Clouds and turbulent moist convection

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Cloud formation

Courtesy : Octave Tessiot

Cloud formation

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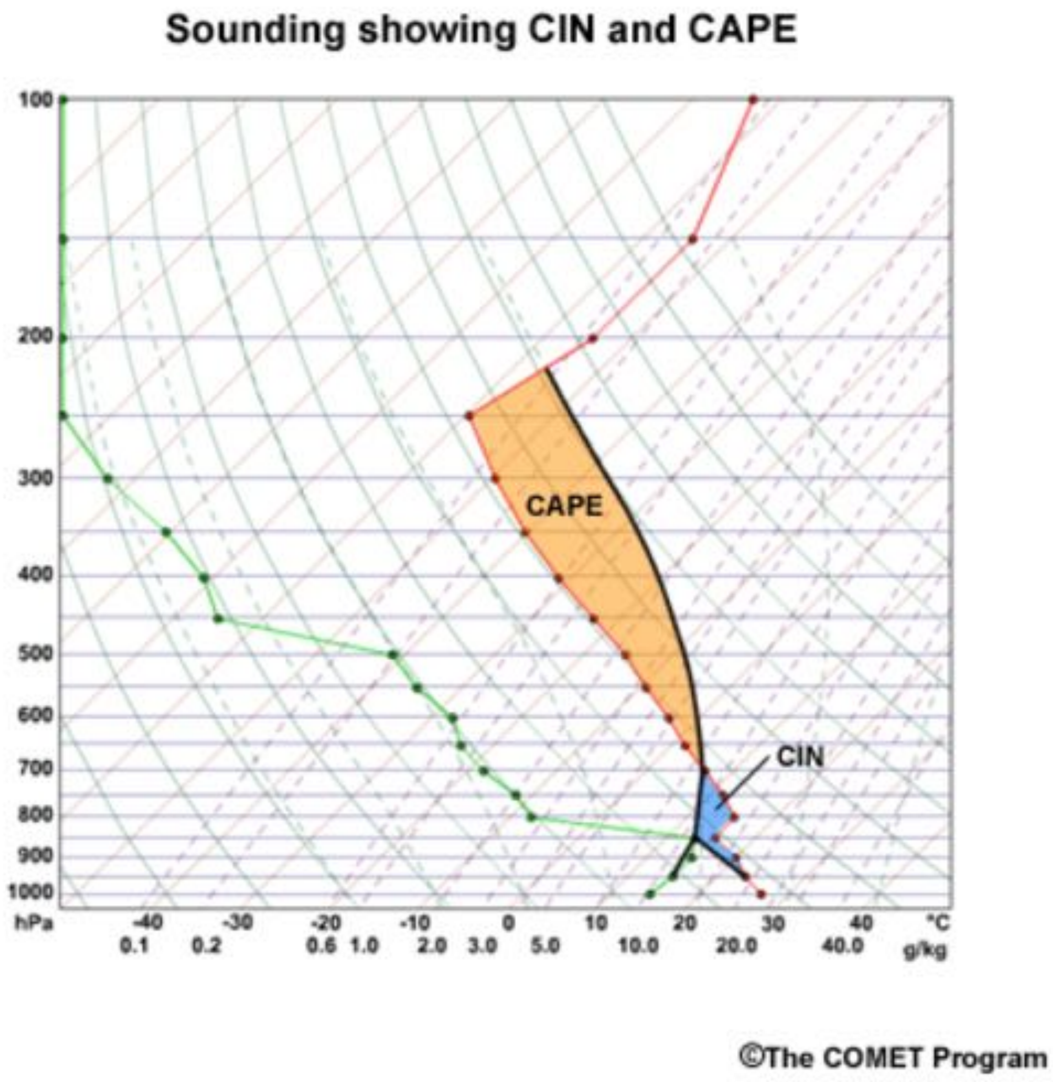
CIN: convective inhibition
CAPE: convective available potential energy

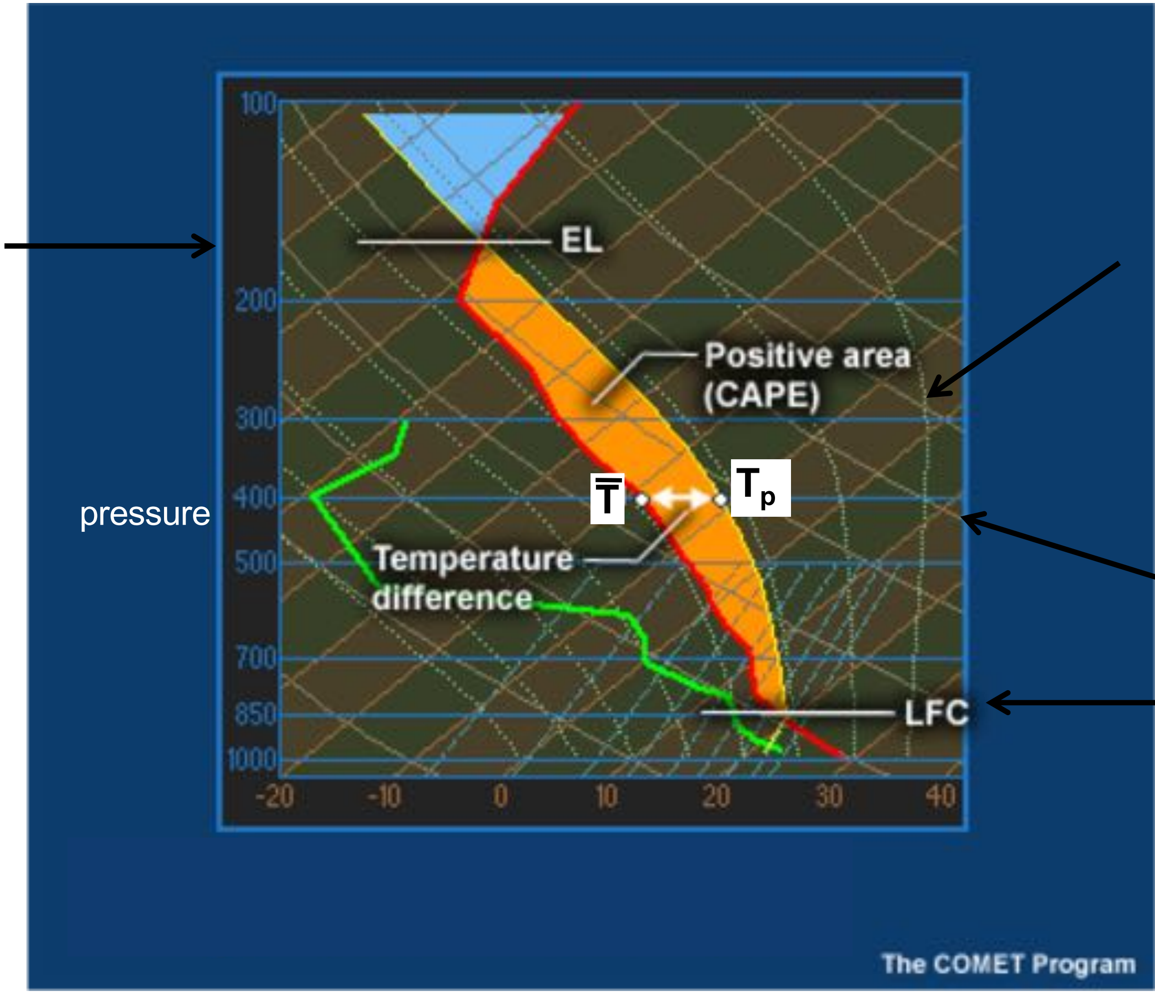


Atmospheric thermodynamics

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)

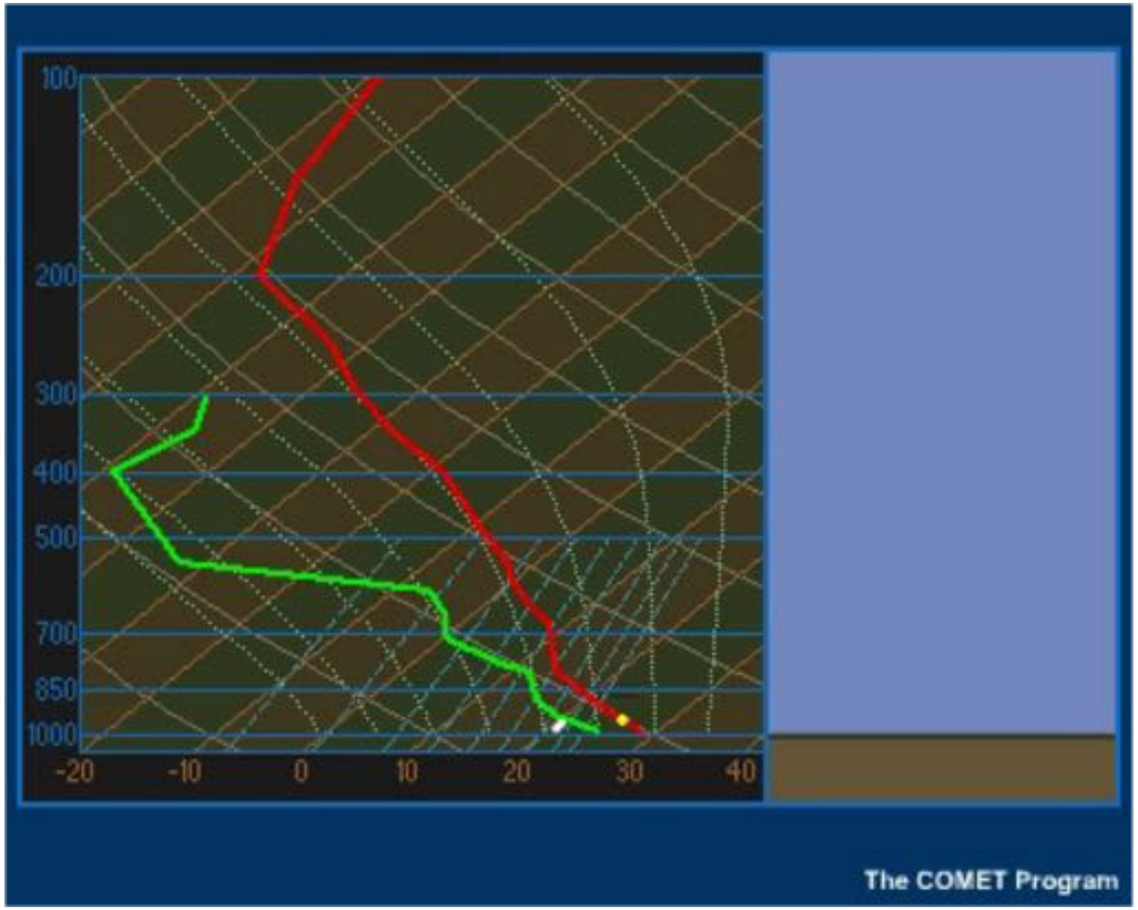
CAPE: convective available potential energy

Convective cloud: Single cell

Moist convection

Parcel = yellow dot

EL equilibrium level



LFC level of free convection

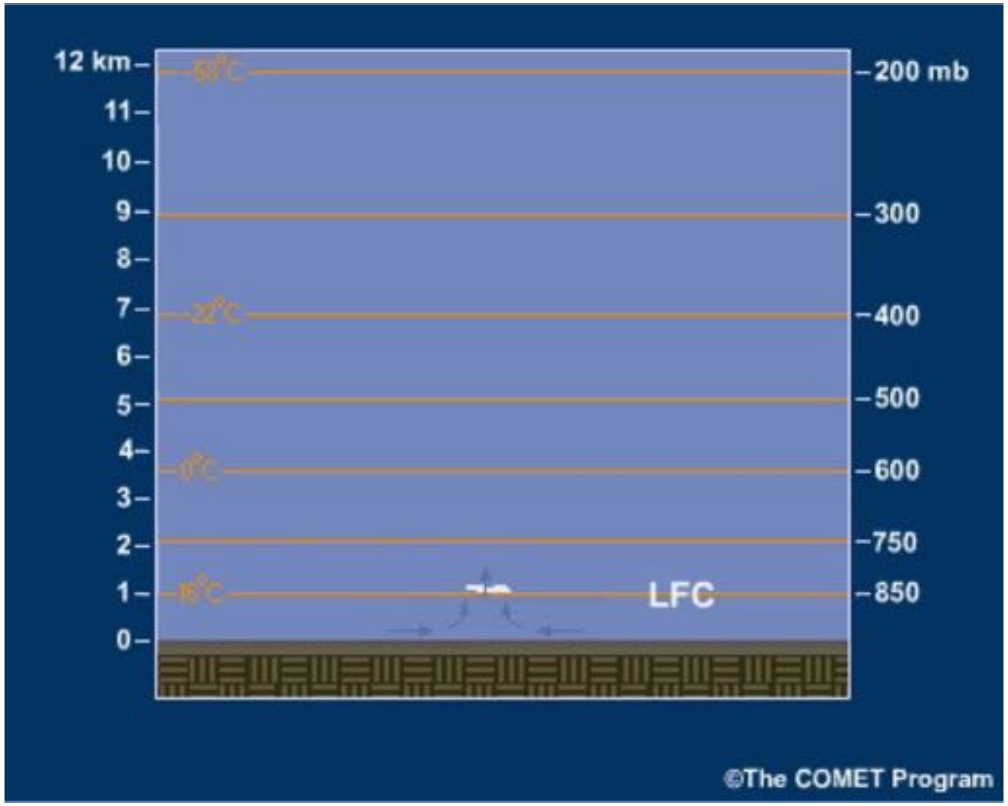
CAPE: convective available potential energy

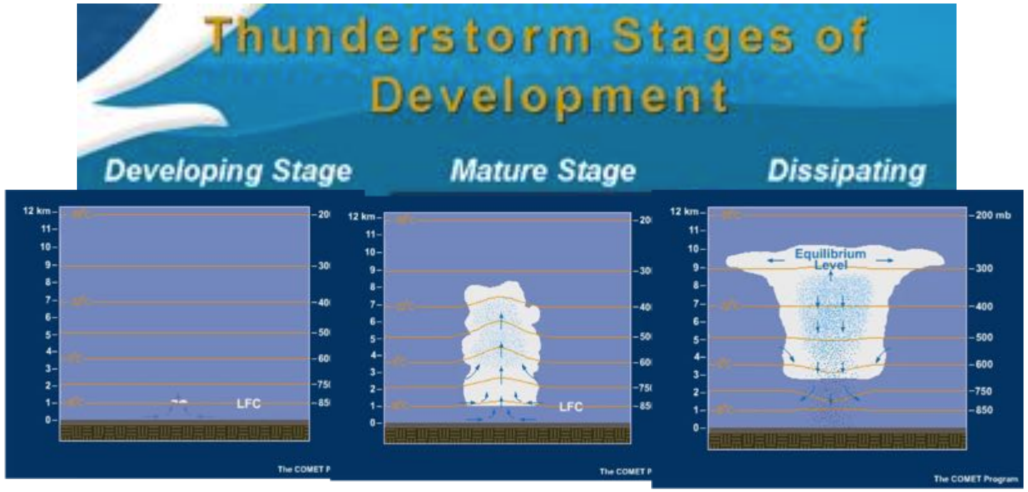
VI.3 Life cycle of a convective cloud in an atmosphere unstable to moist convection

Convective cloud: Single cell

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.



