# Stratocumulus and Stable Layers in the Solar System

(boundaries optional)

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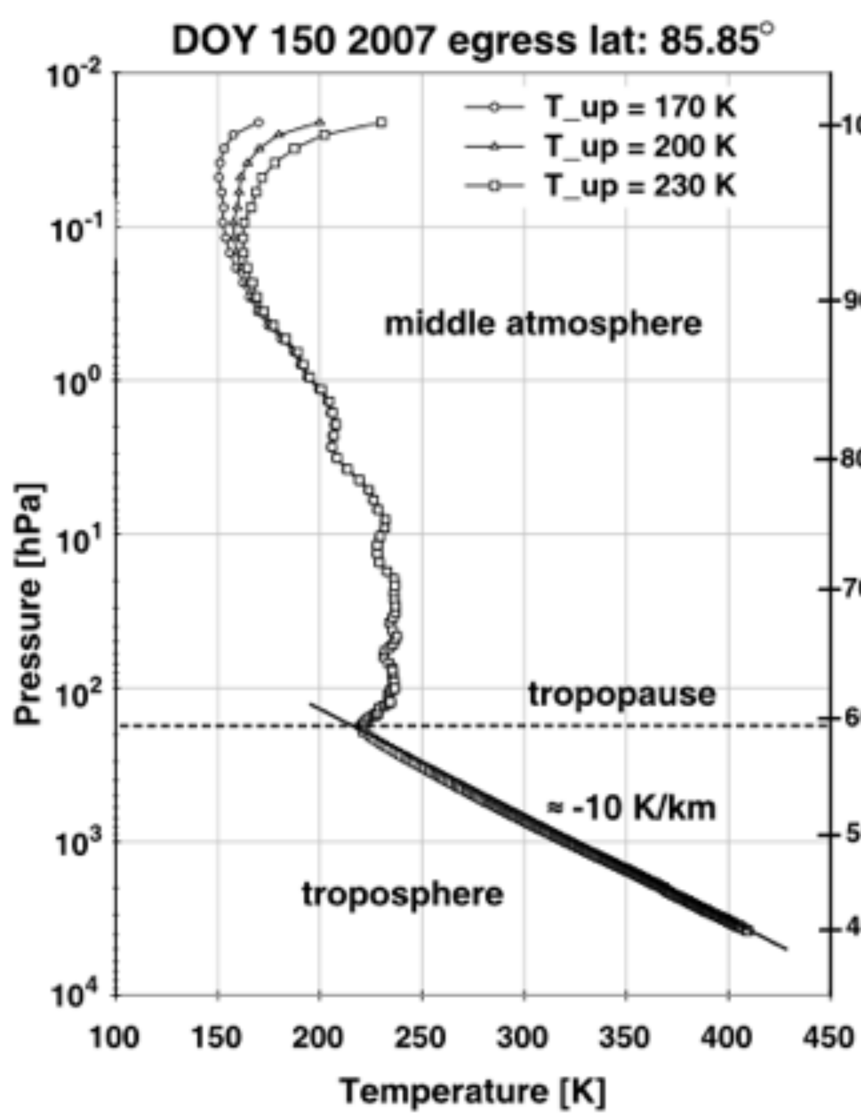
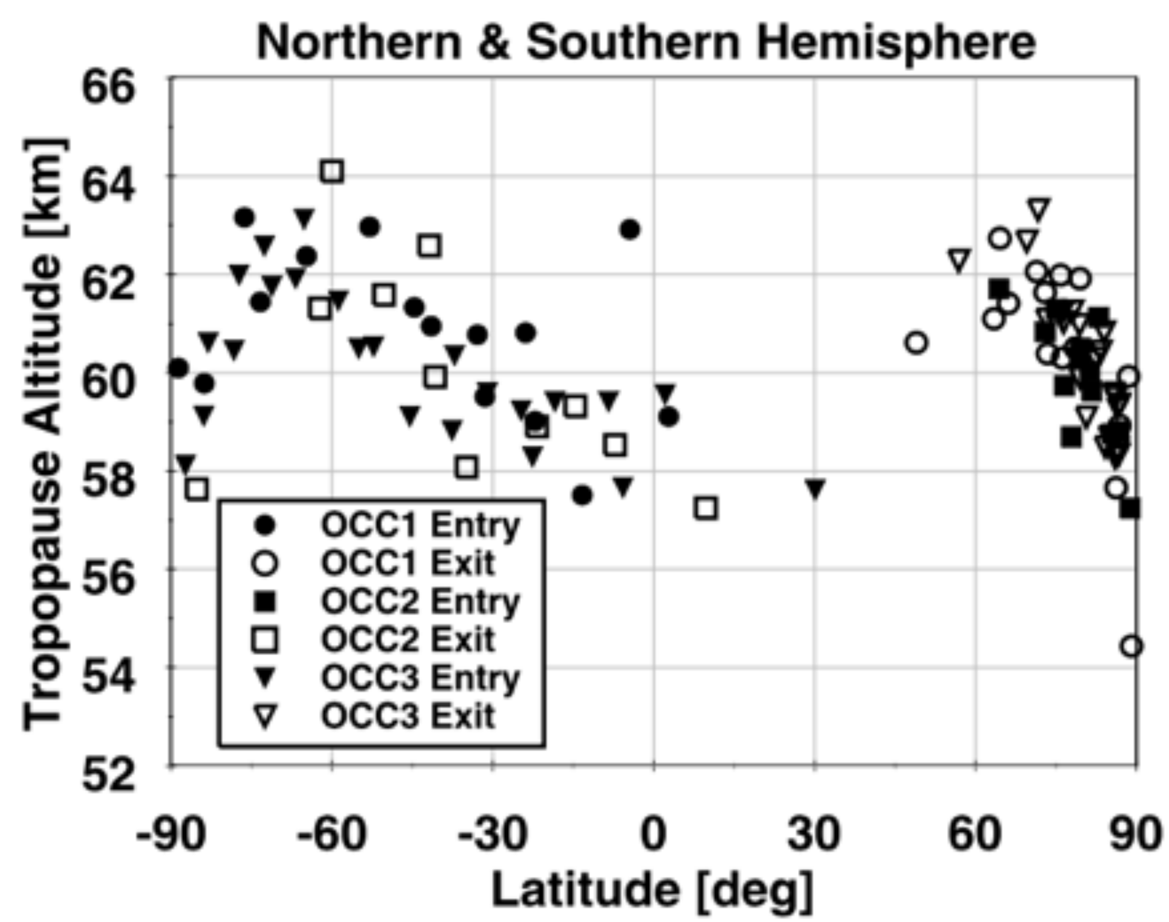
**[work in progress]**

# My original motivation

- Venus' sulfuric acid clouds deepen with lowering insolation, just like marine stratocumulus

