Clouds and atmospheric convection

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Textbooks recommended :
- *"Cloud Dynamics", Houze*
- *"Atmospheric Convection", Emanuel*
- *"Atmospheric Thermodynamics", Bohren & Albrecht*
- *"Physics of Climate", Peixoto & Oort*

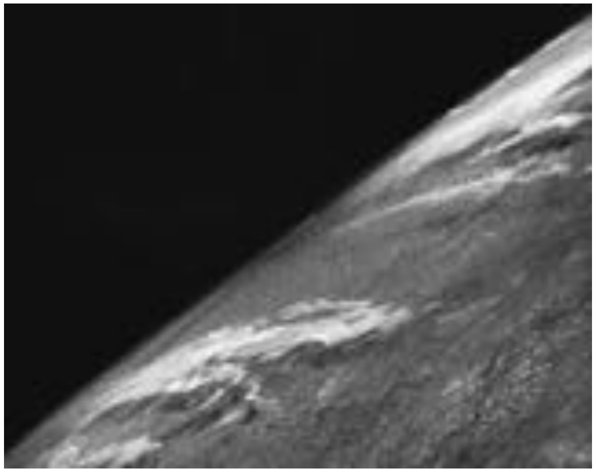
What are clouds ?

Clouds and atmospheric convection

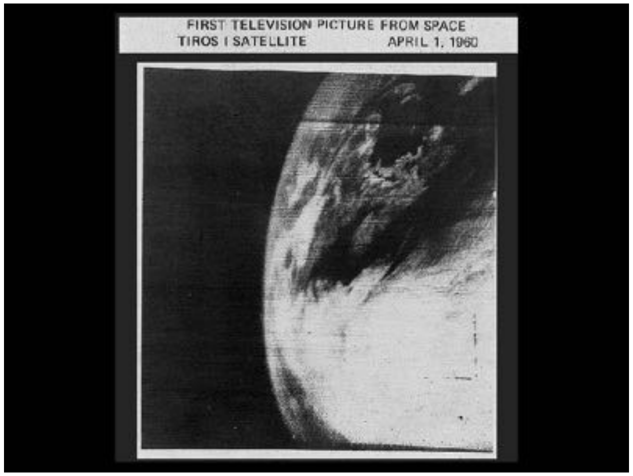
"How inappropriate to call this planet Earth, when clearly it is Ocean." - Arthur C. Clark

What are clouds ?