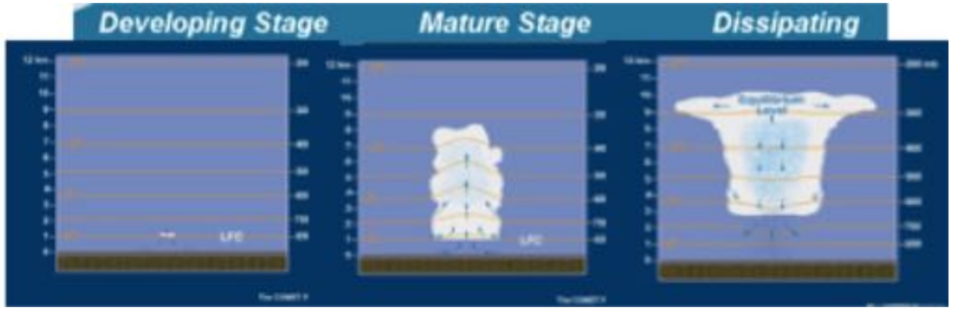


Evaporative driven cold pools

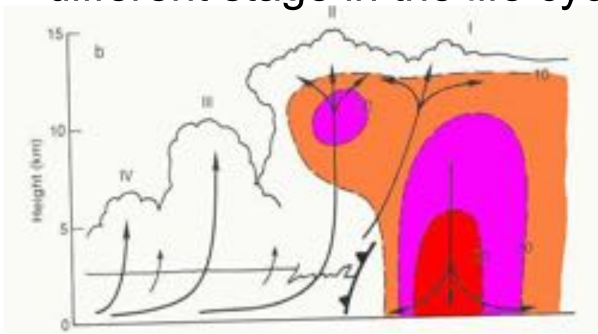
Convective cloud: Single / multi / super - cell

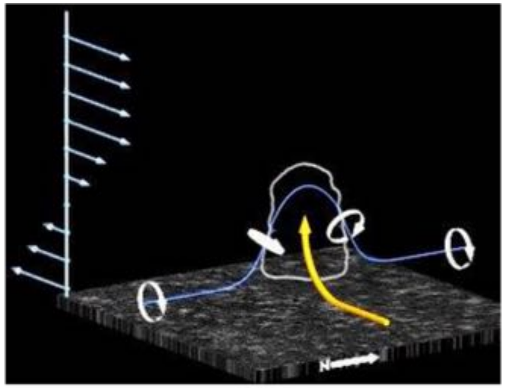
Note that thunderstorms can be :

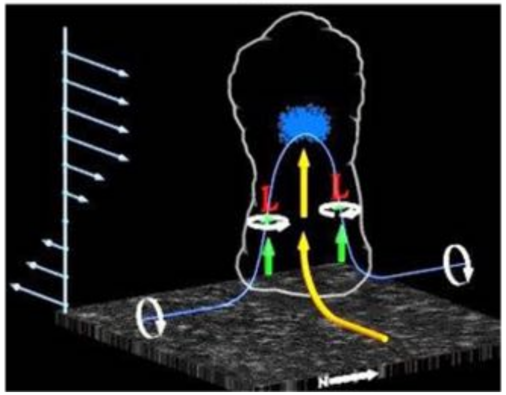
single-cell (typically with weak wind shear)



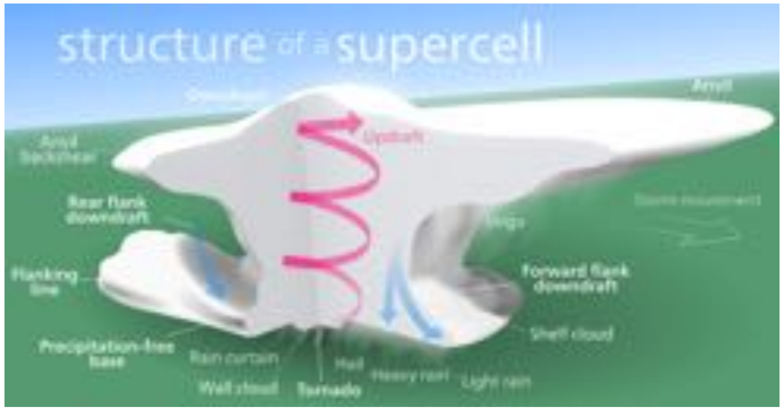
multi-cell (composed of multiple cells, each being at a different stage in the life cycle of a thunderstorm.







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]

Extreme convective clouds are important but rare

If enough atmospheric instability present, cumulus clouds are capable of producing serious storms. But this is RARE !

The typical situation is one with small CAPE

Why?

Extreme convective clouds are important but rare

If enough atmospheric instability present, cumulus clouds are capable of producing serious storms. But this is RARE !

The typical situation is one with small CAPE

Why? **Radiative Convective Equilibrium**

Radiative relaxation time scales ~ 40 days

Convective adjustment time scales: minutes (dry) to hours (moist)

In competition between radiation and convection, convection "wins" and the observed state is much closer to convective neutrality than to radiative equilibrium

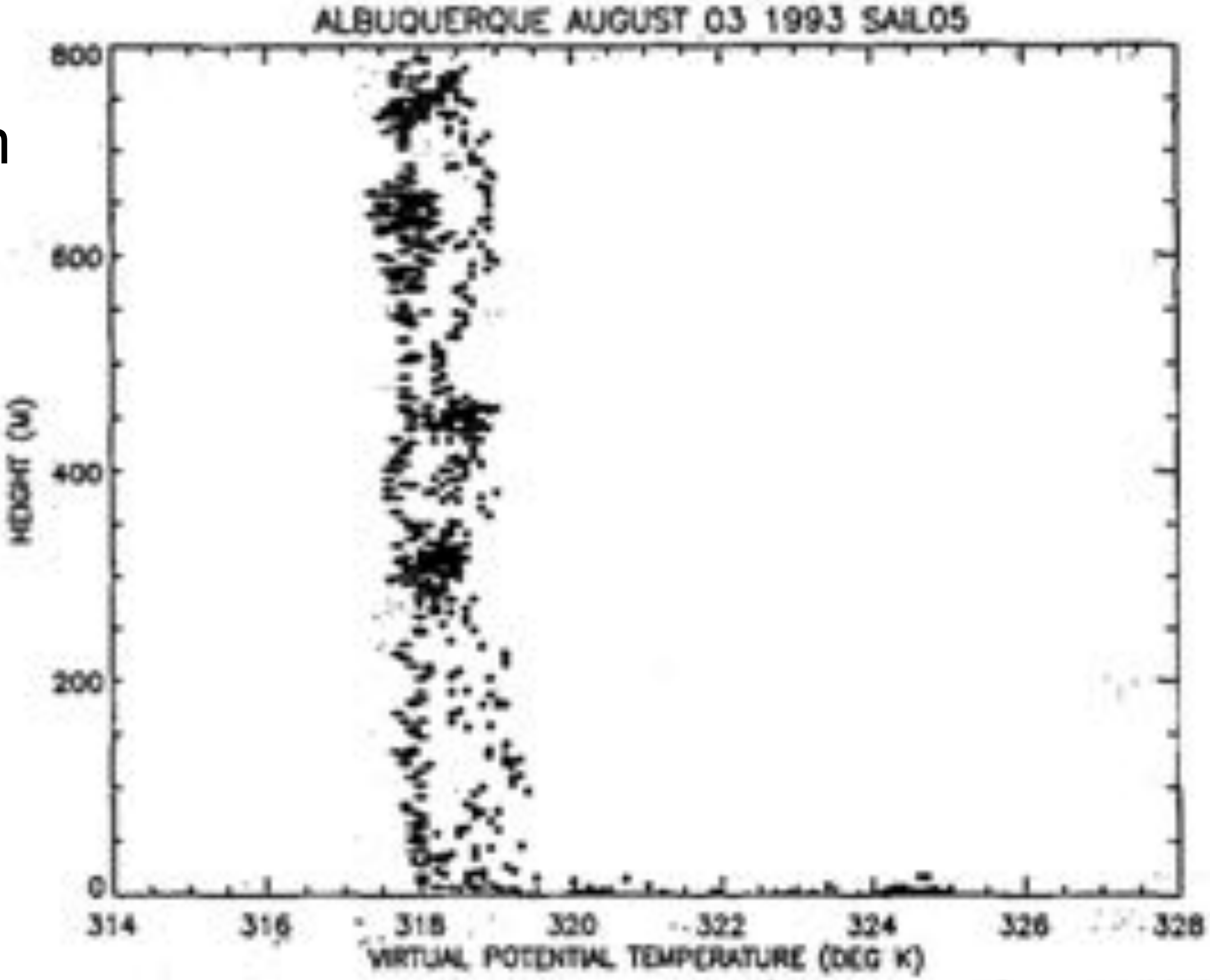
Vertical T profile neutral to dry convection:
θ constant with height

Vertical T profile neutral to moist convection:
θ_e constant with height

Extreme convective clouds are important but rare

Dry convective boundary layer over daytime desert *[Renno and Williams, 1995]*

800m

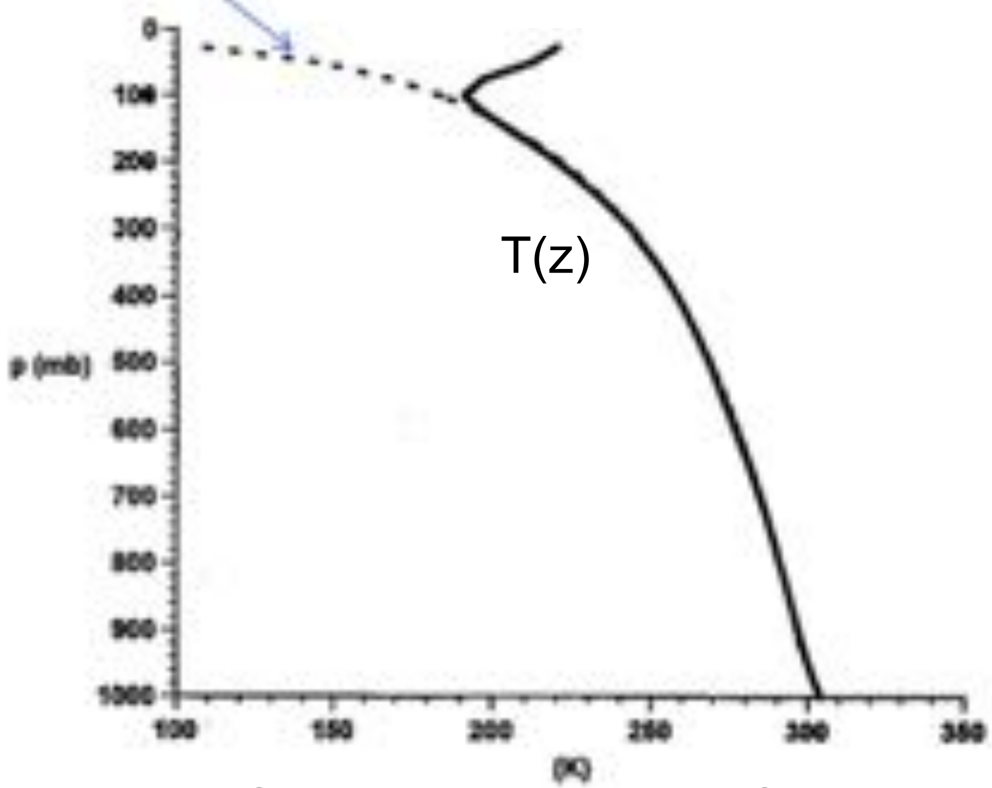


But above a thin boundary layer, most atmospheric convection involves phase change of water: Moist Convection

Extreme convective clouds are important but rare

Tropical sounding => moist adiabatic

Constant θ_e TYPICAL TROPICAL THERMODYNAMIC PROFILE (over oceans)



=> *Convection FAST, quickly consumes CAPE.*
Instability (largely CIN) controlled by large scale circulation

Food for thought :

What determines CAPE is still unknown and subject of research – Singh & O'Gorman 2013 GRL « influence of entrainment on the thermal stratification … »

Conclusion VI.3

Key points :

*in the presence of atmospheric instability (high CAPE), convective clouds can lead to serious storms.
These can be :
-single cell
-multi cell
-super cell

*these extreme unstable cases are important (severe weather), but are RARE
Mostly, atmospheric instability (CAPE) is small.

VII Phenomenology of the different cloud types

1) Cloud classification

2) Processes of cloud formation for each type of cloud

VII.1 Cloud classification

Cumulus: heap, pile

Stratus: flatten out, cover with a layer

Cirrus: lock of hair, tuft of horsehair

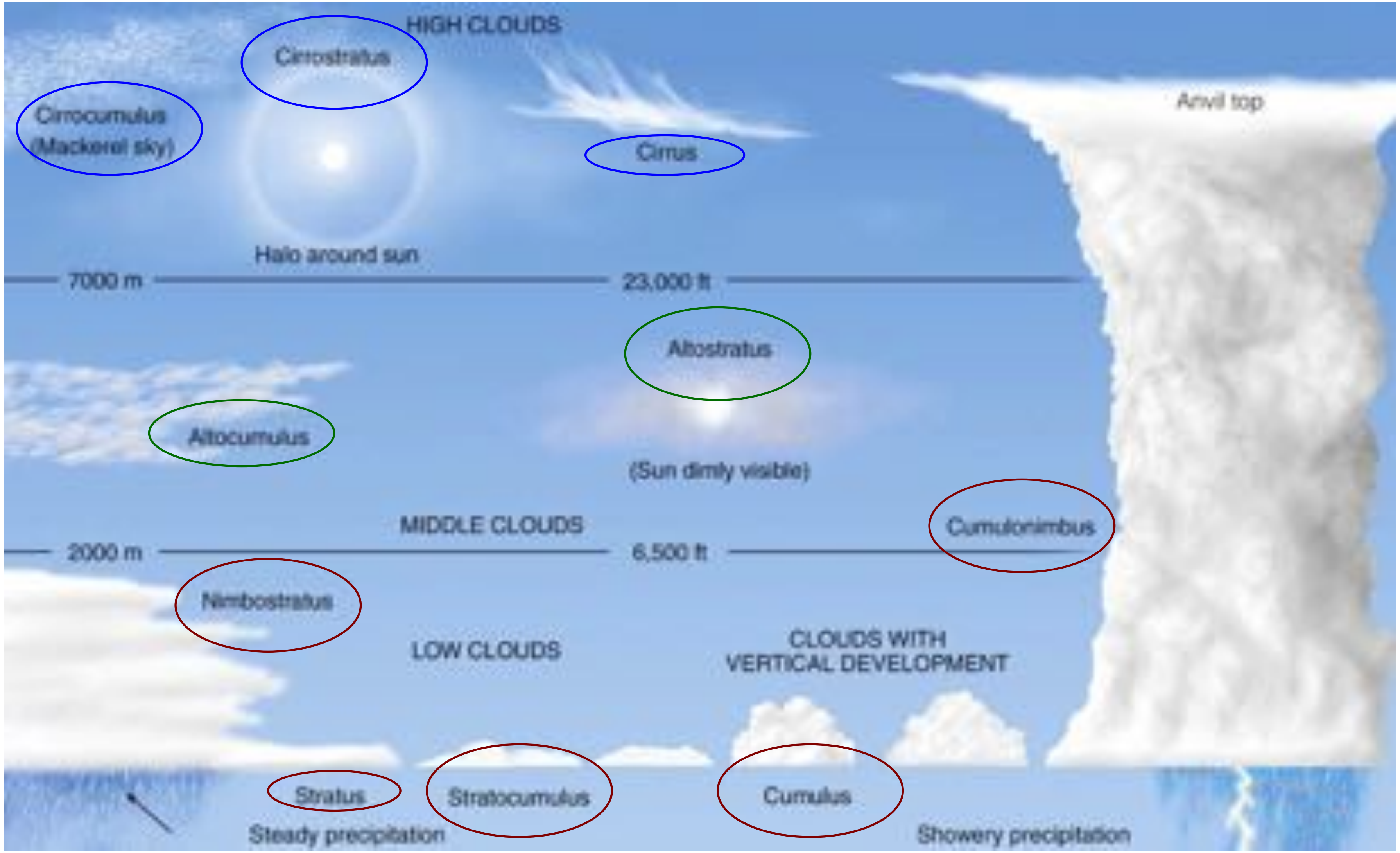
Nimbus: precipitating cloud

Altum: height

Combined to define 10 cloud types

VII.1 Cloud classification

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

High Clouds

Almost entirely ice crystals

Cirrus

Wispy, feathery

Cirrostratus Widespread, sun/moon halo

Cirrocumulus Layered clouds, cumuliform lumpiness

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

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

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)