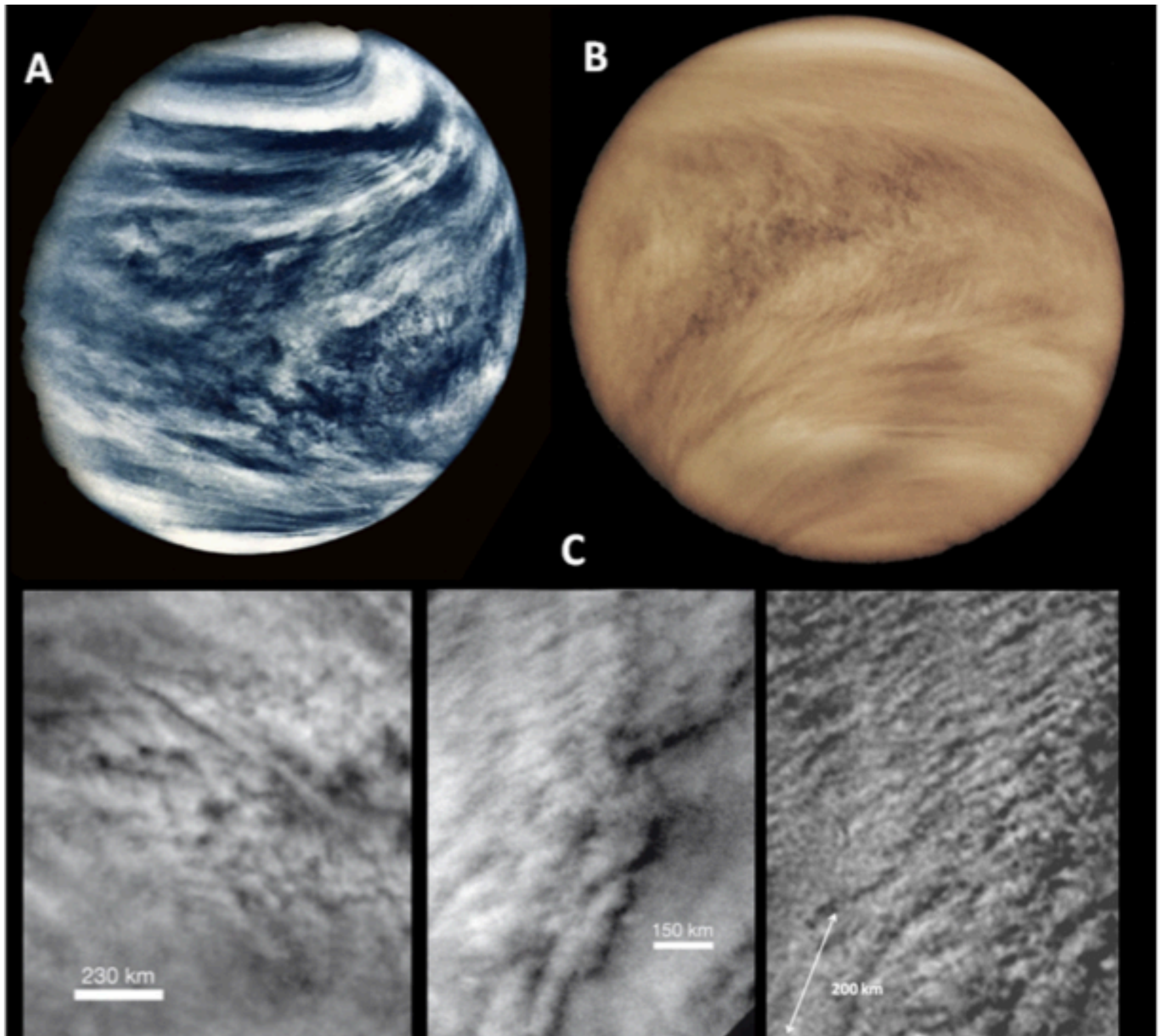



**Tellman et al. 2009**

**Imamura et al. 2014**

# Venus' clouds are global, variable, and account for a ~70% albedo



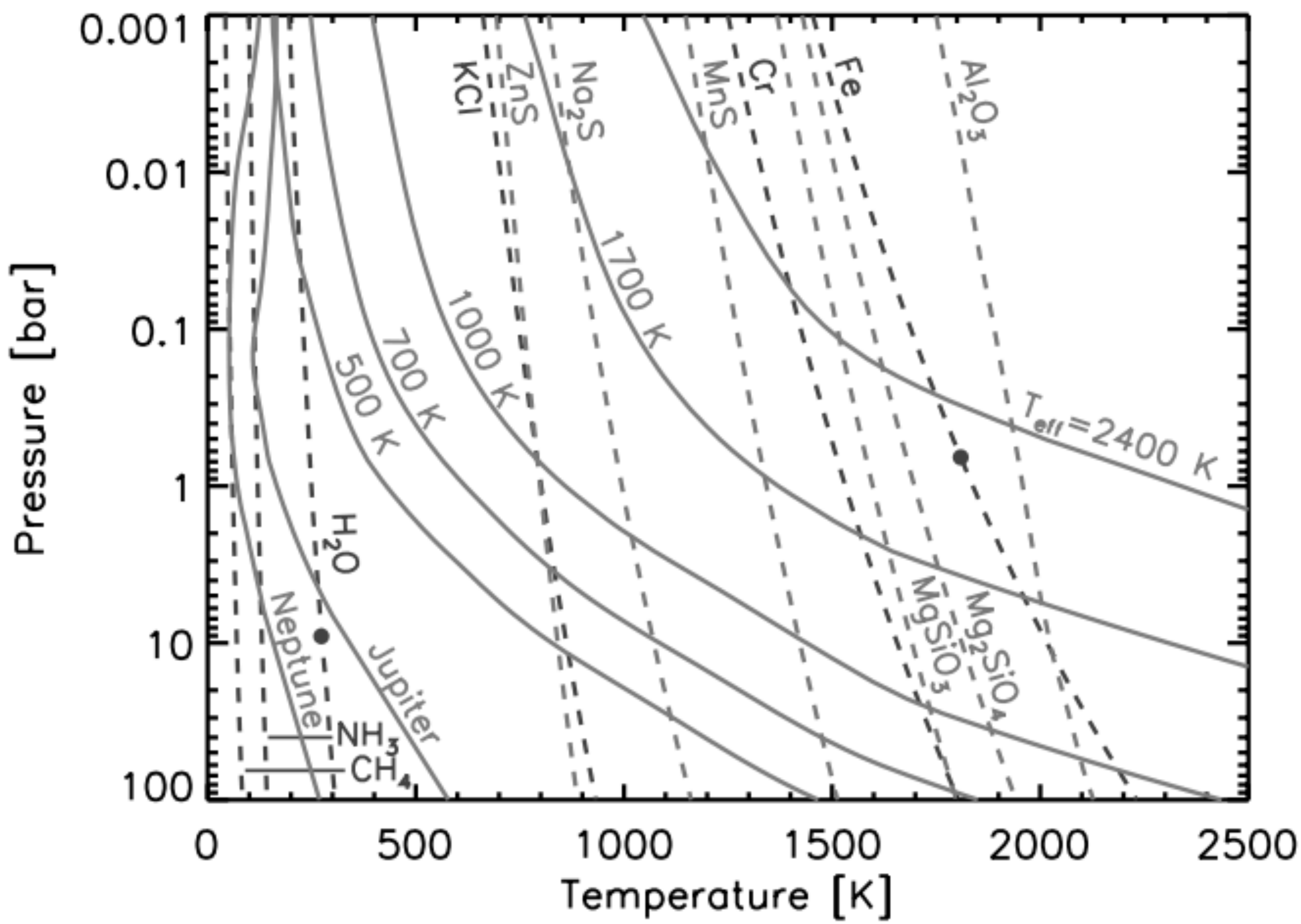

Venus in UV; Sanchez-Lavega et al. 2017

# The big picture: What sets planetary albedo?

- Stratocumulus covers more area than any other cloud type on Earth (Wood 2012)
- Earth is an outlier, in the sense of having a large clear-sky component (Mars ~ doesn't have an atmosphere)
  - Venus — global cloud deck of sulfuric acid, albedo of ~70%
  - Titan — global stratospheric smog layer, albedo of ~55%
- Jupiter, Saturn, Uranus, Neptune have global and/or alternating zones of clouds

