Clouds and atmospheric convection

Caroline Muller

CNRS/Laboratoire de Météorologie Dynamique (LMD)

Département de Géosciences

ENS

Clouds and atmospheric convection

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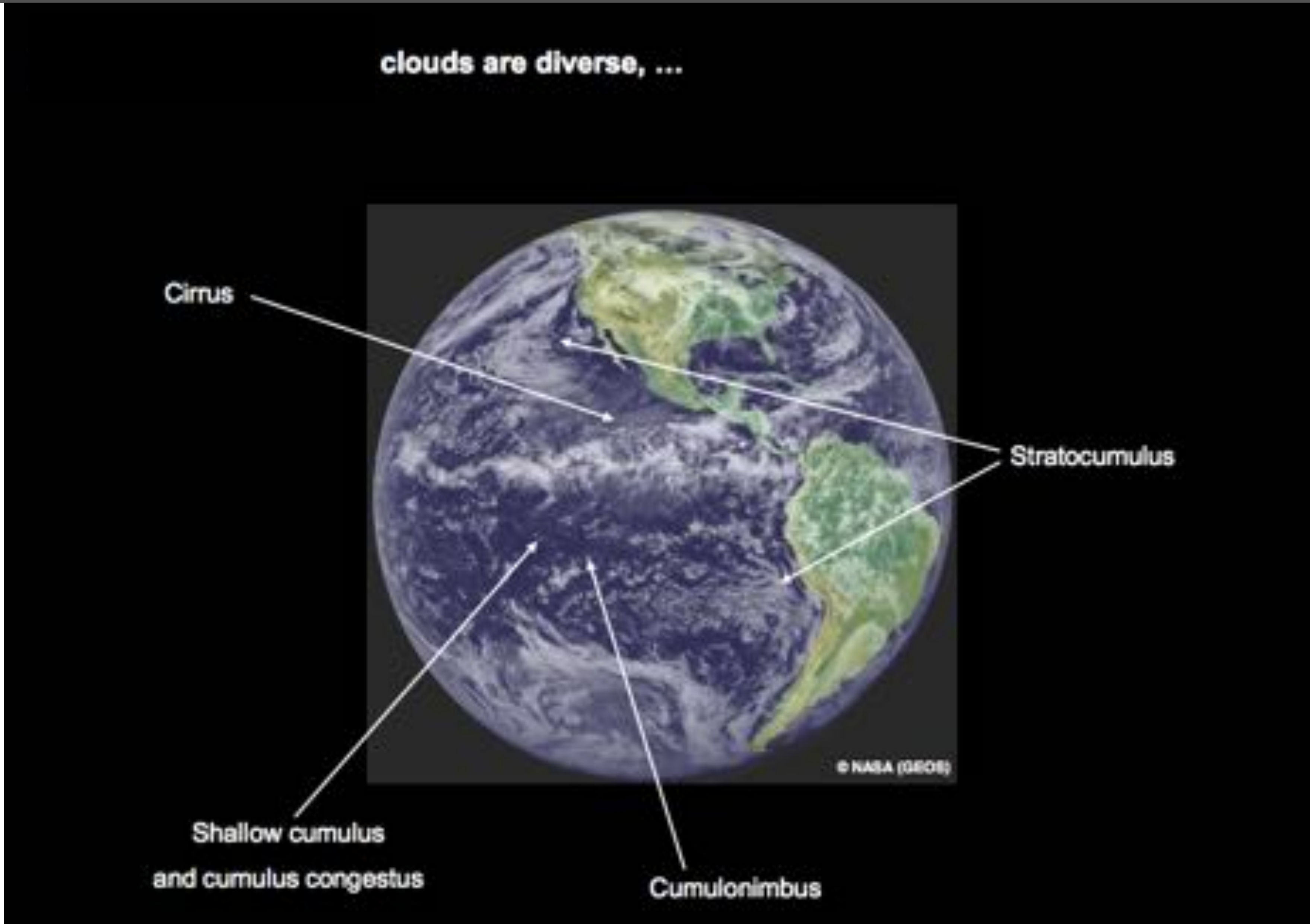
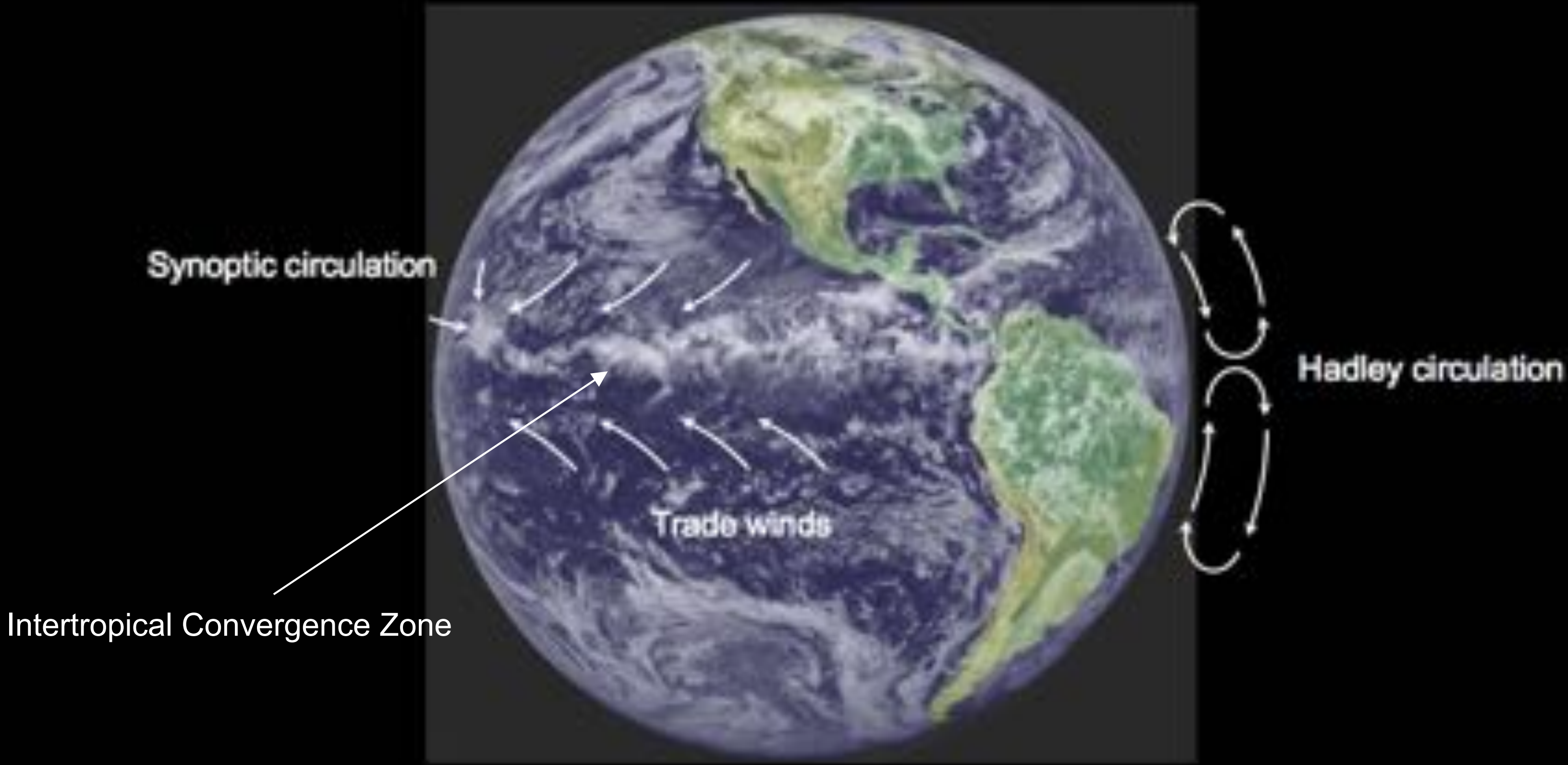


Clouds and atmospheric convection

… and coupled to circulations.



Clouds and atmospheric convection

1. Cloud types

2. Moist thermodynamics and stability

3. Coupling with circulation

1. Cloud types

Cumulus: heap, pile

Stratus: flatten out, cover with a layer

Cirrus: lock of hair, tuft of horsehair

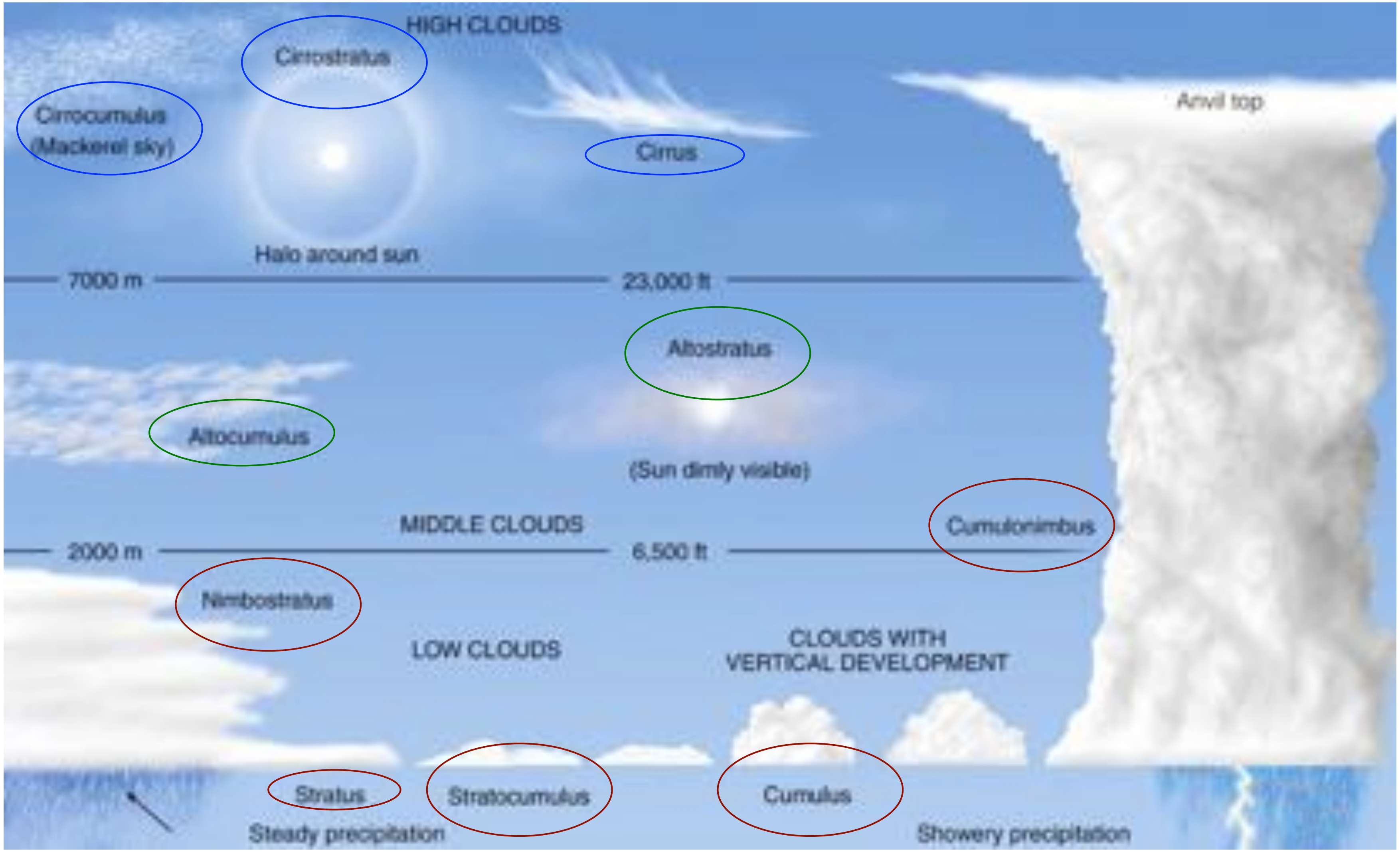
Nimbus: precipitating cloud

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

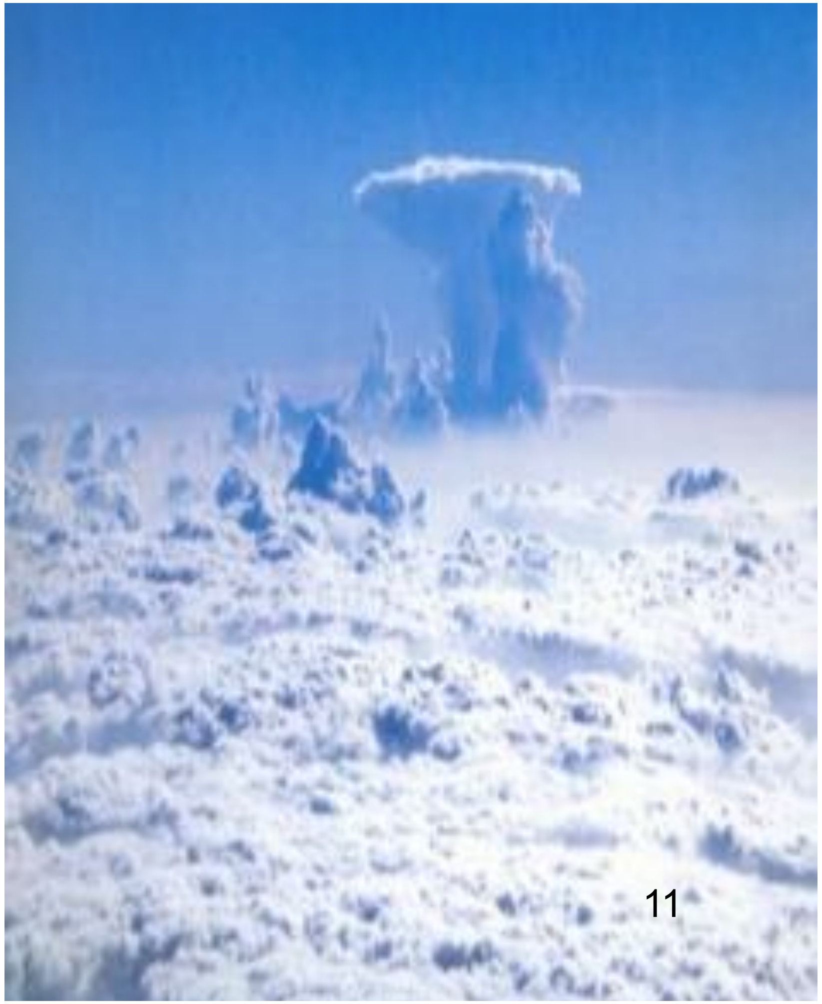
Also called "fair weather cumulus"

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…

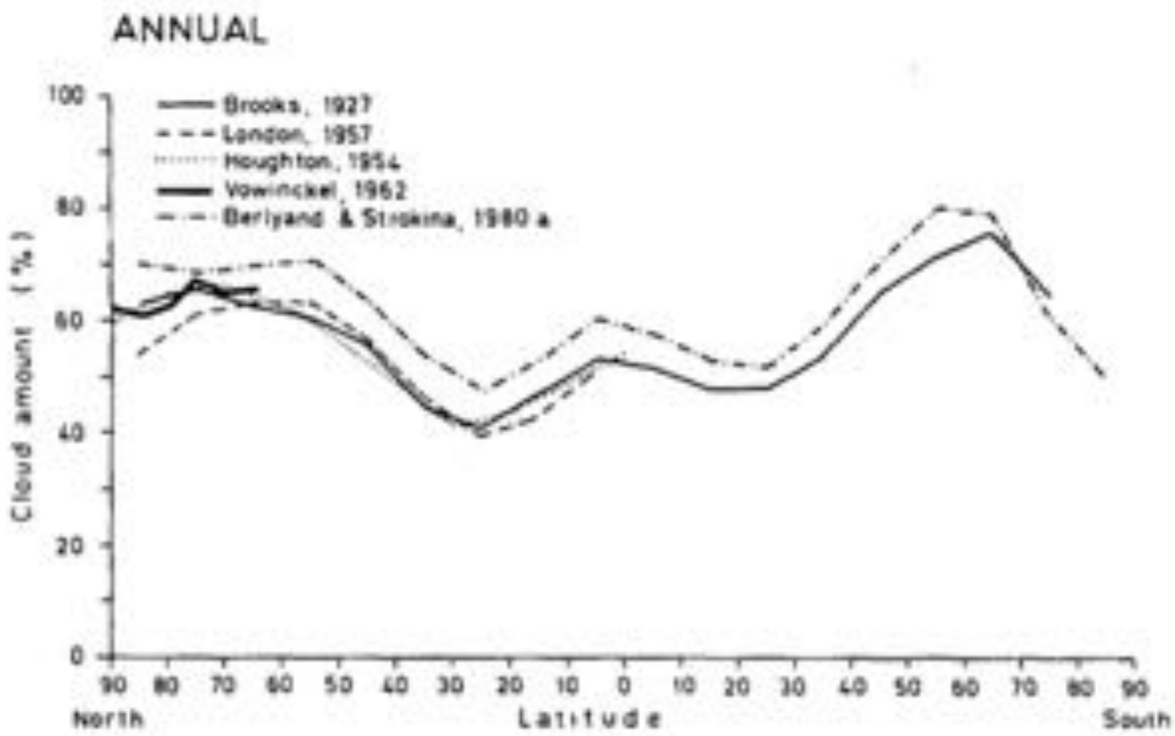
Mammatus clouds (typically below anvil clouds)


Shelf clouds (gust front)


Lenticular clouds (over orography)

Question: Global cloud cover (%)?

