Tropical Meteorology – Clouds

Caroline Muller

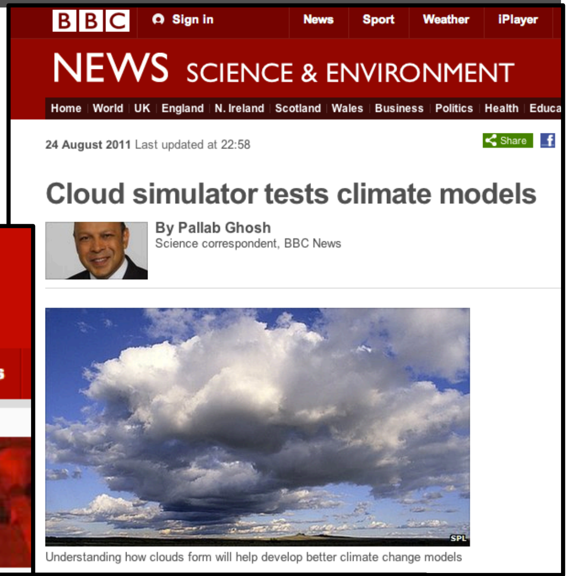
Tropical Meteorology – Clouds

and clouds

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

Tropical Meteorology – Clouds

An era of blooming cloud and climate science



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24 August 2011 Last updated at 22:58

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Cloud simulator tests climate models

By Pallab Ghosh
Science correspondent, BBC News

Understanding how clouds form will help develop better climate change models

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Climate change: Can we even Should we even try?

By Shelby Lin Erdman, CNN

Global warming and the resulting droughts help make climate manipulation a hotly debated issue.

(CNN) -- The Mas Technology has l for its engineerin symposium at MI scientists from ar a hot facet of the

The title of the sy the questions sur science: "Enginee We Do It? Should

The New York Times

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TEMPERATURE RISING

Clouds' Effect on Climate Change Is Last Bastio Dissenters

By JUSTIN GILLIS

Published: April 30, 2012 | 808 Comments

LAMONT, Okla. — For decades, a small group of scientific dissenters has been trying to shoot holes in the prevailing science of climate change, offering one reason after another why the outlook simply must be wrong.

Enlarge This Image

Josh Haner/The New York Times

Over time, nearly every one of their arguments has been knocked down by accumulating evidence, and polls say 97 percent of working climate scientists now see global warming as a serious risk.

Yet in recent years, the climate change skeptics have seized on one last

HOME SEARCH The New York Times

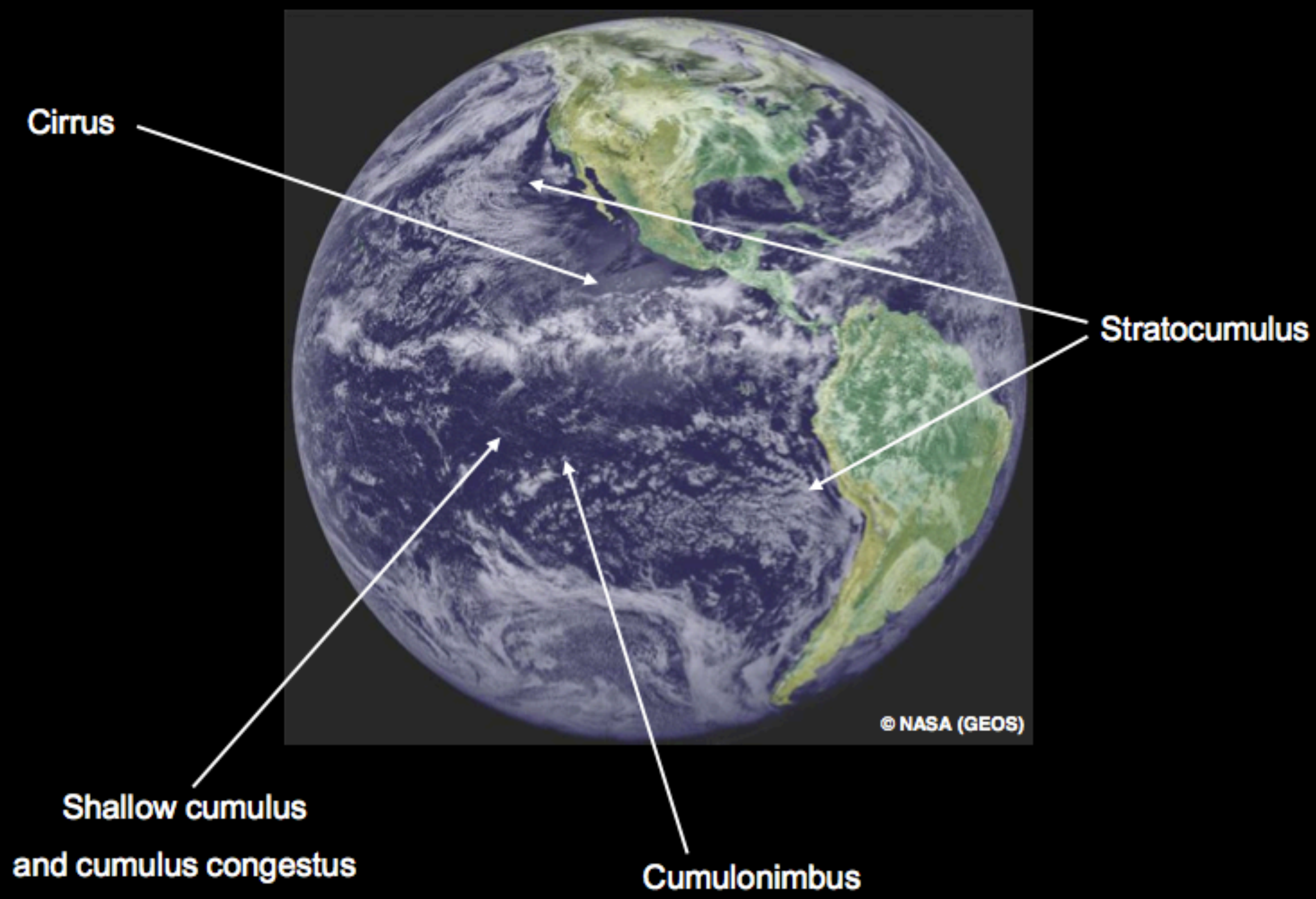
Green
Energy, the Environment and the Bottom Line