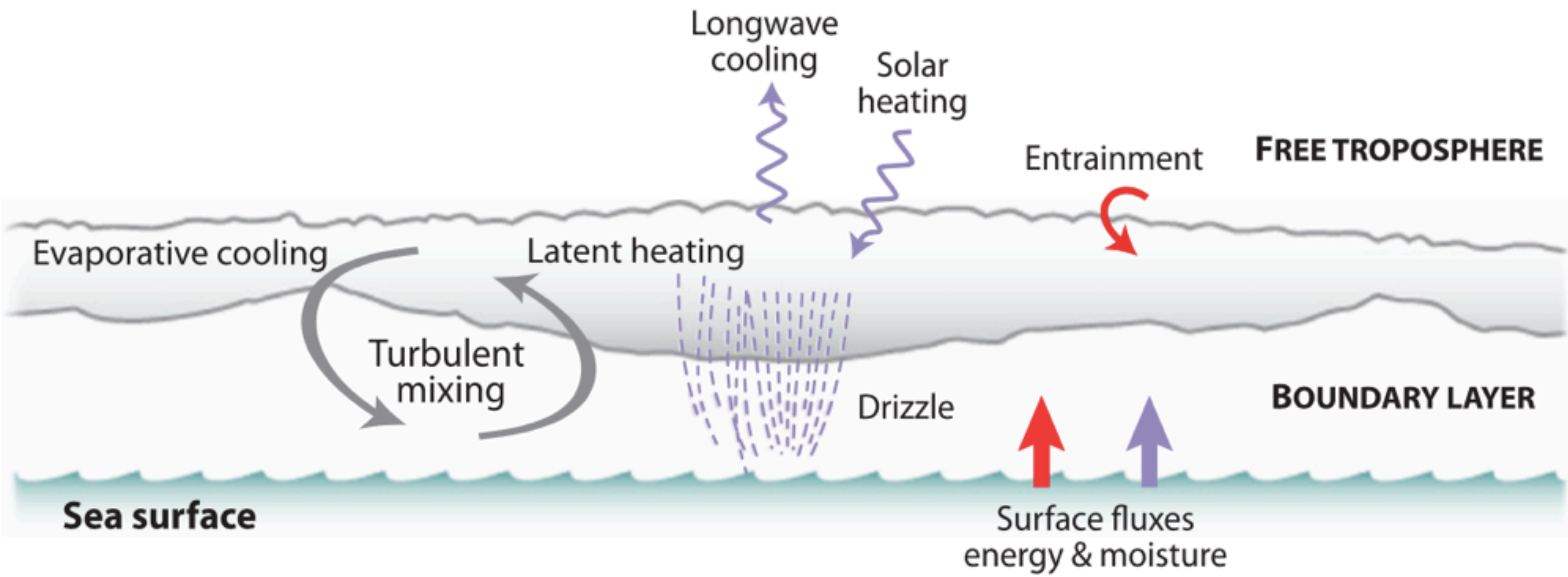
# Exoplanet atmospheres have clouds of iron and rock…

**If so, how do they form? Are they global? Diurnal?**




**Fortney, submitted**

# Stratocumulus forms in stably stratified layers by topside longwave cooling




**Wood 2012, Stevens 2006**

# A rough framework for cloud formation in stably stratified atmospheres

- Fundamentally, stratocumulus is driven by radiative cooling from the top.
- Clouds need to be optically thick to generate the driving buoyancy flux.
- A minimum flux of kinetic energy is required to prevent hydrometeors from settling out.
- In a bulk sense, radiative cooling balances latent and sensible heat fluxes and generates kinetic energy with some (given) efficiency, which must (at least in part) dissipate on hydrometeors.

# Preliminaries:
# BL heat-engine efficiency

$$F_\theta \sim \rho w C_p d\theta \qquad\qquad b \equiv \left( g\frac{d\theta}{\theta} \right) \sim w^2/h$$

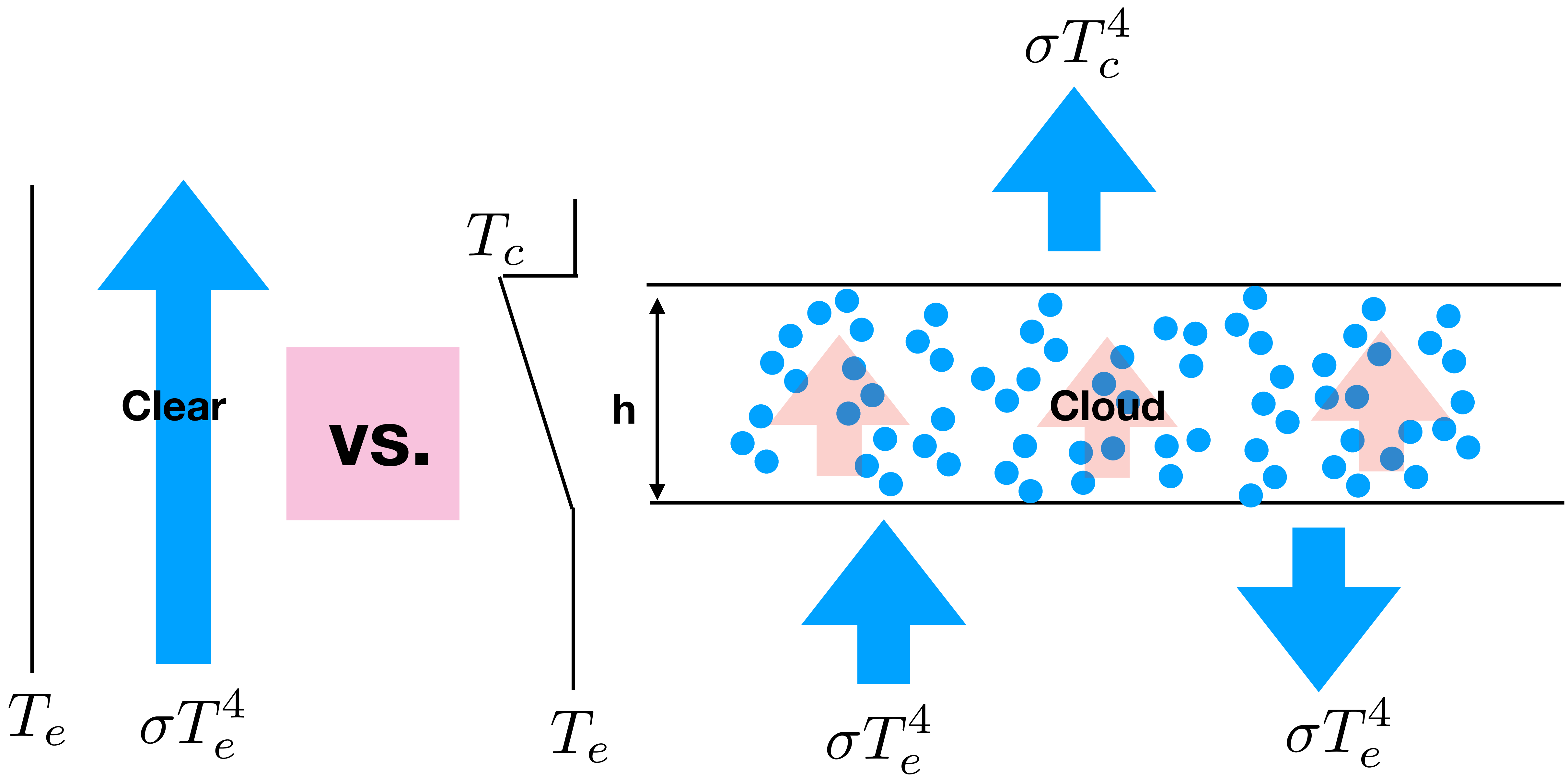
$$F_\theta \sim \rho w \left( g\frac{d\theta}{\theta} \right) \frac{C_p\theta}{g}$$