Earth from rocket 1946



Earth From Weather Satellite 1960

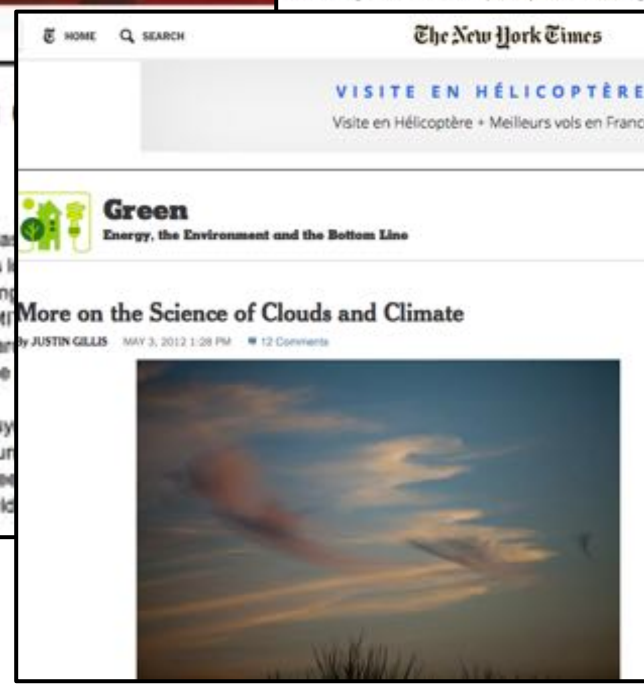


Blue Marble 1972

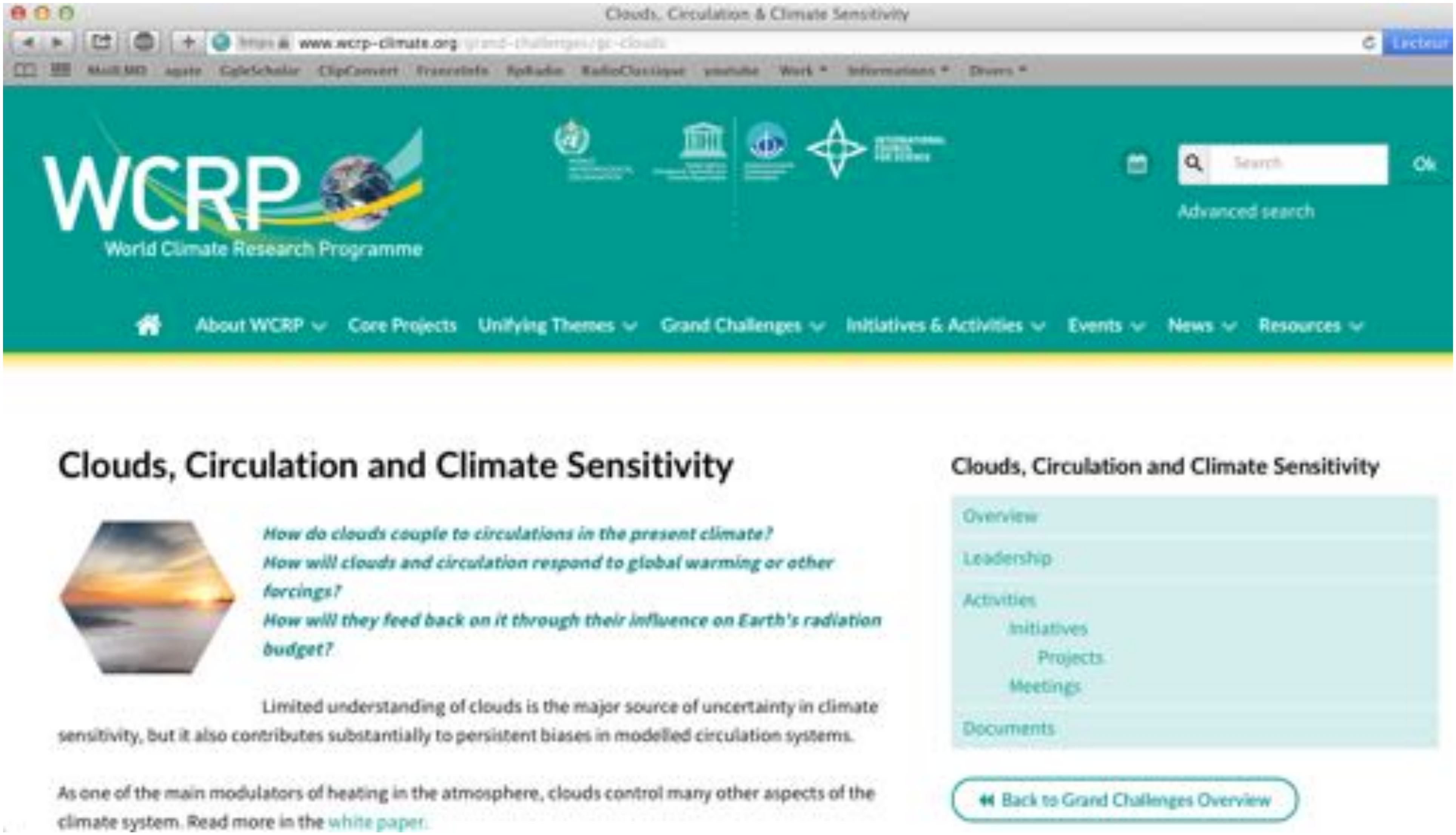
Tintin on the moon 1952

What are clouds? Key actors of climate

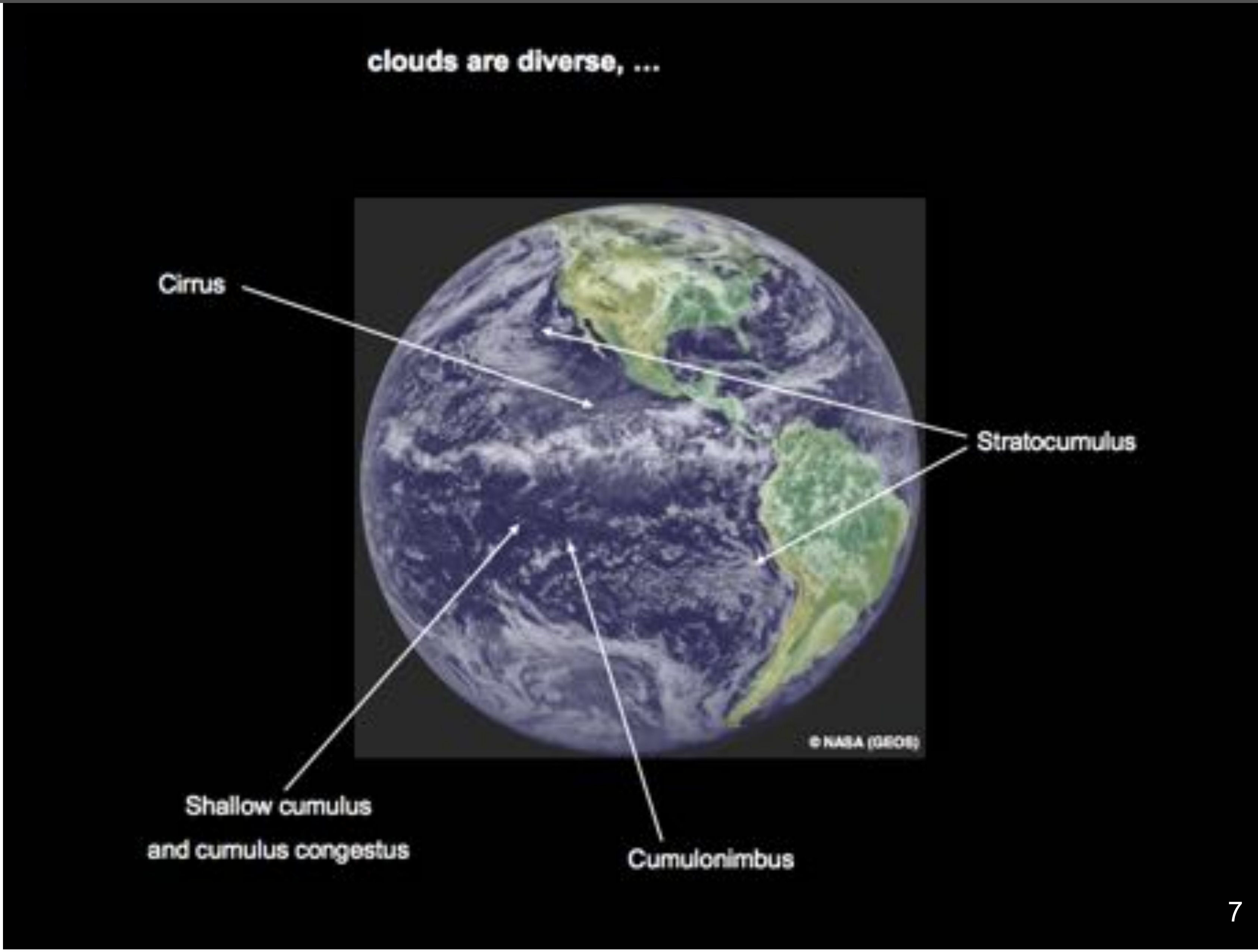
An era of blooming cloud and climate science



