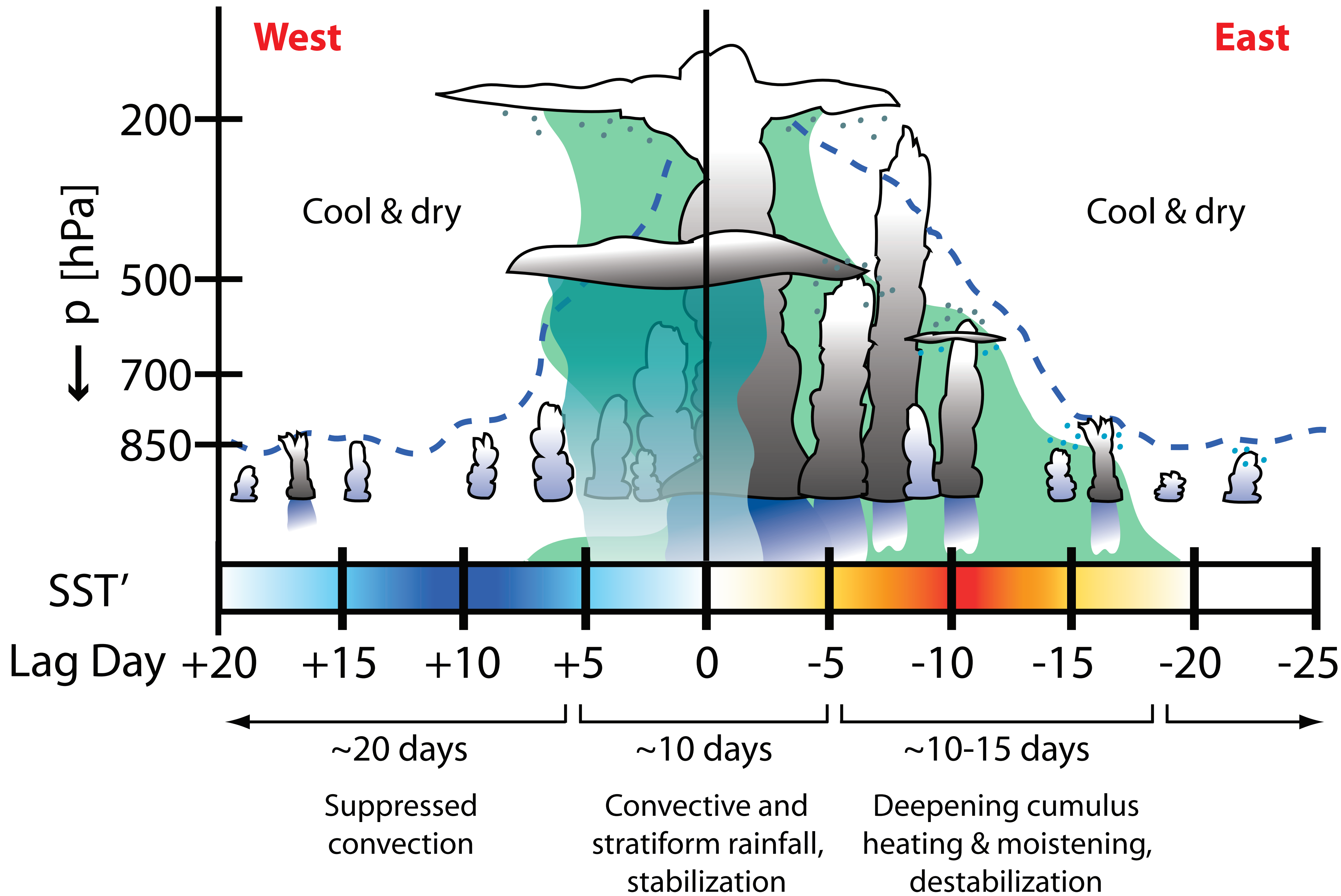
Moist physics, 1

David Randall

What do clouds do?

- Precipitate
- Scatter, absorb, and emit radiation
- Transport things vertically
    - Energy
    - Water
    - Momentum
    - Trace species
- Faciliate chemical reactions

Larger-Scale Circulation Systems



Slide from Jim Benedict

Coupling the Energy and Water Cycles

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- **Globally:**
  - **The atmosphere is cooled radiatively and warmed by latent heat release.**
  - **The surface is warmed radiatively and cooled by evaporation.**

Coupling the Energy and Water Cycles

- Globally:
  - The atmosphere is cooled radiatively and warmed by latent heat release.
  - The surface is warmed radiatively and cooled by evaporation.
- Locally:
  - The atmosphere is warmed radiatively by precipitating cloud systems.
  - The surface is cooled radiatively by precipitating cloud systems.

Cloud regimes

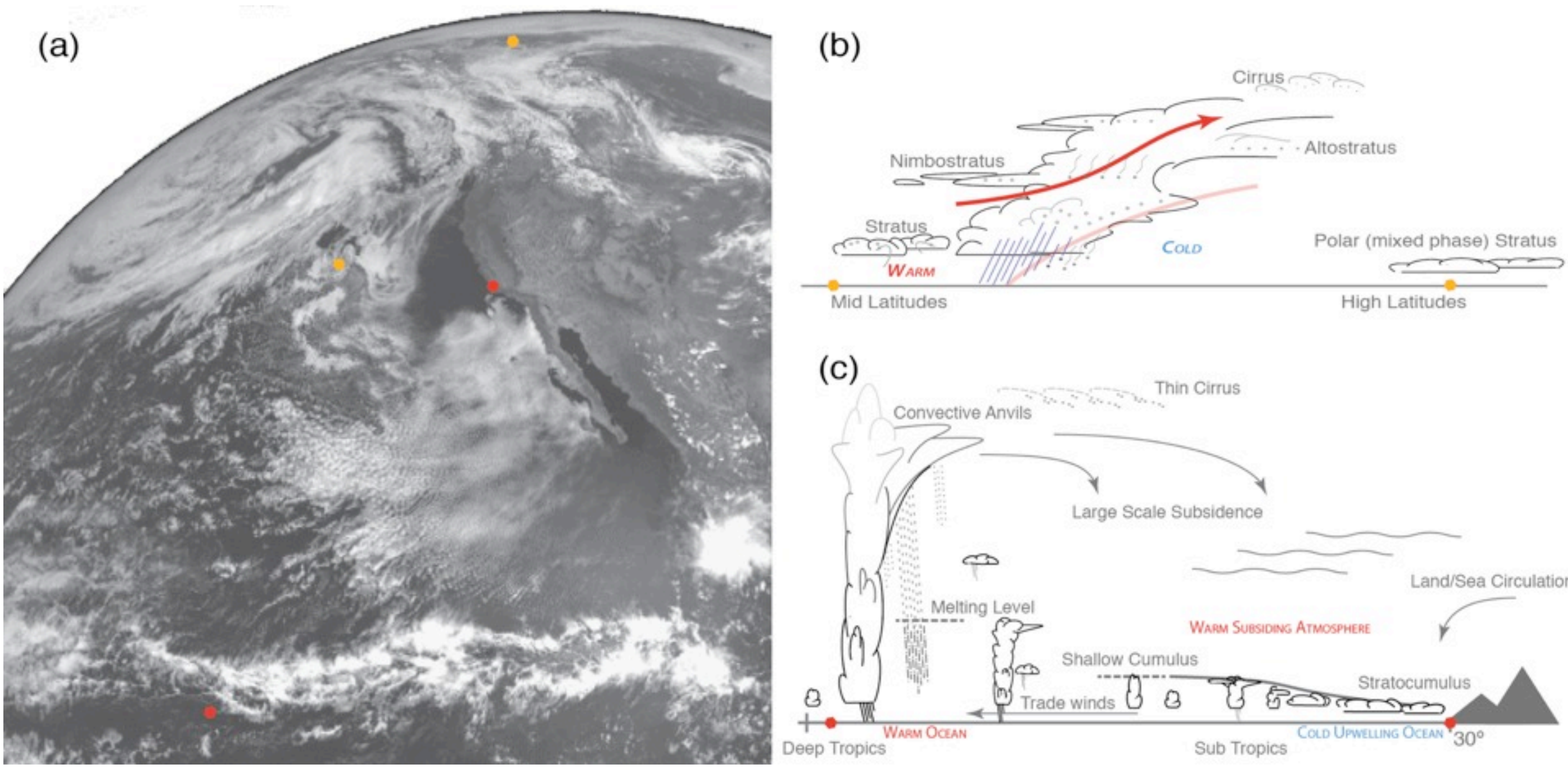
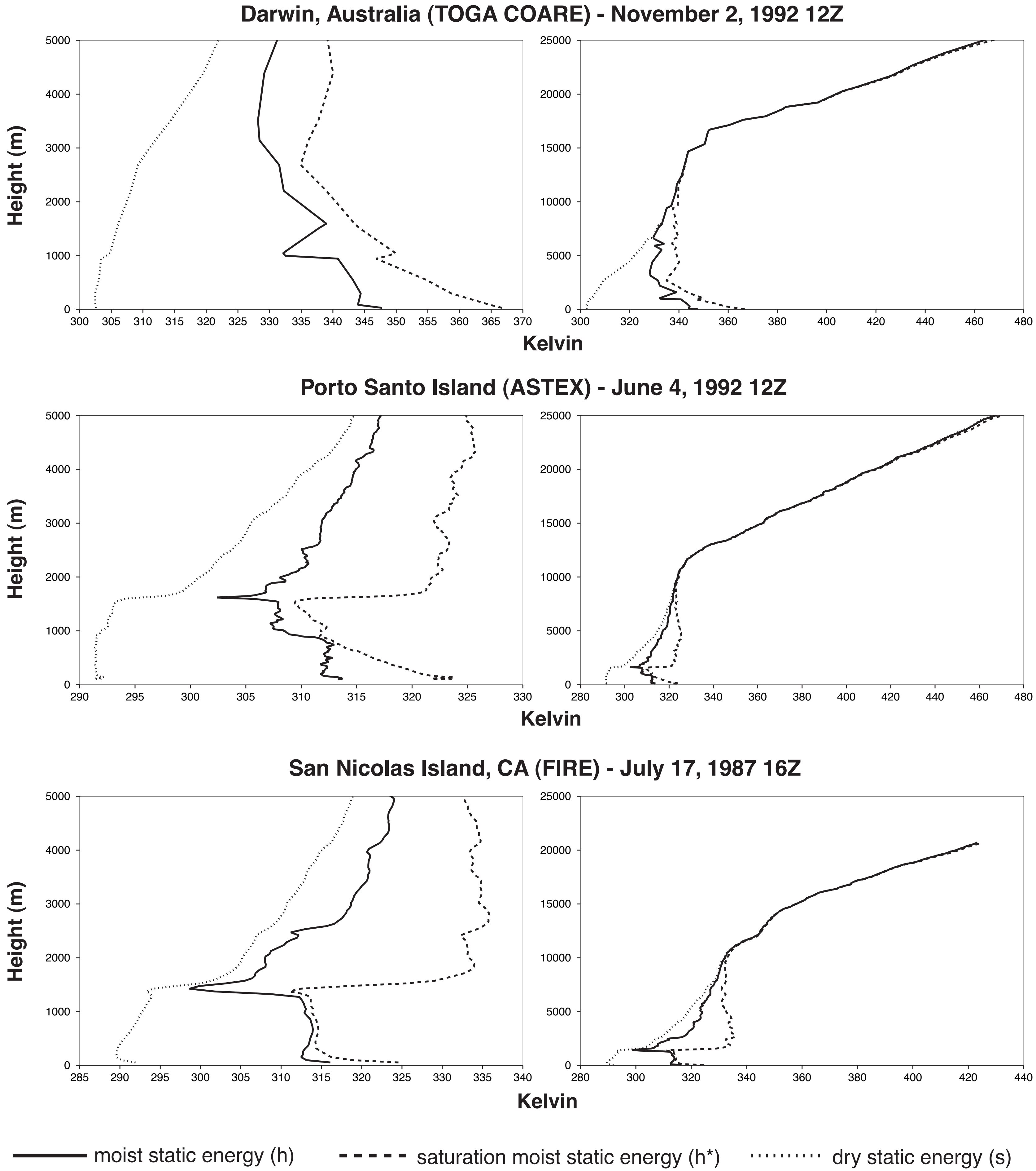


