Observation-based radiative heating rate profiles

Seiji Kato, Seung-Hee Ham, and Fred G. Rose
NASA Langley Research Center

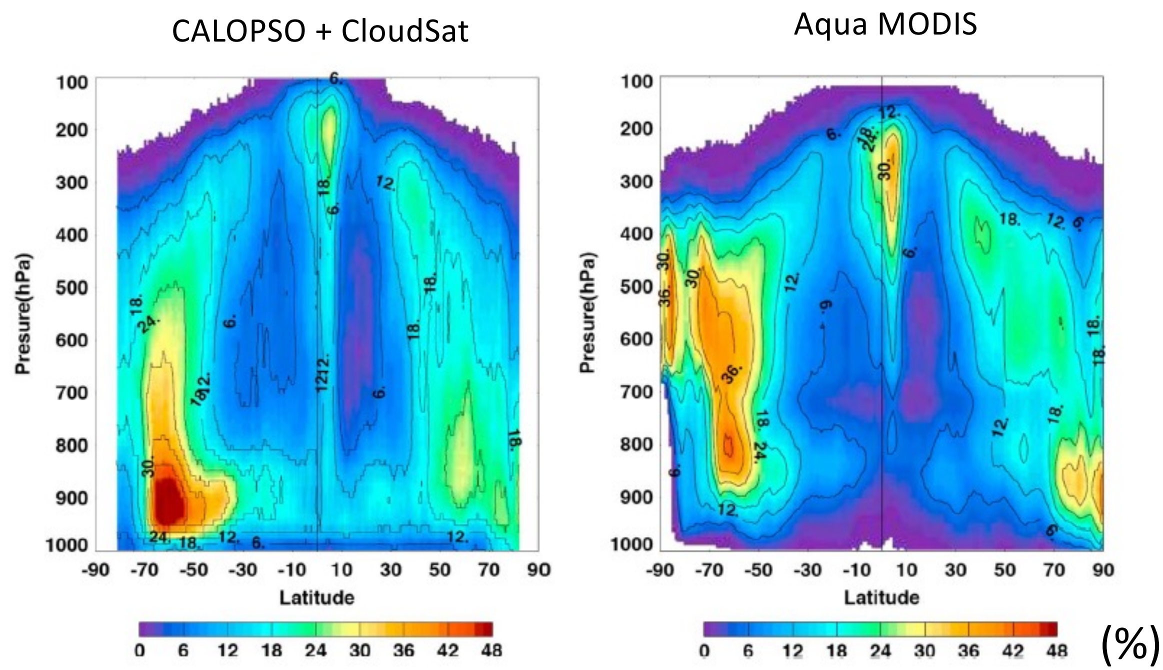
ICCP-GSRA workshop and 2nd EarthCARE modeling workshop
March 27-29, 2023

Outline of this talk

- Tight connections among cloud radiative effects, dynamics in the atmosphere, and hydrological cycle
- Radiative heating rate profile derived from A-train observations
- Entropy balance equation
- Balance among radiative heating rate profiles, irreversible processes, and entropy stored in the atmosphere.
- Irreversible processes associated with clouds are large contributors of entropy production rates in the atmosphere.

Zonal monthly mean active sensor derived cloud vertical profile (April 2010)

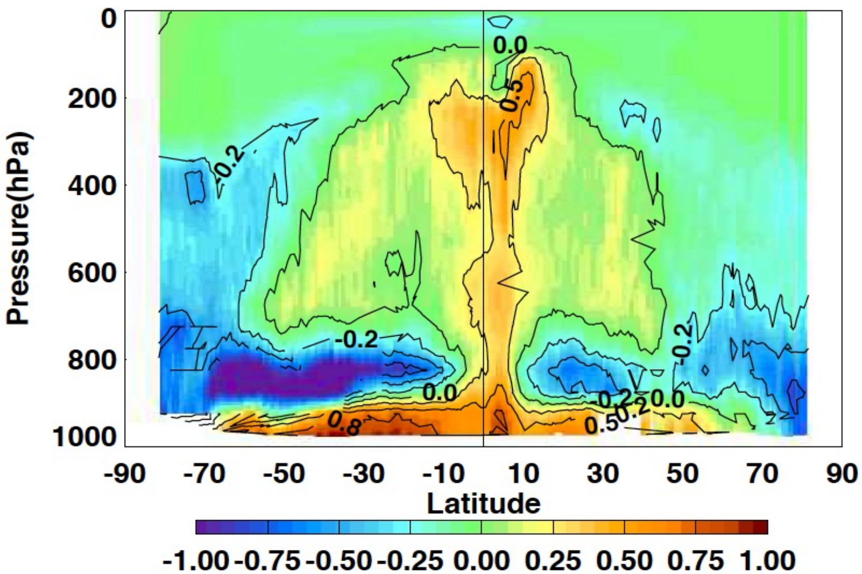
Percentage of cloud occurrence in a 1 degree zonal and 1 hPa layer



