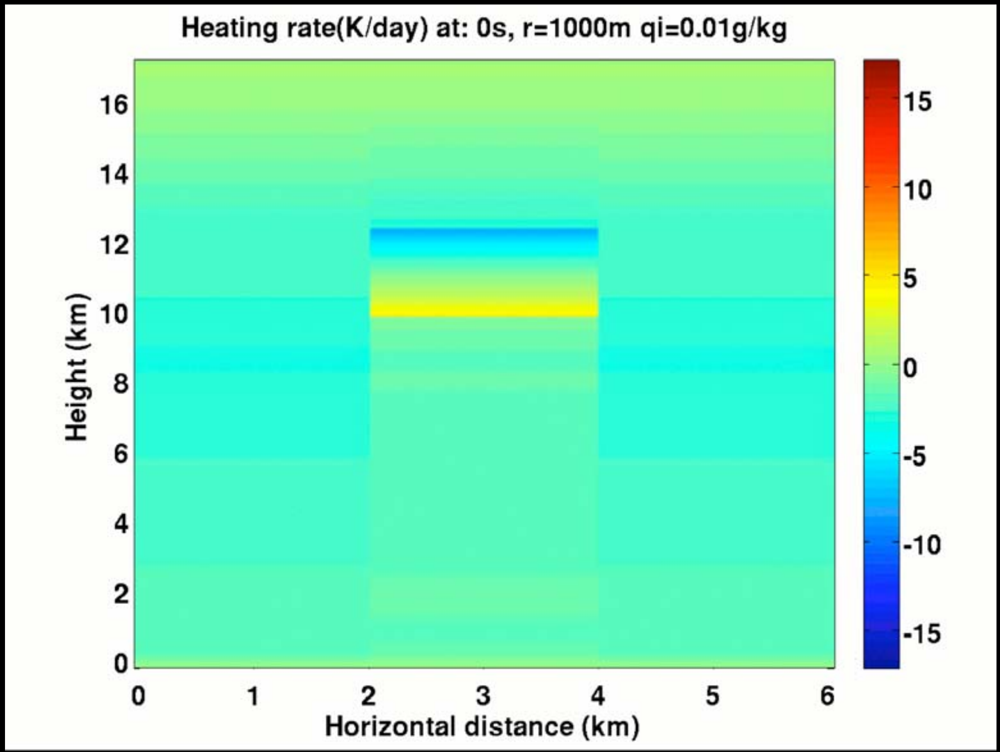
- Tenuous cirrus blob
- 1 km radius, 2.5 km thick
- 0.01 g/kg
- Diffuse radiative energy deposition
- Low heating rates



$$\eta_{spread} = 0.1\, s^{-1}$$

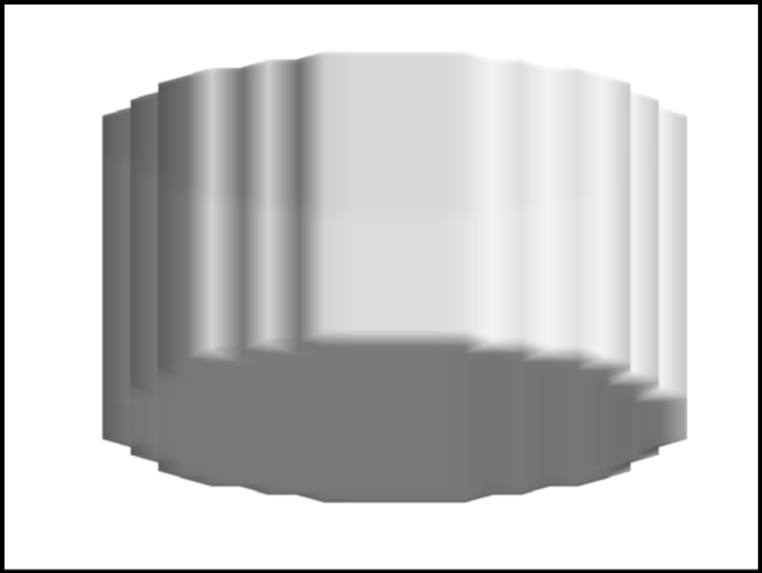
$$\eta_{adj} = 2 \times 10^{-5}\, s^{-1}$$

$$\eta_{mix} = 0.01\, s^{-1}$$



# Case 2

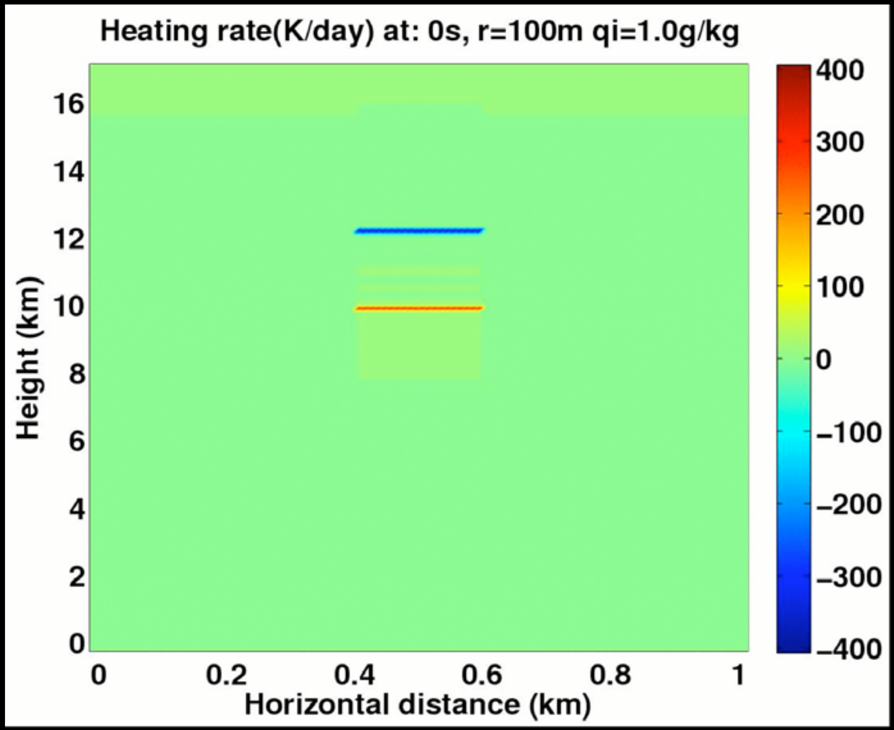
- Dense cirrus - weird cloud
- 100 m radius, 2.5 km thick
- 1 g/kg
- Concentrated radiative energy deposition
- Very high heating rates