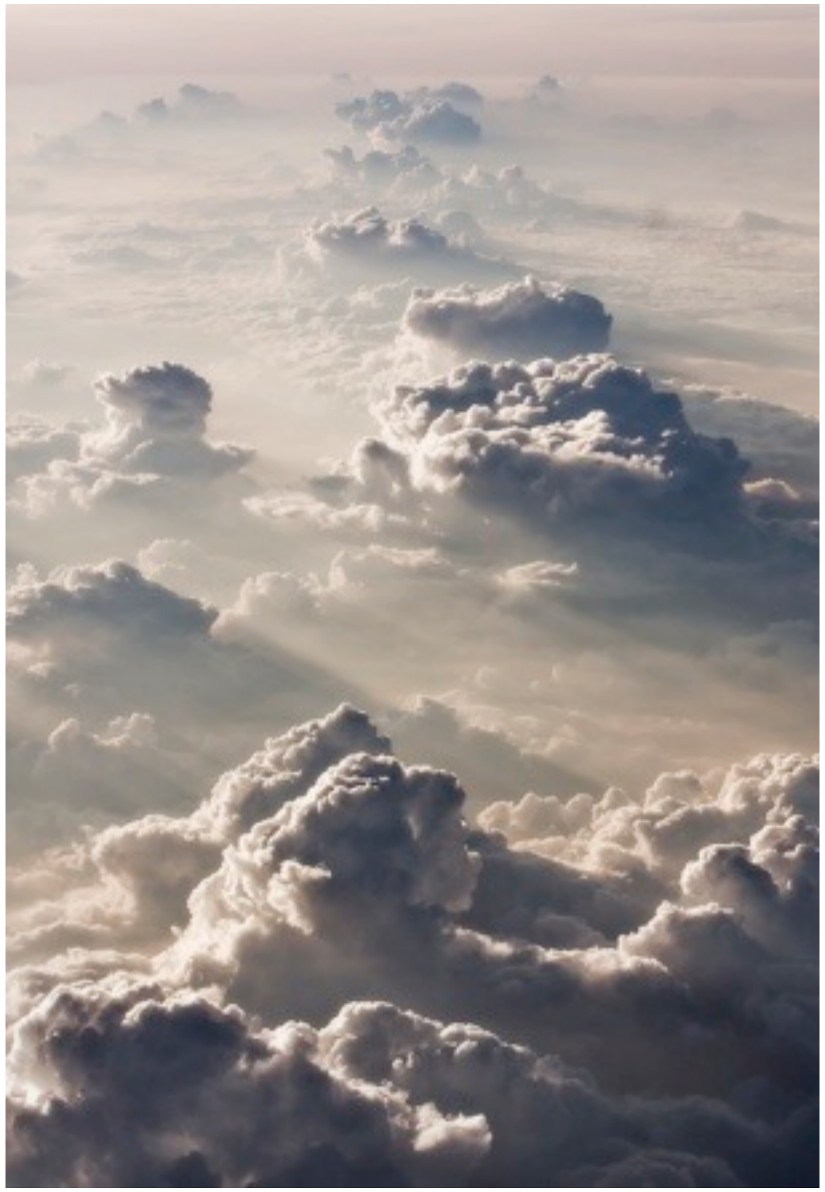
Figure from Bjorn Stevens



Darwin, Australia (TOGA COARE) - November 2, 1992 12Z
Porto Santo Island (ASTEX) - June 4, 1992 12Z
San Nicolas Island, CA (FIRE) - July 17, 1987 16Z
Height (m)
Kelvin
moist static energy (h)
saturation moist static energy (h*)
dry static energy (s)

How large-scale modelers have thought about clouds

- Convective clouds
  - Deep
  - Shallow



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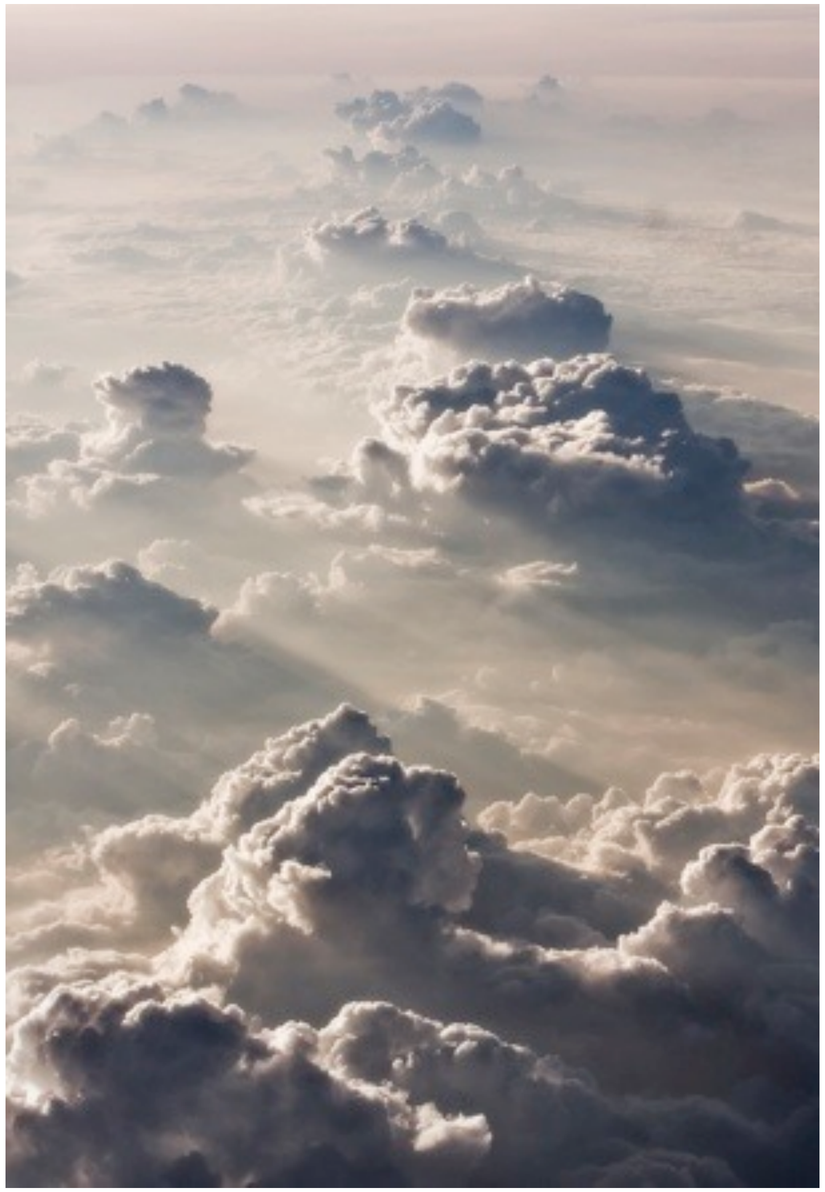
- Stratiform clouds above the boundary layer
  - Convective detrainment
  - Frontal lifting
  - Orographic lifting