Distribution of cloud amount

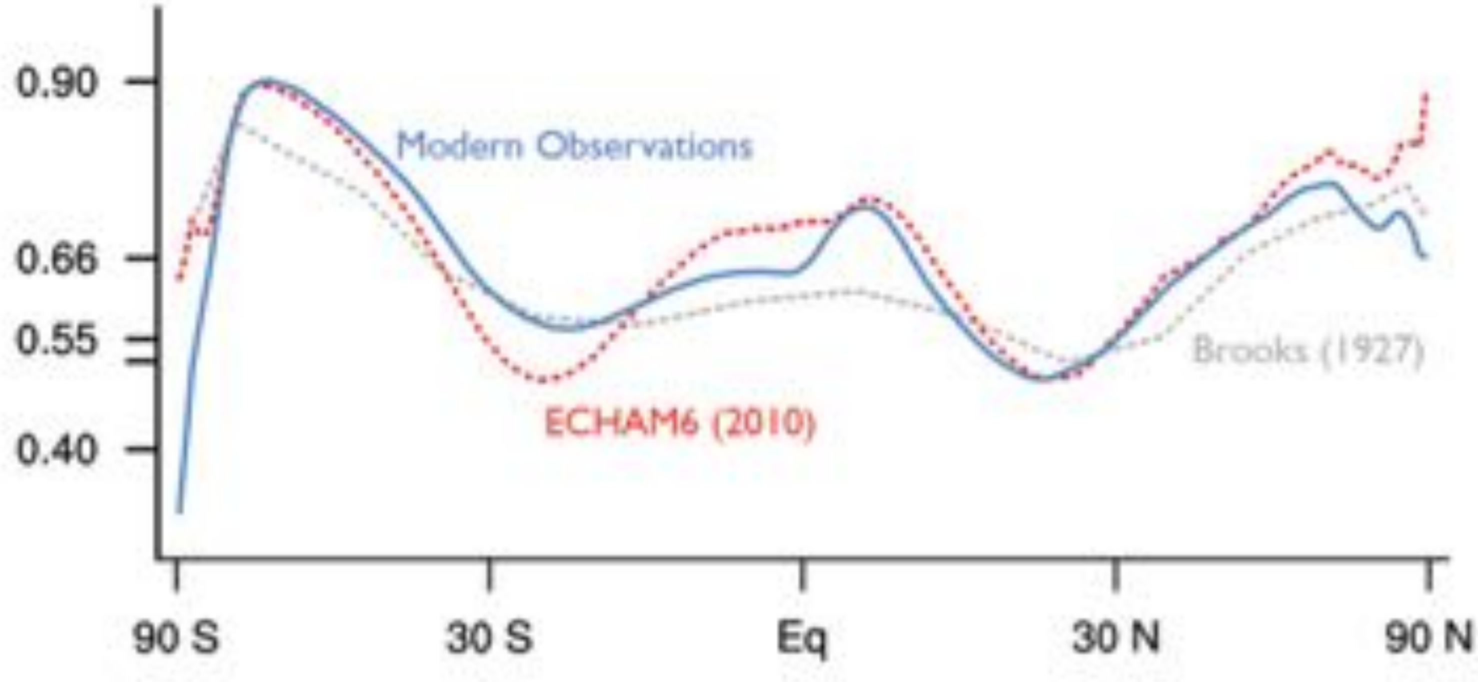


[Hughes 84]

1. Cloud types

Cloud amount was underestimated

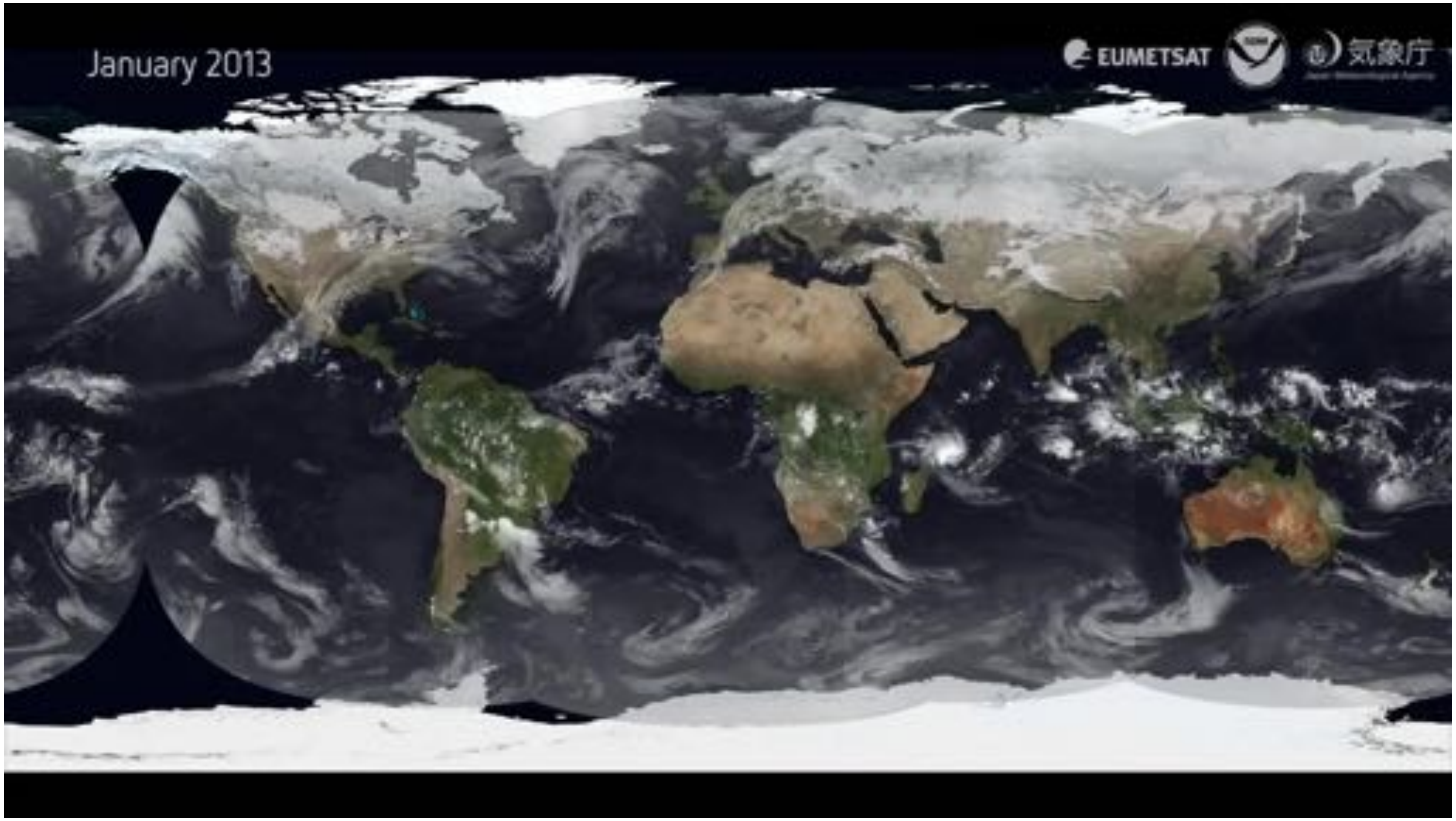
Also note the latitudinal distribution



Courtesy Bjorn Stevens

1. Cloud types

Brightness temperature from satellite (white ⇔ cold cloud tops)



Large extratropical storm systems

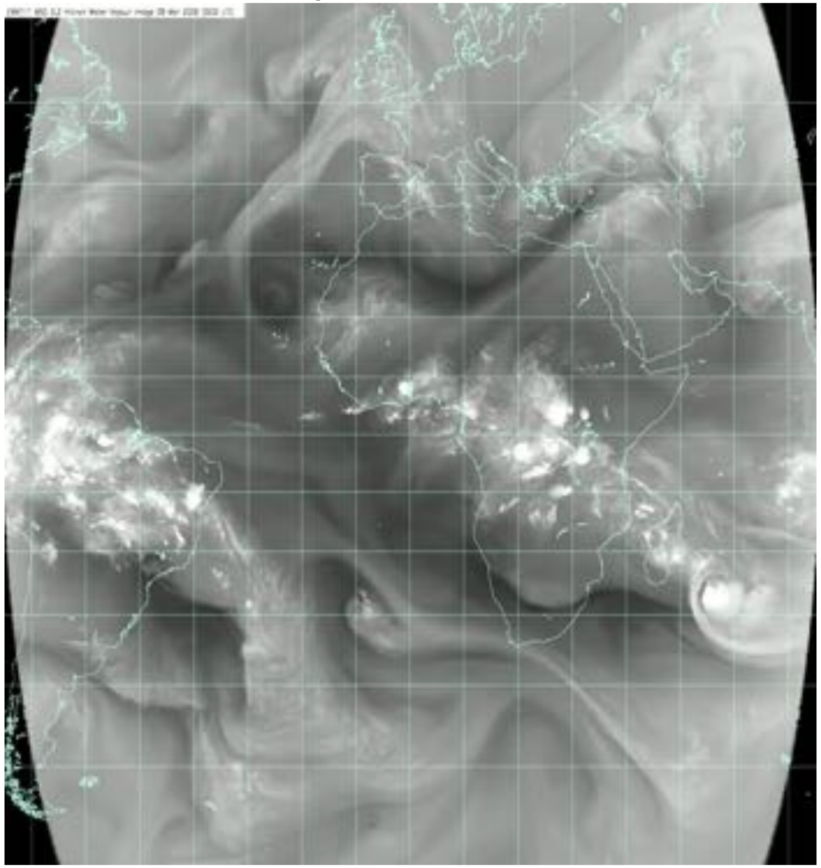
subtropics: ~no high clouds

ITCZ = Intertropical convergent zone

« A year of weather »

1. Cloud types

Water vapor from satellite



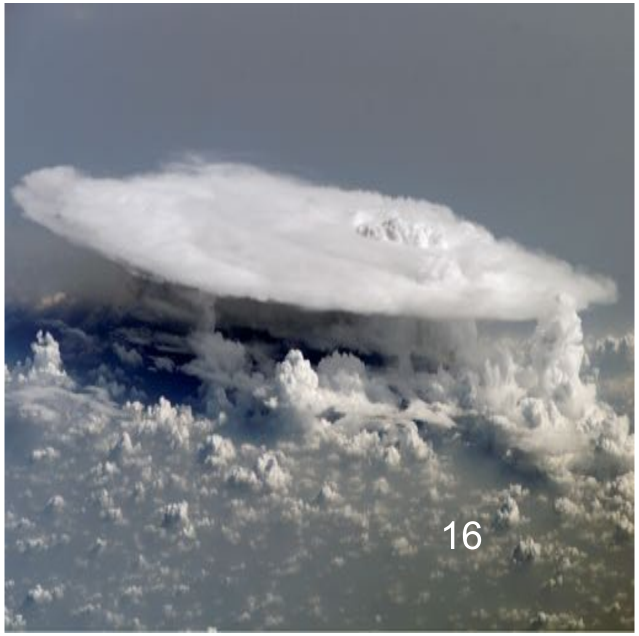
Large extratropical storm systems => Large-scale extratropical convection

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

3. Coupling with circulation

2. Atmospheric thermodynamics: instability

Dry convection

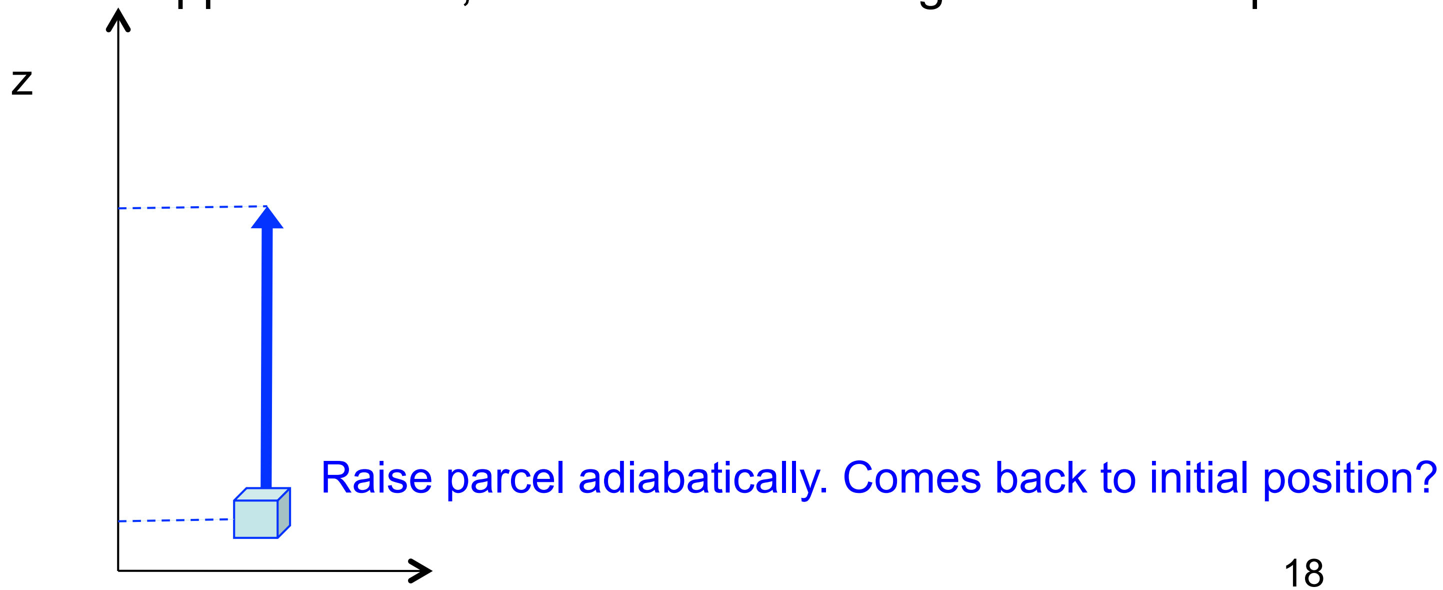
T decreases with height, but p as well. Density = $\rho(T,p)$. How determine stability? The parcel method

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

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

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

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

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)

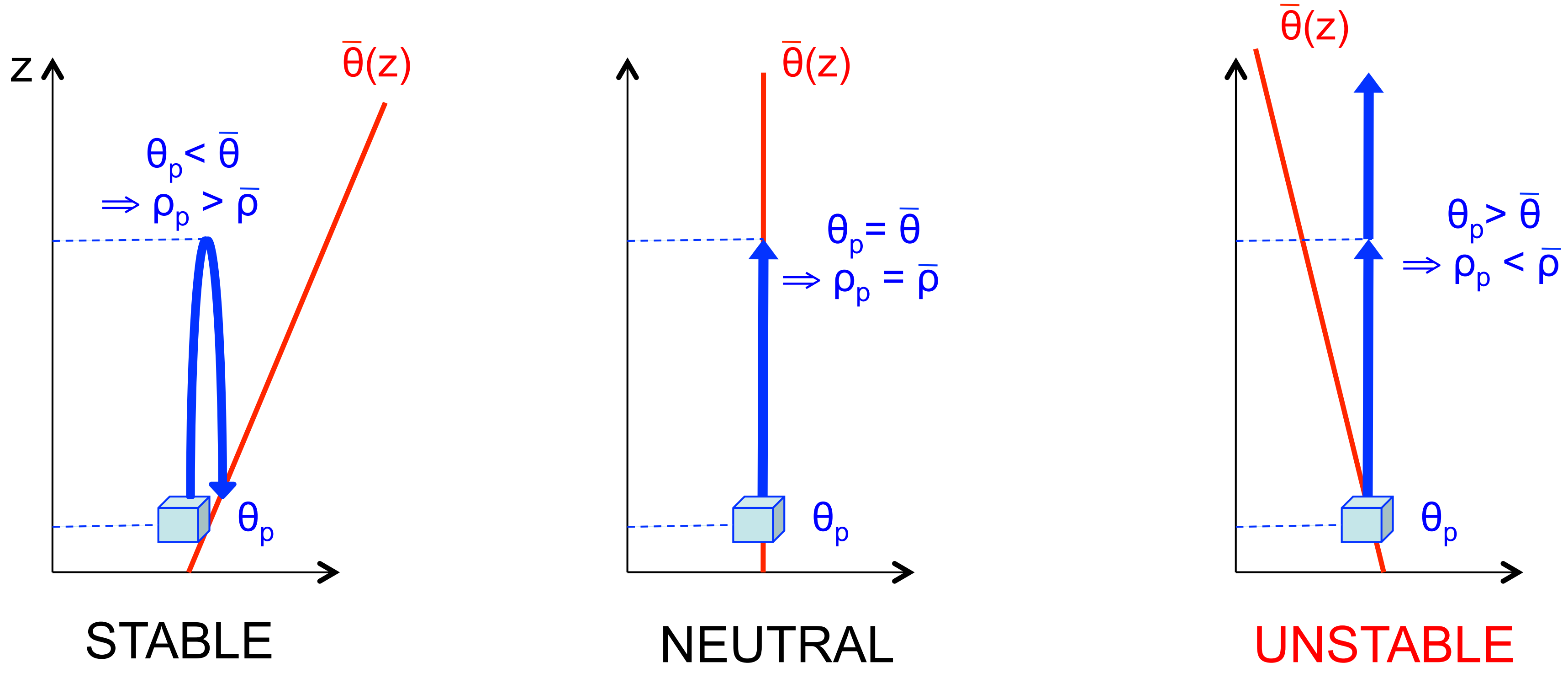
2. Atmospheric thermodynamics: instability

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.



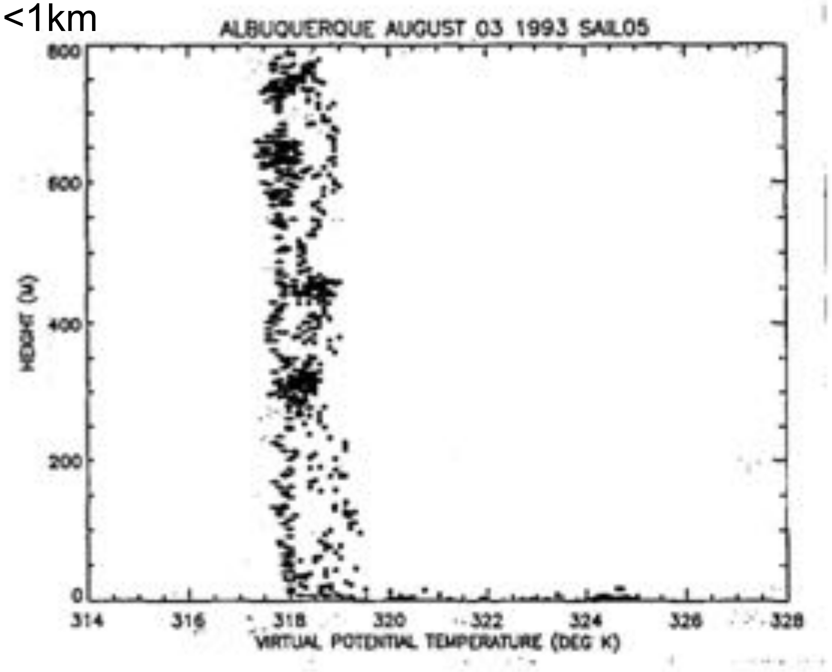
2. Atmospheric thermodynamics: instability

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?…

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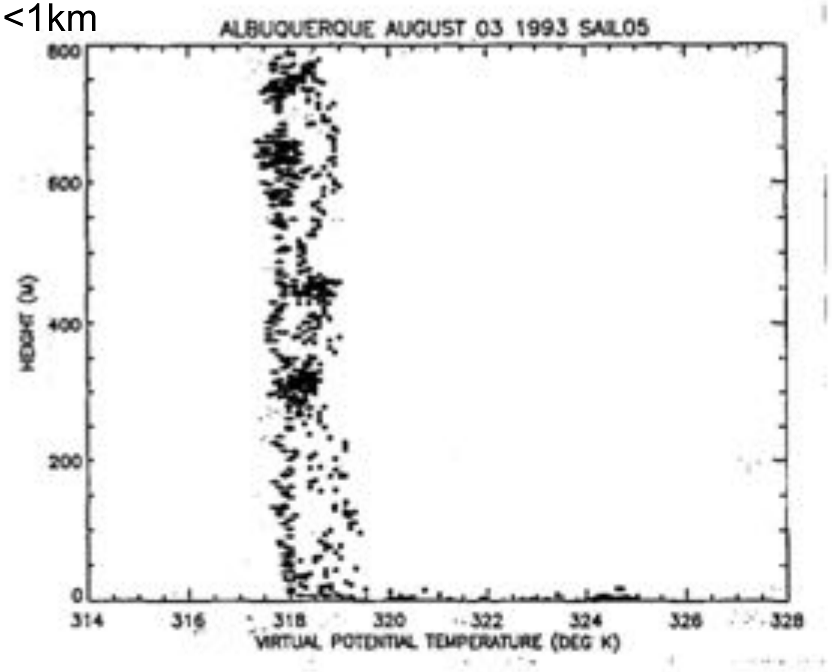


[Renno and Williams, 1995]

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**

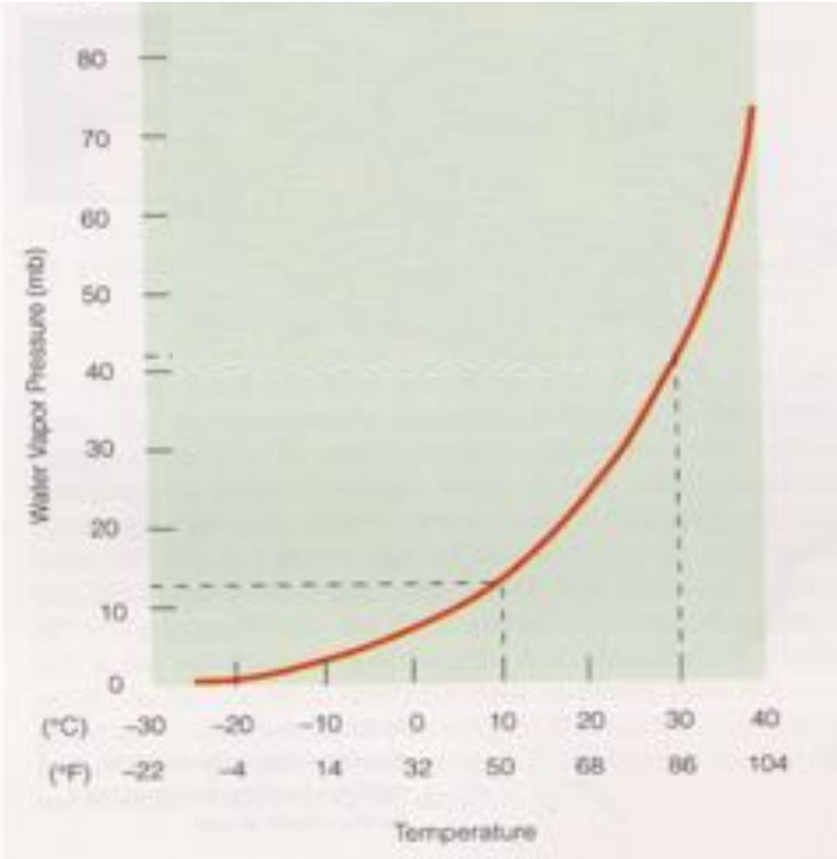
2. Atmospheric thermodynamics: instability

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 : Temperature profile of a dry adiabat.