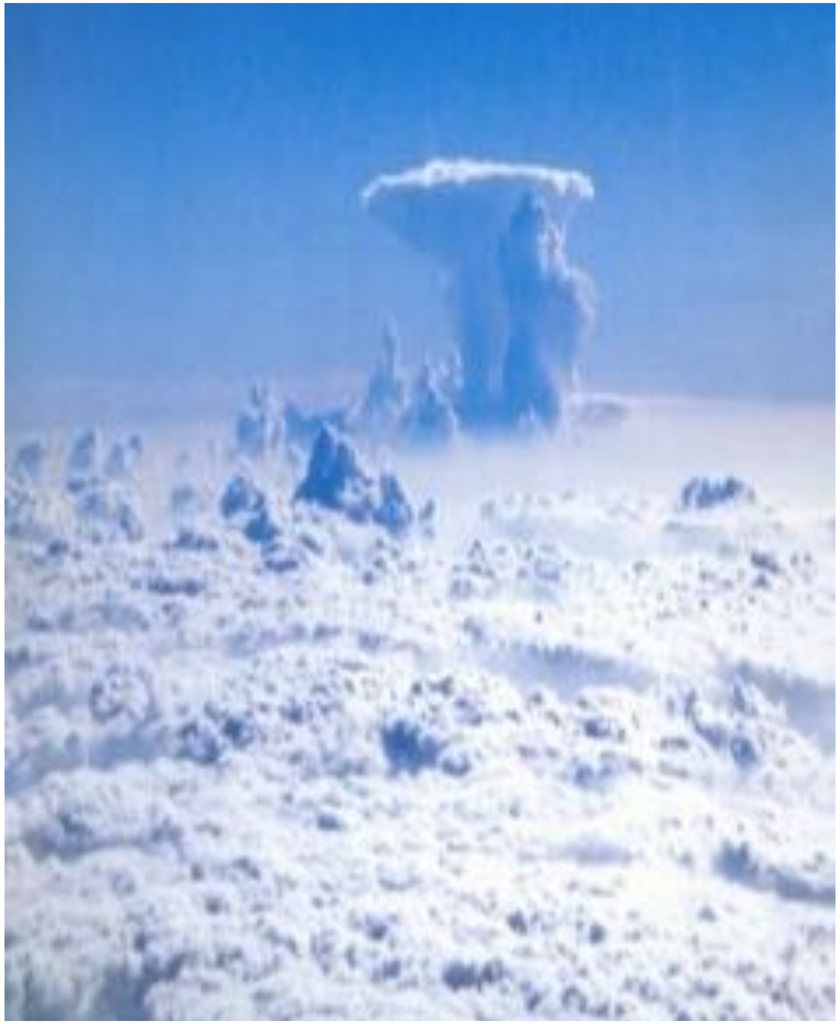
Scattered, with little vertical growth on an otherwise sunny day
Also called "fair weather cumulus"

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.



High Clouds

High Clouds

Cirrostratus

Cirrus

Cirrocumulus

Middle Clouds

Middle Clouds

Altocumulus

Altostratus

Low Clouds

Low Clouds

Stratocumulus

Cumulonimbus

Stratus

Cumulus

Nimbostratus

Other spectacular Clouds…

Mammatus clouds (typically below anvil clouds)

Shelf clouds (gust front)

Lenticular clouds (over orography)

VII Phenomenology of the different cloud types

1) Cloud classification

2) Processes of cloud formation for each type of cloud

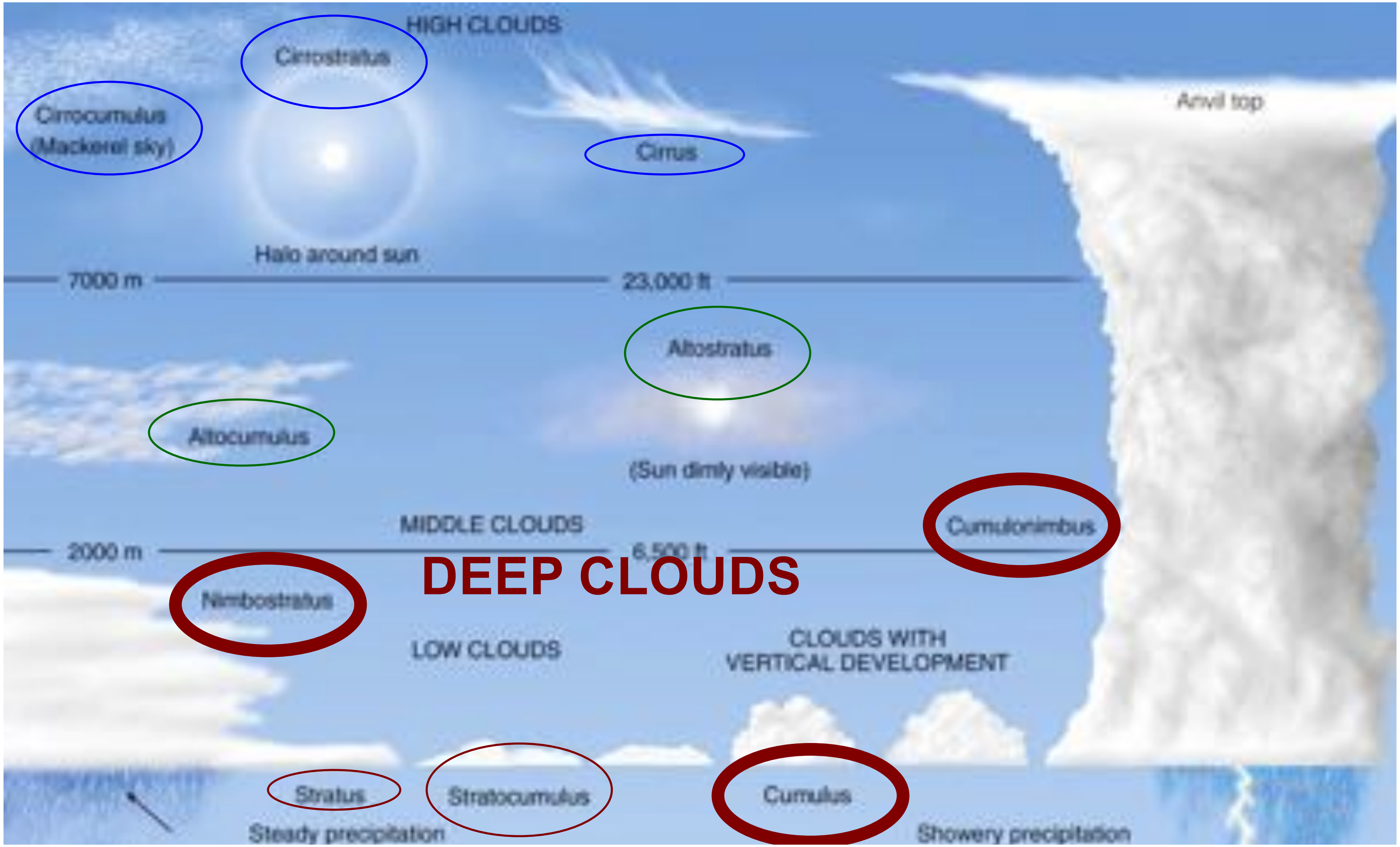
Processes leading to cloud formation

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.

Lifting mechanisms ?



Cloud formation: Deep clouds

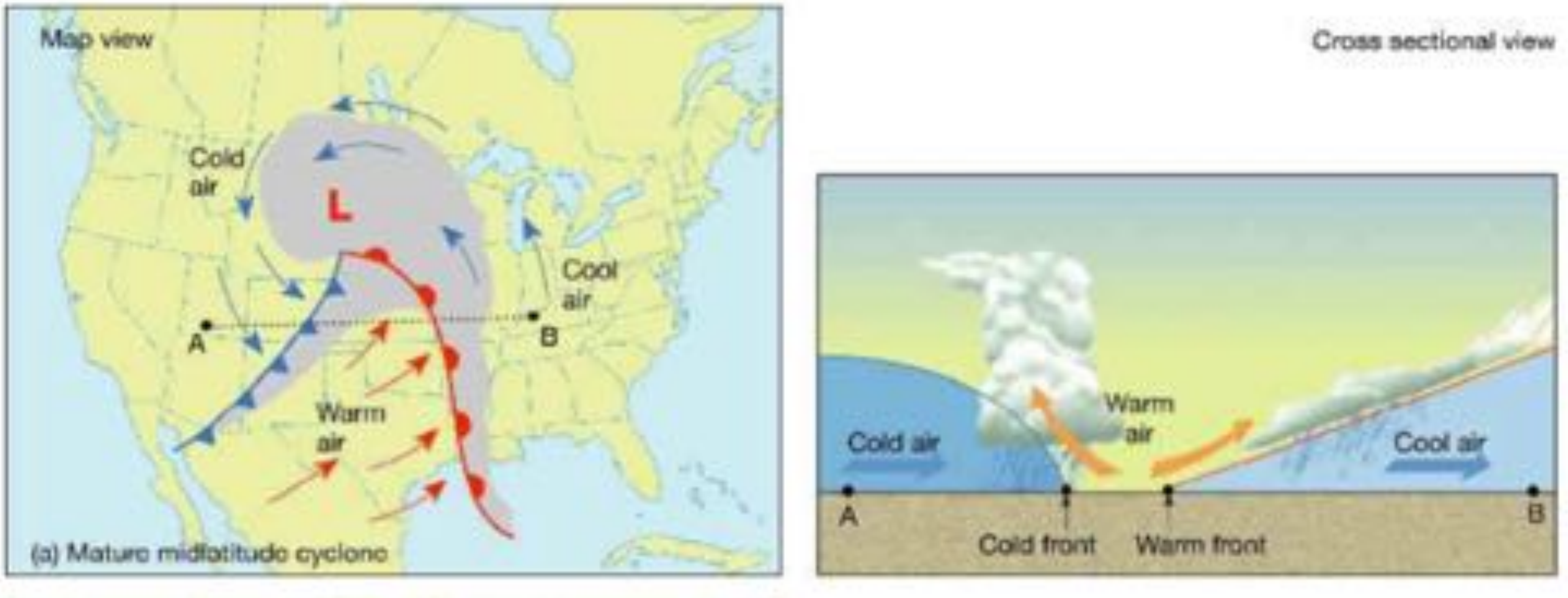
Lifting mechanisms :

1. Surface warming or moistening => adiabatic ascent
2. Orography
3. large-scale convergence
4. 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)

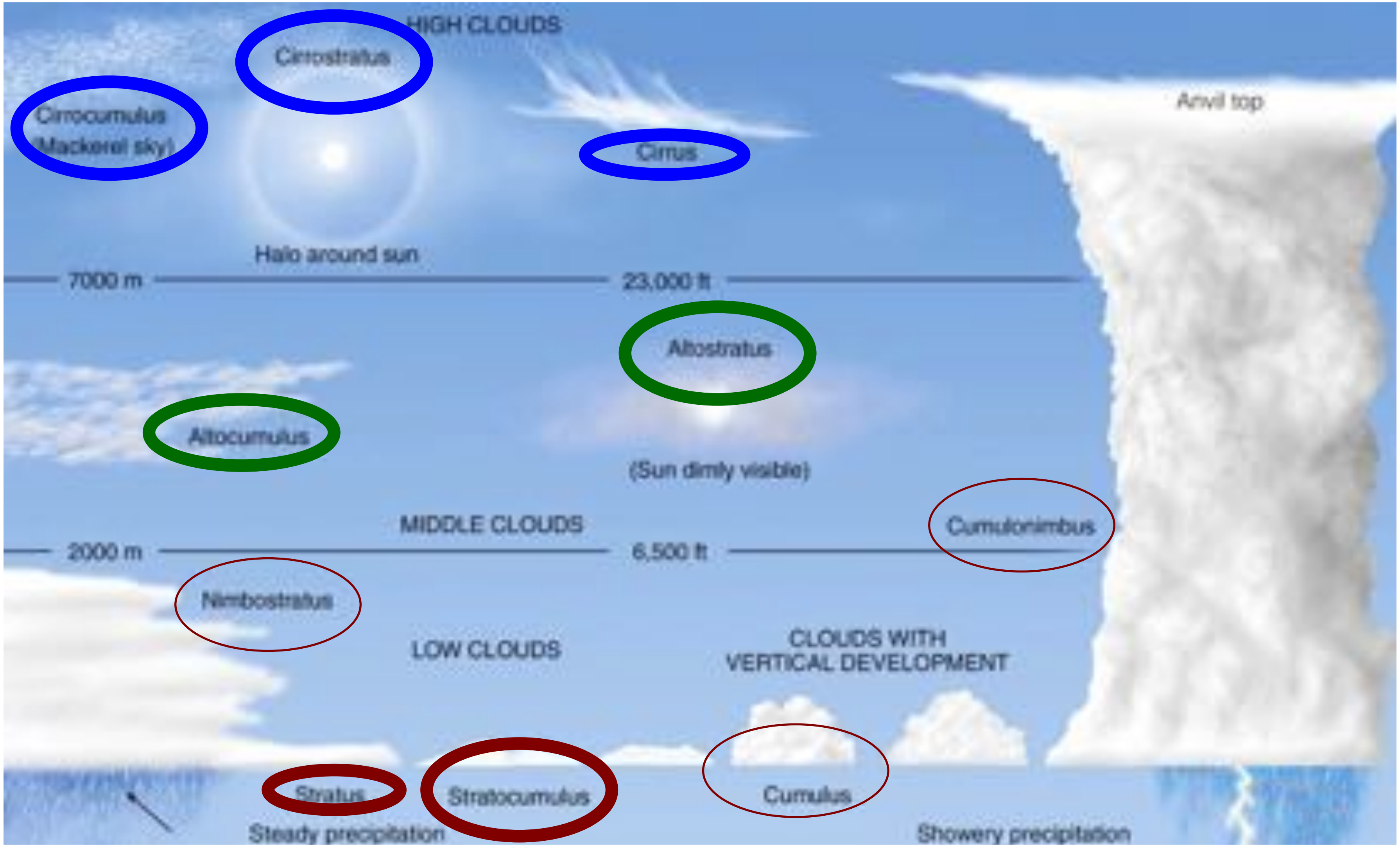


Note: Instability required for convection to grow deep. Else forced ascent with atmosphere stable yields shallow clouds (e.g. lenticular clouds associated with lee waves)

Lenticular clouds (over orography)

Processes leading to cloud formation

HOW ABOUT SHALLOW LAYER CLOUDS?