$$\sim \rho w^3 \frac{C_p\theta}{gh}$$

$$\sim \rho w^3 \frac{\theta}{\Delta T_{\mathrm{ad}}}$$

$$F_{\mathrm{KE}} \sim \rho w^3 \sim \eta F_\theta \quad \textbf{with} \quad \eta \equiv \frac{\Delta T_{\mathrm{ad}}}{\theta}$$

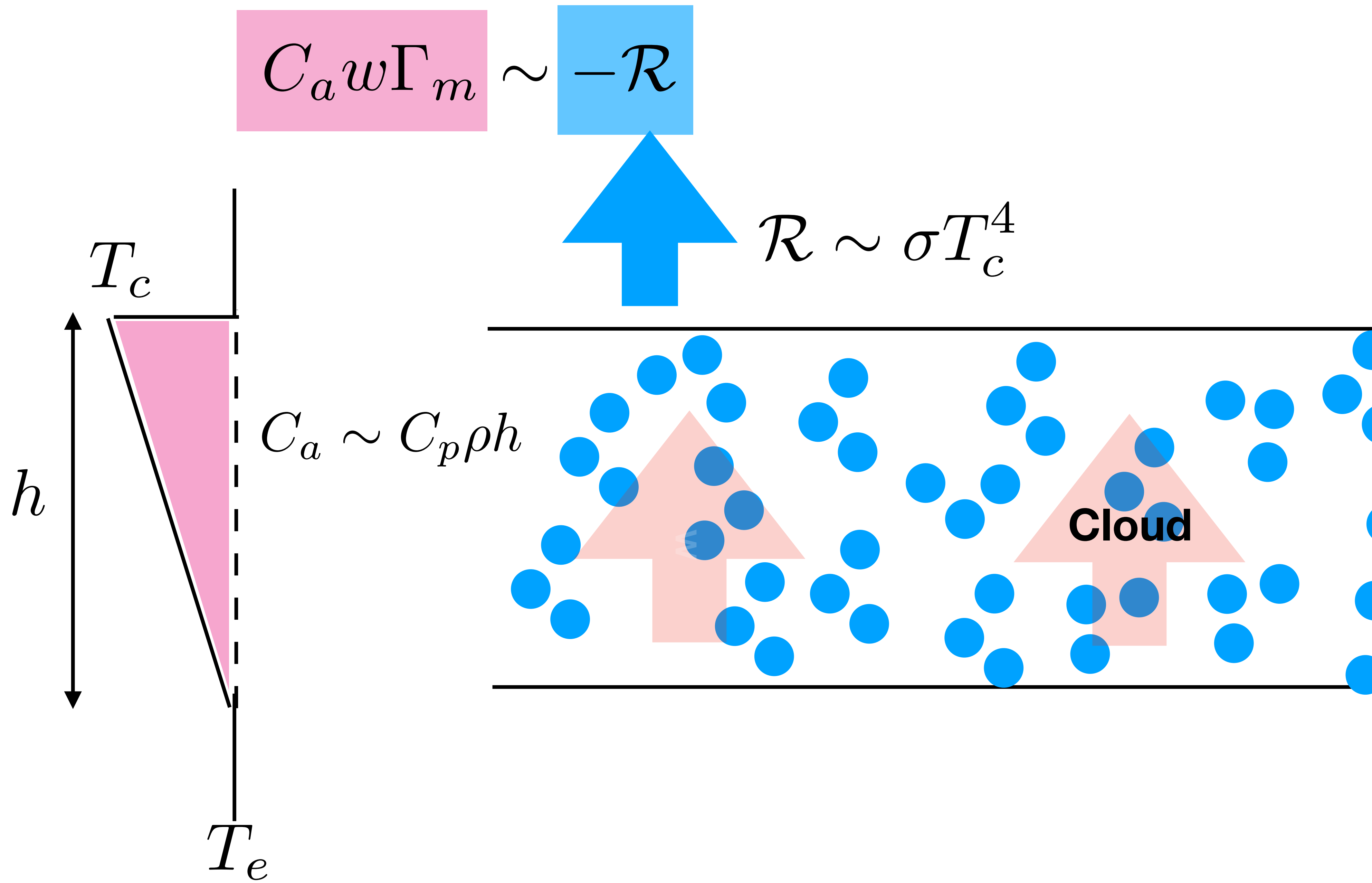
# Conceptual cloud model




$$T_c = T_e - \Gamma_m h$$

$$T_c^4 \sim T_e^4(1 - 4\Gamma_m h/T_e)$$

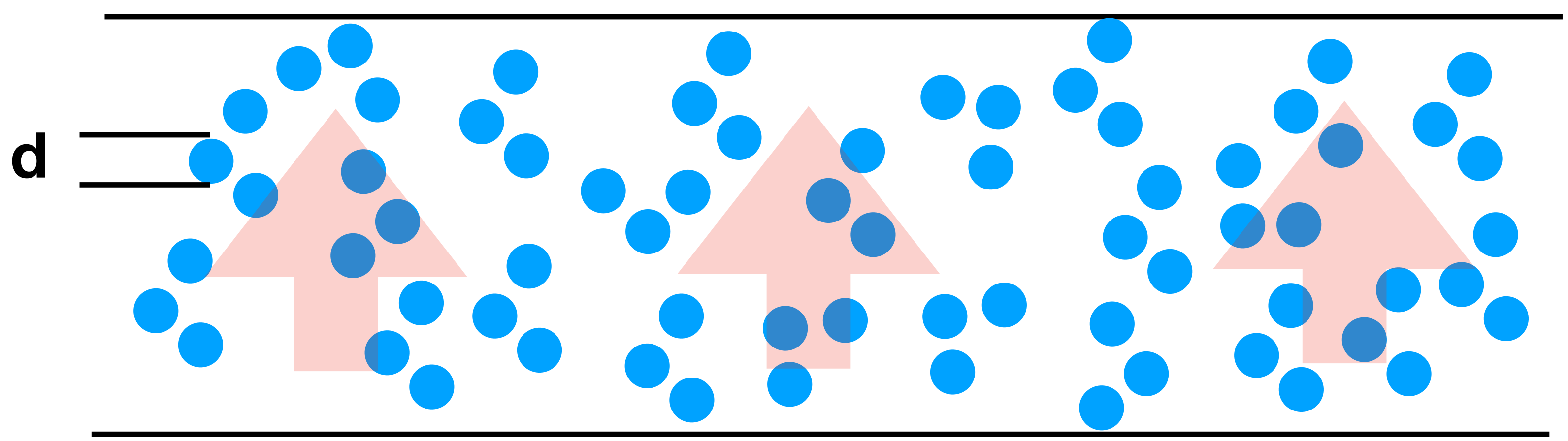
# Adiabatic layer must cool




$$T_c^4 \sim T_e^4 (1 - 4\Gamma_m h / T_e)$$

# Hydrometeors must not settle

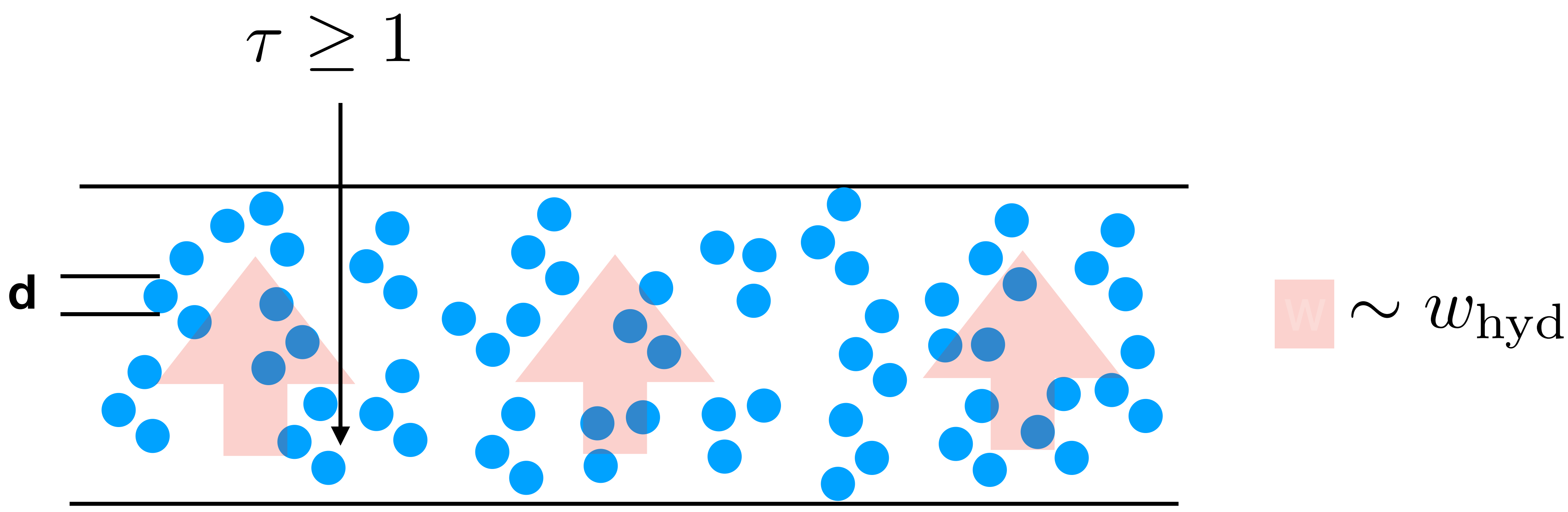
w $\sim w_{\text{term}}$




$$b_{\text{hyd}} \sim C_d w_{\text{term}}^2 / d$$