• 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

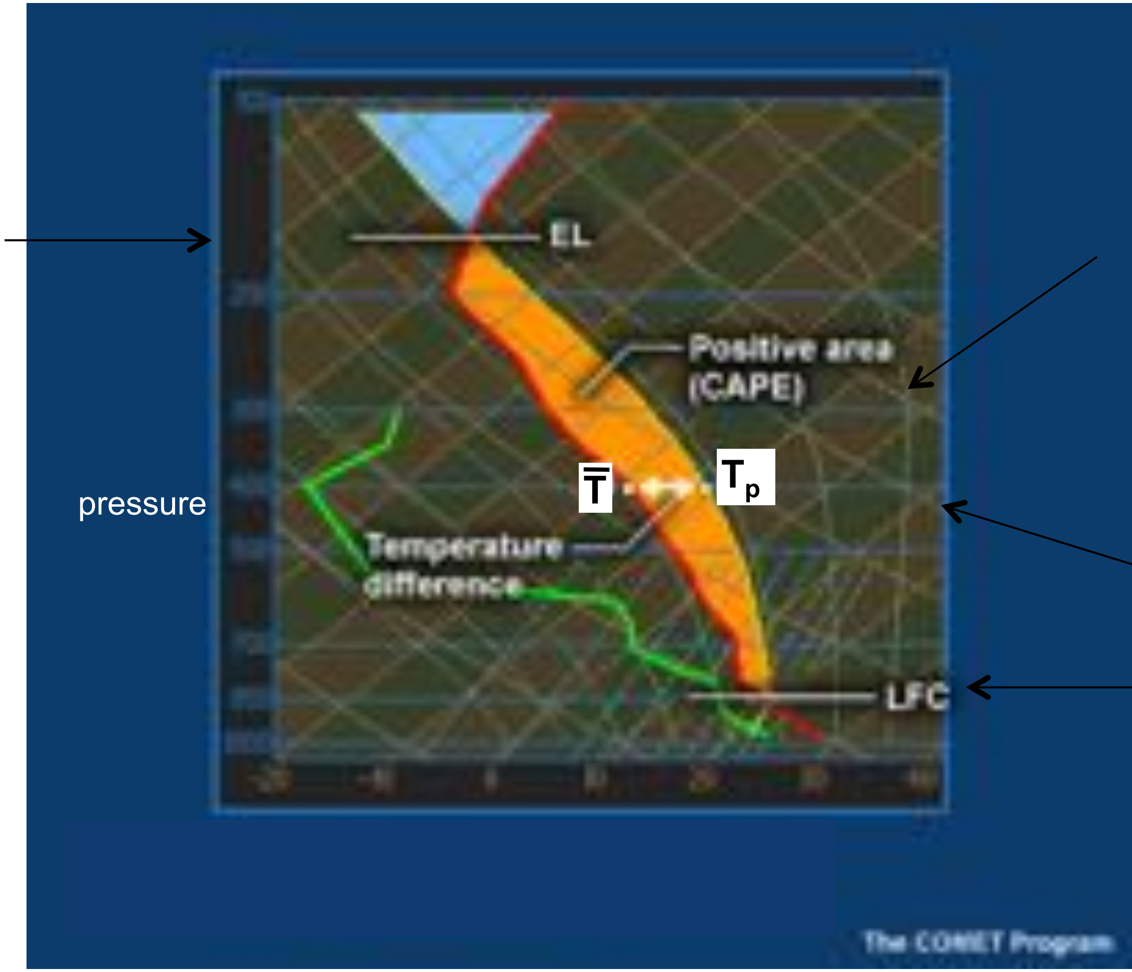
Hence
$\theta_e = T\,(p_0 / p)^{R/c_p}\; e^{\,L_v\,q_v / (c_p\,T)}$ equivalent potential temperature is approximately conserved

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

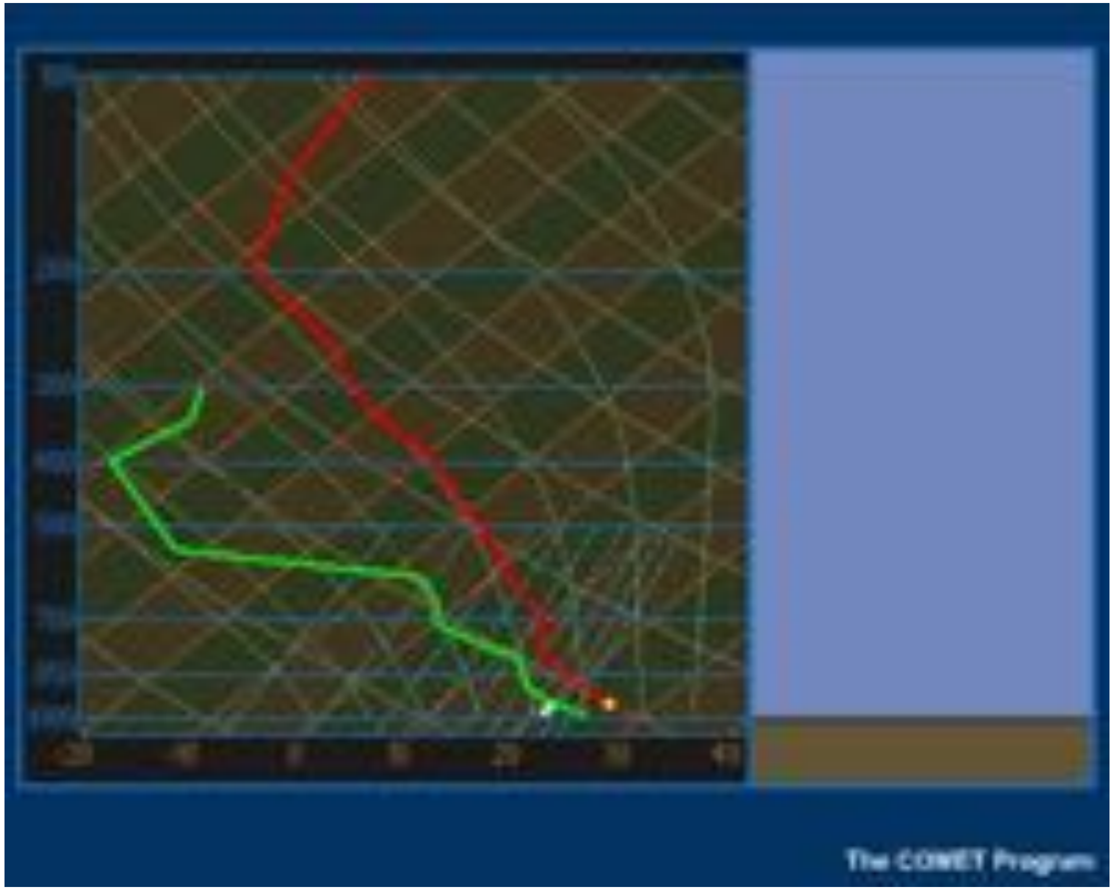
LFC level of free convection (= LCL lifted condensation level for simplicity)

CAPE: convective available potential energy

2. Atmospheric thermodynamics: instability

Parcel = yellow dot

EL equilibrium level



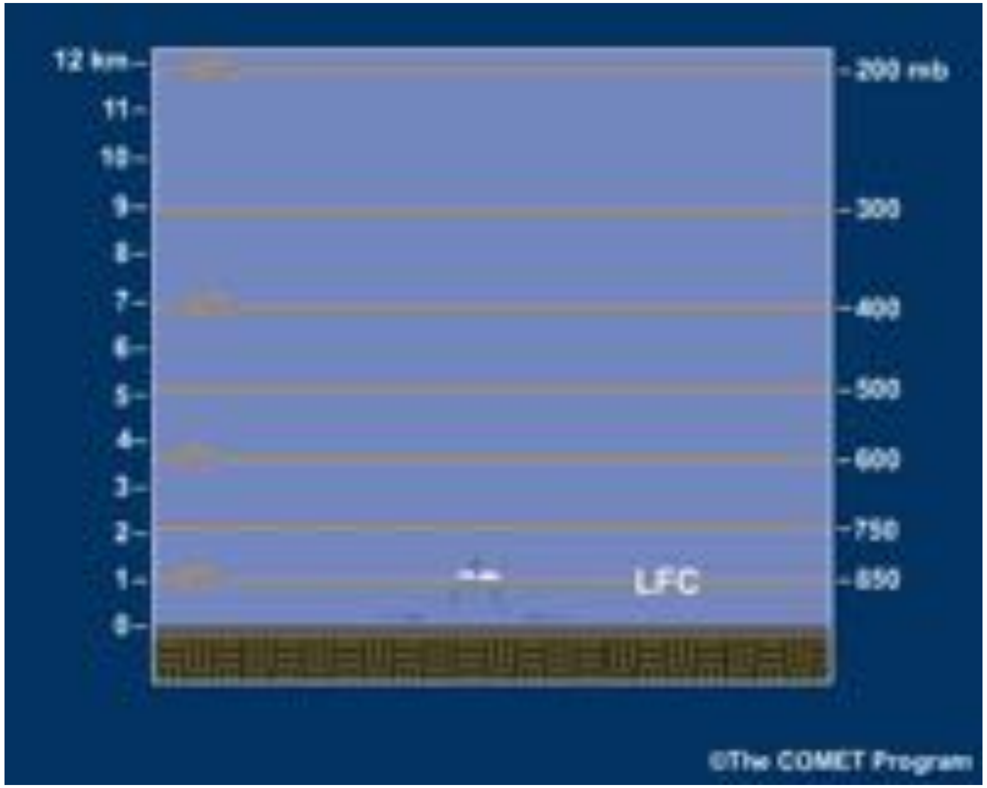
LFC level of free convection

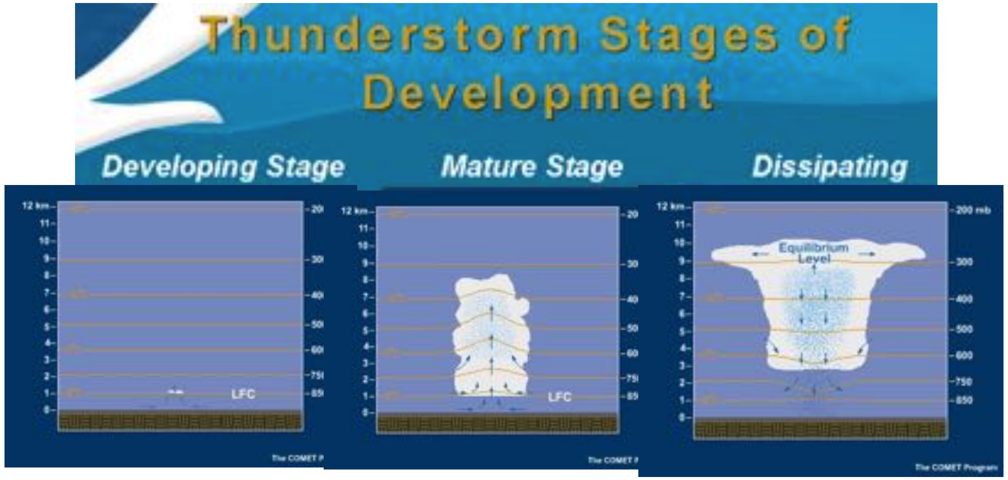
CAPE: convective available potential energy

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

Clouds and atmospheric convection

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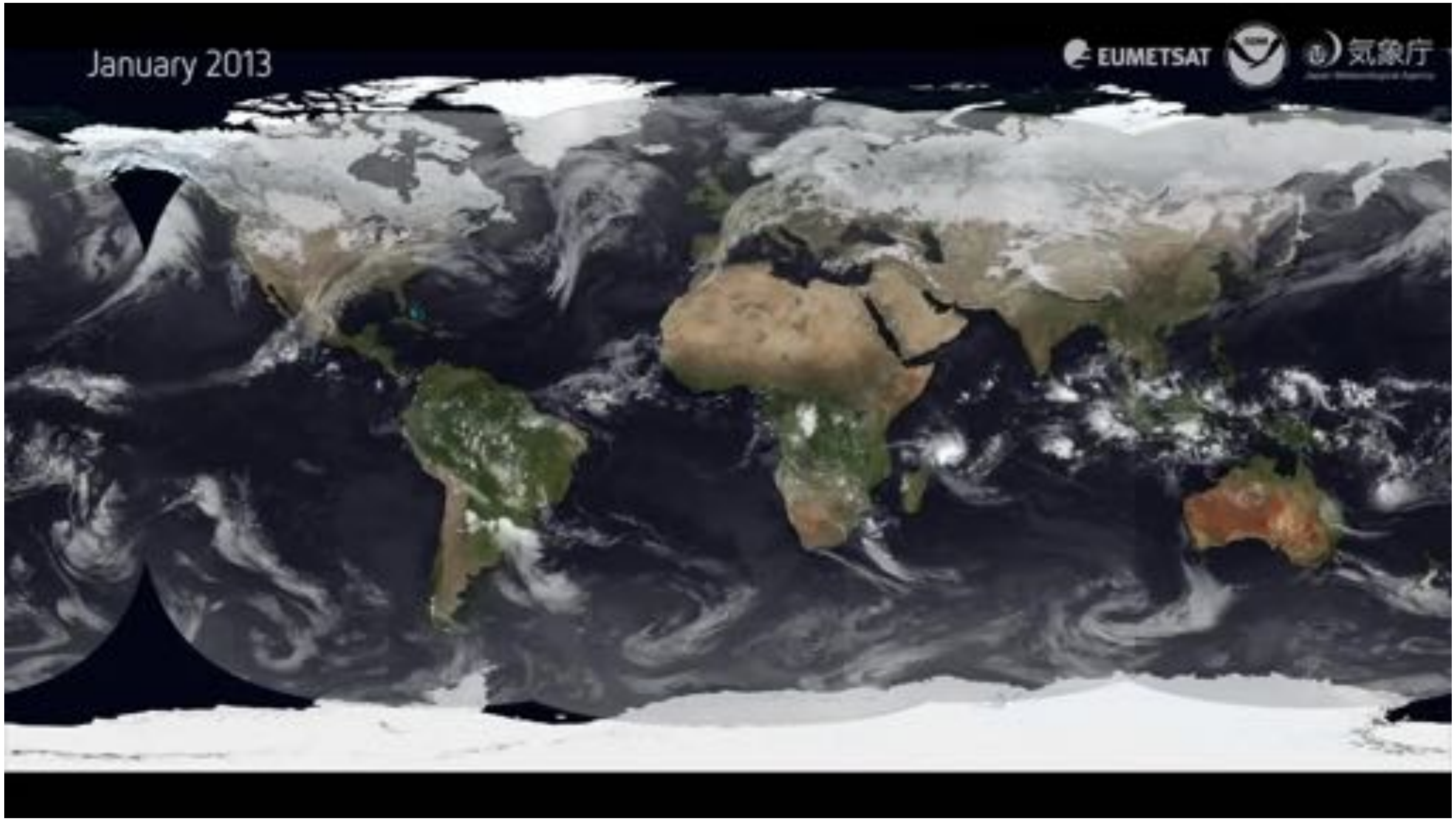
3. Clouds and Circulation

Recall : spatial distribution

Brightness temperature from satellite (white ⇔ cold cloud tops)



Large extratropical storm systems

subtropics: ~no high clouds

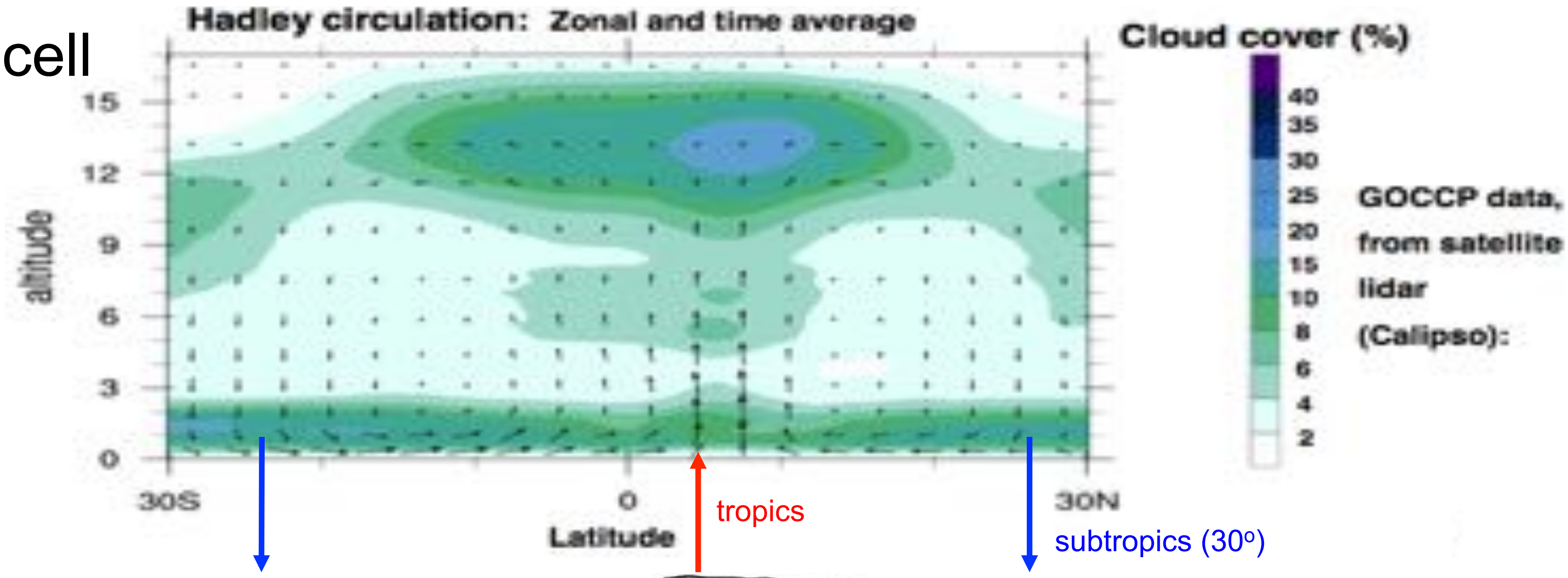
ITCZ = Intertropical convergent zone

« A year of weather »

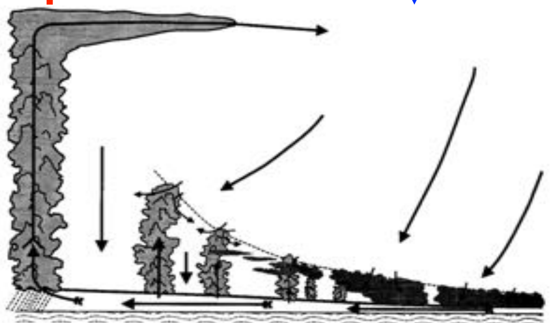
Question: Where are deep clouds more frequent? Why do you think that is?