$$\eta_{spread} = 3 \times 10^{-3}\, s^{-1}$$

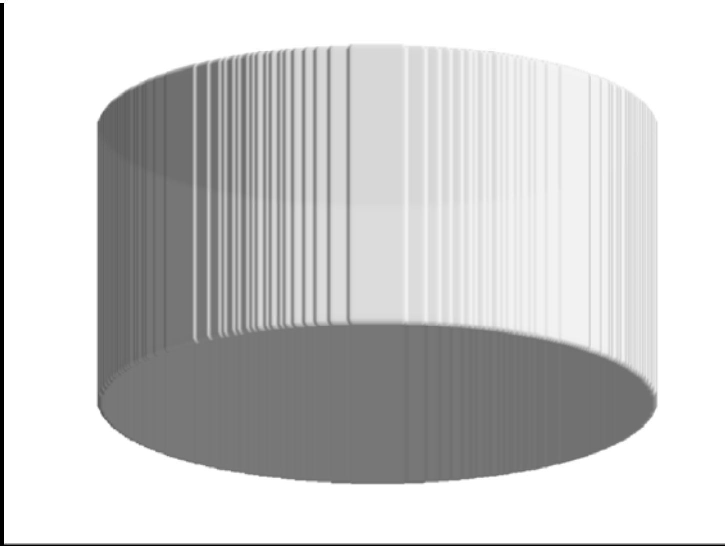
$$\eta_{adj} = 0.04\, s^{-1}$$

$$\eta_{mix} = 0.01\, s^{-1}$$



# Case 3

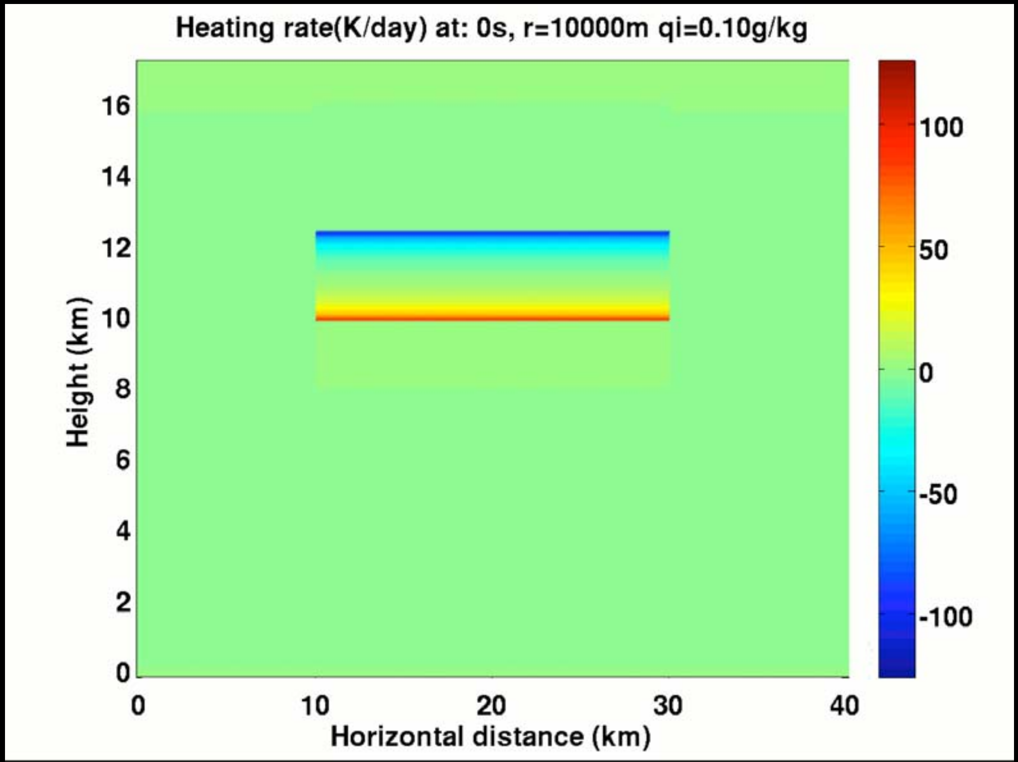
- Thicker cirrus - aged anvil?
- 10 km radius
- 0.1 g/kg
- Medium radiative energy deposition
- Medium heating rates