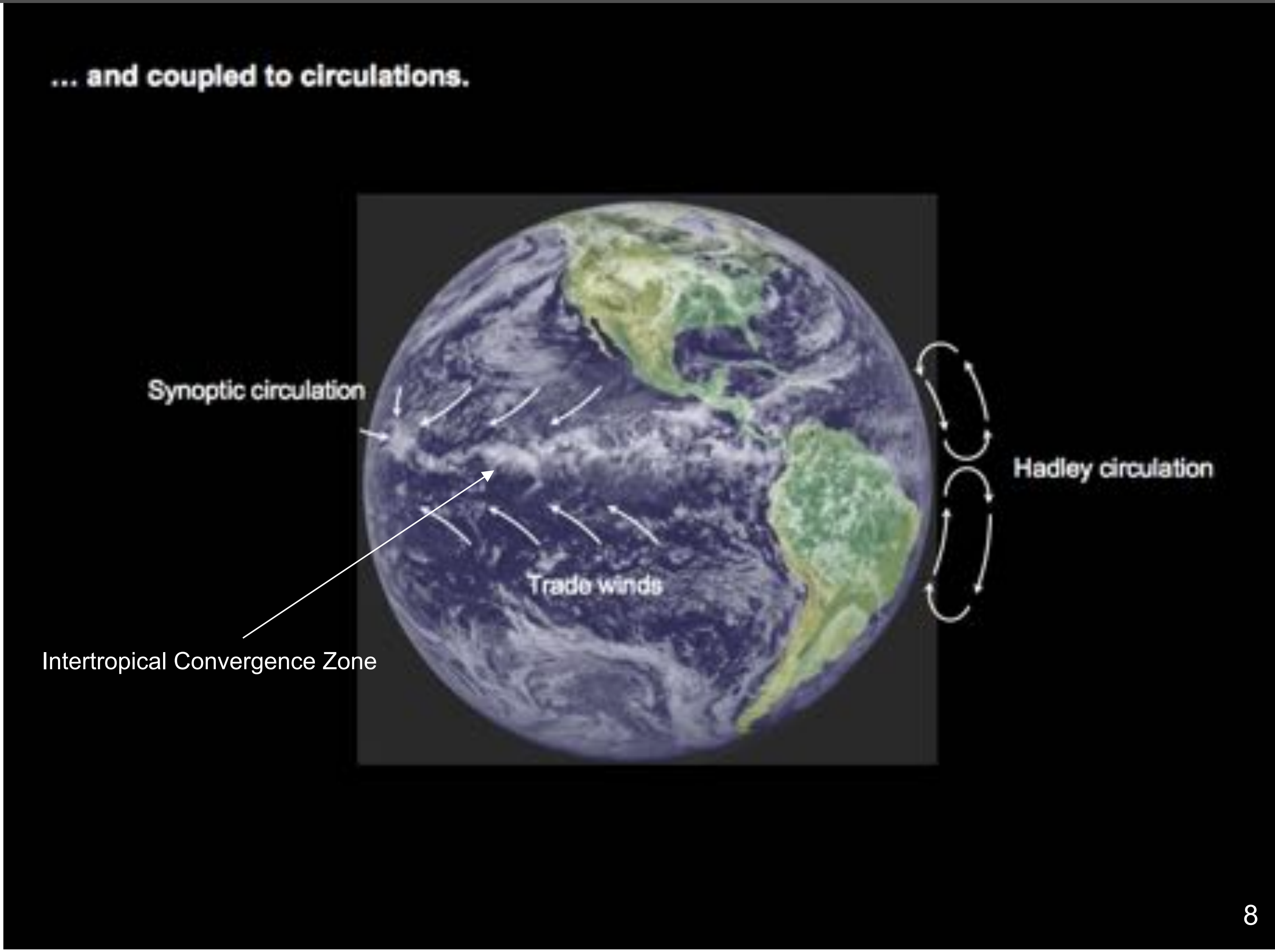
What are clouds? A Grand Challenge



Clouds and atmospheric convection



Clouds and atmospheric convection



Clouds and atmospheric convection

1. Cloud types

2. Moist thermodynamics and stability

1. Cloud types

Cumulus: heap, pile

Stratus: flatten out, cover with a layer

Cirrus: lock of hair, tuft of horsehair

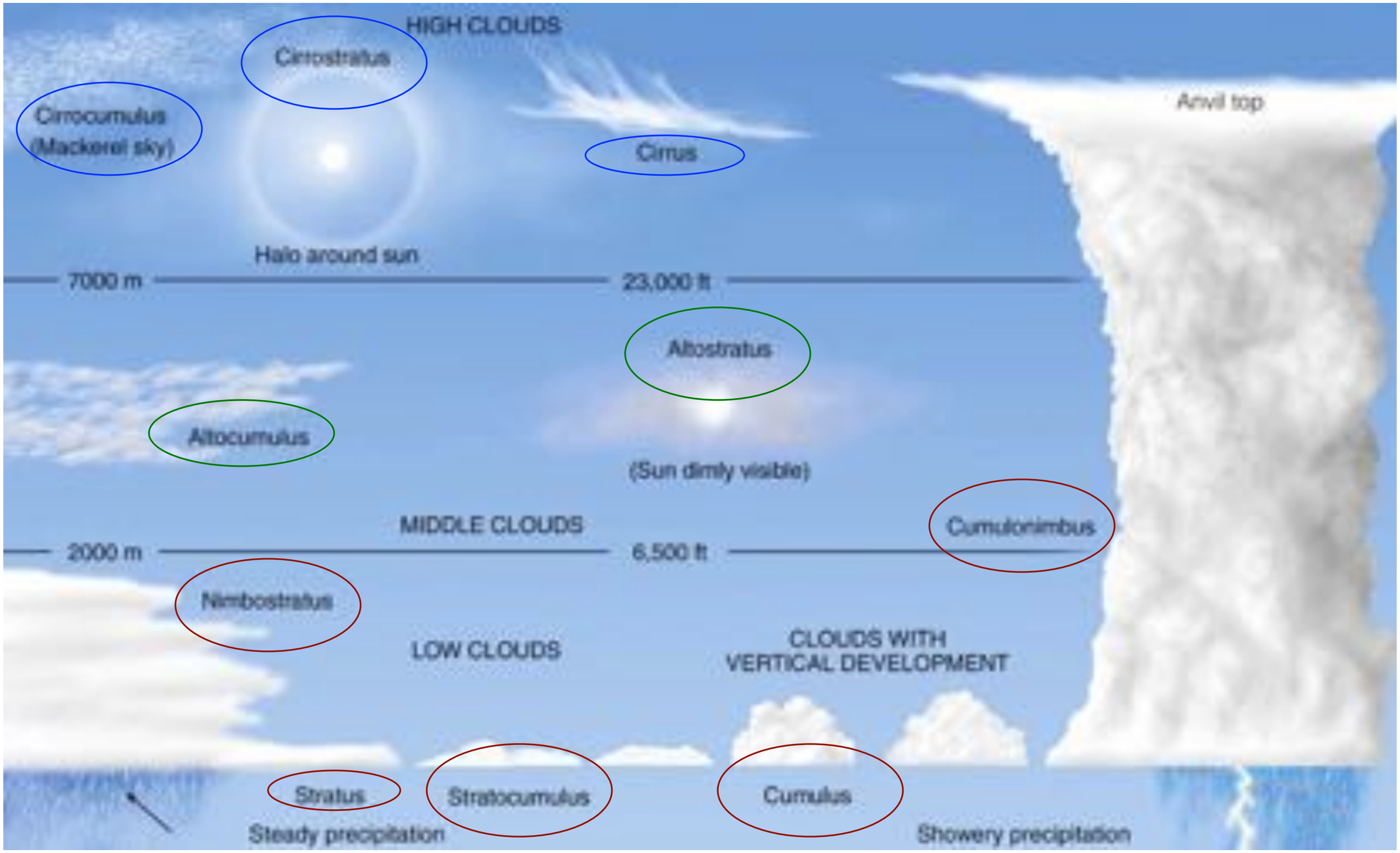
Nimbus: precipitating cloud

Altum: height

Combined to define 10 cloud types

1. Cloud types

Clouds are classified according to height of cloud base and appearance



High clouds
Base: 5 to 12km

Middle clouds
Base: 2 to 6km

Low clouds
Base < 2km

1. High Clouds

Almost entirely ice crystals

Cirrus
Wispy, feathery

Cirrostratus Widespread, sun/moon halo

Cirrocumulus Layered clouds, cumuliform lumpiness

1. Middle Clouds

Liquid water droplets, ice crystals, or a combination of the two, including supercooled droplets (i.e., liquid droplets whose temperatures are below freezing).

Altostratus

Flat and uniform type texture in mid levels

Altocumulus

Heap-like clouds with convective elements in mid levels
May align in rows or streets of clouds

1. Low Clouds

Liquid water droplets or even supercooled droplets, except during cold winter storms when ice crystals (and snow) comprise much of the clouds.

The two main types include **stratus**, which develop horizontally, and **cumulus**, which develop vertically.

Stratocumulus

Hybrids of layered stratus and cellular cumulus

Stratus

Uniform and flat, producing a gray layer of cloud cover

Nimbostratus

Thick, dense stratus or stratocumulus clouds producing steady rain or snow

1. Low Clouds

Liquid water droplets or even supercooled droplets, except during cold winter storms when ice crystals (and snow) comprise much of the clouds.
The two main types include **stratus**, which develop horizontally, and **cumulus**, which develop vertically.

Cumulus (humili)

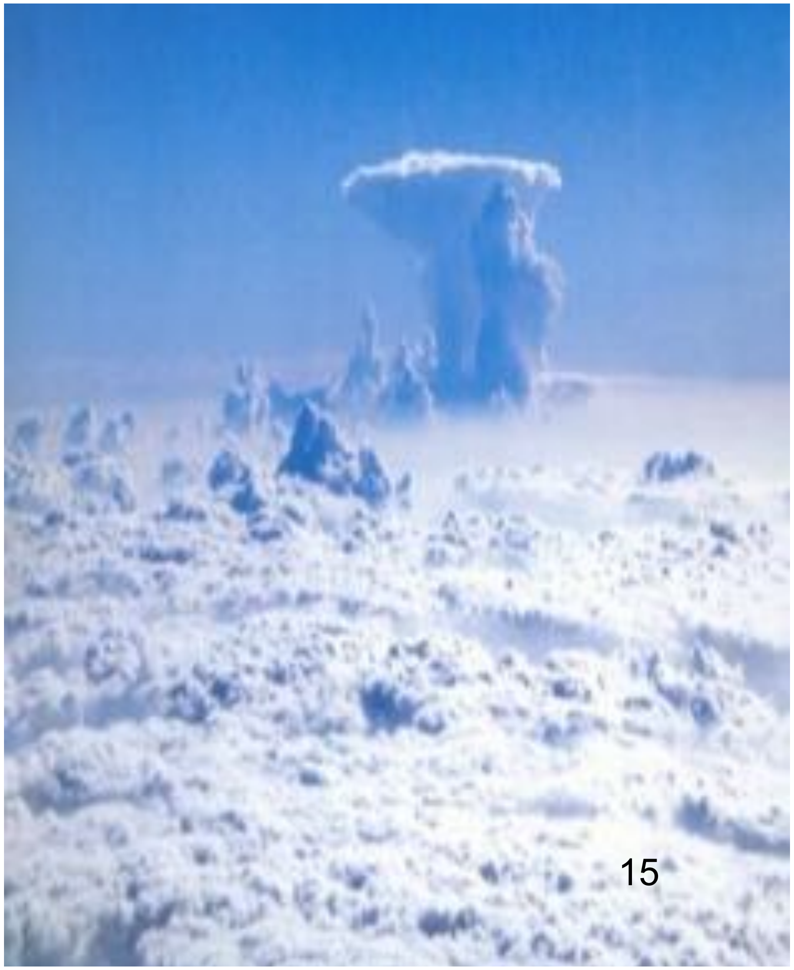
Scattered, with little vertical growth on an otherwise sunny day
Also called "fair weather cumulus"

Cumulus (congestus)

Significant vertical development (but not yet a thunderstorm)

Cumulonimbus

Strong updrafts can develop in the cumulus cloud => mature, deep cumulonimbus cloud, i.e., a thunderstorm producing heavy rain.



1. Other spectacular Clouds…

Mammatus clouds (typically below anvil clouds)

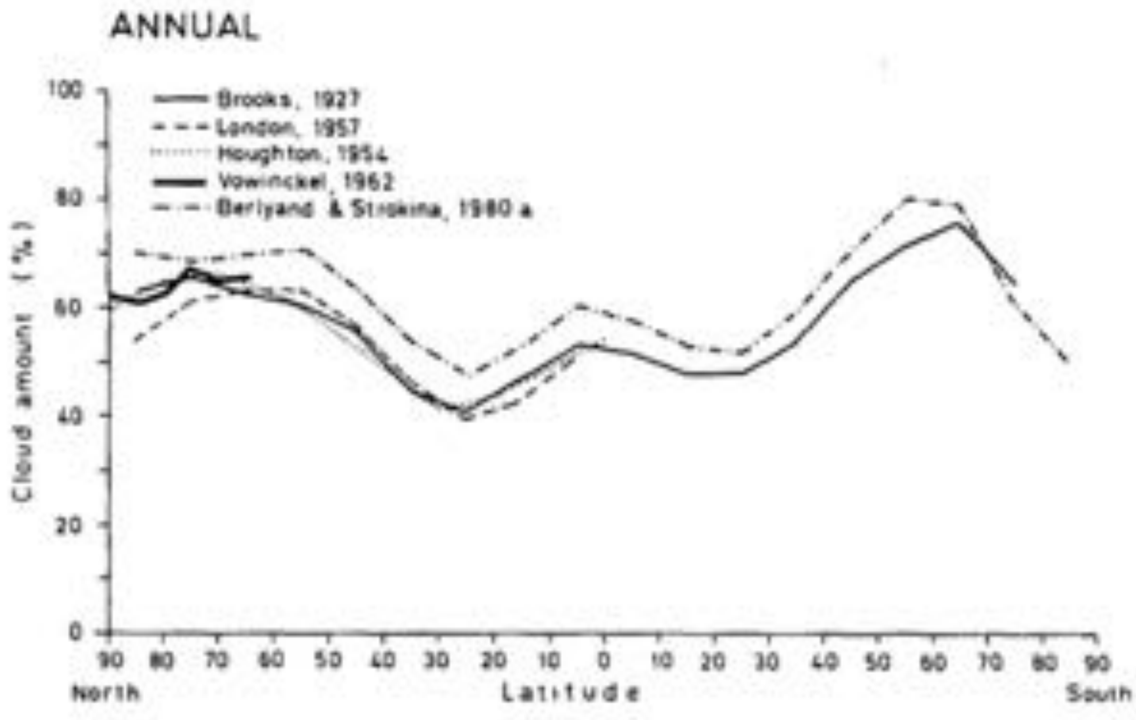
Shelf clouds (gust front)

Lenticular clouds (over orography)

Question: Global cloud cover (%)?

