Clouds and turbulent moist convection

Lecture 2:
Cloud formation and Physics

Caroline Muller

Lectures Outline :

Cloud fundamentals - global distribution, types, visualization and link with large scale circulation

Cloud Formation and Physics - thermodynamics, cloud formation, instability, life cycle of an individual cloud

Organization of deep convection at mesoscales - MCSs, MCCs, Squall lines, Tropical cyclones, Processes, Self-aggregation

Response of the hydrological cycle to climate change - mean precip, precip extremes

Clouds in a changing climate – climate sensitivity, cloud effect, cloud feedback, FAT

Cloud formation

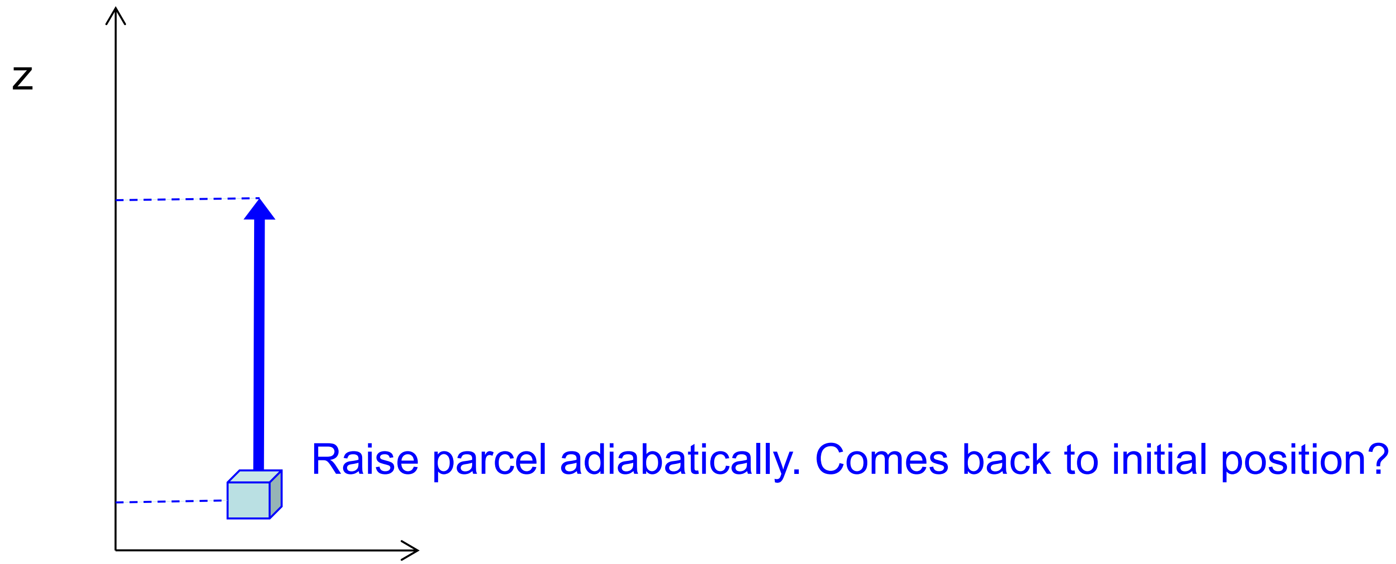
Courtesy : Octave Tessiot

Atmospheric thermodynamics: instability

Dry convection

T decreases with height.
But p as well.

Density = ρ(T,p).
How determine stability? The parcel method



Atmospheric thermodynamics: instability

Dry convection

Potential temperature $\theta = T\,(p_0 / p)^{R/cp}$ conserved under adiabatic displacements :

Adiabatic displacement

1st law thermodynamics: d(internal energy) = ΔQ (heat added) – ΔW (work done by parcel)

$$c_v\, dT = -\ p\, d(1/\rho)$$

Since $p = \rho R T$, $\quad c_v\, dT = -p\, d(R T / p) = -R\, dT + R T\, dp / p$

Since $c_v + R = c_p$, $\quad c_p\, dT / T = R\, dp / p$

$$\Rightarrow d \ln T - R / c_p\, d \ln p = d\, \ln (T / p^{R/cp}) = 0$$
$$\Rightarrow T / p^{R/cp} = \text{constant}$$

$\Rightarrow \theta = T\,(p_0 / p)^{R/cp}$ potential temperature is conserved under adiabatic (reversible) displacement

Remark1: ideal gaz law: $pV = Nkt \Leftrightarrow p = p = \rho R T$, $R=k/m$ where m=molecular mass

Remark2: $c_p = c_v + R > c_v$

Remark3: We assumed $p_{parcel}=p_{environment} \Leftrightarrow$ quasistatic displacement

Remark4: If we make the hydrostatic approximation, dry static energy $h= c_p\, T + g\, z$ is conserved :
$c_p\, dT / T = R\, dp / p \Leftrightarrow c_p\, dT = R\, T\, dp / p = -\, g\, dz \Leftrightarrow c_p\, T + g\, z = \text{constant}$

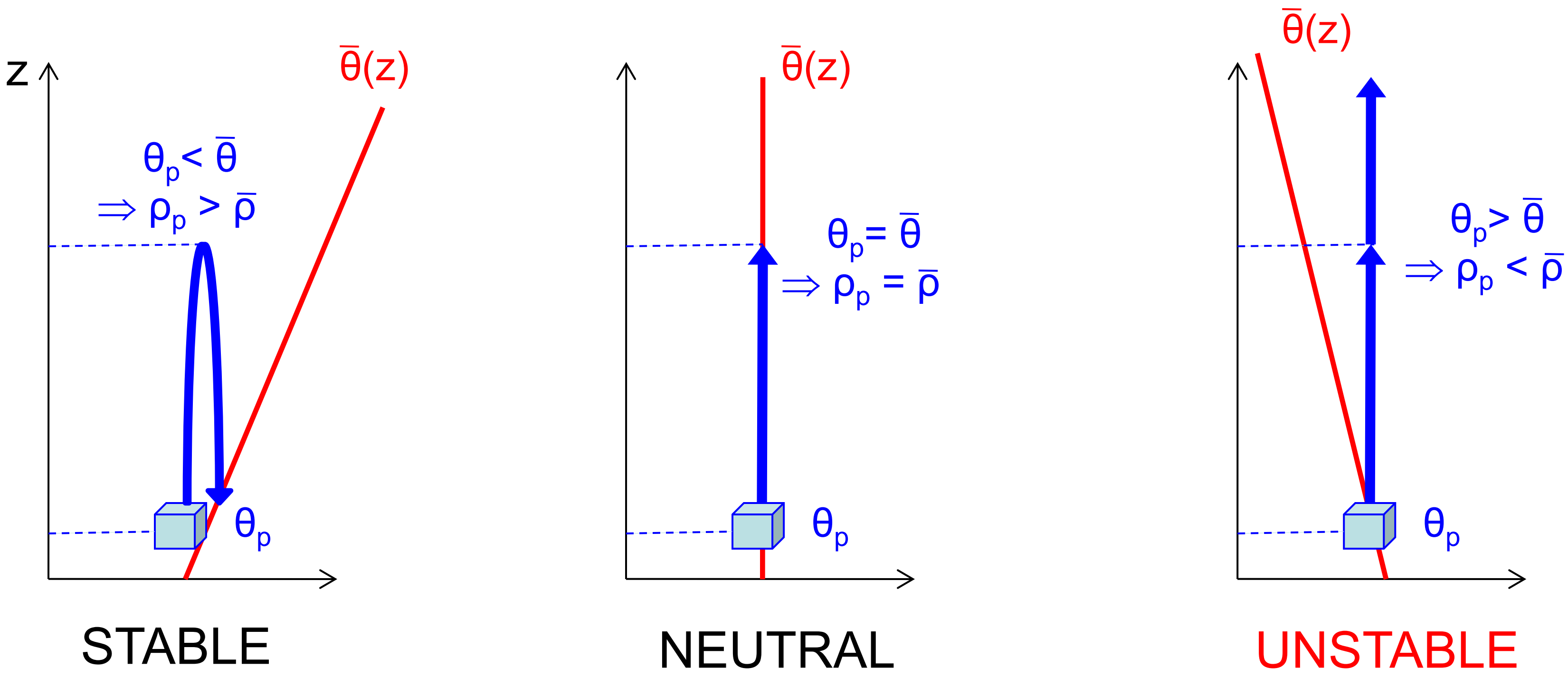
Atmospheric thermodynamics: instability

When is an atmosphere unstable to dry convection?

When potential temperature $\theta = T\,(p_0 / p)^{R/cp}$ decreases with height !

The parcel method:

Small vertical displacement of a fluid parcel adiabatic (=> θ = constant).
During movement, pressure of parcel = pressure of environment.