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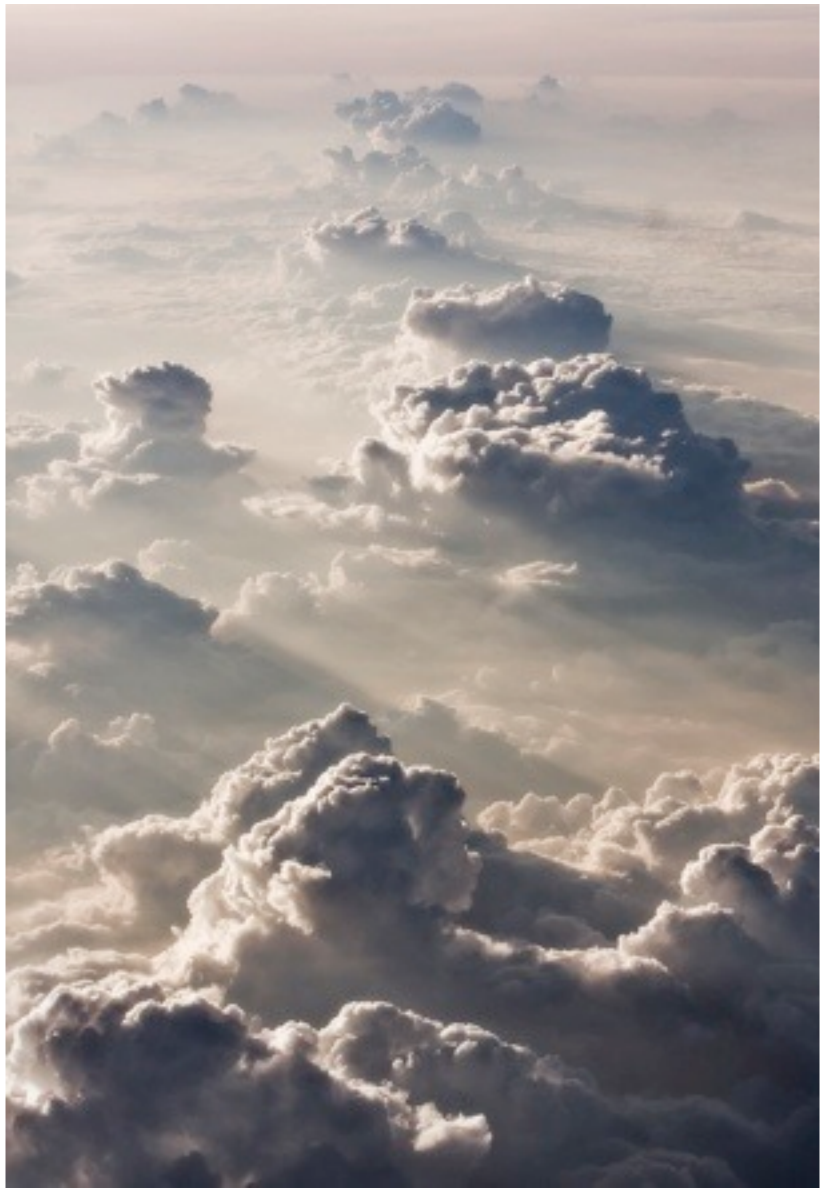
- Marine stratocumulus clouds

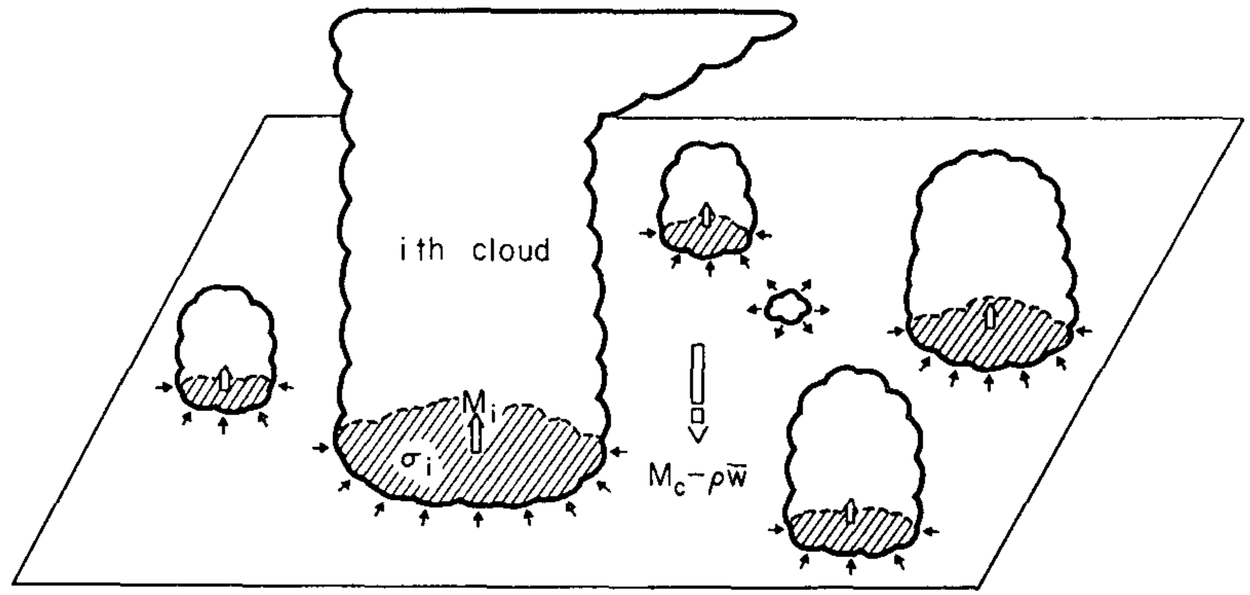


Deep convection

- Conditional instability is necessary but not sufficient.
- Vertical transports are powerful and important.
- The fractional area covered by convective updrafts is very small.

ITCZ

Scale Separation



"Consider a horizontal area ... large enough to contain an ensemble of cumulus clouds, but small enough to cover only a fraction of a large-scale disturbance. The existence of such an area is one of the basic assumptions of this paper."

-- AS 74

Heating and drying

$$Q_1 \equiv LC - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H' s'}) + Q_R$$

$$Q_2 \equiv LC + \frac{L}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'q_v'}) + \frac{L}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H' q_v'})$$

An overbar represents an average over a grid cell area, at a given height and time.

Vertical flux divergences dominate

Horizontal and vertical fluxes are comparable in magnitude.

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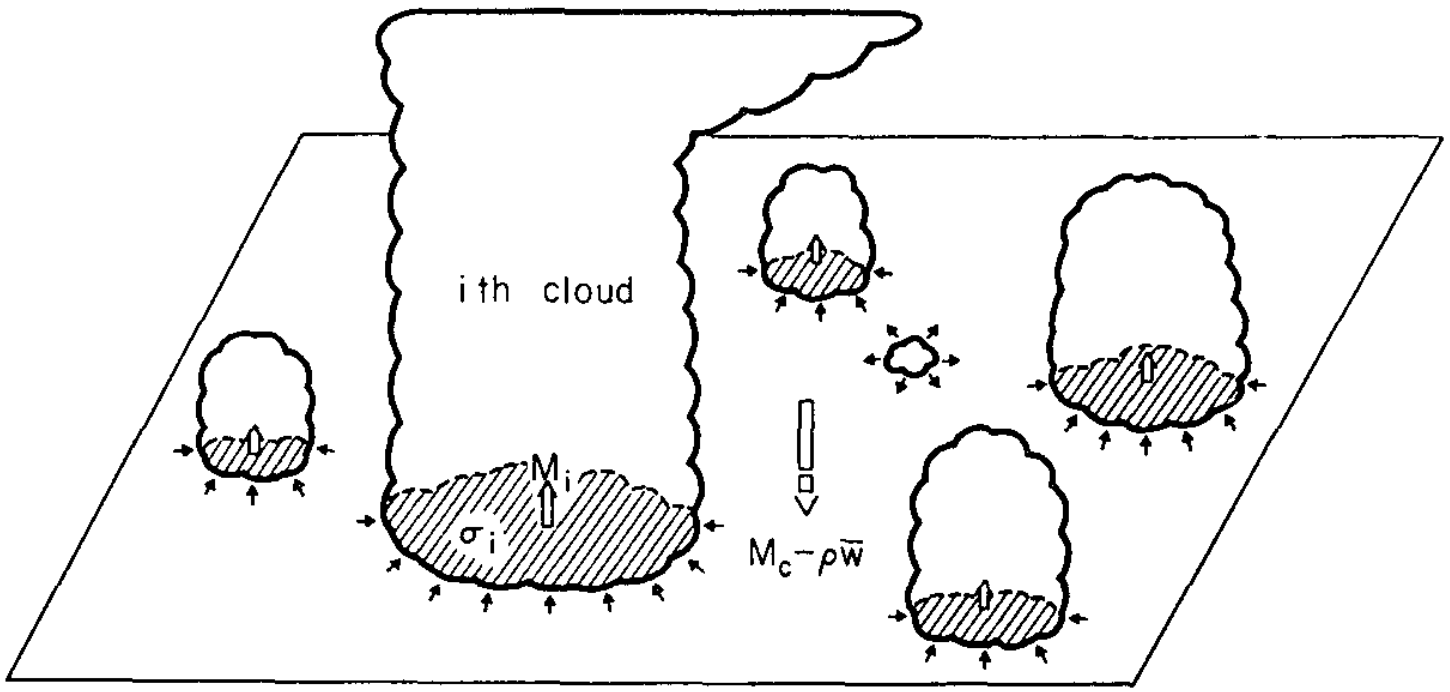
300 m