More on the Science of Clouds and Climate

By JUSTIN GILLIS MAY 3, 2012 1:28 PM 12 Comments

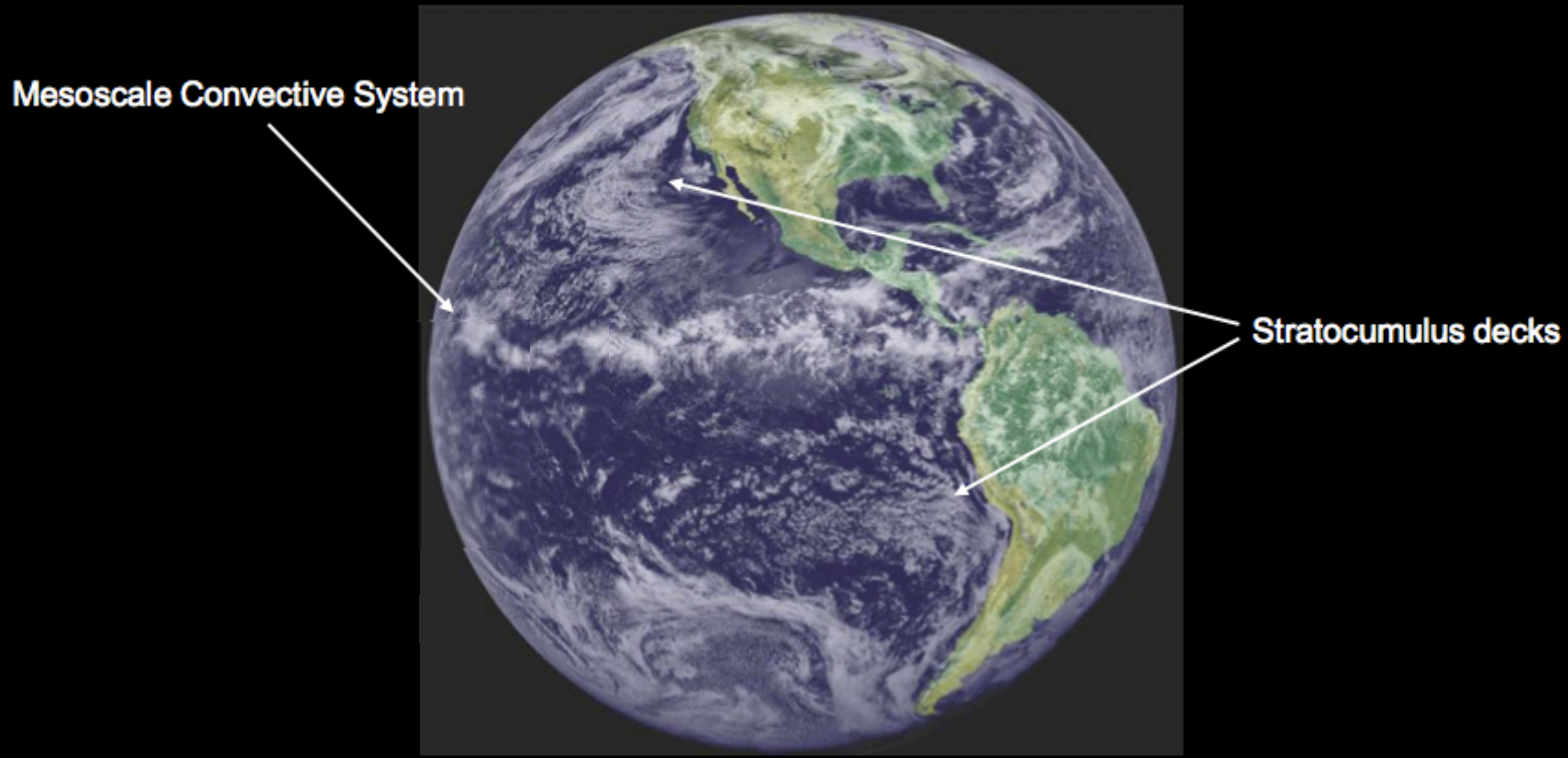
Tropical Meteorology – Clouds

Tropical and subtropical clouds are diverse, …



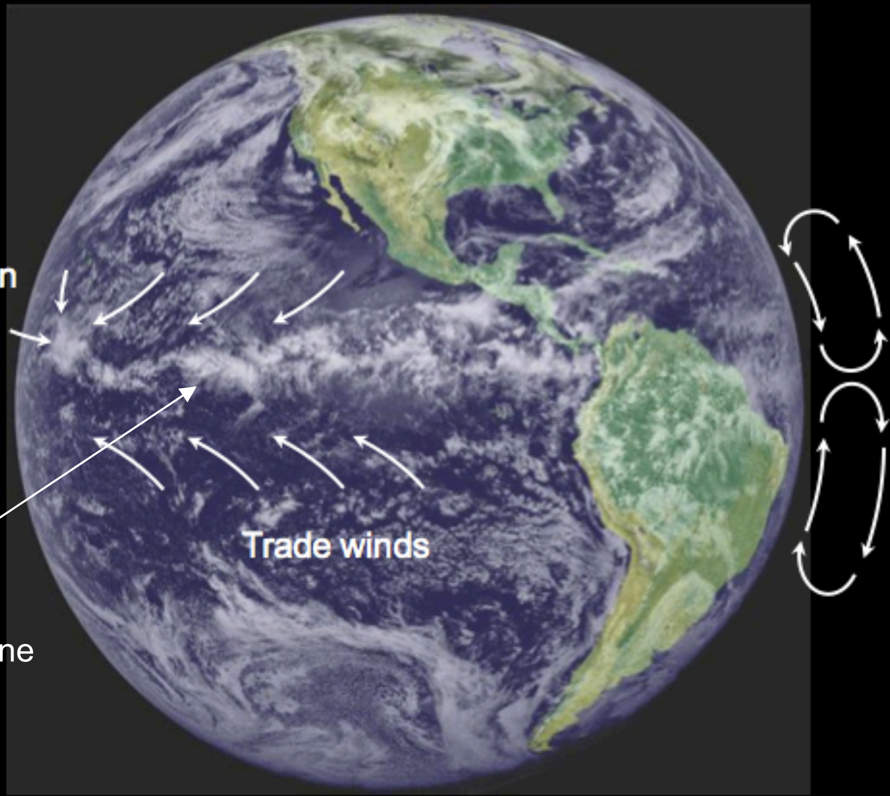
Tropical Meteorology – Clouds

… often spatially organized, …



Tropical Meteorology – Clouds

… and coupled to circulations.



Tropical Meteorology – Clouds

Cloud types, atmospheric thermodynamics

Convective organization

Coupling with circulation

Cloud types

Cumulus: heap, pile

Stratus: flatten out, cover with a layer

Cirrus: lock of hair, tuft of horsehair

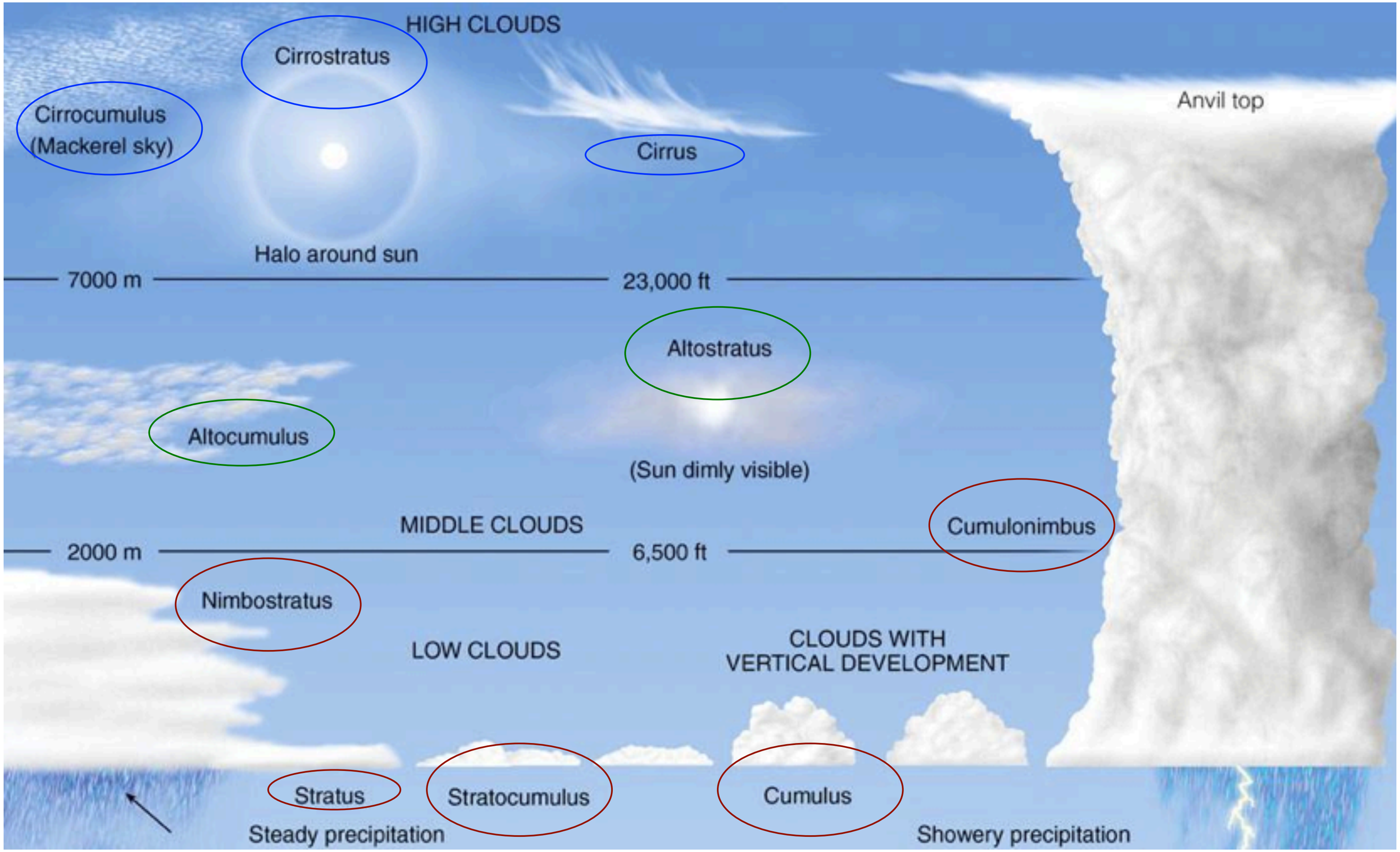
Nimbus: precipitating cloud

Altum: height

Combined to define 10 cloud types

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

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

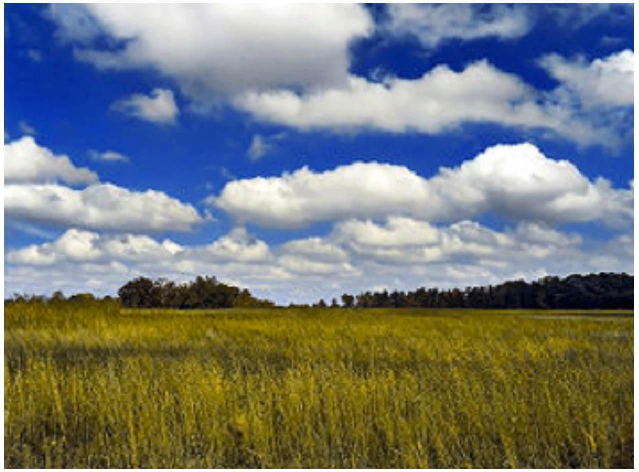
Thick, dense stratus or stratocumulus clouds producing steady rain or snow

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: cirrus, cirrocumulus, cirrostratus

High Clouds

Cirrostratus

Cirrus

Cirrocumulus

Middle Clouds: altocumulus, altostratus

Middle Clouds

Altocumulus

Altostratus

Low Clouds: Stratus, Nimbostratus, Stratocumulus, Cumulus, Cumulonimbus

Low Clouds

Stratocumulus

Cumulonimbus

Stratus

Nimbostratus

Cumulus

Other spectacular Clouds…

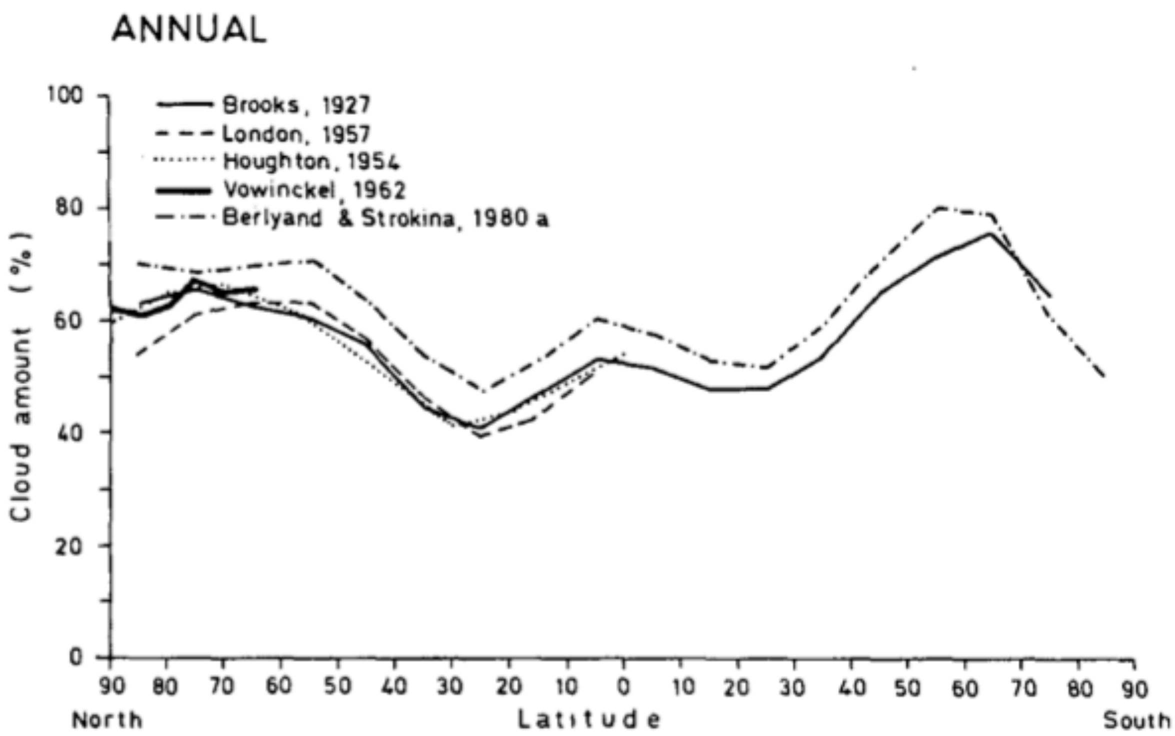
Mammatus clouds (typically below anvil clouds)

Shelf clouds (gust front)

Lenticular clouds (over orography)