1. Cloud types

Distribution of cloud amount

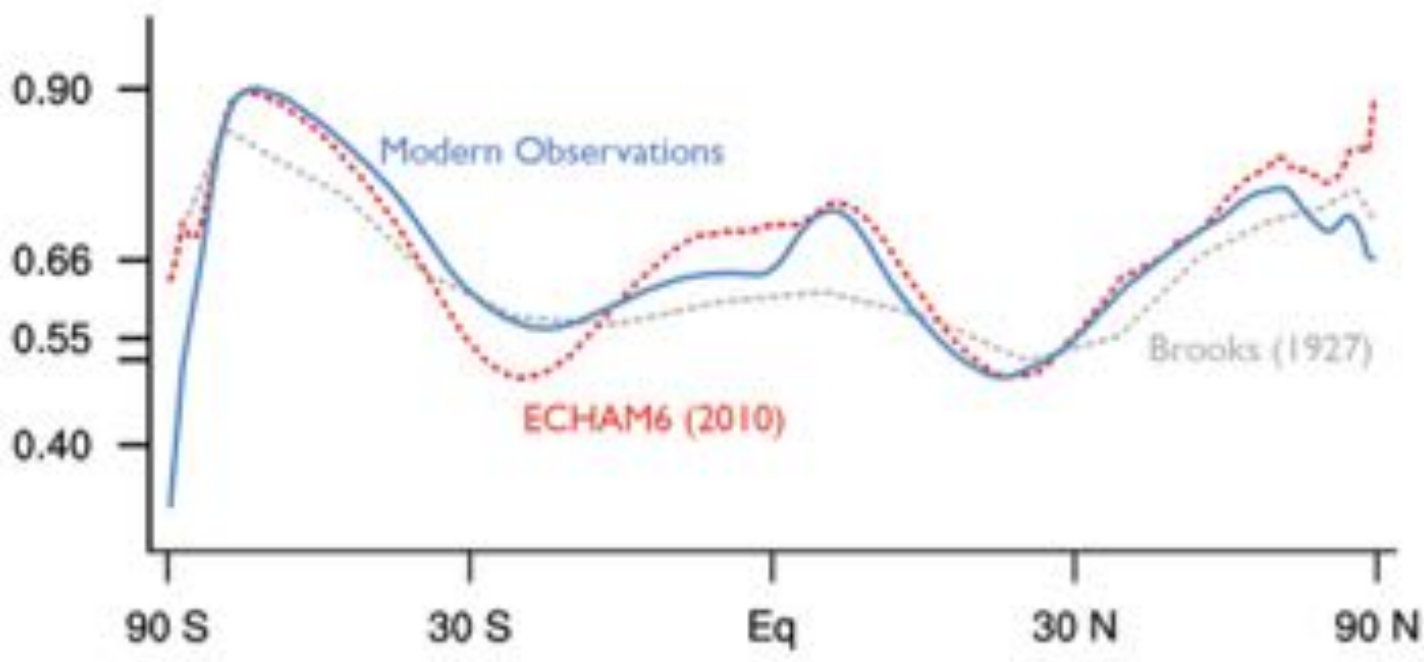


[Hughes 84]

1. Cloud types

Cloud amount was underestimated

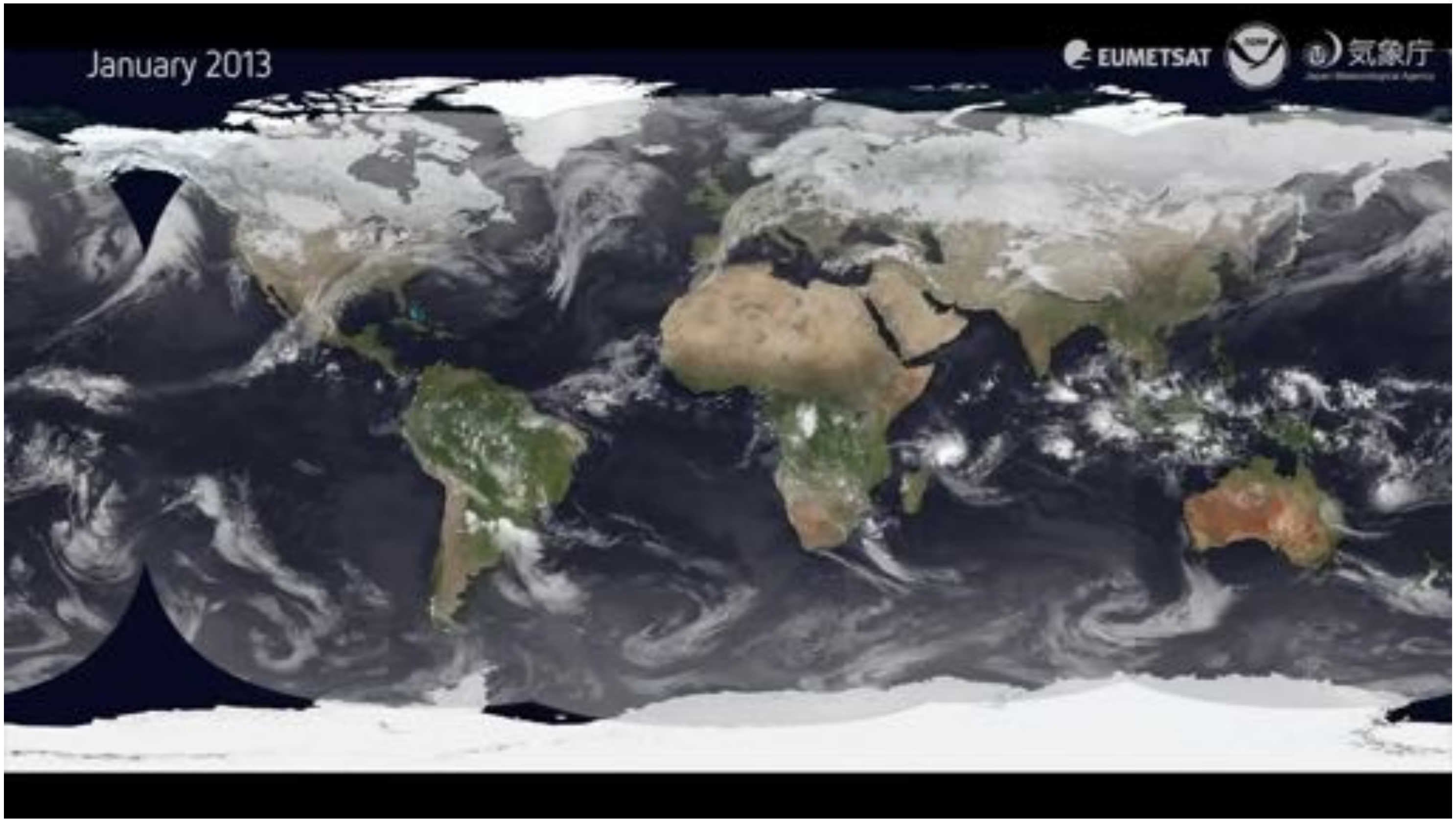
Also note the latitudinal distribution



Courtesy Bjorn Stevens

1. Cloud types

Brightness temperature from satellite (white ⇔ cold cloud tops)



Large extratropical storm systems

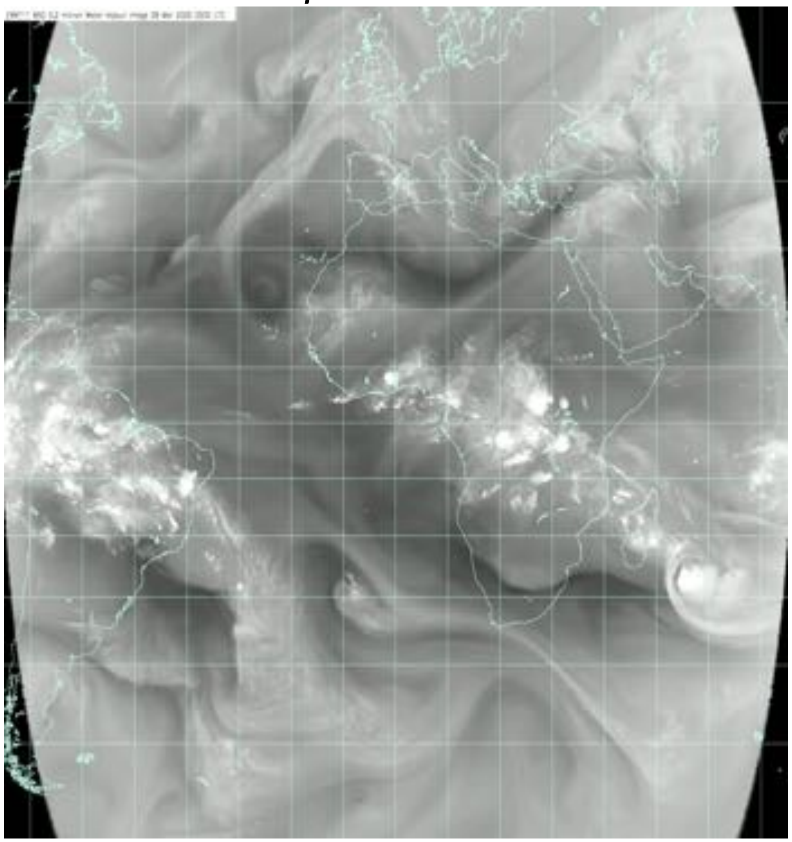
subtropics: ~no high clouds

ITCZ = Intertropical convergent zone

« A year of weather »

1. Cloud types

Water vapor from satellite



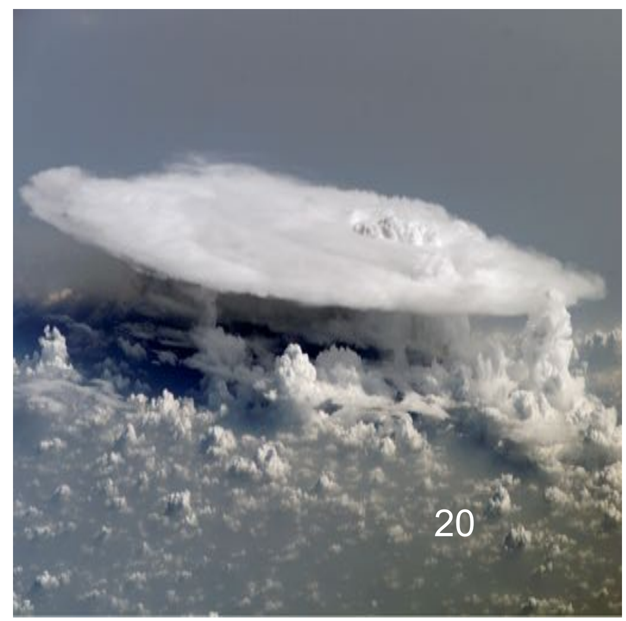
Large extratropical storm systems => Large-scale extratropical convection

subtropics: ~no high clouds => shallow clouds

ITCZ = Intertropical convergent zone => Small-scale tropical convection

… but not always that small!