$$\sim C_d w^2 / d$$

$$C_a w \Gamma_m \sim -\mathcal{R}$$
$$T_c^4 \sim T_e^4 (1 - 4\Gamma_m h / T_e)$$

# Cloud must be optically thick




$$\tau \sim nd^2 h \geq 1$$

Radius ~ 10microns

Number density ~ 100-200 /cc

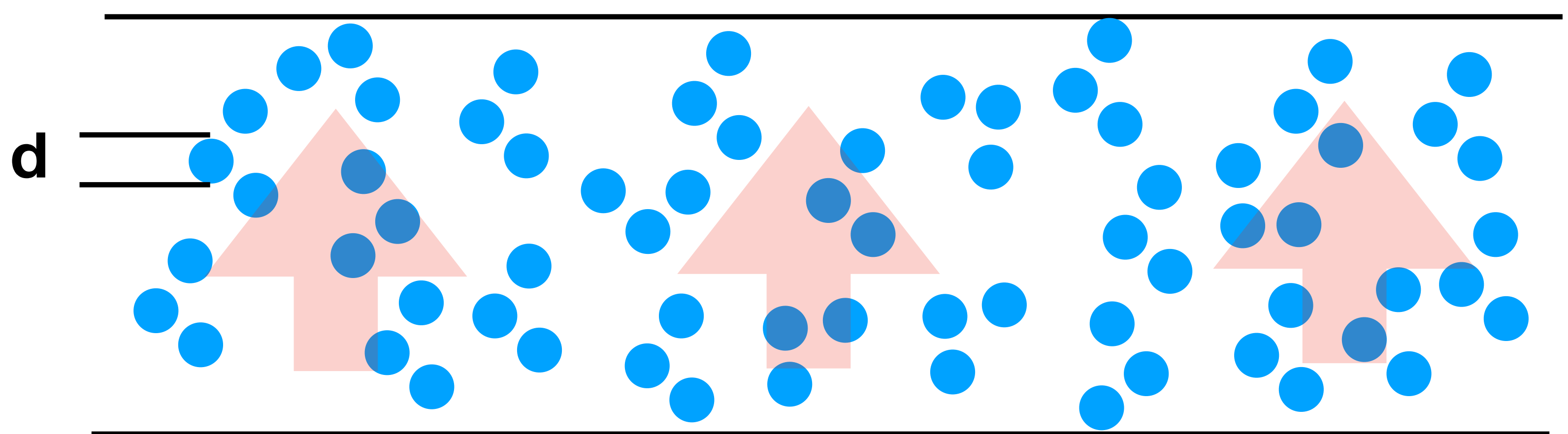
—> optical depth unity requires ~50-100m layer

$$b_{\rm hyd} \sim C_d w^2 / d$$

$$C_a w \Gamma_m \sim -\mathcal{R}$$

$$T_c^4 \sim T_e^4 (1 - 4\Gamma_m h / T_e)$$

# Work done on hydrometeors requires a minimum KE flux




$$W \sim w_{\mathrm{hyd}}$$

$$F_{\mathrm{KE}} \sim N m_{\mathrm{hyd}} b_{\mathrm{hyd}} w_{\mathrm{hyd}} / A$$