Cloud types

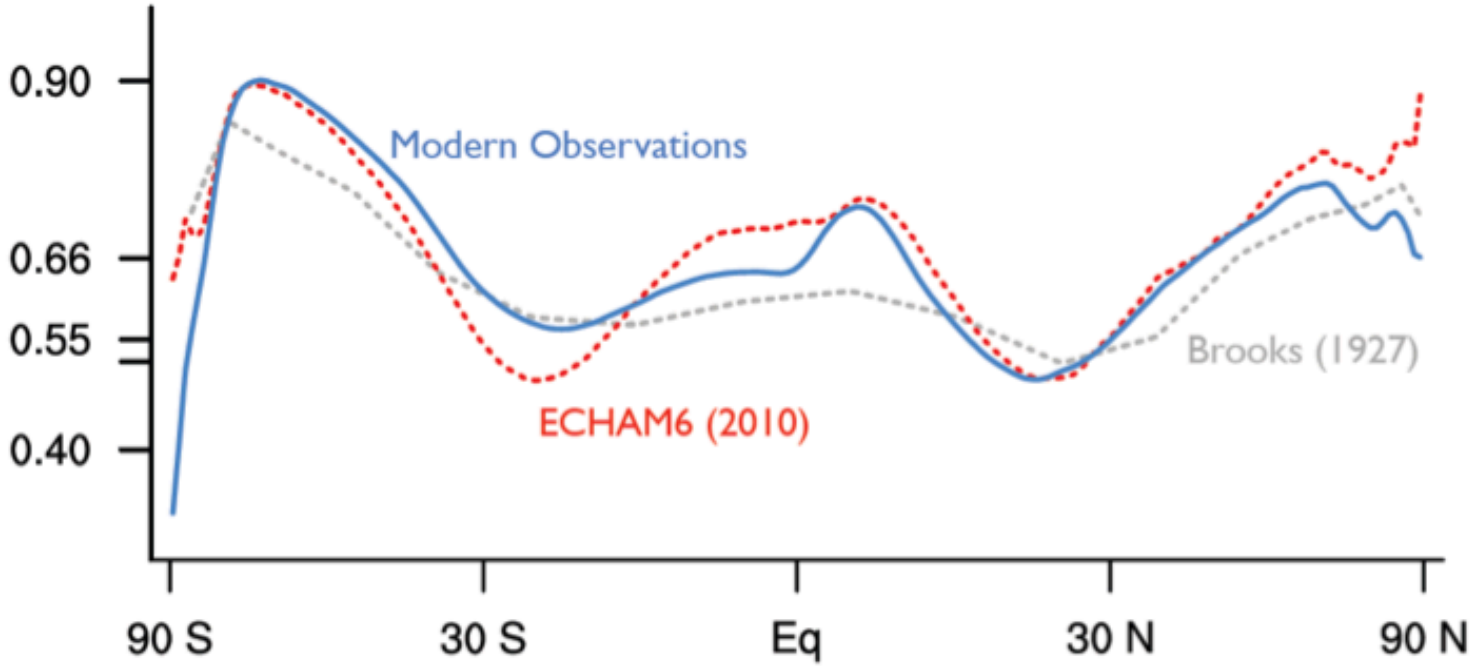
Distribution of cloud amount



[Hughes 84]

Cloud types

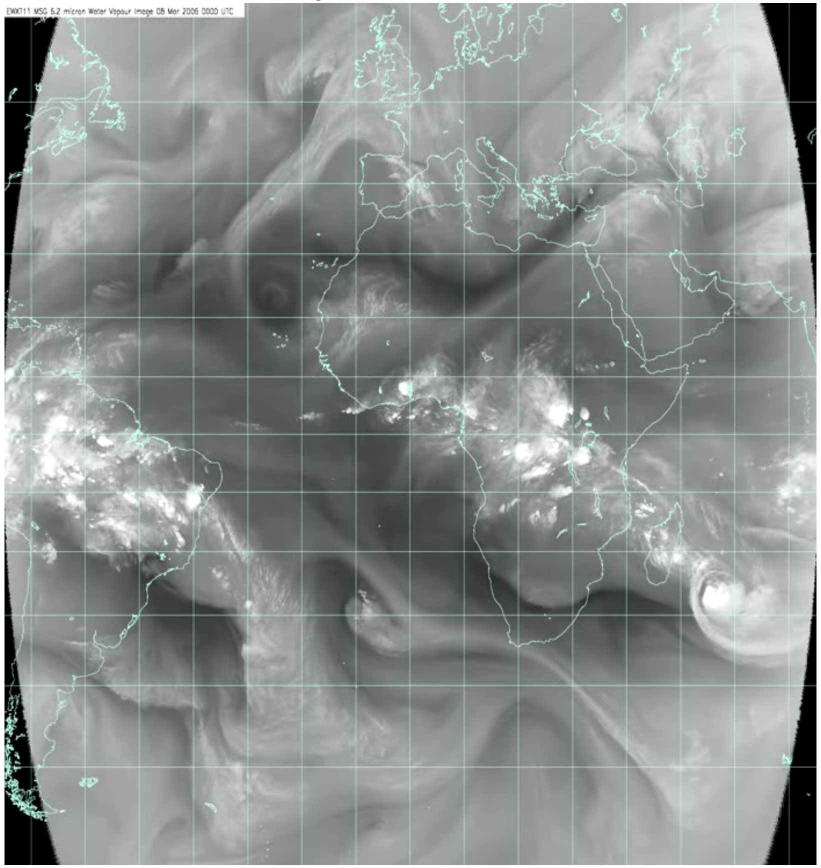
Cloud amount was underestimated



Courtesy Bjorn Stevens

Cloud types

Water vapor from satellite



Larger-scale extratropical convection

Small-scale tropical convection

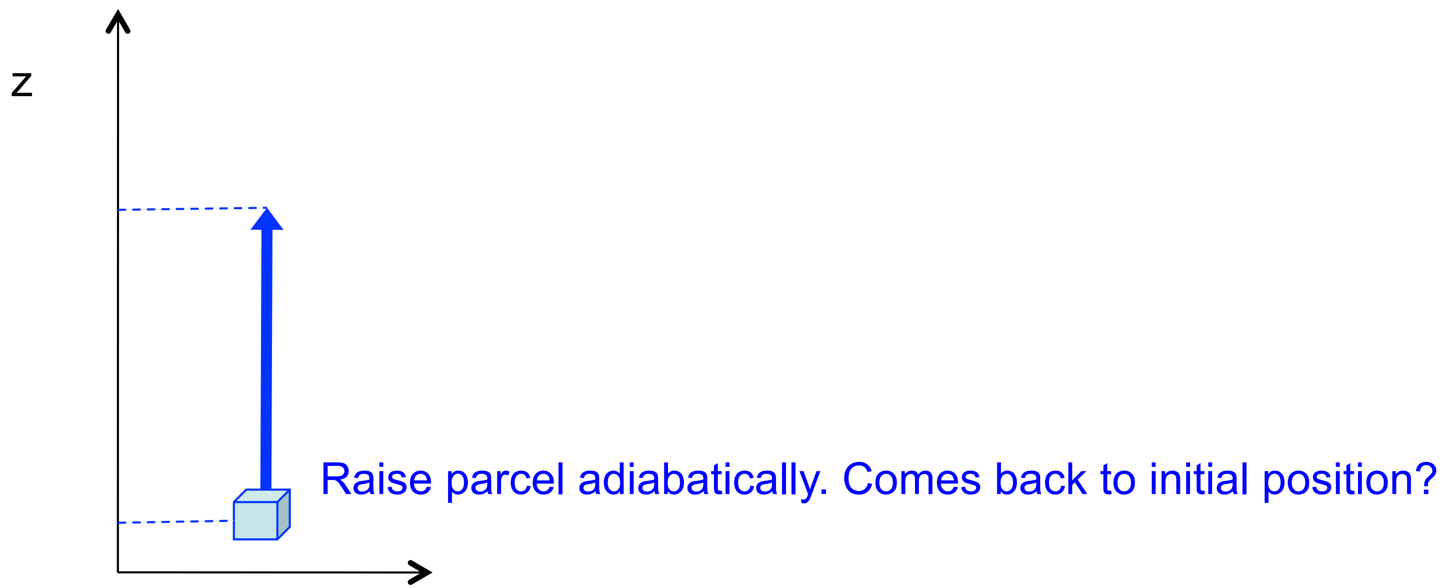
Deep convective system over Brazil

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) = 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

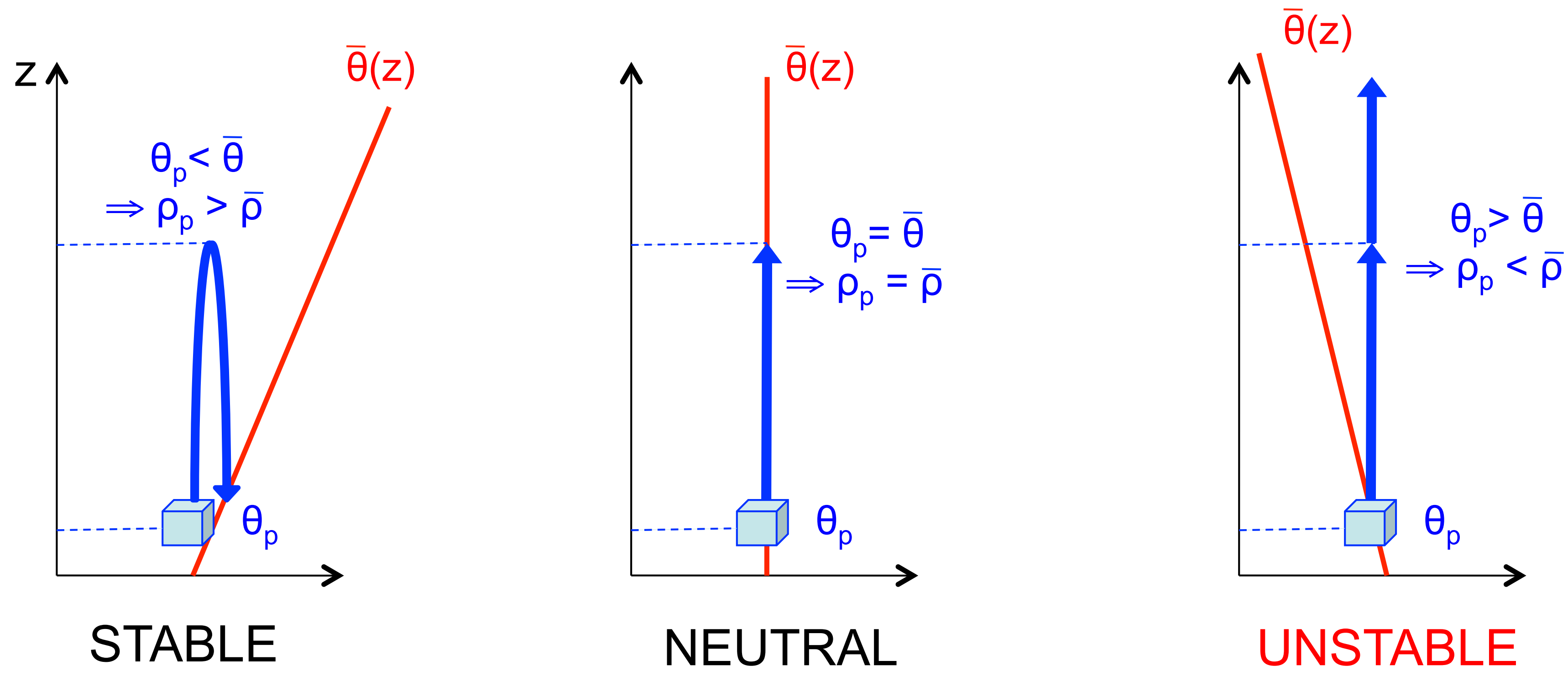
Atmospheric thermodynamics: instability

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.