Cloud formation: Shallow layer clouds

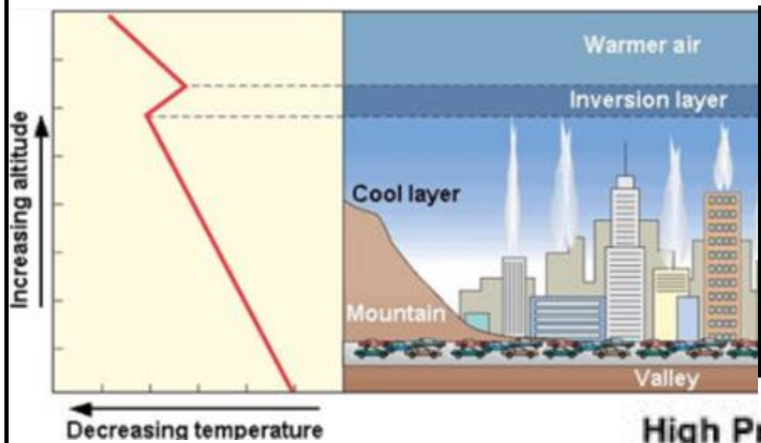
SHALLOW LAYER CLOUDS

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

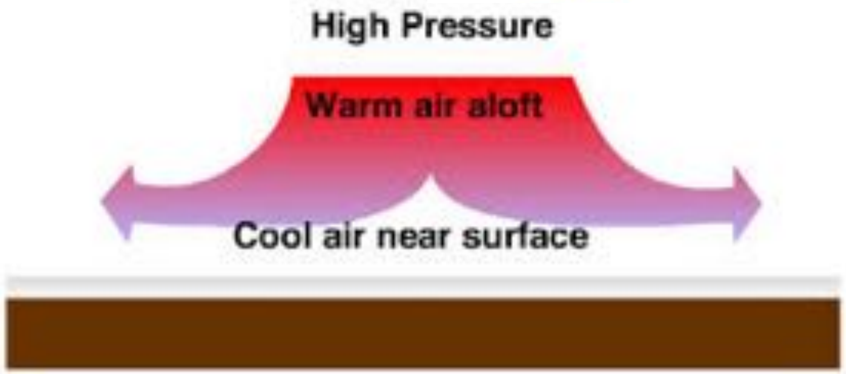
2. Stratus or stratocumulus or shallow cumulus: in BL heated from below and/or cooled from above (radiative cooling at the top of the cloud layer can also destabilize and lead to convection)
   => Unstable BL, with a stable atmosphere above.

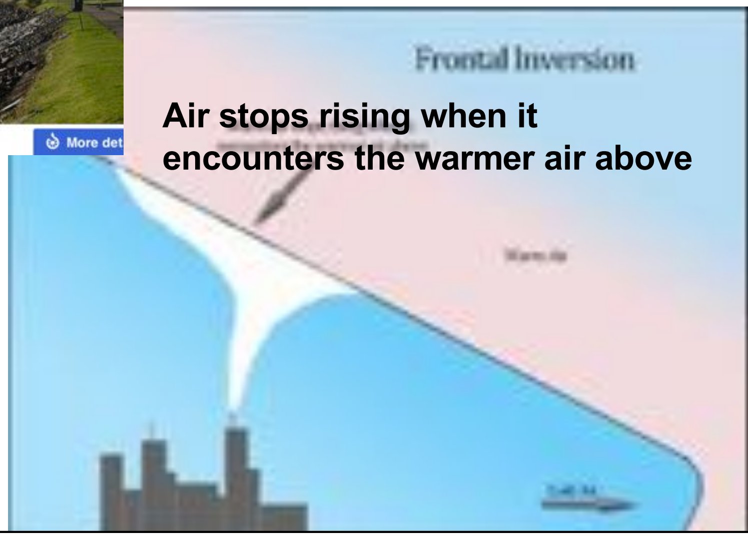
When do we have unstable layer capped by stable layer ? Warm air above cold air « T inversion »

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).





Cloud formation: Shallow layer clouds

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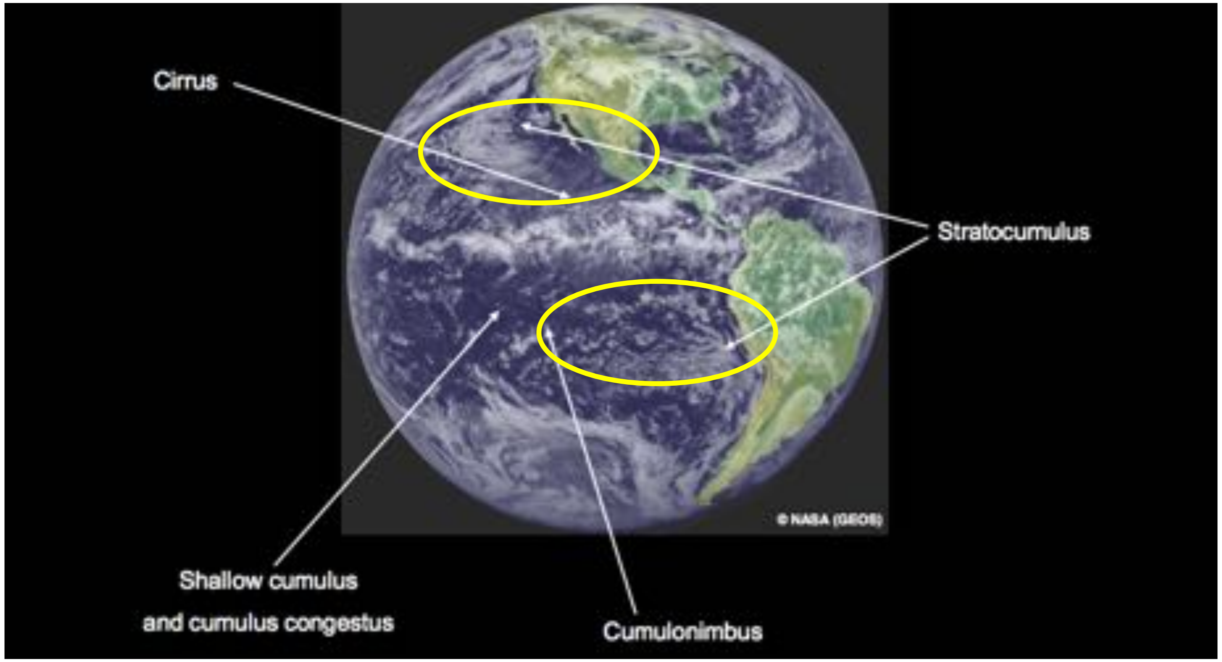
=> Unstable BL, with a stable atmosphere above.

e.g. - subtropical latitudes west of continents stratus and stratocumulus associated with anticyclones around high pressure and cold ocean Ts
- 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

SHALLOW LAYER CLOUDS

3. 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 occur away from generating source when unstable layer aloft or

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

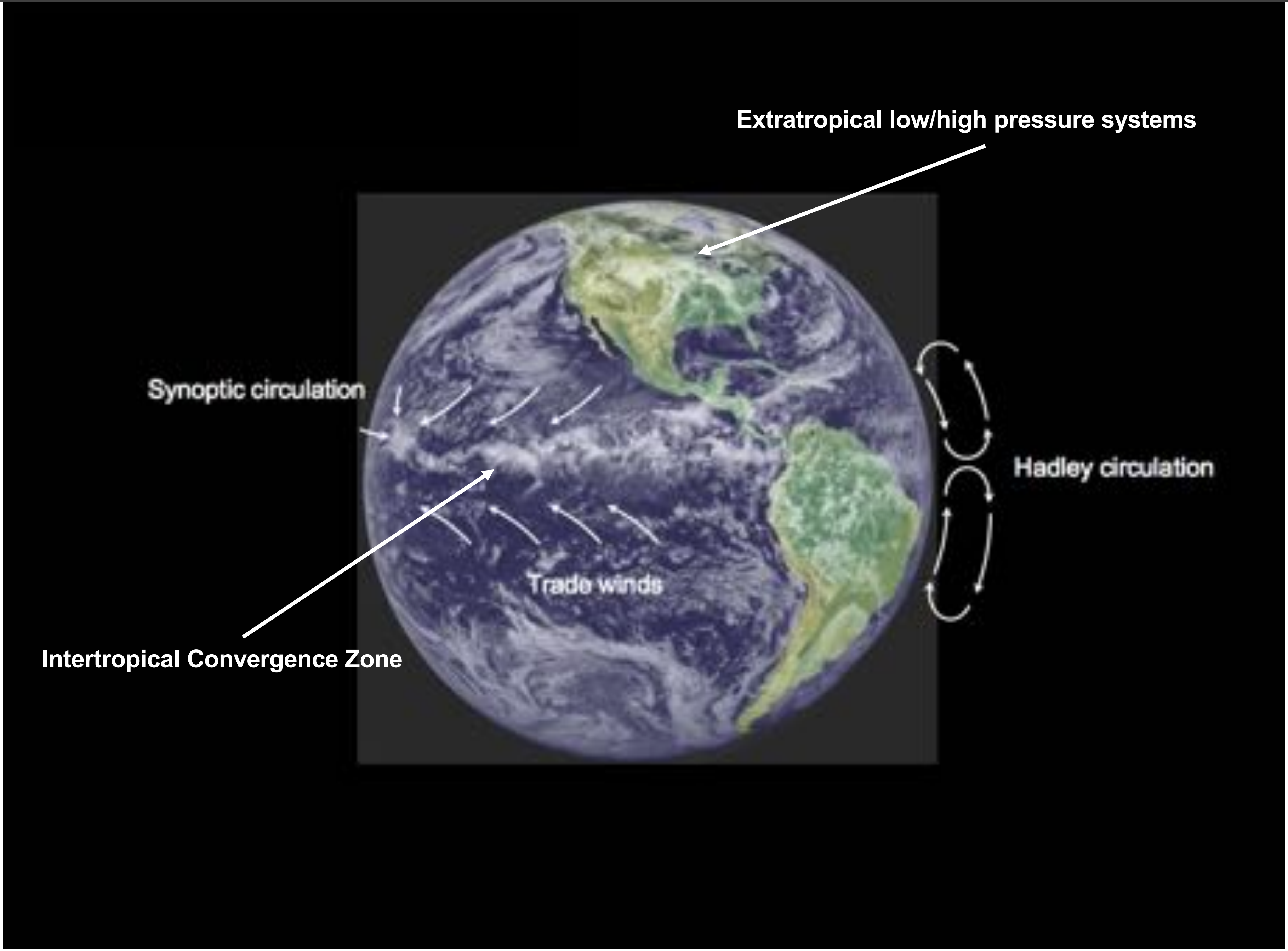
4. Altostratus & altocumulus: these can be

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

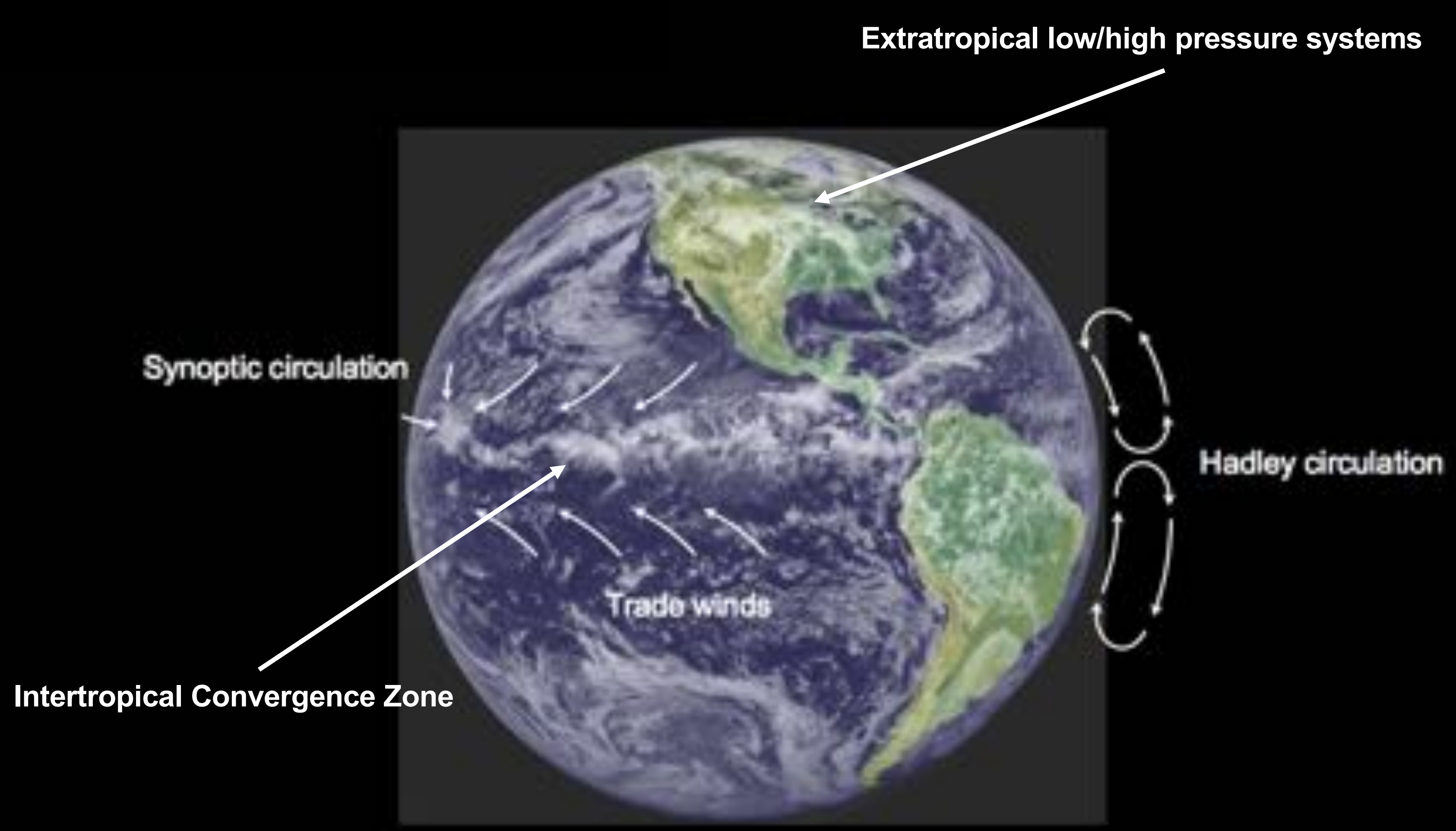
-Altocumulus also sometimes high-based convective clouds => same dynamics as deep convective clouds

-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)