Deep convective system over Brazil:



Clouds and atmospheric convection

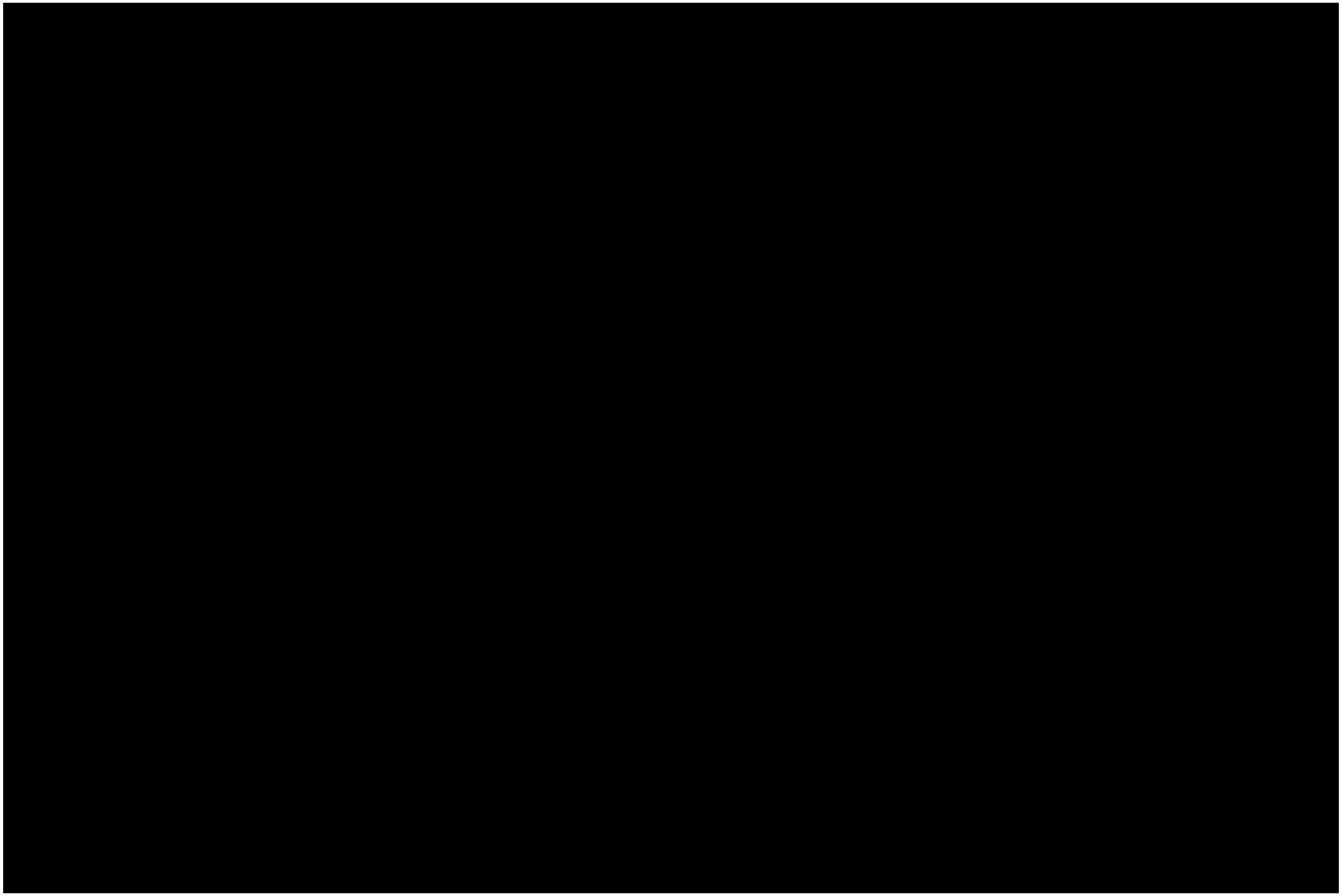
1. Cloud types

2. Moist thermodynamics and stability

Cloud formation

Courtesy : Octave Tessiot

Cloud formation



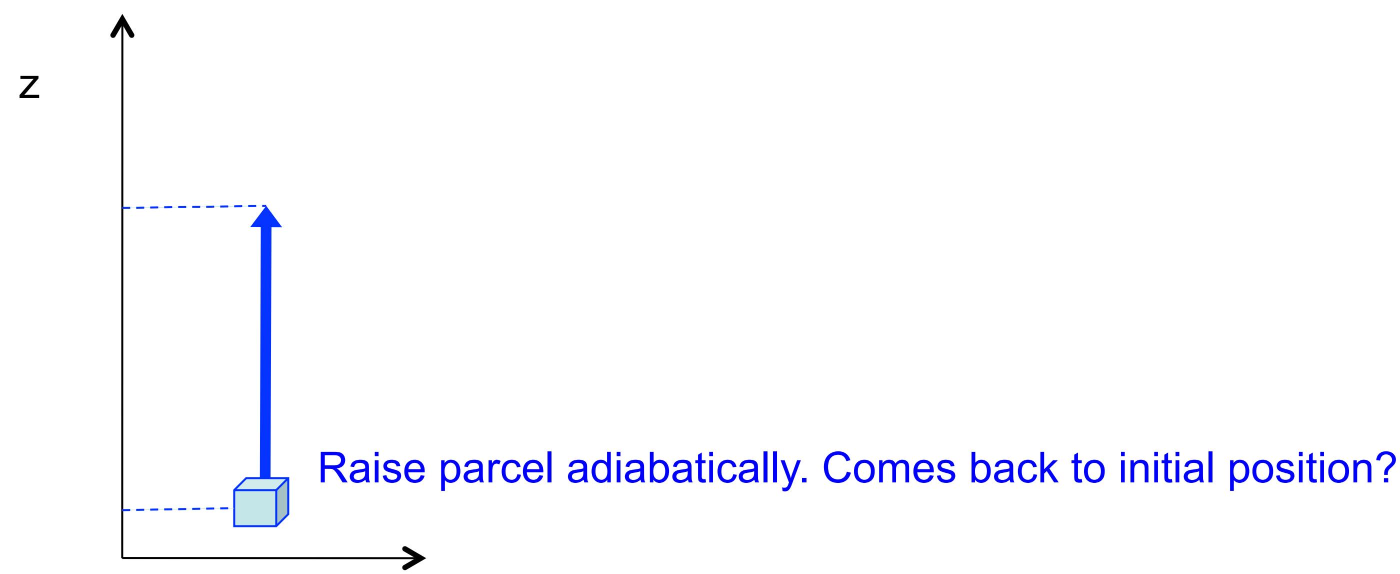
Courtesy : Octave Tessiot

Atmospheric thermodynamics

Dry convection

T decreases with height.
But p as well.

Density = $\rho(T,p)$.
How determine stability? The parcel method



2. Atmospheric thermodynamics: instability

Dry convection

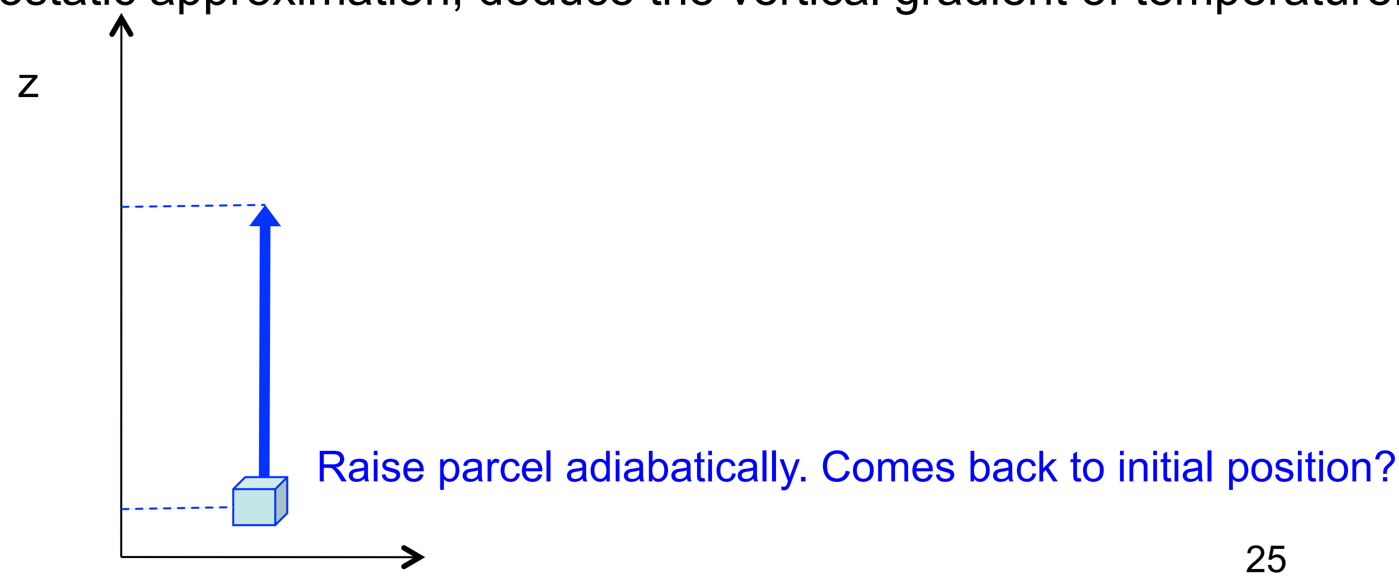
T decreases with height, but p as well. Density = ρ(T,p). How determine stability? The parcel method

Exercise : Temperature profile of a dry adiabat.