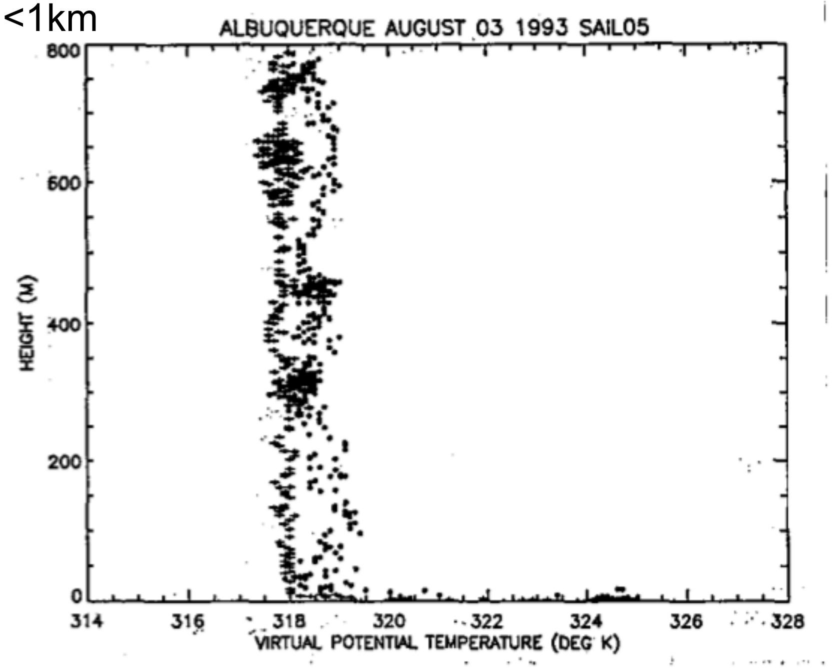
Atmospheric thermodynamics: instability

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]

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

Atmospheric thermodynamics: instability

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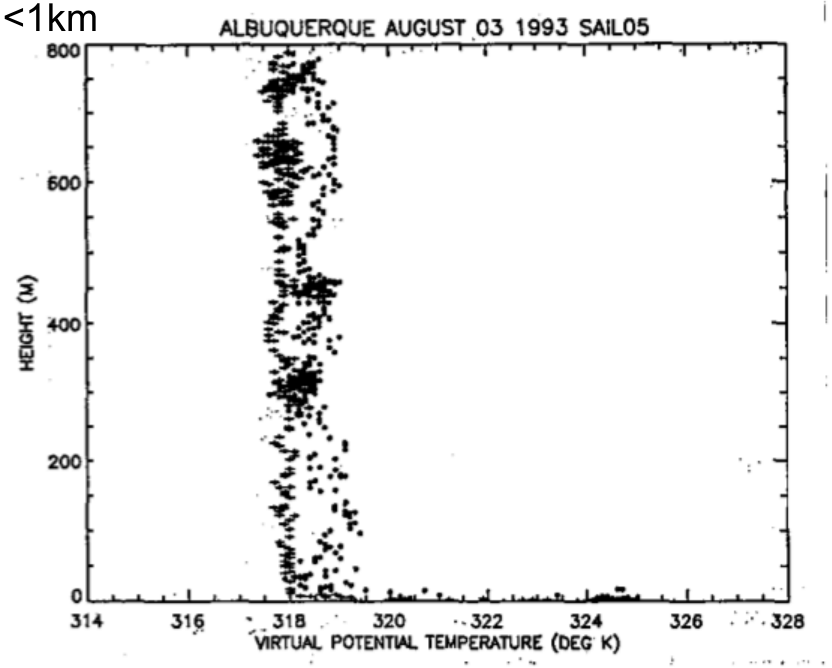


[Renno and Williams, 1995]

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

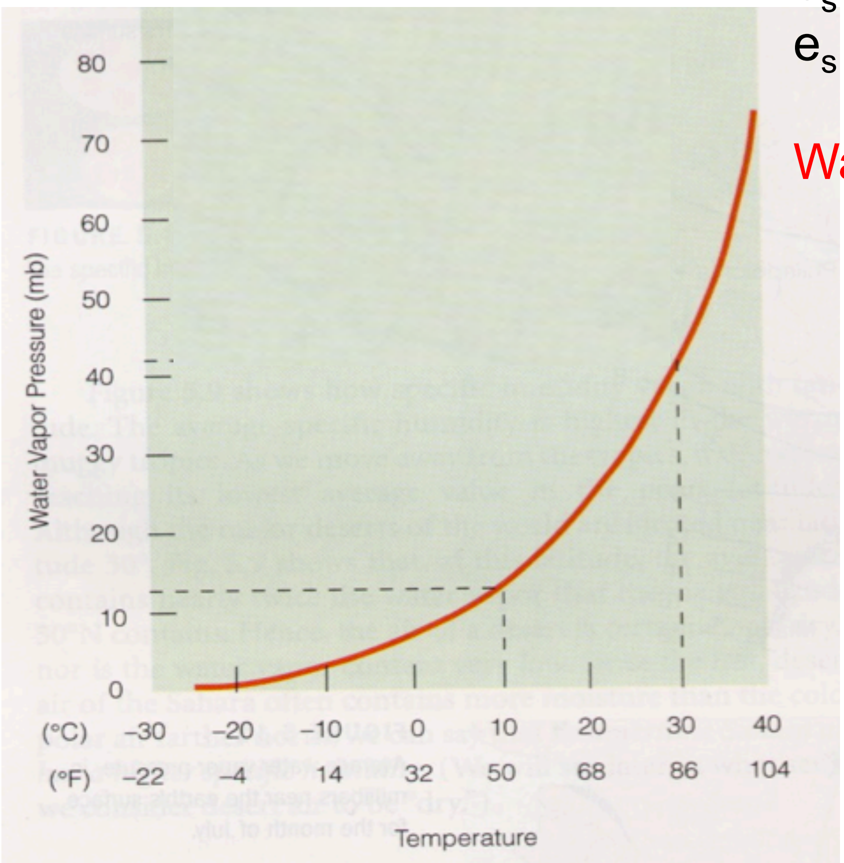
Atmospheric thermodynamics: instability

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

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

Cloud in a bottle MOVIE 1 : Clausius Clapeyron

Cloud in a bottle MOVIE 2 : condensation nuclei

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 ($q_v=q_s$) :

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

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

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

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

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 (approximately) conserved

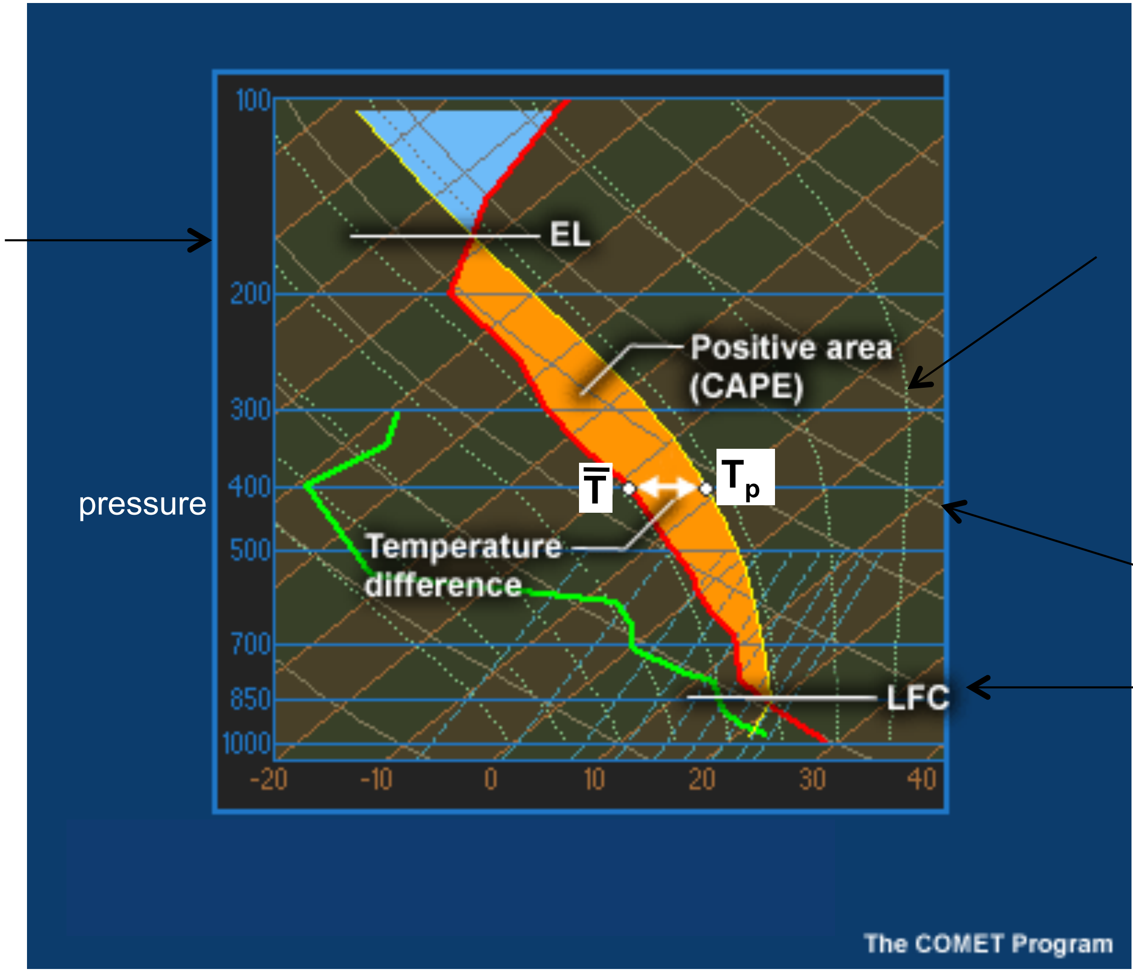
Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