$$\eta_{spread} = 3 \times 10^{-4}\, s^{-1}$$

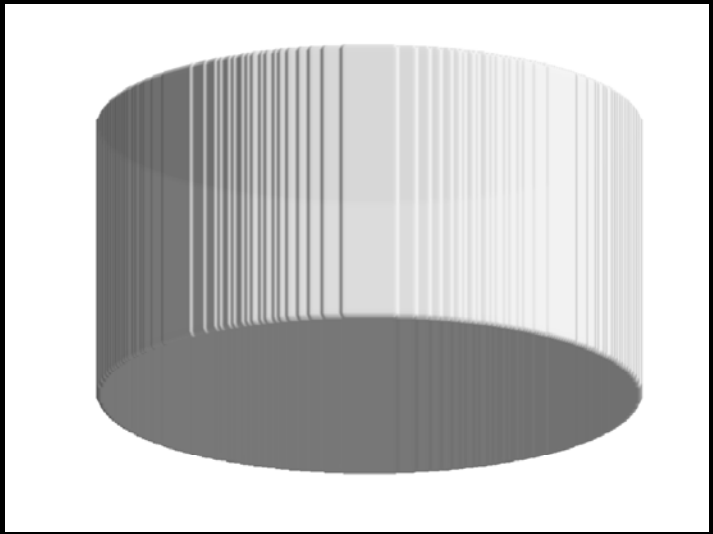
$$\eta_{adj} = 1 \times 10^{-3}\, s^{-1}$$

$$\eta_{mix} = 0.01\, s^{-1}$$



# Case 4

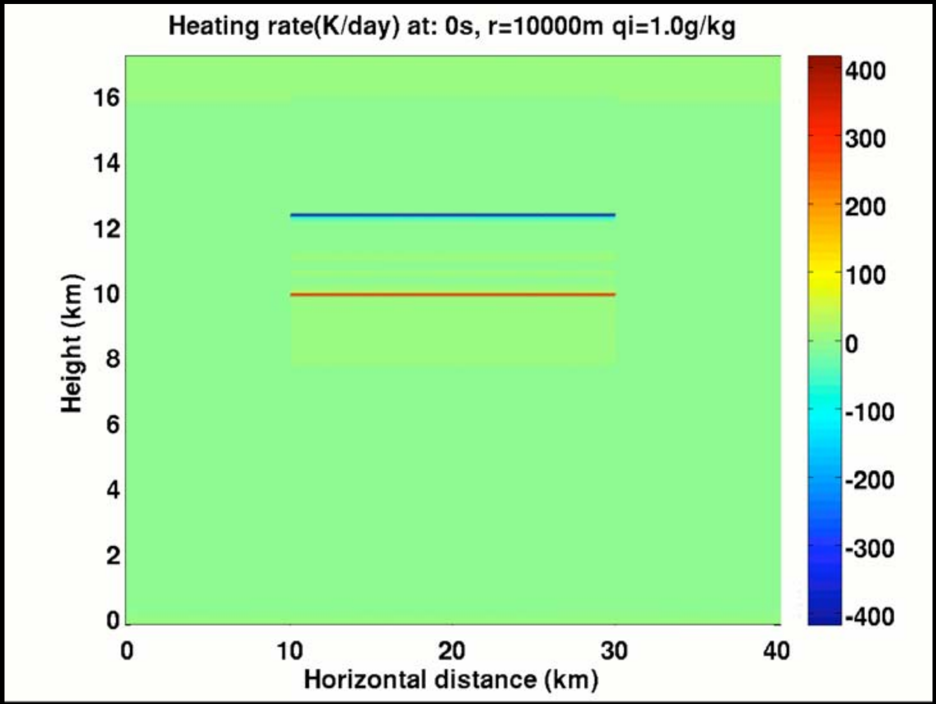
- Dense newly formed cirrus anvil
- 10 km radius
- 1 g/kg
- High radiative energy deposition
- Very high heating rates