• Use the first law of thermodynamics and the ideal gaz law to show that under adiabatic displacement, a parcel of air satisfies $dT / T - R / c_p \, dp / p = 0$ (specify what the variables and symbols are).

• Deduce that potential temperature $\theta = T (p_0/p)^{R/c_p}$ is conserved under adiabatic displacement (p_0 denotes a reference pressure usually 1000hPa).

• If we make the hydrostatic approximation, deduce the vertical gradient of temperature.



2. 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) = Q (heat added) – W (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 $c_v + R = c_p$, $\quad c_p\, dT / T = R\, dp / p$

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

$$\Rightarrow T / p^{R/cp} = \text{constant}$$

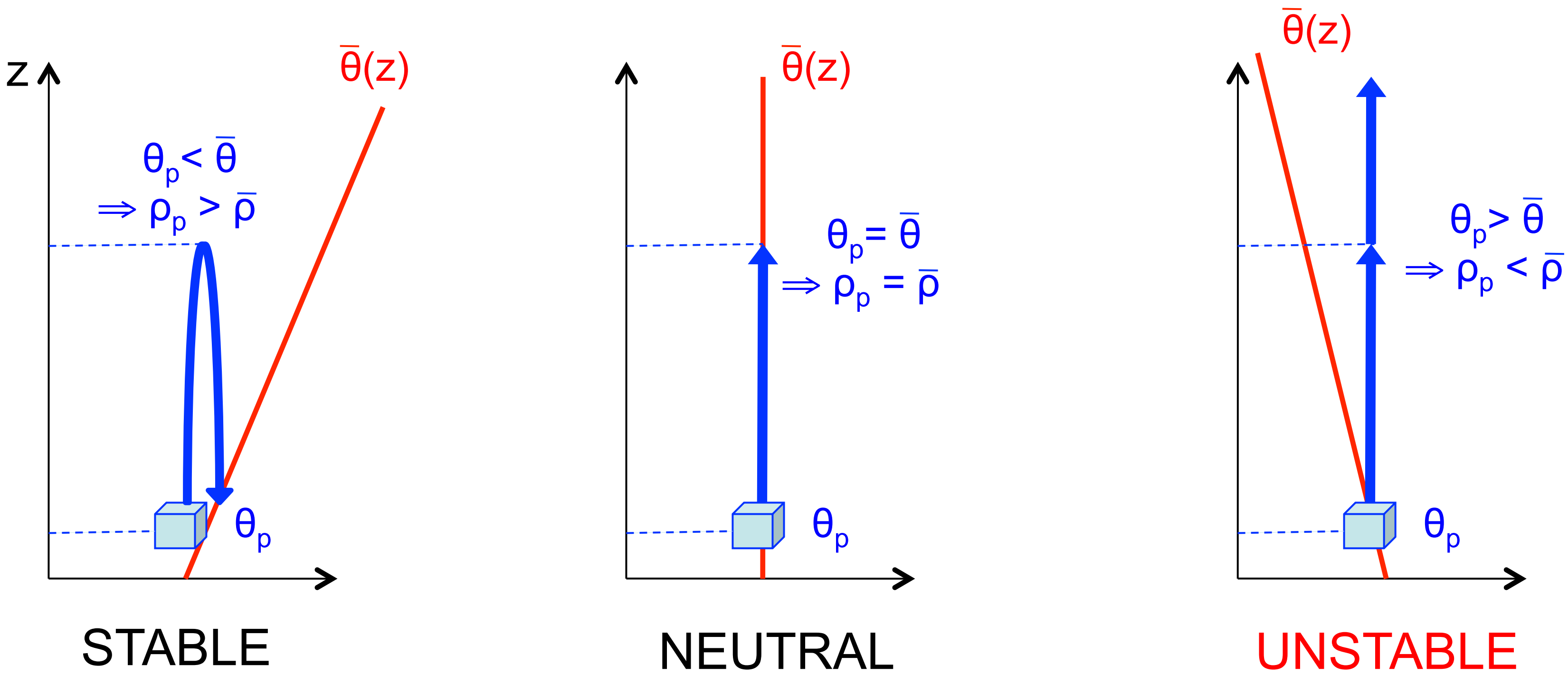
Hence $\theta = T\,(p_0 / p)^{R/cp}$ potential temperature is conserved under adiabatic displacement

(R=gaz constant of dry air; c_p=specific heat capacity at constant pressure; $R/c_p \sim 0.286$ for air)

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.



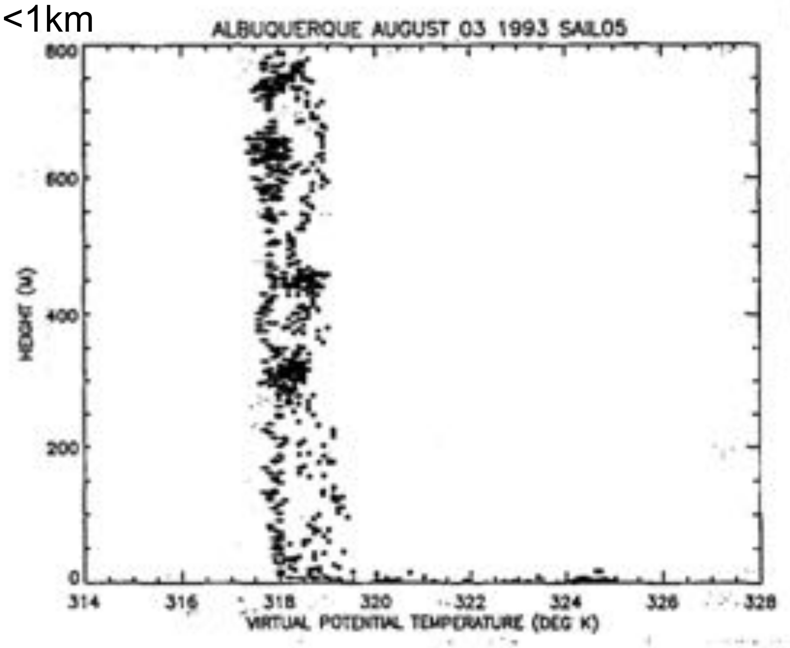
2. Atmospheric thermodynamics: instability

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]

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

Atmospheric thermodynamics: instability

inversion

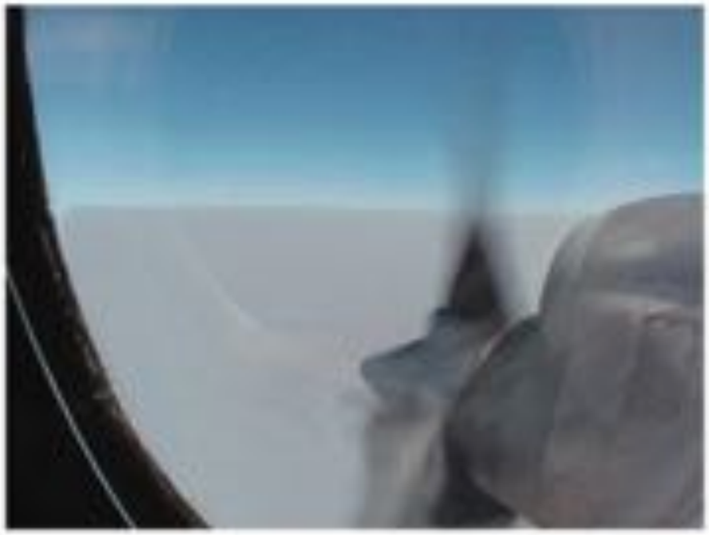


Fig. 3.15 Looking down onto widespread haze over southern Africa during the biomass-burning season. The haze is confined below a temperature inversion. Above the inversion, the air is remarkably clean and the visibility is excellent. (Photo: P. V. Hobbs.)

