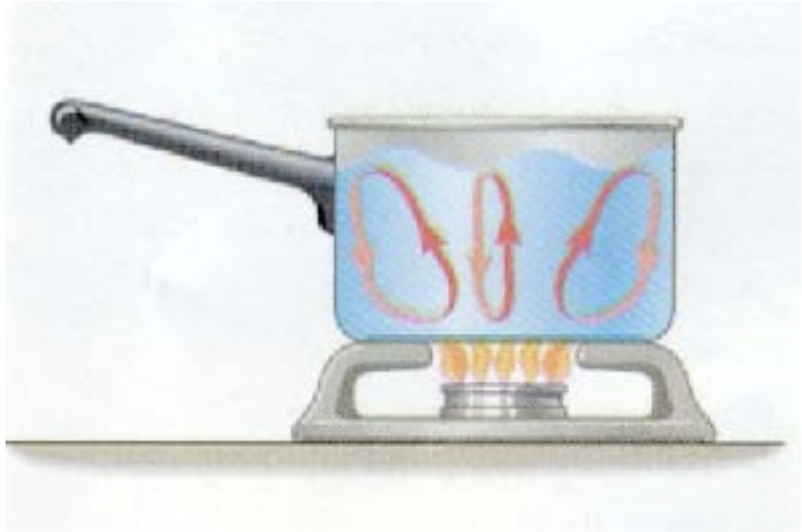
Convection I

Steve Sherwood

Cargese Summer School 2009



Convection: hot (light) stuff goes up, cold (dense) goes down.
Upward heat transport = $\rho c_p \langle T'w' \rangle$

Lecture I (today)
Fundamentals of convective layers

Lecture II:
Atmospheric deep convection

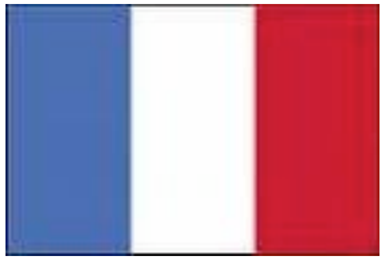
Lecture III:
Interactions across scales / climate

Point of view will be from climate, not weather.

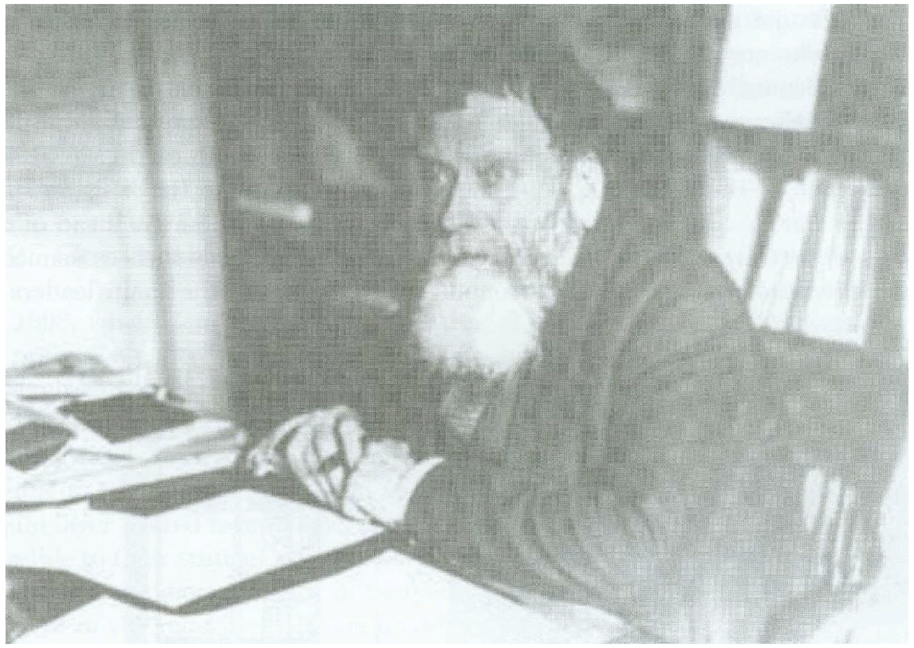
Benjamin Thompson, Count Rumford (1753-1814)

- American experimentalist, professional soldier, spy for the British during Revolutionary War; military/political counsellor to royal family in Bavaria; founder of Royal Institution in London
- Known for foundational work on ”heat” and thermodynamics and for dispelling the ”caloric theory”
- First published investigation of convection (1797) (except the word ”convection” didn’t exist) to understand insulating properties of military clothing

Henri Claude Bénard (1874-1939)



- French physicist/engineer
- While making a dielectric medium for his thesis work, discovered by accident patterns formed in heated, melted paraffin
- Constructed sophisticated experiments with precise temperature control to study onset of thermal convection in paraffin and spermacetti (whale fat).



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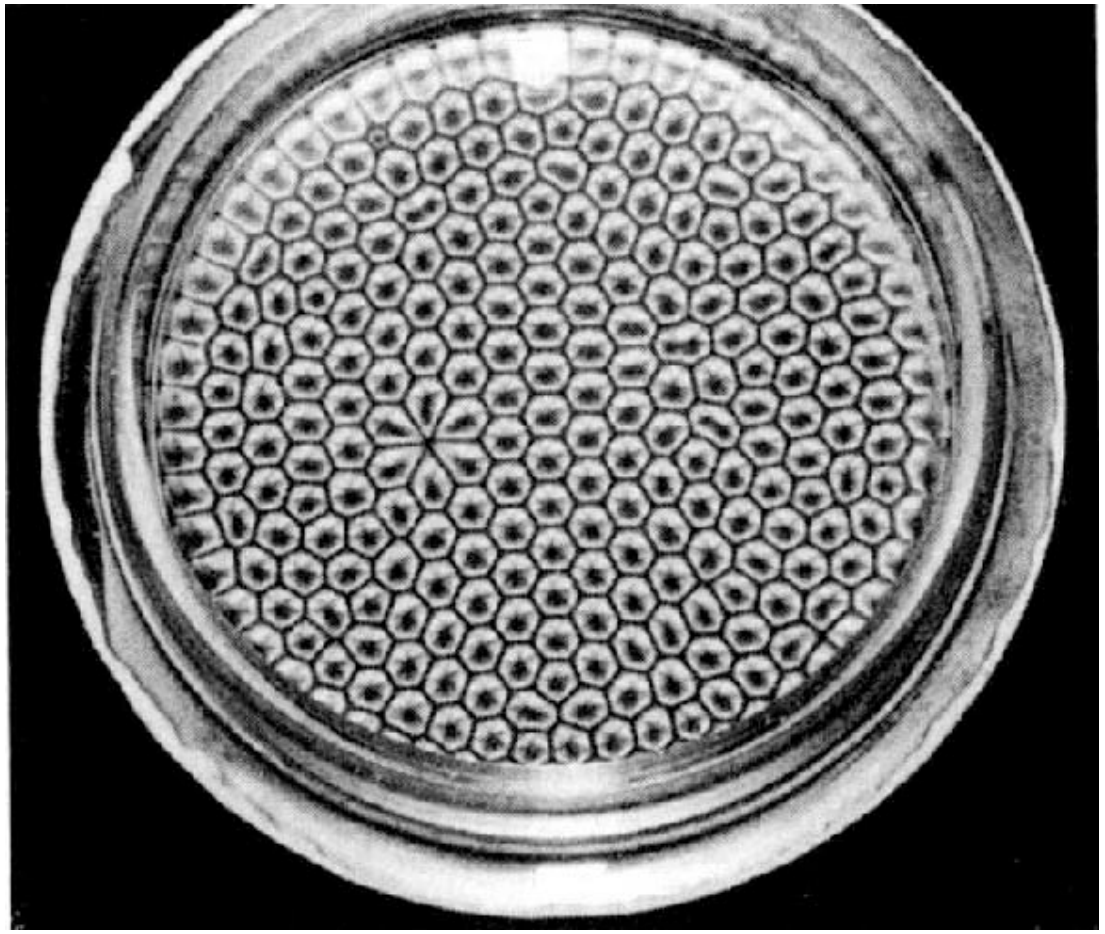
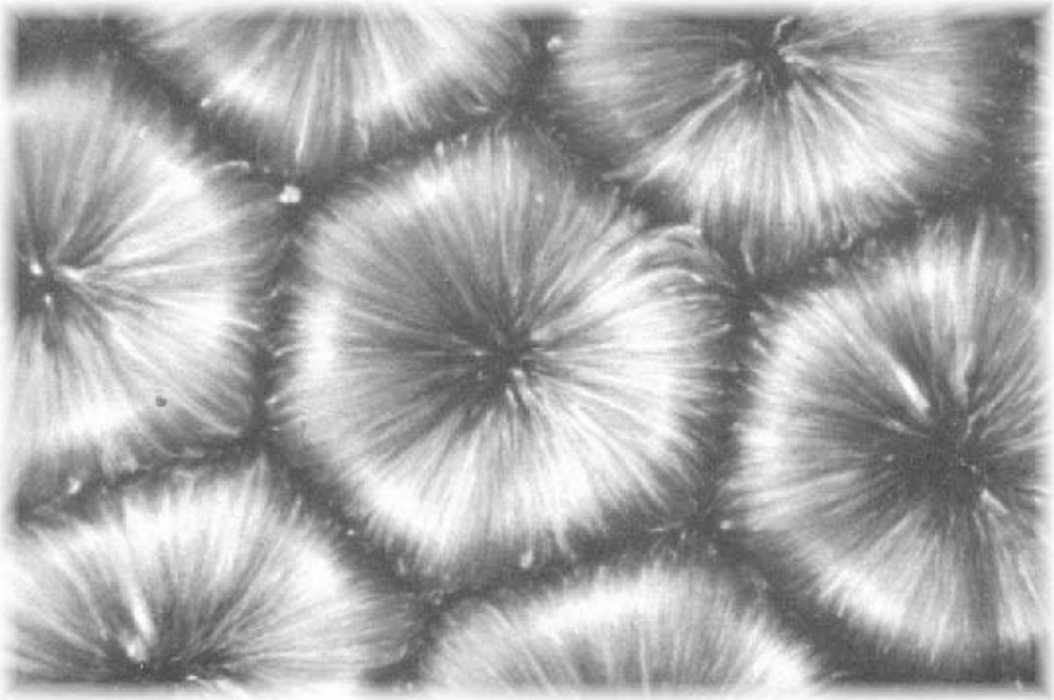


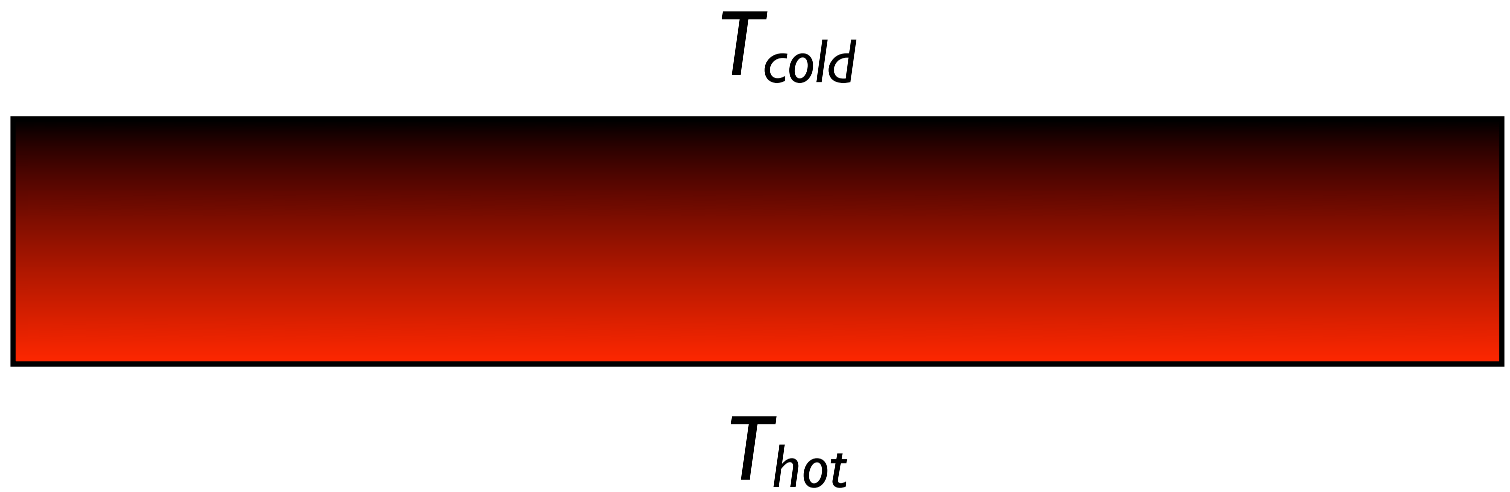


- ”First” systematic study of convection (except earlier work by James Thomson, Lord Kelvin’s older brother, on evaporative convection)
- Became subject of his PhD dissertation (1900-1901), which however was received with little enthusiasm by his doctoral committee
- Later analysis found that he wasn’t really studying pure thermal convection but a combination of thermal with surface-tension driven convection (”Marangoni convection”)

John William Strutt, Lord Rayleigh (1842-1919)

- British physicist, mathematician
- Pioneering work in, e.g., sound and elastic waves (Rayleigh waves), light scattering (Rayleigh scattering), radiation (Rayleigh-Jeans criterion for spectra of black body radiation)
- Nobel Prize for isolating atmospheric Argon
- In 1916, wrote seminal theoretical paper analyzing Bénard's experiments from 15 years earlier: cornerstone of all theories on convection
- The mismatch between their work (theory vs experiment) was not resolved until the late 1950's: surface tension in the experiments.

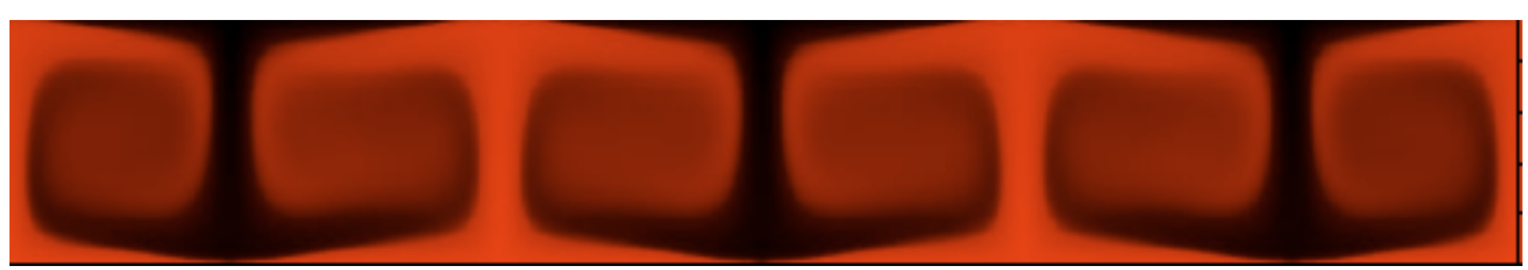
How does it work?



- System driven away from equilibrium by imposed temperature gradient $\Delta T = T_{hot} - T_{cold}$ (picture above initial condition)

- With small ΔT, heat transfer is by *conduction* (picture above in steady state)

- With large ΔT, heat transfer is by convection (hot blobs rise to top, cold sink to bottom):



How does it work?

T_{hot}

d

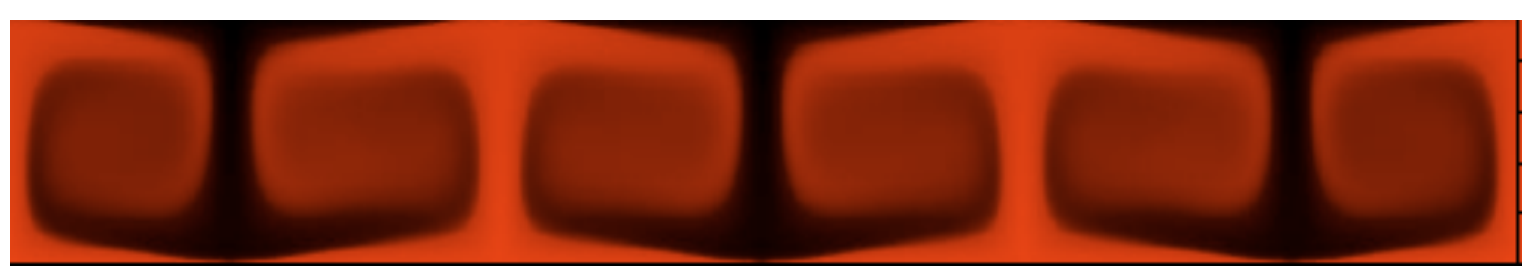
T_{cold}

Rayleigh showed that the convection would behave according to a dimensionless parameter (the "Rayleigh number")

$$Ra = g\alpha\Delta T d^3 / \nu\kappa$$

α = thermal expansion coefficient (K^{-1}) (~ 0.003 for air)
ν = viscosity (m^2/s) (~2 x 10^{-5} m^2/s for air)
κ = thermal diffusivity (m^2/s) (~2 x 10^{-5} m^2/s for air)

determined by the ratio of buoyancy forces to viscous forces and diffusivity.



Ra (air) ~ $10^8 d^3 \Delta T$ (mks)

Equilibrium and Stability: Onset of convection

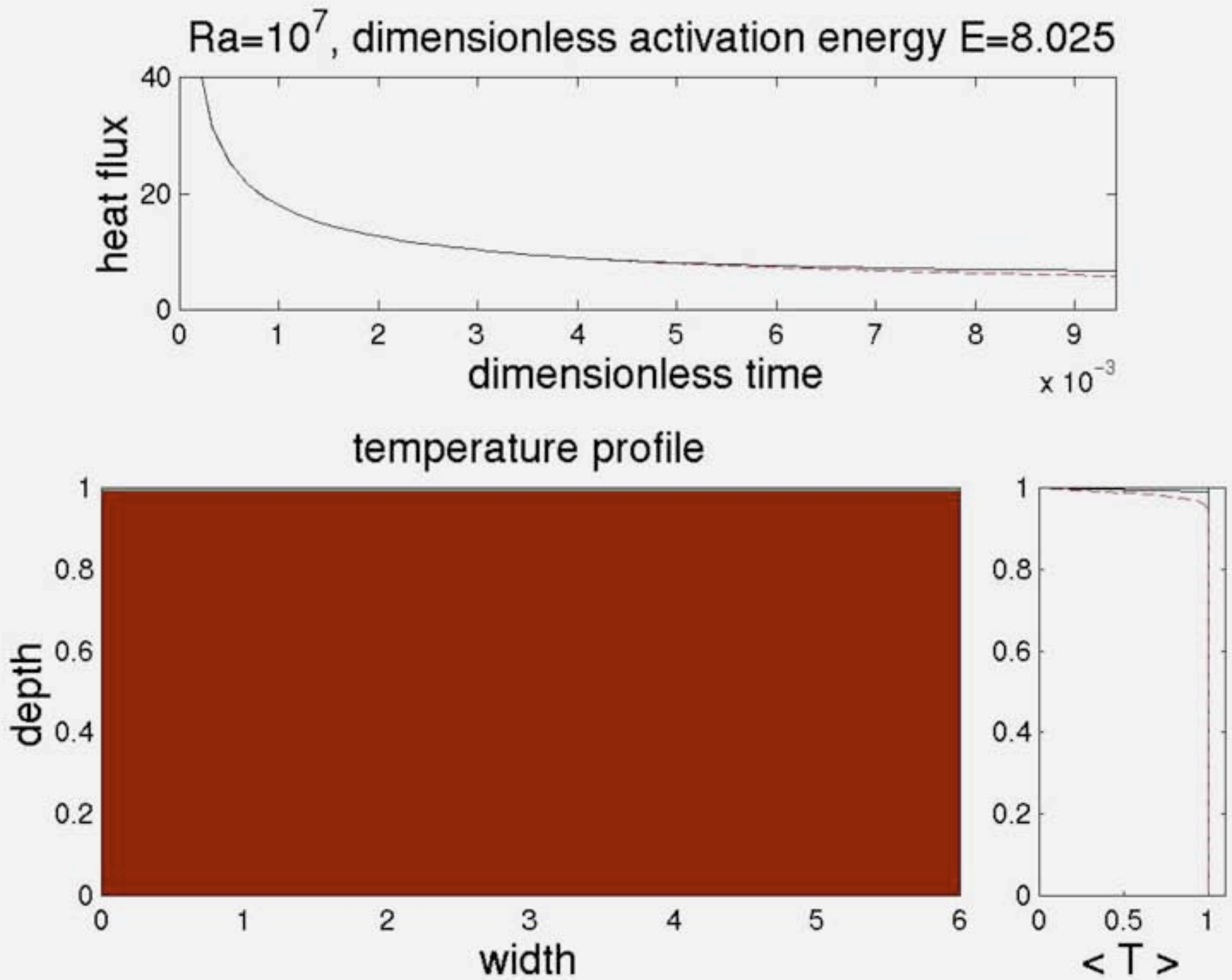
Intuitive approach:

- "Equilibrium" state for a fluid layer: heated uniformly; conducts heat out through colder top
- Hot on bottom, cold on top: gravitationally unstable, BUT not necessarily convectively unstable
- Perturbations of all sizes jostle fluid, try to flip it over by hot/cold blobs rising/sinking.
- Smaller blobs lose heat too fast and dissipate: **convectively stable**
- Larger blobs too hard to move and dissipate away: **also convectively stable**
- Intermediate size blobs are "just right" to make layer go **convectively unstable**, with enough heating: Called most **unstable mode**.