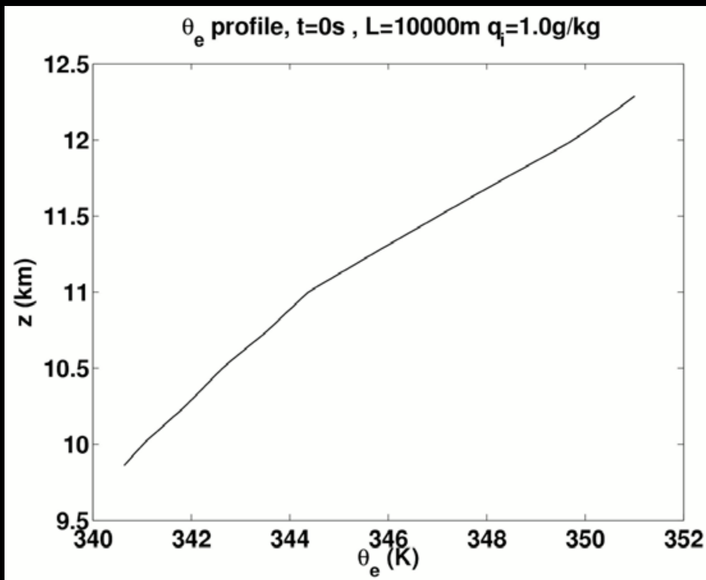


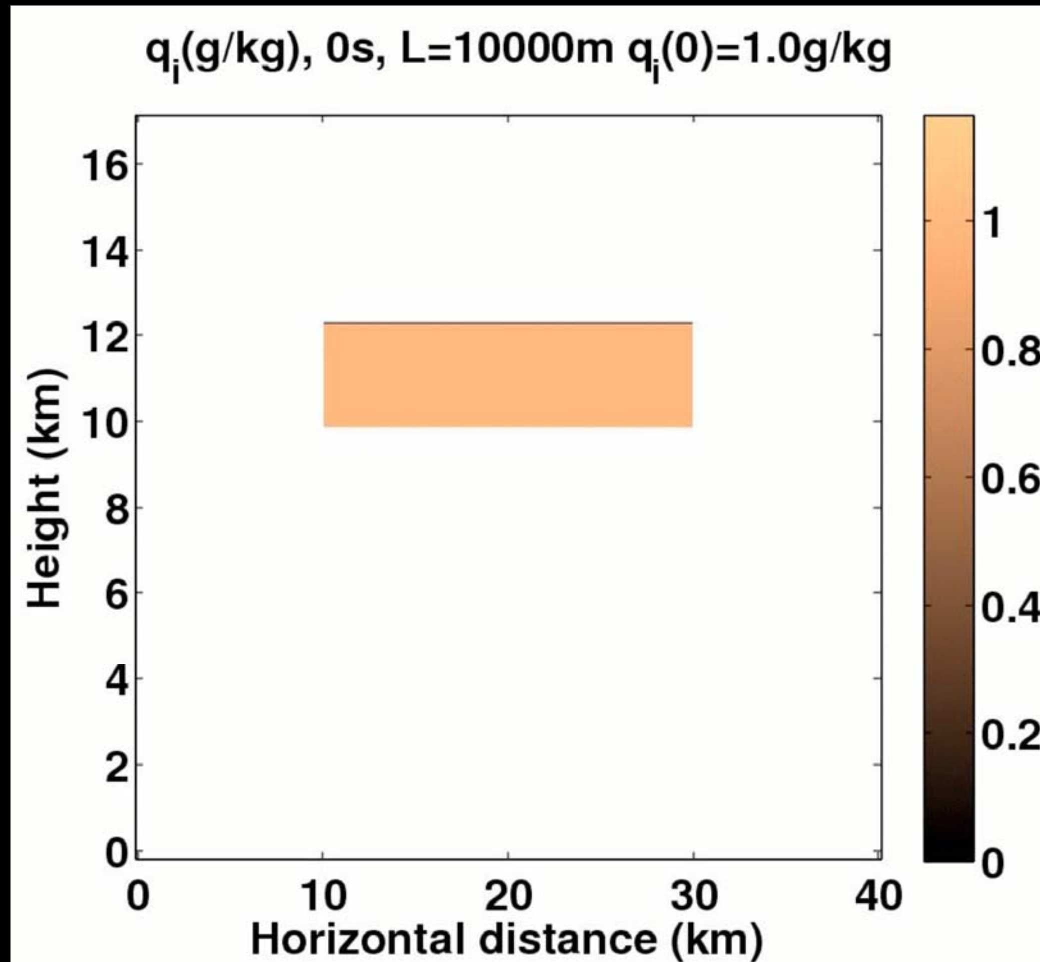
$$\eta_{spread} = 3 \times 10^{-5}\, s^{-1}$$

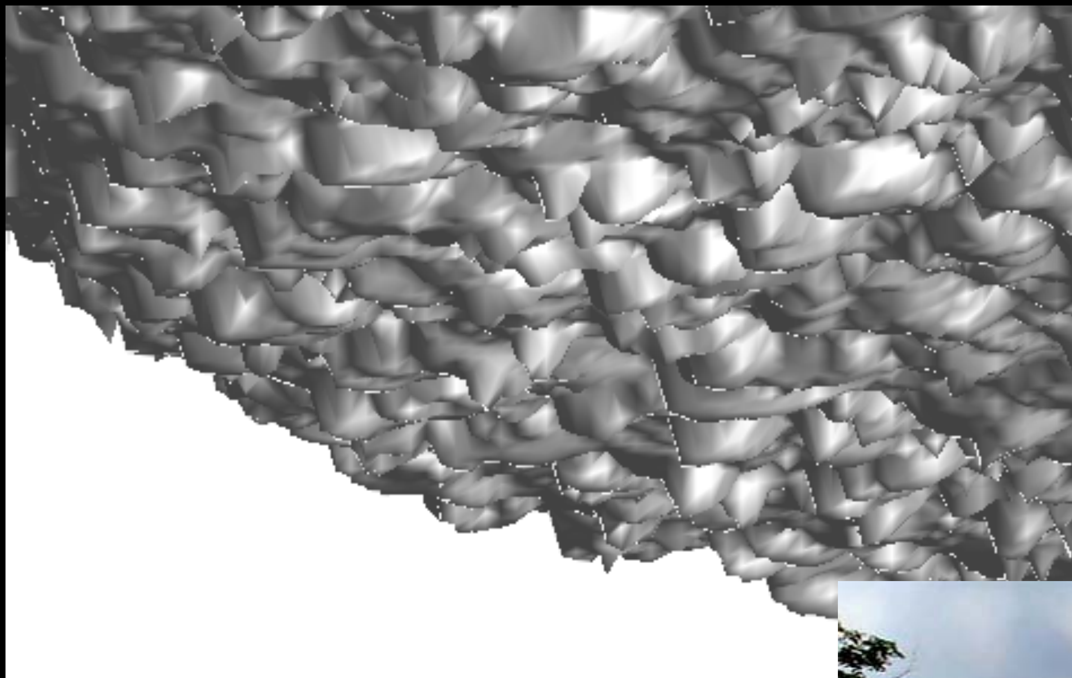
$$\eta_{adj} = 0.05\, s^{-1}$$

$$\eta_{mix} = 0.01\, s^{-1}$$




θe profile, t=0s , L=10000m qi=1.0g/kg
z (km)
θe (K)
12.5
12
11.5
11
10.5
10
9.5
340
342
344
346
348
350
352


qi(g/kg), 0s, L=10000m qi(0)=1.0g/kg
Height (km)
Horizontal distance (km)
16
14
12
10
8
6
4
2
0
0
10
20
30
40
1
0.8
0.6
0.4
0.2
0