100 km

$$Q_1 \cong LC - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) + Q_R$$

$$Q_2 \cong LC + \frac{L}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'q_v'})$$

Toy updrafts & downdrafts



Mass fluxes

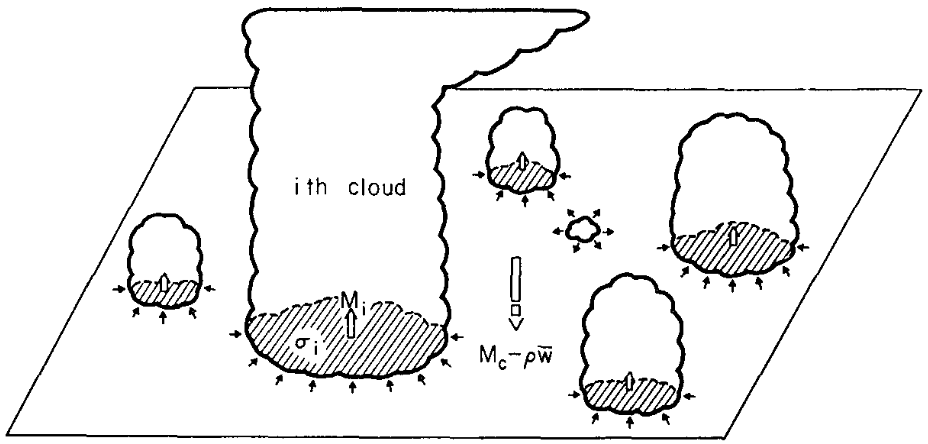
$$\sum_{i=1}^{N}\sigma_i = 1$$

$$\sum_{i=1}^{N}\sigma_i w_i = \overline{w}$$

$$\sum_{i=1}^{N}\sigma_i h_i = \overline{h}$$

$$F_h \equiv \rho\overline{wh} - \rho\overline{w}\overline{h} = \sum_{i=1}^{N} M_i\left(h_i - \overline{h}\right)$$

$$M_i \equiv \rho\sigma_i\left(w_i - \overline{w}\right)$$



A critical simplifying assumption

$$\sigma_c \ll 1, \text{ and } \tilde{\sigma} \cong 1$$

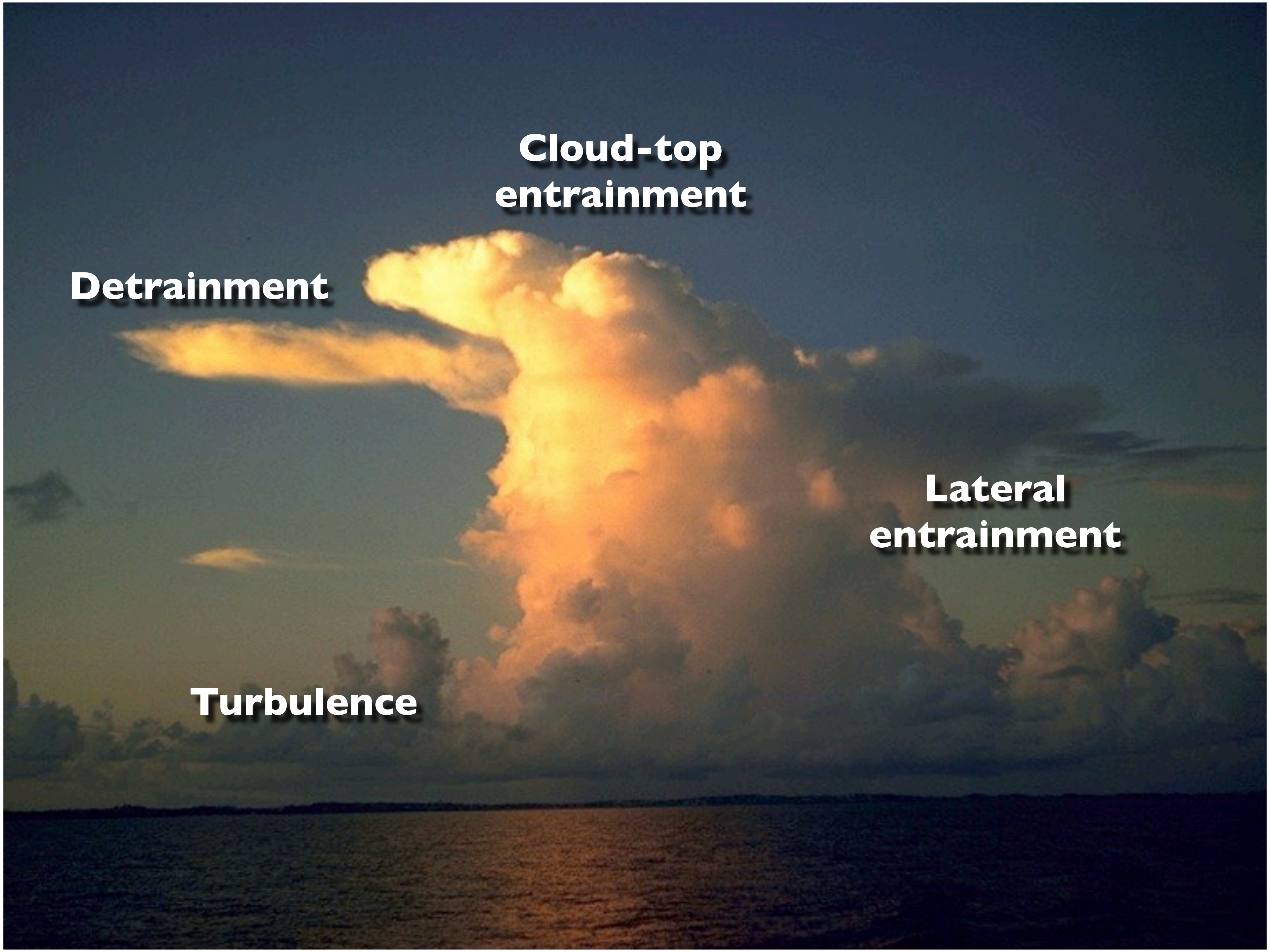
The simple reasons for this observed fact were explained by Jacob Bjerknes in a 1938 paper.

It follows that the "environment" has almost the same thermodynamic properties as the grid-cell average.

$$\tilde{h} \cong \overline{h}$$

Because this is true, we can equate the heating and drying of the environment with the heating and drying of the grid-scale average, and we can avoid computing sigma.

Cumulus entrainment



Entraining plumes

$$\frac{\partial M_c(z)}{\partial z} = E(z) - D(z)$$

Mass budget

$$\frac{\partial}{\partial z}\left[M_c(z)h_c(z)\right] = E(z)\bar{h}(z) - D(z)h_c(z)$$

Moist static energy budget

$$\frac{\partial h_c(z)}{\partial z} = \frac{E(z)}{M_c}\left[\bar{h}(z) - h_c(z)\right]$$

Dilution

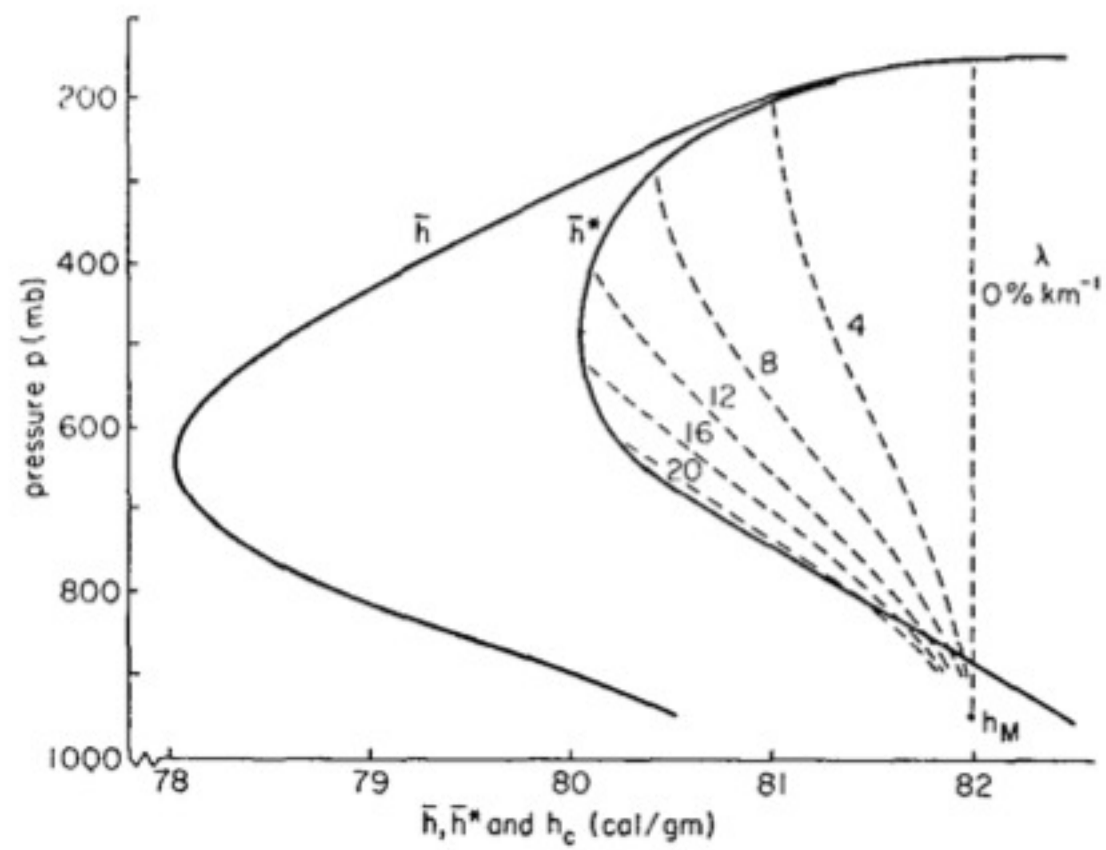


FIG. 6. Vertical profiles of $\bar{h}(p)$, $\bar{h}^*(p)$ and $h_c(p,\lambda)$; $h_c(p,\lambda)$ lines are dashed and labeled with the value of λ in percent per kilometer. Profiles of $\bar{h}$ and $\bar{h}^*$ were obtained from Jordan's (1958) "mean hurricane season" sounding. The top p_B of the mixed layer is assumed to be 950 mb; h_M is assumed to be 82 cal gm^{-1}.