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

EL equilibrium level

pressure



Moist adiabat θ_e= cstt

Dry adiabat θ = cstt

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

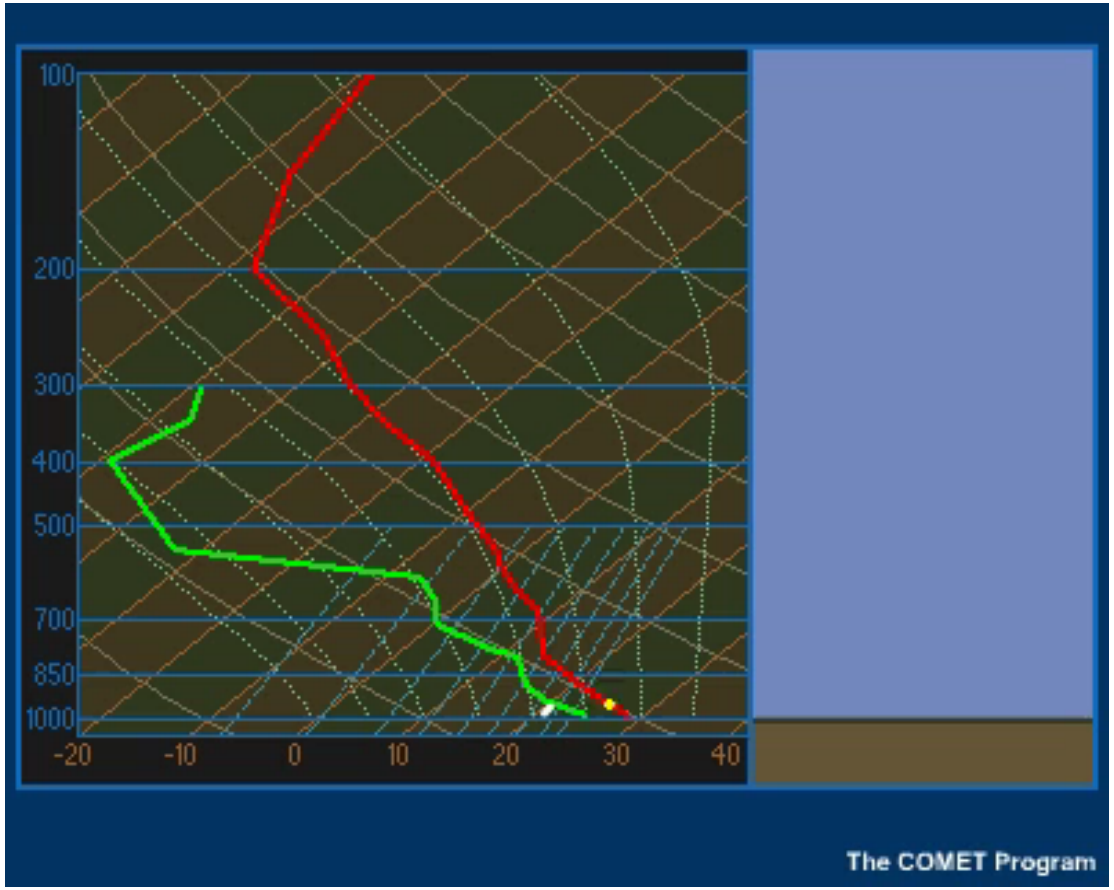
CAPE: convective available potential energy

Atmospheric thermodynamics: instability

Moist convection

Parcel = yellow dot

EL equilibrium level



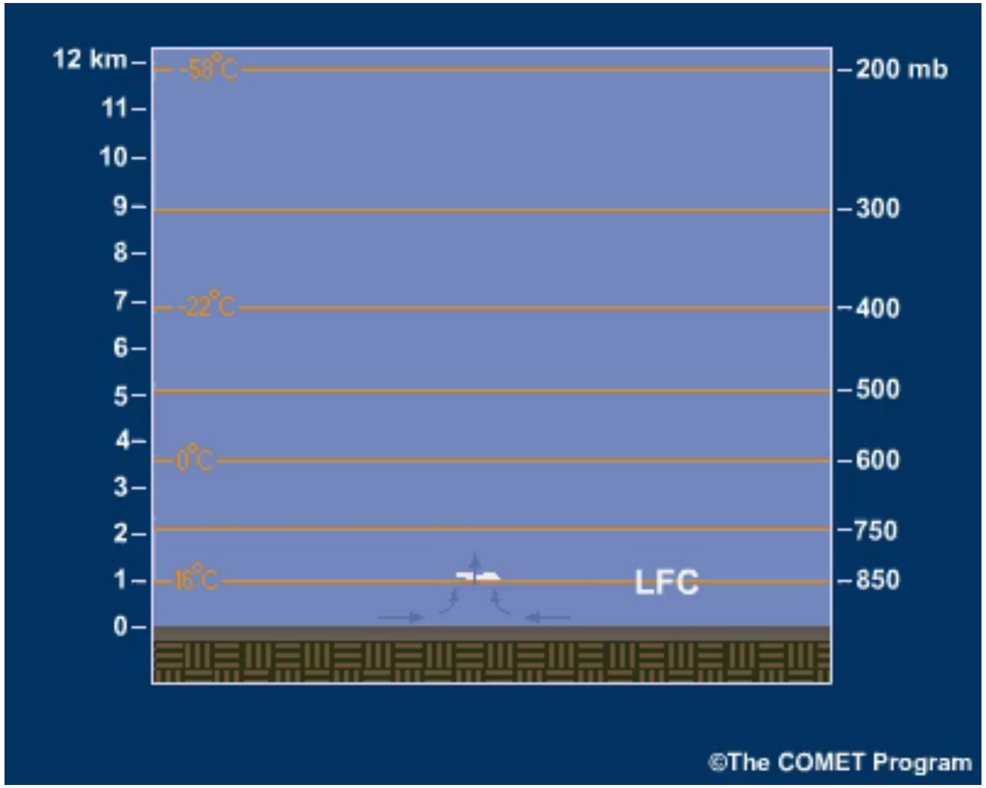
LFC level of free convection

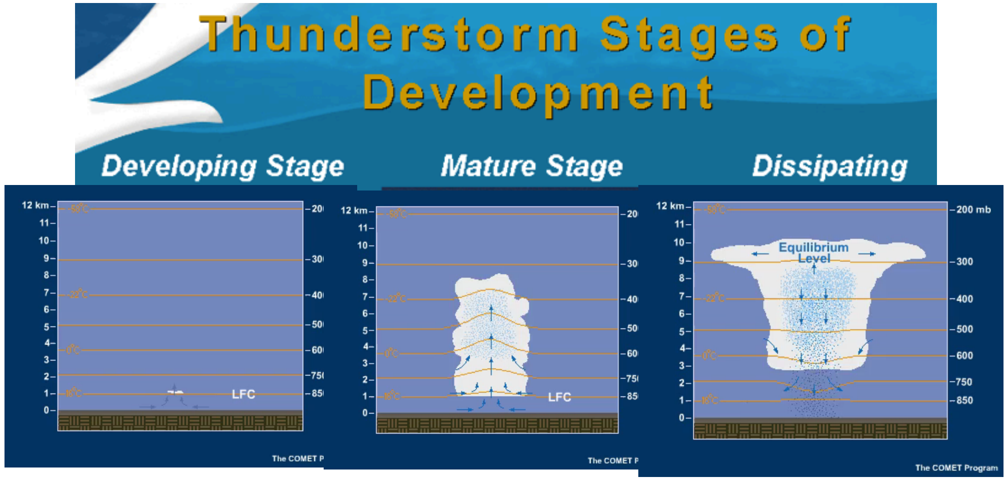
CAPE: convective available potential energy

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.