Mammatus associated with radiatively driven convective overturning near cloud base

$$\eta_{adj} = 0.05\, s^{-1}$$

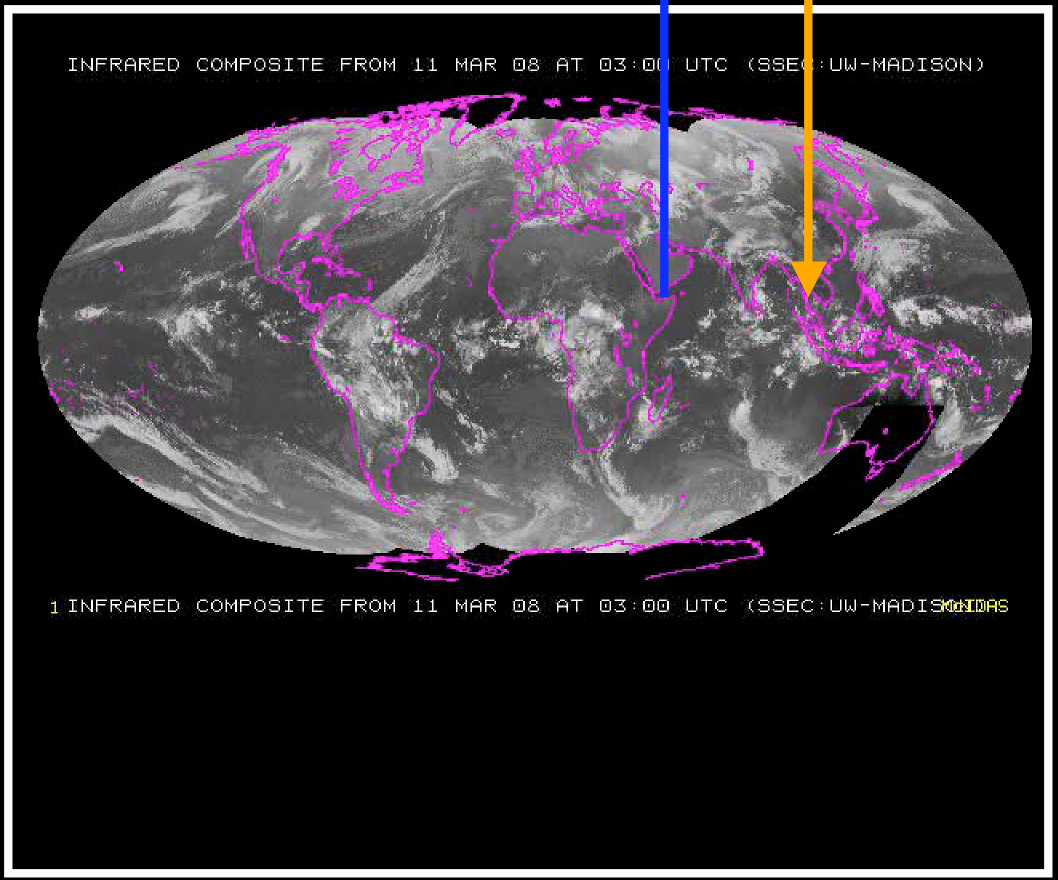
$$\eta_{mix} = 0.01\, s^{-1}$$

Overturning is “fitter” than isentropic adjustment for consumption of available potential energy supply

255 K

$C = 240\ \mathrm{W\ m^{-2}}$

$d(\delta G)/dt = 240\ \mathrm{W\ m^{-2}}$




$$\frac{dS}{dt}\Big|_\theta = \frac{C}{T_o} = \frac{d\left(\delta G\right)/dt}{T_o}\Big|_\theta \geq 0$$

Entropy production is about $1\ \mathrm{W\ K^{-1}\ m^{-2}}$

Evolution is defined by many processes going on simultaneously

$$\sum_i C_i = C$$

Specific energy consumption is constrained by the total available: competition

$$\frac{dC}{dt} = \sum_i \eta_i C_i \rightarrow 0$$

Under quasi-equilibrium transitions, high specific energy consumption is favored by a low feedback parameter: survival of the fittest?

# Summary

- Entropy production is a representation of the conversion of available potential energy to a lower temperature form - energy consumption

# Summary

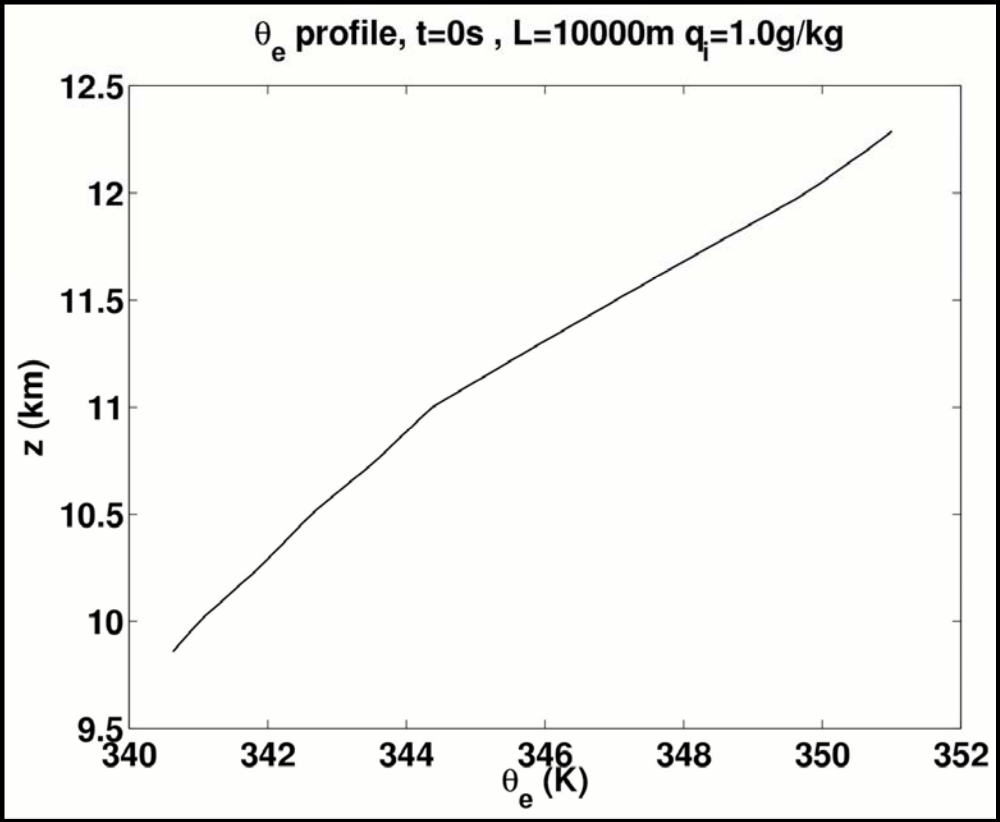
- Case 1: Consumption of available energy is constant; zero feedback $\eta$
- Example: Global/regional clouds and climate
- “The more things change, the more things stay the same”