VII.3 Coupling with circulation



VII.3 Coupling with circulation

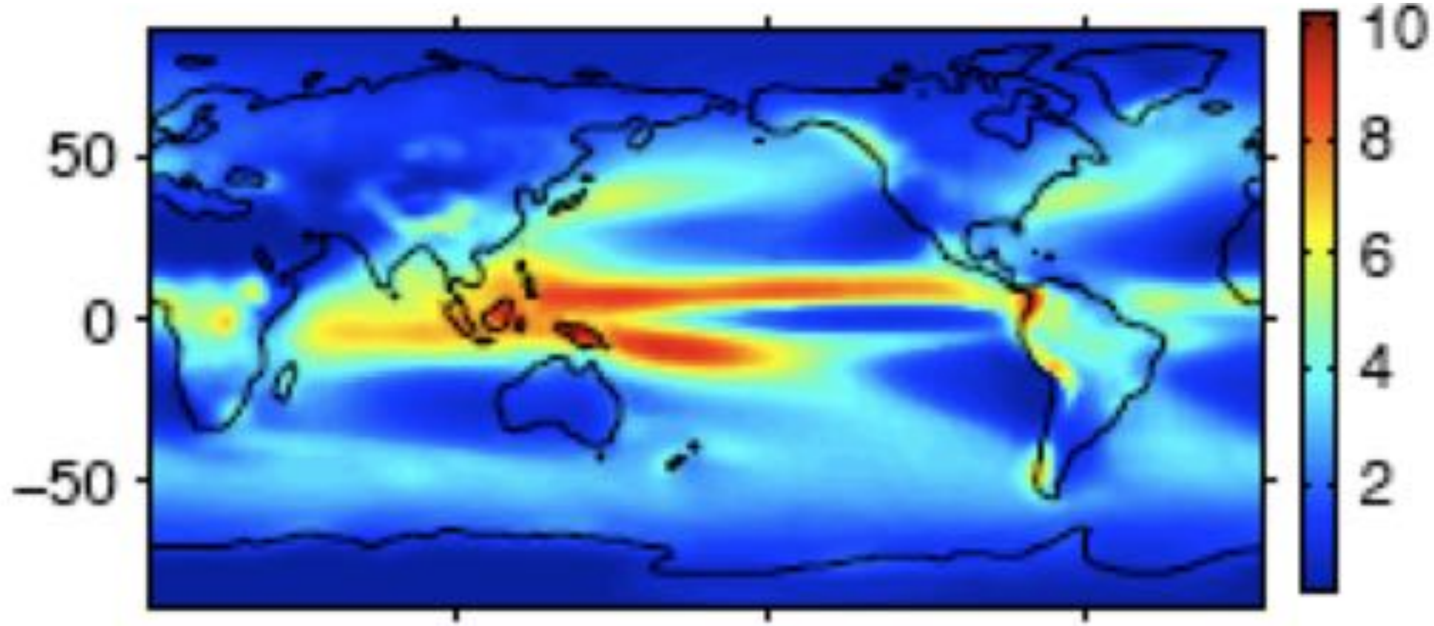


Planetary scale : ITCZ, Hadley, Walker (ENSO), monsoon

Synoptic scale : Equatorial waves, Extratropical frontal systems

Clouds and Circulation: ITCZ

P (mm/day)
1981-1999 climatology, multimodel mean

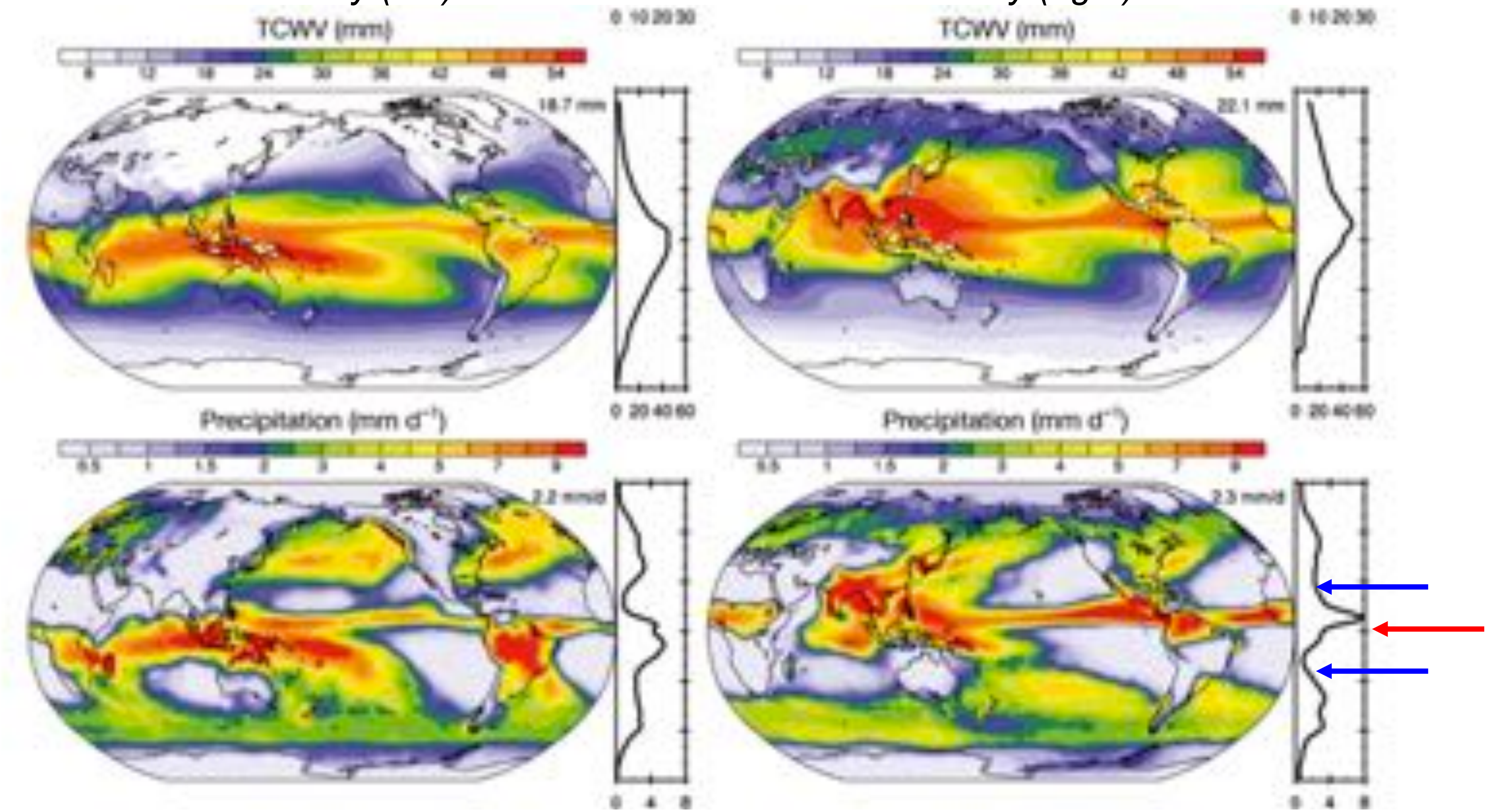


[Muller & O'Gorman, 2011]

Clouds and Circulation: ITCZ

Total column water vapor (TCWV) and precipitation (mm/day)

January (left) *July (right)*

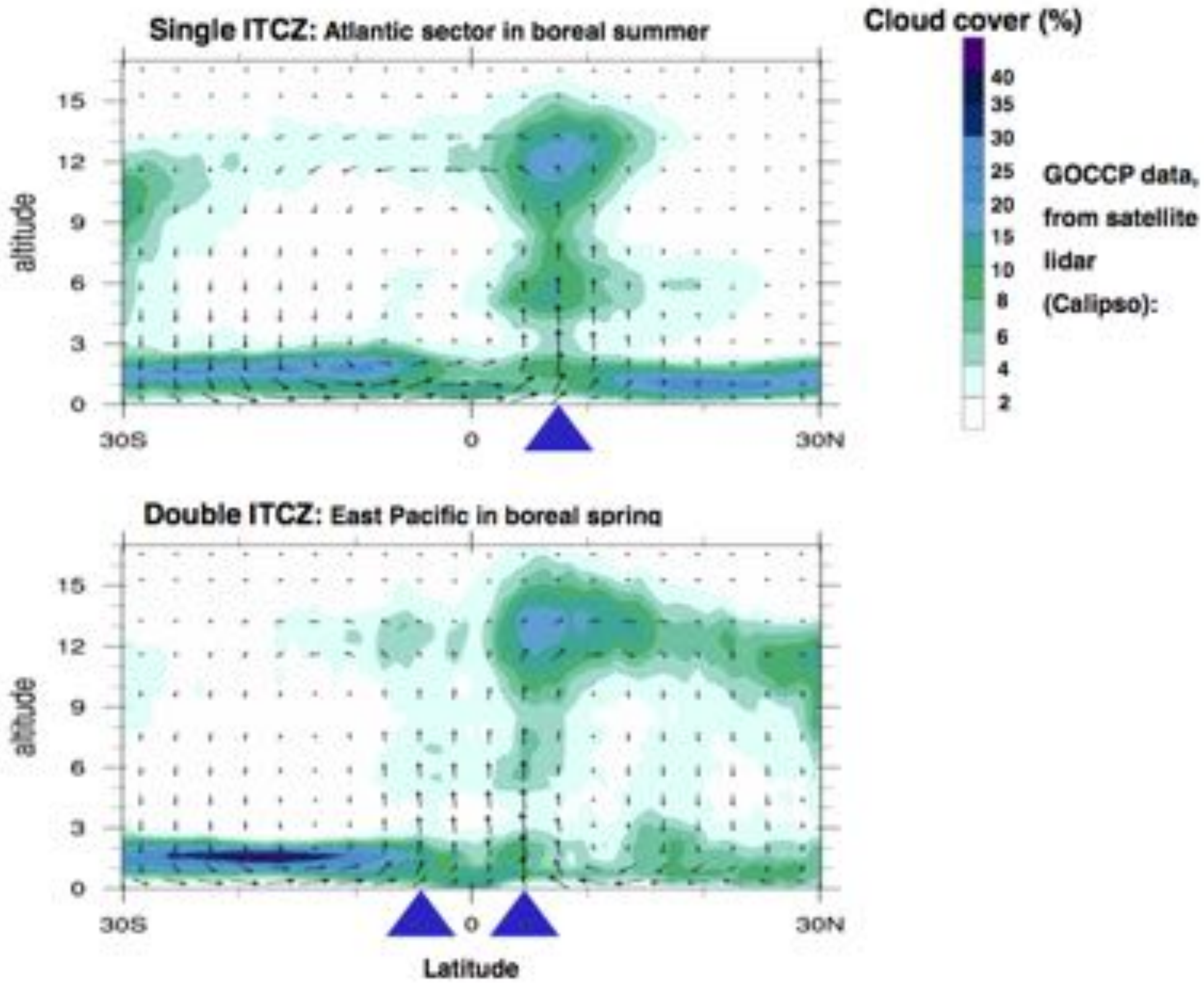


Small in Subtropics (descent)

Large in Tropics (ascent)

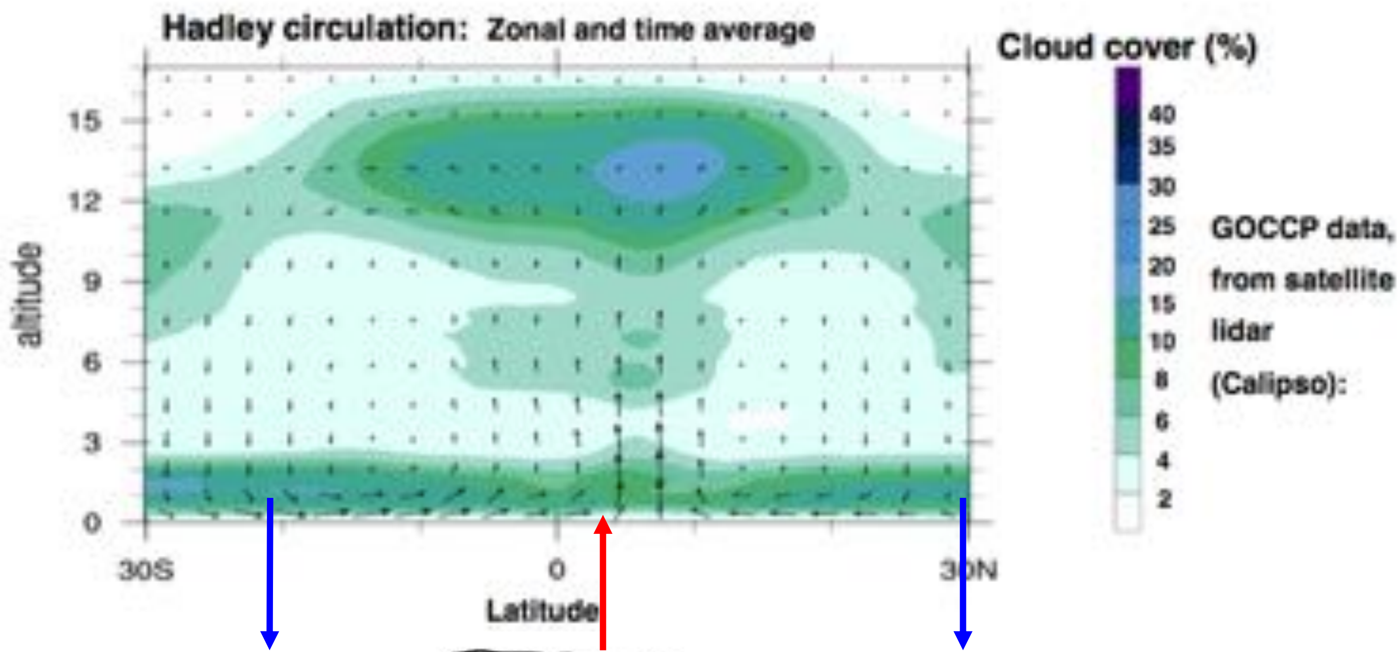
[Trenberth 2011]

Clouds and Circulation: ITCZ

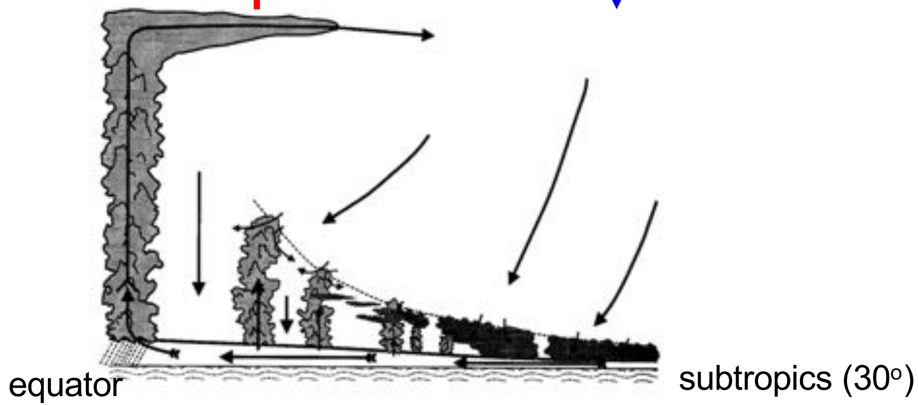


Courtesy Gilles Bellon

Clouds and Circulation: Hadley cell



Cloud types:

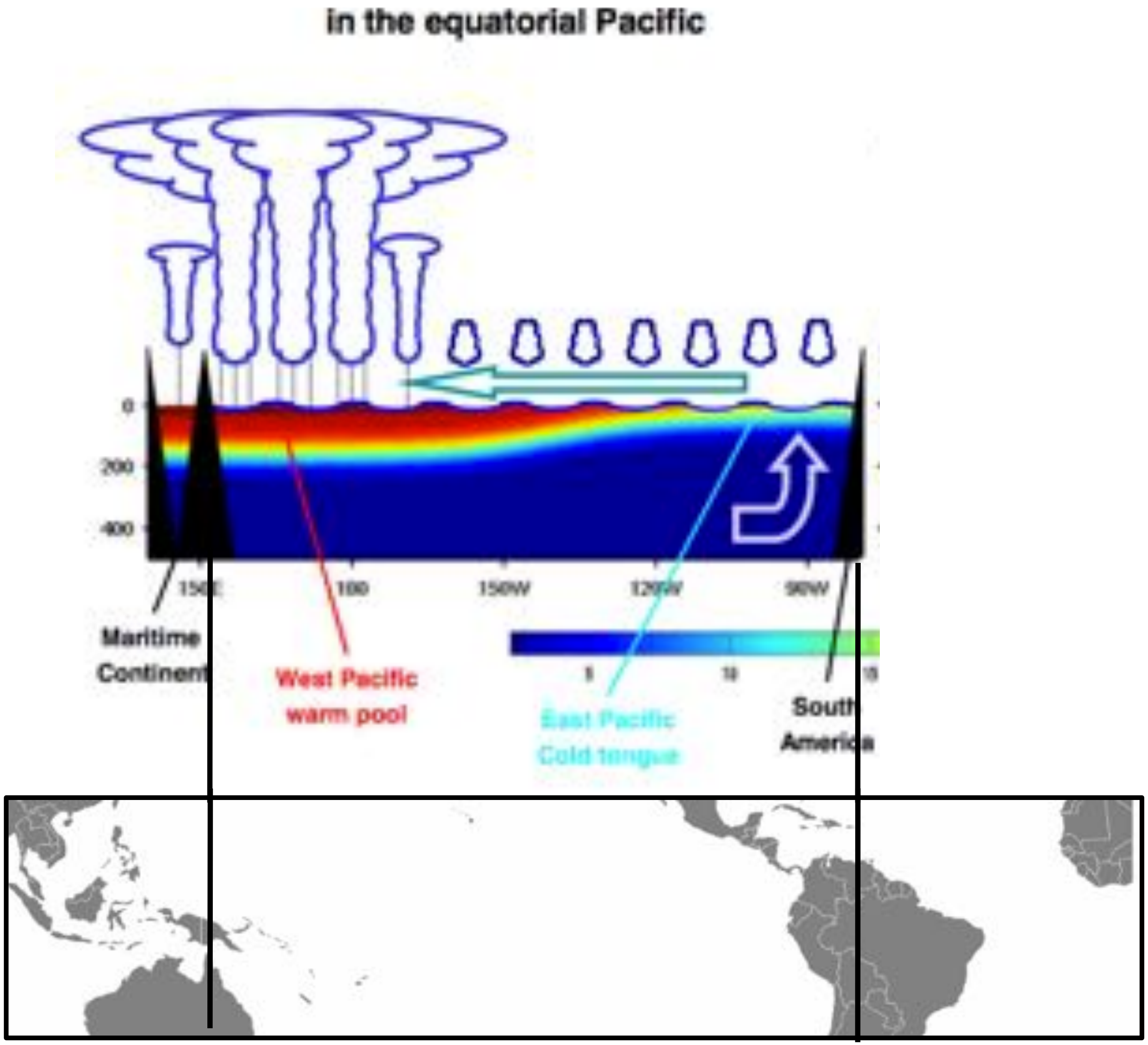


Deep cumulonimbus

Fair weather cumulus

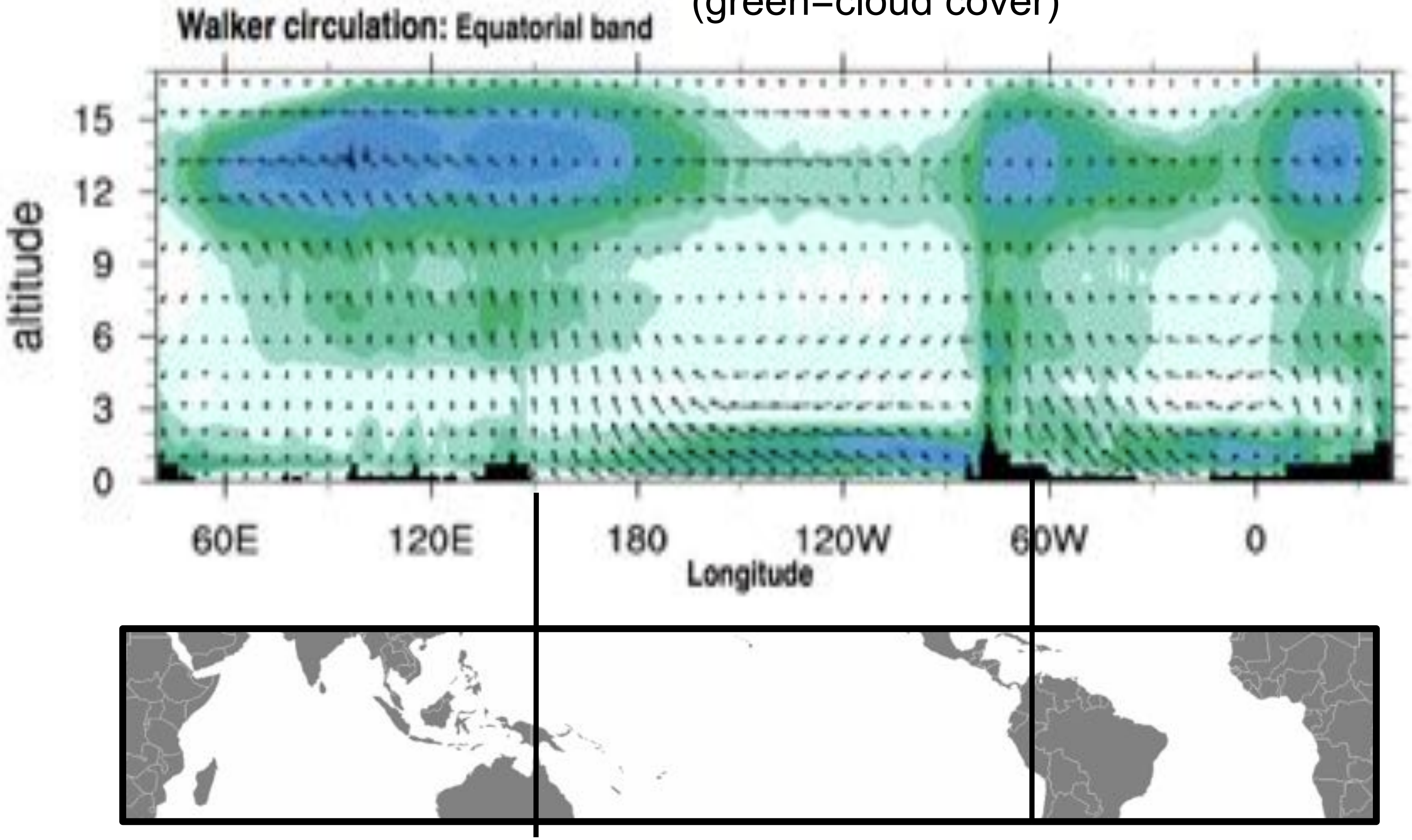
stratus

Clouds and Circulation: Walker cell



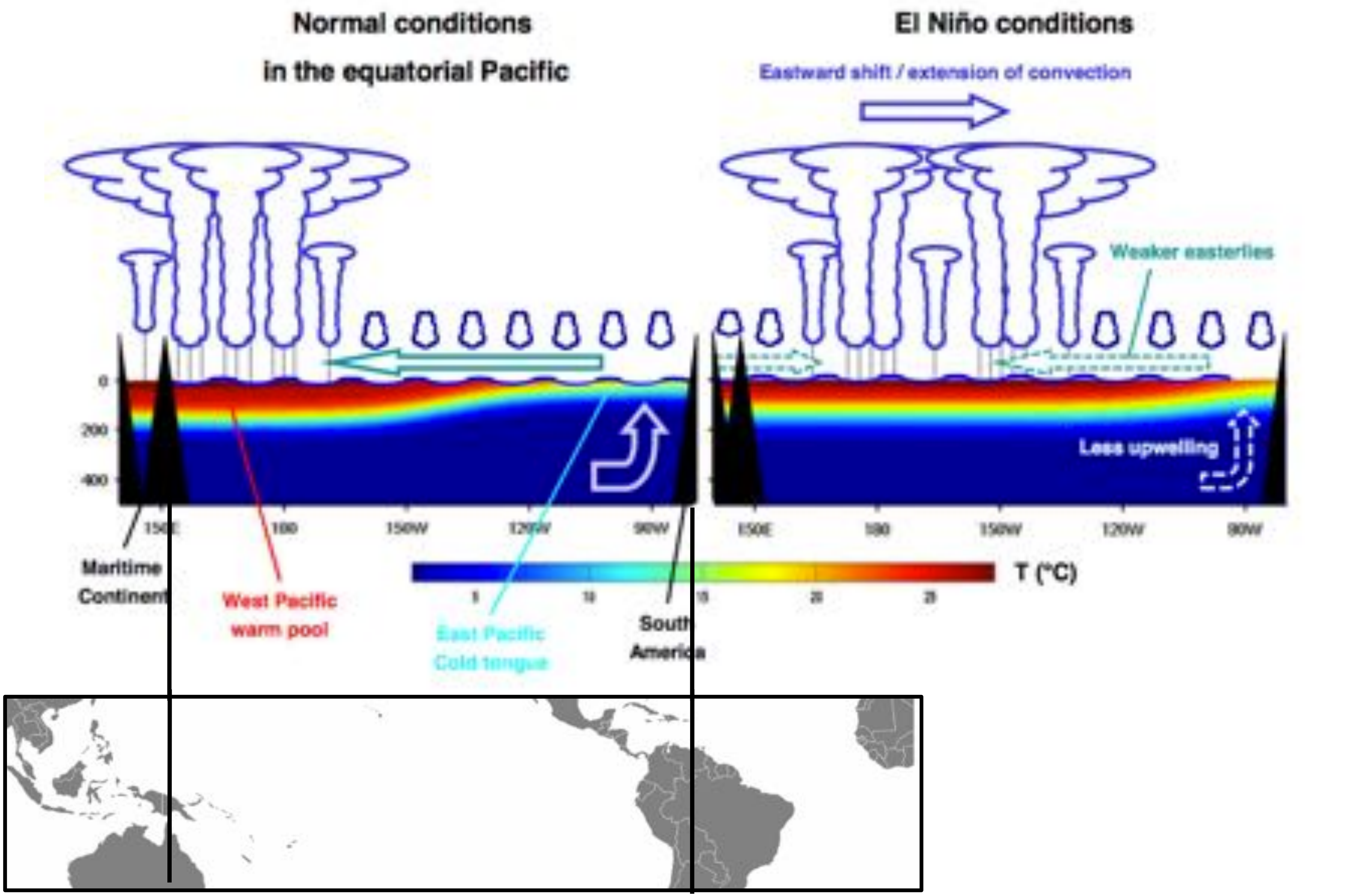
Clouds and Circulation: Walker cell

(green=cloud cover)



Courtesy Gilles Bellon

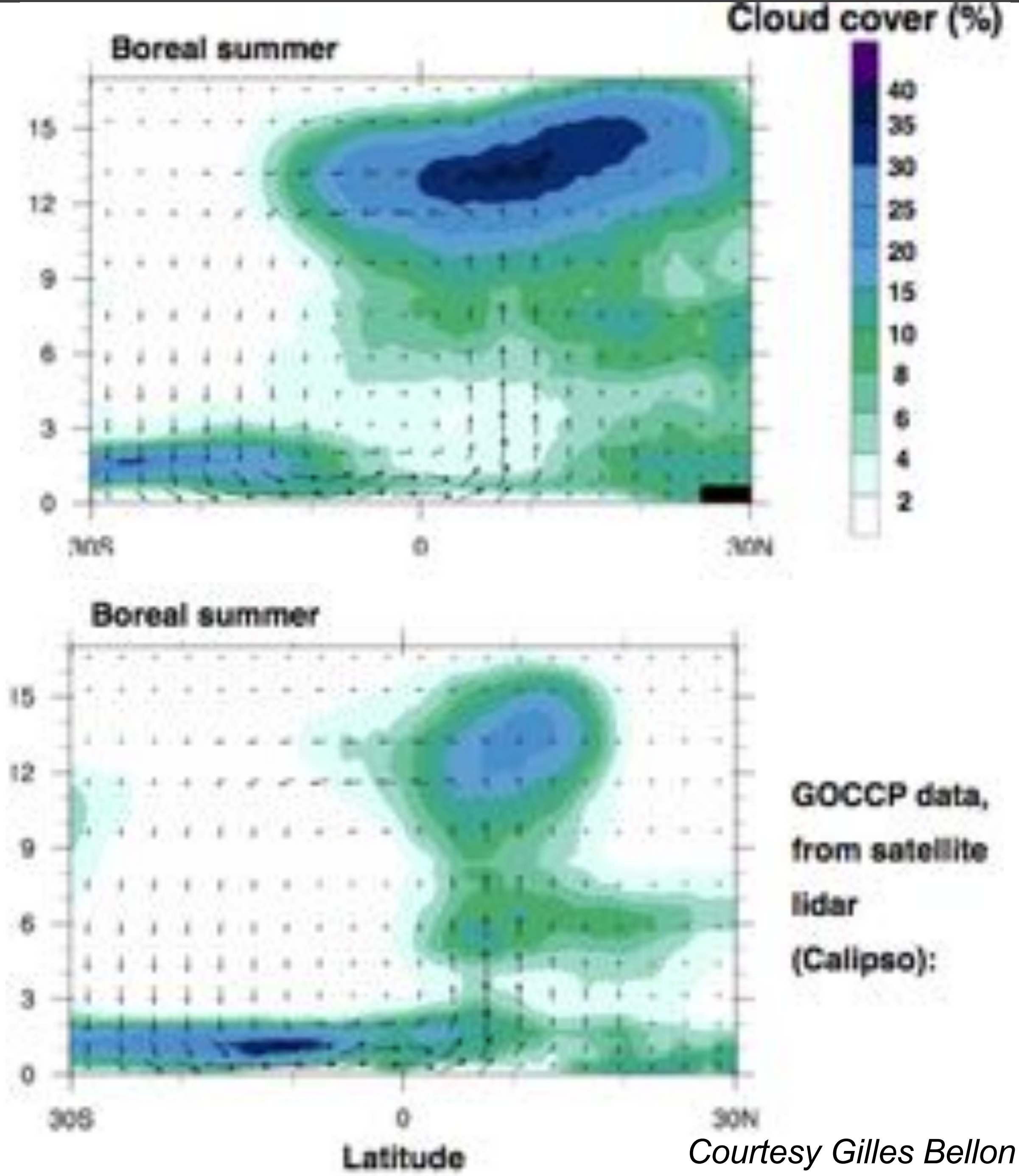
Clouds and Circulation: El Nino



Clouds and Circulation: Monsoon

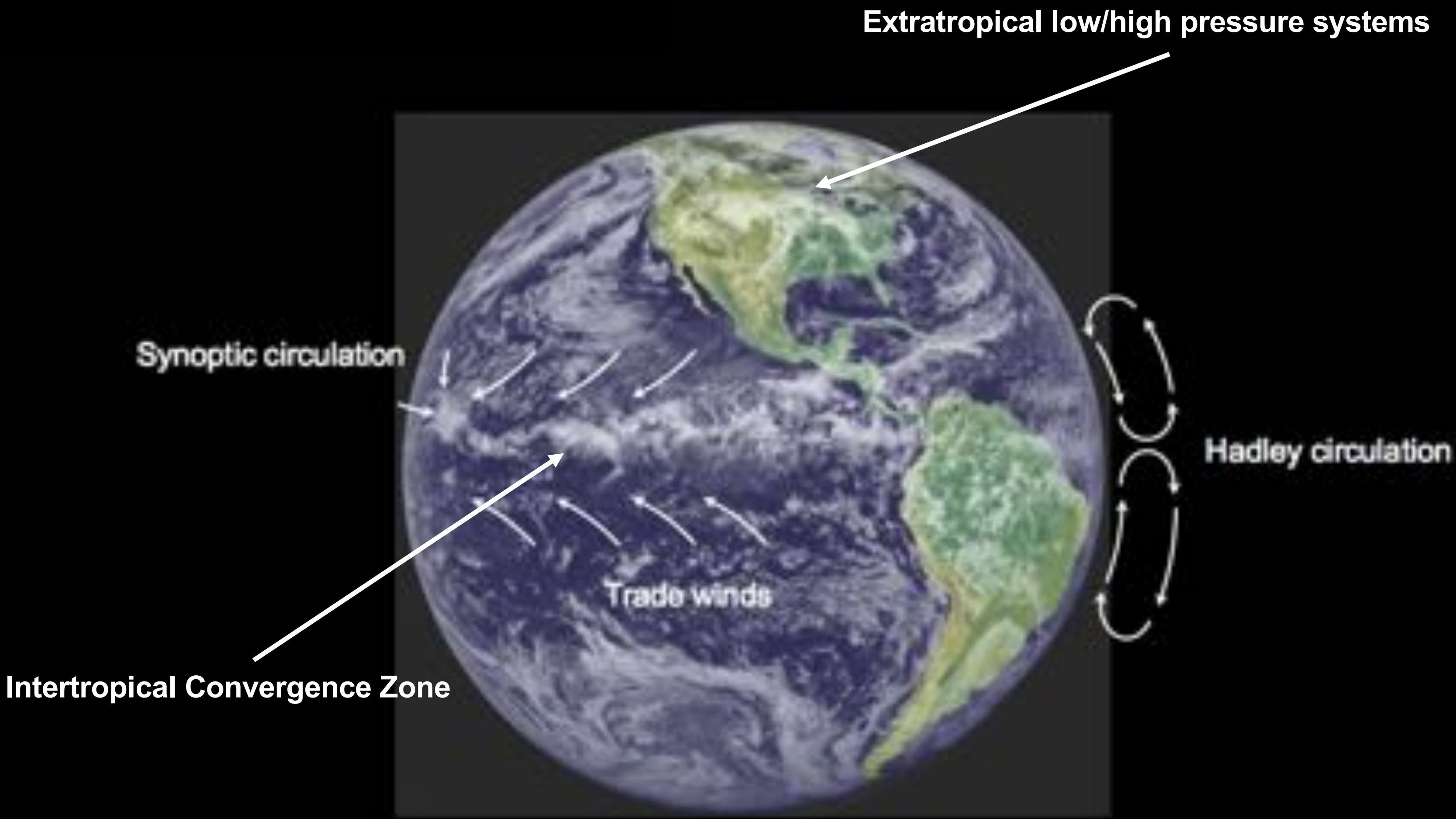
Asian monsoon

West-African monsoon



Courtesy Gilles Bellon

Clouds are coupled with circulation



Planetary scale : ITCZ, Hadley, Walker (ENSO), monsoon

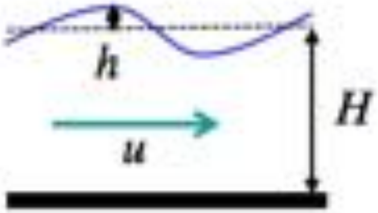
Synoptic scale : Equatorial waves, Extratropical frontal systems