3. Clouds and Circulation: Tropics and Subtropics

Hadley cell



Cloud types:



Deep cumulonimbus Fair weather cumulus stratus

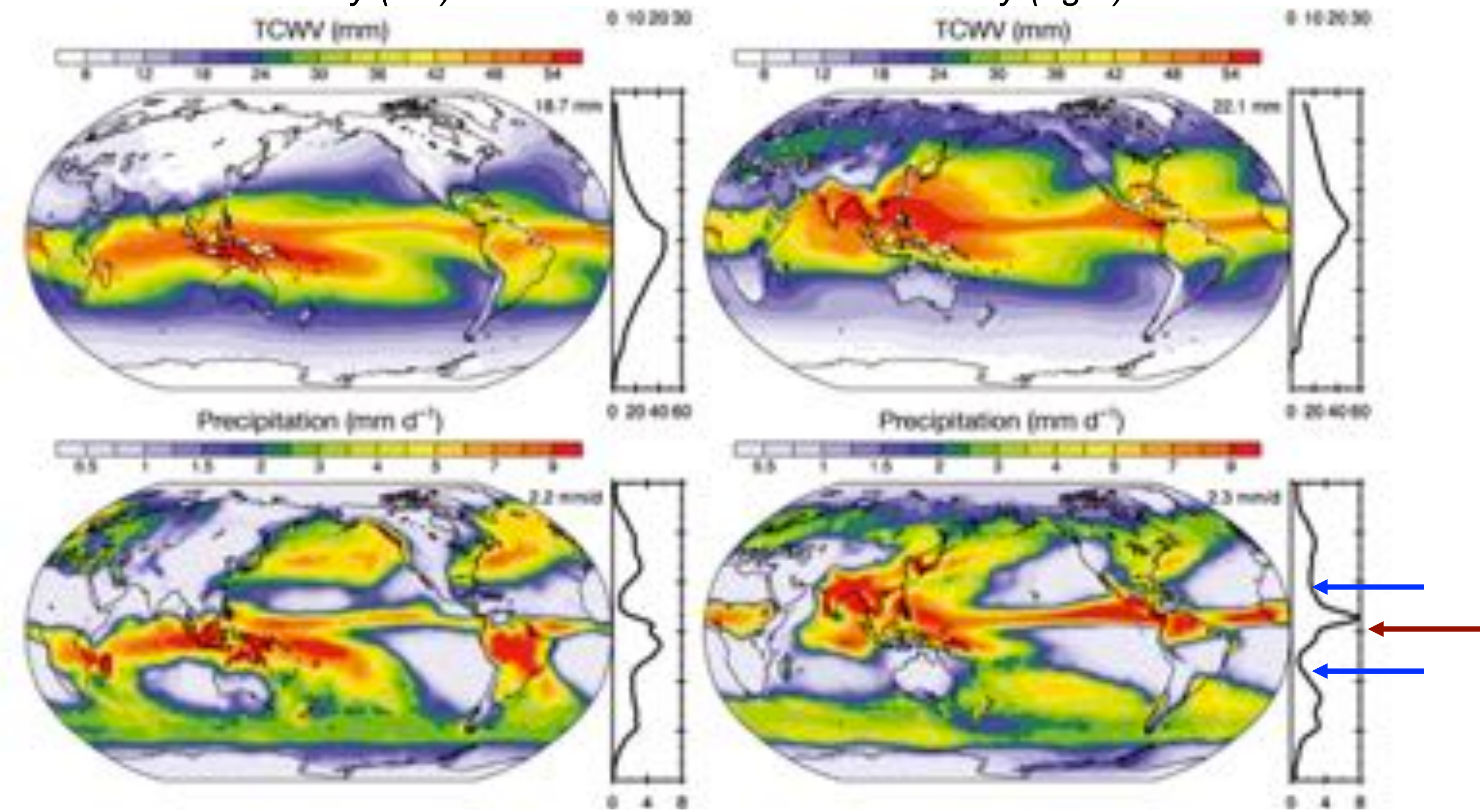
⇒**On average:**

Deep clouds are favored where there is large-scale ascent ;
Shallow clouds are favored where there is descent.

3. Clouds and Circulation: Tropics and Subtropics

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

January (left) *July (right)*



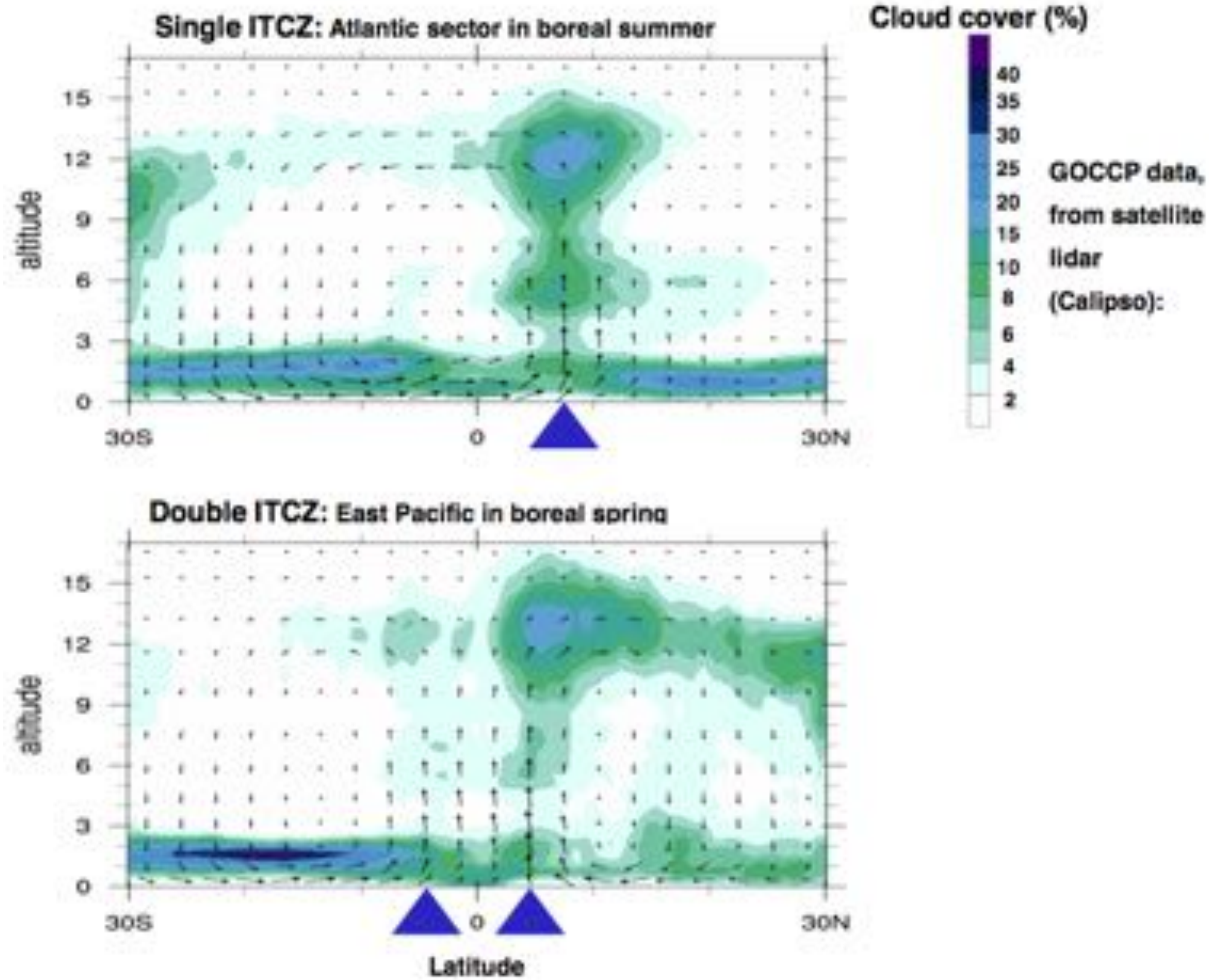
Small in Subtropics (descent)

Large in Tropics (ascent)

[Trenberth 2011]

3. Clouds and Circulation: Tropics and Subtropics

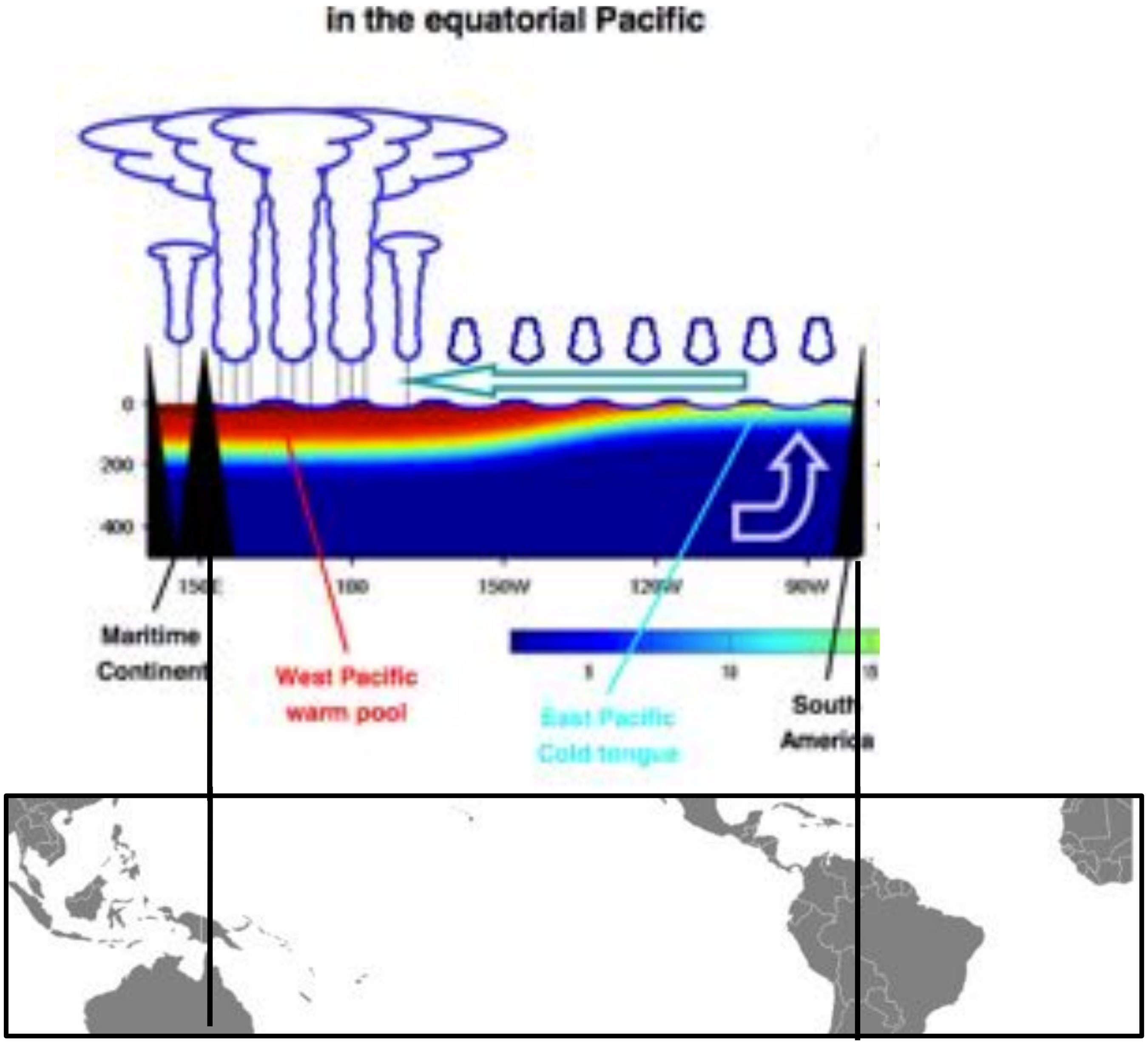
double ITCZ



Courtesy Gilles Bellon

3. Clouds and Circulation: Tropics and Subtropics

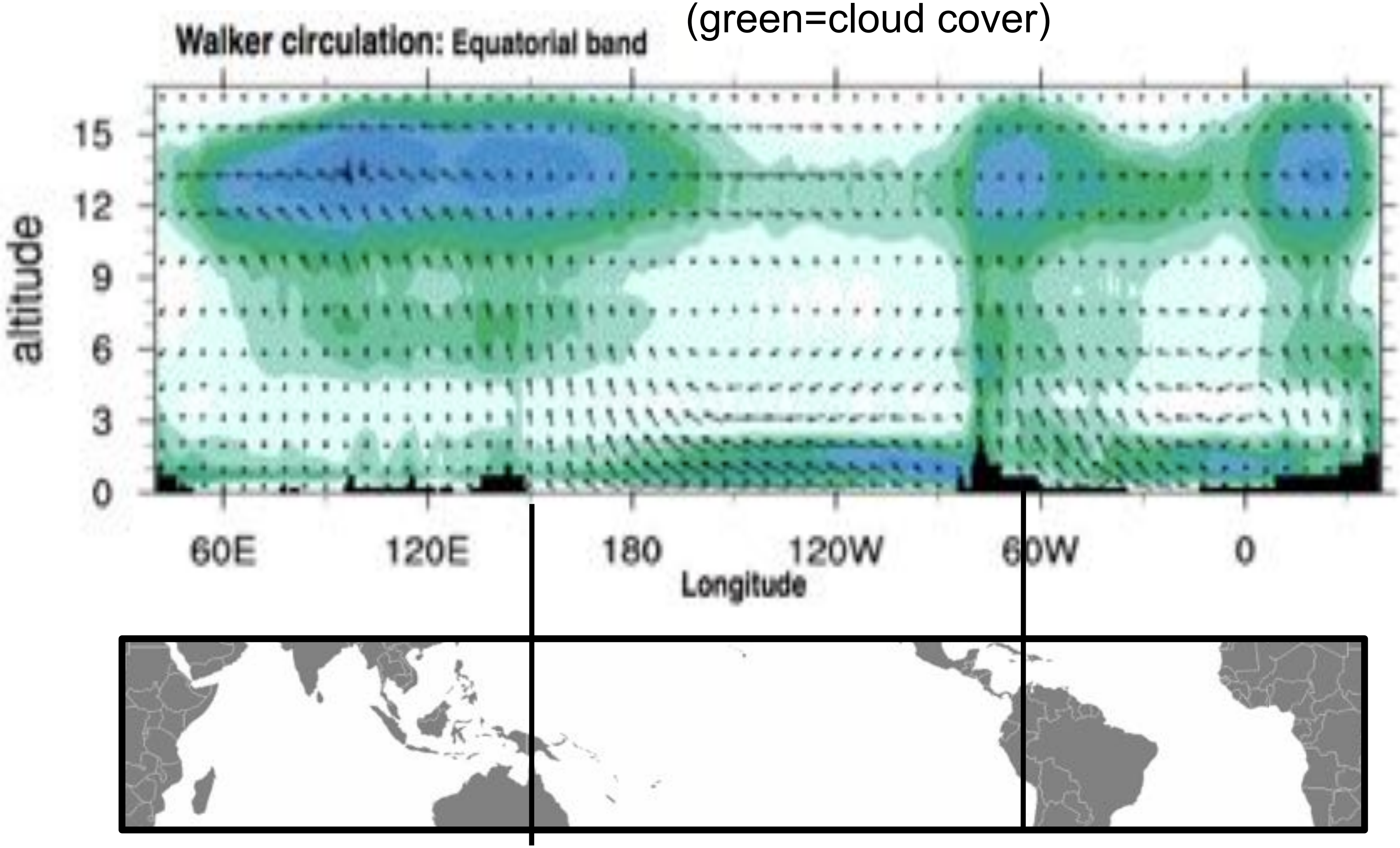
Walker cell



3. Clouds and Circulation: Tropics and Subtropics

Walker cell

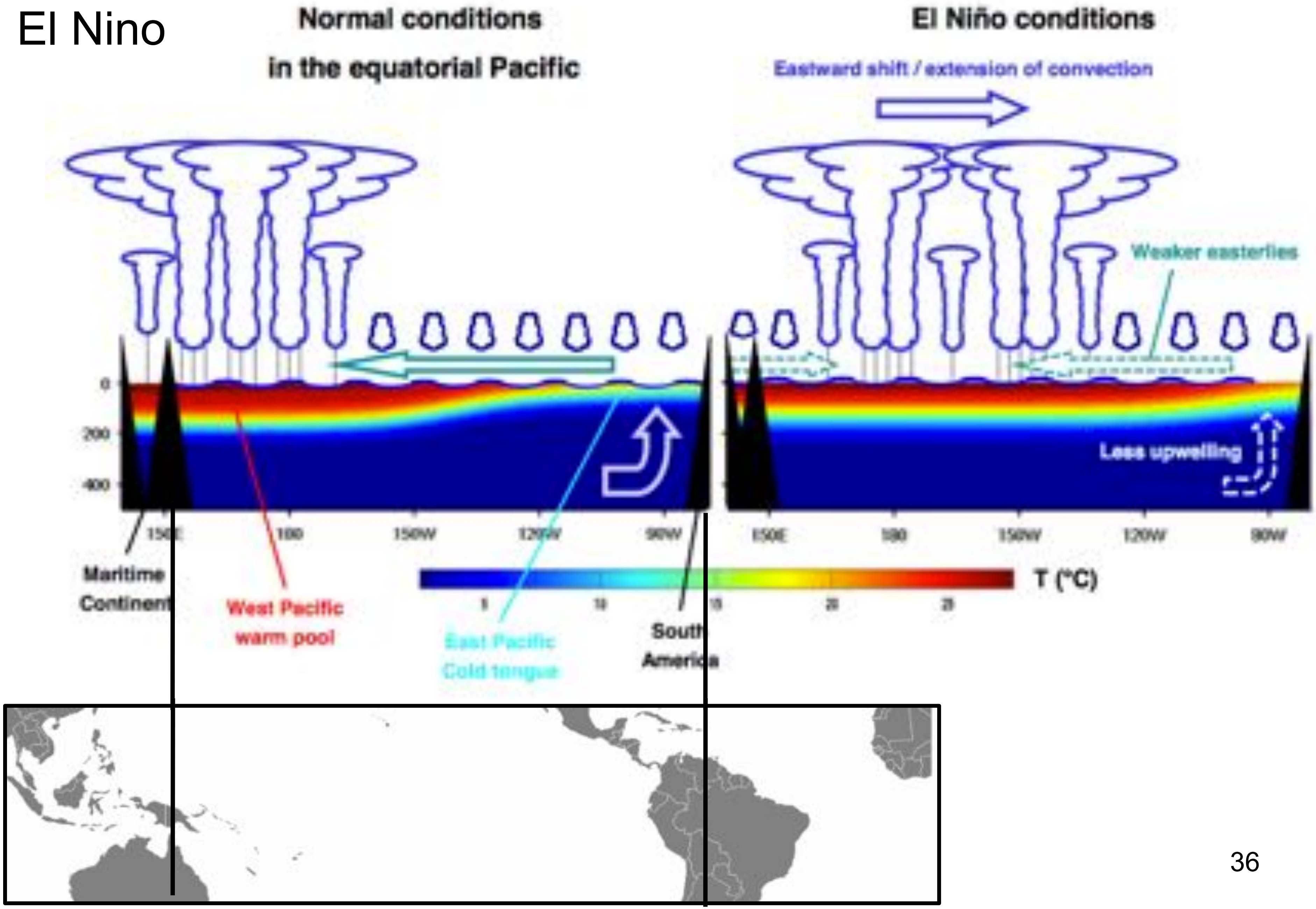
(green=cloud cover)