Arakawa & Schubert, 1974

How to determine the mass flux?

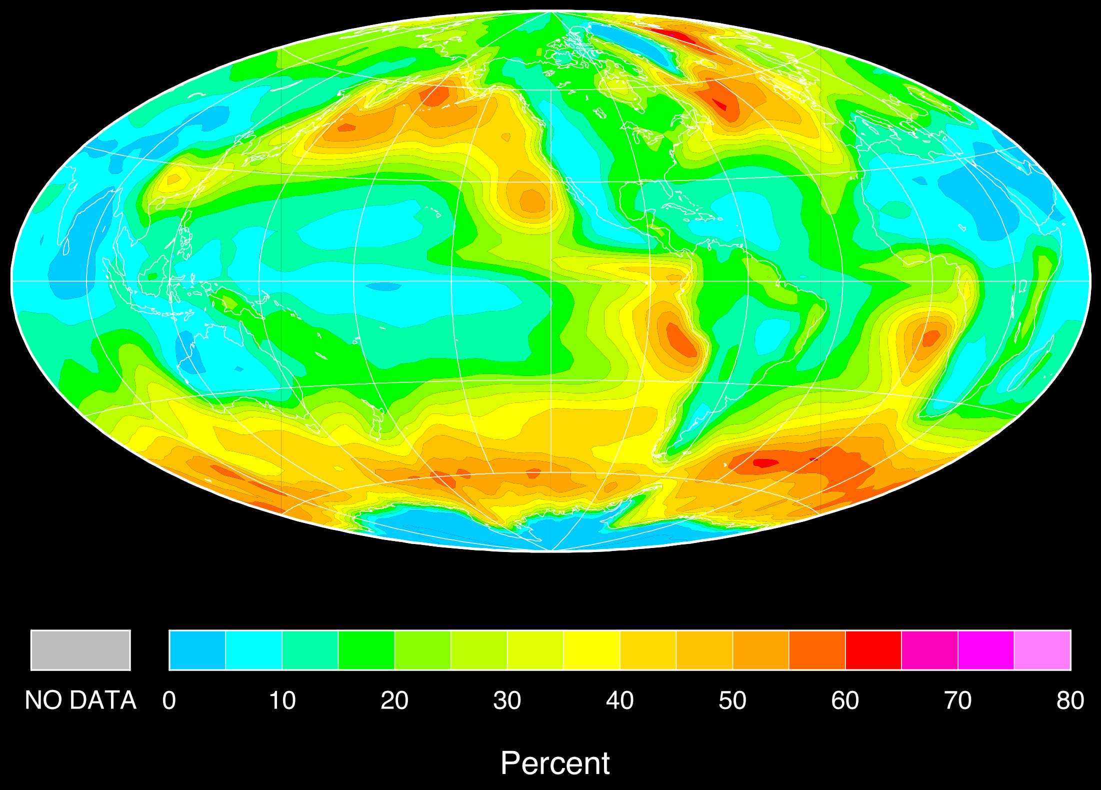
- Convection converts CAPE into convective kinetic energy.
- If this process is "fast," then CAPE is destroyed as fast as it is generated.
- This "quasi-equilibrium" assumption can be used to determine the mass flux by solving a linear algebraic system.
- A better approach is to choose a mass flux that pushes the CAPE towards zero on a short but finite time scale.
  - "Relaxation", as in relaxed Arakawa-Schubert
  - Prognostic closure

Sources and sinks of CAPE

- Sources -- anything that steepens the lapse rate or moistens the lower troposphere
  - Surface fluxes
  - Radiative cooling aloft
  - Large-scale rising motion
  - Warm advection down low
  - Cold advection aloft
- Sinks
  - Convective warming
  - Convective drying


Marine stratocumulus clouds

Annual ISCCP C2 Inferred Stratus Cloud Amount



Annual ERBE Net Radiative Cloud Forcing

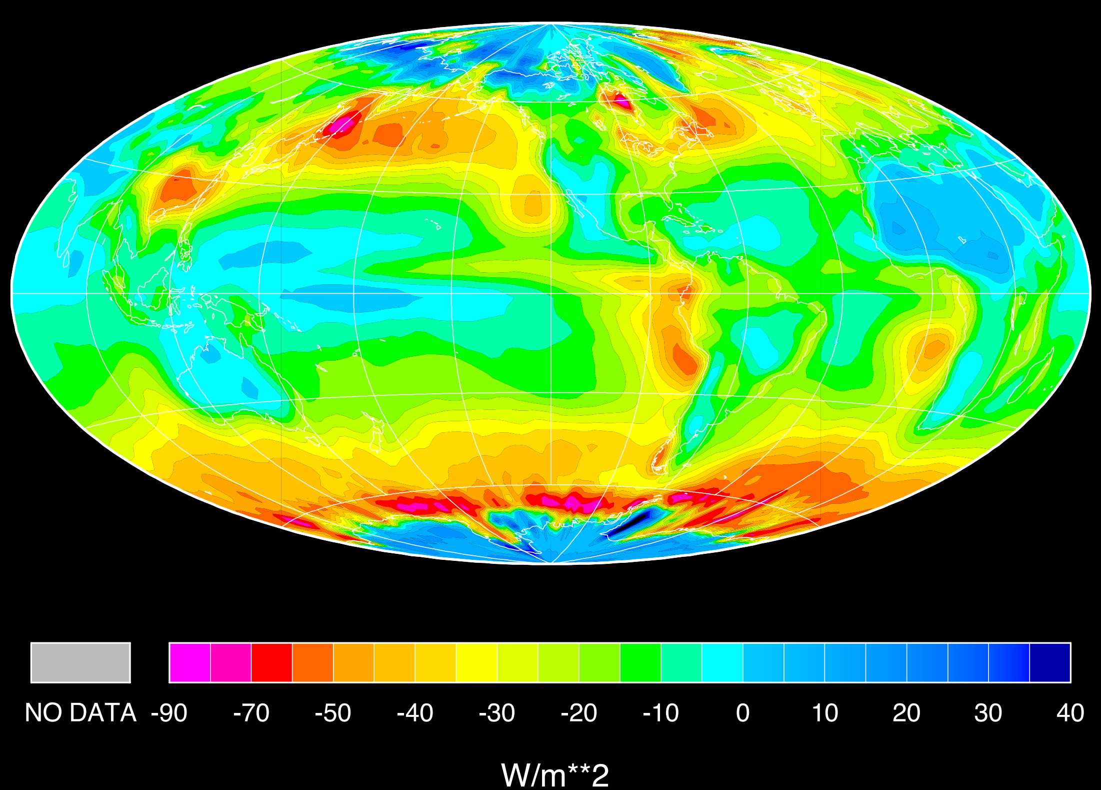


Figure from Norris & Leovy

Wimpy clouds, but difficult

- Marine stratocumulus cloud layers are just a few hundred meters deep.
- They are capped by a strong inversion that is even thinner.
- The in-cloud turbulence is driven mainly by very strong radiative cooling confined to an extremely thin layer.
- It is virtually impossible to explicitly resolve these features in a large-scale model.

“Models of cloud-topped mixed layers”