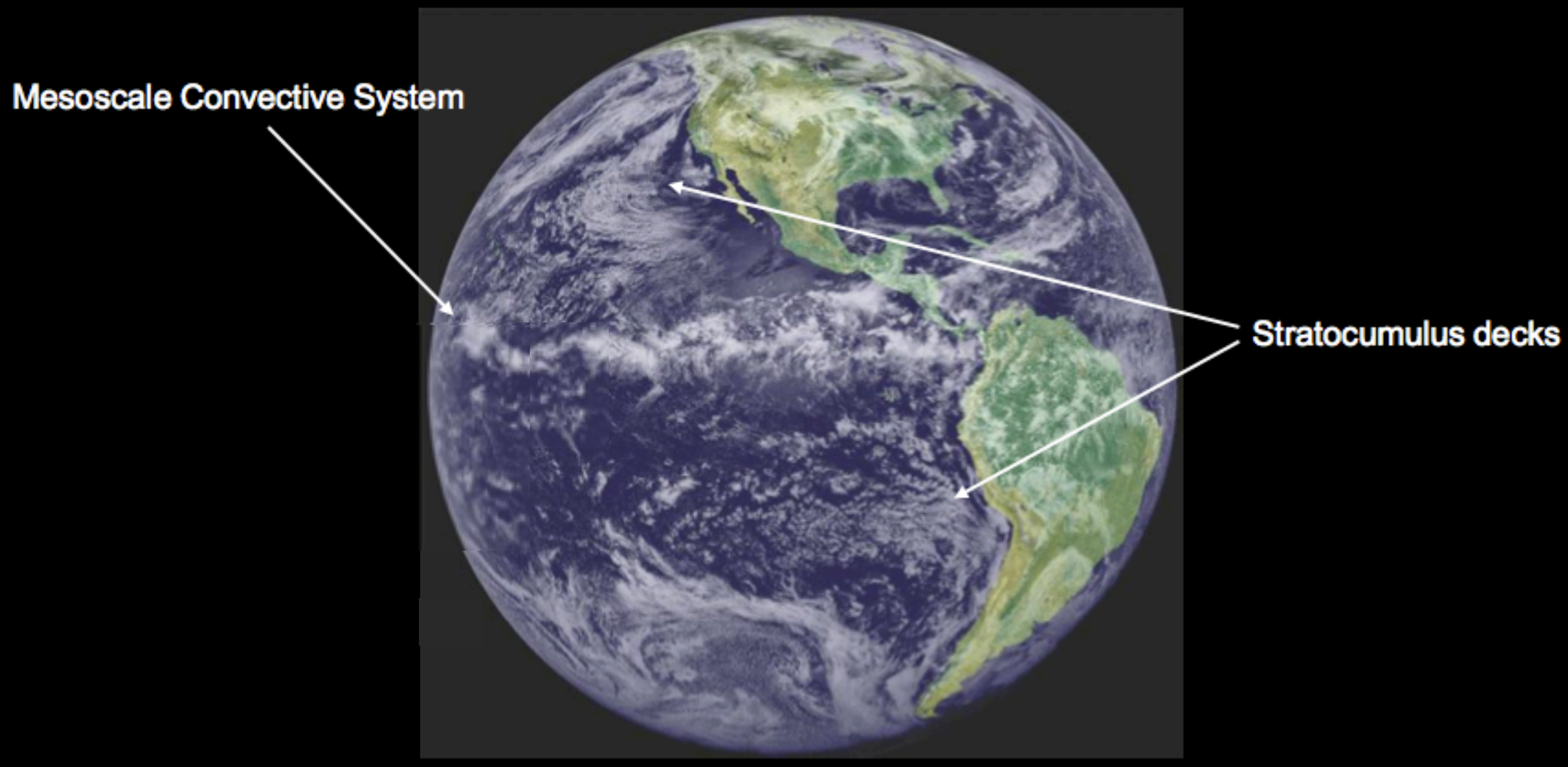




Evaporative driven cold pools

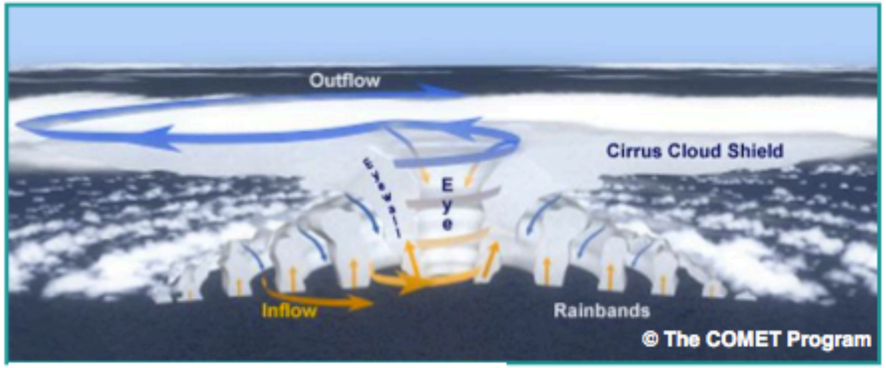
Convective organization

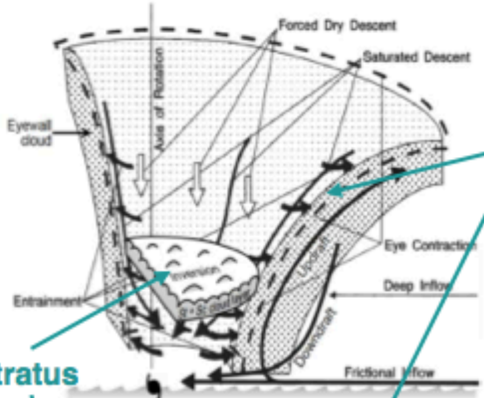
… often spatially organized, …



Convective organization: hurricanes

Hurricanes

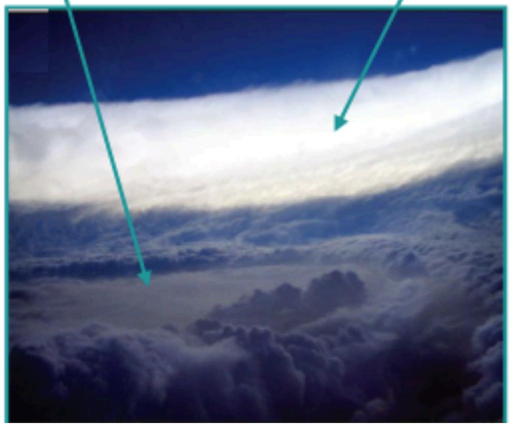


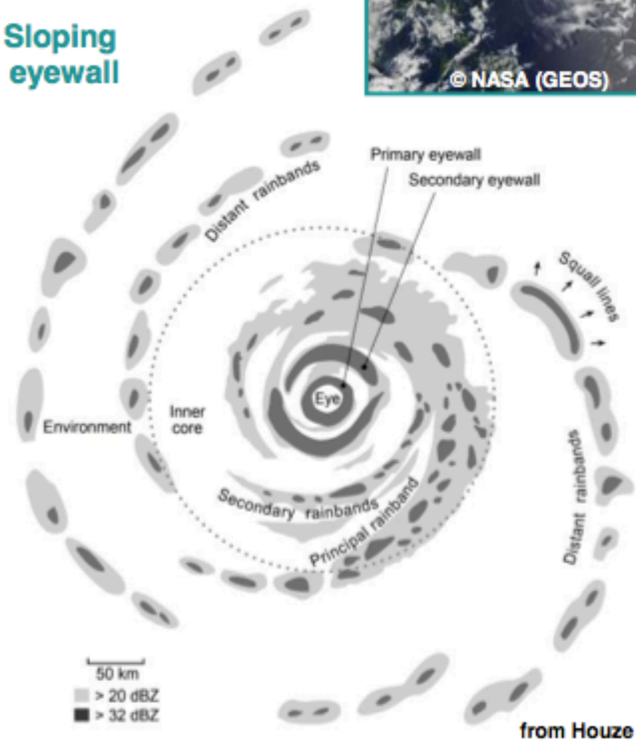


from Willoughby (1998)

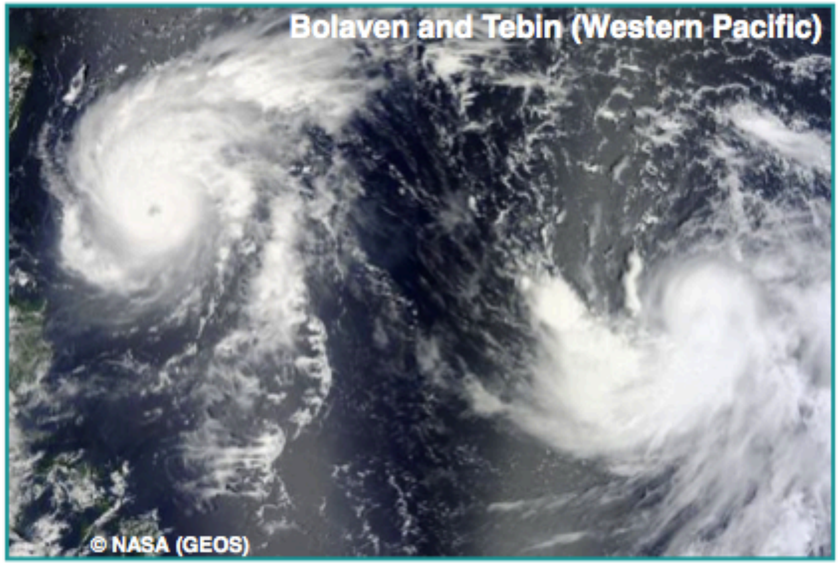
Sloping eyewall

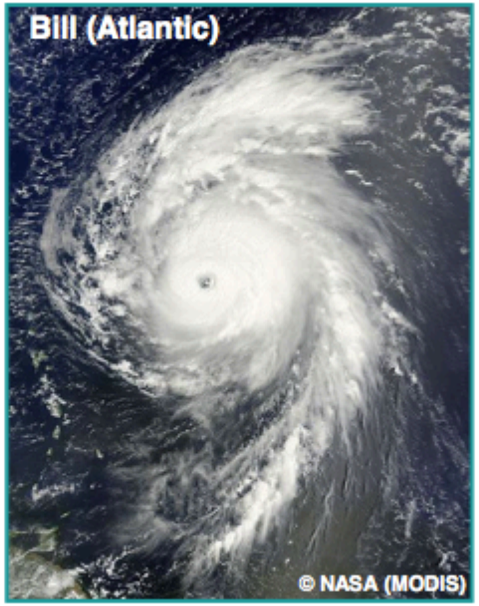
Stratus





from Houze (2010)

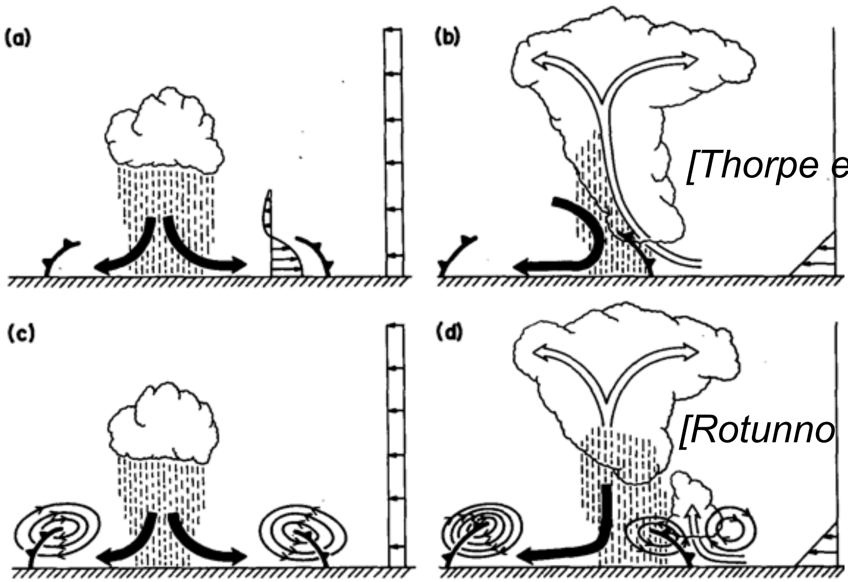




Convective organization: squall lines

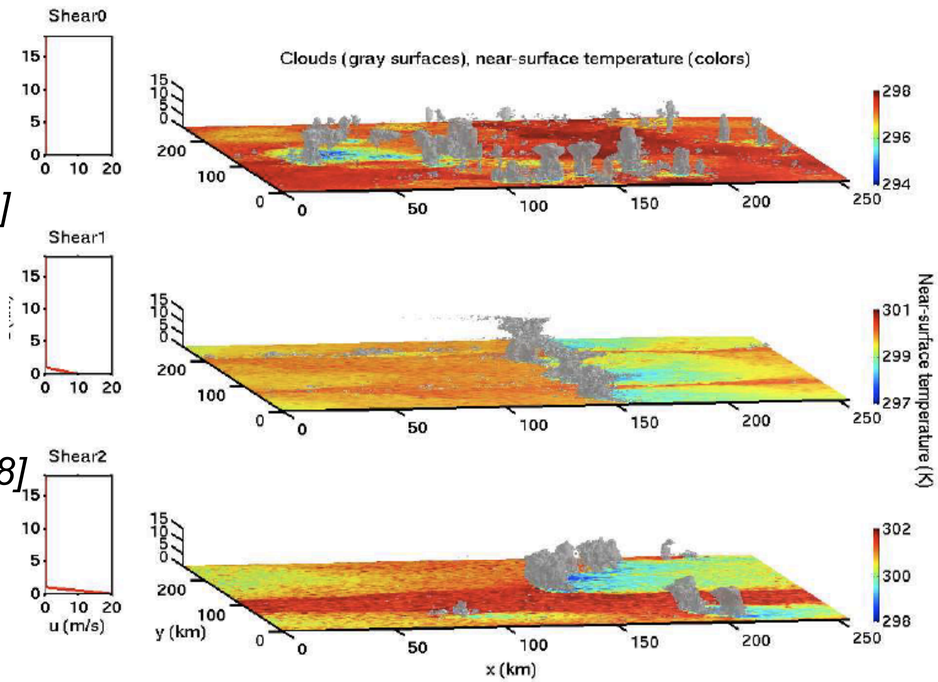
Squall lines

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]