Courtesy Gilles Bellon

3. Clouds and Circulation: Tropics and Subtropics

El Nino

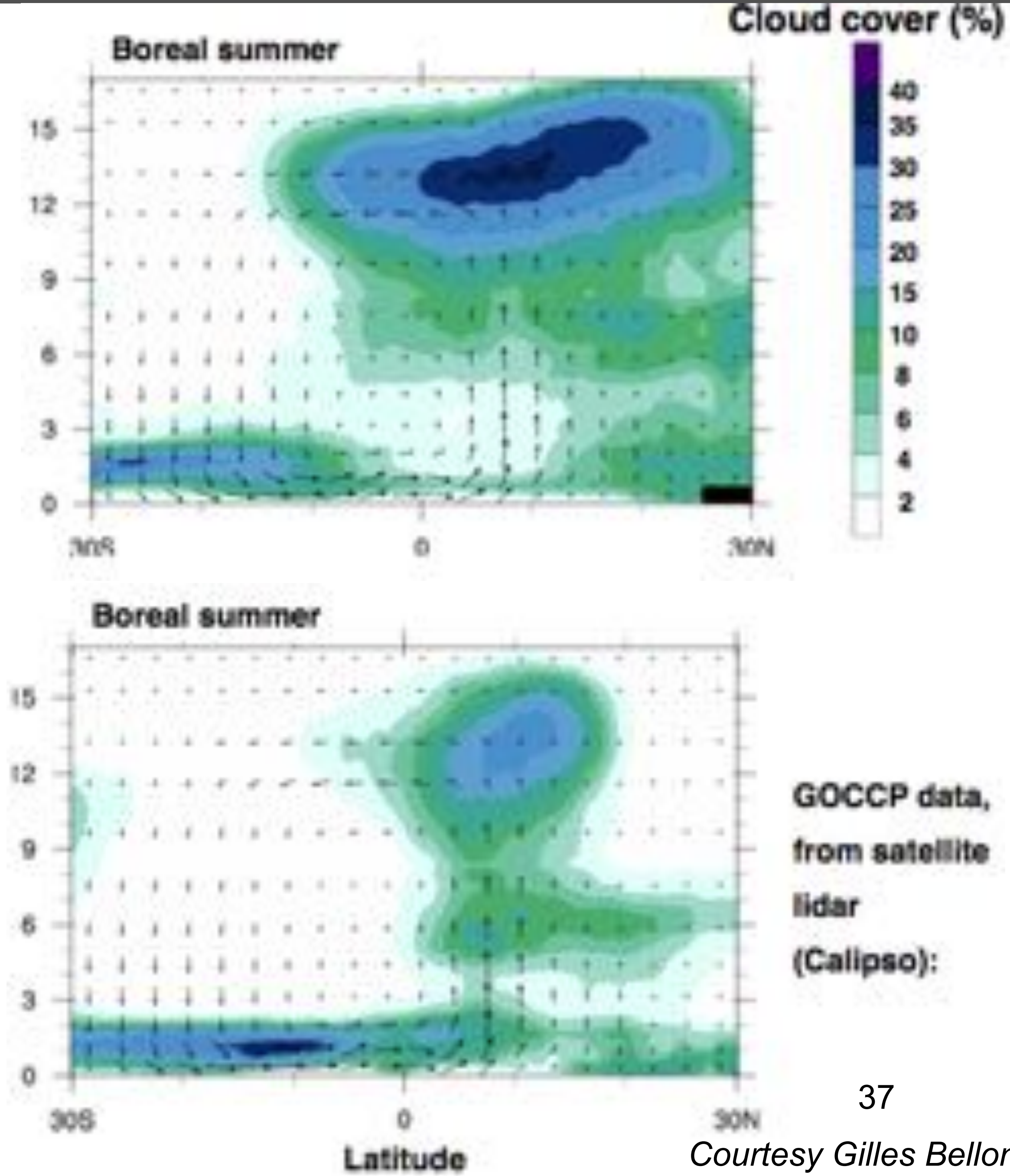


3. Clouds and Circulation: Tropics and Subtropics

Monsoons

Asian monsoon

West-African monsoon



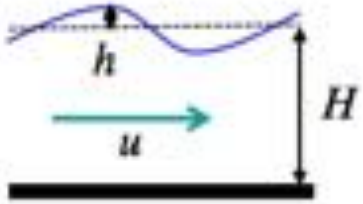
Courtesy Gilles Bellon

Equatorial waves

Linearized shallow-water equations on a β-plane:

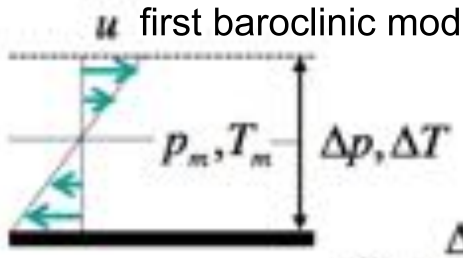
➢ **Classical formulation:**

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



➢ **Tropical atmosphere:**

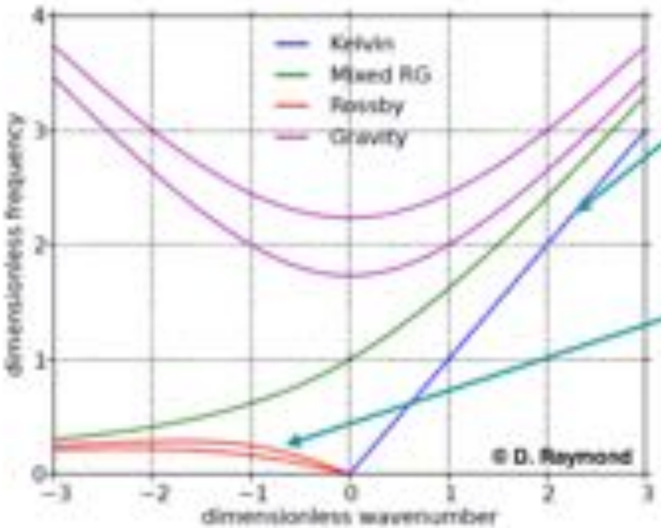
$$\begin{cases} \partial_t u - \beta y v = -\alpha\partial_x T_m \\ \partial_t v + \beta y u = -\alpha\partial_y T_m \\ \partial_t T + \Delta T(\partial_x u + \partial_y v) = 0 \end{cases}$$



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

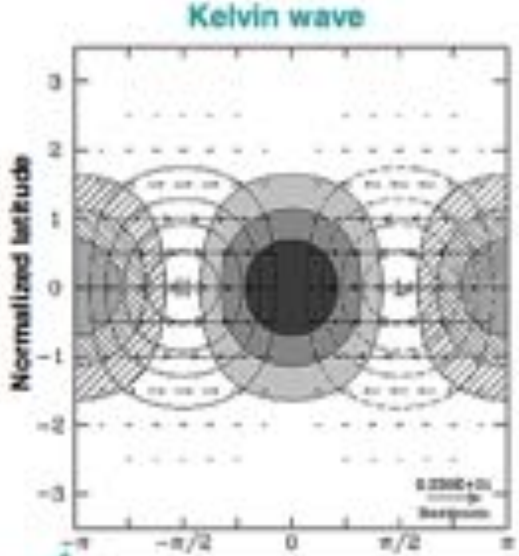
[Matsuno 66]

Dispersion diagram:

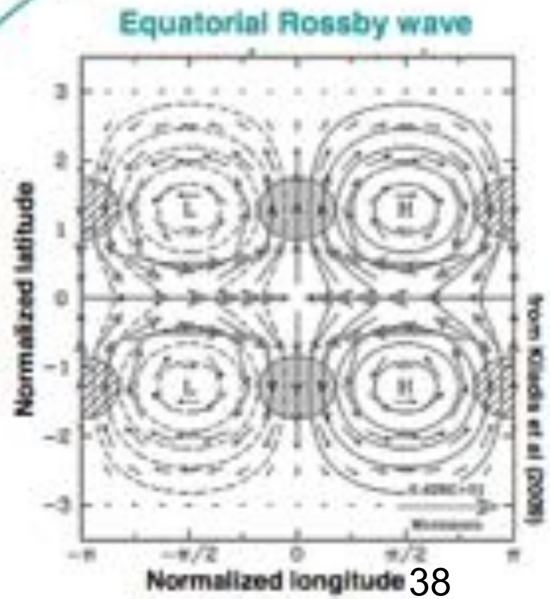


shading ⇔ convergence/divergence

Kelvin wave



Equatorial Rossby wave



3. Clouds and Circulation: Tropics and Subtropics

Equatorial waves

shading ⇔ convergence/divergence

Linearized shallow-water equations on a β-plane:

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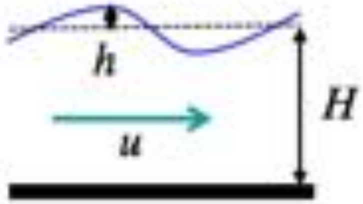

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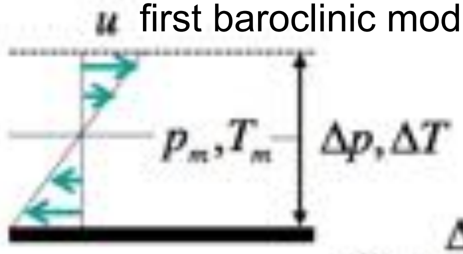
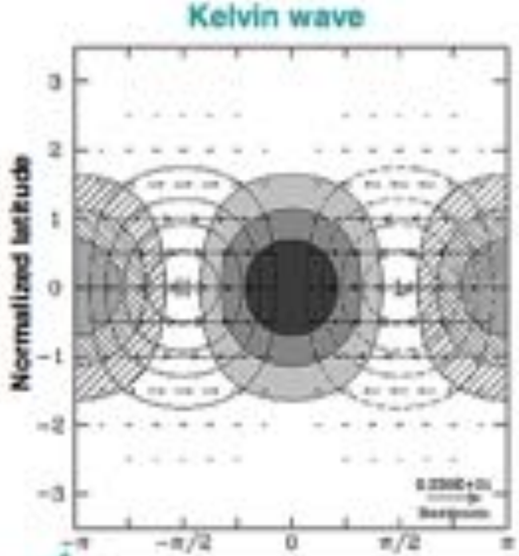
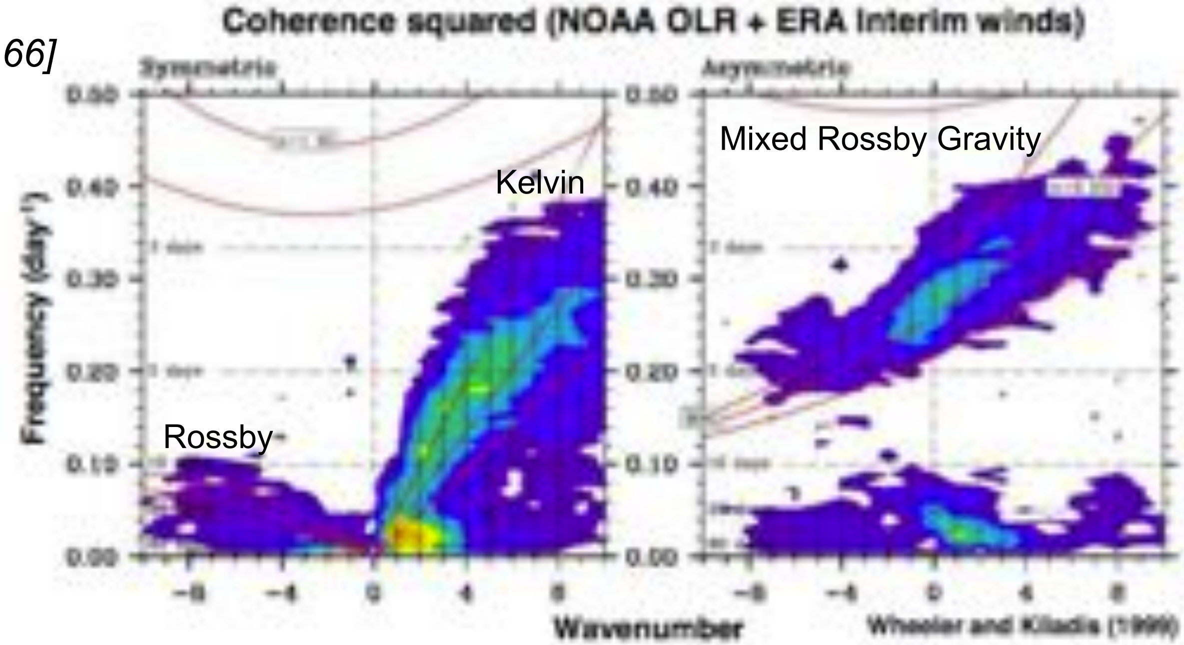
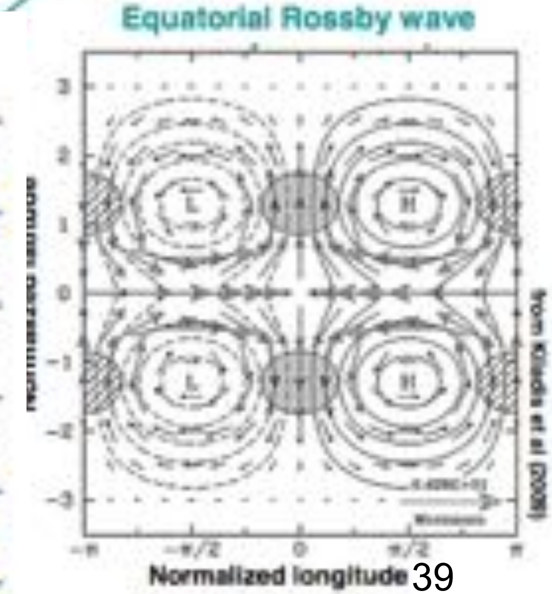




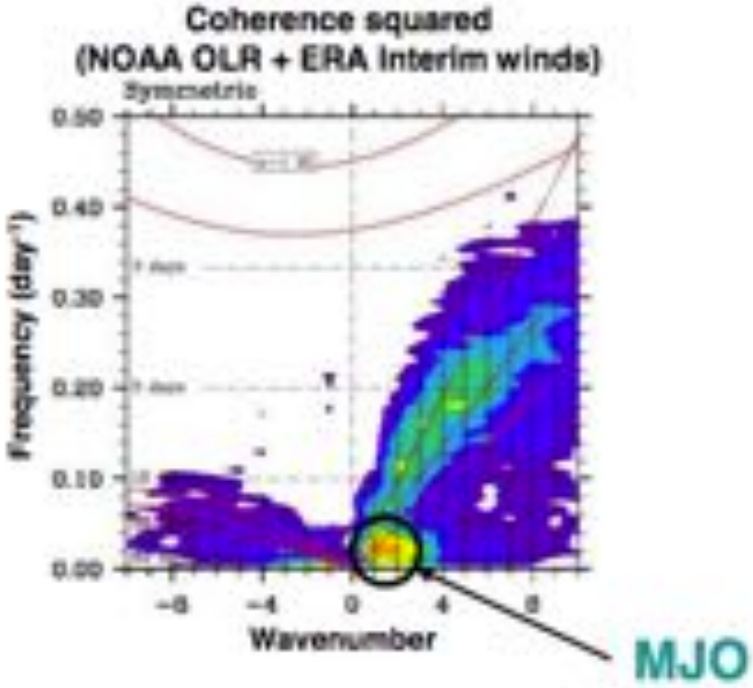
[Matsuno 66]