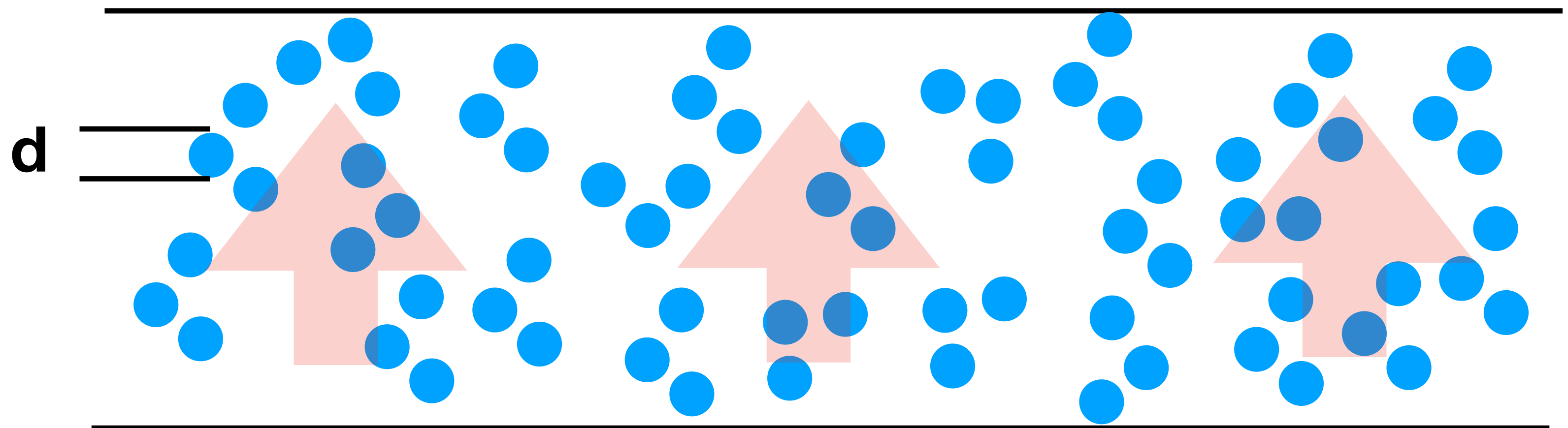
$$\tau \sim n d^2 h \geq 1$$

$$b_{\mathrm{hyd}} \sim C_d w^2 / d$$

$$C_a w \Gamma_m \sim -\mathcal{R}$$

$$T_c^4 \sim T_e^4 (1 - 4\Gamma_m h / T_e)$$

# Work done on hydrometeors requires a minimum KE flux

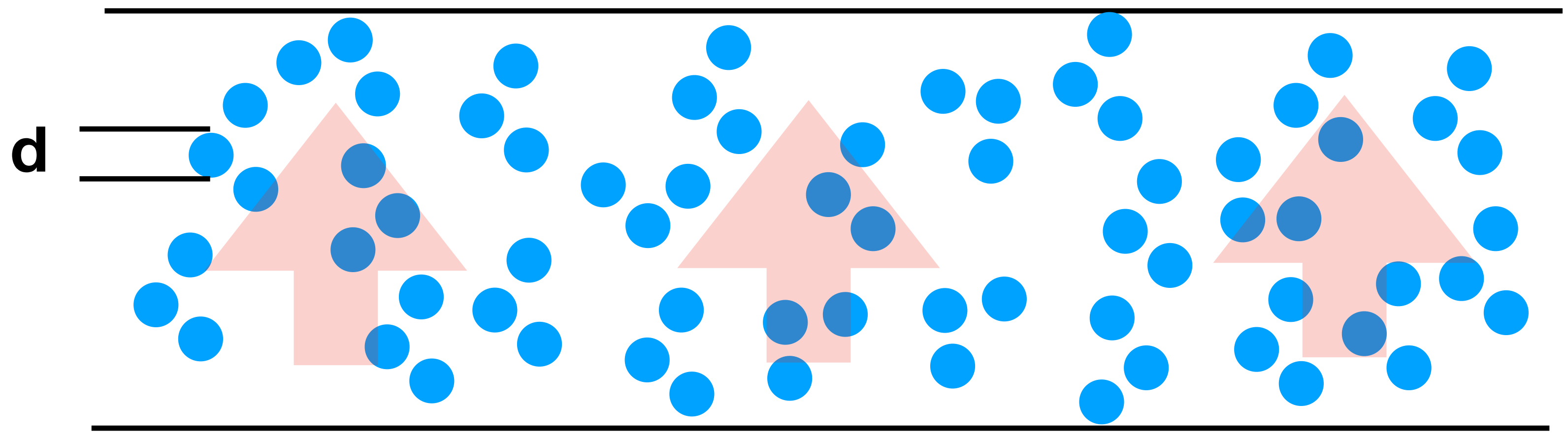



$$F_{\mathrm{KE}} \sim N m_{\mathrm{hyd}} b_{\mathrm{hyd}} w_{\mathrm{hyd}} / A$$
$$\sim n d^2 h \rho_{\mathrm{hyd}} C_d w^3$$

W $\sim w_{\mathrm{hyd}}$

$$\tau \sim n d^2 h \geq 1$$
$$b_{\mathrm{hyd}} \sim C_d w^2 / d$$
$$C_a w \Gamma_m \sim -\mathcal{R}$$
$$T_c^4 \sim T_e^4 (1 - 4\Gamma_m h / T_e)$$

# Putting it together




$$F_{\mathrm{KE}} \sim N m_{\mathrm{hyd}} b_{\mathrm{hyd}} w_{\mathrm{hyd}} / A$$
$$\sim n d^2 h \rho_{\mathrm{hyd}} C_d w^3$$
$$\geq C_d \rho_{\mathrm{hyd}} w^3$$

$$w \sim w_{\mathrm{hyd}}$$

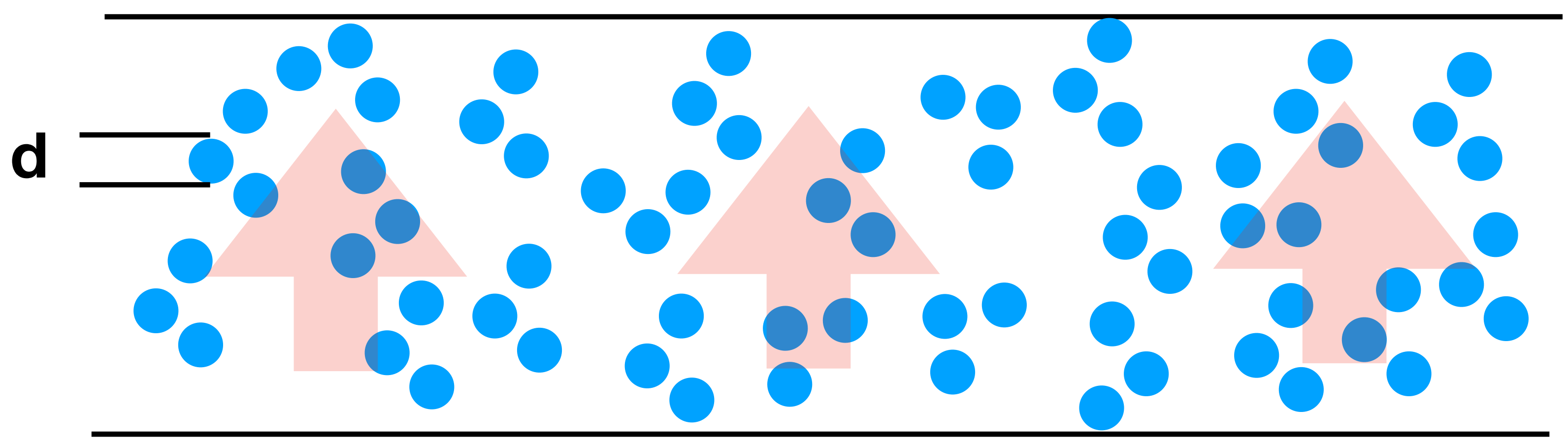
$$\tau \sim n d^2 h \geq 1$$
$$b_{\mathrm{hyd}} \sim C_d w^2 / d$$
$$C_a w \Gamma_m \sim -\mathcal{R}$$
$$T_c^4 \sim T_e^4 (1 - 4\Gamma_m h / T_e)$$