Convective organization: equatorial waves

Linearized shallow-water equations on a β-plane:

➢ Classical formulation:

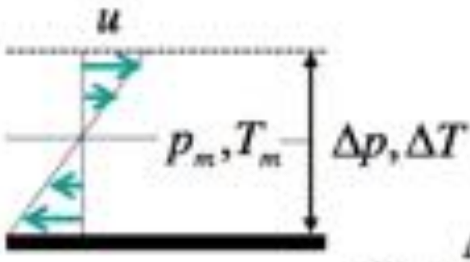
$$\begin{cases} \partial_t u - \beta y v = -g \partial_x h \\ \partial_t v + \beta y u = -g \partial_y h \\ \partial_t h + H(\partial_x u + \partial_y v) = 0 \end{cases}$$



[Matsuno 66]

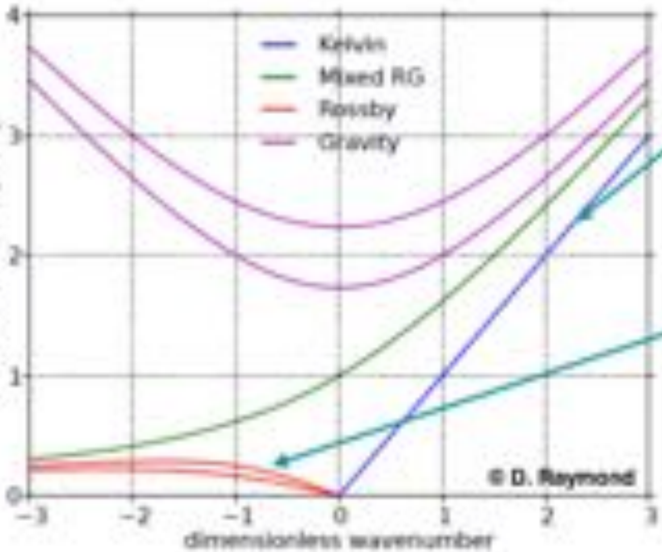
➢ Tropical atmosphere:

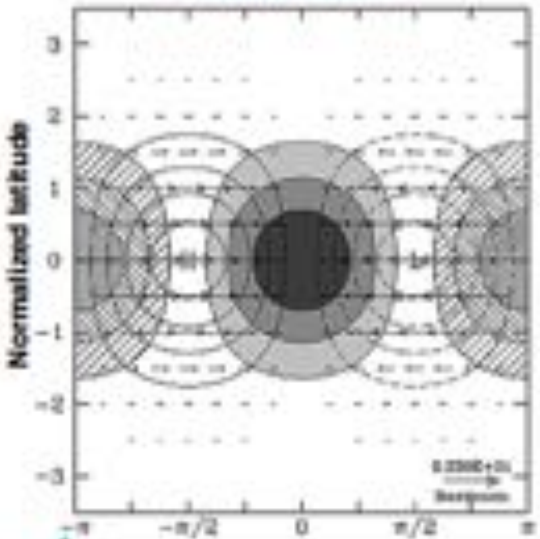
$$\begin{cases} \partial_t u - \beta y v = -\alpha \partial_x T_m \\ \partial_t v + \beta y u = -\alpha \partial_y T_m \\ \partial_t T + \Delta T(\partial_x u + \partial_y v) = 0 \end{cases}$$

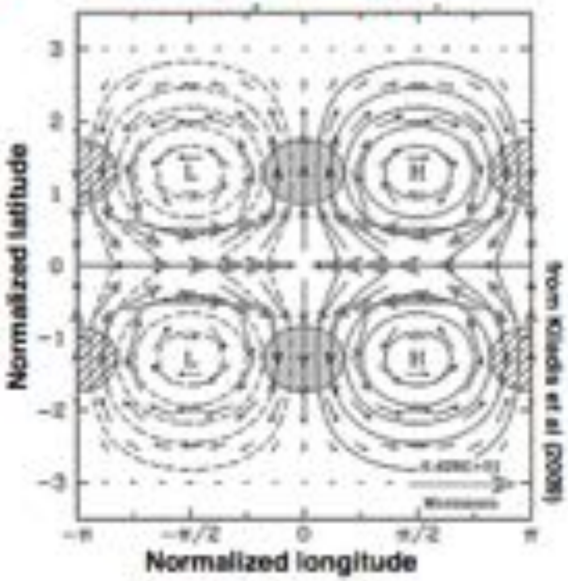


$$\alpha = \frac{\Delta p}{2 p_m} R$$

Dispersion diagram:







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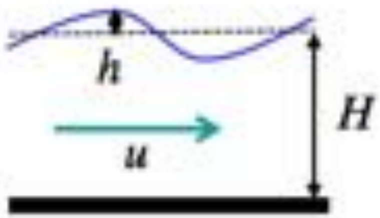

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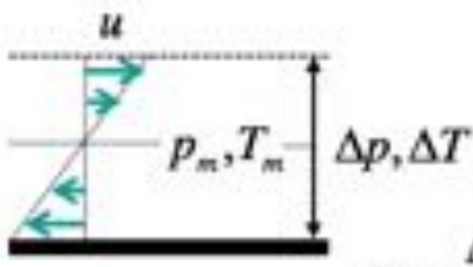
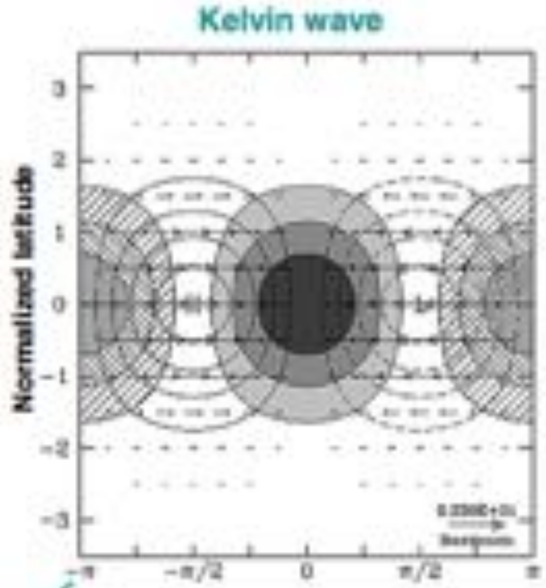
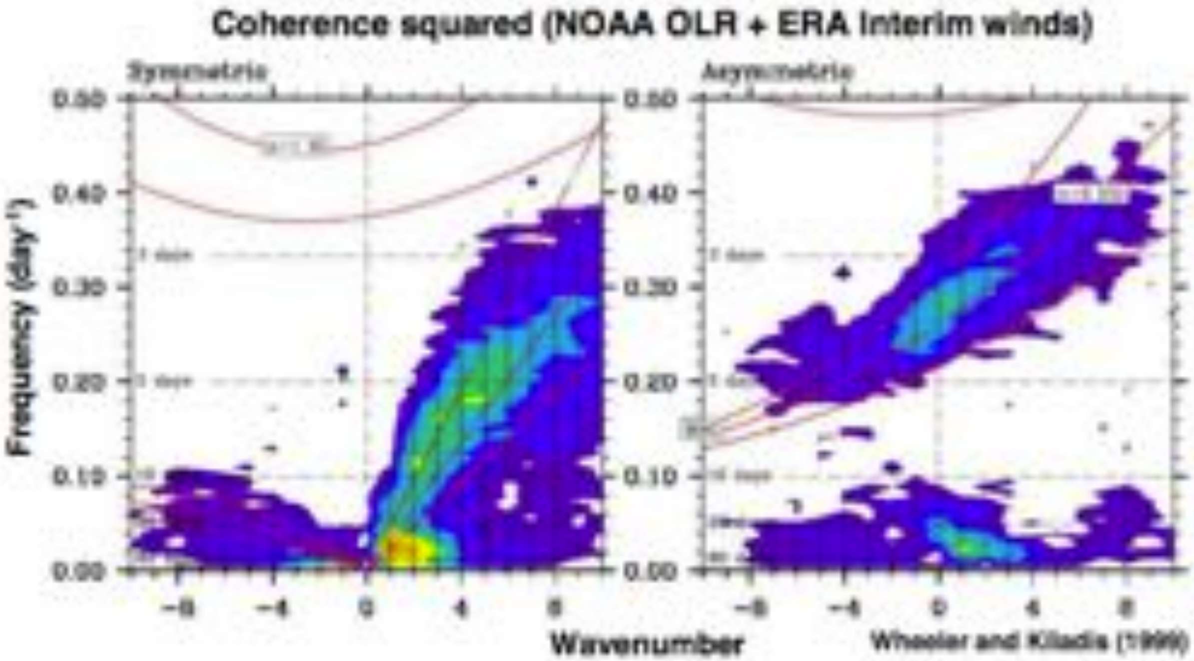
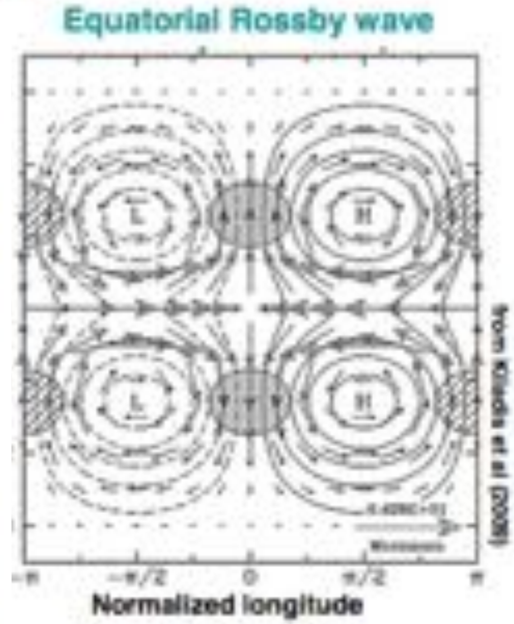