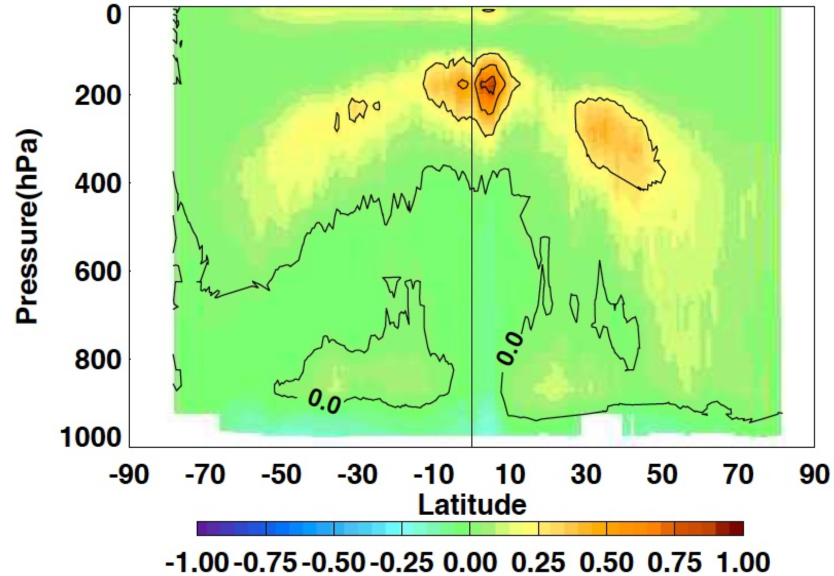
Kato et al. 2019

Zonal monthly mean cloud radiative effect in K day^{-1}

Longwave



Shortwave



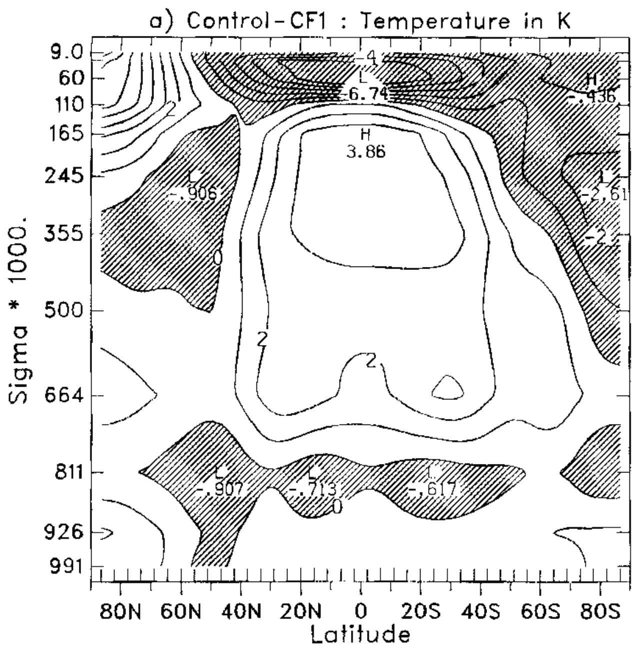
Clouds help reducing radiative cooling in the tropics and enhance radiative cooling in polar regions i.e. contributing the production of mean zonal available potential energy

Large cloud top cooling and warming in the tropics between 400 hPa to 200 hPa

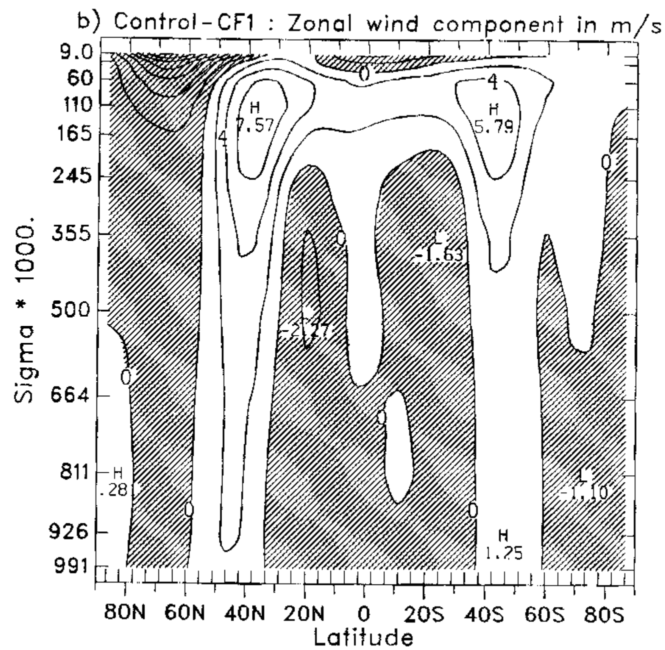
Kato et al. 2019

Effect of longwave cloud effect (Control – no LW cloud effects)