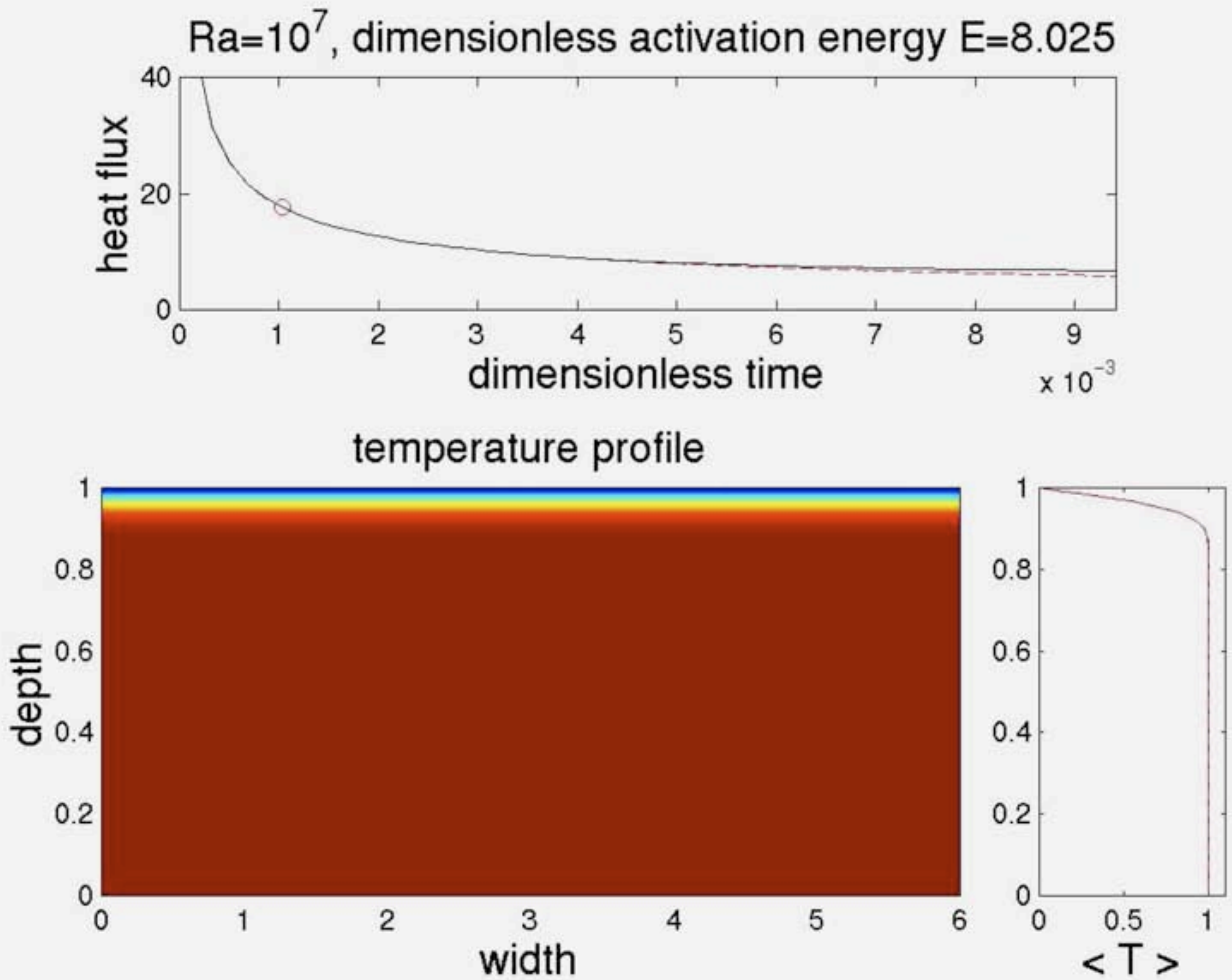
Quantitative approach:

- Begin with equations of motion; perform linear stability analysis w/assumed harmonic solutions
- Find fastest-growing solution and identify region of parameter space where growth > 0.
- Scale of fastest-growing solution will appear first?

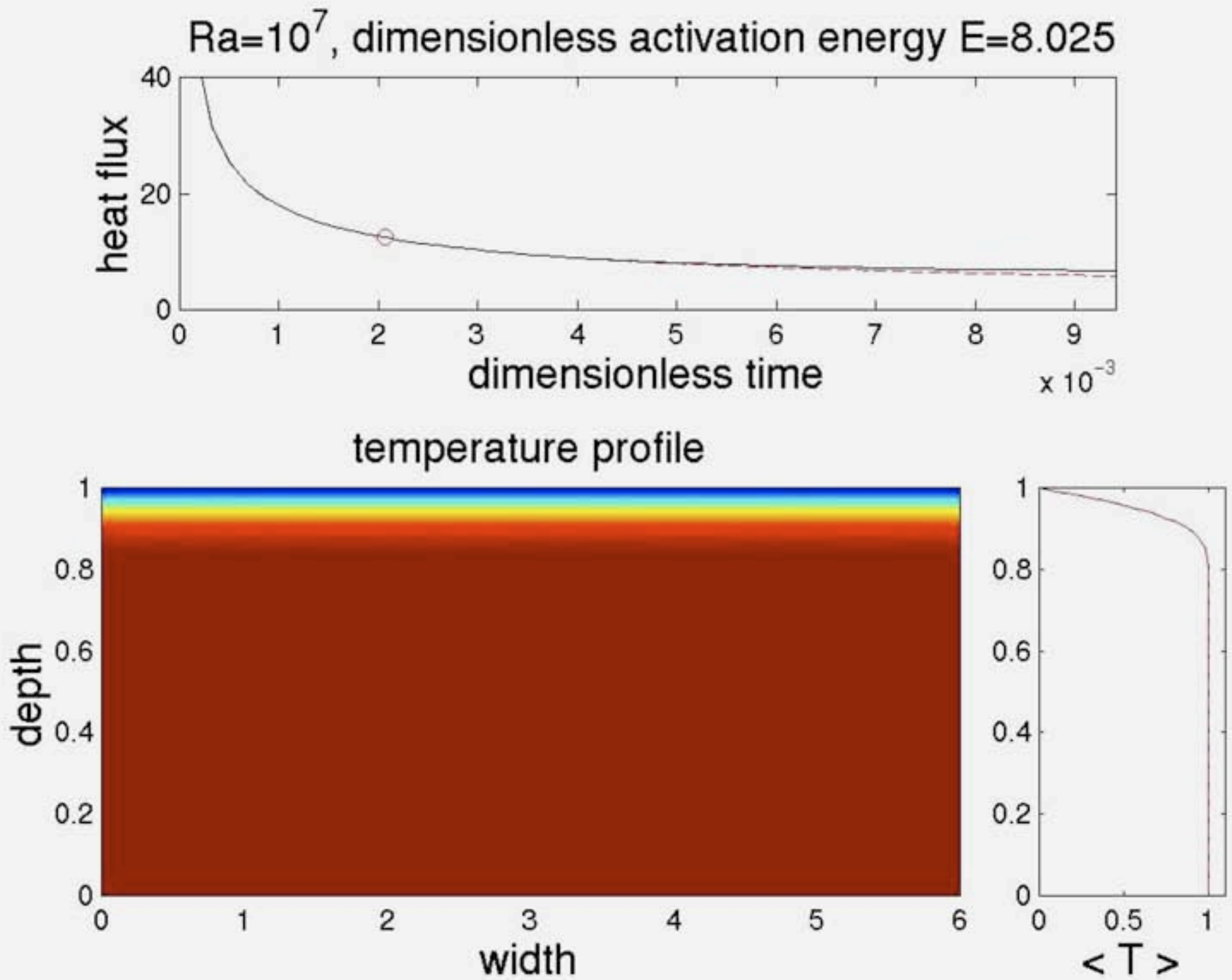
Numerical simulation, transient cooling from top



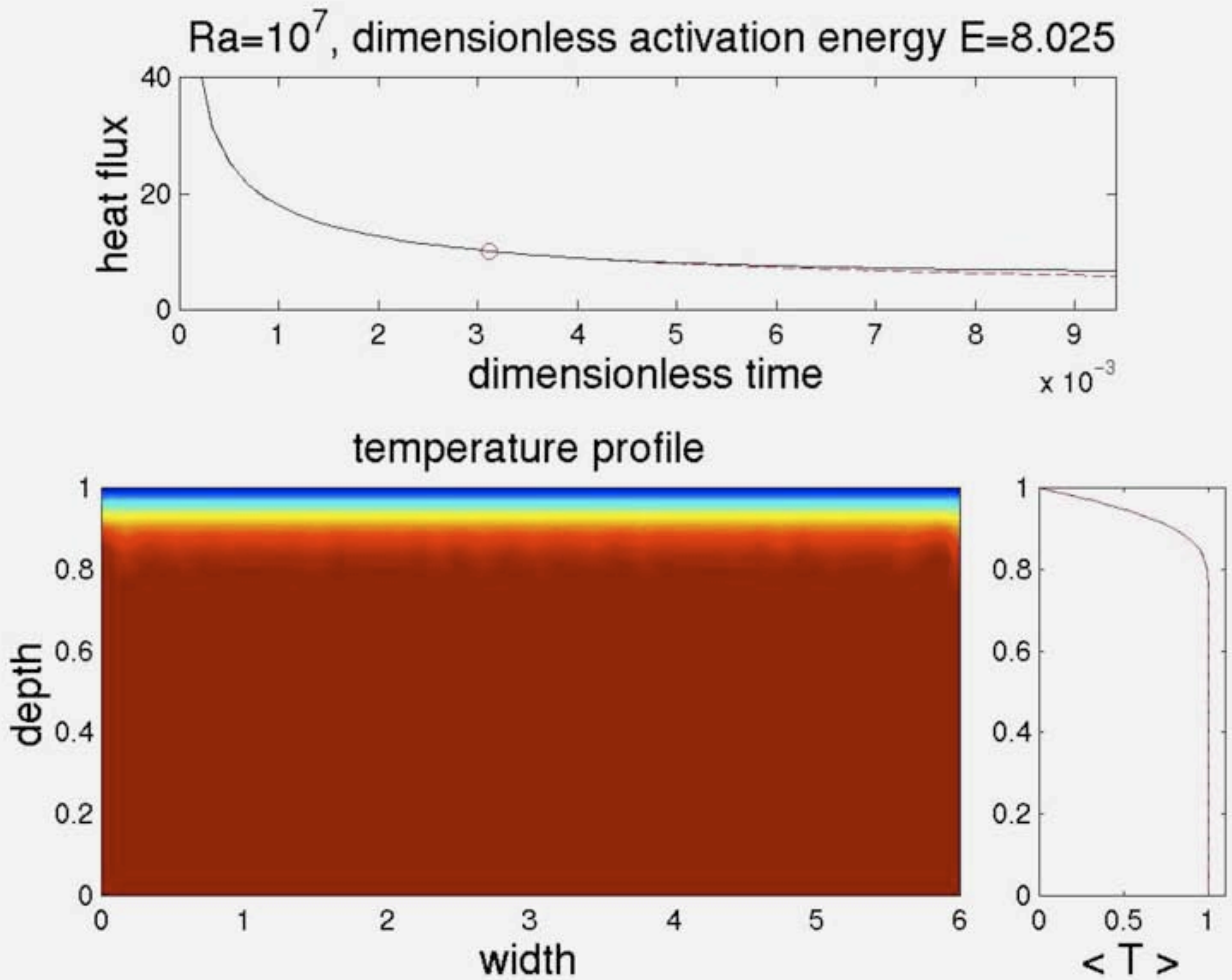
Numerical simulation, transient cooling from top



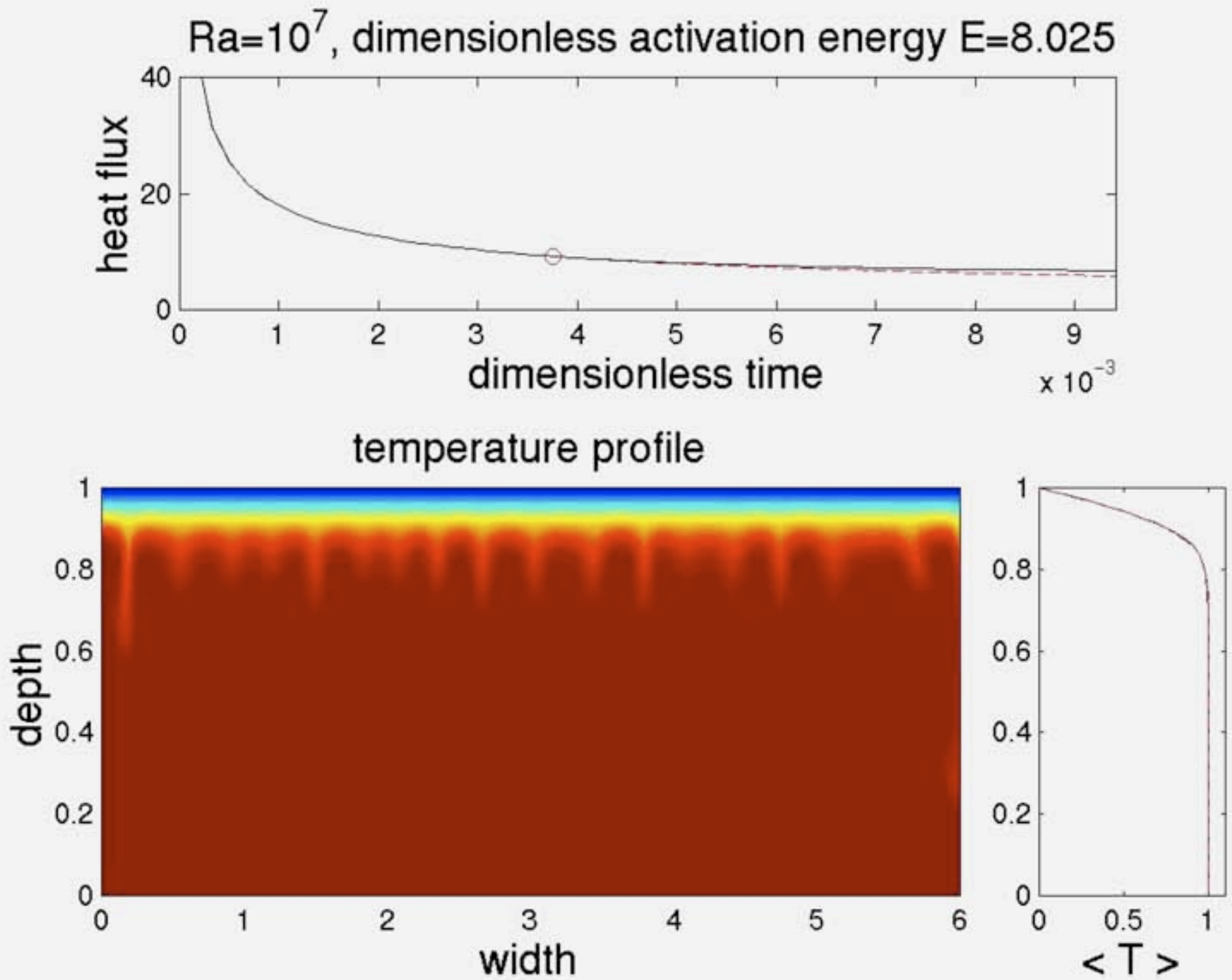
Numerical simulation, transient cooling from top



Numerical simulation, transient cooling from top



Numerical simulation, transient cooling from top



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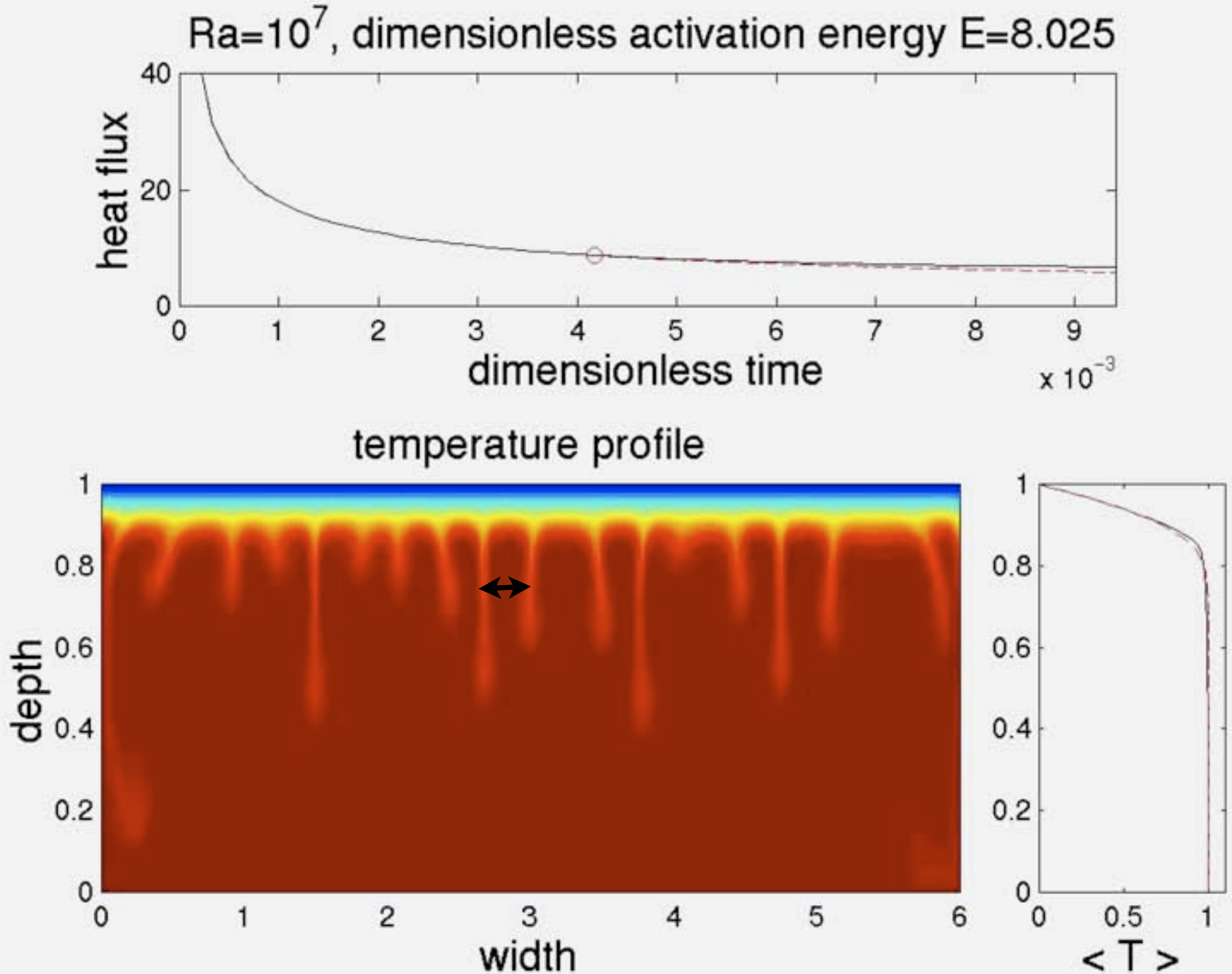
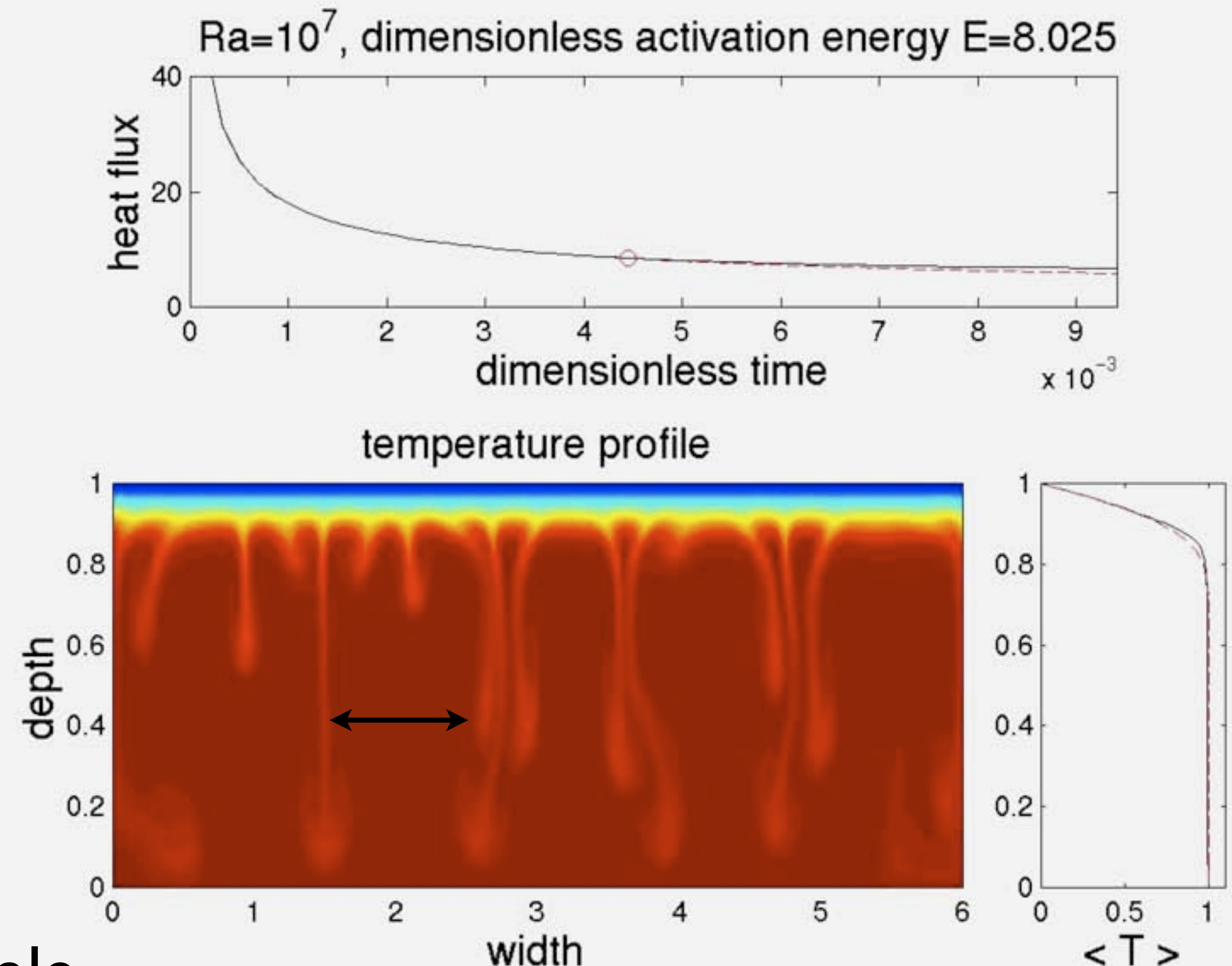