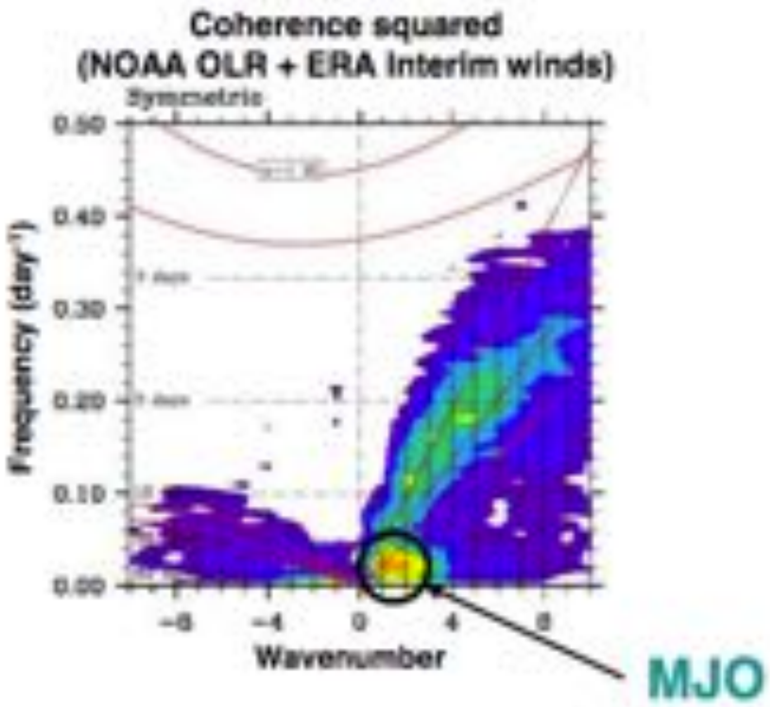
$\alpha = \frac{\Delta p}{} R$

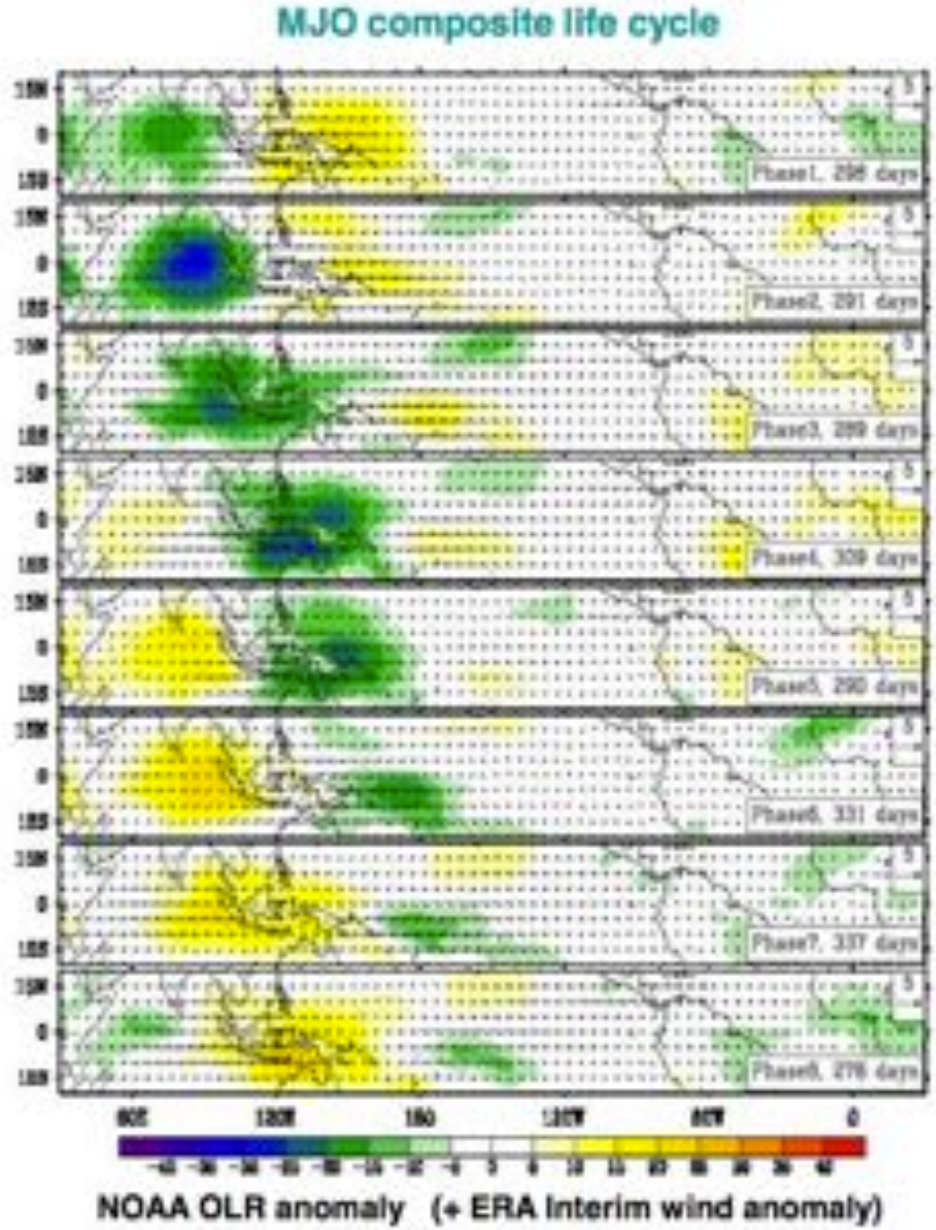




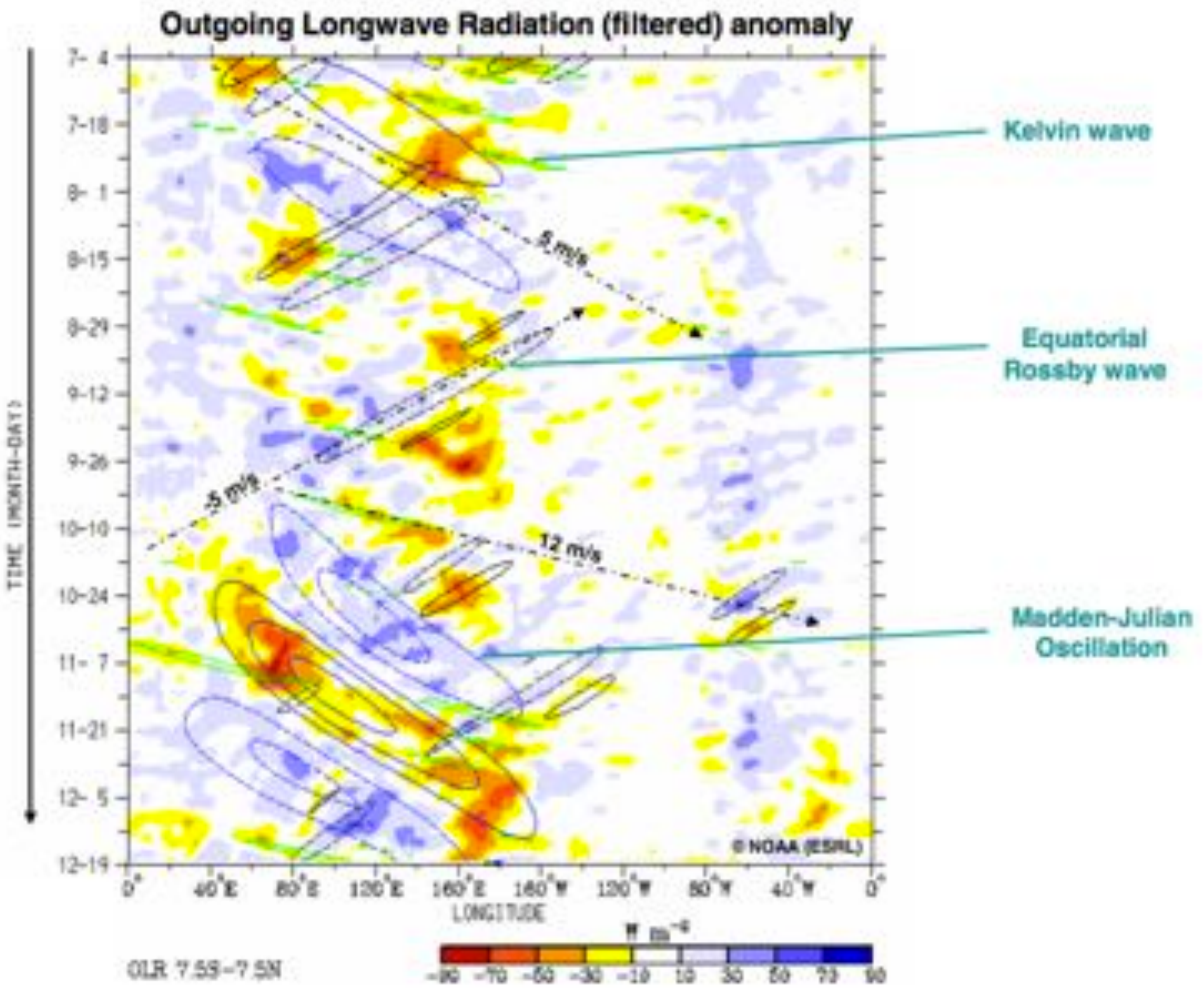


Convective organization: MJO

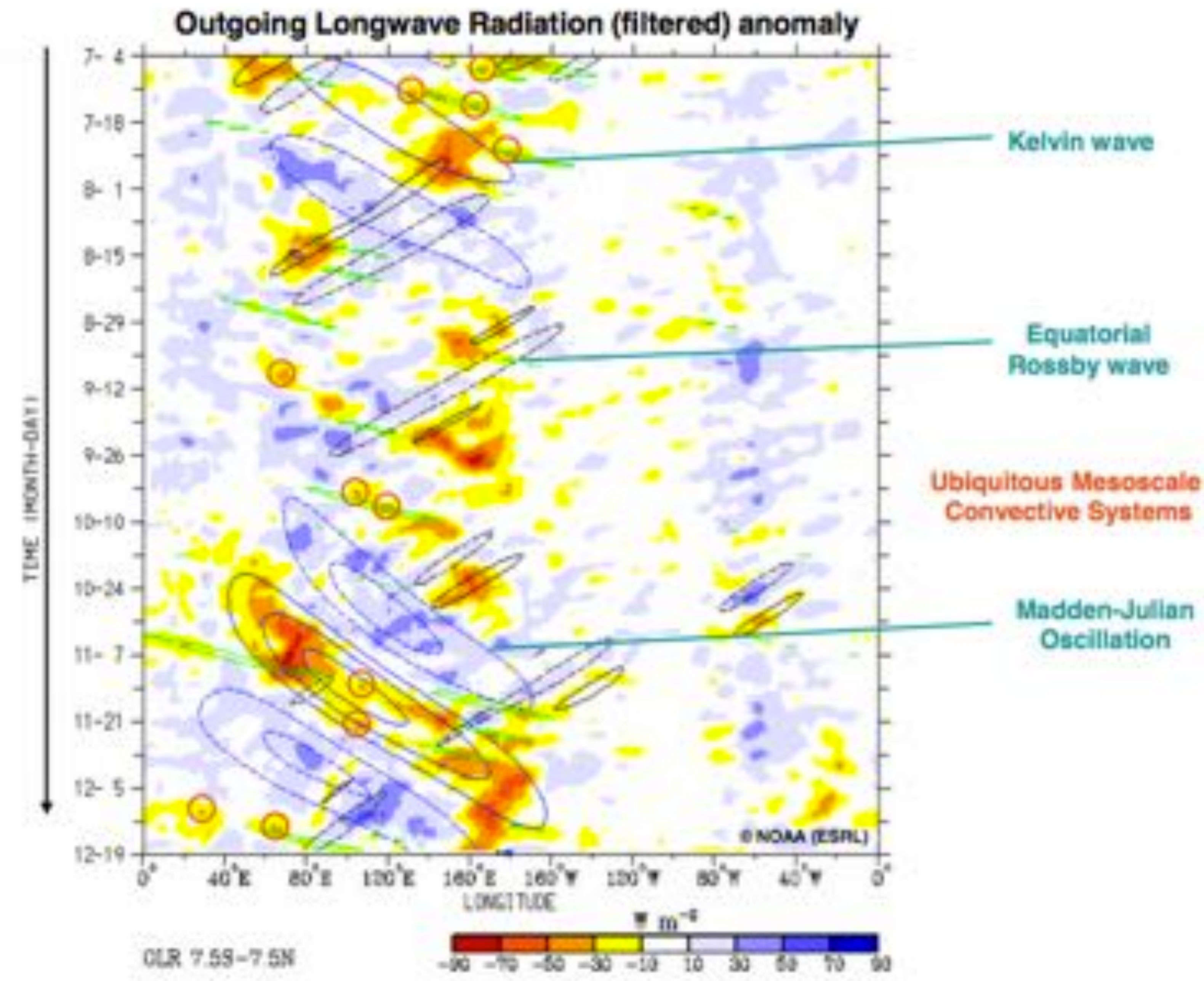




Convective organization: equatorial waves

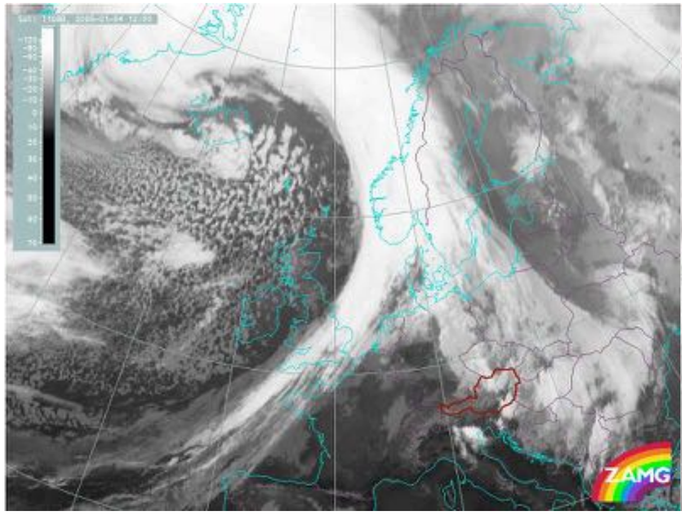


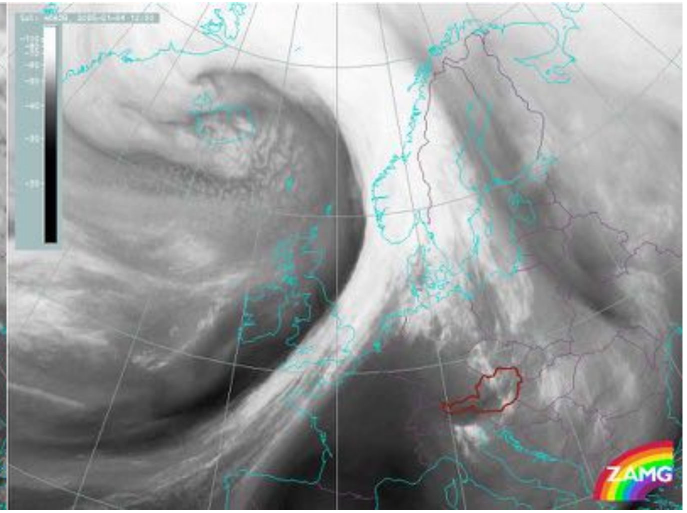
Convective organization: equatorial waves



Frontal systems and clouds

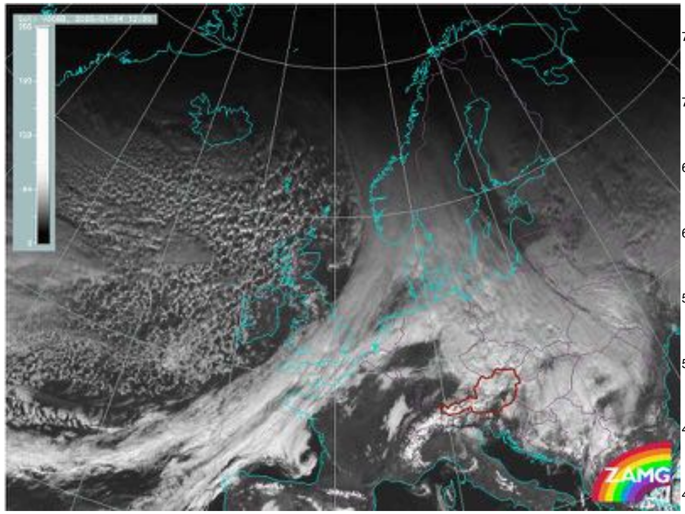
IR

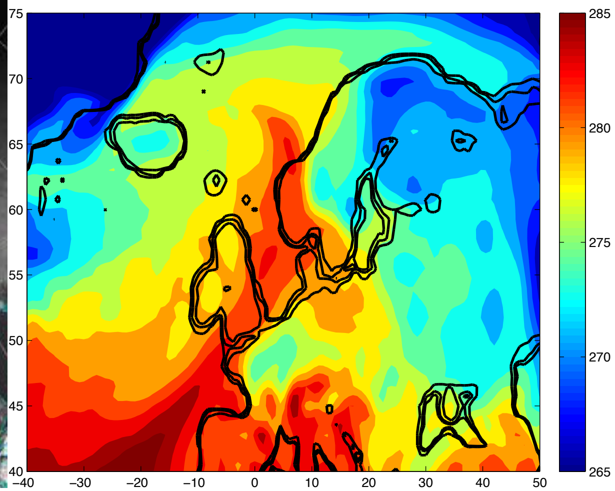




WV

VIS





Corresponding T field
Clouds are clearly linked to the dynamics of frontal systems

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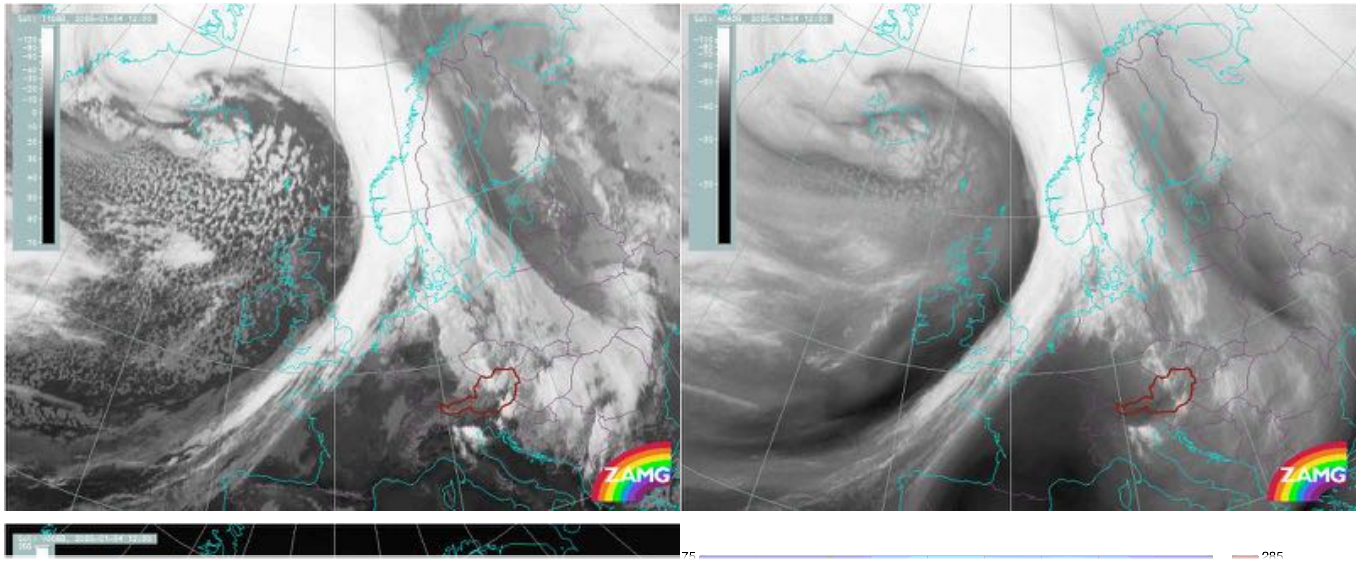

WV

VIS