Temperature (K)



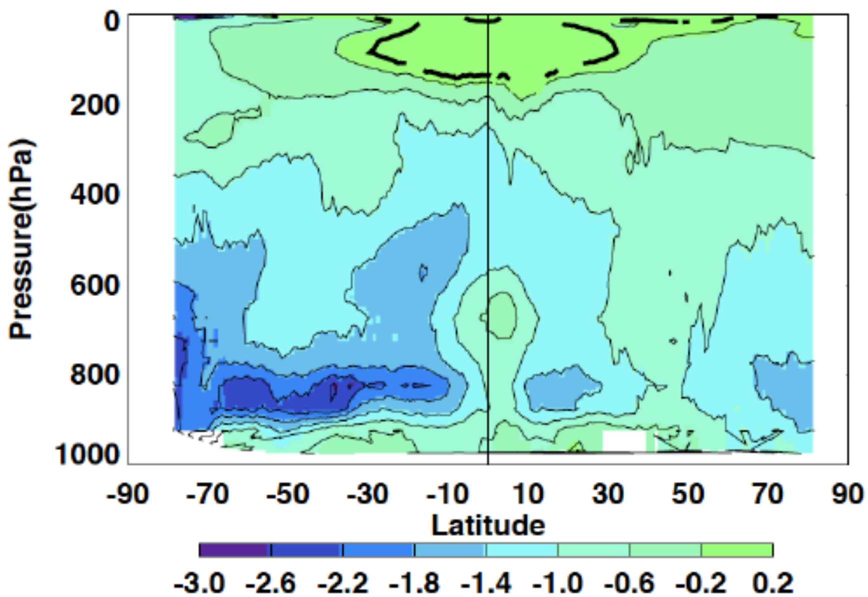
Zonal wind (ms^{-1})



Hatched: negative values

Longwave cloud radiative effect:
Warm the tropical mid-latitude atmosphere, strengthening zonal wind (Slingo and Slingo 1988)
Clouds on-off klimate Intercomparison Experiment (COOKIE, Stevens et al.)

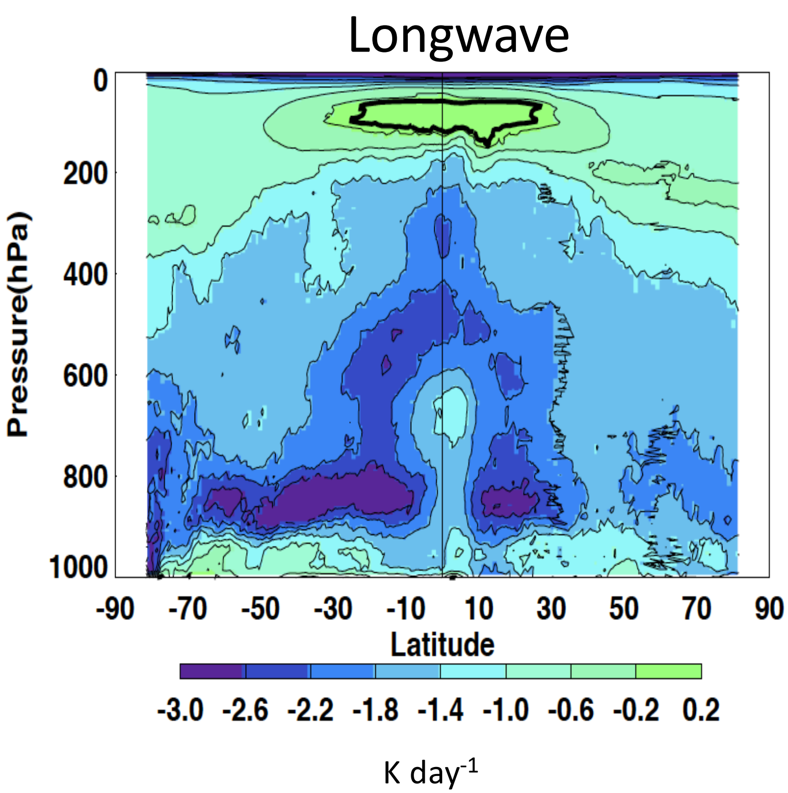
Mean zonal longwave + shortwave radiative heating rates in K day^{-1}