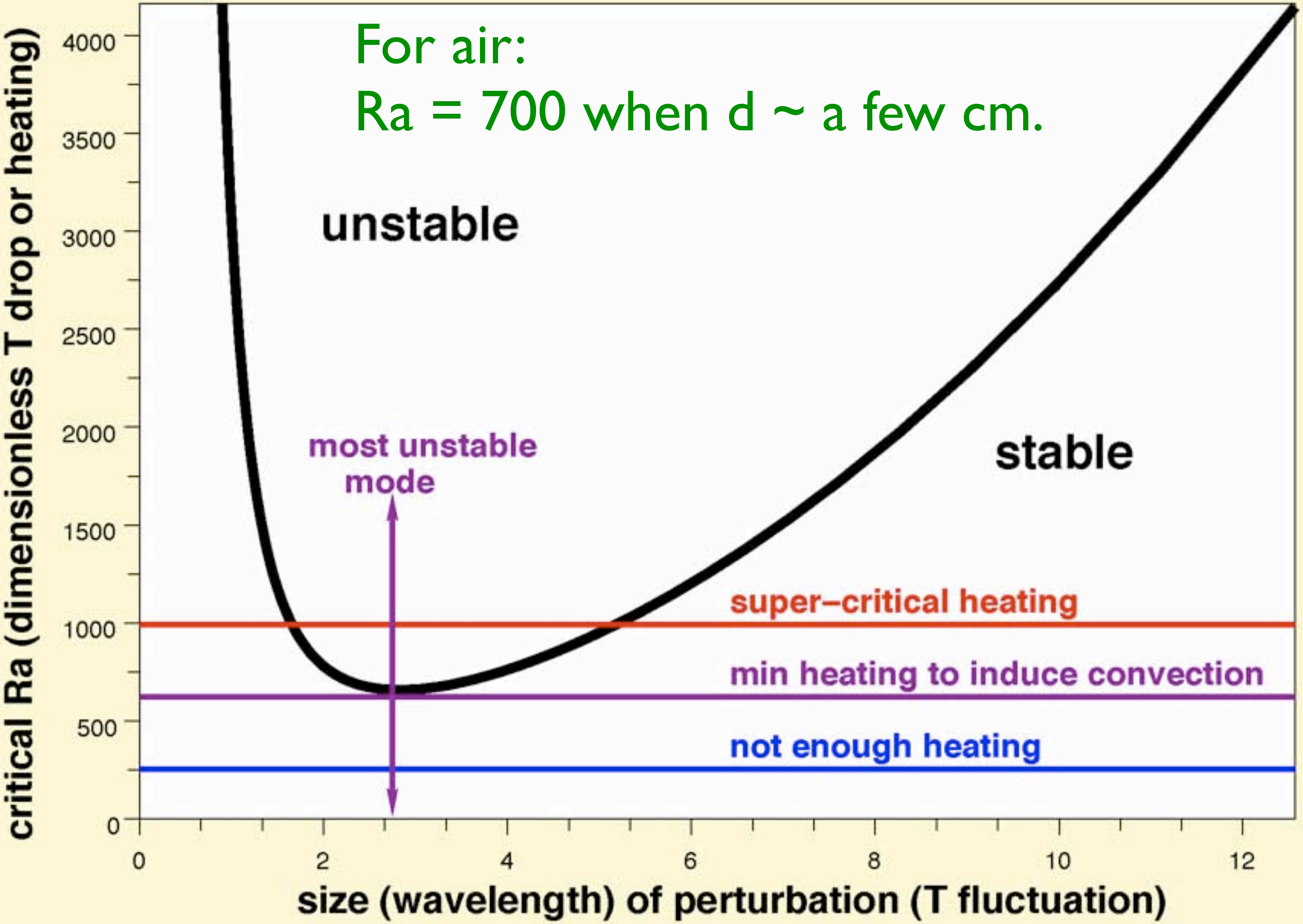
Initial growth scale

Numerical simulation, transient cooling from top



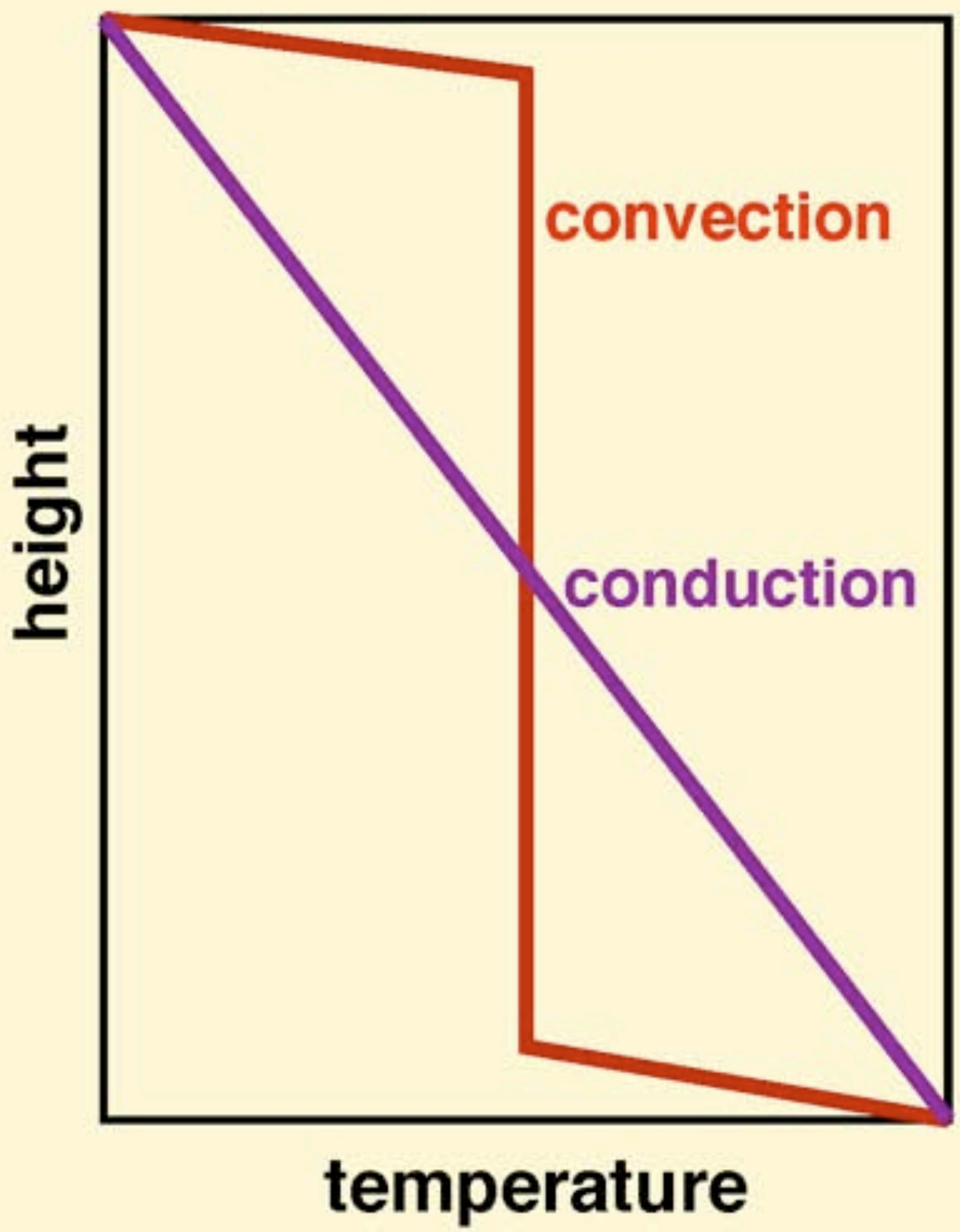
Upscale cascade

Onset of convection: Critical Ra and pattern selection



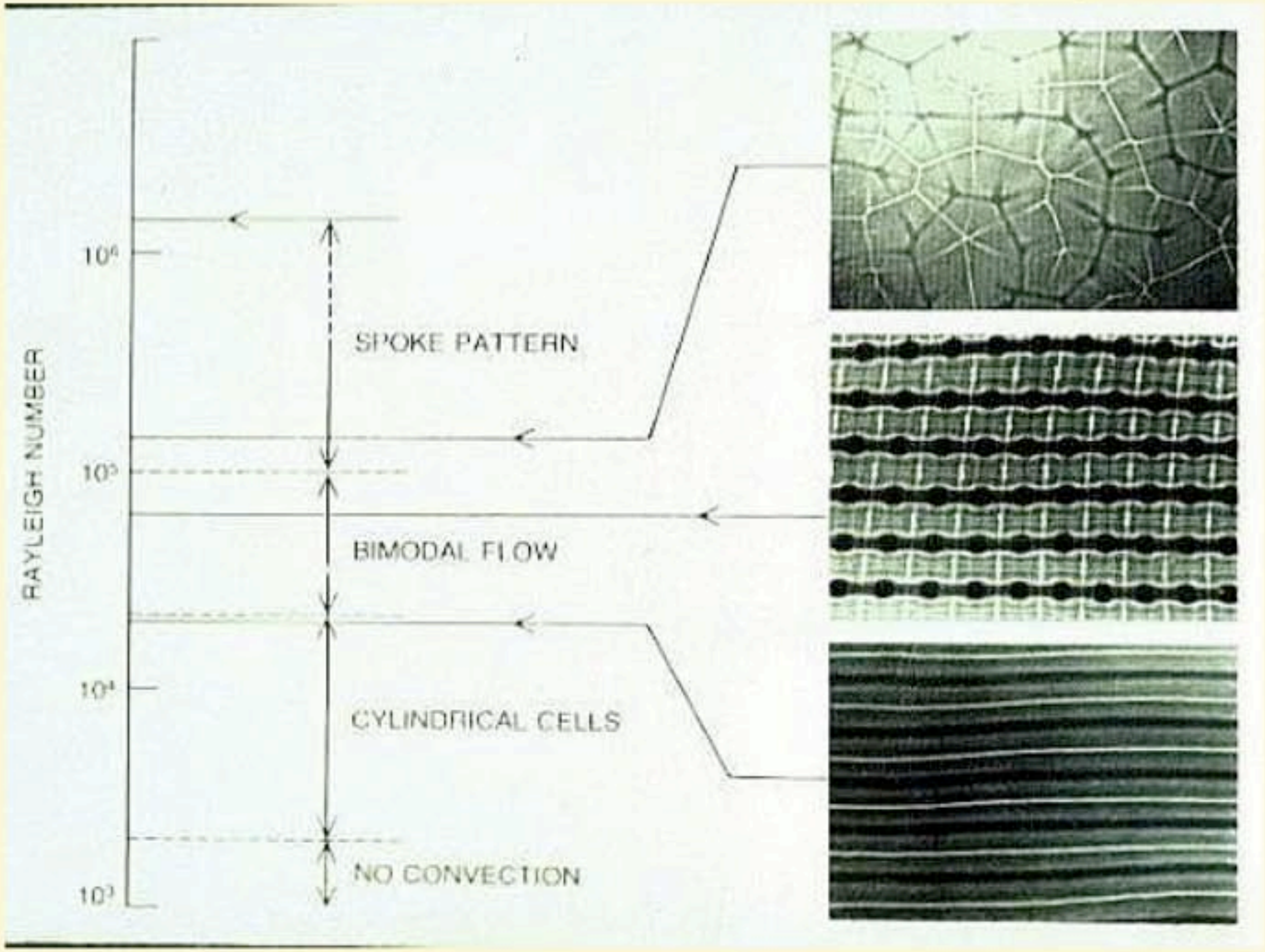
From Rayleigh's 1916 theory

Convection gets the heat out



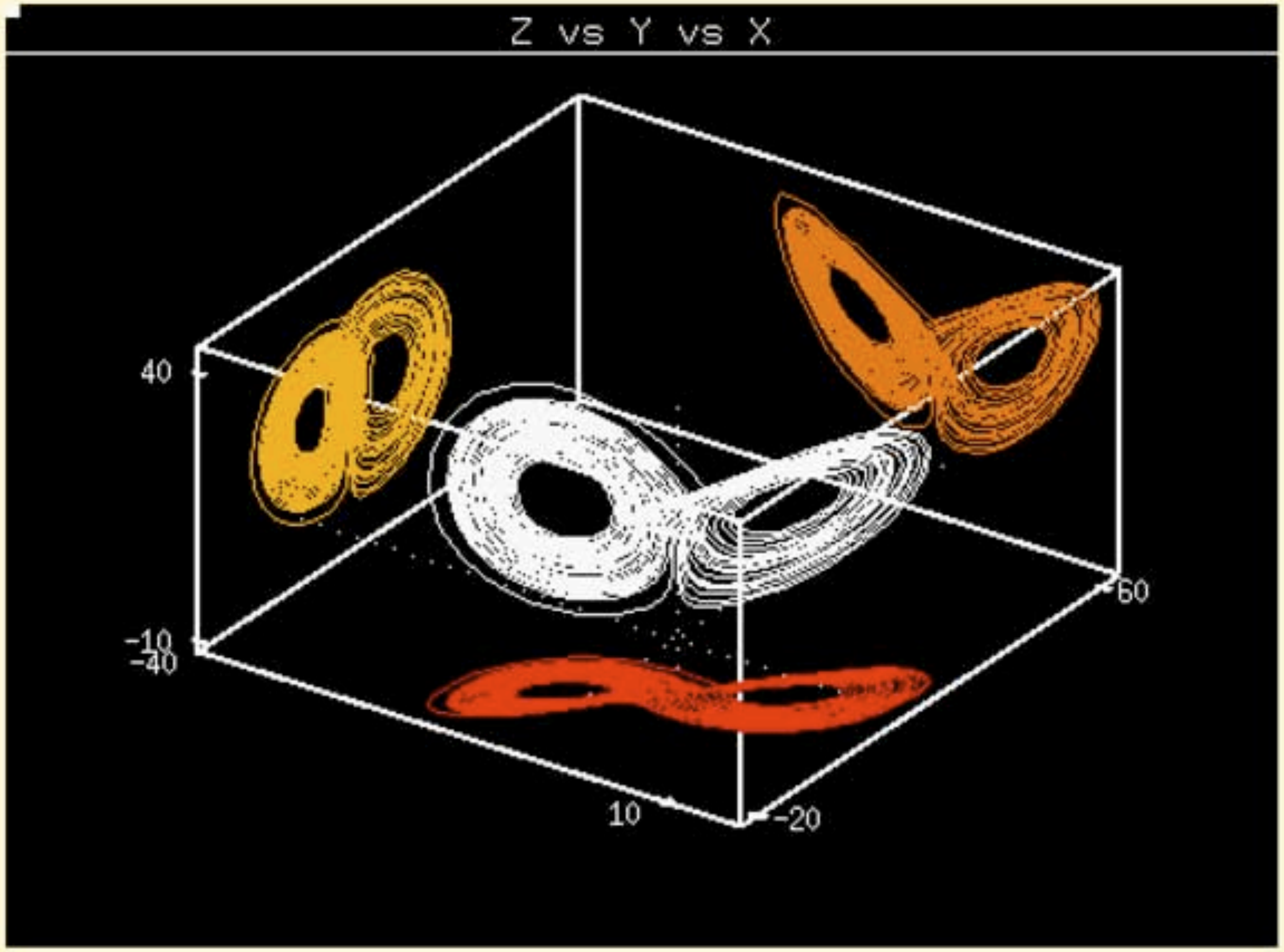
- With rigorous convection...
- Convective mixing homogenizes most of interior temperature
- But fluid T must still match boundary T:
  - transition from interior T to boundary T occurs over thin *boundary layers* of thickness δ
  - boundary layers get thinner (more excavated) the stronger convection (higher Ra)
- Heatflow across boundary layers $\sim k\Delta T/\delta$ where $k =$ thermal conductivity
  - Heatflow greatly enhanced by convection through mixing

Transitions in convective patterns



- With more heating (increasing Ra), convection undergoes pattern transitions (rolls, to squares to spoke, etc)
- Eventually transition to time-dependence (classically to periodic behavior ["Hopf Bifurcation"], then period doubling, then eventually chaotic behavior)

Chaos

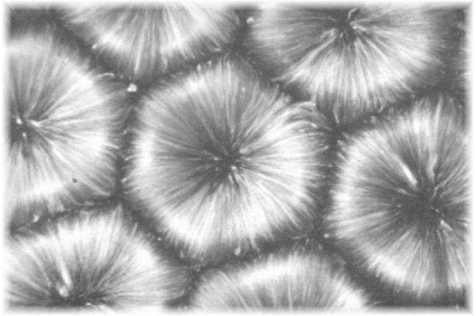


- Classical example of chaos: Lorenz equations
- Very simplified model: velocity X of one convection cell, the temperature difference between its hot and cold limbs Y, and heatflow Z out of layer
  - Chaos needs at least 3 variables (3D "phase space")
- Paths in (X, Y, Z) space that nearly intersect can undergo big separation after finite time: Butterfly effect

Anisotropy in real-world convection

Benard convection

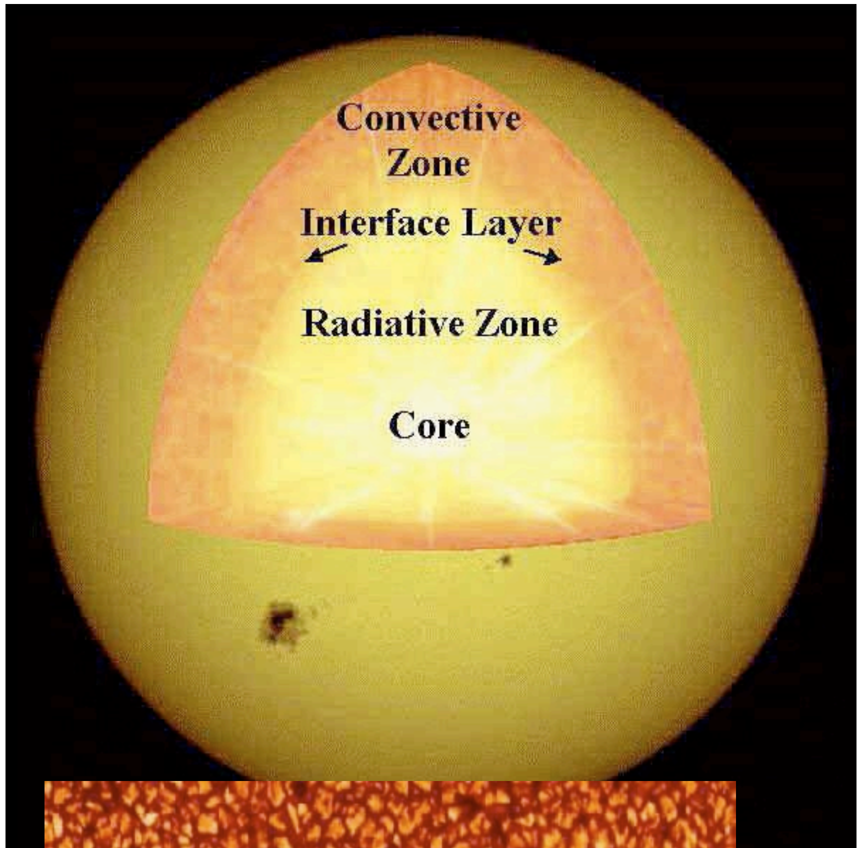
- Surface tension at upper boundary

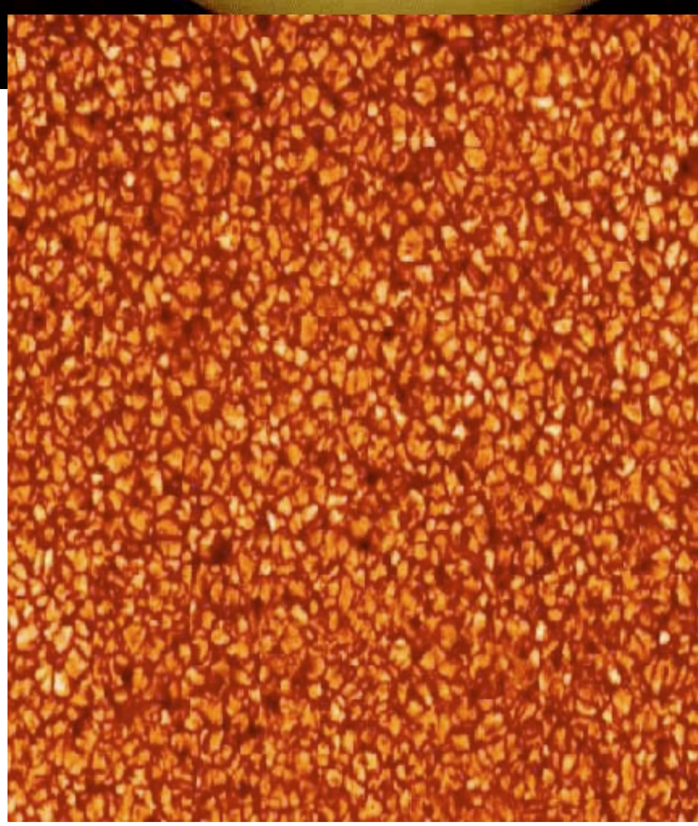


Atmospheric convection

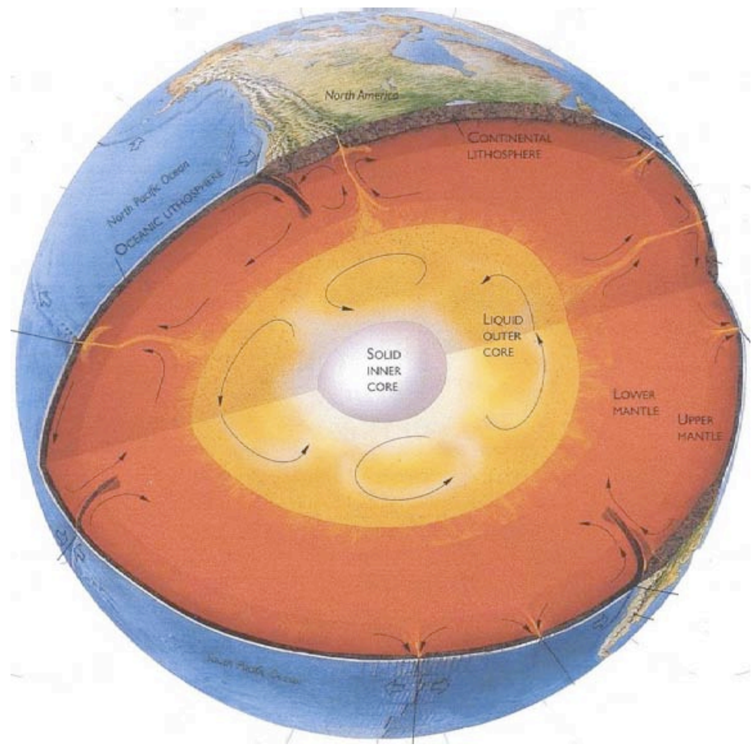
- Cooling, by radiation, is vertically extensive rather than at plate/interface; solar heating all at the surface. Heating is nonsteady.
- Friction at lower boundary, wind shear (variable) at top boundary.
- Kinematically rigid lower boundary, soft upper boundary.
- Condensational heating of ascending air, usually no corresponding cooling of descending air --> narrow, strong updrafts, broad downdrafts.