# Summary

- Case 2: Consumption of available energy is evolving; non-zero feedback $\eta$
- Quasi-equilibrium transitions
- The process that dominates evolution is the one with the lowest feedback parameter - “Survival of the fittest” or “Haste makes waste?”
- Example: clouds on more local scales

# Thankyou

Support from NASA New Investigator Program
Work done with Stina Sjostrom and Clint Schmidt



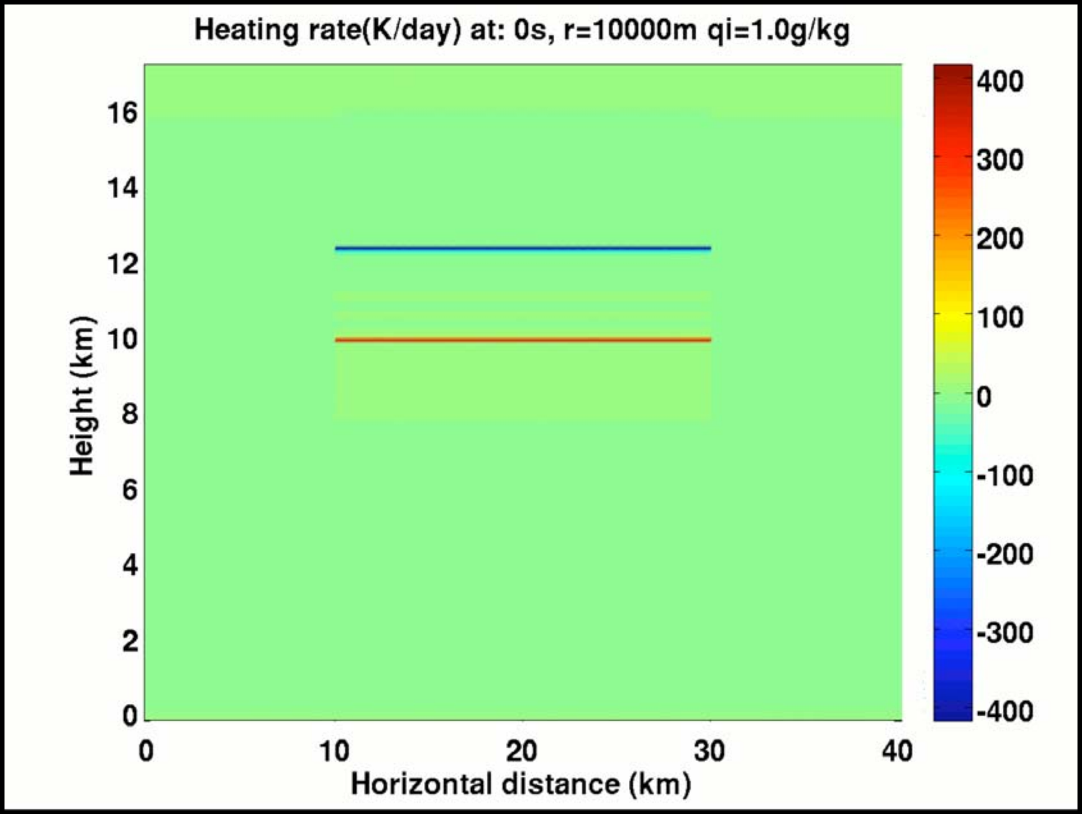

Potential temperature change due to convective mixing

$$\frac{1}{\theta}\frac{d\theta}{dt}\Big|_{\theta,A} \simeq \frac{1}{h}\frac{d\,(\delta z)}{dt}$$

$$\frac{1}{\theta}\frac{d\theta}{dt}\Big|_{\theta,A,z} \simeq \frac{1}{h}\frac{d\,(\delta z)}{dt} = \frac{w^{\star}}{h} = \frac{Nh}{h} = N$$