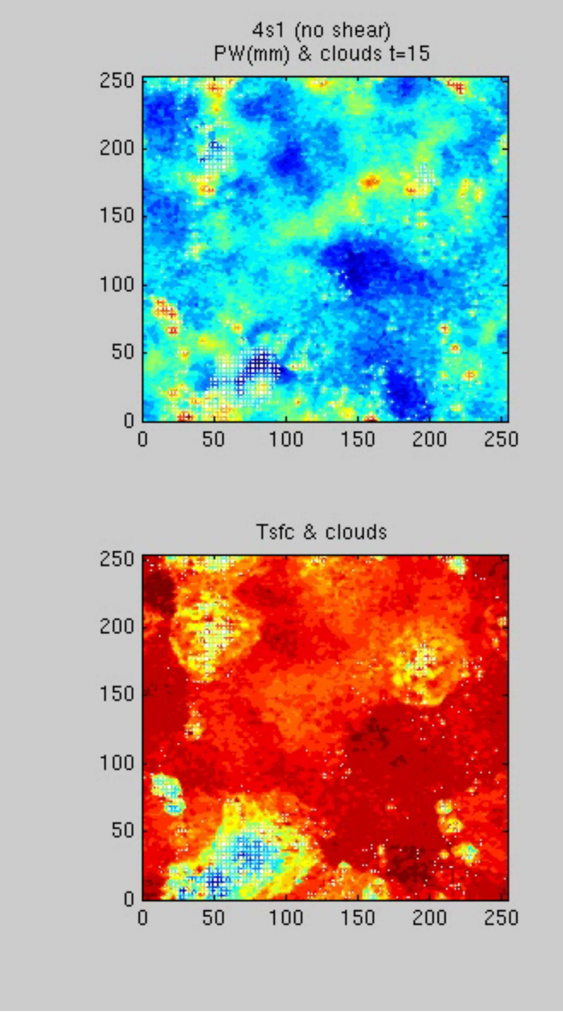
Convective organization: squall lines

No shear

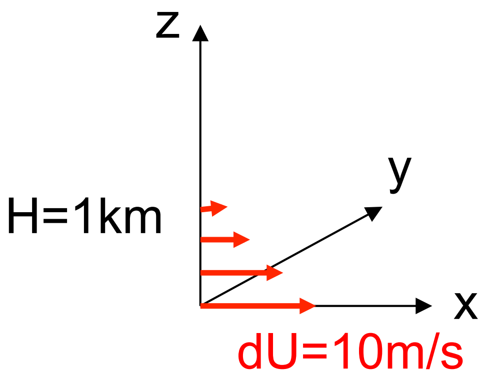
Top view

Color: PW

Color: Tsfc



Convective organization: squall lines

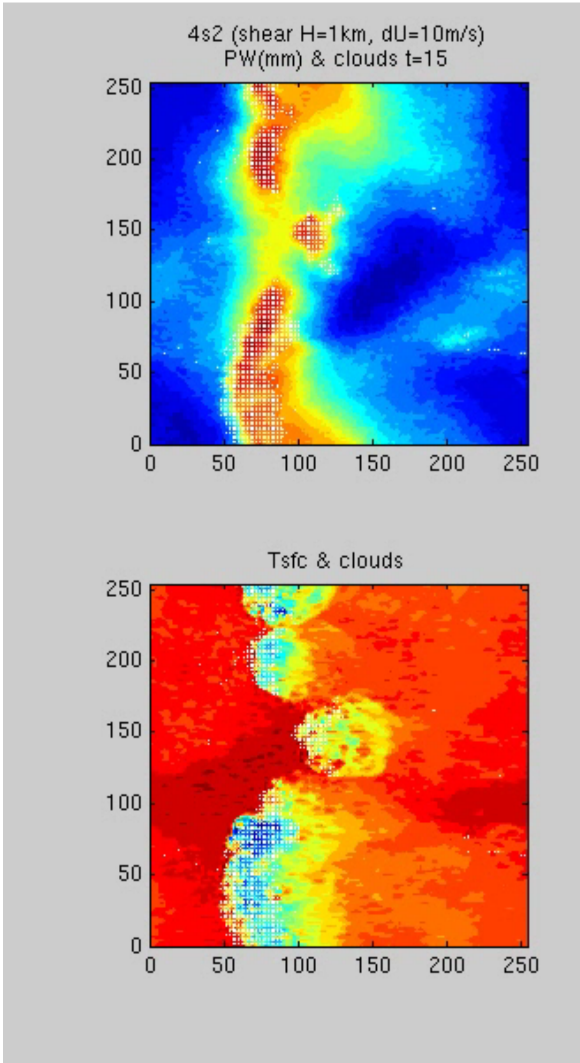


Critical shear

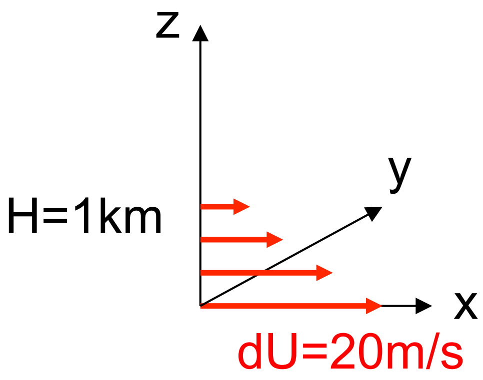
Top view

Color: PW

Color: Tsfc



Convective organization: squall lines

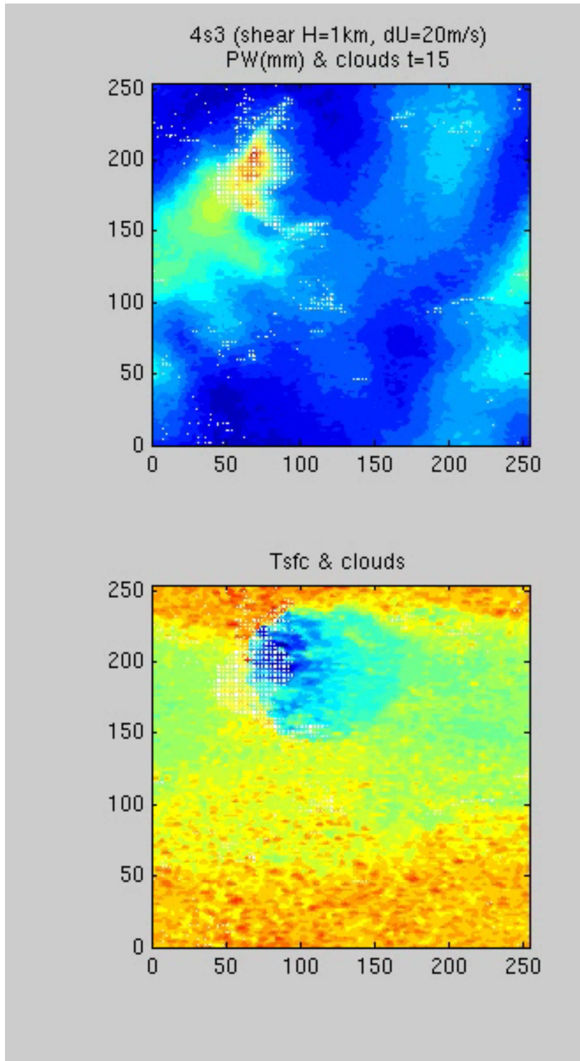