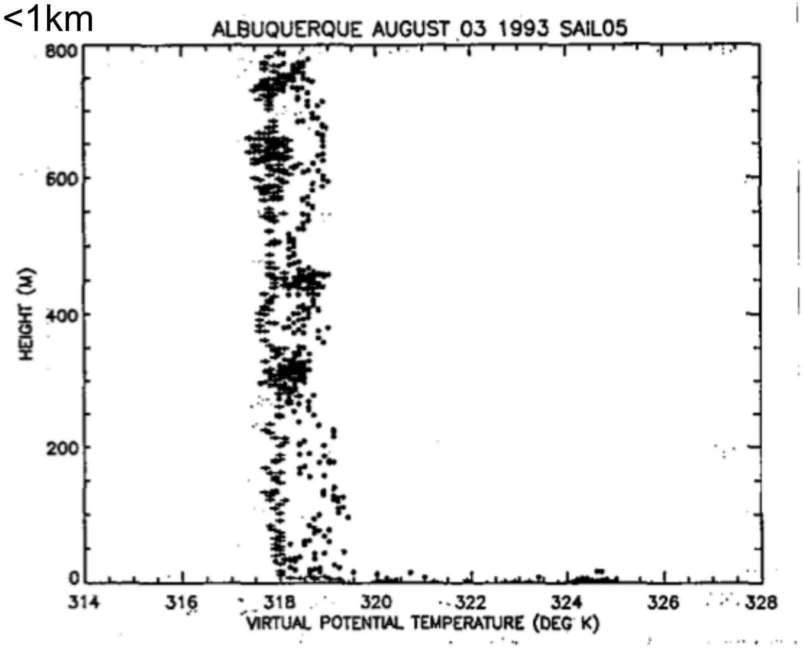
Atmospheric thermodynamics: instability

Convective adjustment time scales is very fast (minutes for dry convection) compared to destabilizing factors (surface warming, atmospheric radiative cooling…)

=> The observed state is very close to convective neutrality

Dry convective boundary layer over daytime desert

<1km



[Renno and Williams, 1995]

Atmospheric thermodynamics: instability

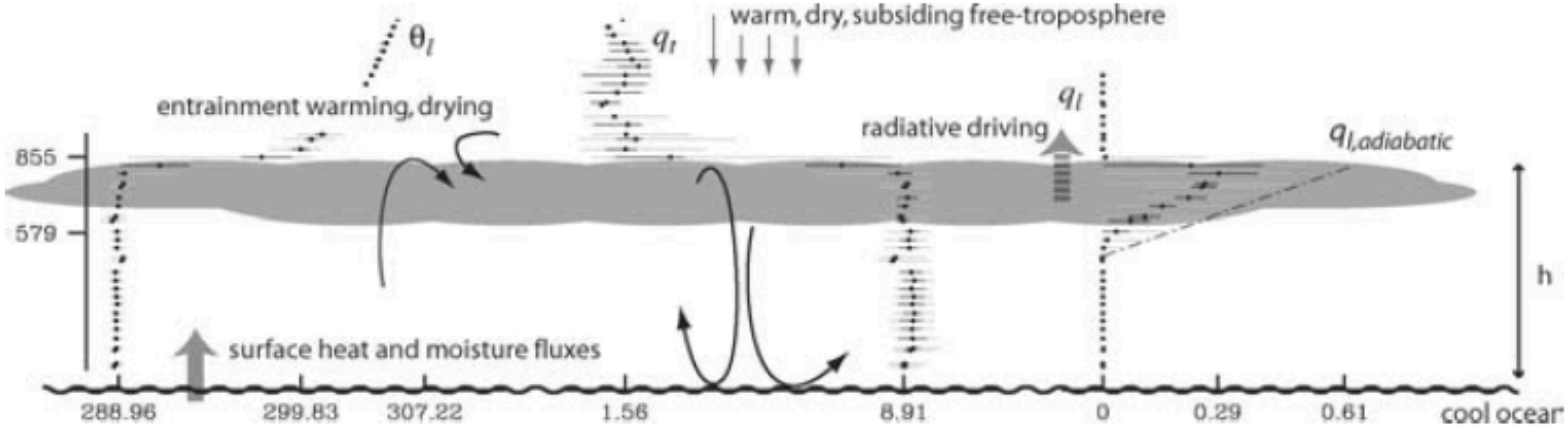


Figure 4 Cartoon of well-mixed, nonprecipitating, stratocumulus layer, overlaid with data from research flight 1 of DYCOMS-II. Plotted are the full range, middle quartile, and mean of θ_l, q_t, and q_l from all the data over the target region binned in 30-m intervals. Heights of cloud base and top are indicated, as are mixed layer values and values just above the top of the boundary layer of various thermodynamic quantities. The adiabatic liquid water content is indicated by the dash-dot line.

Stevens review 2005

Atmospheric thermodynamics: instability

inversion

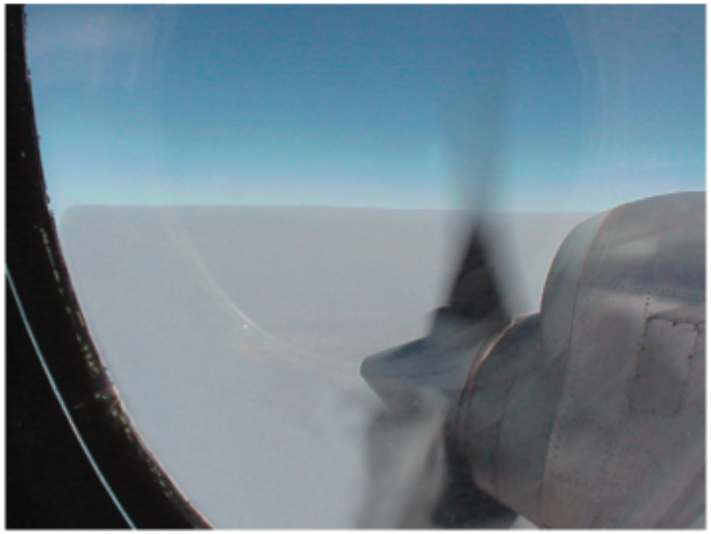


Fig. 3.15 Looking down onto widespread haze over southern Africa during the biomass-burning season. The haze is confined below a temperature inversion. Above the inversion, the air is remarkably clean and the visibility is excellent. (Photo: P. V. Hobbs.)

Smoke rising in Lochcarron, Scotland, is stopped by an overlying layer of warmer air (2006).

More det

Atmospheric thermodynamics: instability

Dry adiabatic lapse rate

We saw that on a dry adiabat, the potential temperature $\theta = T\,(p_0 / p)^{R/cp}$ is constant. If in addition we make the hydrostatic approximation, we can deduce the dry adiabatic lapse rate $\Gamma_d = -\,dT/dz$

Recall in that case $c_p T + g z = \text{constant}$

$$\Leftrightarrow dT/dz = -\,g / c_p$$

$$\Leftrightarrow \Gamma_d = g / c_p$$

Atmospheric thermodynamics: instability

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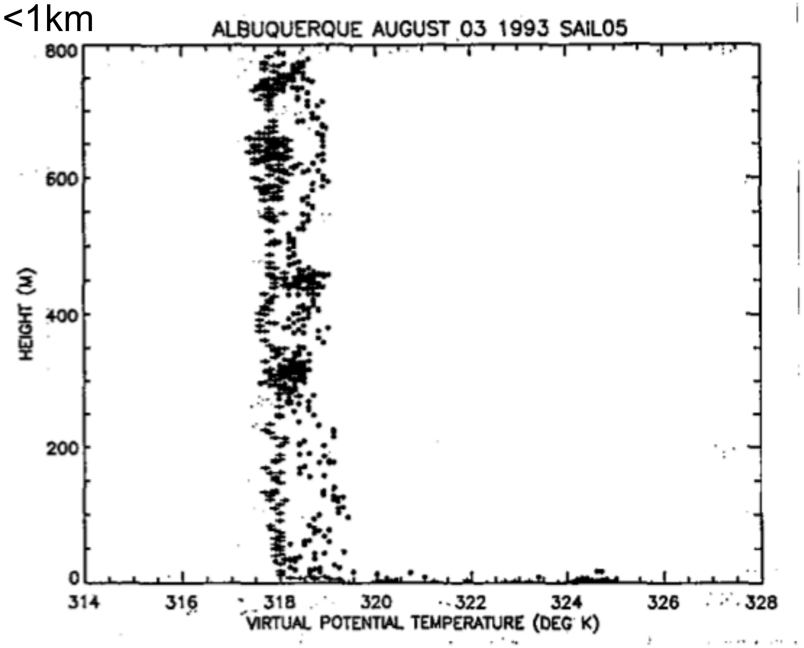


[Renno and Williams, 1995]

But above a thin boundary layer, not true anymore that θ = constant. Why?…

Most atmospheric convection involves phase change of water
Significant latent heat with phase changes of water = Moist Convection

Atmospheric thermodynamics: instability

Moist variables:

ρ_v = M_v/V water vapor density
ρ_d = M_d/V dry air density
ρ = $\rho_v + \rho_d$ total air density

q_v = ρ_v / ρ water vapor specific humidity
r = ρ_v / ρ_d water vapor mixing ratio

e = partial pressure of water vapor = $\rho_v R_v T$ (ideal gaz law for water vapor)
p_d = partial pressure of dry air = $\rho_d R_d T$ (ideal gaz law for dry air)
p = $p_d + e$ total pressure (Dalton's law)

T_d = dew point temperature : T at which a parcel must be cooled at constant pressure to reach saturation

T_v = virtual temperature : T that dry air would have to have the same density as moist air at same pressure

Question 1 : Is moist air lighter or heavier than dry air ? In other words is T_v greater or smaller than T ?
Question 2 : Express T_v as a function of T, q_v and $R_d/R_v=\varepsilon$

Atmospheric thermodynamics: instability

Question 1 : Is moist air lighter or heavier than dry air ? In other words is T_v greater or smaller than T ?