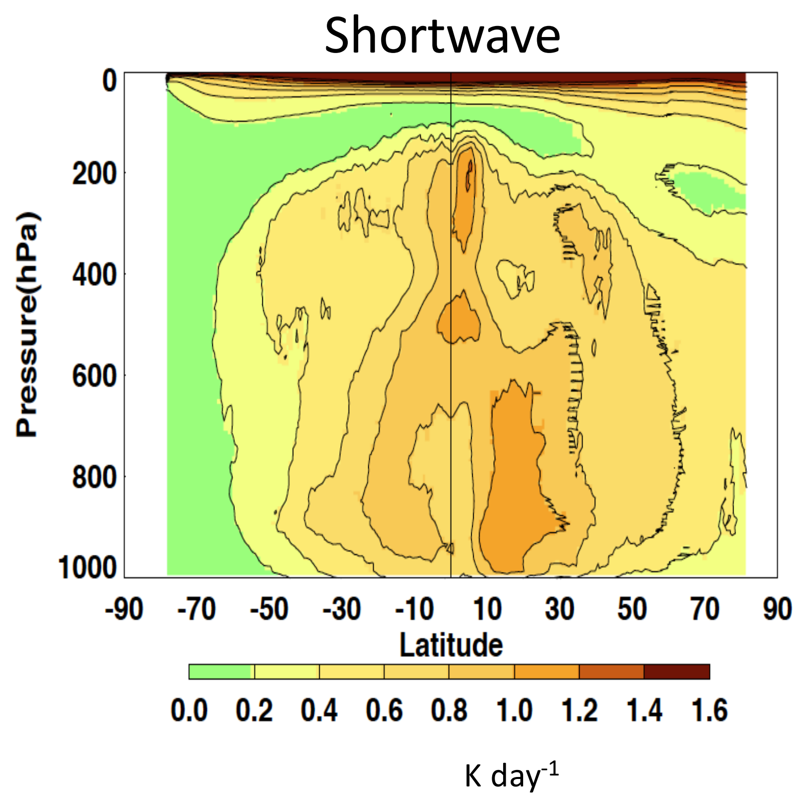


K day^{-1}

- Atmosphere is cooled radiatively
- Radiative cooling is relatively flat zonally
- But diabatic heating by precipitation is much larger in the tropics

Longwave and shortwave monthly zonal mean radiative heating rate in K day^{-1} for April 2010





From a modeling perspective, we need accurate cloud properties to compute heating rates

Another way to look the relationship between radiative heating rates and cloud processes

A thermodynamic view of Earth energy imbalance
A conceptional model to understand an entropy view

Entropy budget equation

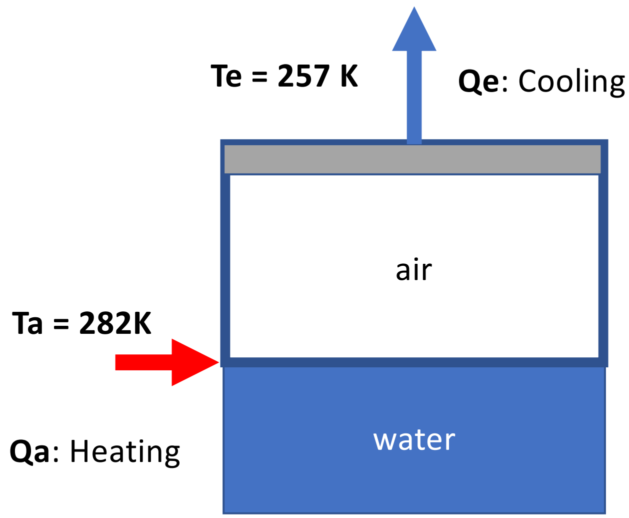
$$\frac{dS}{dt} = \frac{Q_a}{T_a} - \frac{Q_e}{T_e} + \dot{\Sigma}_{\mathrm{irr}}$$

$$\frac{F_{TOA}^{net}}{T_{SST}} = \int \frac{F_{net}^{SW}(z)}{T(z)} dz - \int \frac{T_{trans}(z) F_{up}^{LW}(z)}{T(z)} dz + \dot{\Sigma}_{\mathrm{irr}}$$

$\dot{\Sigma}_{\mathrm{irr}}$ includes entropy produced by all irreversible process in the Earth system

Ta and Te are effective absorption and emission temperatures

The CERES team computed shortwave absorption divide by the layer temperature and longwave emission to space divide by the layer temperature and estimated entropy production rate (Edition 4.1 SYN1deg)



We do not ask how Earth is heated and cooled.