Examples of convection in nature:





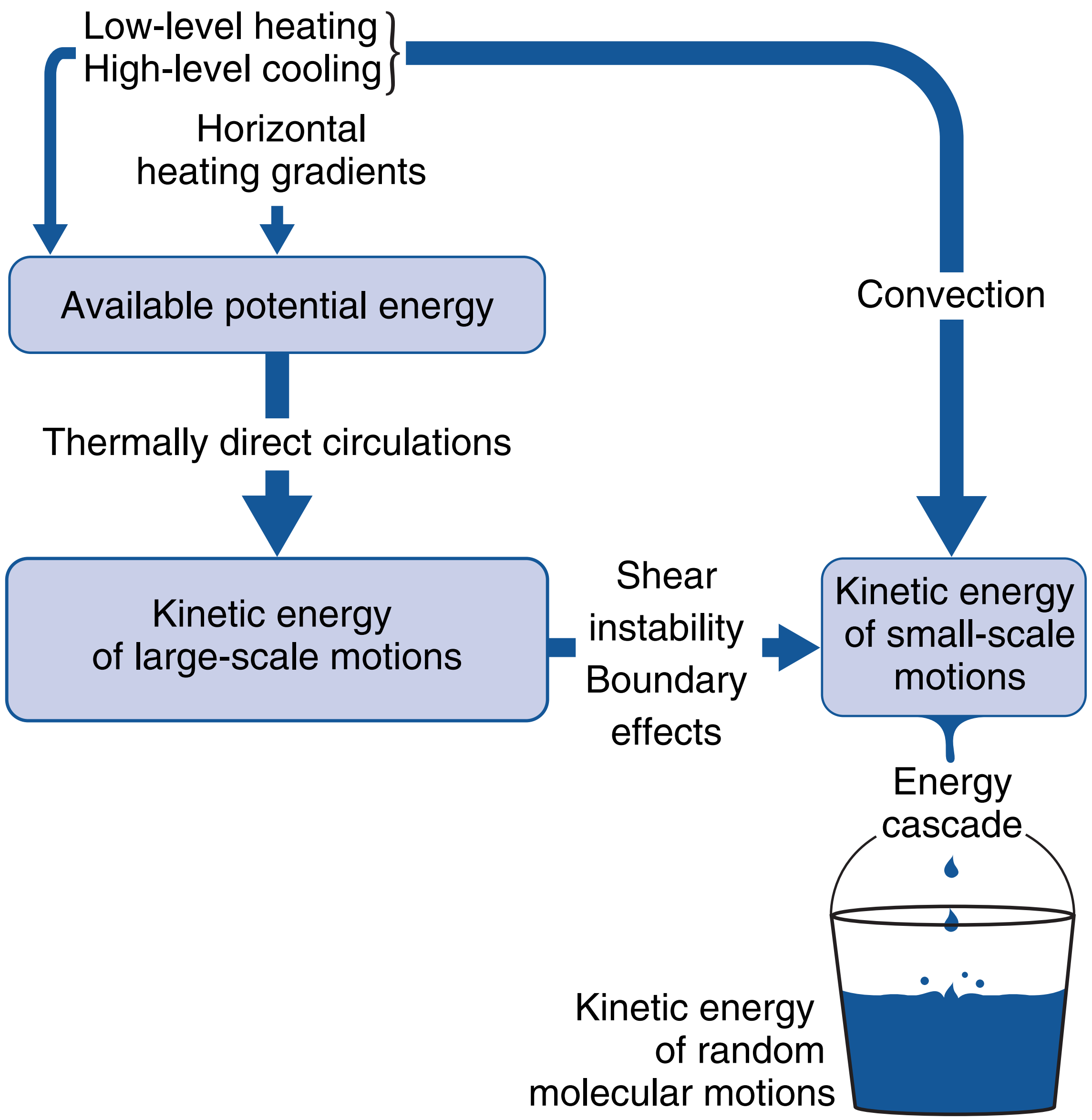
Sun

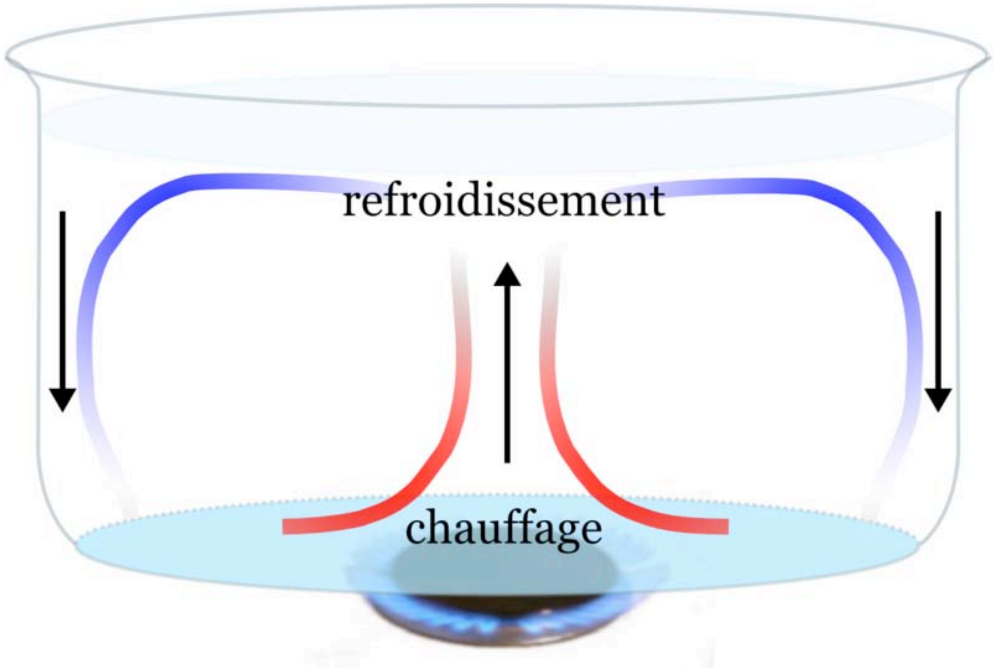


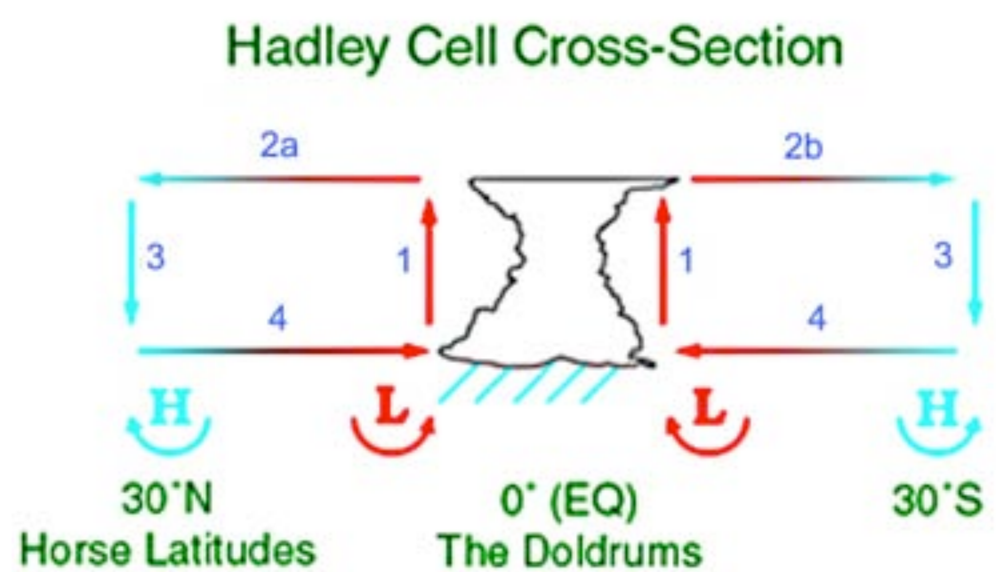
Mantle

Atmospheres

Atmospheric convection: an identity crisis

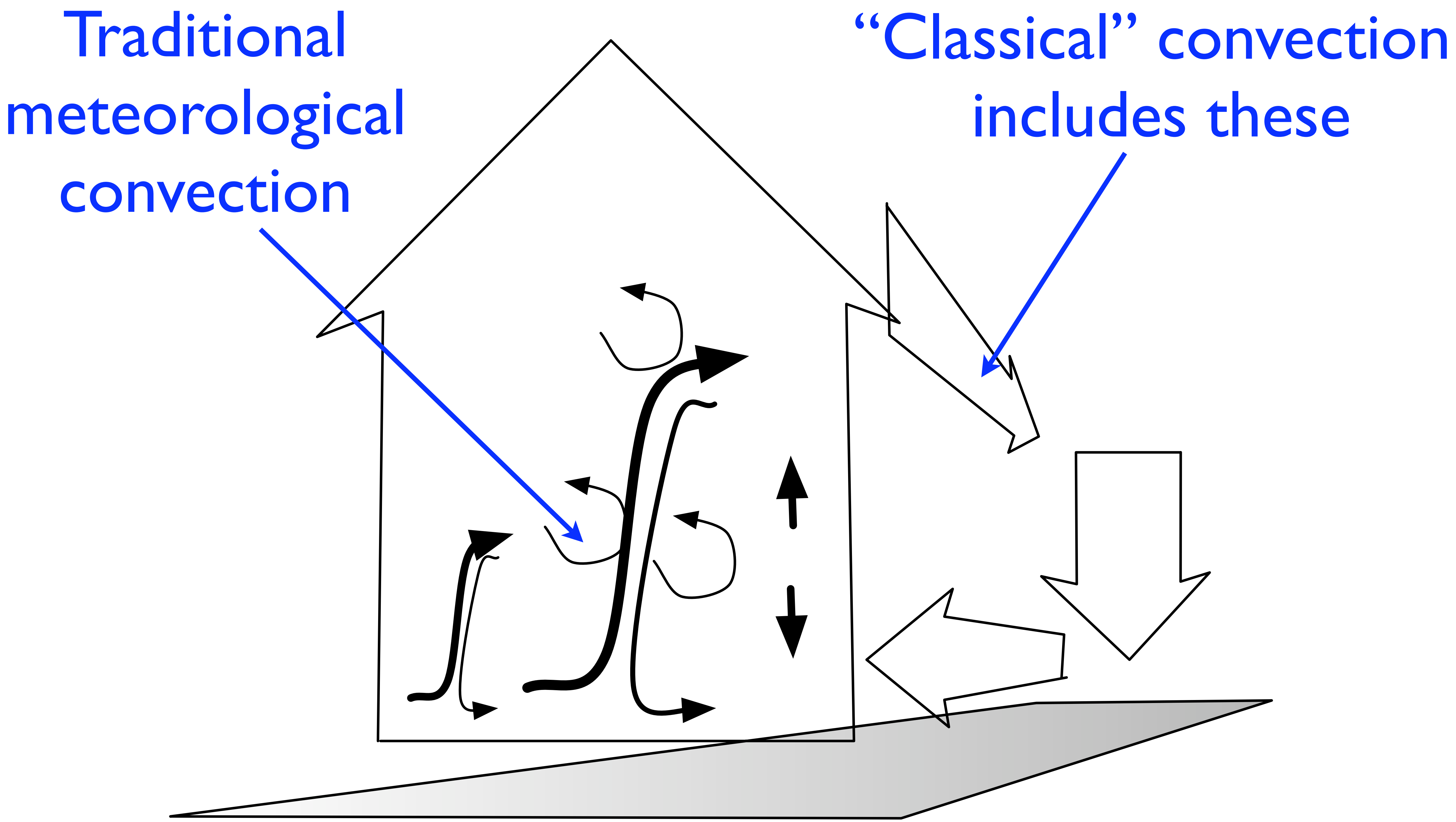


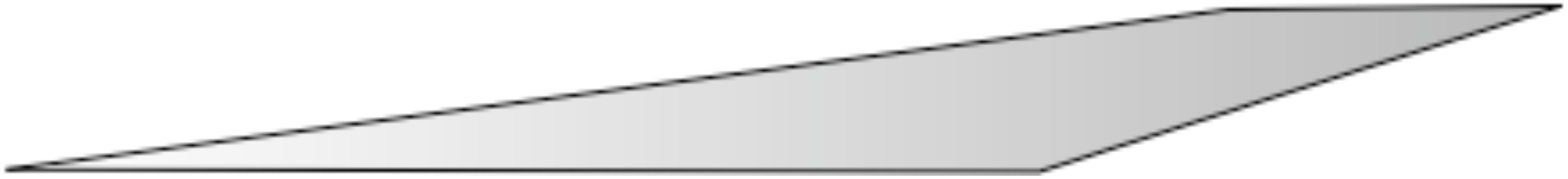




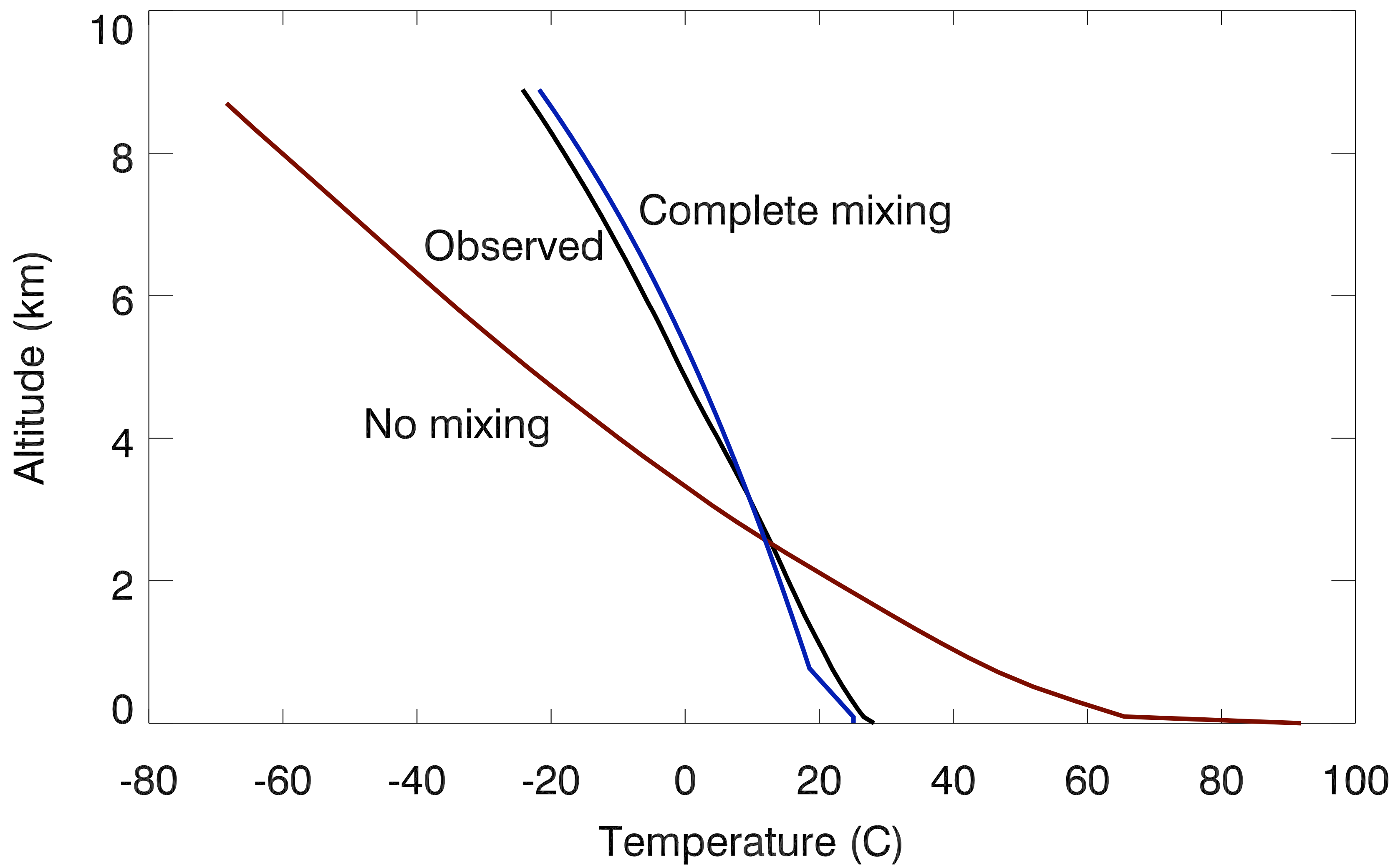
Traditional meteorological view: Convection vs. large scale motions.

Fundamental view: convection includes Hadley, Walker cells, slantwise midlatitude eddies.

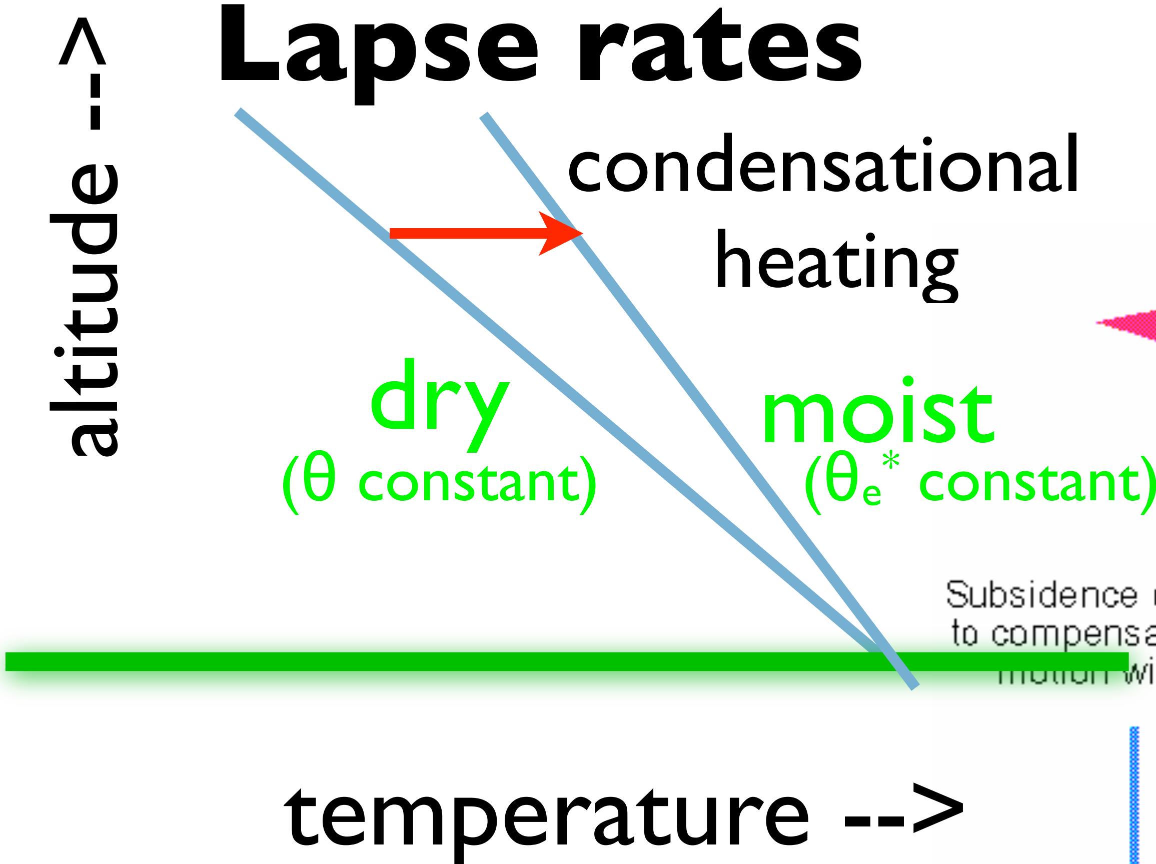

Traditional meteorological convection
"Classical" convection includes these

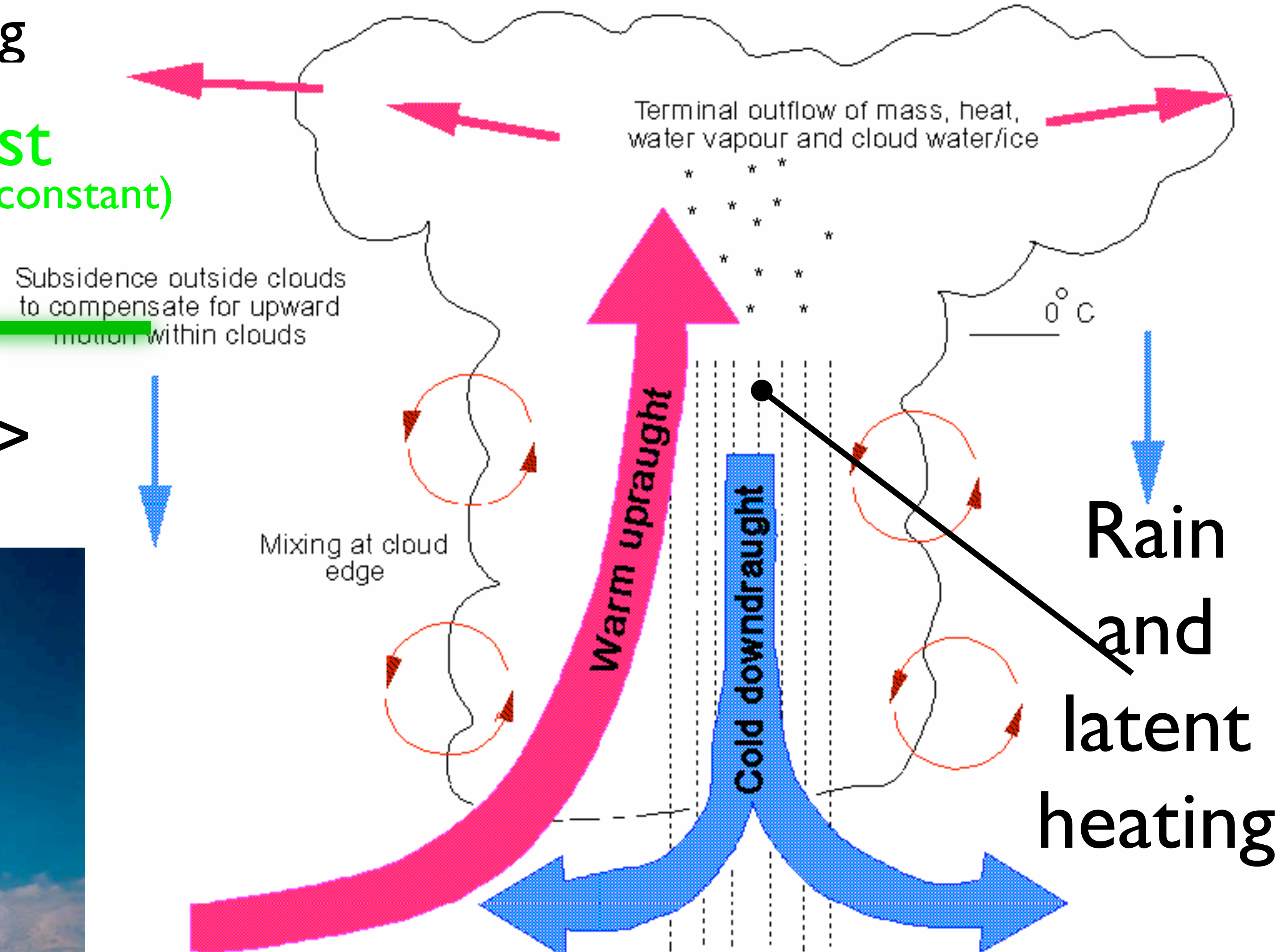


Convection (classical definition) maintains a moist adiabat (θ_e^* constant) through most of the troposphere