Let's consider a volume of air V at pressure p and temperature T. The ideal gaz law implies that pV=NkT where N is the number of molecules in V. So regardless of whether the air is moist or not, the number of molecules is the same. In other words, *moist air is not formed by adding water molecules to the air, but by replacing dry air molecules with water molecules.*

If we compare the molecular masses of H_20 , N_2 and O_2, clearly H_20 is the lightest :
$m_{H20}=(2+16)m_H$; $m_{O2}=2*16m_H$; $m_{N2}=2*14m_{H.}$
So moist air is lighter than dry air. Hence $T_v > T$.
In fact the ratio of molecular masses is $m_v/m_d \sim .622 = \varepsilon$

In atmospheric applications we use the ideal gaz law with density :
$pV=NkT \Leftrightarrow p = (N\, m / V)\, (k/m)\, T = \rho\, R\, T$

Question 2 : Express T_v as a function of T, q_v and $R_d/R_v = \varepsilon$

By definition, T_v satisfies $p= \rho\, R_d\, T_v$ with $p = e + p_d = (\rho_v R_v + \rho_d R_d)\, T$.
So $T_v = \{ \rho_v/\rho\, R_v /R_d + (\rho - \rho_v) /\rho \}\, T = \{ q_v / \varepsilon +1- q_v \}\, T$
$\Rightarrow T_v = \{1 + (1 / \varepsilon - 1)\, q_v \}\, T \sim (1 + .61\, q_v)\, T > T$ as expected.

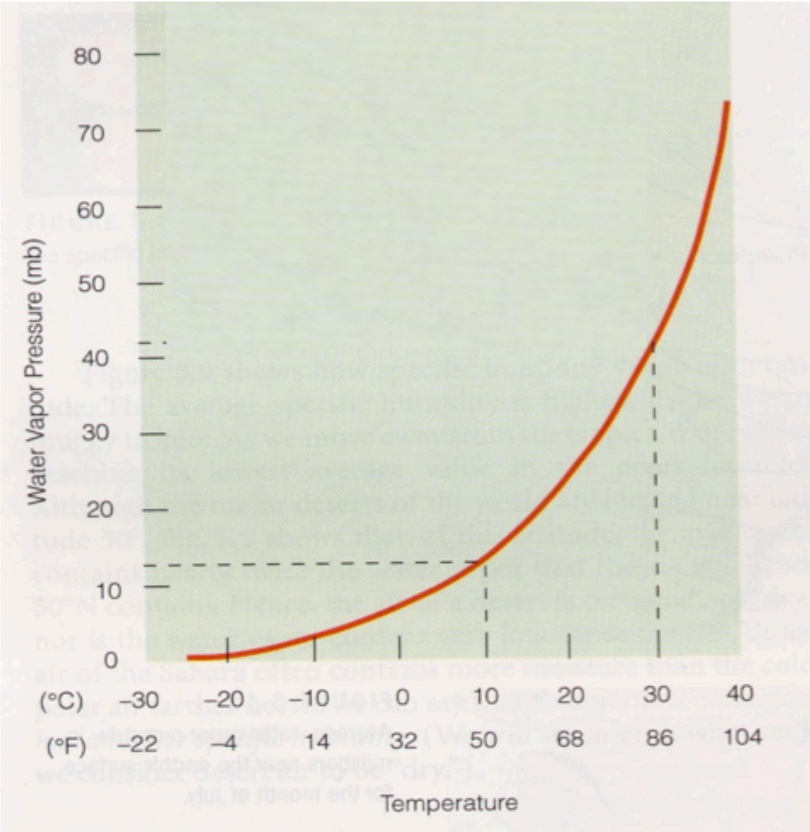
Atmospheric thermodynamics: instability

Clausius Clapeyron $$\frac{\mathrm{d}e_s}{\mathrm{d}T} = \frac{L_v(T)e_s}{R_v T^2}$$

where:

- e_s is saturation vapor pressure,
- T is a temperature,
- L_v is the specific latent heat of evaporation,
- R_v is water vapor gas constant.

$e_s(T)$



e_s depends only on temperature

e_s increases roughly exponentially with T

Saturation water vapor amount increases with temperature

RH = relative humidity = e/e_s

Remark on « sponge theory » :
« Warm air can hold more water vapor than cold air » …
Has nothing to do with air, similar in other gaz !
CC ⇔ Equilibrium between condensation and evaporation

Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

Equivalent potential temperature $\theta_e = T\,(p_0 / p)^{R/cp}\ e^{\,Lv\,qv\,/\,(cp\,T)}$ is *approximately* conserved under adiabatic displacements :

1st law thermodynamics if air saturated (q_v=q_s) :

$$\text{d(internal energy)} = \text{Q (latent heat)} - \text{W (work done by parcel)}$$

$$c_v\, dT = -\ L_v\, dq_s - \ p\, d(1/\rho)$$

$$\Rightarrow d \ln T - R / c_p\, d \ln p = d\ \ln (T / p^{R/cp}) = -L_v / (c_p\, T)\, dq_s$$

$$\Rightarrow\ T / p^{R/cp}\ e^{\,Lv\,qs\,/\,(cp\,T)} \sim \text{constant}$$

Note: Air saturated => q_v=q_s
Air unsaturated => q_v conserved

Hence

$\theta_e = T\,(p_0 / p)^{R/cp}\ e^{\,Lv\,qv\,/\,(cp\,T)}$ equivalent potential temperature is conserved

Remark : If we make the hydrostatic approximation, MOIST STATIC ENERGY $h = c_p\, T + g\, z + L_v\, q_v$ is conserved :

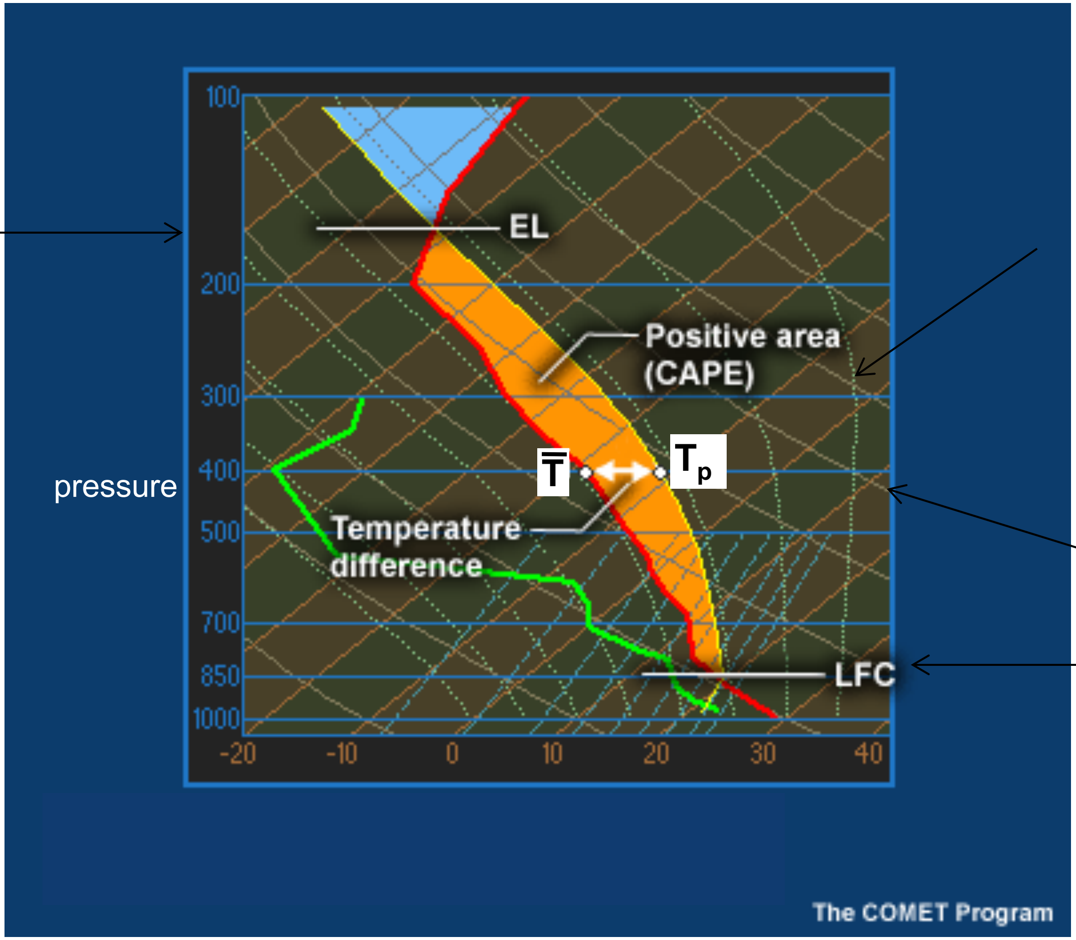
$c_p\, d\,T - R\,T\,dp / p = -L_v\ dq_s \Leftrightarrow c_p\, d\,T + g\,d\,z = -L_v\ dq_s \Leftrightarrow c_p\,T + g\,z + L_v\,q_v = \text{constant}$

Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

Skew T diagram (isoT slanted), atmospheric T in red

EL equilibrium level



Moist adiabat θ_e= cstt

Dry adiabat θ = cstt

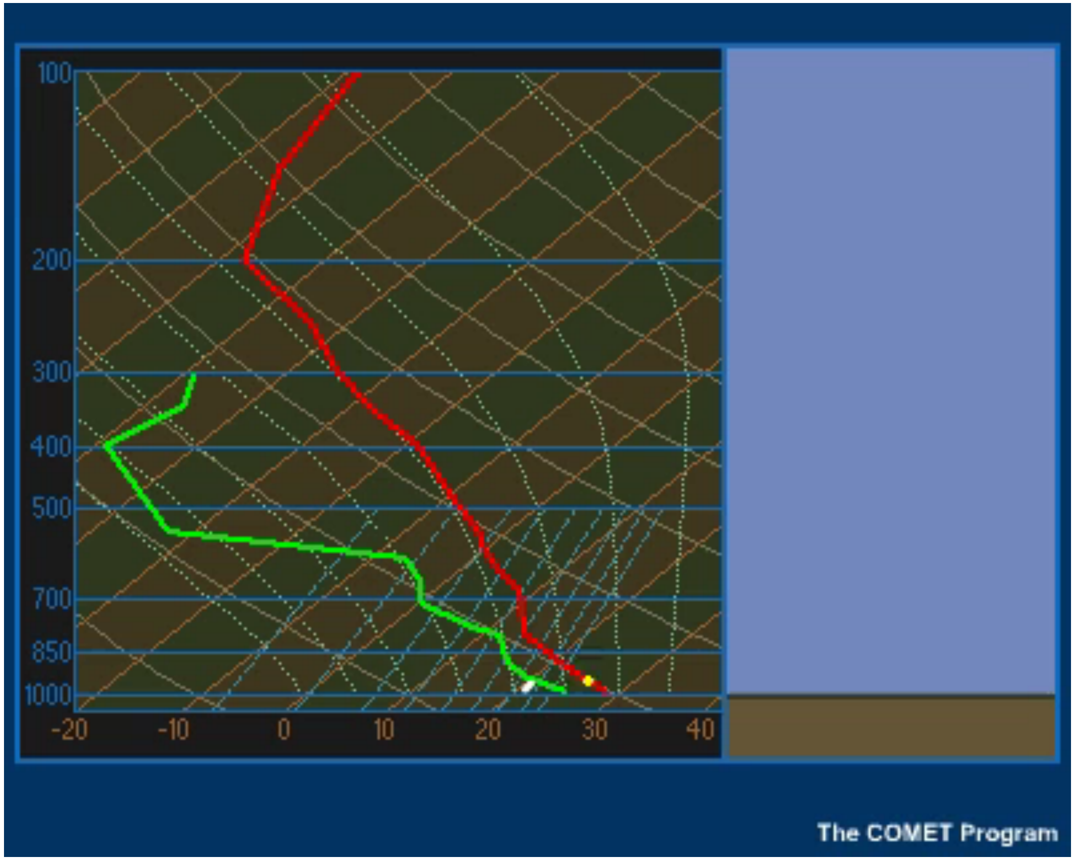
LFC level of free convection (= LCL lifted condensation level for simplicity)

CAPE: convective available potential energy

Moist convection

Parcel = yellow dot

EL equilibrium level



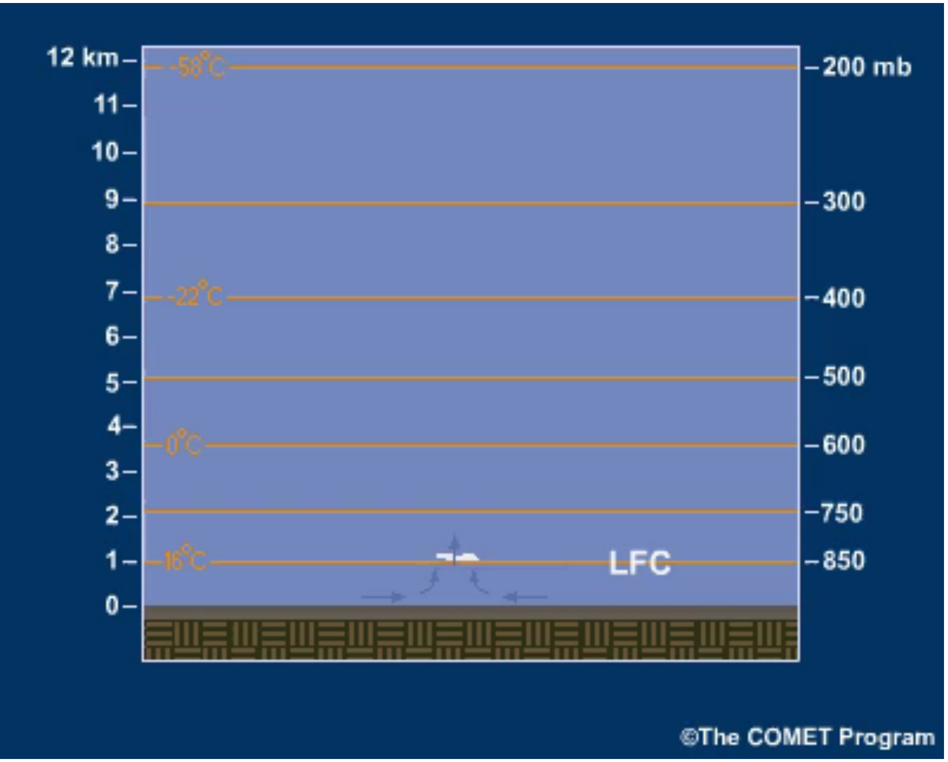
LFC level of free convection

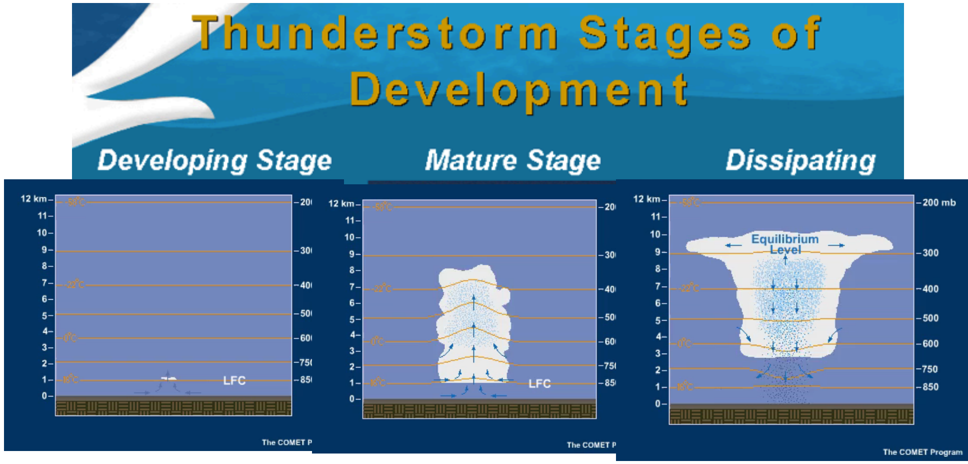
CAPE: convective available potential energy

Atmospheric thermodynamics: instability

If enough atmospheric instability present, cumulus clouds are capable of producing serious storms!!!

Strong updrafts develop in the cumulus cloud => mature, deep cumulonimbus cloud. Associated with heavy rain, lightning and thunder.