Magnitude of entropy production by process

Entropy source	Expression	Conditions	Size (W kg^{-1} K^{-1})
$\dot{s}_{dif}$ Diffusion of enthalpy by air-hydrometeor (liquid) conduction	$\frac{r_l c_l (T_l - T)^2}{T_l T \tau_{cl}}$	Liquid water content at 500 hPa: 5 g m^{-3} Mixing ratio r_l: 7.5×10^{-3} Specific heat capacity of liquid water c_l:4218 J kg^{-1} K^{-1} Air temperature T: 265 K Hydrometeor temperature T_l: 275 K Conductive timescale: $\tau_{cl} \approx 100s$	4×10^{-4}
$\dot{s}_{dif}$ Diffusion of kinetic energy through air-hydrometeor drag force (raindrops)	$r_l \frac{\mathbf{v}_l \cdot \mathbf{v}_l}{\tau_{vl} T}$	Rain rate of 10 mm hr^{-1} Mixing ratio r_l: 0.4×10^{-3} Terminal velocity V_T:10 m s^{-1} Viscous time $\tau_{vl} \approx \frac{V_T}{g} = 1s$ Air temperature: 265 K	2×10^{-4}
$\dot{s}_{rad}$ Radiative heating	$\frac{\dot{q}_{rad}}{T}$	Heating rate: 1 K day^{-1} Air temperature: 273 K	4×10^{-5}
$\dot{s}_{dif}$ Diffusion of enthalpy by air-hydrometeor (ice) conduction	$\frac{r_i c_i (T_i - T)^2}{T_l T \tau_{cl}}$	Ice water content 0.3 g m^{-3} at 400 hPa Mixing ratio r_i: 5.5×10^{-4} Specific heat capacity of liquid water c_i:2106 J kg^{-1} K^{-1} Air temperature T = 265 K Hydrometeor temperature: T_l = 270 K	2×10^{-5}
$\dot{s}_{dif}$ Diffusion by conduction in moist air	$\frac{k_T}{\rho_a T^2}(\nabla T \cdot \nabla T)$	Thermal conductivity k_T: $32\times10^{-4} W m^{-1} K^{-1}$ Air density ρ_a: $0.66\ kgm^{-3}$ Air temperature T: 265 K Temperature gradient ∇T:10 K m^{-1}	7×10^{-6}
$\dot{s}_{dif}$ Diffusion of kinetic energy through air-hydrometeor drag force (cloud drops)	$r_l \frac{\mathbf{v}_l \cdot \mathbf{v}_l}{\tau_{vl} T}$	10 µm diameter with the concentration of 500 cm^{-3} Mixing ratio r_l: 2.8×10^{-4} Terminal velocity v_l:1 cm s^{-1} Viscous time: $\frac{10^{-2}}{g} = 10^{-3}$ s Air temperature: 265 K	1×10^{-7}

Large entropy productions in the atmosphere occur in processes associated with clouds

Summary

- Cloud radiative effects have impacts on dynamics and hydrological cycle.
- Active sensors provide vertical profile of clouds and aerosol properties that can be used to compute radiative heating profiles.
- According to the entropy balance equation, vertical radiative heating rate profiles is balanced with entropy production rate by reversible processes and entropy stored in the atmosphere.
- Processes associated with clouds contribute most to entropy production rate in the atmosphere.
- Accurate radiative heating rates are necessary to model cloud processes
- Observation-based radiative heating rate profiles will be available for modeling community (what temporal and spatial scales?).

Back-ups

Simplest system (Planck 1906)

Temperature of the atmosphere (black) = Ta

Temperature of the surface (black) = Ts

Entropy produced by the surface is the sum of 1) and 2)

1) Due to heating and cooling $\sigma(Ta^4\text{-}Ts^4)/Ts$
2) Due to radiation exchange $(4/3)\sigma Ts^4/Ts - (4/3)\sigma Ta^4/Ta$

Total entropy production by the surface

$\sigma(Ta^4\text{-}Ts^4)/Ts + (4/3)\sigma Ts^4/Ts - (4/3)\sigma Ta^4/Ta$

(the second and third term can be looked as the entropy flux, positive outward)

Zonal monthly mean active sensor derived cloud vertical profile (April 2010)

Percentage of cloud occurrence in a 1 degree zonal and 1 hPa layer