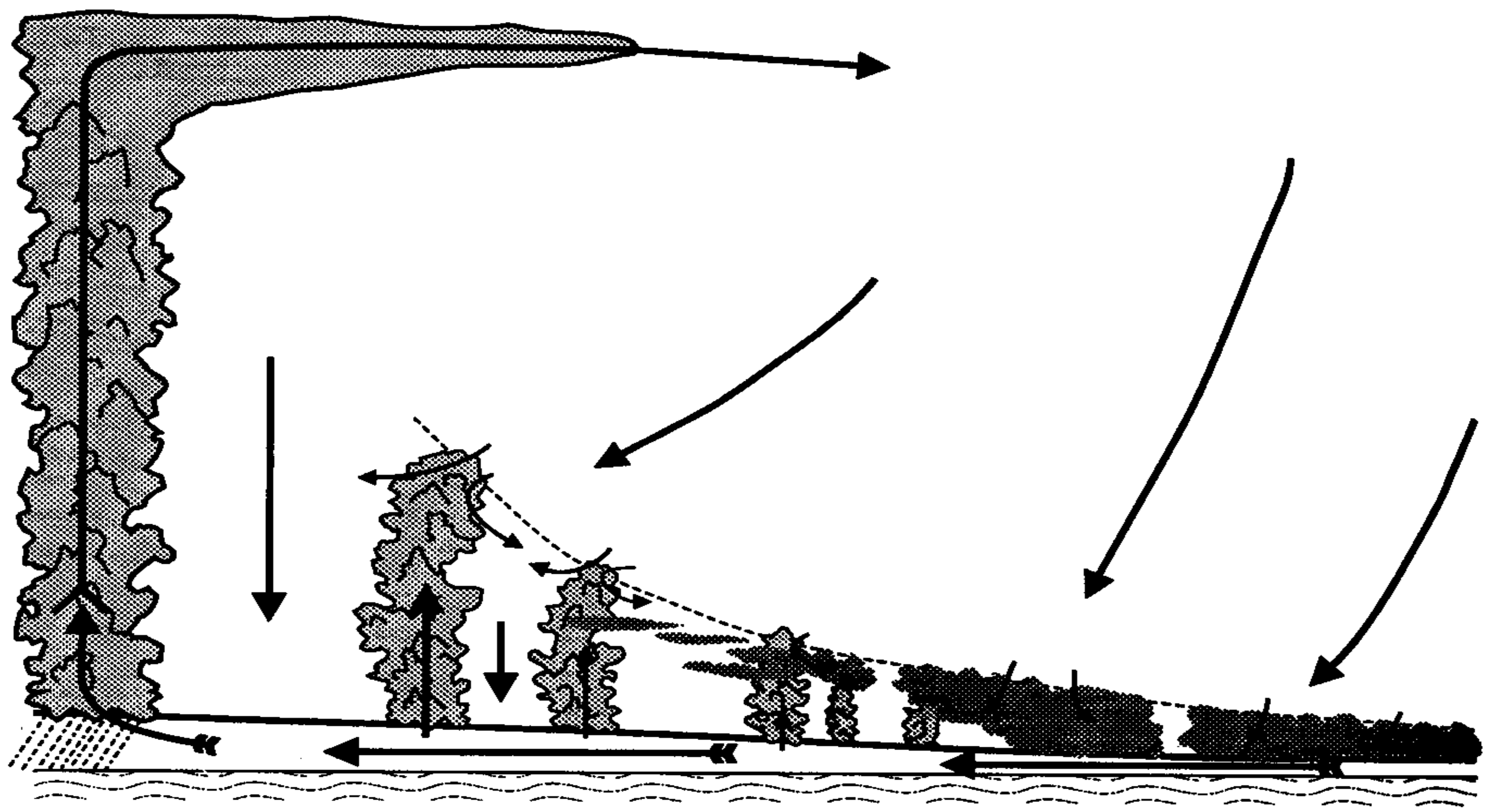
Lapse rates





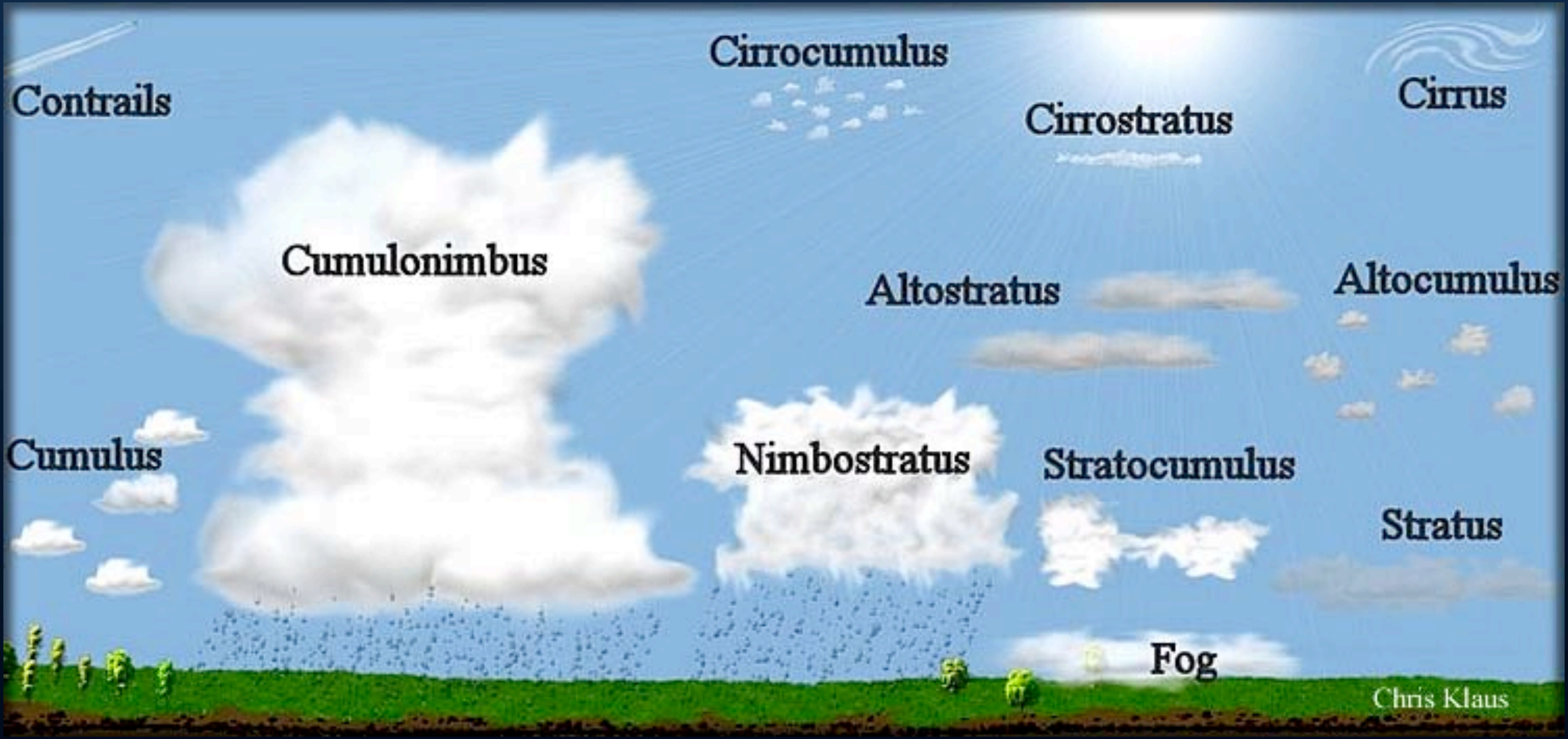
Environment is stable ($d\theta/dz > 0$). Sustained vertical motion if (and only if) commensurate phase change!

Idealised Walker or Hadley tropical overturning.

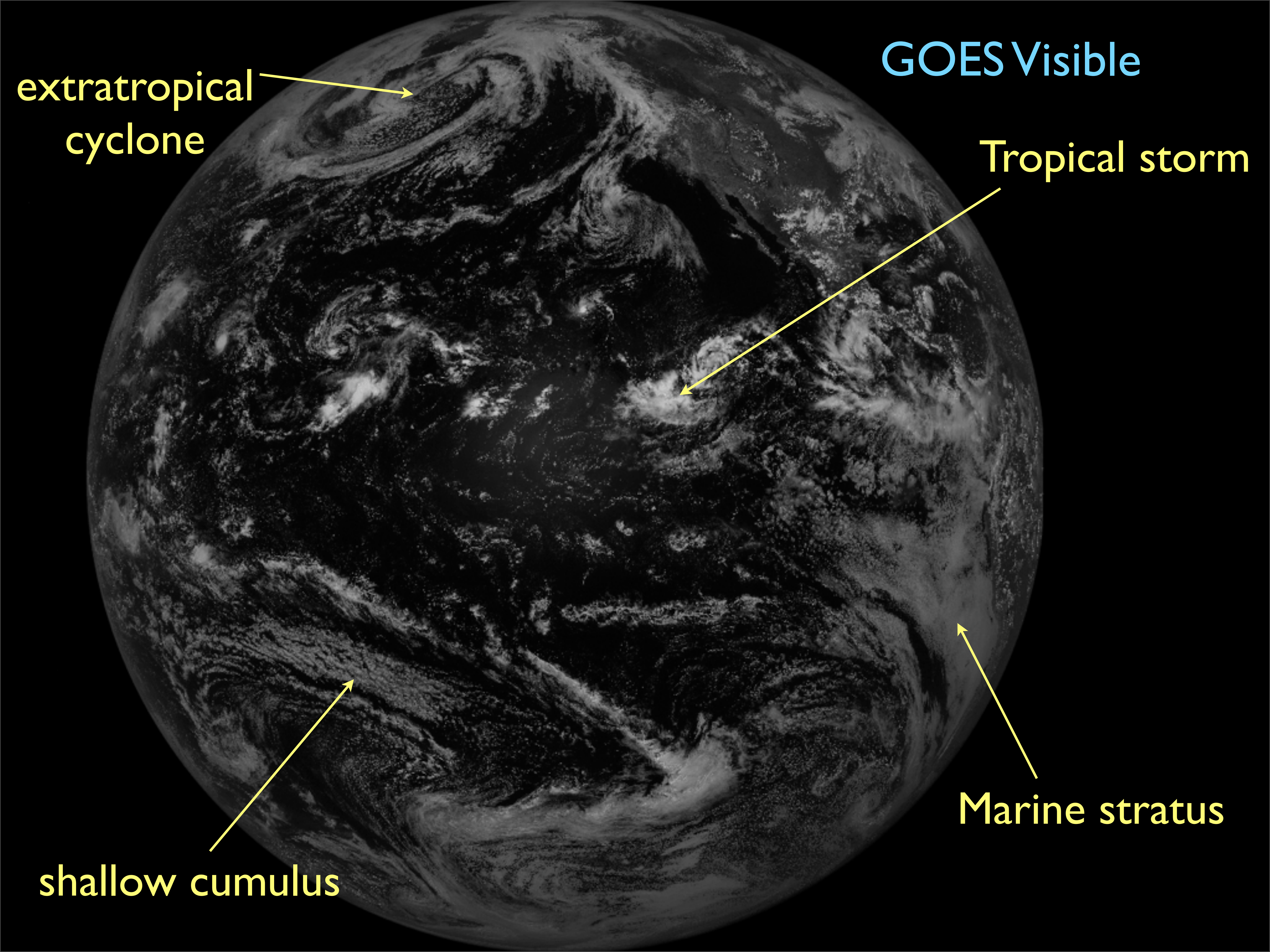


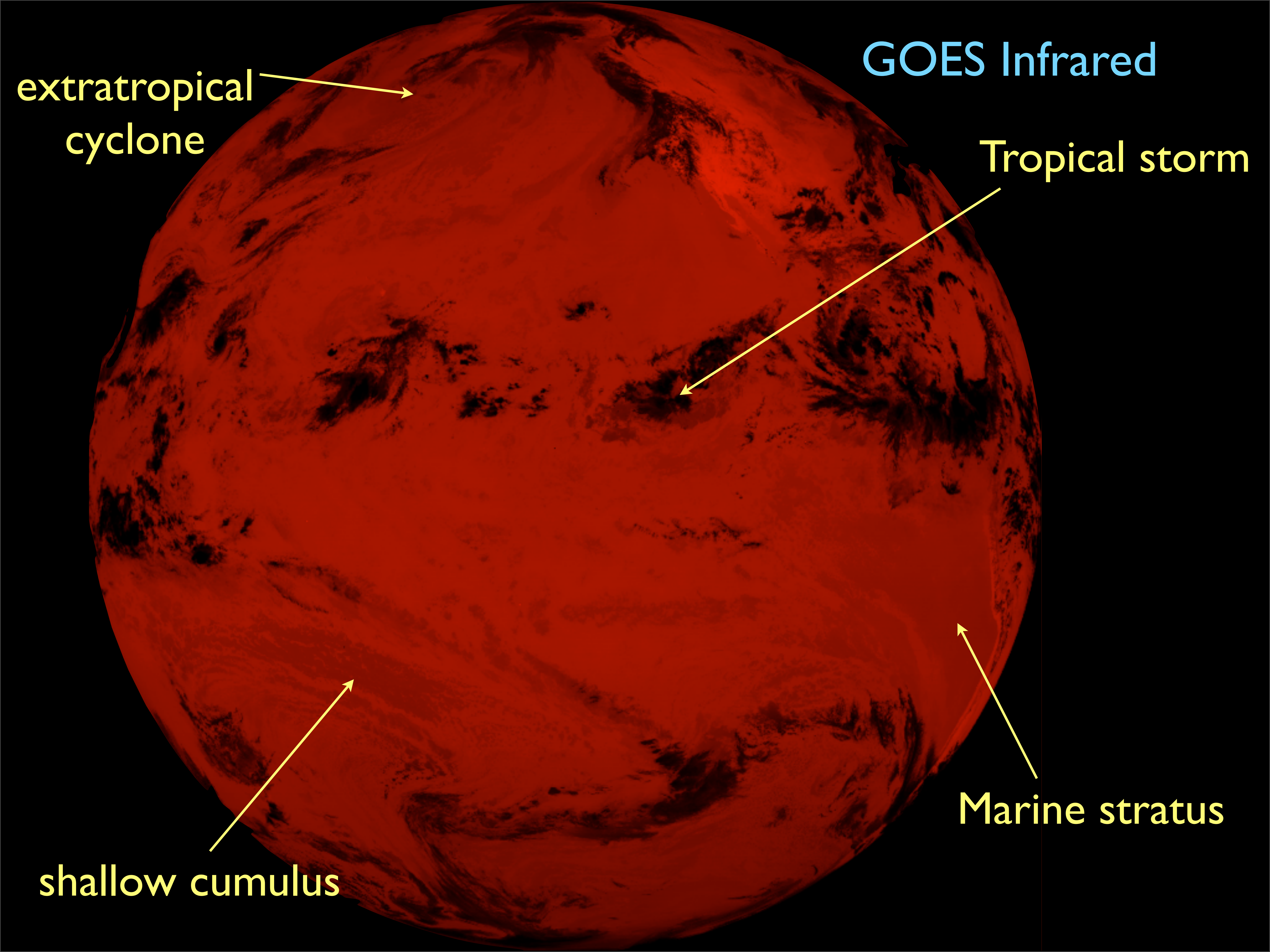
- Boundary layer thickening
- Convective deepening
- Mean vertical velocity increasingly upward
- Sustained upward motion occurs only inside clouds!

Main cloud types

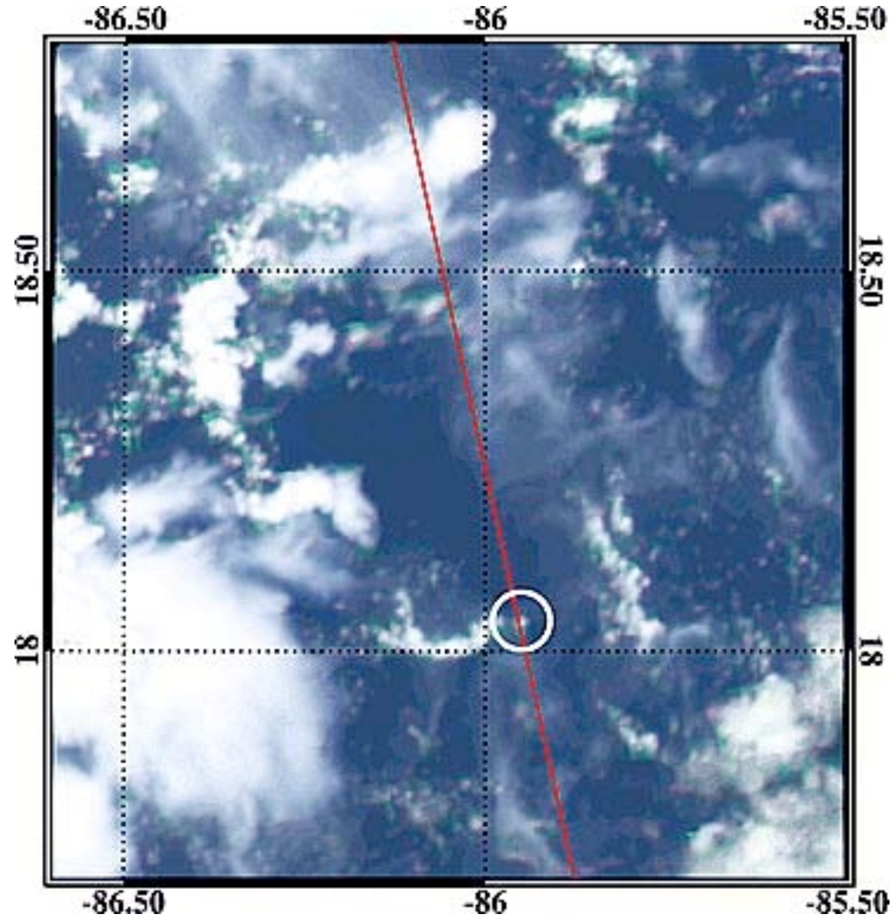


- Cumuliform clouds form in unstable environments
- Stratiform clouds form in stable environments

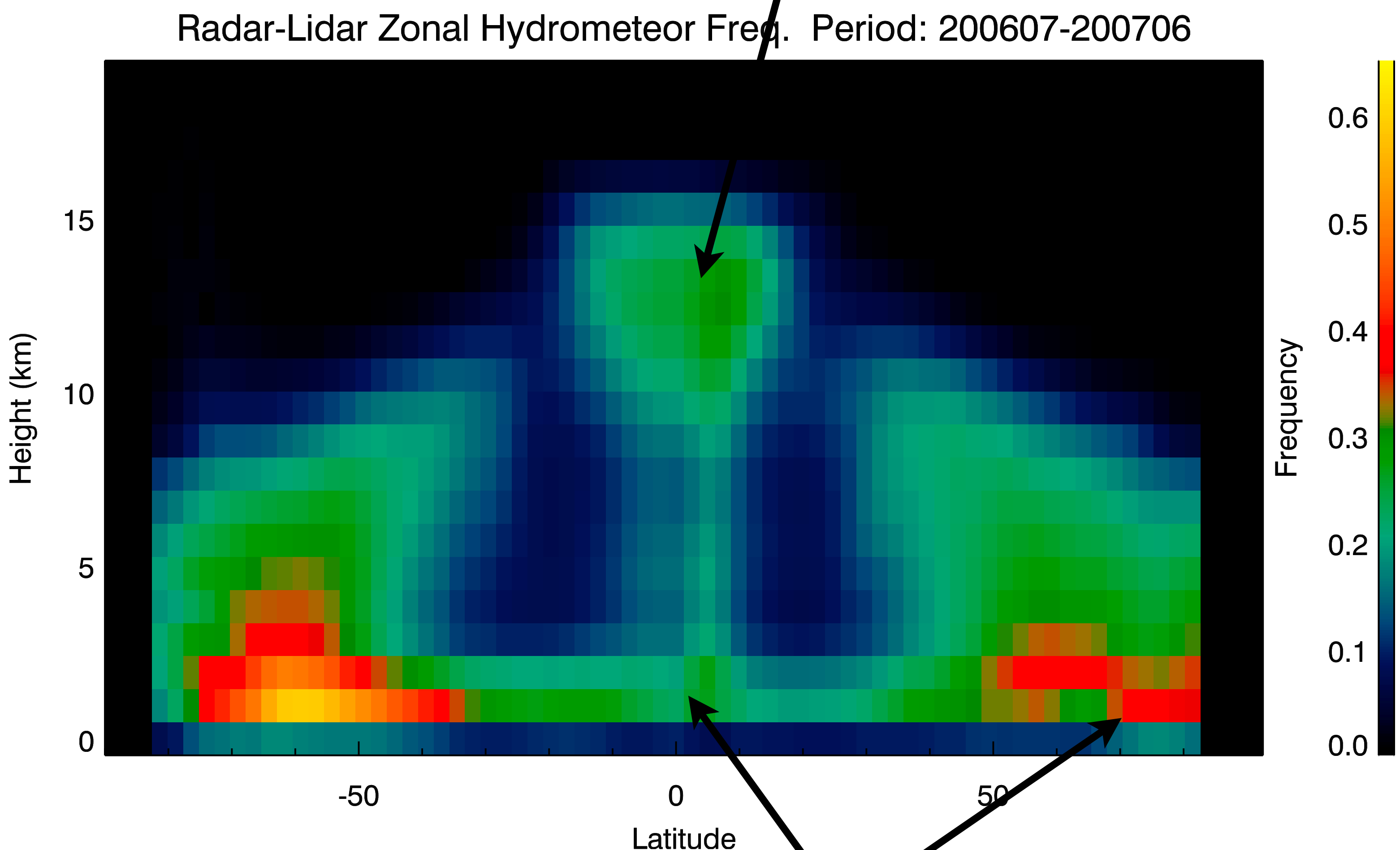

GOES Visible
extratropical cyclone
Tropical storm
Marine stratus
shallow cumulus


GOES Infrared
extratropical
cyclone
Tropical storm
Marine stratus
shallow cumulus

CloudSat and Calipso: first active cloud soundings from space



mostly over land, warm ocean



Shallow, deep modes in Tropics (why?)