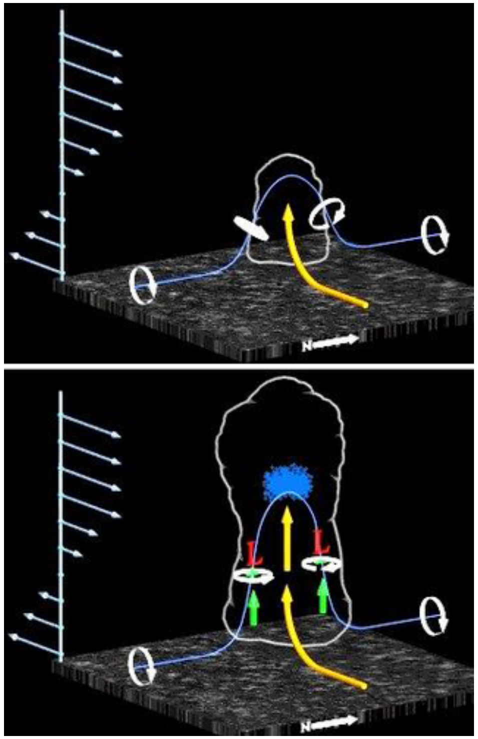




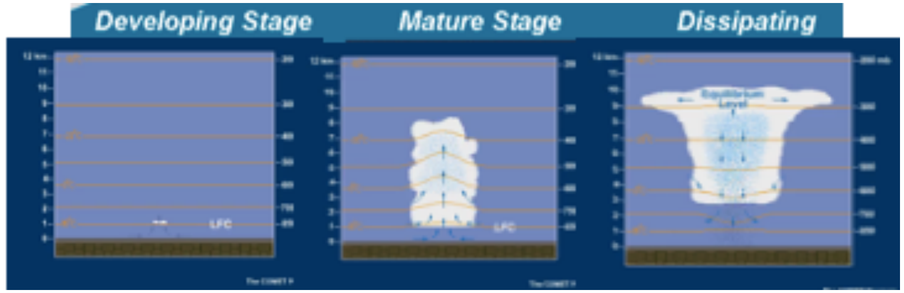
Evaporative driven cold pools

Atmospheric thermodynamics: instability

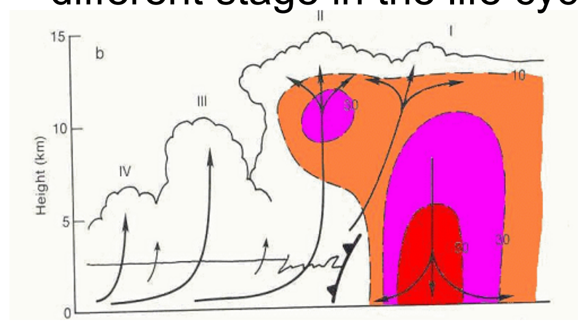
Note that thunderstorms can be :



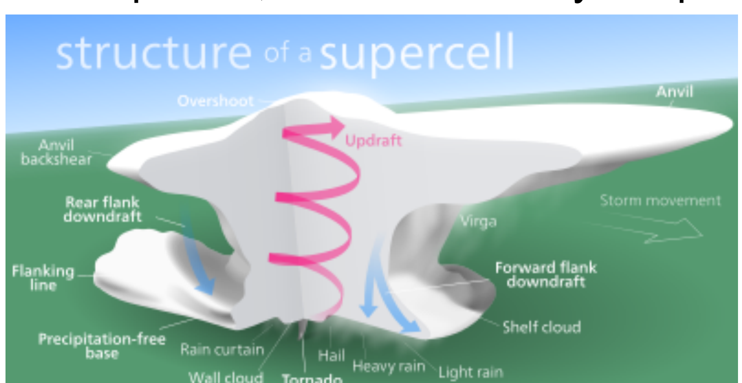
single-cell (typically with weak wind shear)



multi-cell (composed of multiple cells, each being at a different stage in the life cycle of a thunderstorm.



or supercell, characterized by the presence of a deep, rotating updraft



Typically occur in a significant vertically-sheared environment

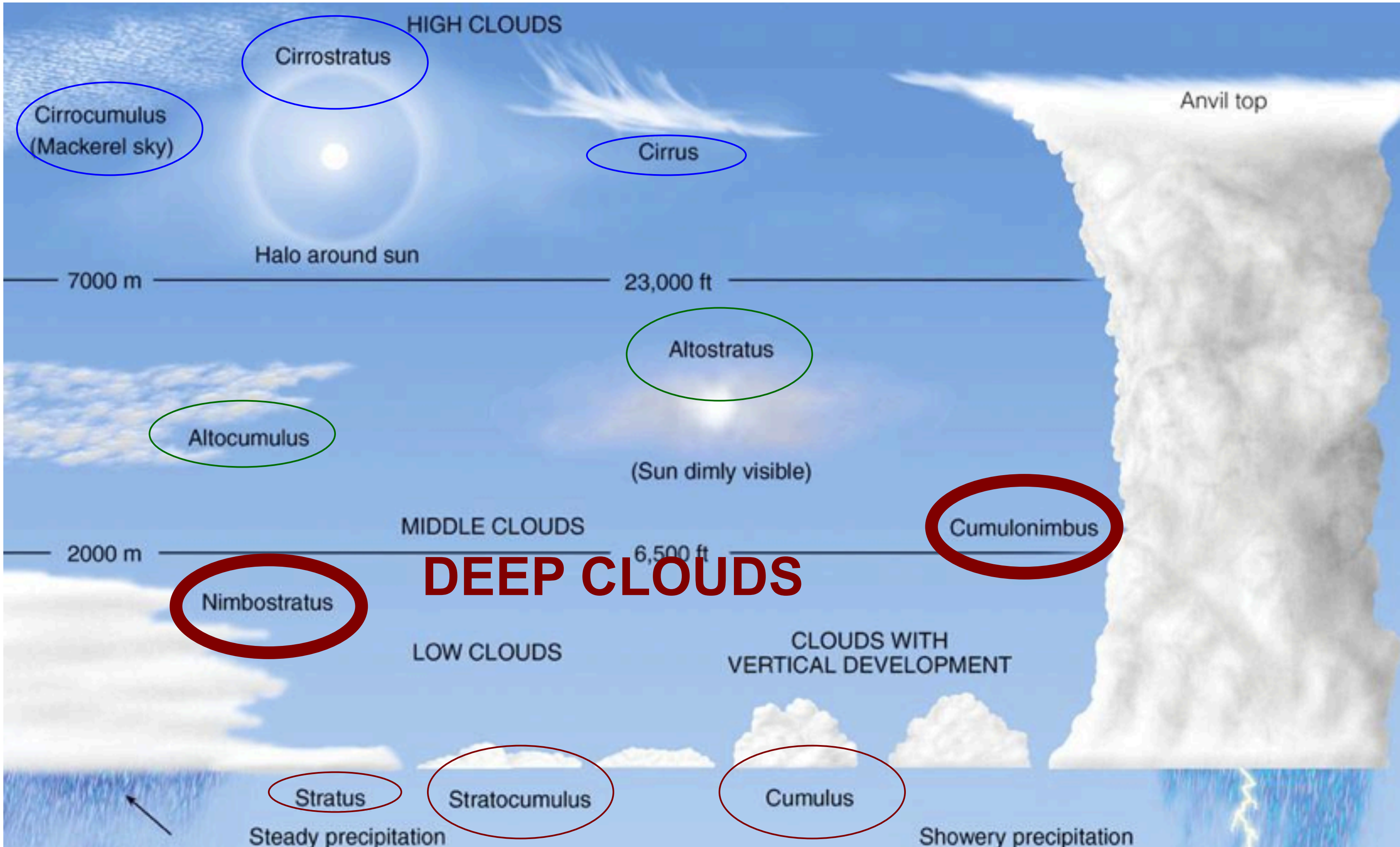
Processes leading to cloud formation

How do those physical considerations explain cloud formation ?

=> FOR DEEP CLOUDS :

We saw that for deep clouds, adiabatic ascent from an unstable BL parcel (warm and/or moist) *rising through an unstable atmospheric T profile* can lead to strong deep convection.

Other lifting mechanisms ?