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

2. Atmospheric thermodynamics: instability

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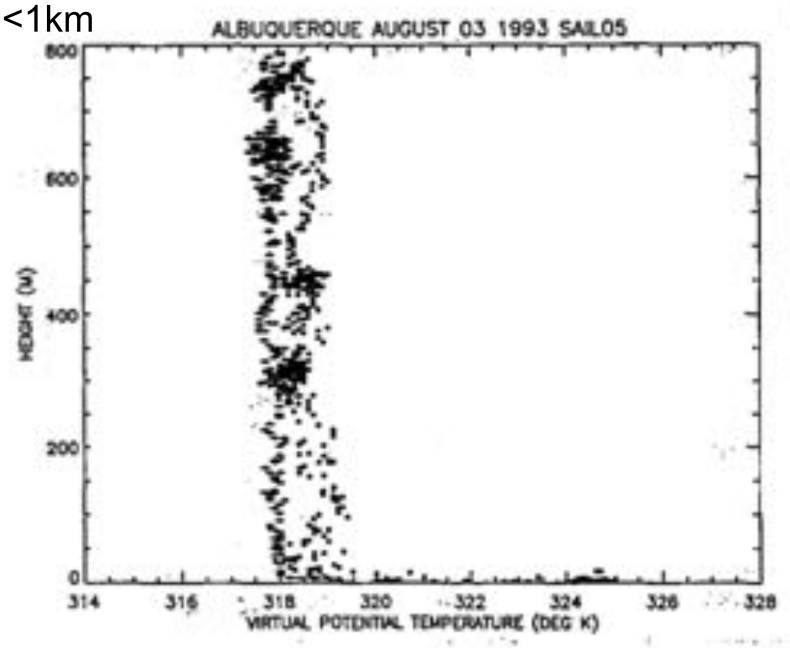


[Renno and Williams, 1995]

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**

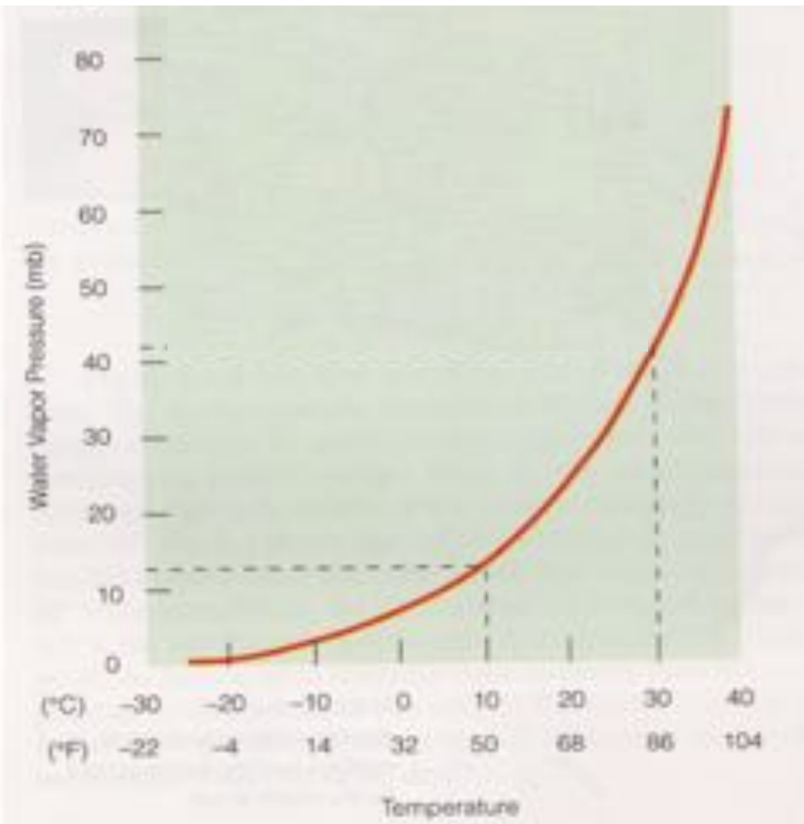
2. Atmospheric thermodynamics: instability

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

Warm air can hold more water vapor than cold air

2. Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

Exercise :

• Show that under adiabatic displacement, a parcel of moist air satisfies
$dT / T – R / c_p \, dp / p = - L_v / (c_p T) \, dq_v$.

• Deduce that equivalent potential temperature $\theta_e = T (p_0/p)^{R/c_p} e^{L_v q_v / (c_p T)}$ is approximately conserved.

Some helpful values and orders of magnitude :

- specific heat capacity at constant pressure c_p = 1005 J kg^{-1} K^{-1}
- gaz constant of dry air R = 287 J kg^{-1} K^{-1}
- latent heat of vaporization L_v=2.5 x 10^6 J kg^{-1}
- water vapor mixing ratio (kg of water vapor per kg of dry air) q_v = O(10^{-3})
- temperature T = O(3 x 10^2 K)

2. 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 conserved under adiabatic displacements :

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

d(internal energy) = Q (latent heat) – W (work done by parcel)

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

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

$$= - L_v / c_p\ d(q_s / T) + L_v\, q_s / (c_p\, T)\, d \ln T \approx - L_v / c_p\ d(q_s / T)$$

since $L_v\, q_s / (c_p\, T) \ll 1$.

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

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

Hence

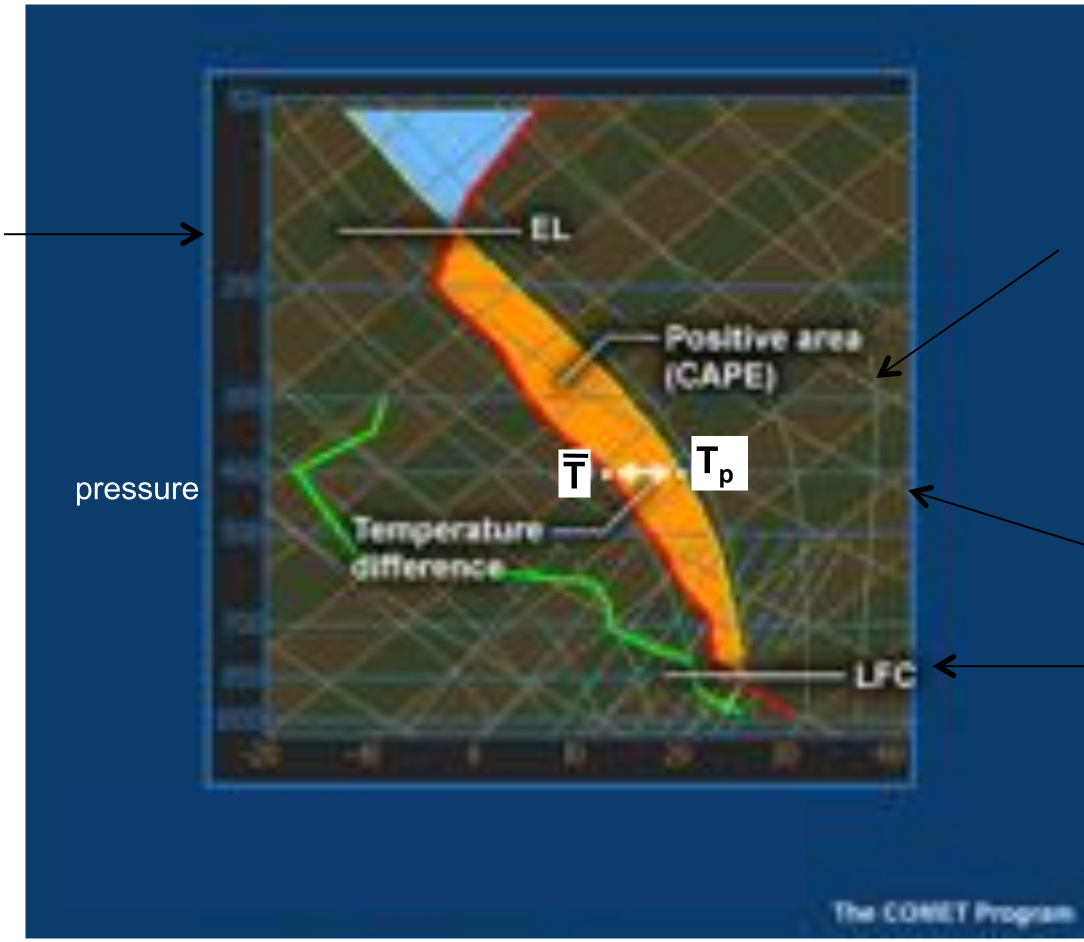
$\theta_e = T\,(p_0 / p)^{R/c_p}\, e^{L_v\, q_v / (c_p\, T)}$ equivalent potential temperature is approximately conserved

2. 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

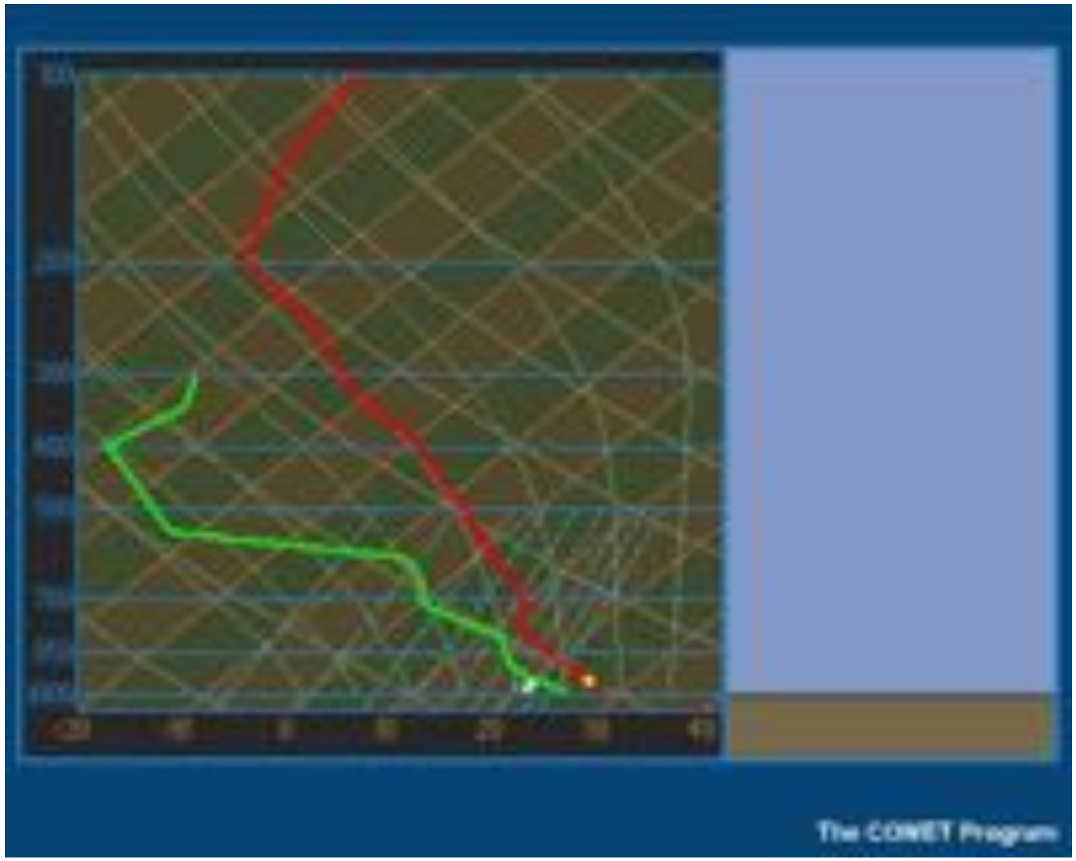
LFC level of free convection (= LCL lifted condensation level for simplicity)