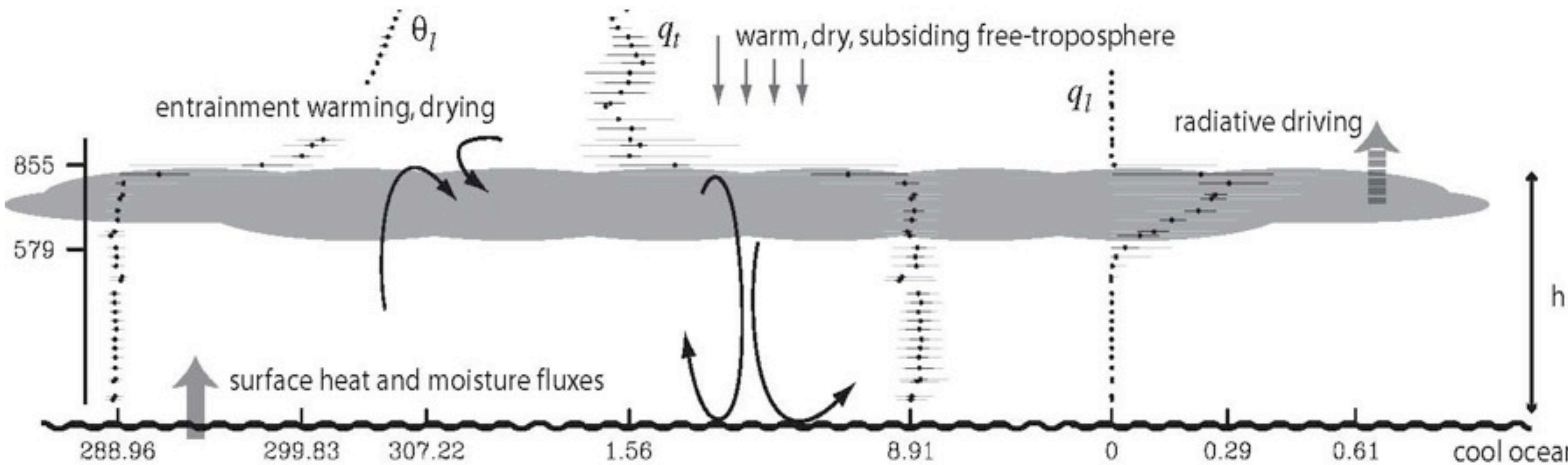
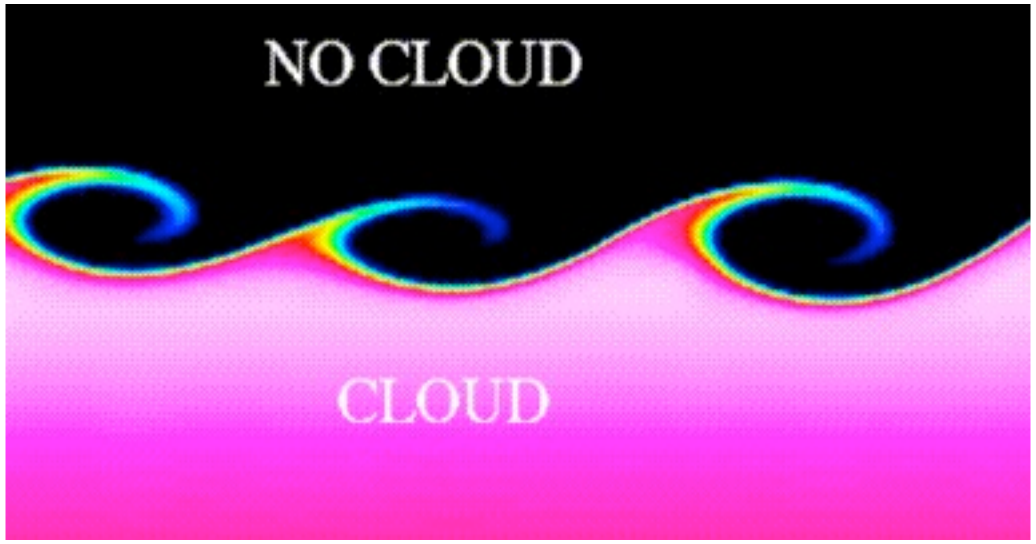


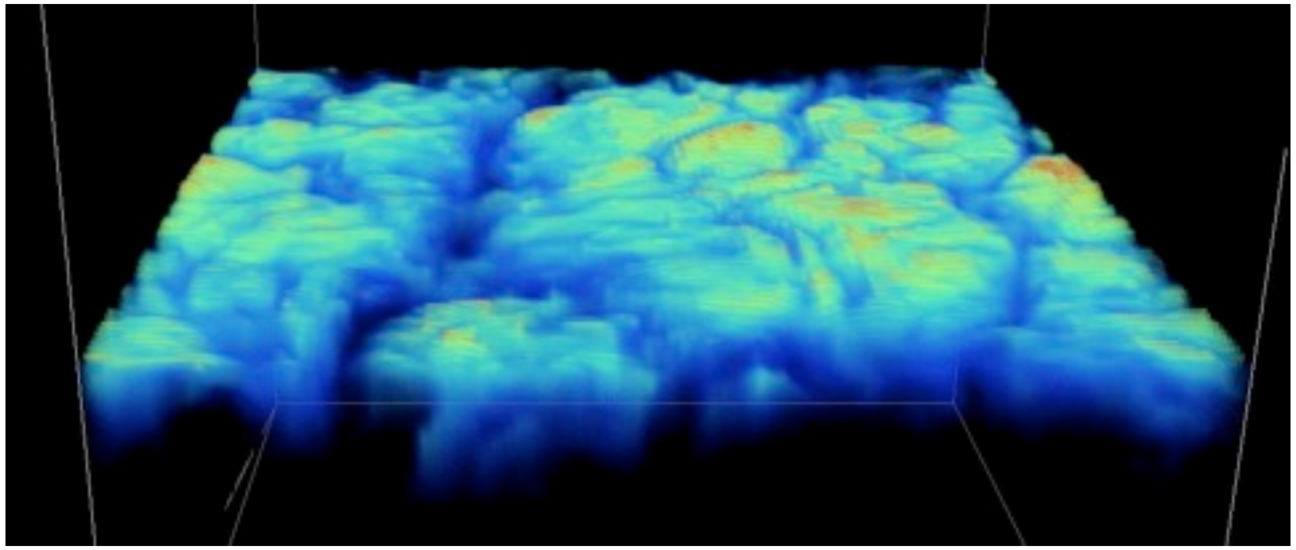
Figure from Bjorn Stevens

What is entrainment?

- **Clouds don't entrain.**
- **Turbulence entrains.**
- **Clouds are turbulent.**

Entrainment is the active annexation of quiet fluid by turbulence.





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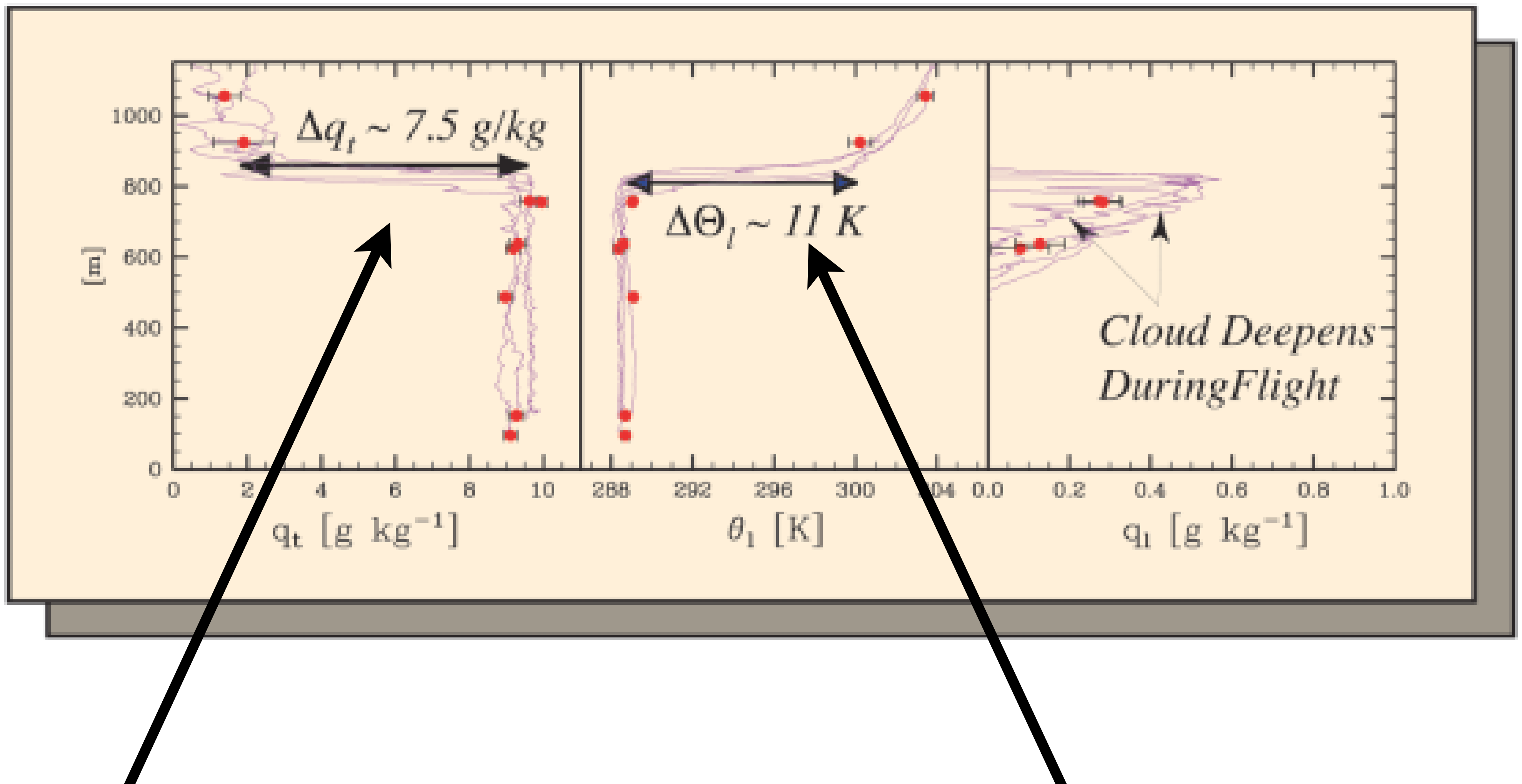

$$(F_{qt})_B = -E\Delta q_t$$

$$(F_{\theta_l})_B = -E\Delta\theta_l + \Delta R$$

Figure from Stevens et al. (2003)