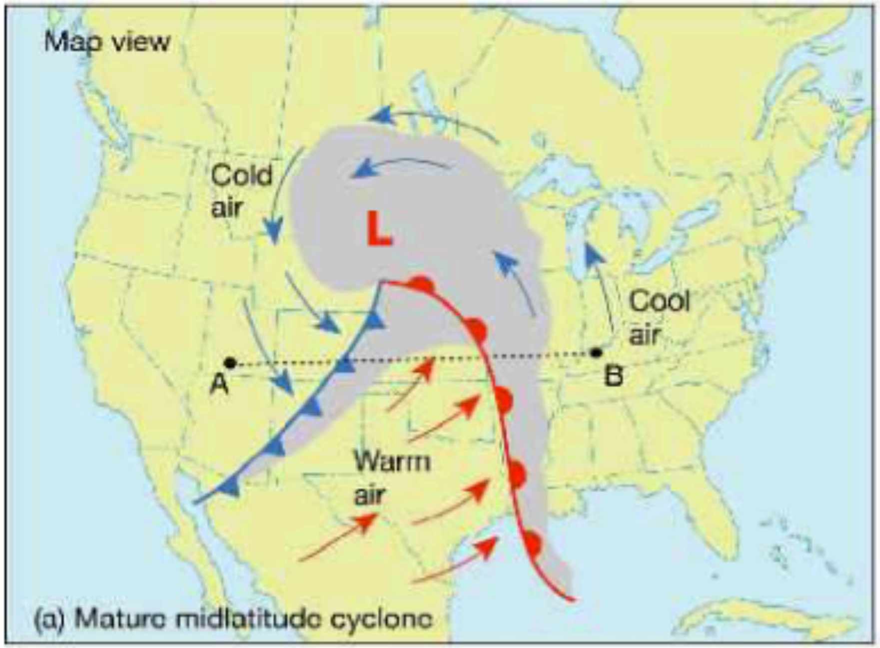
Cloud formation: Deep clouds

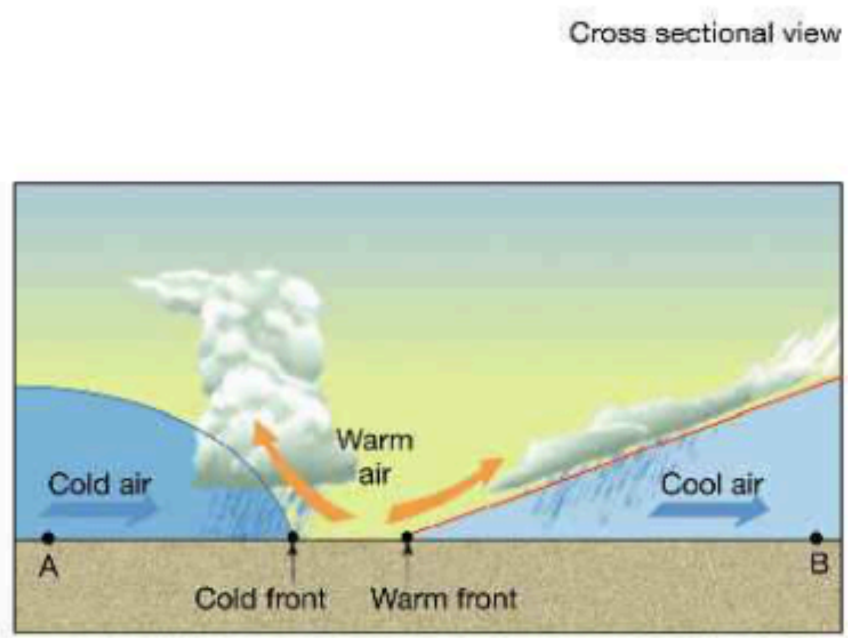
Other lifting mechanisms :

- -orography
- -large-scale convergence
- -fronts

=> All force ascent, and leads to *deep convection if atmosphere above is unstable*

Clouds associated with a frontal system
(blue : cold front, steep and fast; red: warm front, shallower and slower)





Cloud formation: Shallow layer clouds

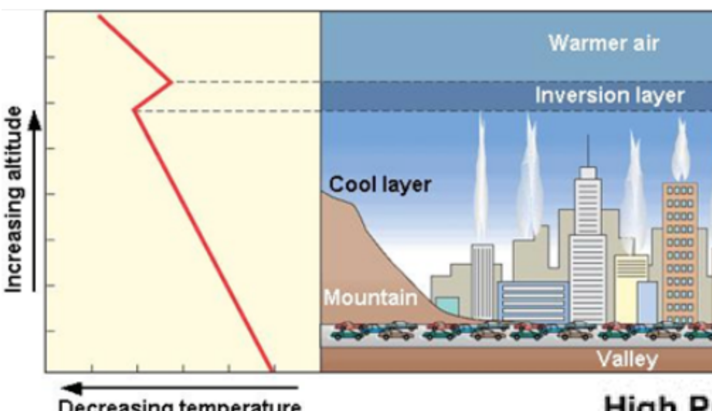
SHALLOW LAYER CLOUDS

- Fog and stratus: in BL cooled from below, by radiation or conduction from cold surface
  => Stable BL, reach saturation by cooling

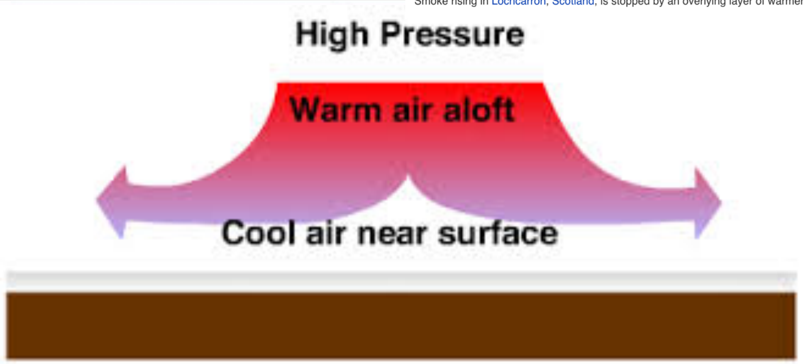
- Stratus or stratocumulus or shallow cumulus: in BL heated from below
  => Unstable BL, with a stable atmosphere above. Also radiative cooling at the top of the cloud layer destabilizes the layer and contributes to the convection.

When do we have unstable layer capped by stable layer ? Warm air above cold air « T inversion »

An inversion can develop aloft as a result of air gradually sinking over a wide area and being warmed by adiabatic compression, e.g. associated with subtropical high-pressure areas.



Smoke rising in Lochcarron, Scotland, is stopped by an overlying layer of warmer air (2006).



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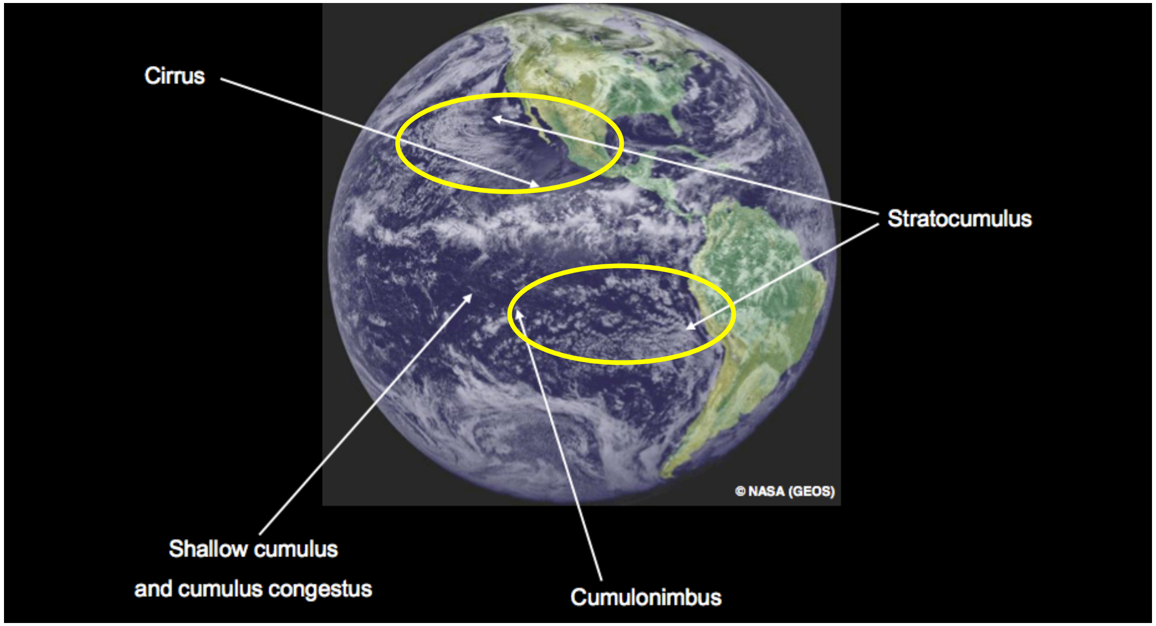
  e.g. - subtropical latitudes west of continents stratus and stratocumulus associated with anticyclones around high pressure
  - middle and high latitudes cold air offshore accross the coastlines of cold continents or ice sheets, over warm ocean => stratocumulus