$$\boxed{\eta_{mix} = N}$$

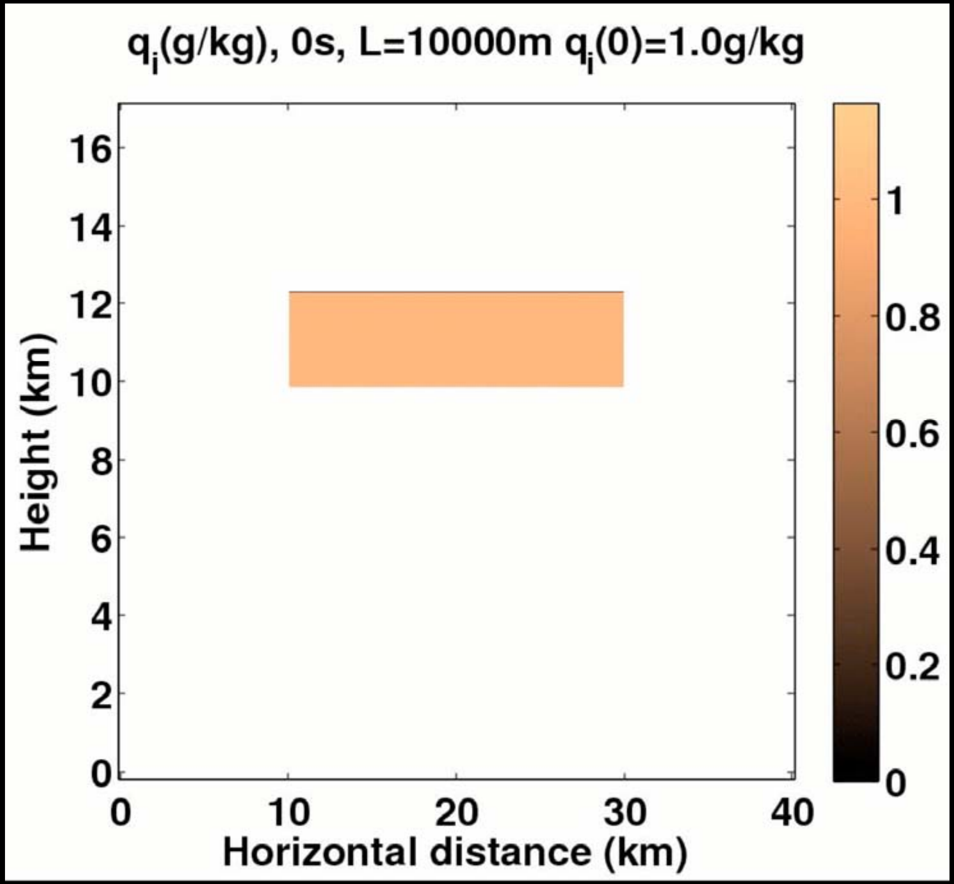
$$N = \left(\frac{g}{\theta}\frac{d\theta}{dz}\right)^{1/2}$$




Potential temperature change due to isentropic adjustment

$$\frac{1}{\theta}\frac{d\theta}{dt}\Big|_{\theta,A,TKE} \simeq \frac{1}{h}\frac{d\left(\delta z\right)}{dt} = \frac{w_{strat}}{h} = \frac{1}{h}\frac{d\theta/dt}{d\theta/dz} = \frac{\mathcal{H}g}{\theta N^2 h}$$