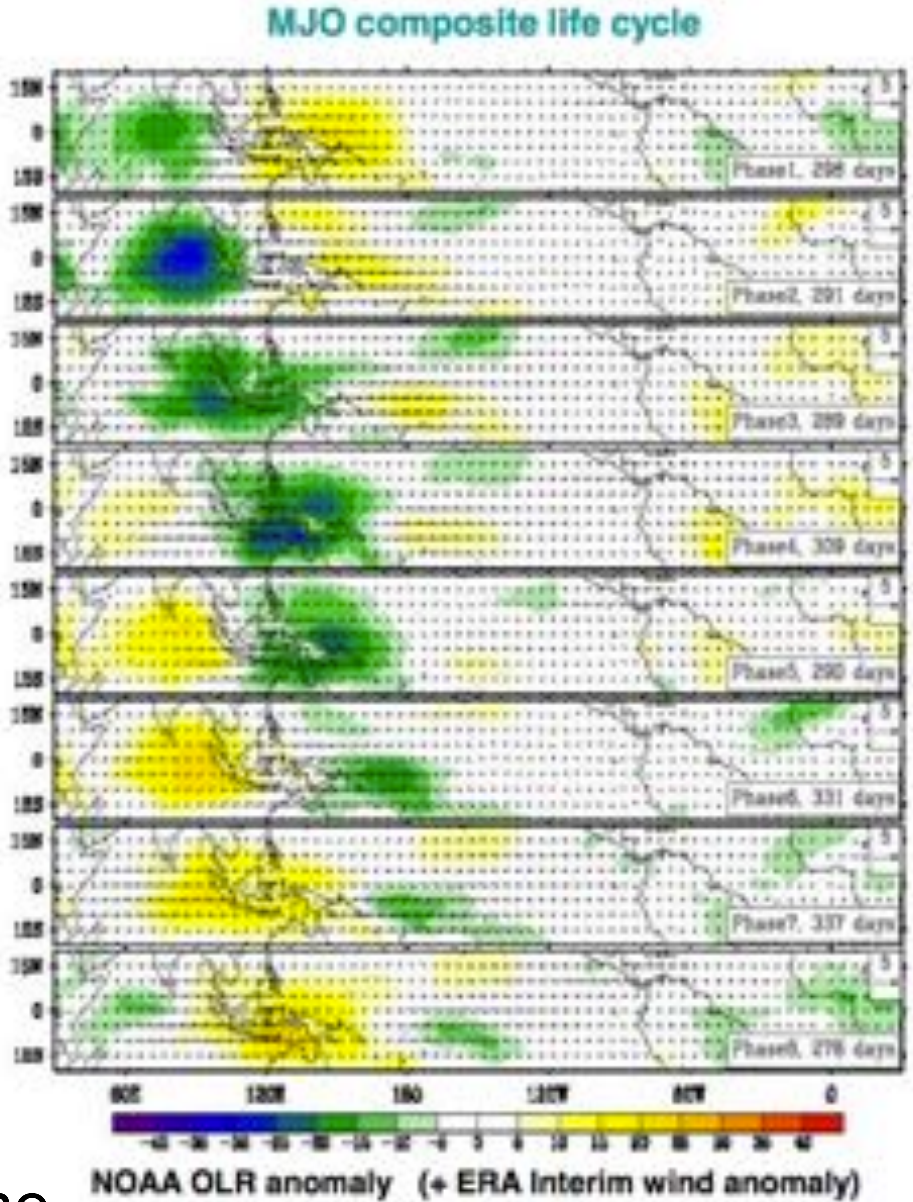




3. Clouds and Circulation: Tropics and Subtropics

MJO

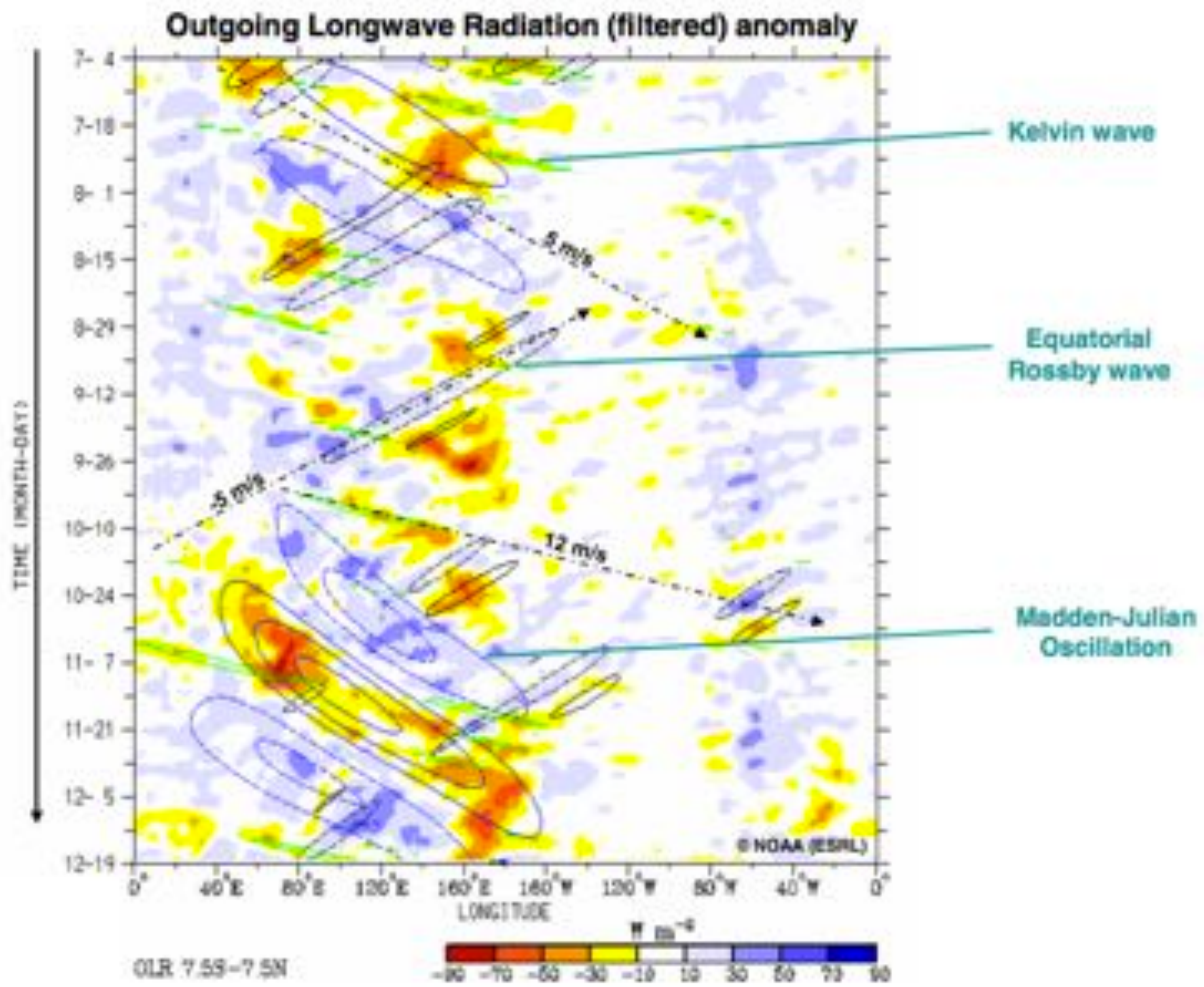




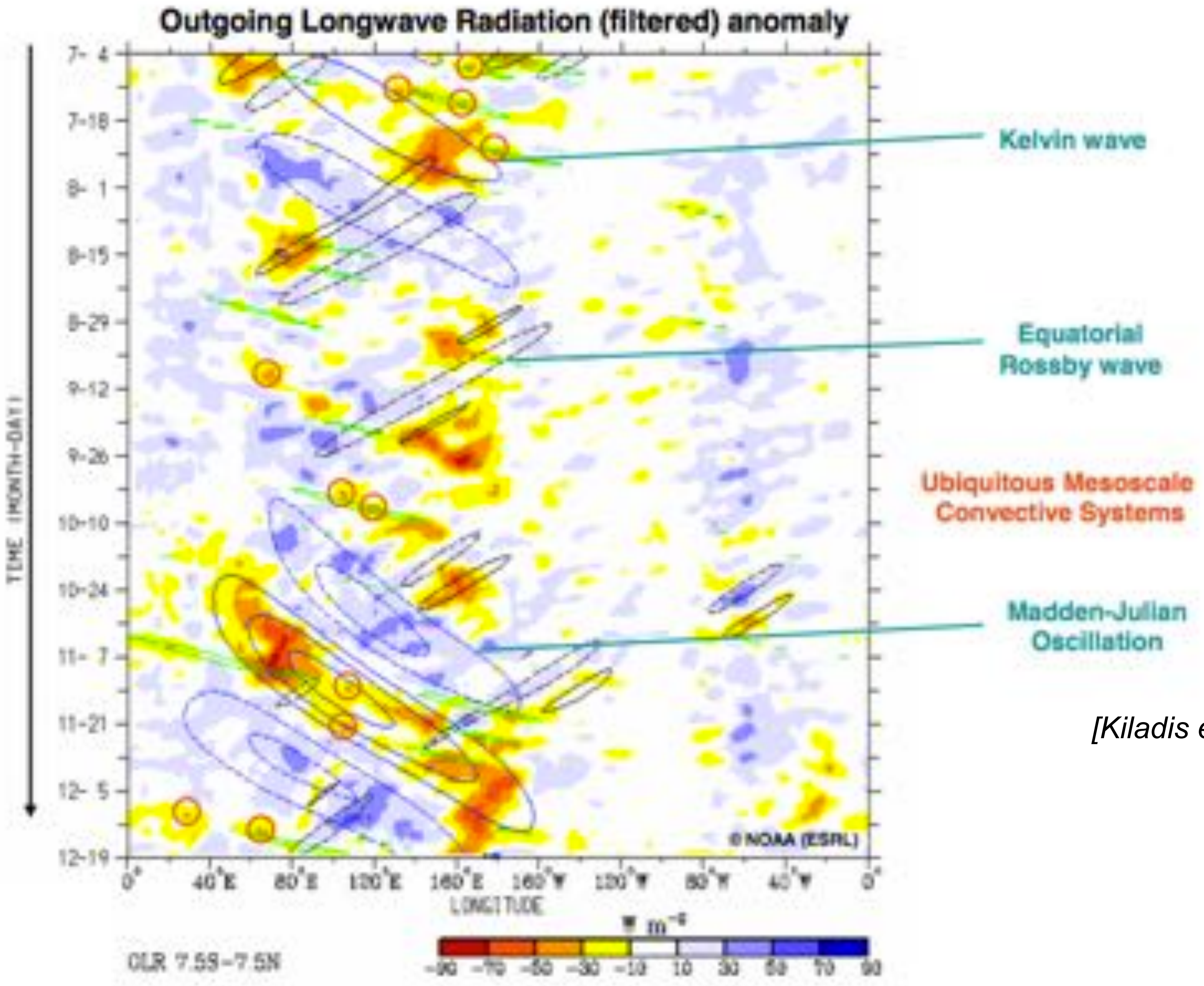
eastward phase speed (4-8 m/s)

time

3. Clouds and Circulation: Tropics and Subtropics



3. Clouds and Circulation: Tropics and Subtropics

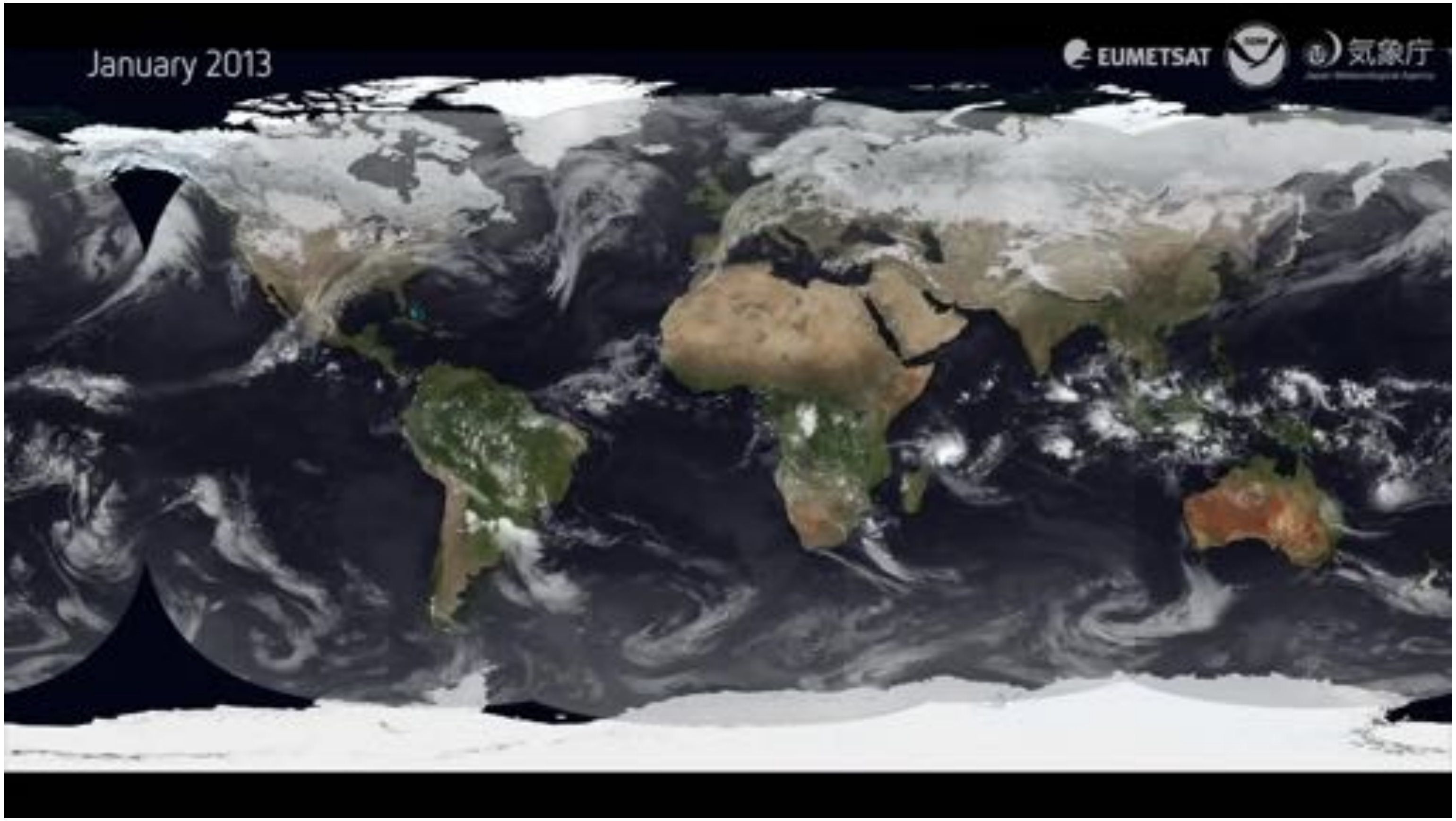


[Kiladis et al 09]

3. Clouds and Circulation

Recall : spatial distribution

Brightness temperature from satellite (white ⇔ cold cloud tops)



Large extratropical storm systems

subtropics: ~no high clouds

ITCZ = Intertropical convergent zone

« A year of weather »

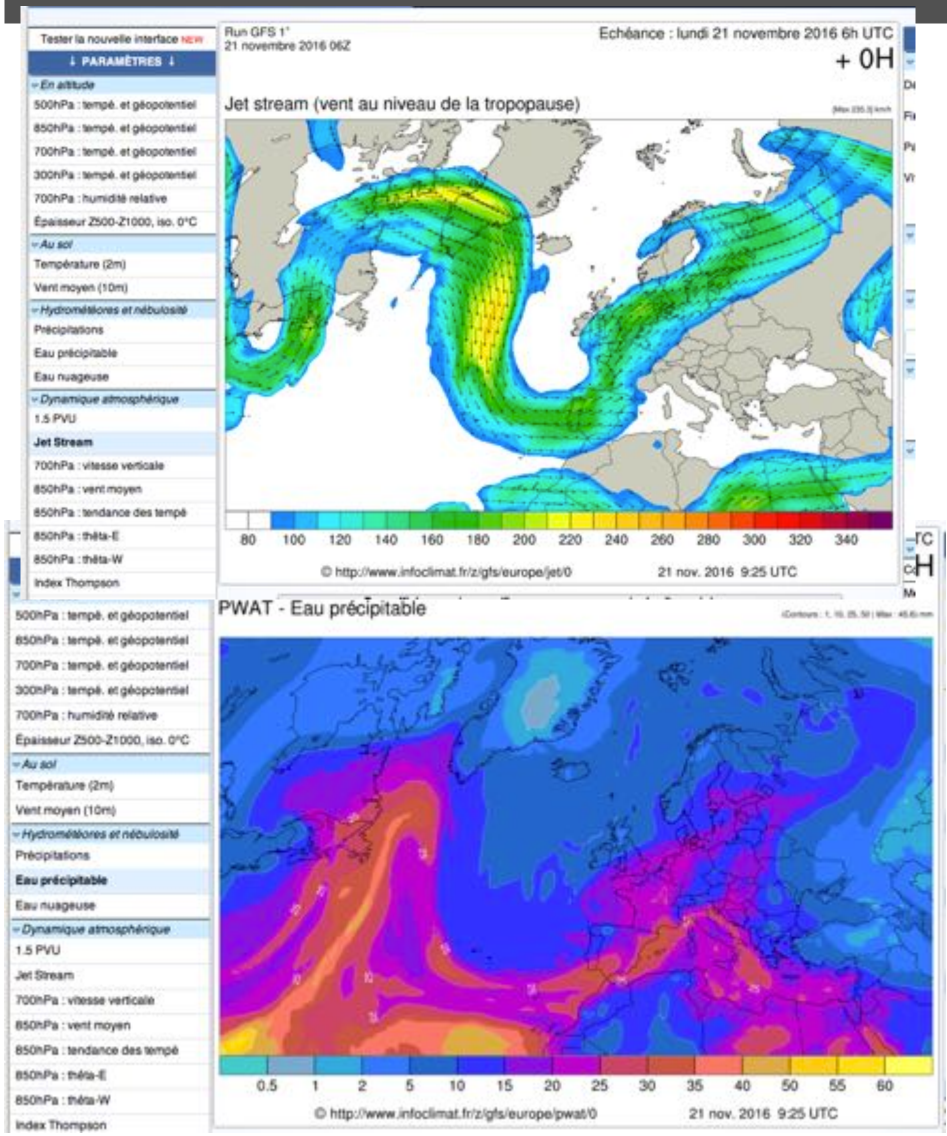
Extratropics: low and high pressure systems within the polar jet

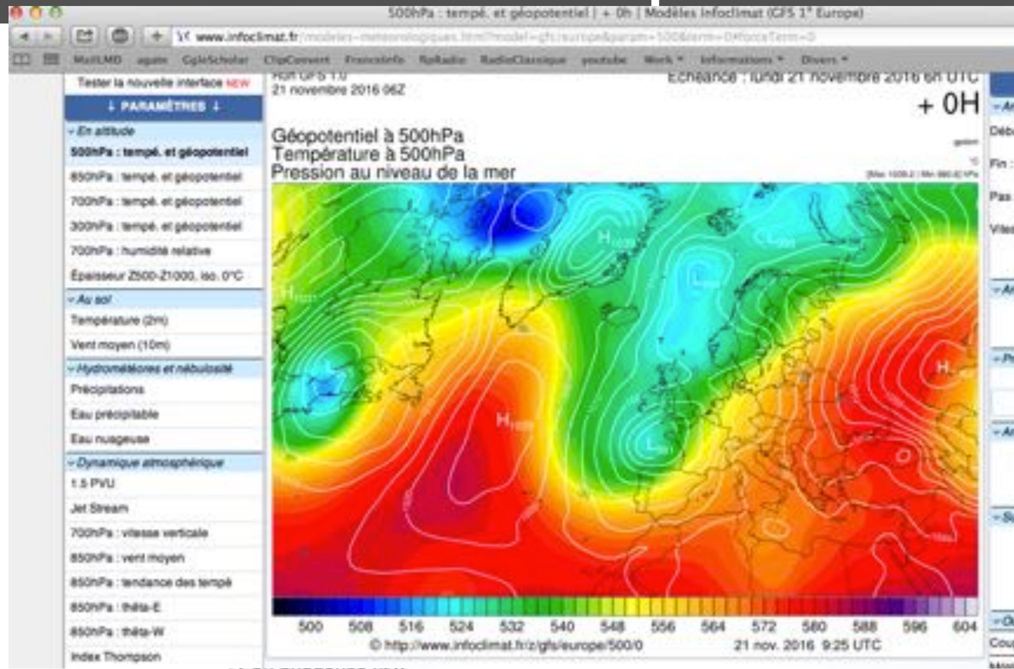
Question: What explains different behaviors between tropics and extratropics?

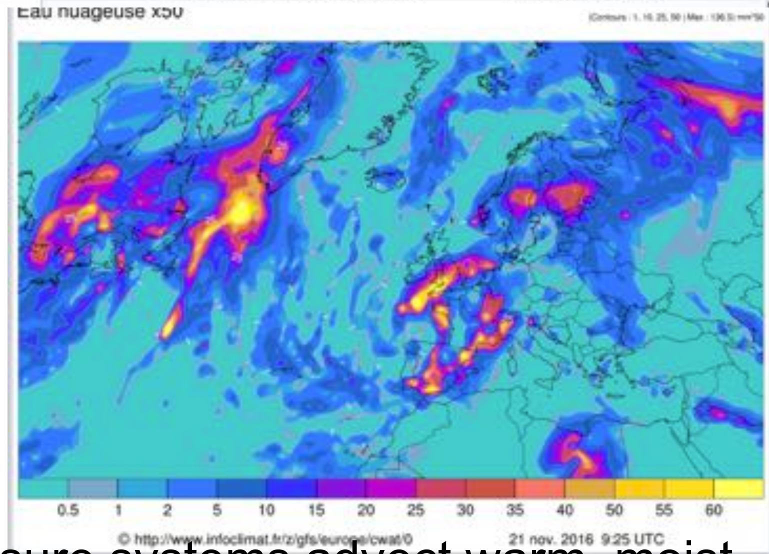
3. Clouds and Circulation: Extratropics

atmospheric jet (near tropopause)

3. Clouds and Circulation: Extratropics







Weather map :

- Clouds and precip are found where low/high pressure systems advect warm, moist air into northern colder latitudes => East of lows
- Note that highs are typically associated with reduced rain and cloudiness.