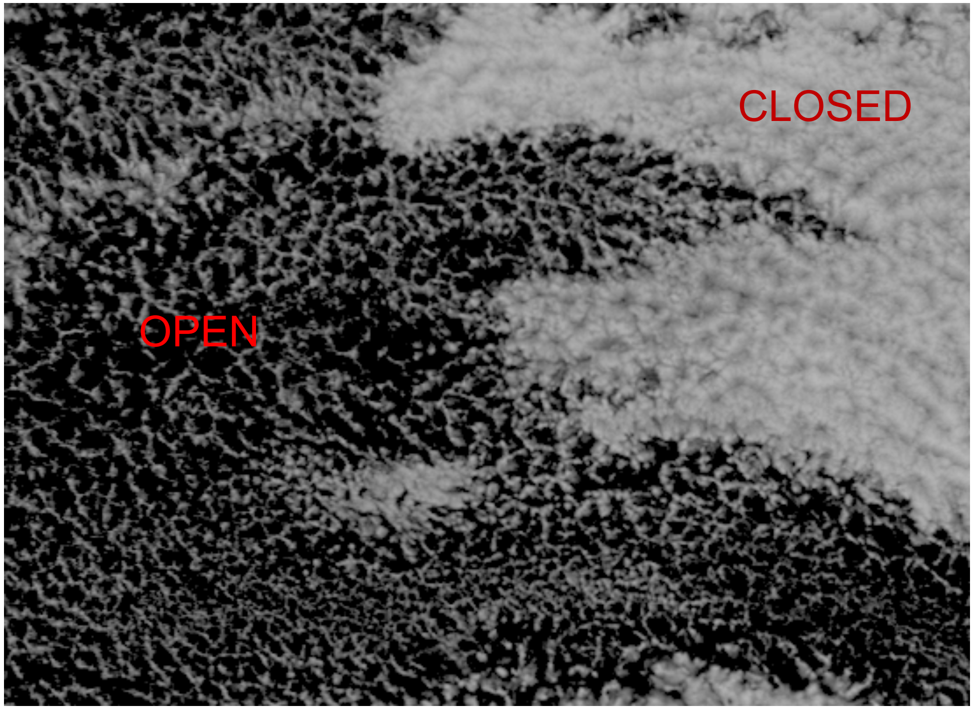


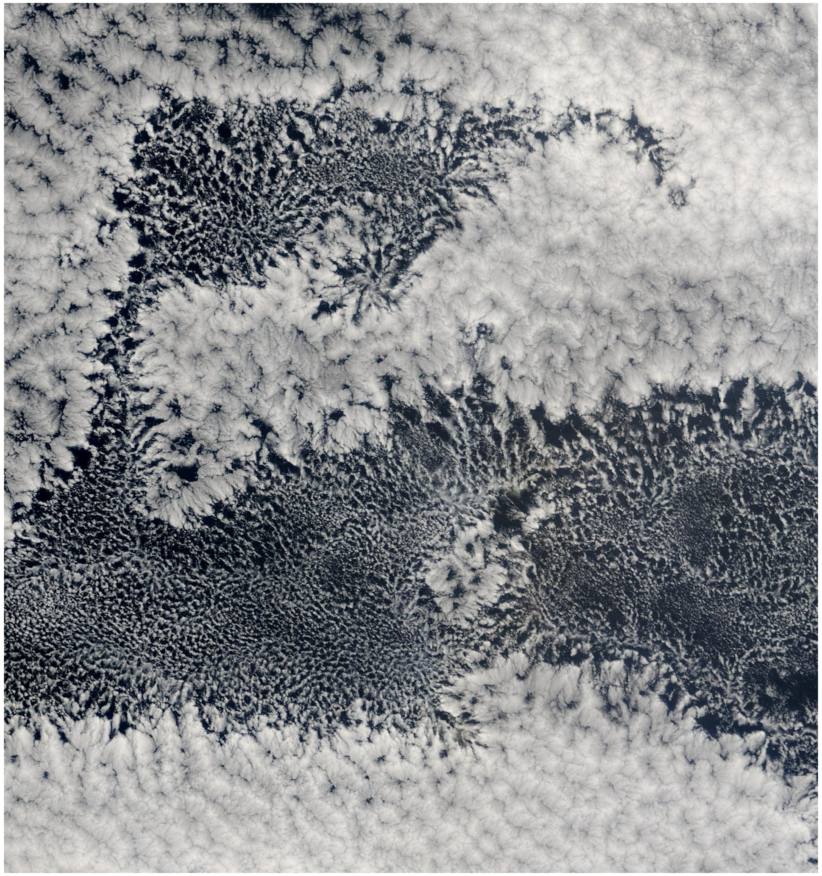
Cloud formation: Shallow layer clouds

MESOSCALE ORGANIZATION OF THOSE CLOUDS : Open and closed cells

Not all is known, but some processes appear to play a role : shear, thermal instabilities of the BL, cloud-top entrainment and precipitation-driven cold pools (aerosols ?)

Mesoscale cellularity in marine stratocumulus clouds. This MODIS image (approximately 800 km across) shows the sharp transitions that occur between the closed and open cells.





Cloud formation: Shallow layer clouds

Mesoscale organization of shallow clouds : Open and closed cells shallow convection

172 5 Shallow-Layer Clouds

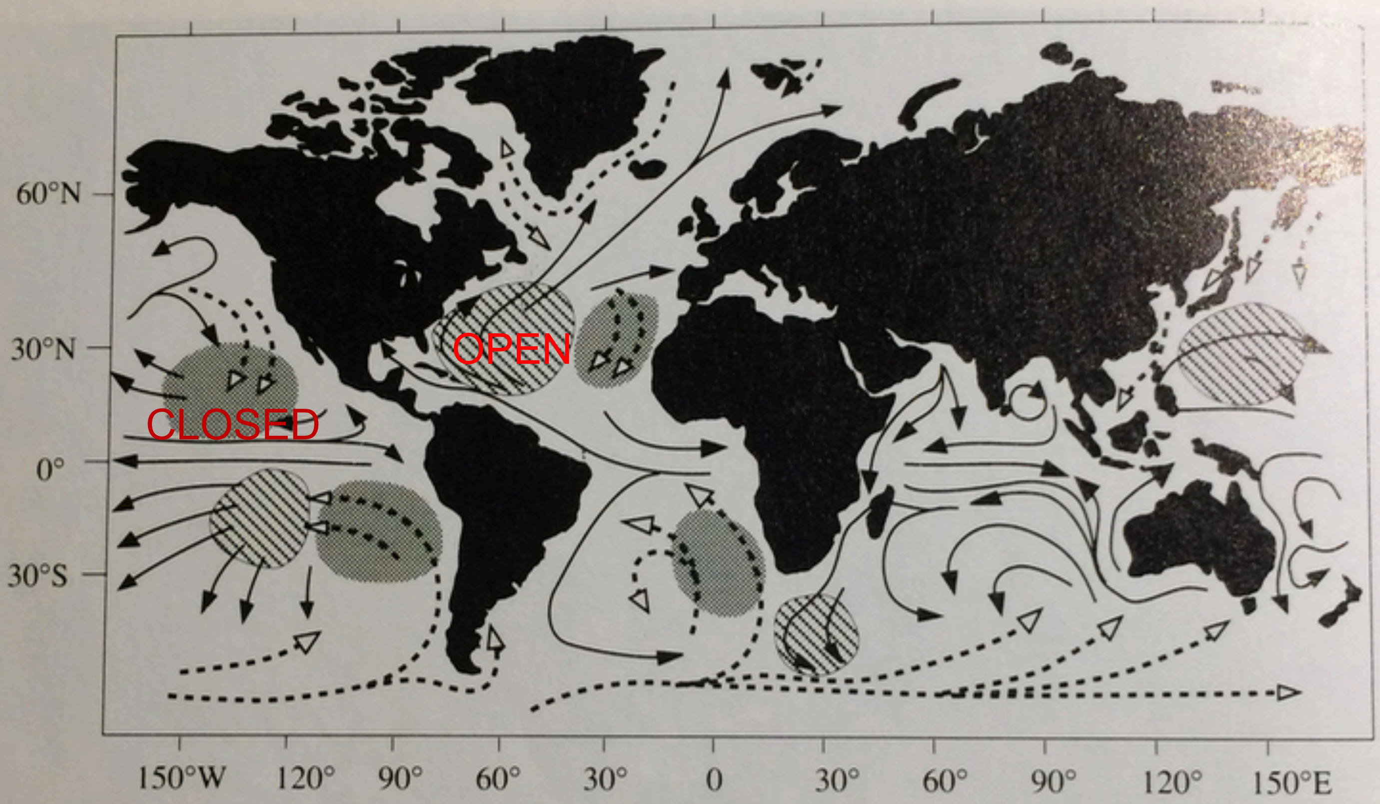
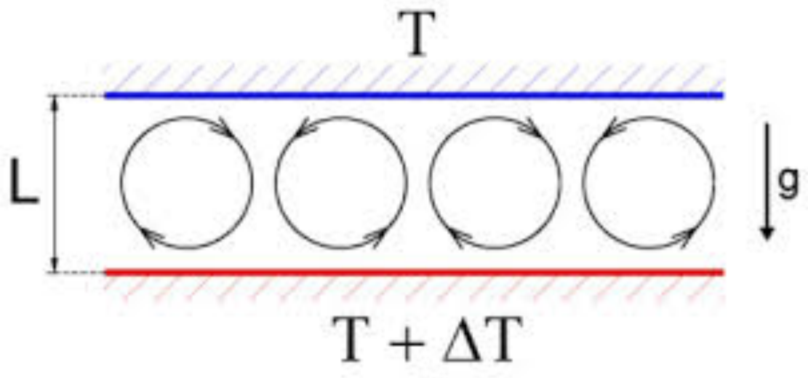