$$\boxed{\eta_{adj} = \frac{\mathcal{H}g}{\theta N^2 h}}$$



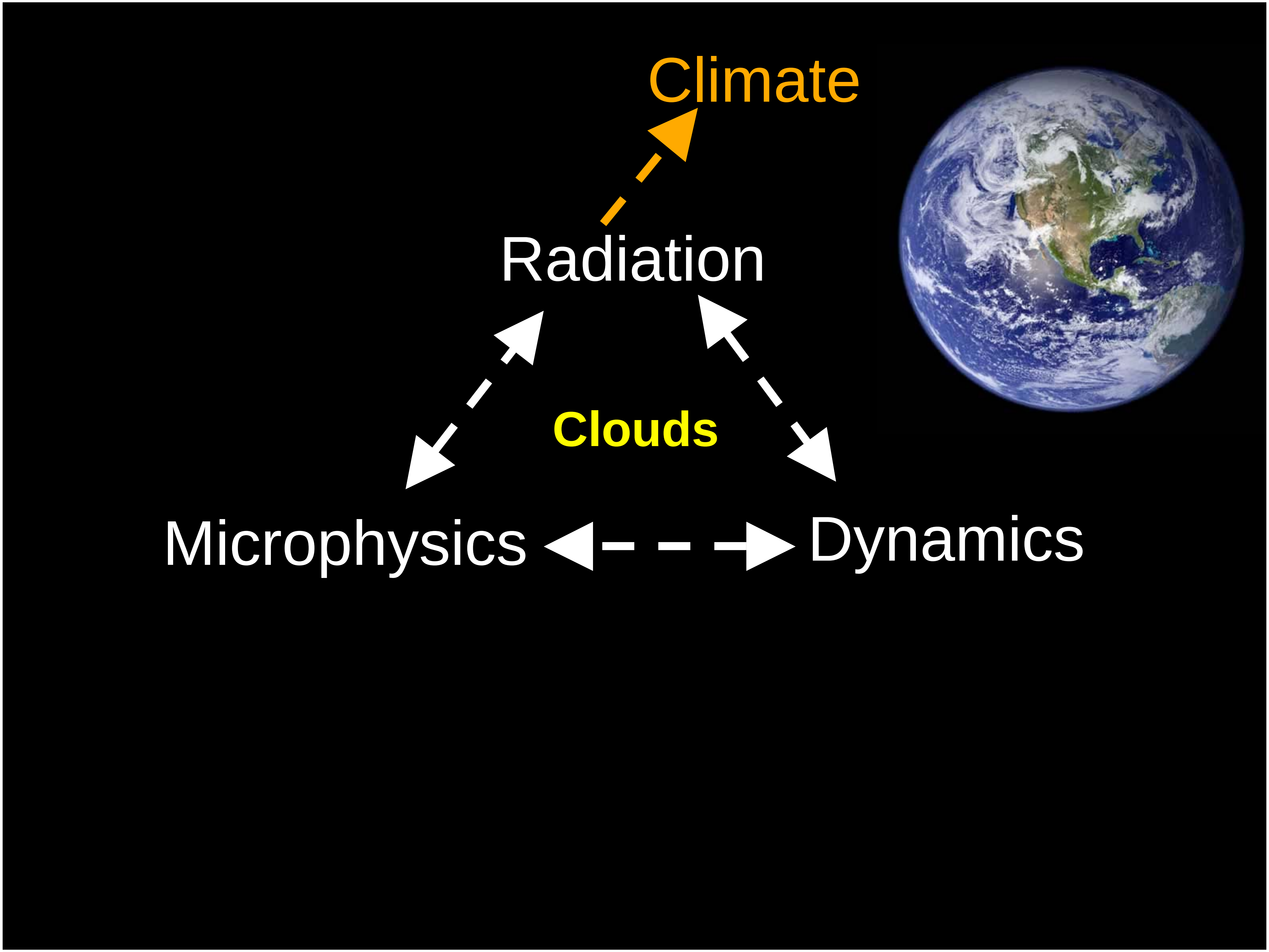

Area change due to Spreading in density currents

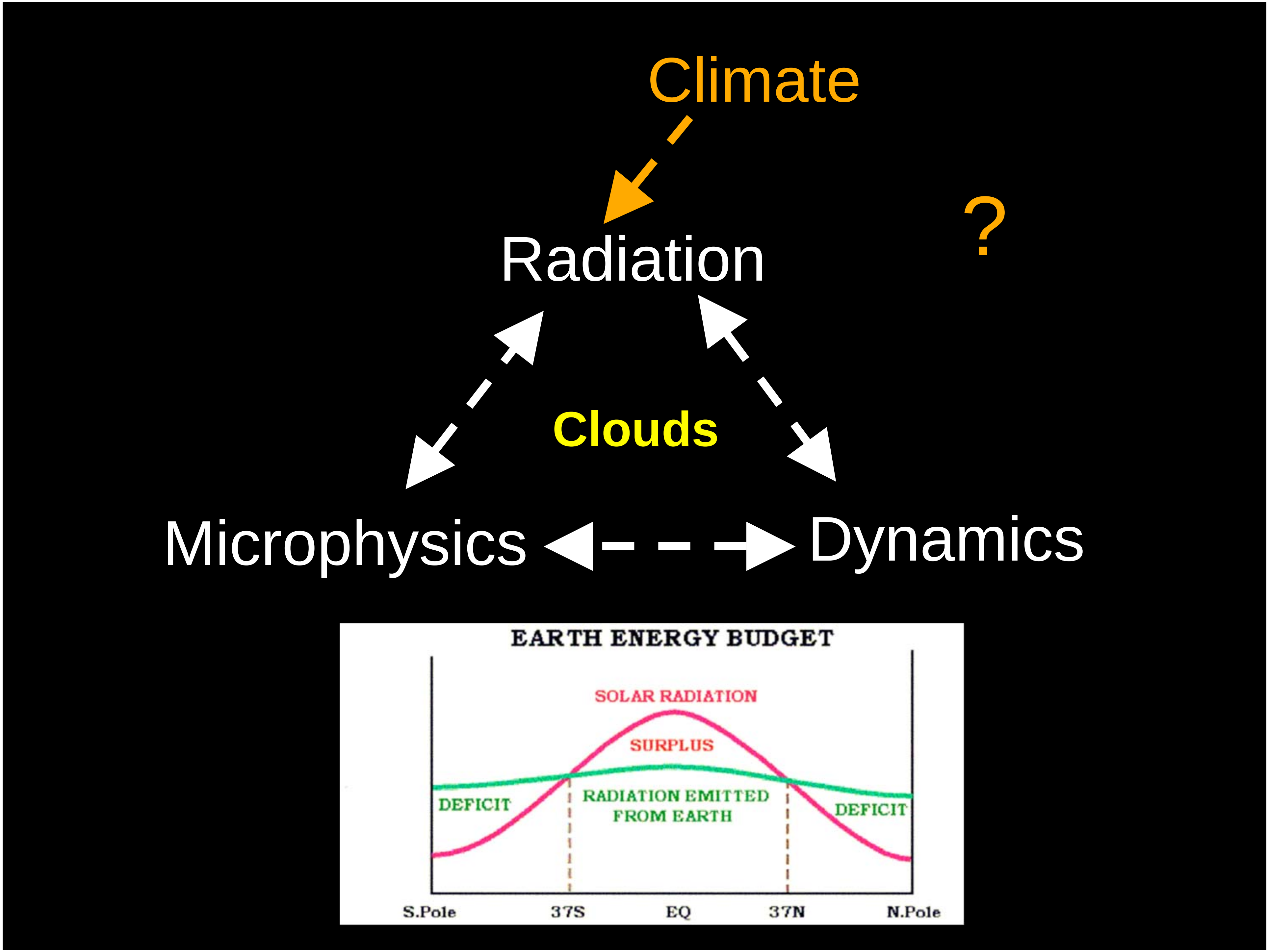
$$u^{\star 2} \simeq N^2 h^2$$

$$h = \frac{1}{\gamma k(r_{ice}) m_i n_i}$$

$$\frac{d \ln A}{dt}|_{\theta,\Delta F} \sim \frac{d \ln L}{dt}|_{\theta,\Delta F} = \frac{Nh}{L}$$

$$\boxed{\eta_{spread} = \frac{Nh}{L}}$$


Climate
Radiation
Clouds
Microphysics
Dynamics


Climate
?
Radiation
Clouds
Microphysics
Dynamics
EARTH ENERGY BUDGET
SOLAR RADIATION
SURPLUS
DEFICIT
RADIATION EMITTED
FROM EARTH
DEFICIT
S.Pole
37S
EQ
37N
N.Pole