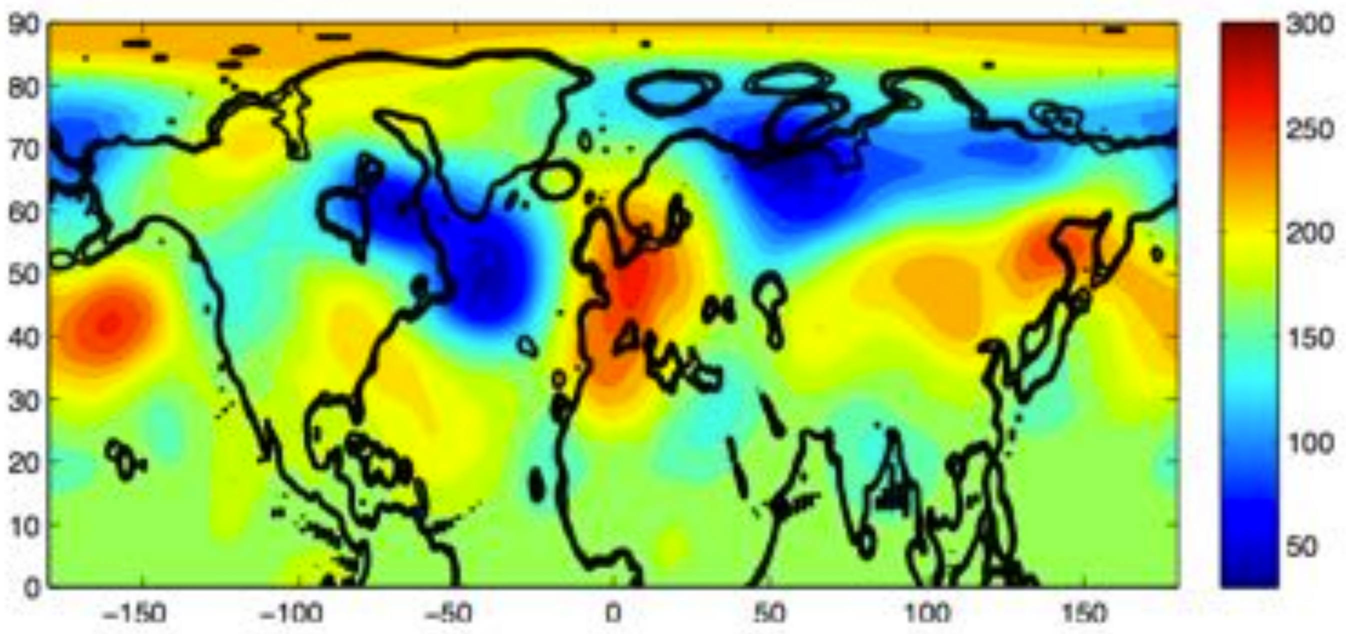
3. Clouds and Circulation: Extratropics

Exercise

Here is a map of the 500hPa geopotential height.

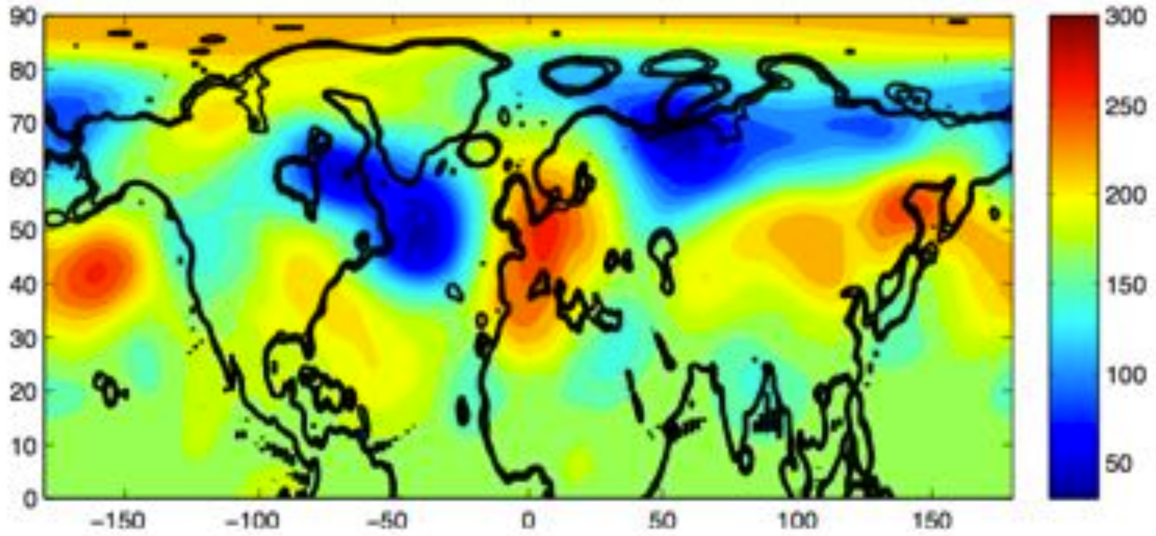
- Indicate the lows, the highs, and the circulation around them.

- Where do you expect the strongest precip to occur? The weakest?

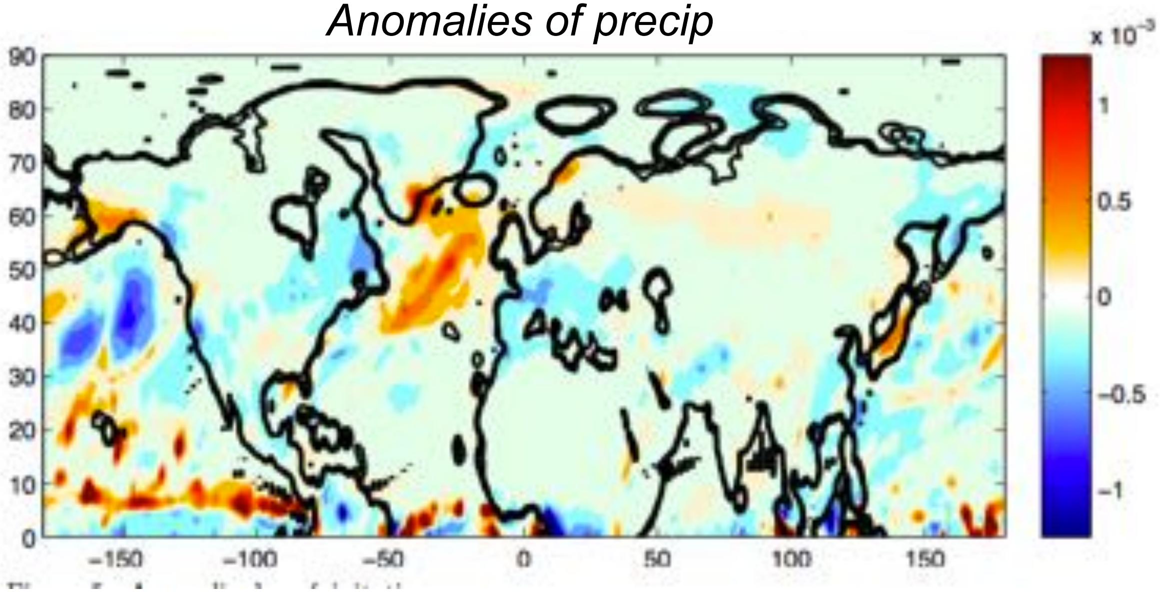


3. Clouds and Circulation: Extratropics

500hPa geopotential height

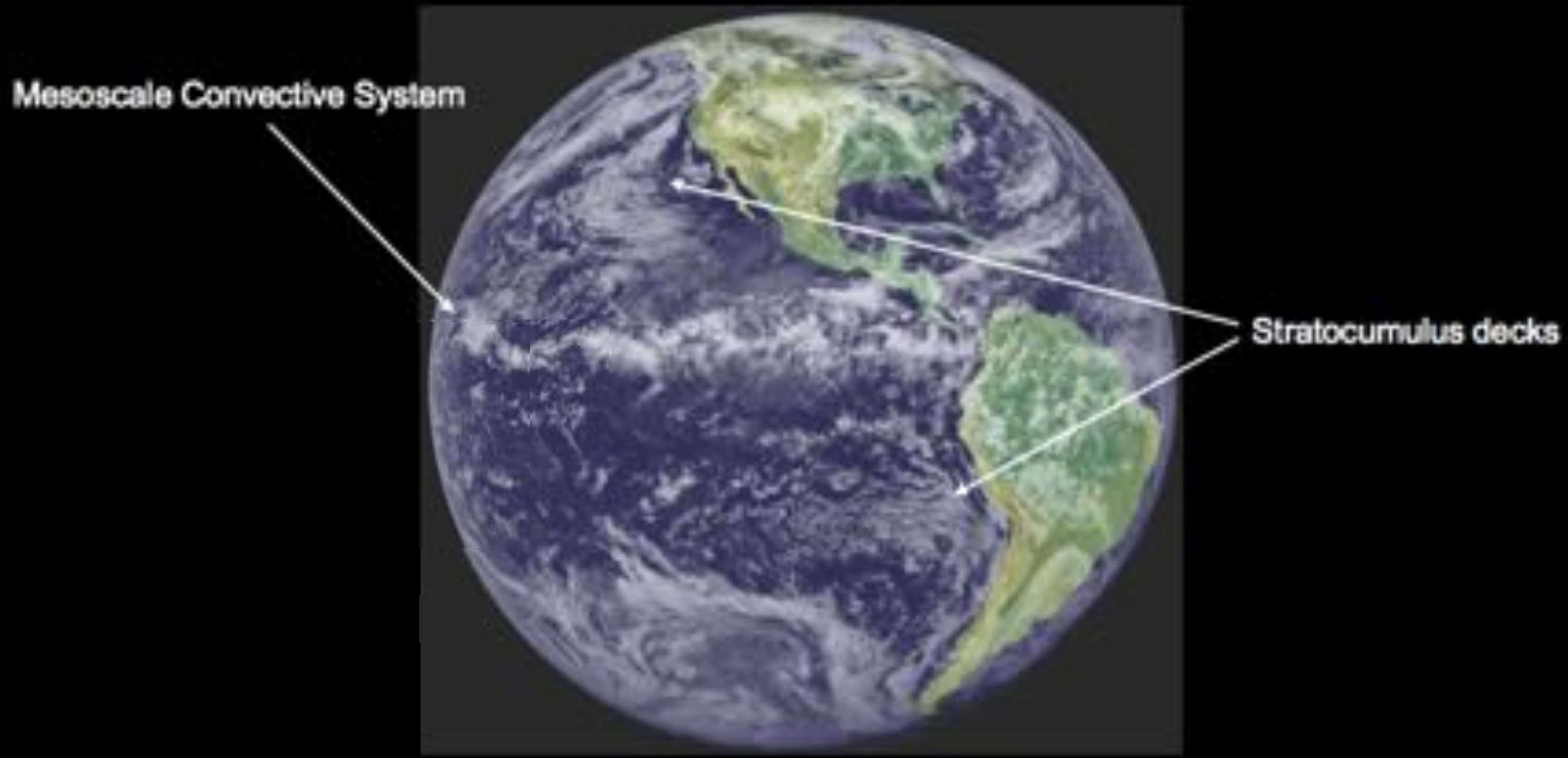


Anomalies of precip



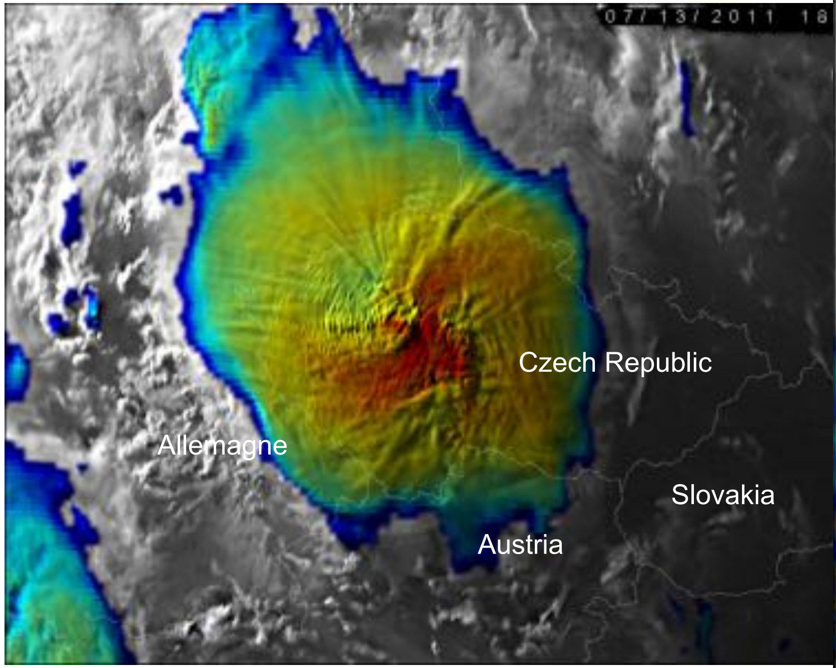
Convective organization

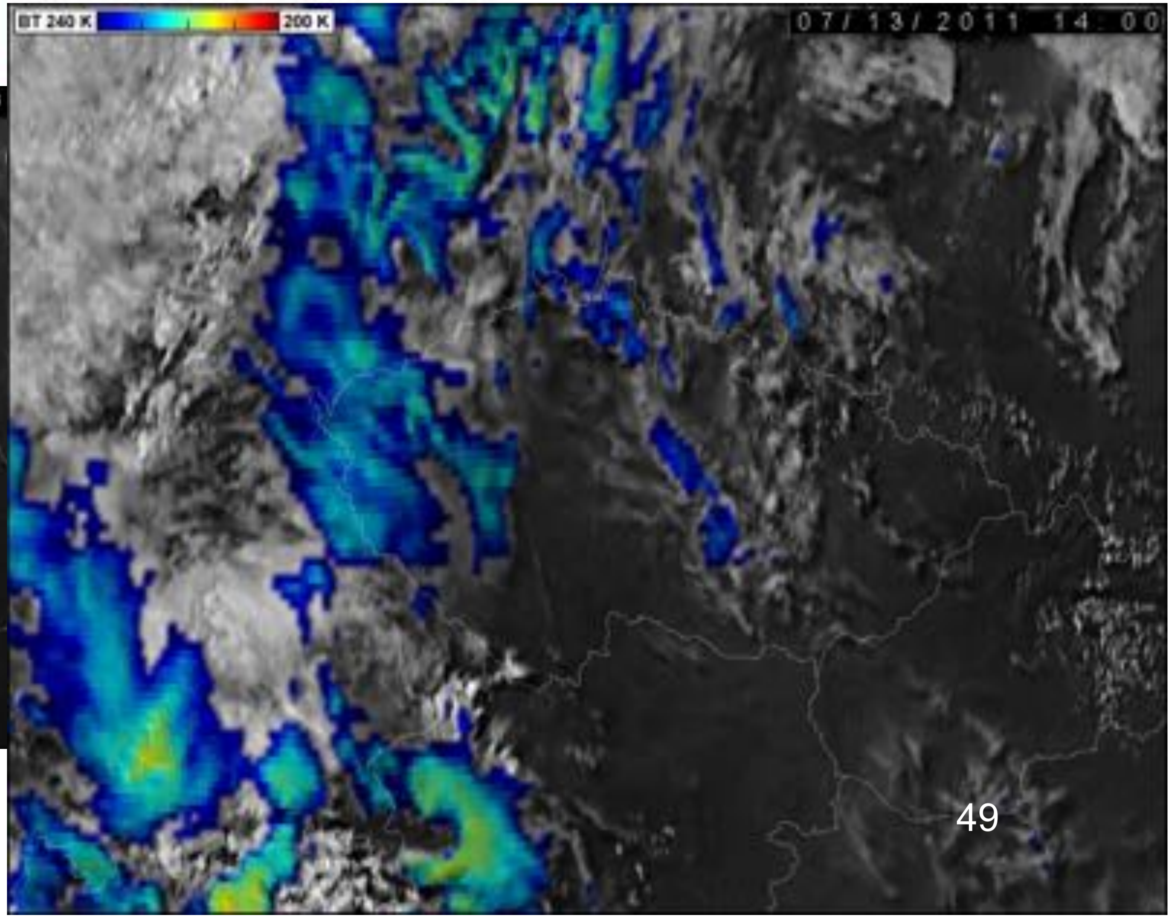
Note:
Many more interesting phenomena associated with clouds!
For instance, clouds are also often spatially organized at the mesoscale …



Convective organization: MCCs

Mesoscale convective systems: include Mesoscale Convective Complexes (MCCs), squall lines, hurricanes…

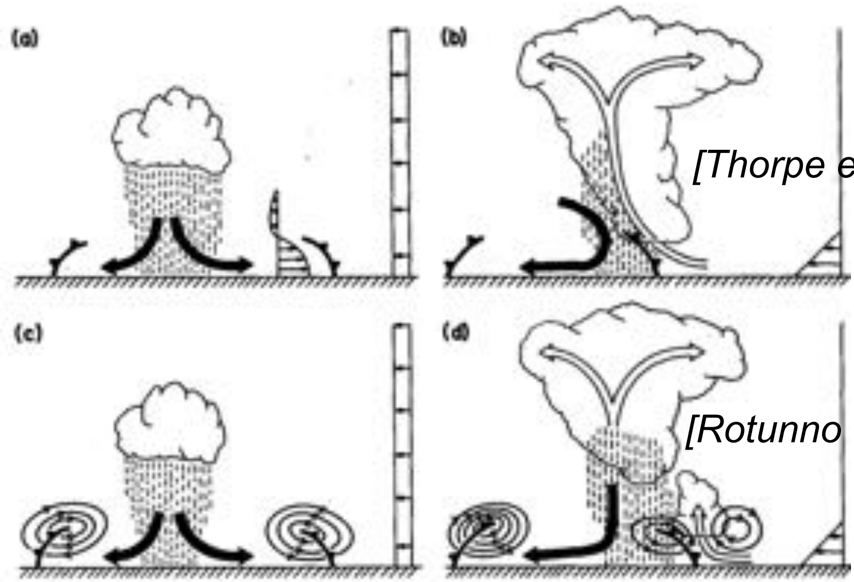




Convective organization: squall lines

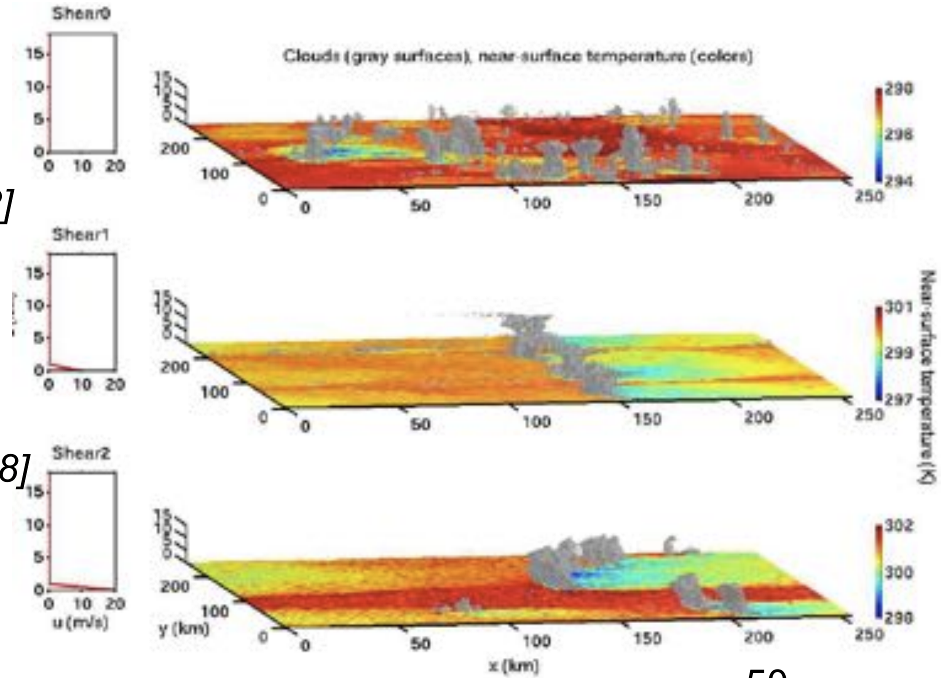
Squall lines

Role of vertical shear & cold pools



[Thorpe et al 1982]

[Rotunno et al 1988]



[Rotunno et al. 1988; Fovell and Ogura 1988; Garner and Thorpe 1992; Weisman and Rotunno 2004; Houze 2004; Moncrieff 2010]