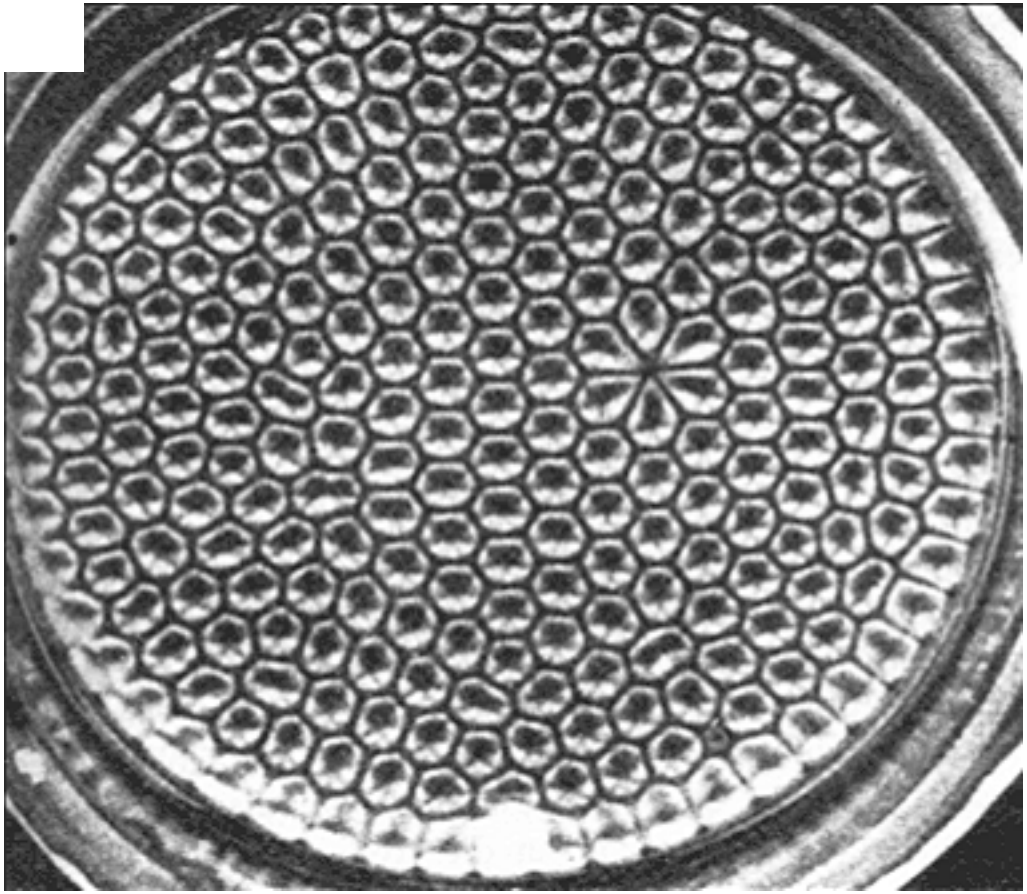
Figure 5.24 Global climatology of cellular structure of stratocumulus and small cumulus over oceans. Shaded areas are regions where closed cells predominate. Hatched areas show where open cells are more common. Solid streamlines show locations of warm ocean currents. Dashed streamlines show cold currents. Land masses are blackened. (Adapted from Agee *et al.*, 1973. Reproduced with permission from the American Meteorological Society.)

Houze « Cloud Dynamics »

Cloud formation: Shallow layer clouds



Rayleigh-Benard convection



Cloud formation: Shallow layer clouds

Rayleigh-Benard convection

Gold paint dissolved in acetone. Put it in a shallow dish. Cover it so that the acetone does not evaporate. Let stabilise and then remove the cover. Evaporation of the acetone causes the top layer to cool thus starting convection.

Cloud formation: Shallow layer clouds

SHALLOW LAYER CLOUDS

- Cirriform clouds:

  Not much water vapor at those high altitudes => mainly radiation driven.
  Clouds of (mainly) ice in an unstable layer between two stable layers
  SW heating throughout the clouds, while LW cools above and warms below

  -Can be detrained from deep convective clouds (most often, consistent with largest cirrus cover in the tropics and in the extratropics where deep convection), or

  -Can occur away from generating source when unstable layer aloft

- Altostratus & altocumulus: these can be

  -Remnants of other clouds: protruding layers in middle levels due to horizontal wind

  -Altocumulus also sometimes high-based convective clouds => same dynamics as deep convective clouds

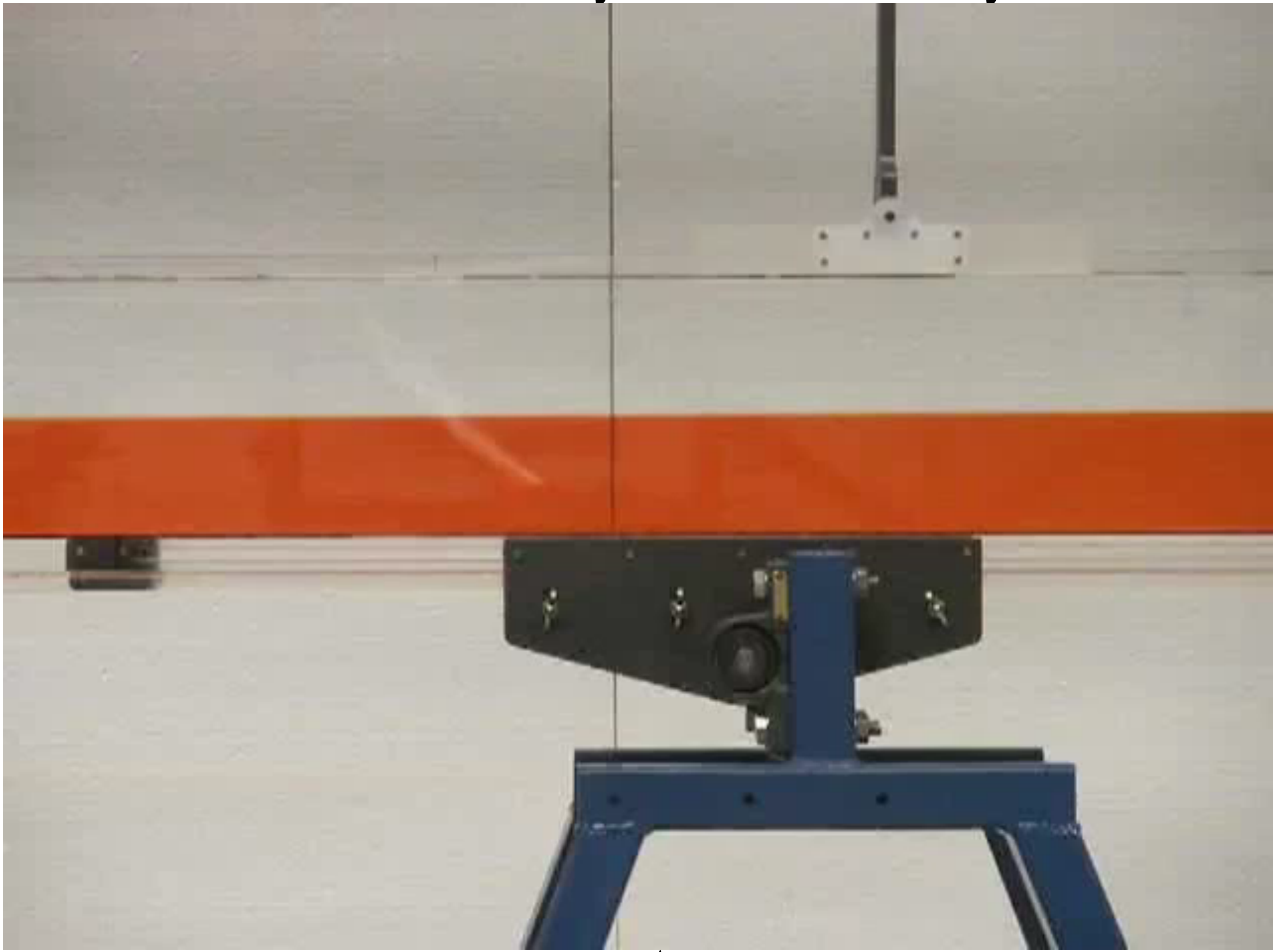
  -Altostratus or shallow layer of altocumulus can also resemble a radiatively driven « mixed layer » aloft, leading to a cloud-filled layer radiatively driven at its top
  (Can lead to rolls in the absence of shear)

Atmospheric thermodynamics: instability

Kelvin Helmholtz Instability : destabilized by shear

Atmospheric thermodynamics: instability

Kelvin Helmholtz Instability : destabilized by shear



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Response of the hydrological cycle to climate change - mean precip, precip extremes

Clouds in a changing climate – climate sensitivity, cloud effect, cloud feedback, FAT