# Suspending hydrometeors and being optically thick requires…

$$\frac{1}{C_d} \geq \frac{\rho_{\mathrm{hyd}}}{\rho}$$

**Sorta amazing it doesn't depend on droplet size or number density.**

# Putting it all together




w $\sim w_{\rm hyd}$

$$F_{\rm KE} \geq C_d \rho_{\rm hyd} w^3$$
$$\geq C_d \rho_{\rm hyd} \left( \frac{-\mathcal{R}}{C_a \Gamma_m} \right)^3$$

$$\tau \sim n d^2 h \geq 1$$
$$b_{\rm hyd} \sim C_d w^2 / d$$
$$C_a w \Gamma_m \sim -\mathcal{R}$$
$$T_c^4 \sim T_e^4 (1 - 4\Gamma_m h / T_e)$$

# Putting it all together

**Balance requires** $F_{\mathrm{KE}} = \eta F_\theta \sim -\eta \mathcal{R}$

$$-\eta \mathcal{R} \geq C_d \rho_{\mathrm{hyd}} \left( \frac{-\mathcal{R}}{C_p \rho h \Gamma_m} \right)^3$$

**—or—**

$$-\eta (\sigma T_c^4)^2 \geq \frac{C_d \rho_{\mathrm{hyd}}}{(C_p \rho h \Gamma_m)^3}$$

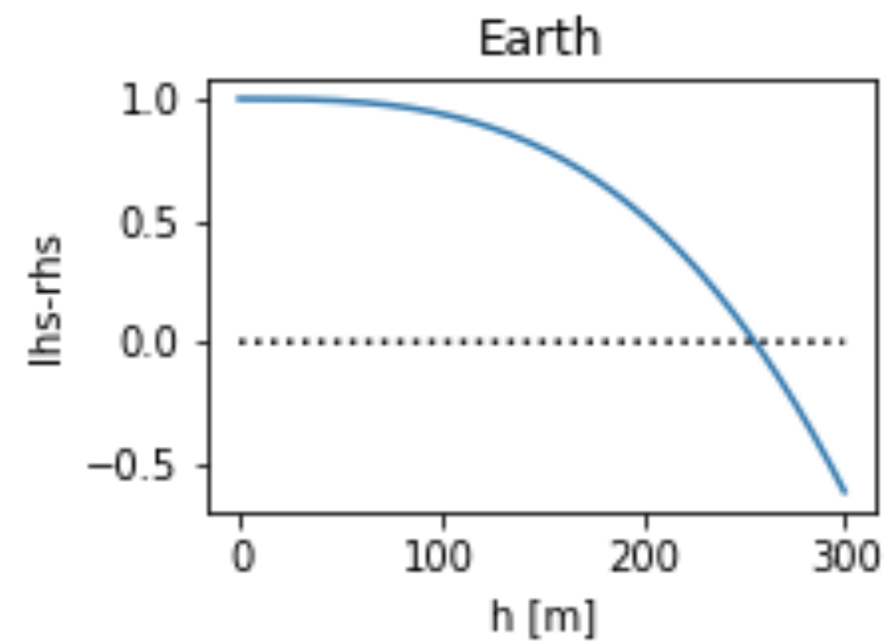
**—or—**

$$1 - 8\Gamma_m h / T_e \geq \eta \frac{(C_p \rho h \Gamma_m)^3}{C_d \rho_{\mathrm{hyd}} \sigma^2 T_e^8}$$

**[lhs]** **[rhs]**

# Moist layers:
# Earth, Venus and Titan*

- Earth -> Few hundred meters (in PBL)
- Titan -> Few meters (in PBL)
- Venus -> Few meters (@40-60km)




h ~ 250m
W ~ 1 m/s

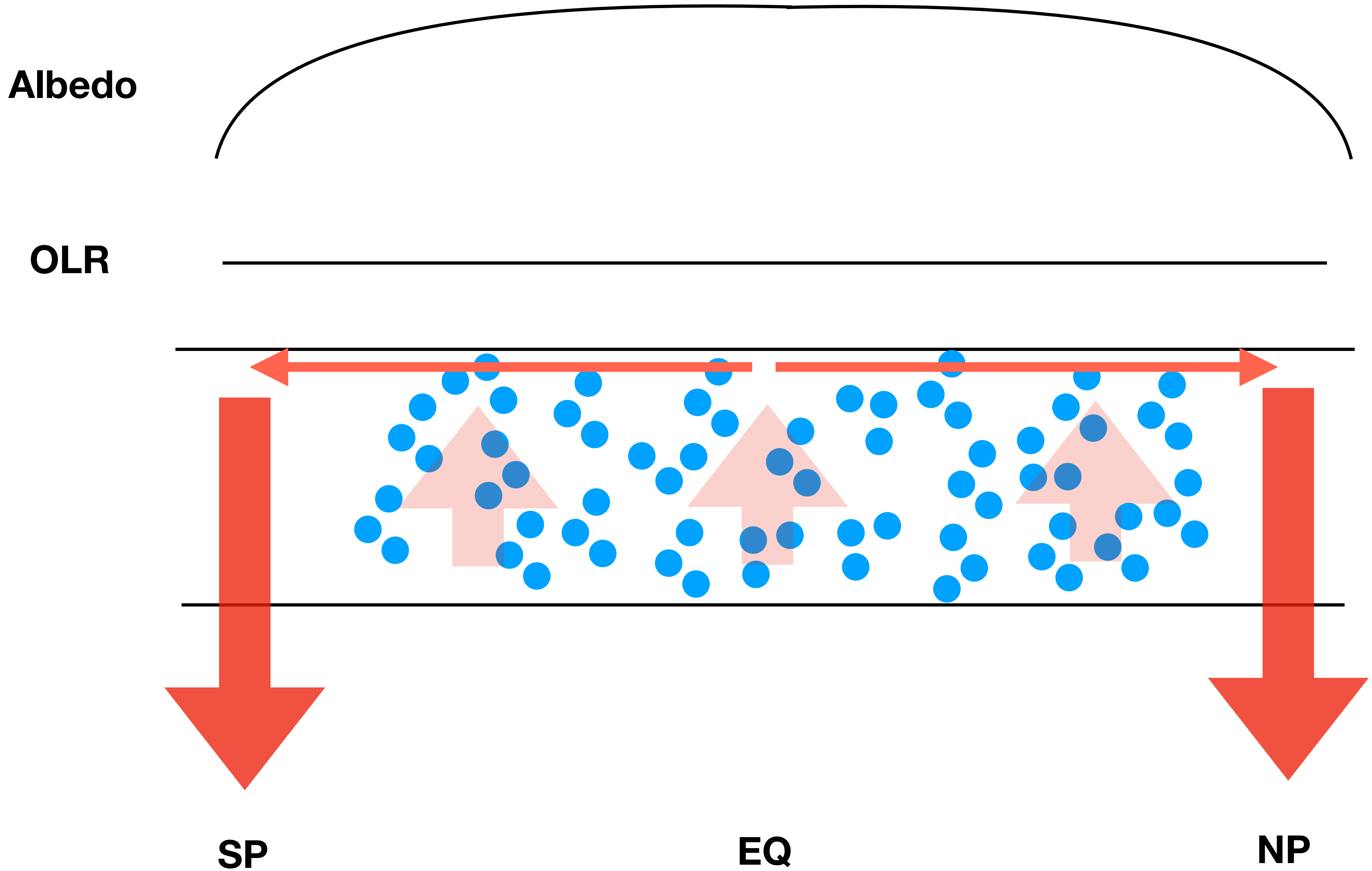
- So I'm under-estimating
  - Stratocumulus is a "topping", not necessarily a "filling" mode
  - Lot's of order unity factors dropped