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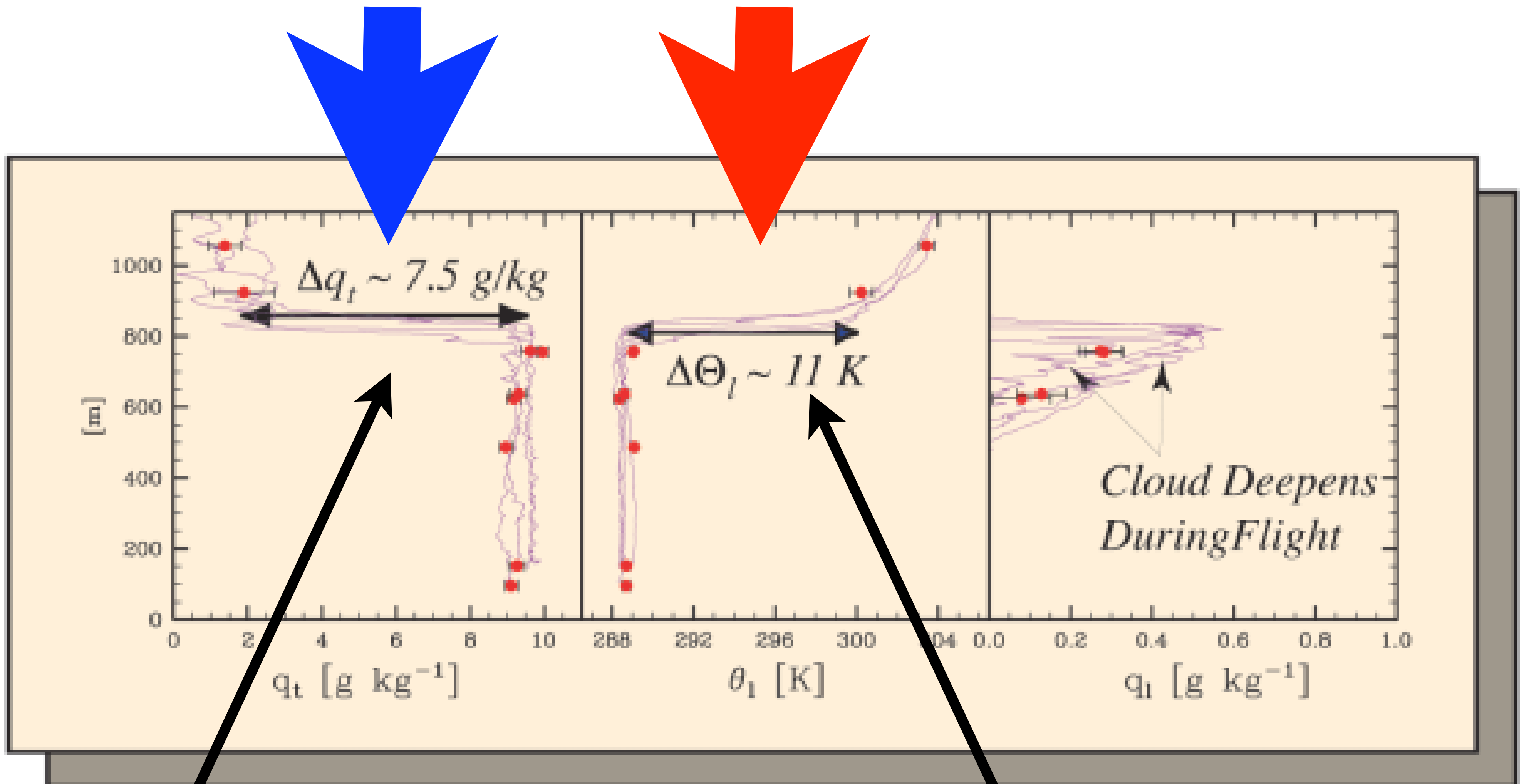

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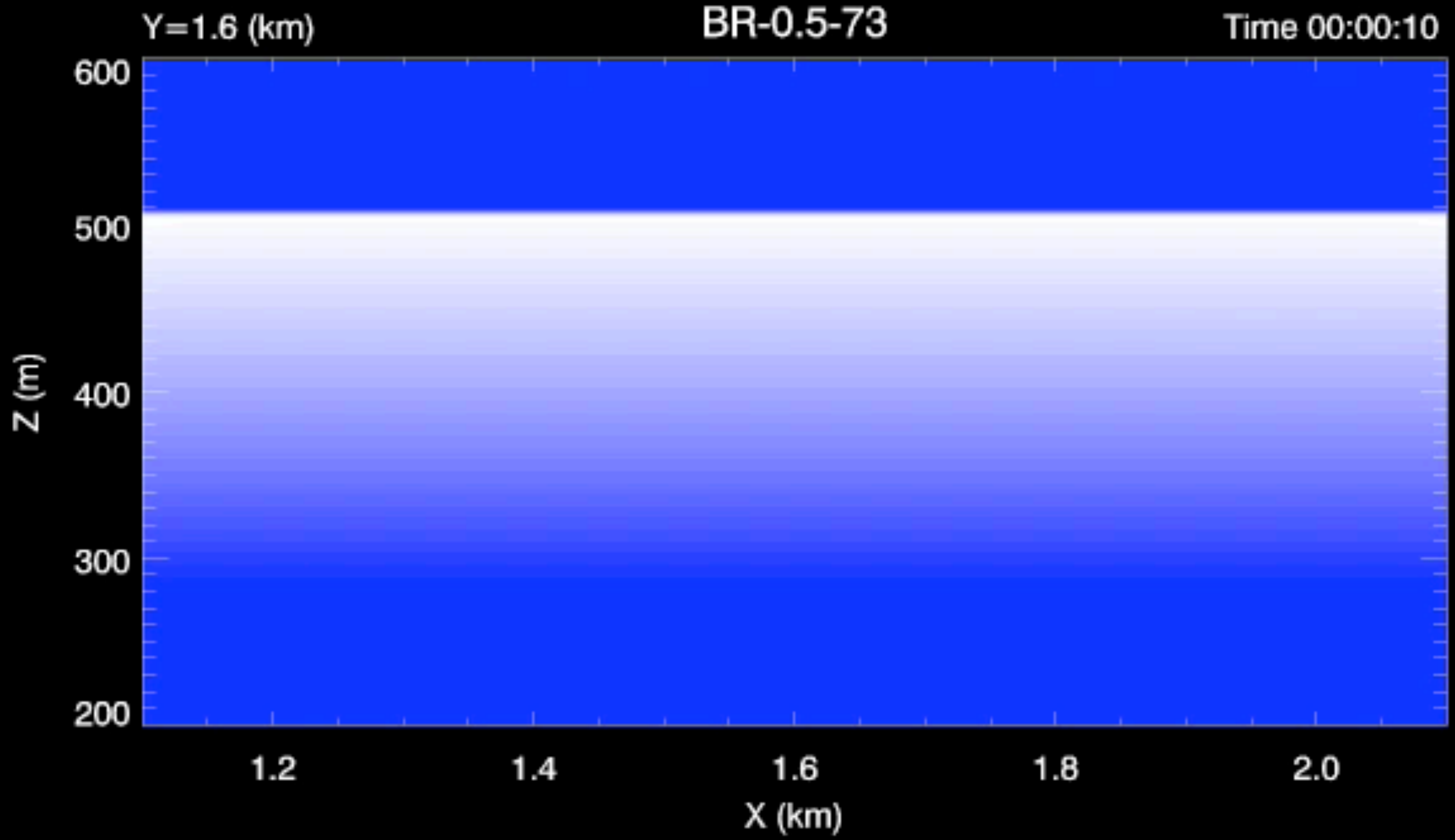
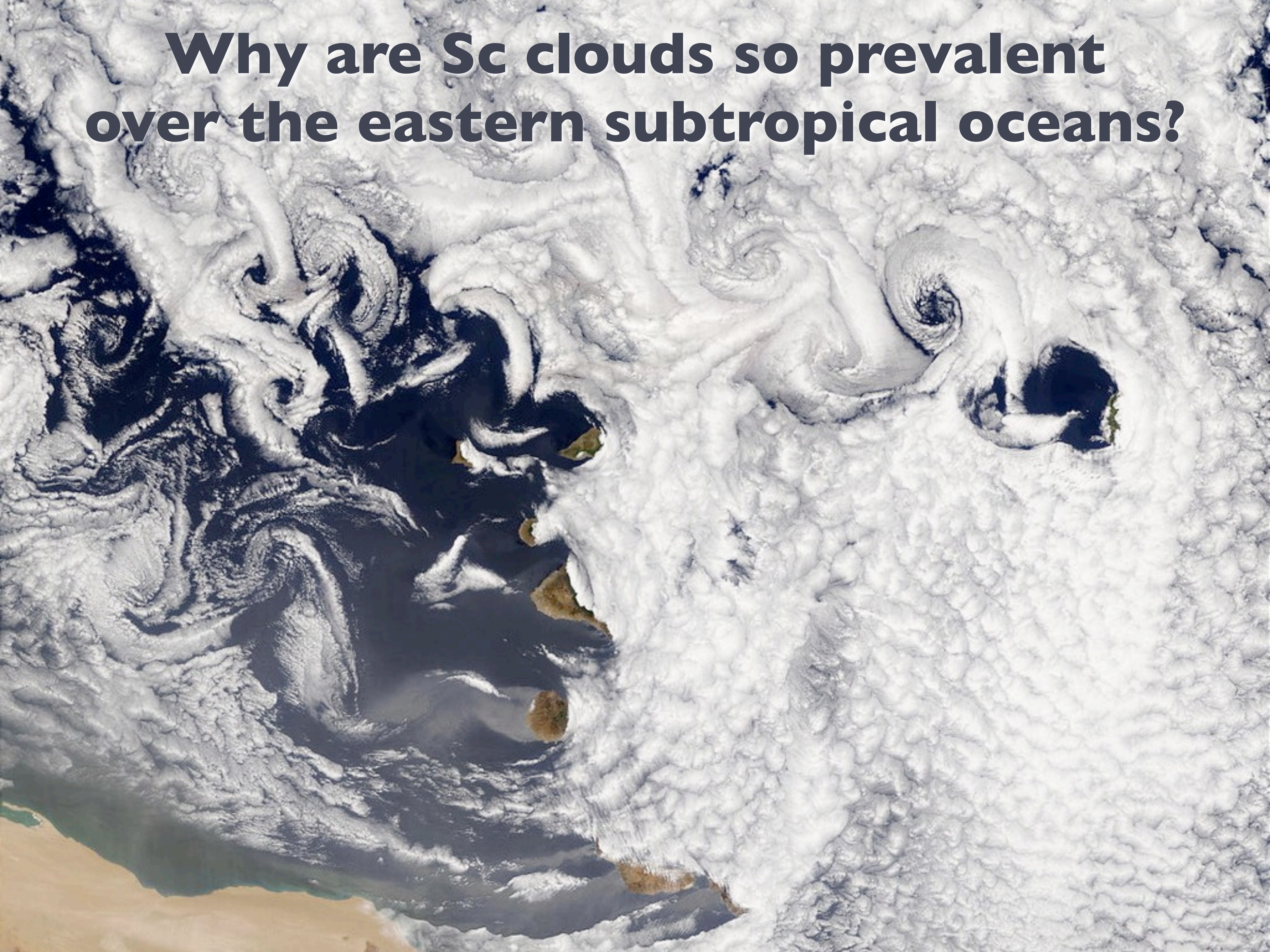
Slow entrainment driven by cloud-top evaporation



Movie by Tak Yamaguchi

Why are Sc clouds so prevalent over the eastern subtropical oceans?