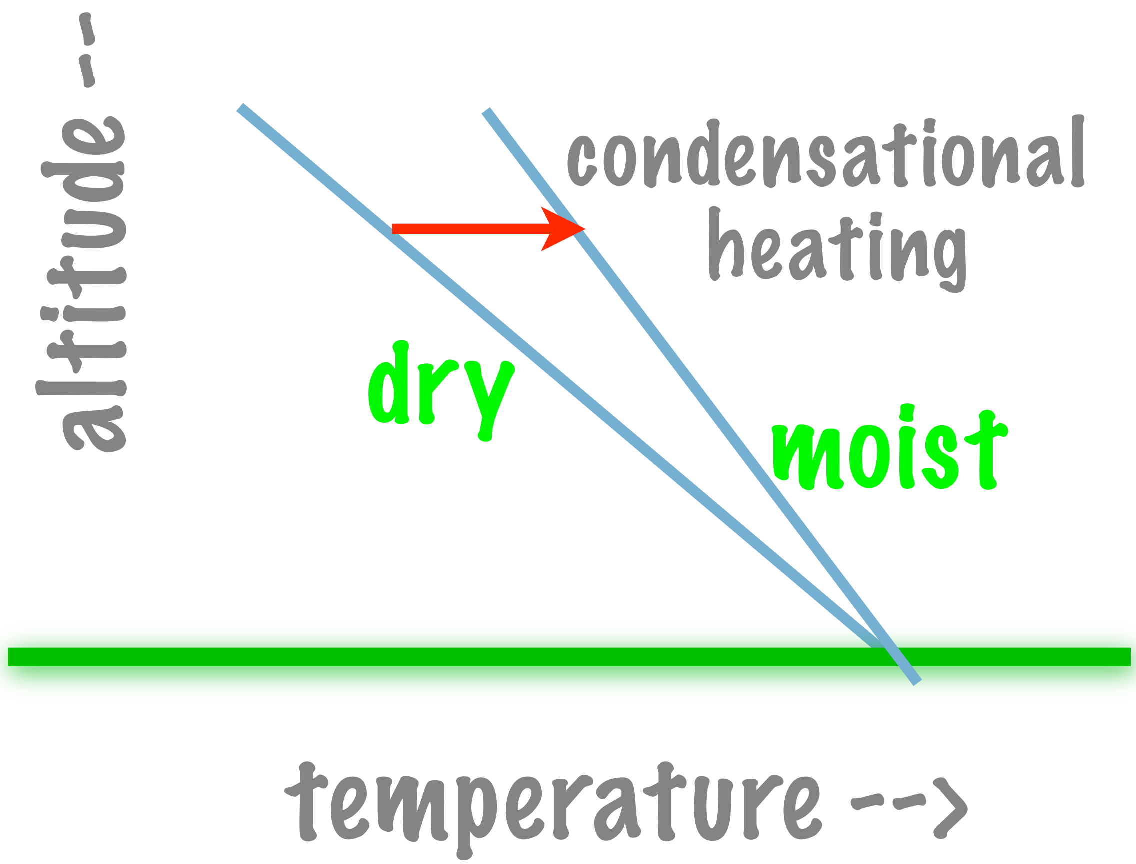
Smoother distribution in midlats

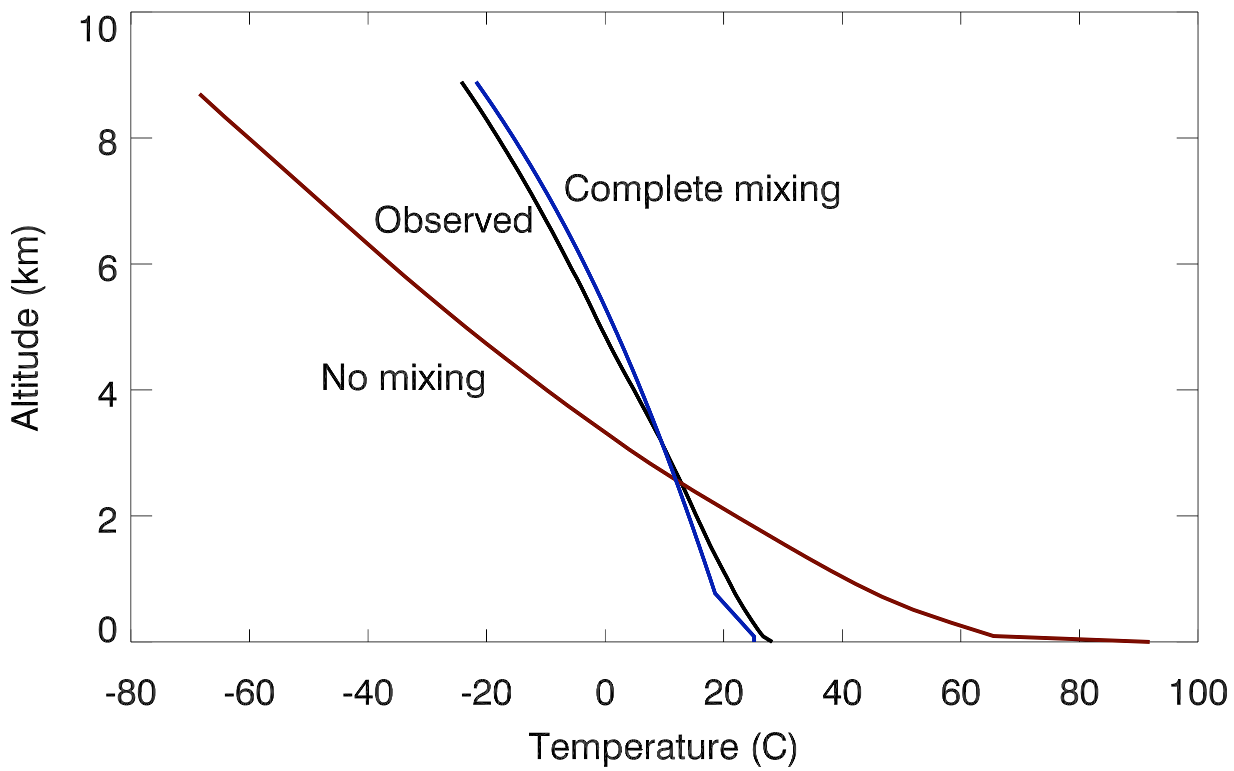
What controls this?

Mace et al. 2009

mostly over ocean

Radiative-convective equilibrium



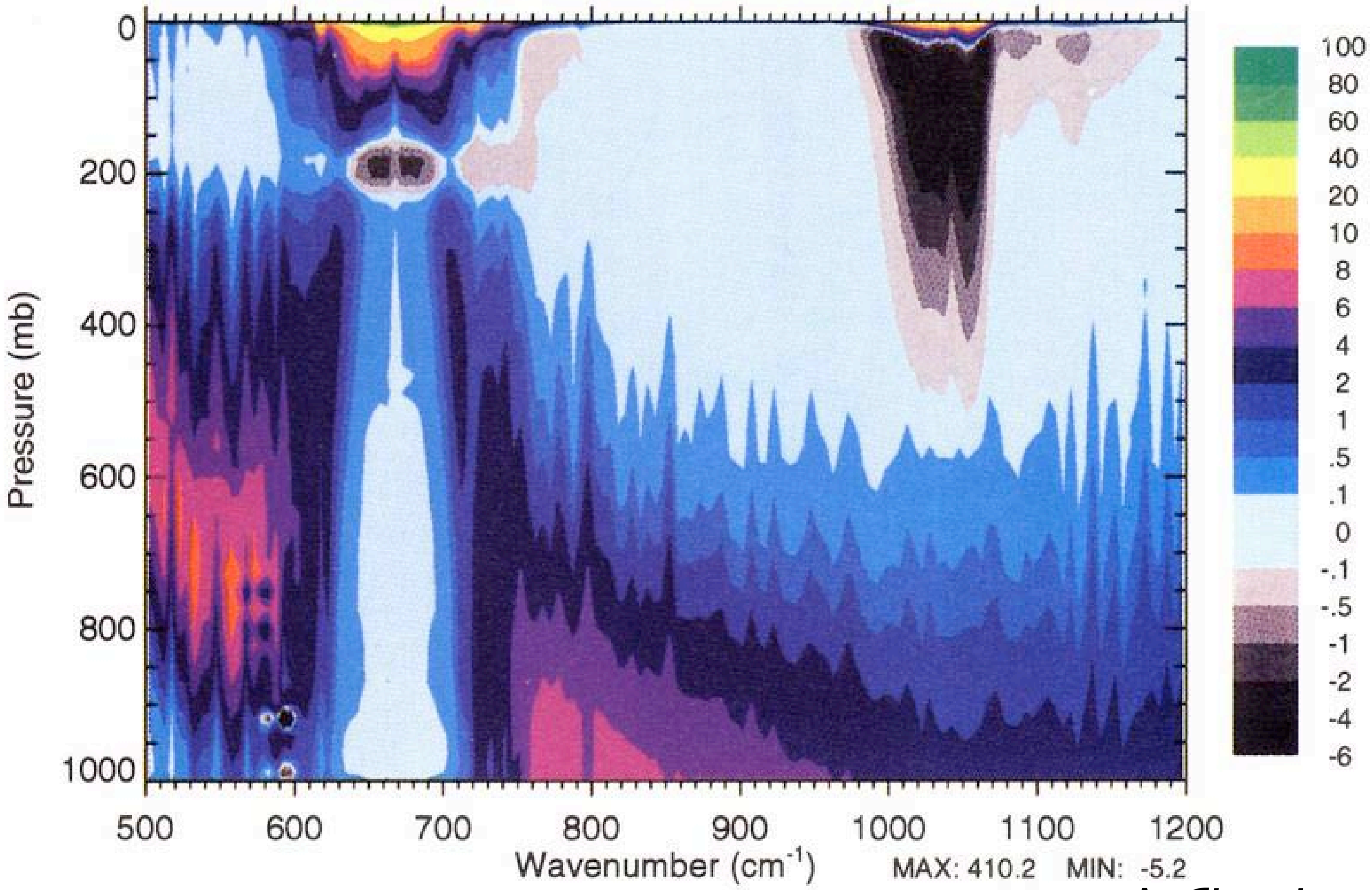


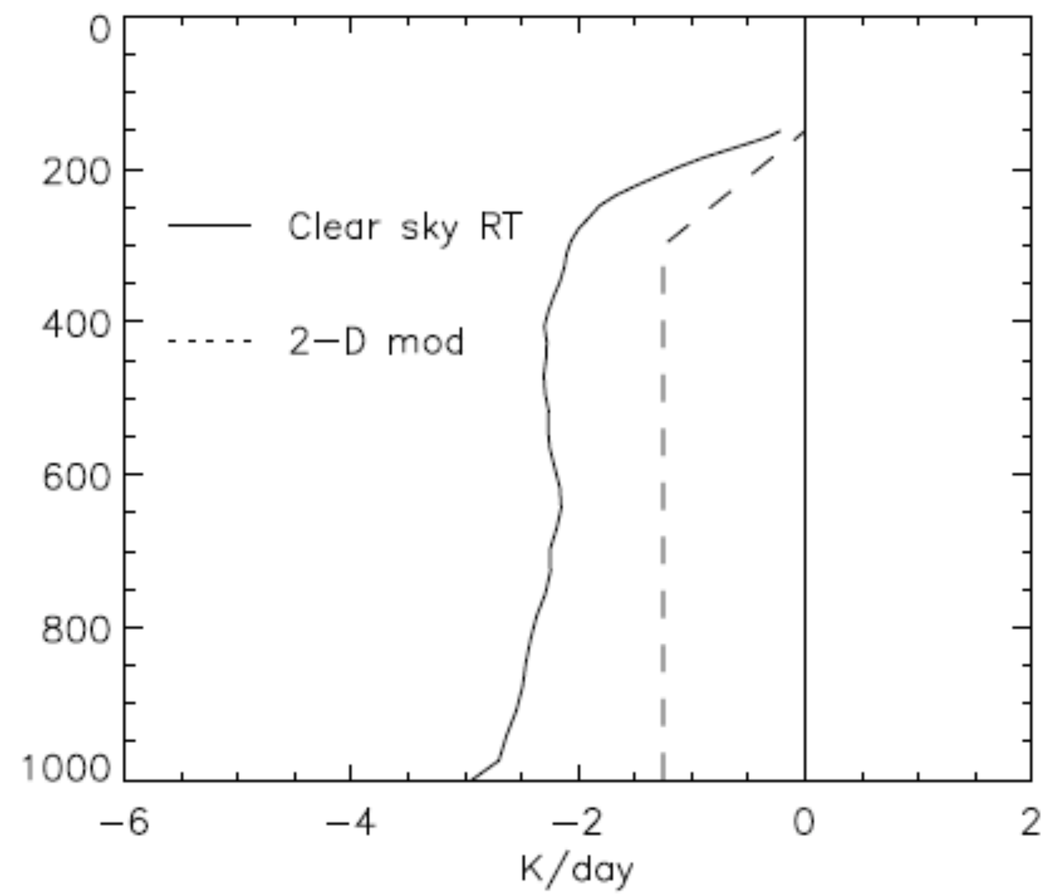
"Complete mixing" = moist adiabat

"No mixing" = radiative equilibrium

Observations very close to moist adiabat;
T(z) profile determined by convection up to the tropopause.

Radiative-convective equilibrium





A. Clough

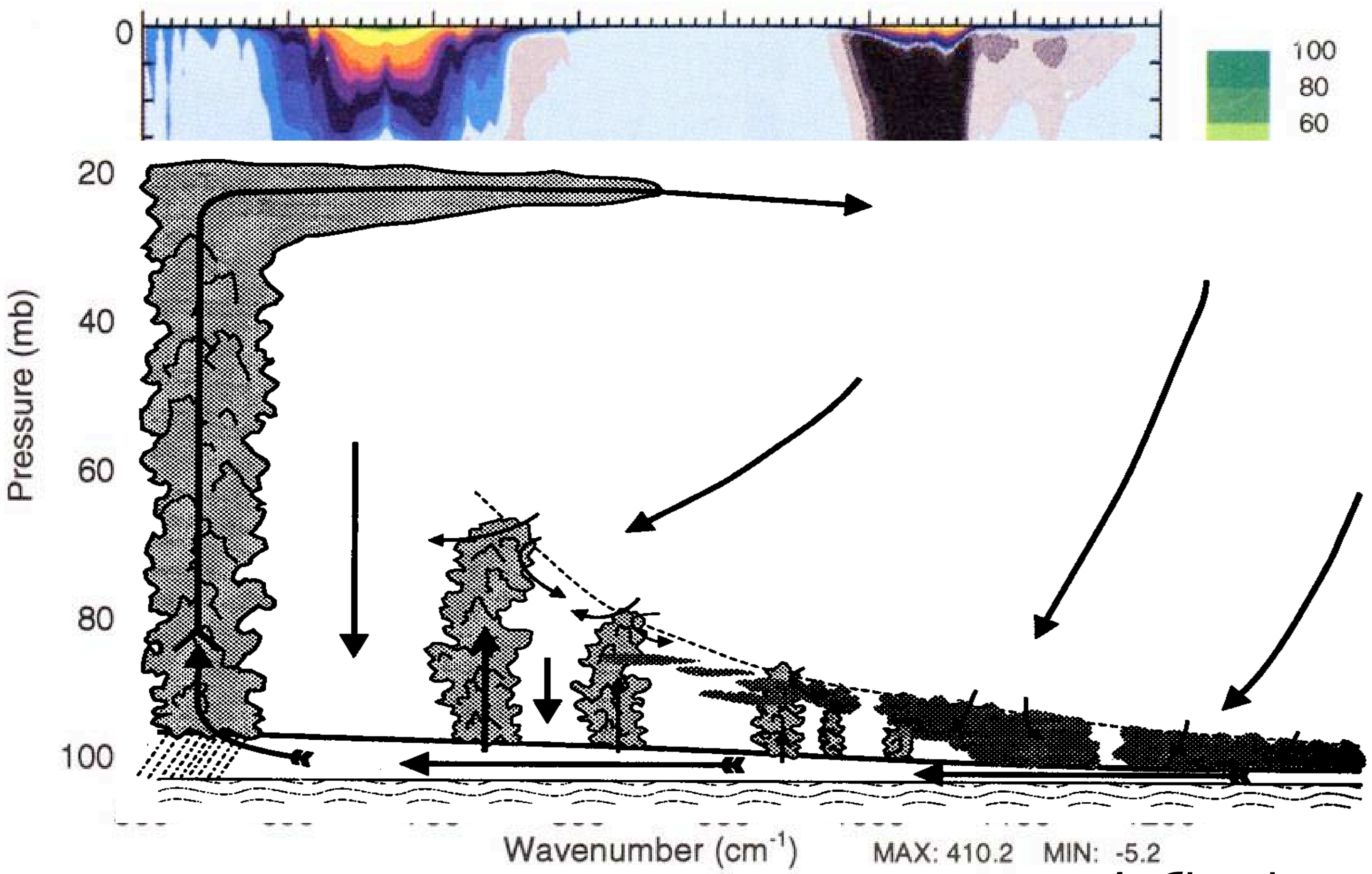
•Subsidence heating ($wd\theta/dz$) approximately balances net radiative cooling

•Radiative cooling by all gases turns out to be relatively constant up to ~300 hPa in today's Tropics (similar to lower heights at higher latitudes)

•∴ Subsidence is nearly constant up to ~300 hPa, zero near 150 hPa. Mass balance requires convergence / convective outflow where $dw/dz > 0$

•Full solution must be iterative since circulation -> H_2O -> radiative cooling.

Radiative-convective equilibrium



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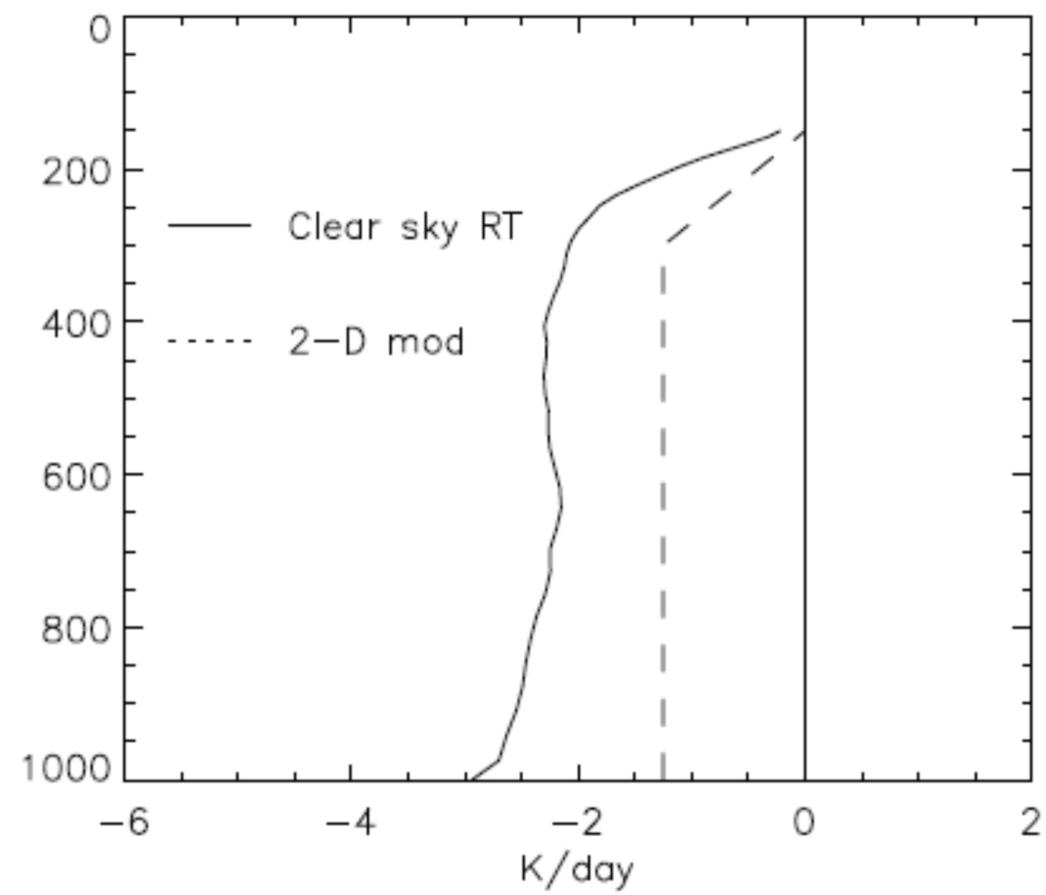