CAPE: convective available potential energy

2. Atmospheric thermodynamics: instability

Parcel = yellow dot

EL equilibrium level



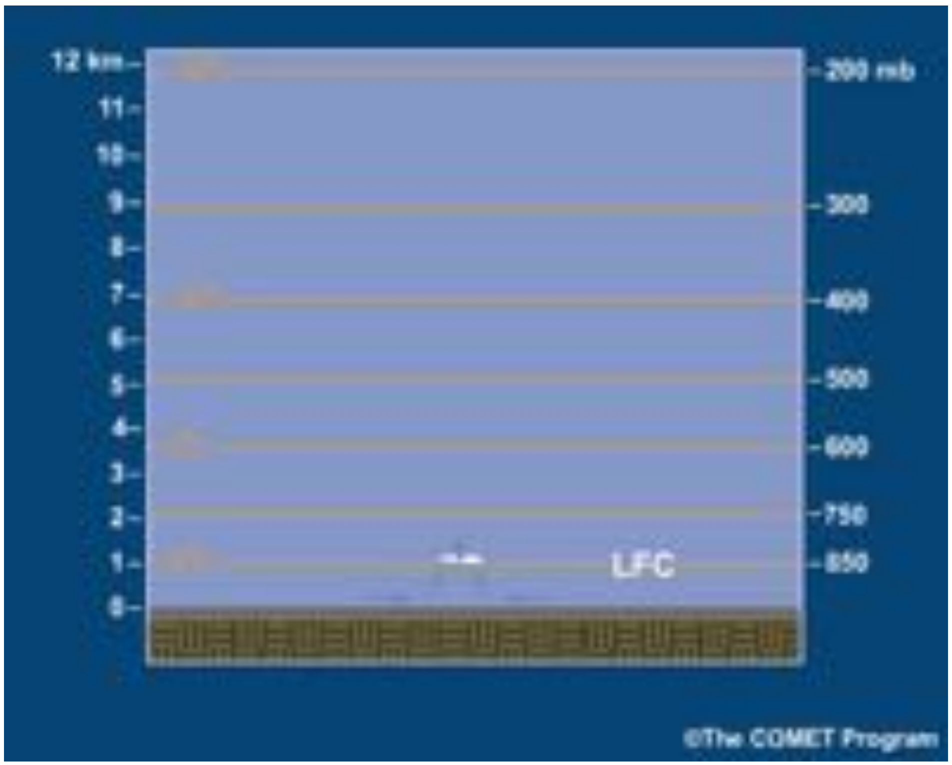
LFC level of free convection

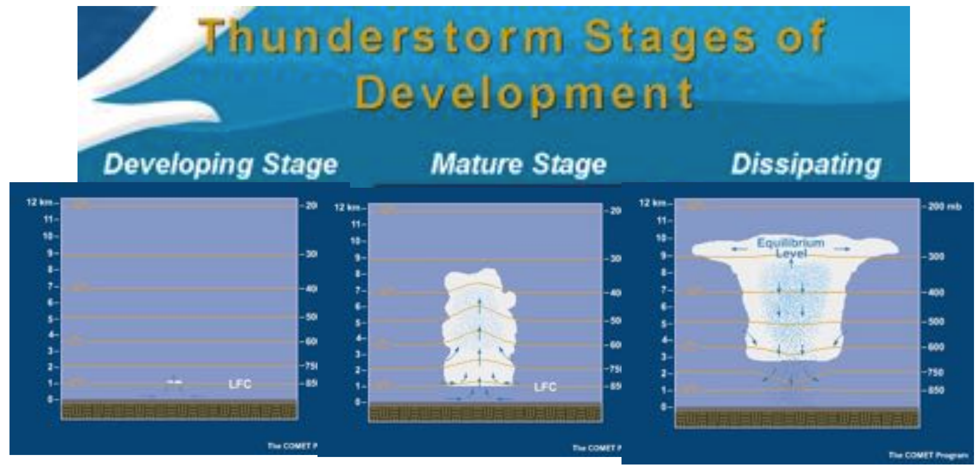
CAPE: convective available potential energy

2. 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.





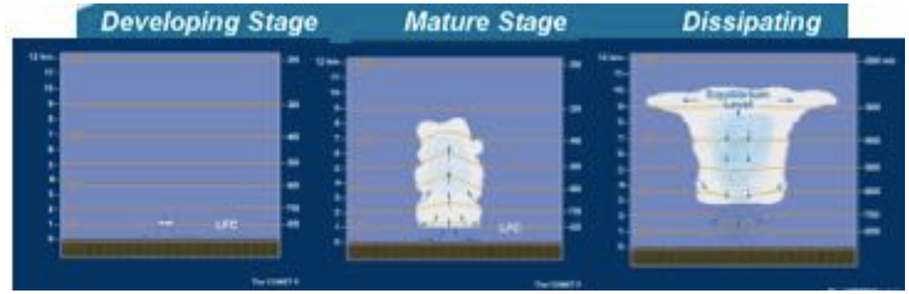
Evaporative driven cold pools

For more: see « atmospheric thermodynamics » by Bohren and Albrecht

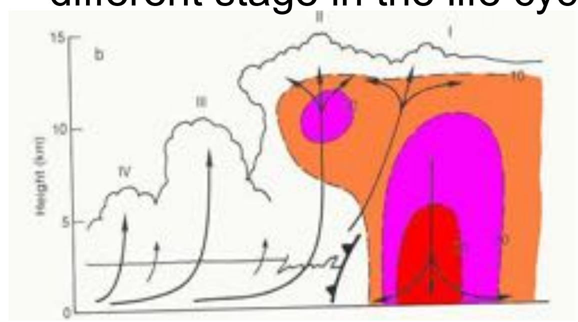
Atmospheric thermodynamics: instability

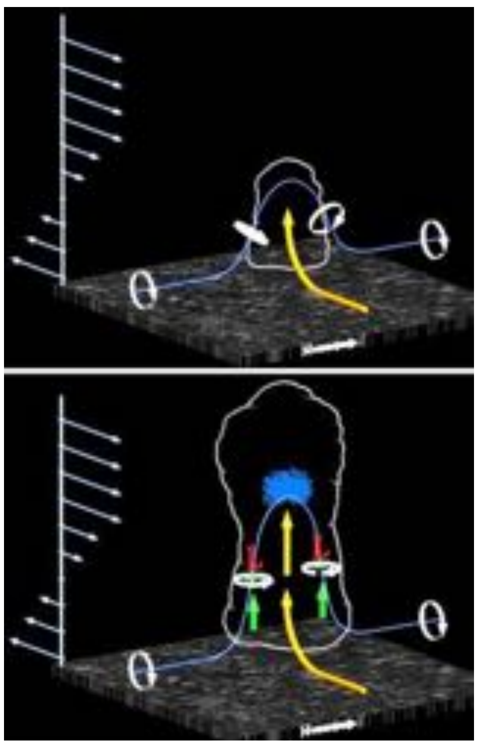
Note that thunderstorms can be :

single-cell (typically with weak wind shear)

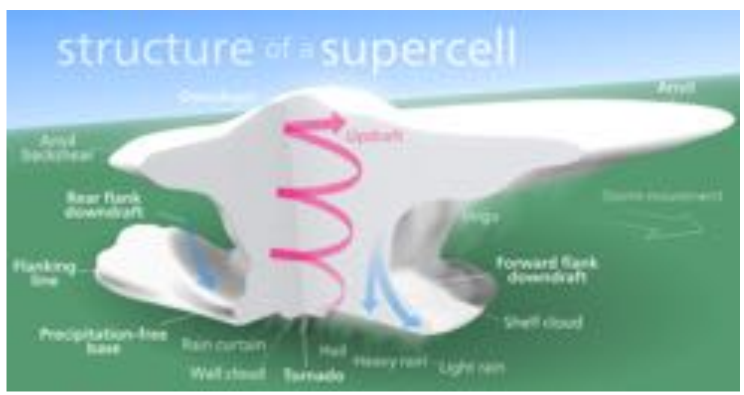


multi-cell (composed of multiple cells, each being at a different stage in the life cycle of a thunderstorm.





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



Typically occur in a significant vertically-sheared environment

[See Houze book: Cloud Dynamics; Muller – Cloud chapter, Les Houches Summer School Lecture Notes]