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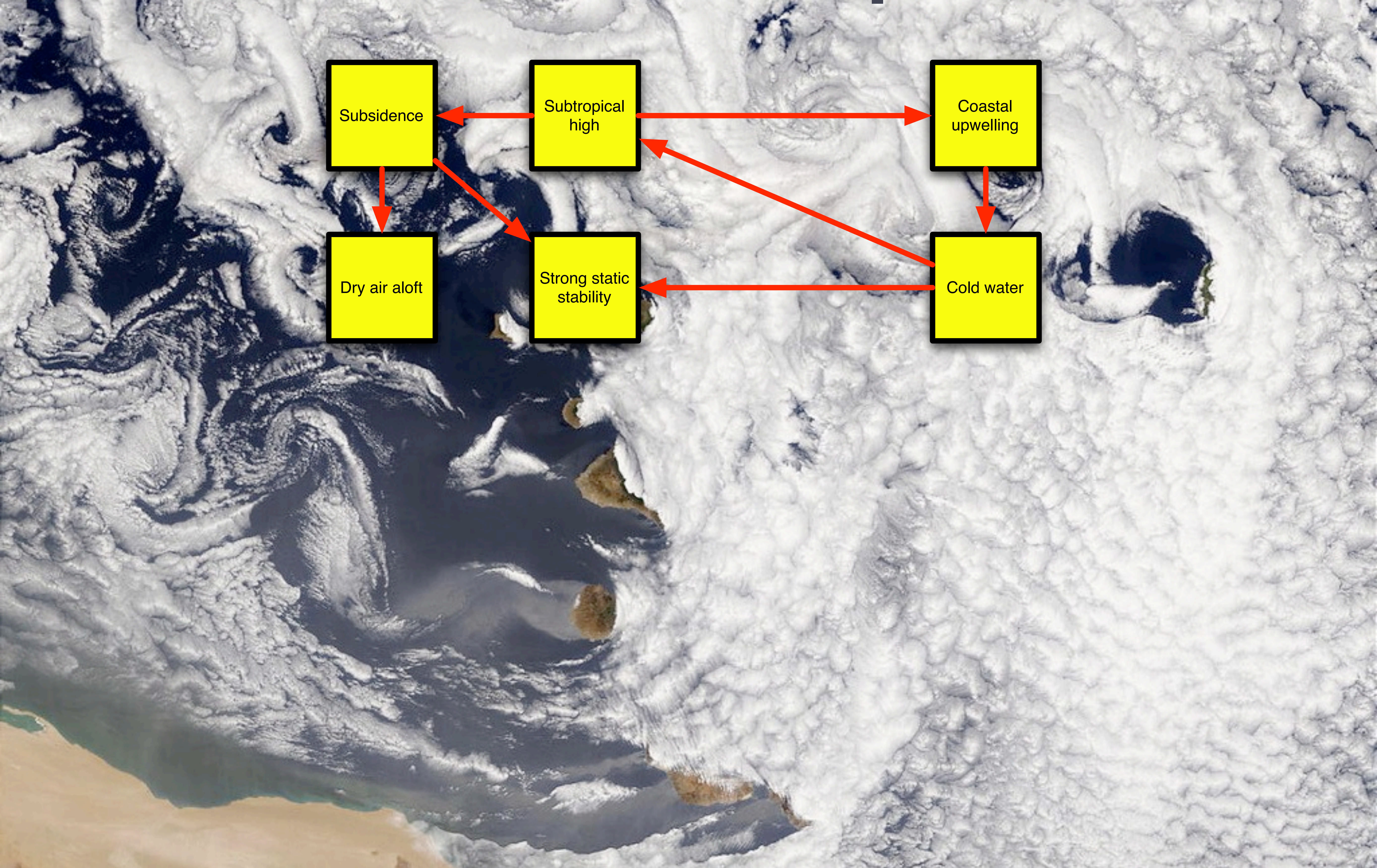

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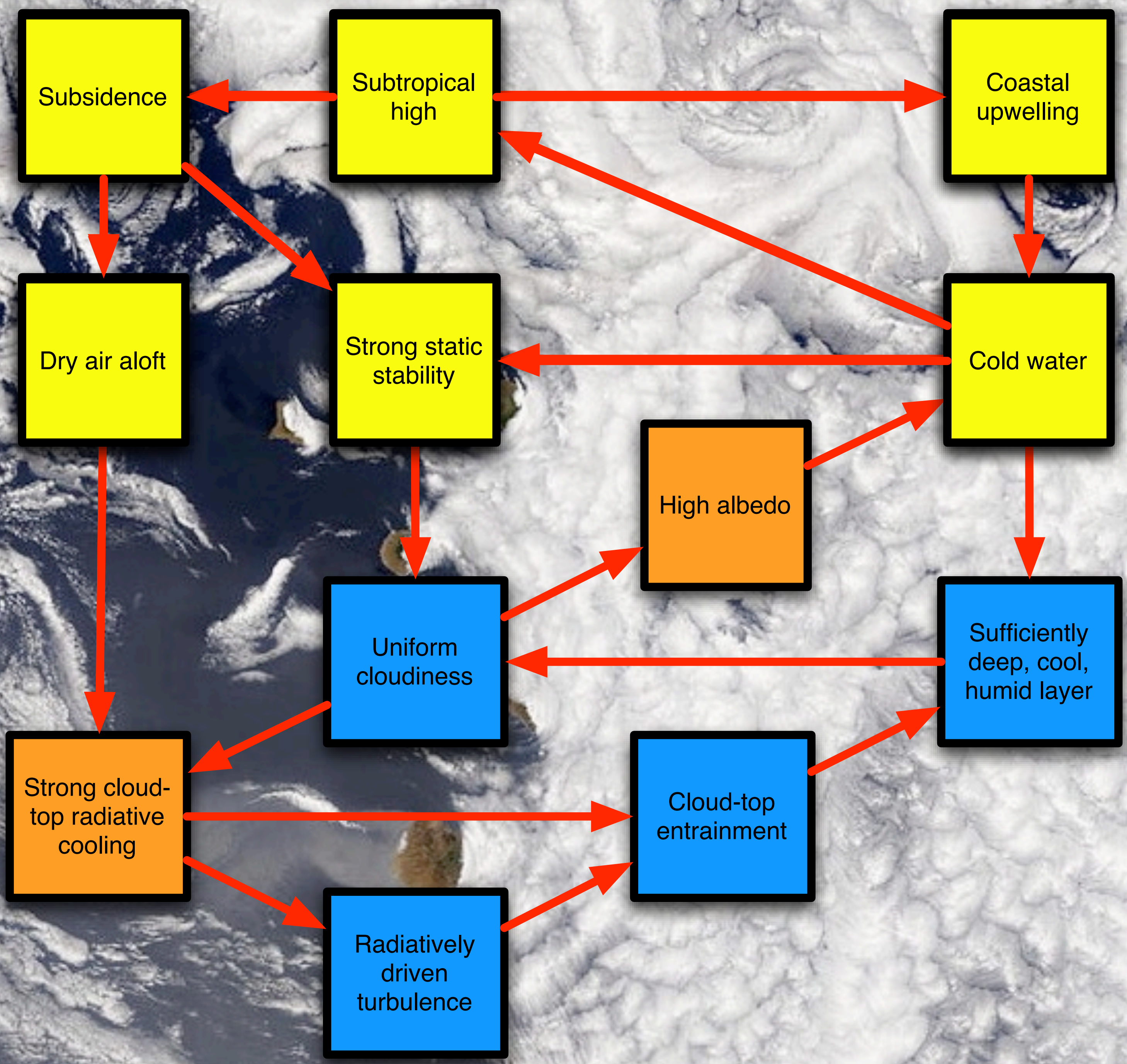

Current issues in conventional cloud parameterizations

- Microphysics
  - How many water species?
  - Aerosols?
- Convective entrainment
  - How many cloud “types”?
  - What controls entrainment?
- Convective closures
- Coupling deep convection with the boundary layer
  - Updrafts?
  - Downdrafts?

Conclusions

- Clouds matter for radiation, precipitation, vertical transports, and chemistry.
- Convection parameterizations rely on the fact that the fractional area covered by updrafts is very small.
- The convective mass flux can be determined by assuming that CAPE is consumed as fast as it is generated.
- Stratocumulus clouds are radiatively important, but don't rain much.
- Stratocumulus clouds are vertically thin but complicated and hard to simulate realistically.