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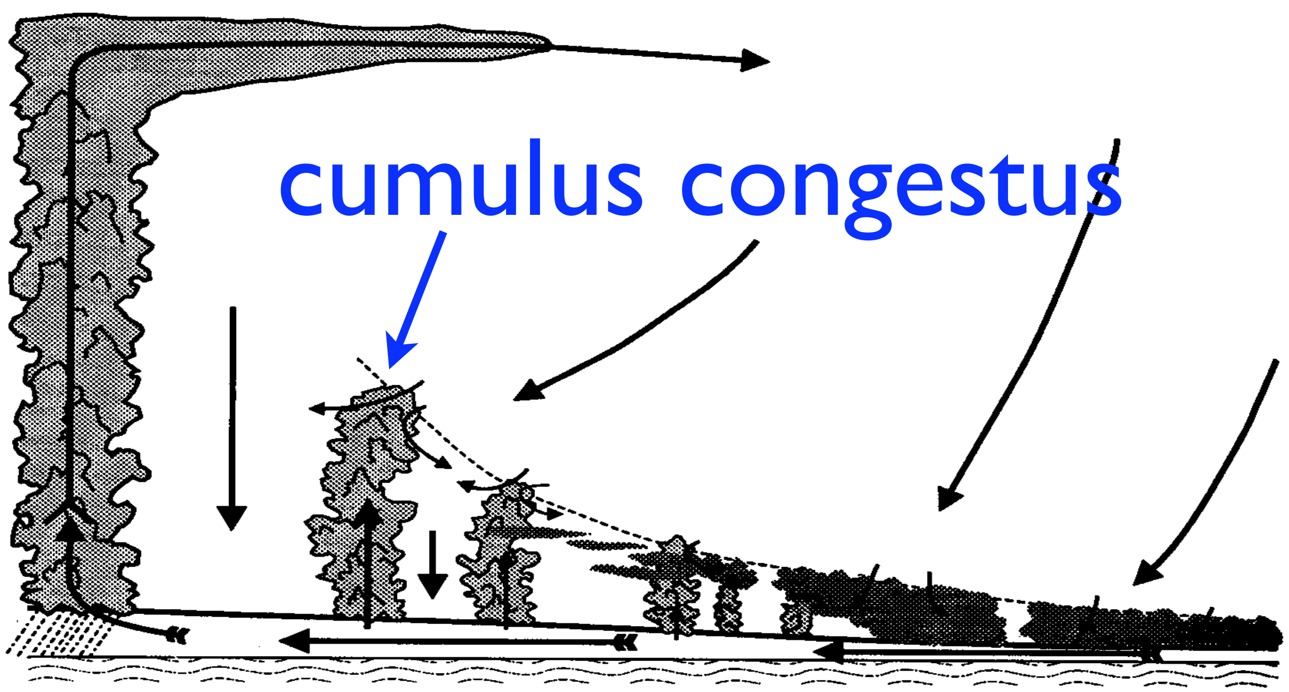
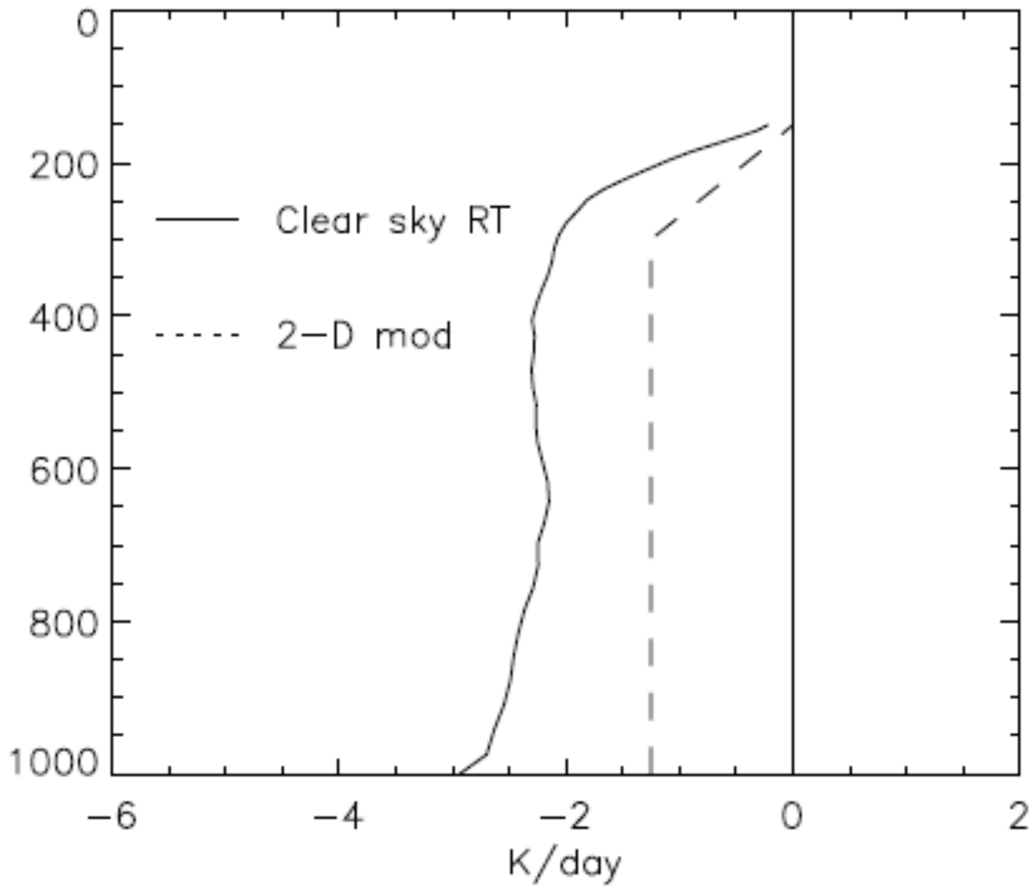
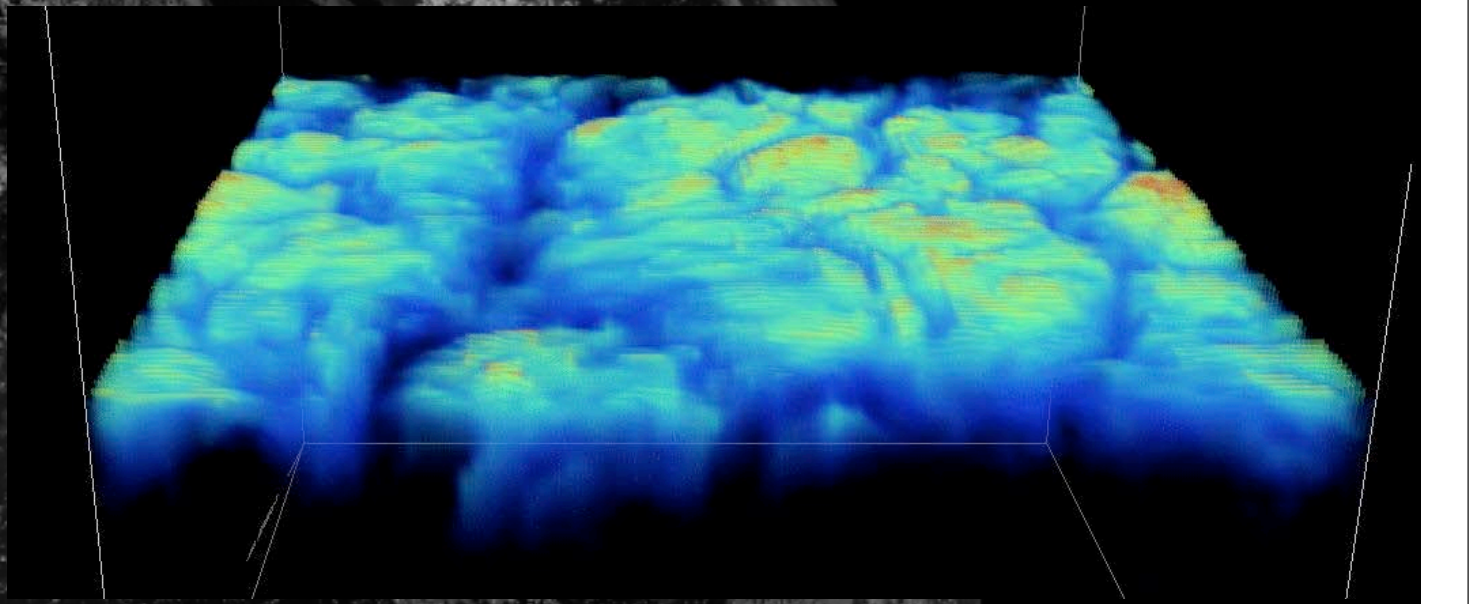




A. Clough

- Convective outflow (hence anvil cloud) concentrated near 200 hPa because air below this needs to be heated. Radiation dictates an upper-level peak in anvil cloud. Little *net* outflow can occur lower than this. BUT...don't forget congestus!
- Tropical convection that heats the atmosphere must reach high to produce this mass outflow. Convection is deep.
- Other convection is limited unless it doesn't generate much heat (rain).

Shallow / nonprecipitating convection



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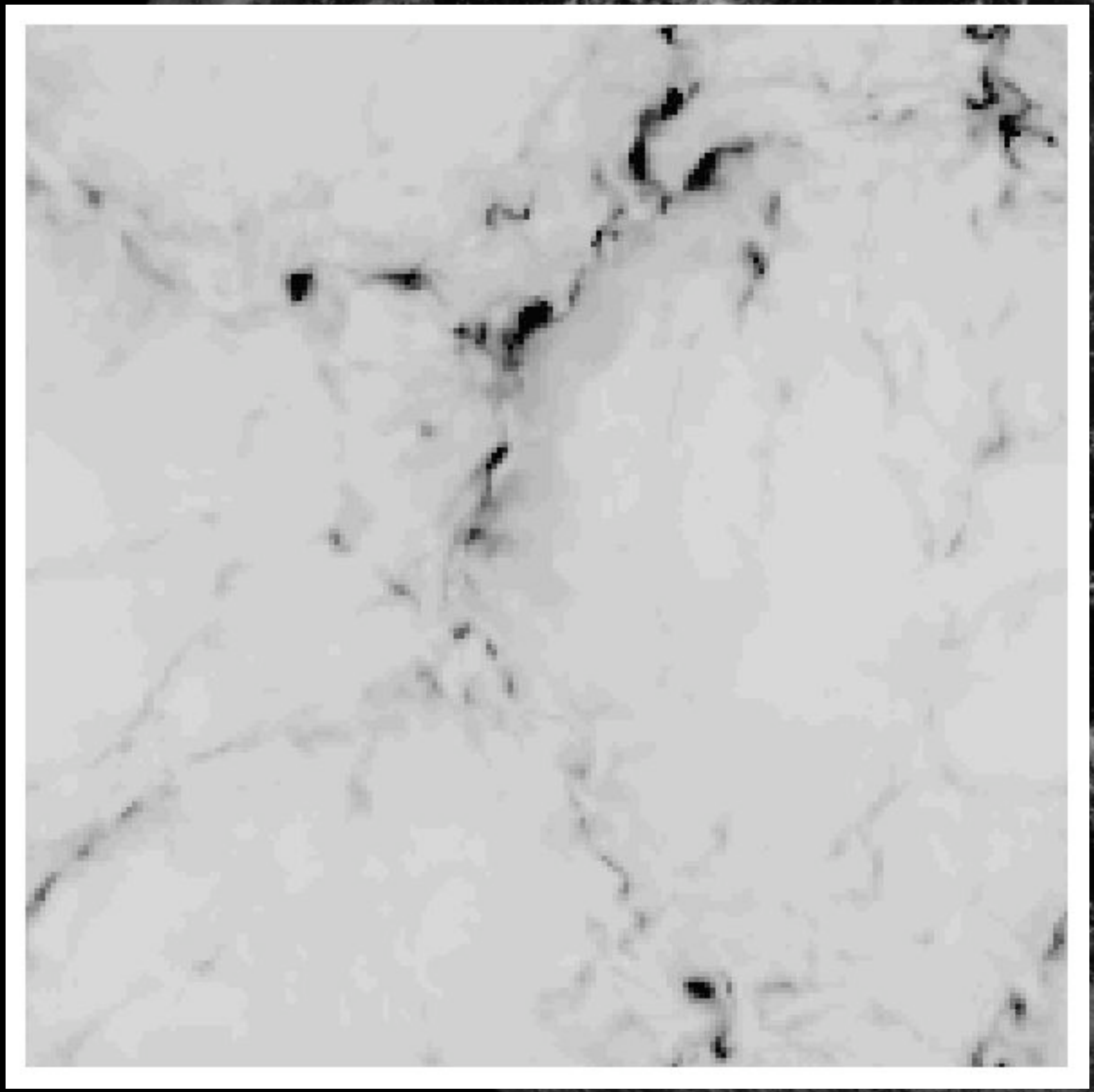
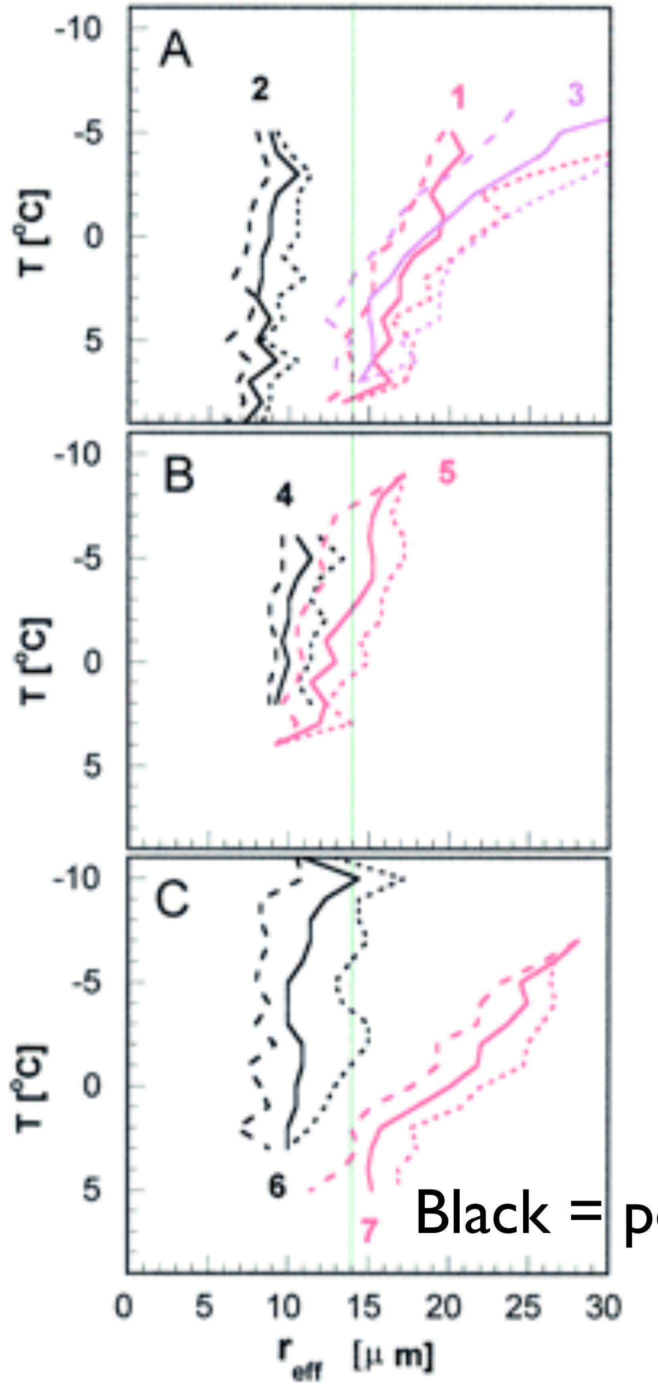


B. Stevens

How can there be non-precipitating convection?

- Adiabatic liquid water content $q_{lAd} = q_{init} - q_{sat}$ above cloud base (q = specific humidity)
- Droplet radius = $3/(4\pi)\sqrt[3]{}\ (q_{lAd}N/\rho_l)$ (N = # concentration of nuclei)
- Radius must reach ~14 microns for collision/coalescence...finite cloud depth required for rain (up to 8 km for "pyrocumulus" w/ N approaching 10,000; as little as 1 km for marine clouds w/N of a few 100.)
- Clouds that are too shallow or short-lived won't rain.



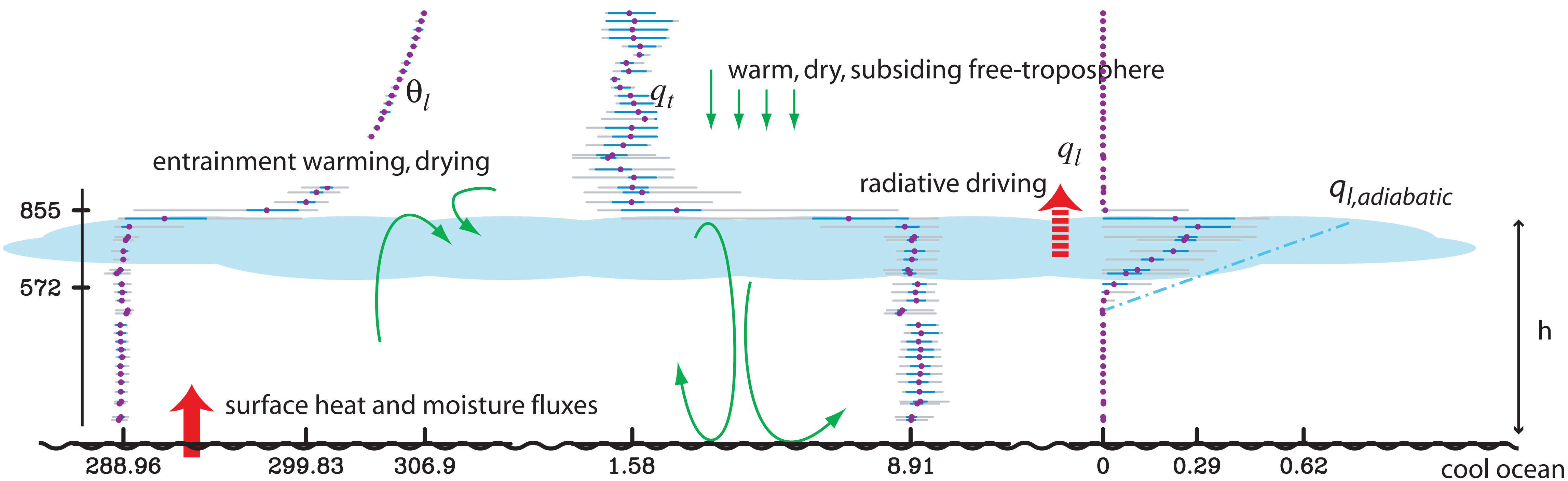
Black = polluted

Rosenfeld 2000

Squall off Key Biscayne, Florida

R. Smith

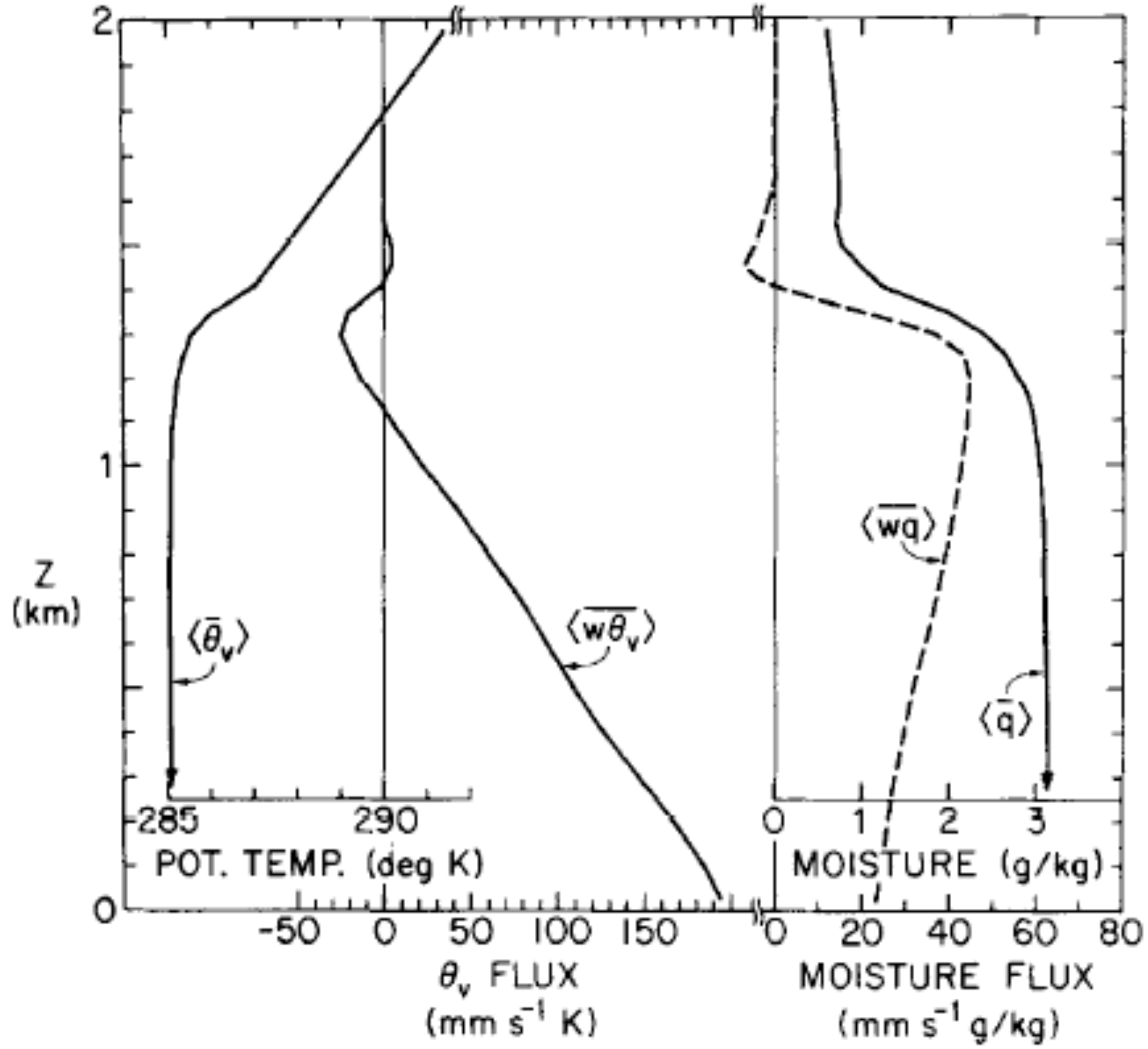
Shallow / nonprecipitating convection



Stevens 2005

q_t = total water
q_l = liquid water
θ_l = θ w/liquid evaporated

- Subsidence balances entrainment in steady case



Deardorff 1980a

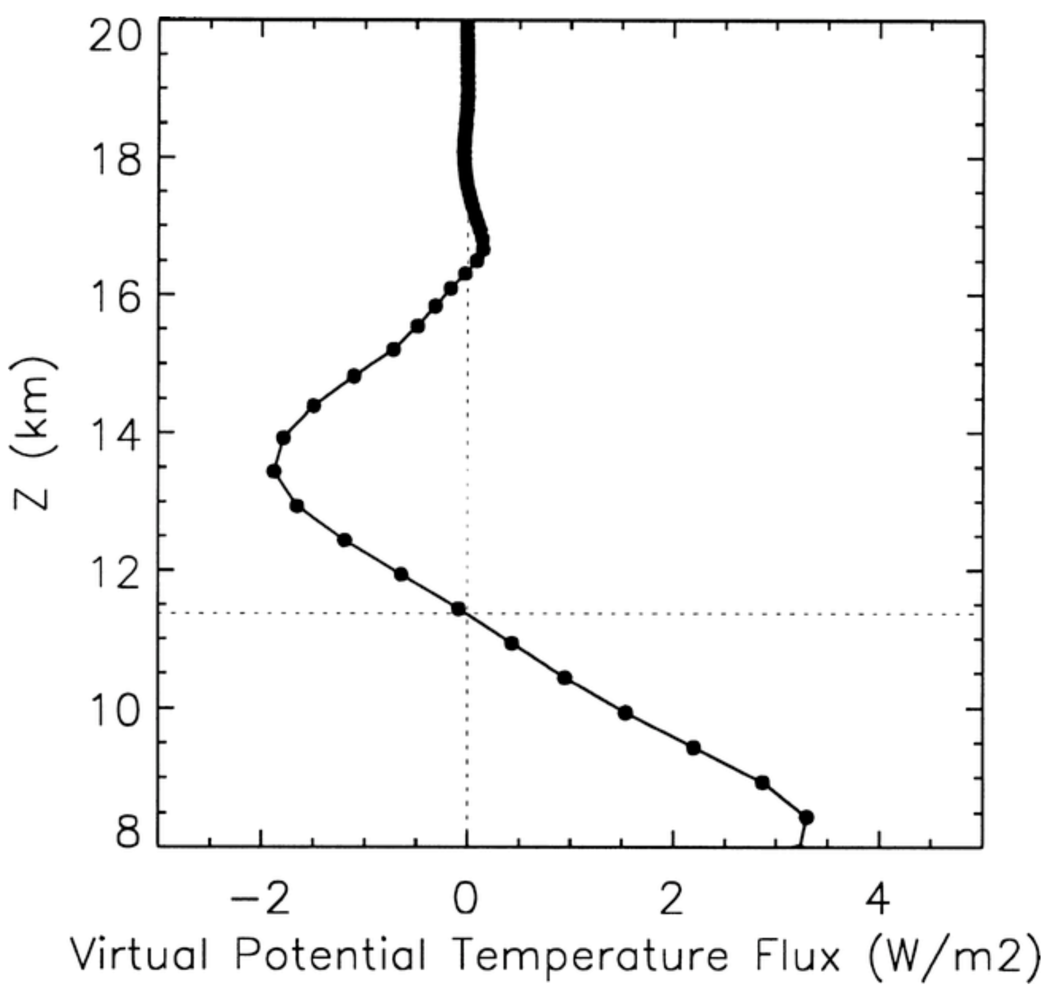
Energy balance requires these sum to zero:

- $w d\theta/dz$
- $d/dz\langle w'\theta'\rangle$
- radiative cooling
- L_v x net evaporation

- Due to overshooting of updrafts, $\langle w'\theta'\rangle$ becomes negative in an "entrainment zone" within the capping inversion; for simple (no cloud) cases it reaches ~−0.2 times surface value.
- Entrainment dries and heats the mixed layer; prevents runaway cloud growth

The troposphere as a convective layer

Kuang and Bretherton 2004



Negative convective heat flux at top of layer would help balance the energy budget (Sherwood 2000).

Seen in:

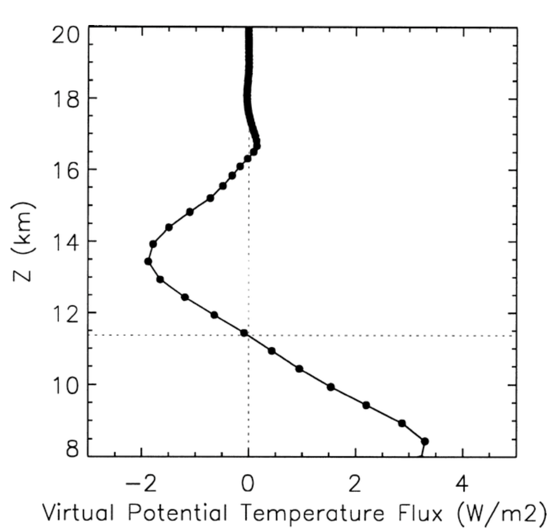
- Composite radiosonde data (Sherwood et al 2003)
- Equilibrium CRM simulations (Kuang and Bretherton 2004)

The troposphere as a convective layer

Differences between Tropical Tropopause Layer and PBL entrainment zone

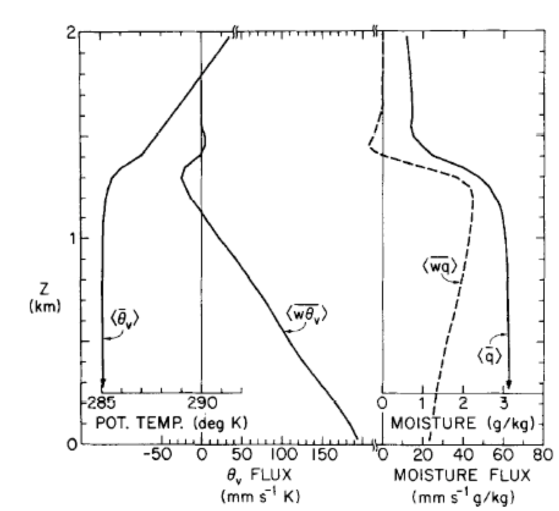
TTL

- Net radiative heating and ascent; influence on stratosphere
- Stratus easily maintained, optically thin
- Latent heating negligible
- T(z) becomes controlled by radiation as you go up



PBL entrainment zone

- Net radiative cooling and descent; influence on boundary layer
- Stratus not easily maintained, optically thick
- Latent heating crucial to dynamics
- T(z) becomes controlled by remote convection (+ baroclinic adjustment) as you go up.



The troposphere as a convective layer

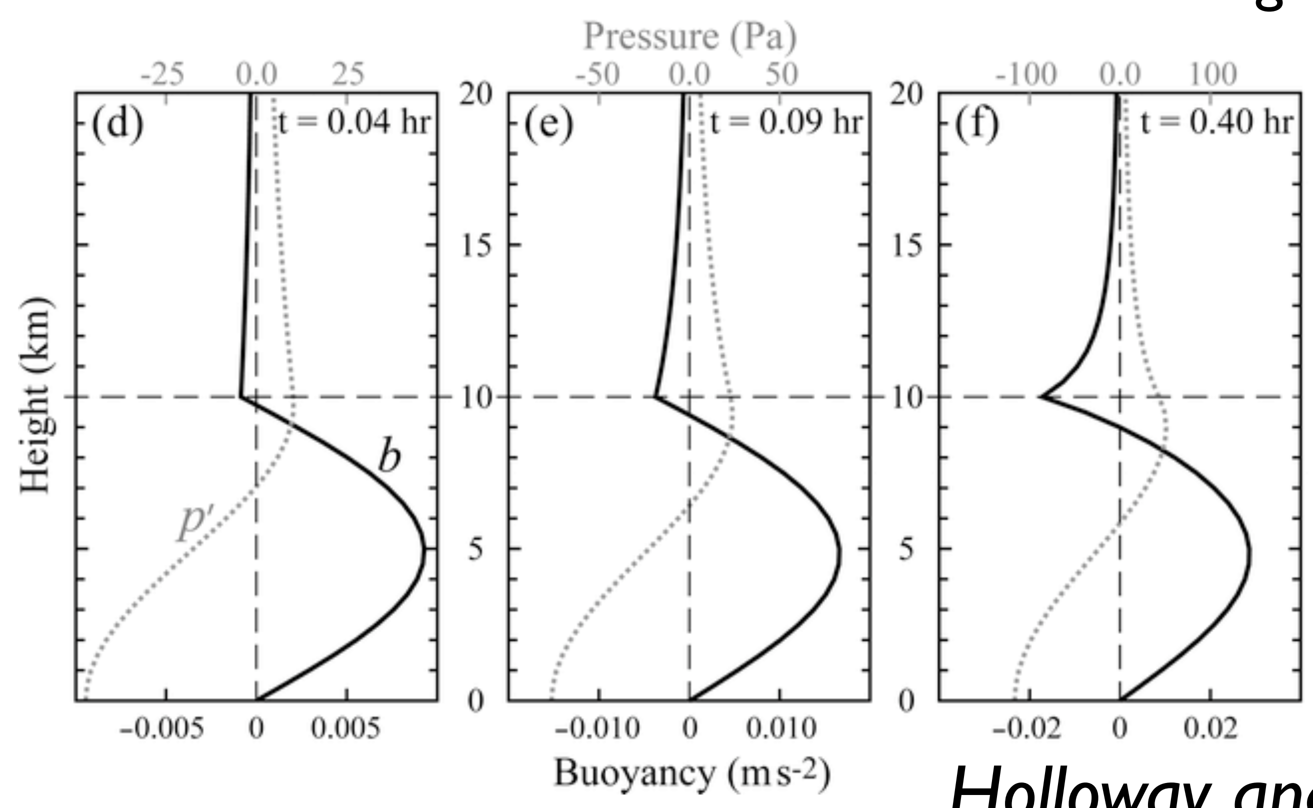
Differences between Tropical Tropopause Layer and PBL entrainment zone

TTL

- T is lower over deep convection, due largely to the latent heating+dynamic response, not the turbulent fluxes. Slow adjustment time --> large T response.

PBL entrainment zone

- Latent heat release is small below the entrainment zone, and adjustment is fast --> layer T relatively horizontally homogeneous.



See also Highwood and Hoskins 1998

Holloway and Neelin 2008

Breakup-why does it happen?

- Drizzle
- Larger drops
- fewer aerosols
- see Wood et al 2008

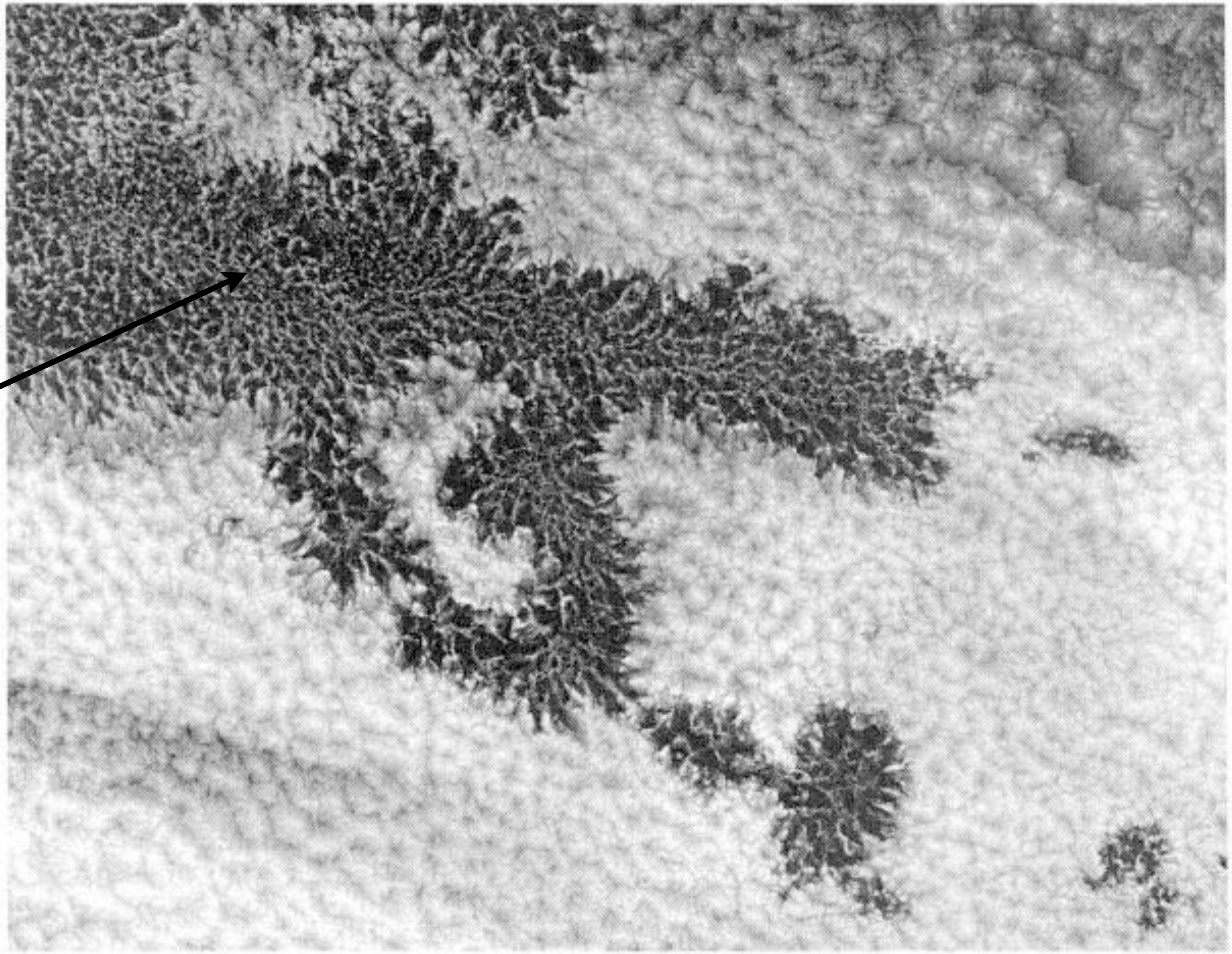
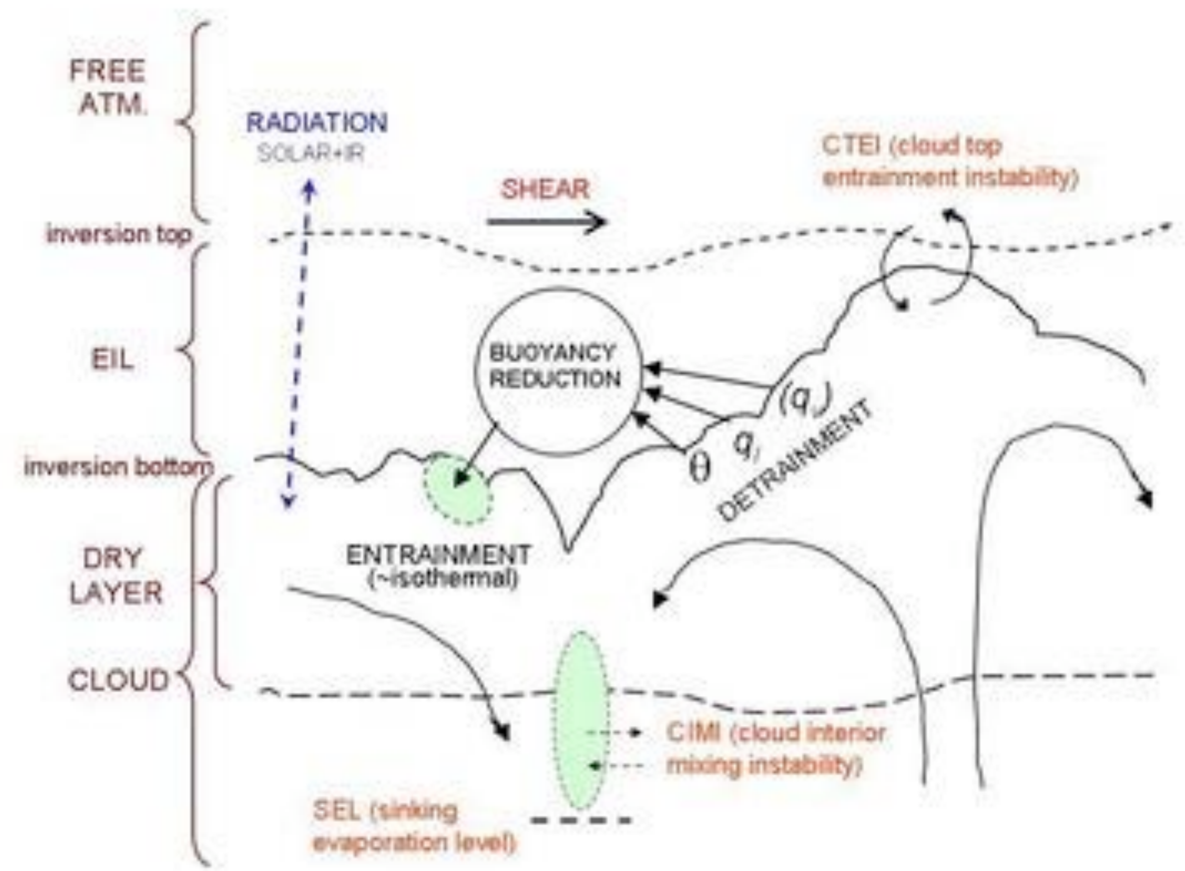


Figure 5 Example of a region of open cellular convection (*dark cell interiors, with bright cell walls*) embedded in a broader region of closed cellular convection (*bright cells with darkened cell walls*). Open cellular regions have scales ranging from 5–50 km and have been hypothesized to be envelopes where drizzle is more prevalent.

Stevens 2005

Breakup--why does it happen?

- Structure of inversion (Cloud Top Entrainment Instability, CTEI)
  - proposed by Lilly (1969), Randall (1976, 1980), Deardorff (1980b)
  - Mixing at cloud top leads to negatively buoyant parcels (roughly, when θ_e is lower above inversion than below). Humidity above inversion important.
- Lack of aerosol (+ drizzle-cleansing feedback)
- Something else?



LES simulations

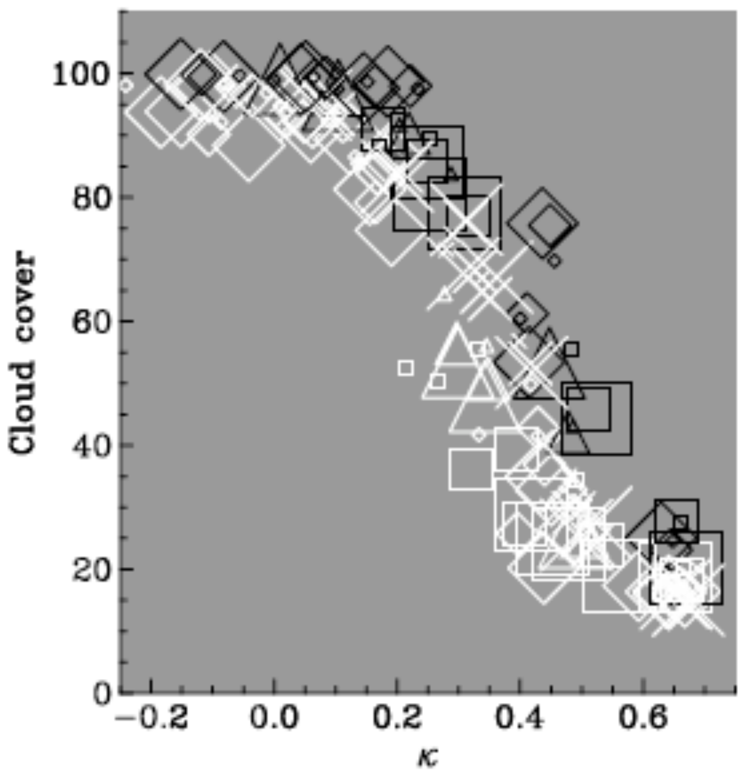
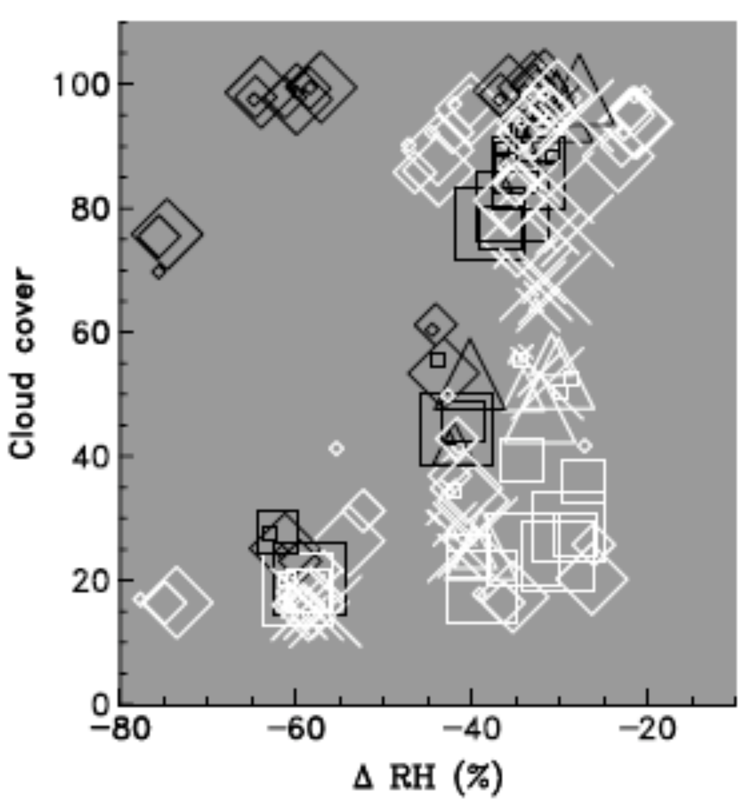


Figure 10. As Figure 9. but shaded cloud cover is plotted against contemporary values of κ and the first three hours are excluded.



Lock 2009

Stevens 2001:
Shallow stratus simulations require absurdly fine resolution near the trade inversion; numerical singularity.

Yamaguchi and Randall 2008:
CTEI works in theory but not in practice, because cloud liquid water amounts are too small for evaporative cooling to compete with radiation (though may not be true in simulations).

Lock 2009: Stevens' sensitivity can be avoided. Criterion $\kappa = c_p\Delta\theta_e/L\Delta q_l$ works well as instantaneous discriminator for cloud cover, but there is gradual decrease rather than catastrophic breakup.

Outstanding questions:

- What causes the catastrophic collapse of marine stratus to open-cell form? Do aerosols play a causative, or merely correlative role?
- Is CTEI adequate for prediction and how should it be represented in a model?
- What controls the length scale of convective cells (~50 km)?
- What controls the cloud water content and vertical extent?
- Many TTL questions (later talks)