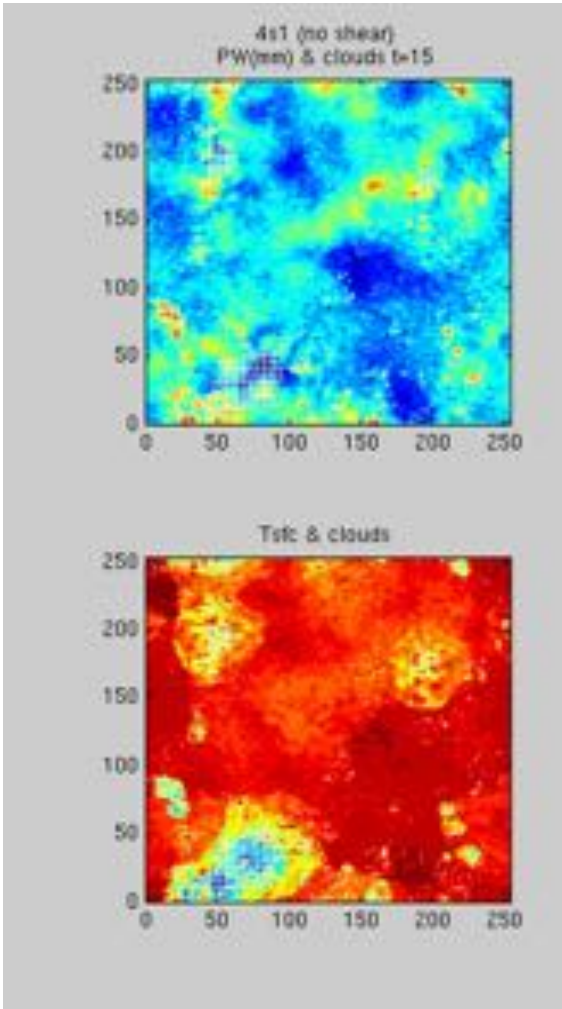
Convective organization: squall lines

No shear

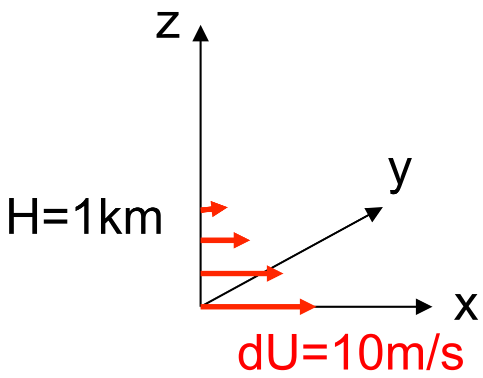
Top view

Color: PW

Color: Tsfc



Convective organization: squall lines

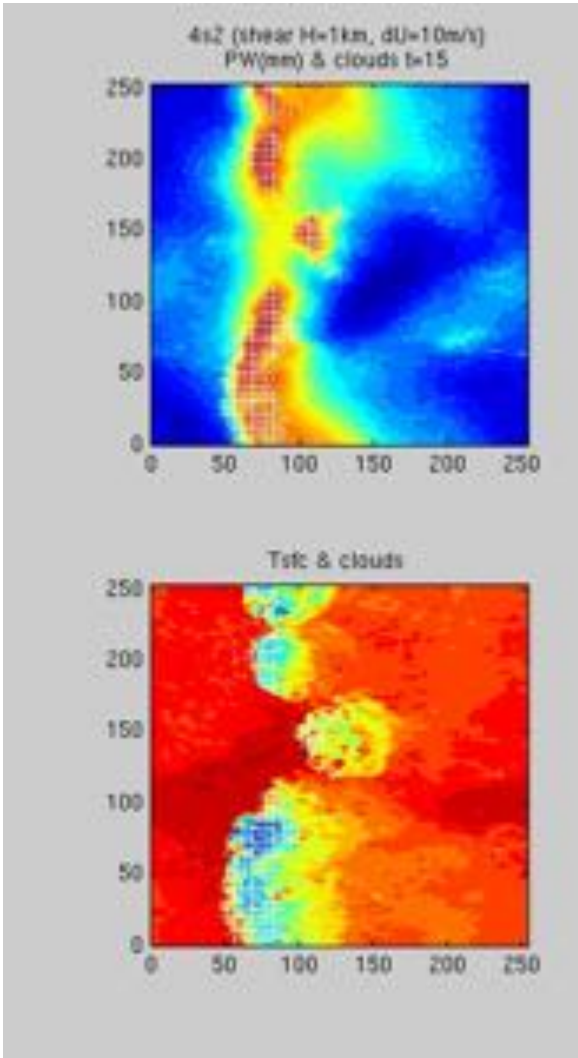


Critical shear

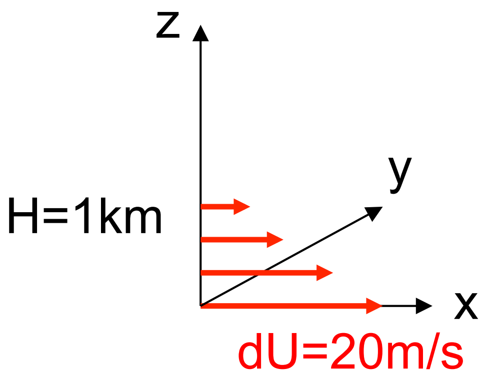
Top view

Color: PW

Color: Tsfc



Convective organization: squall lines

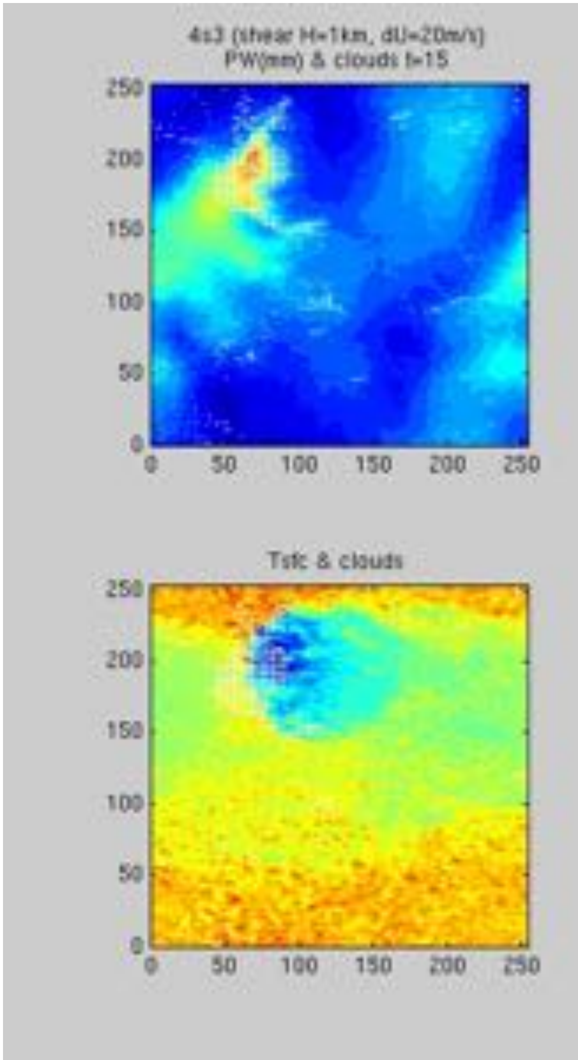


Super critical shear

Top view

Color: PW →

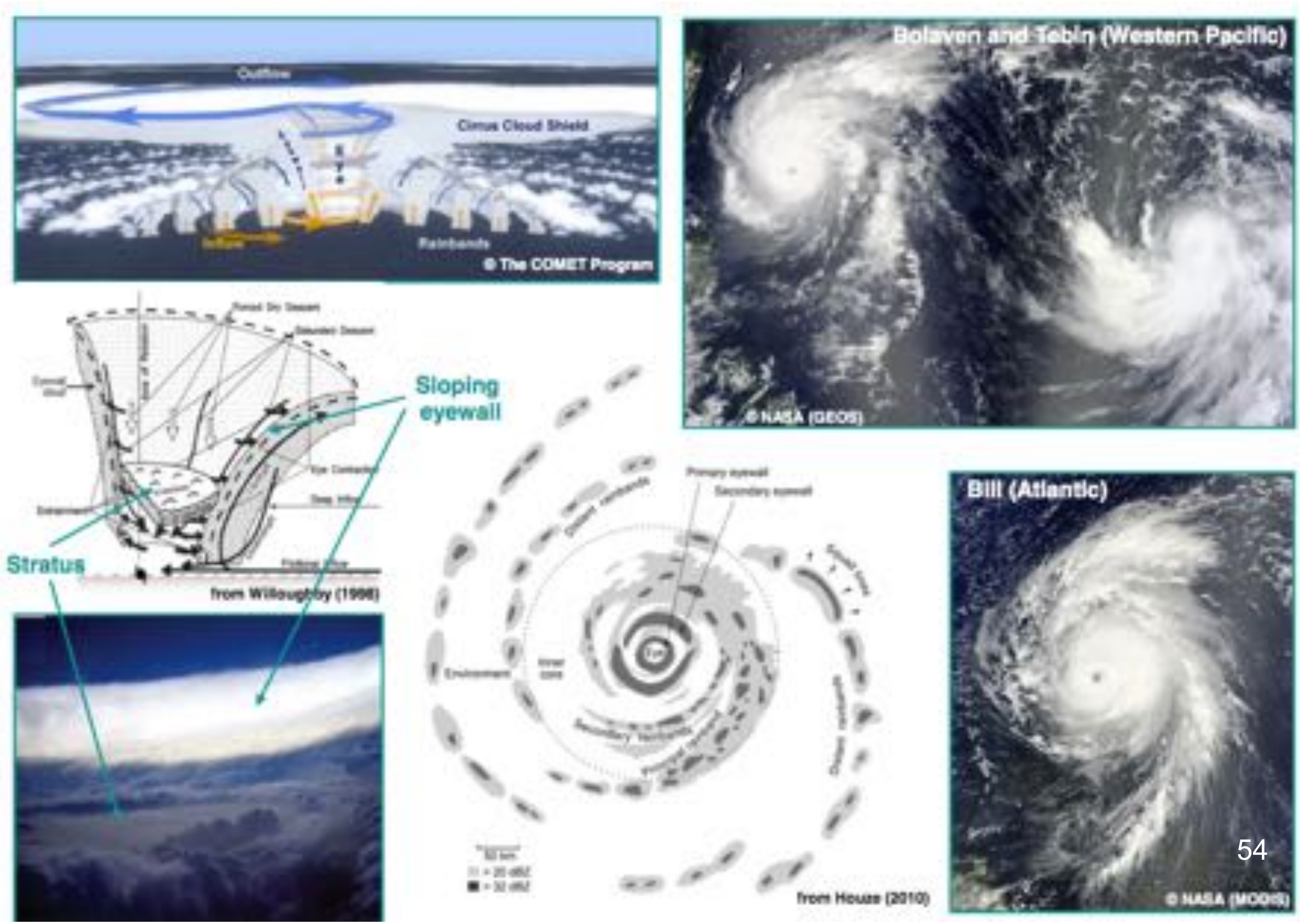
Color: Tsfc →



[Robe & Emanuel 1996; Muller 2013]

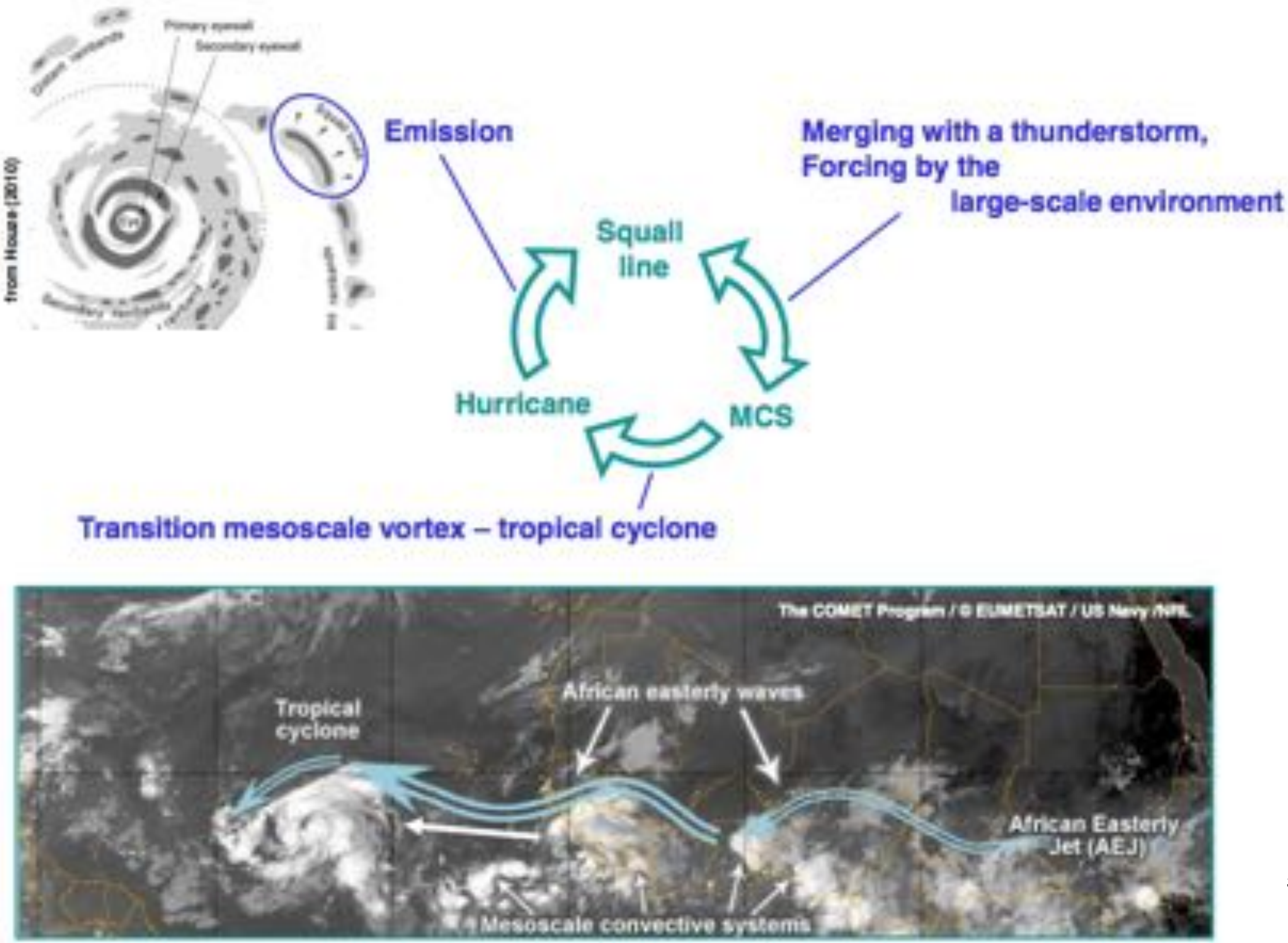
Convective organization: hurricanes

Hurricanes

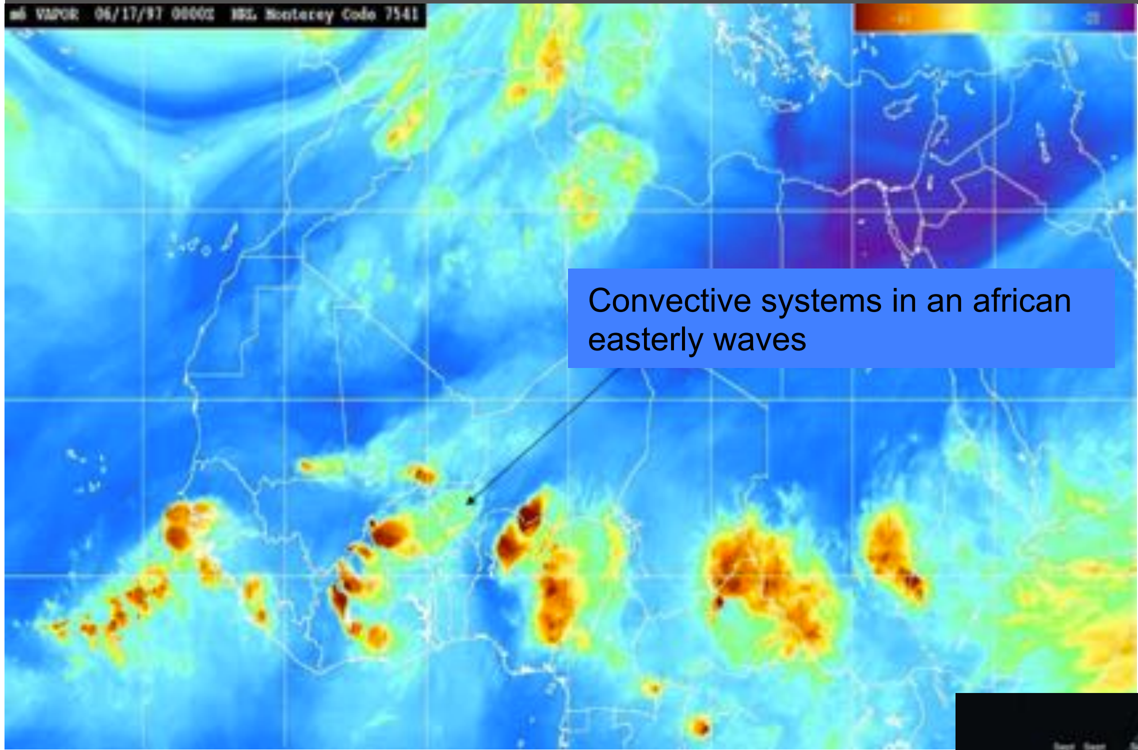


Convective organization

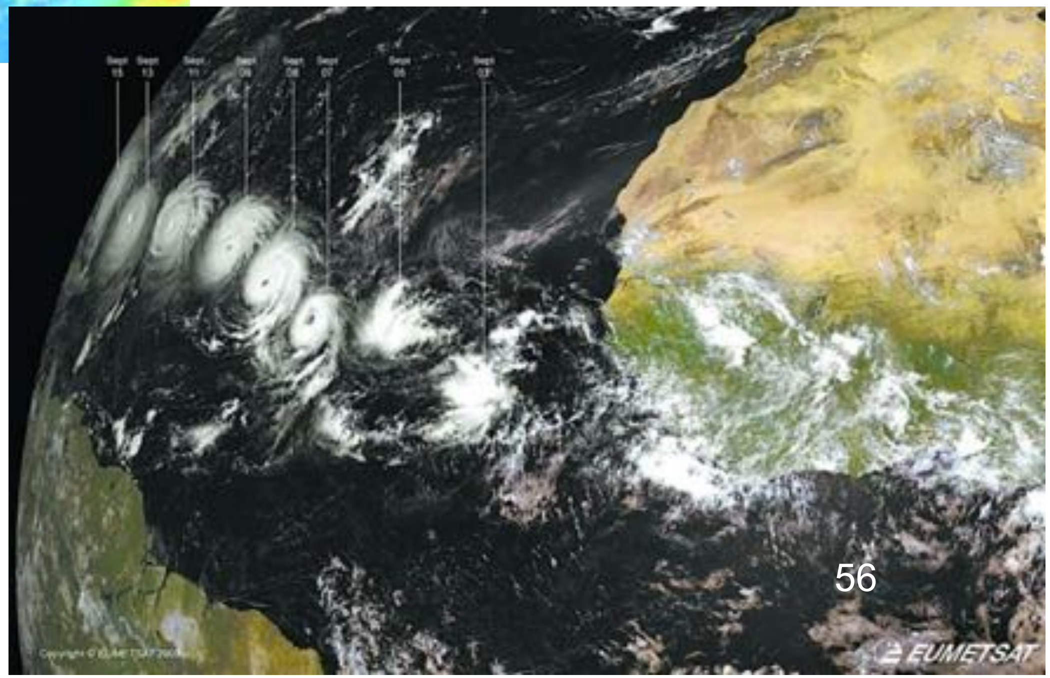
Transitions between organized structures



Convective organization



Hurricane Isabel off the coast of Africa



Clouds and atmospheric convection: THE END

Caroline Muller

CNRS/Laboratoire de Météorologie Dynamique (LMD)

Département de Géosciences

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