***Titan's atmosphere isn't optically thin**

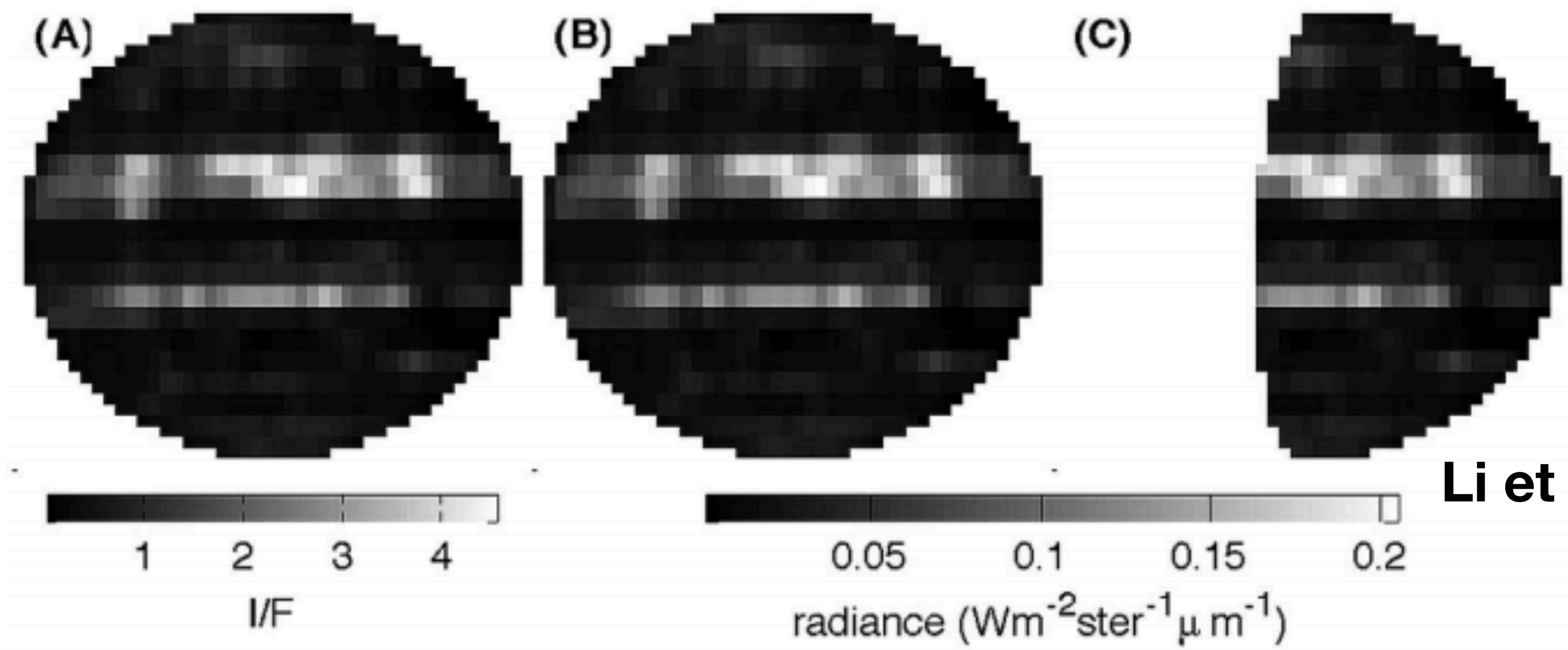
# Venus and Jupiter as end-members

- Venus’ cloud deck is ~global
  - Except at the poles where large buoyancy flux is removed, causing enhanced downwelling there? [akin to bottom-water formation]
  - Could polar downwelling balance upwelling over the rest of the globe?
  - How does this compare to the implied flux due to cloud granularity observed by Venus Express?
- Jupiter, being rotationally constrained, develops alternating up- and down-welling cells.
  - IR emission is concentrated in clear-sky downwelling regions, especially on the flanks of the equator
  - Polar region may host very deep convection, similarly to Venus. Perhaps we should be thinking about ocean analogies…

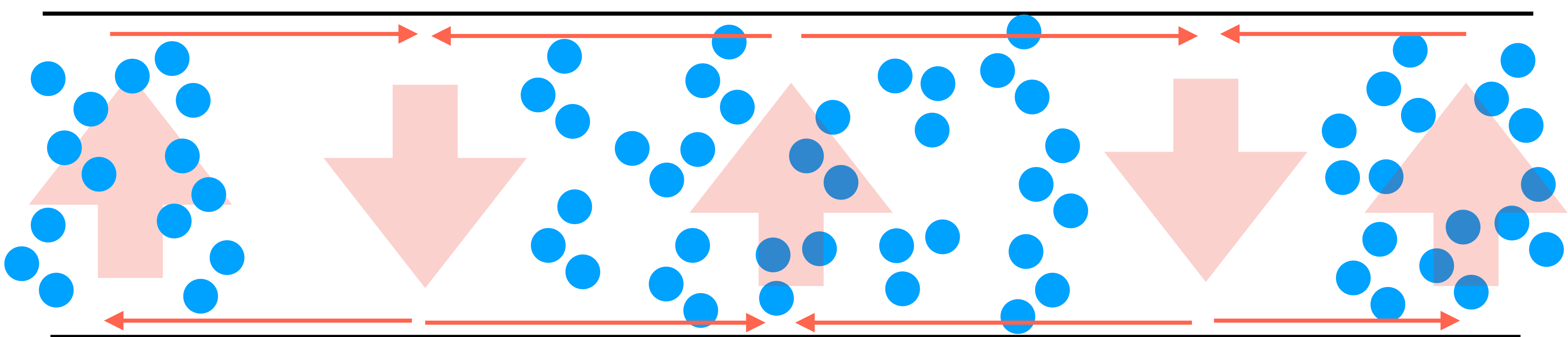
# Venus model



# Jupiter model




**Li et al. 2012**



**[here be monsters]**

**EQ**

# Questions

- How does the mass budget close in a (nearly) global mode of stratocumulus?
- What happens in a very hot, moist climate?
- Are there general, guiding principles of planetary albedo?