Super critical shear

Top view

Color: PW

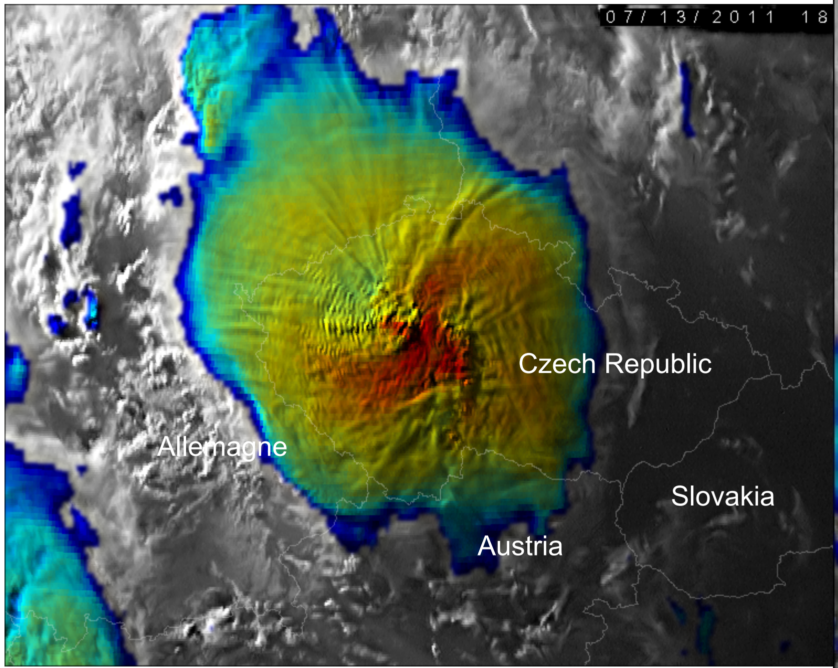
Color: Tsfc

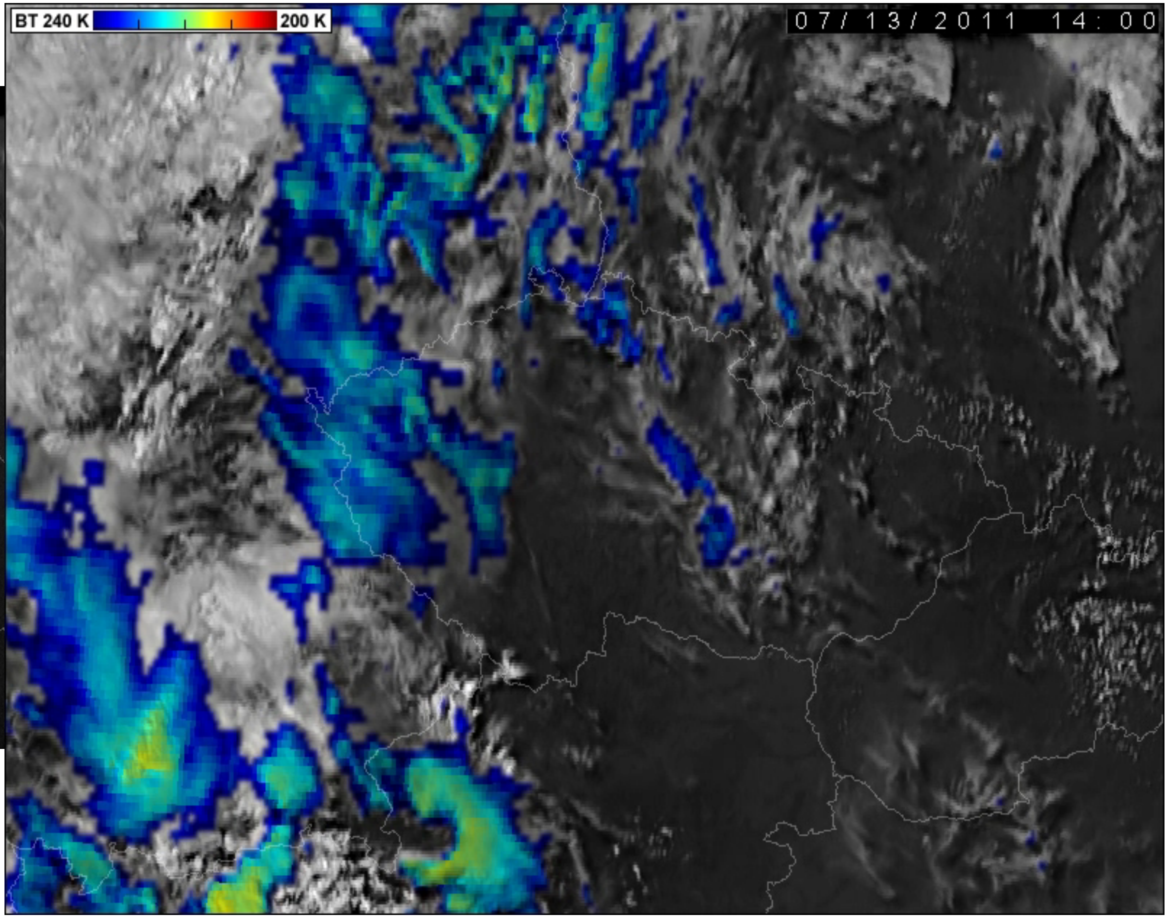


[Robe & Emanuel 1996; Muller 2013]

Convective organization: MCS

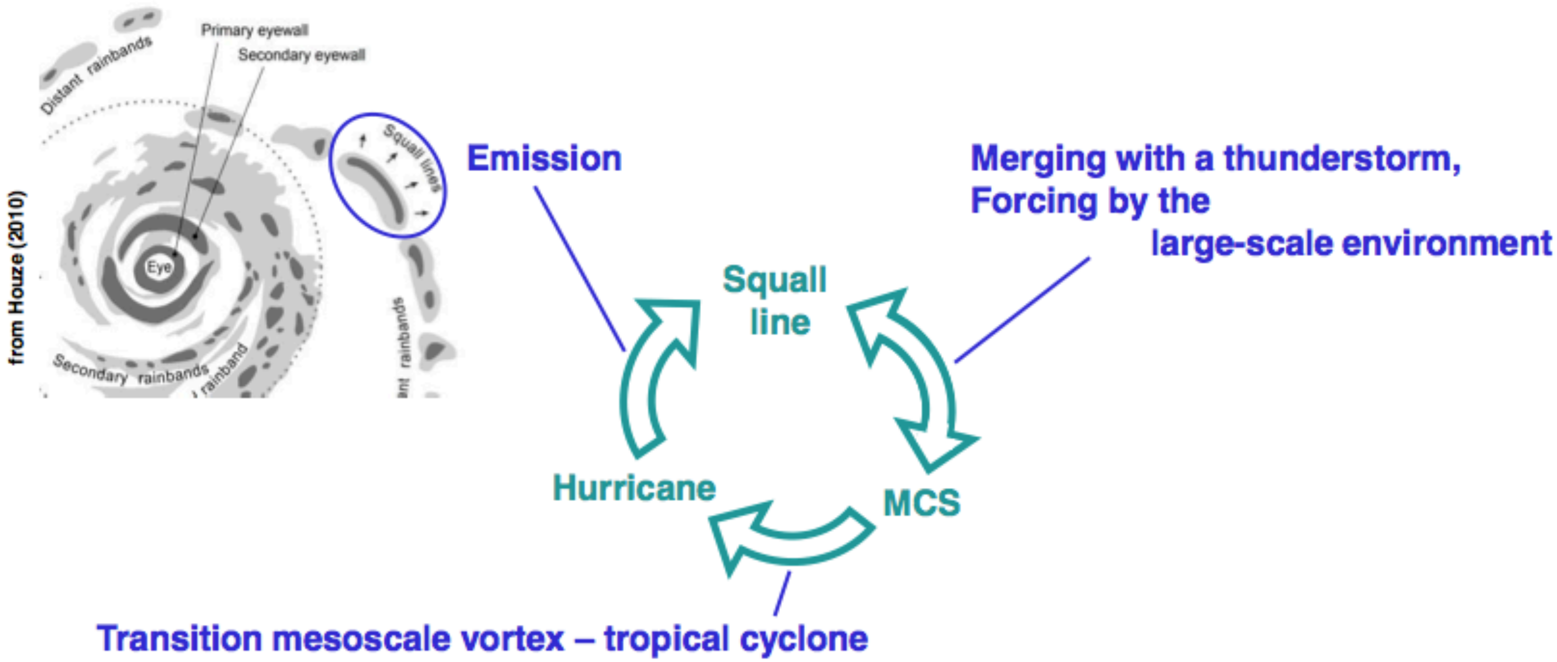
Mesoscale convective systems

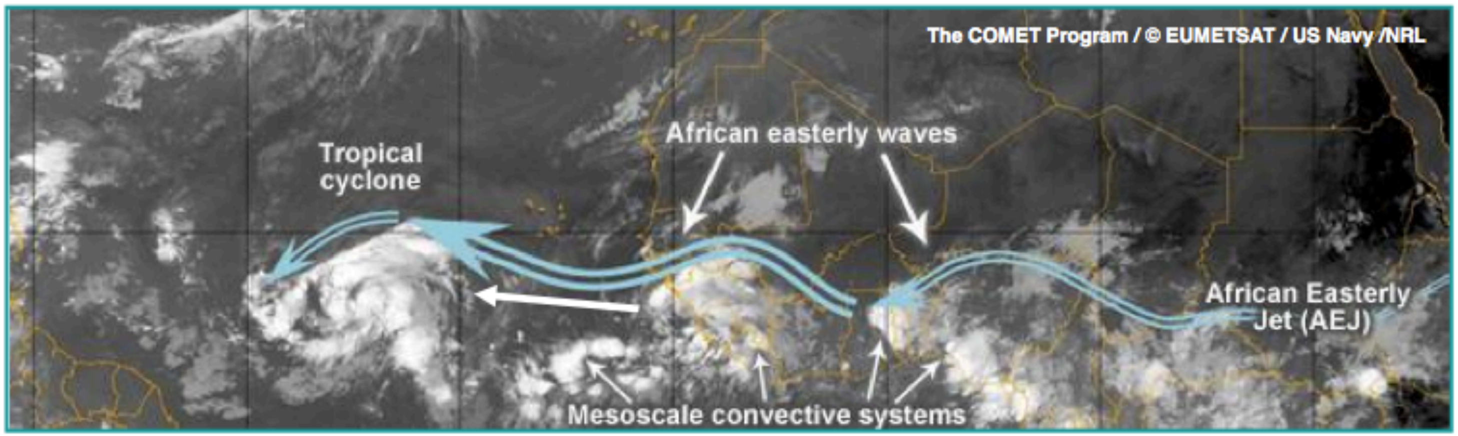




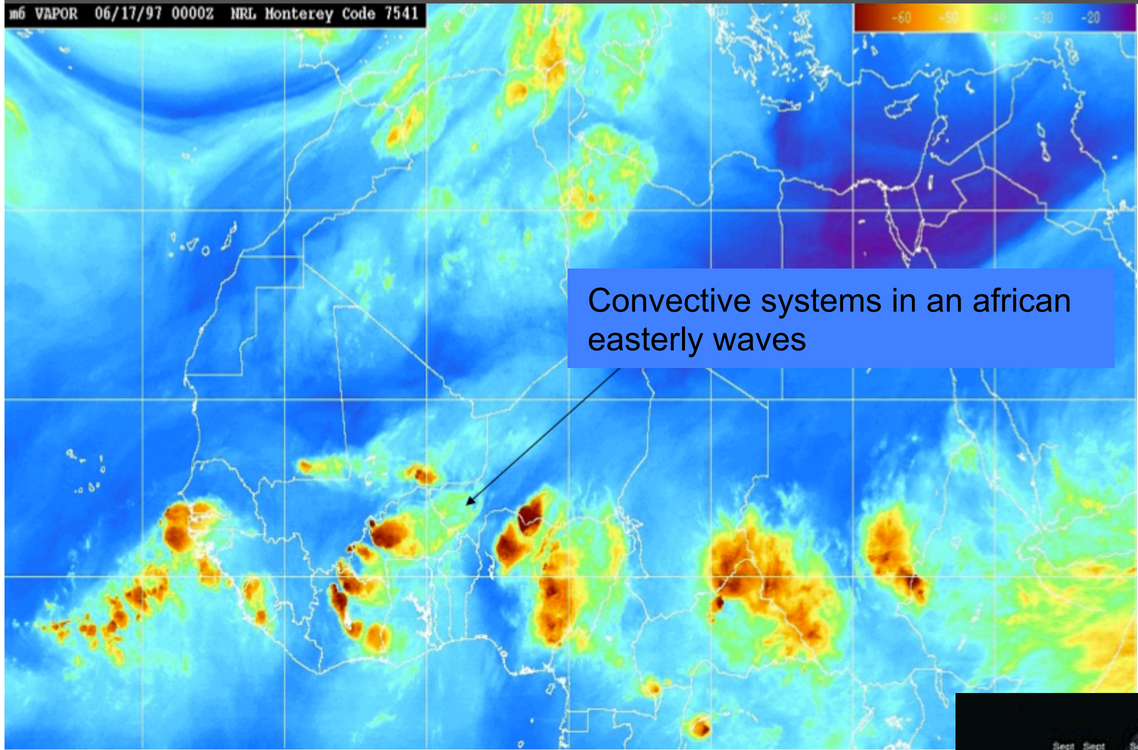
Convective organization

Transitions between organized structures

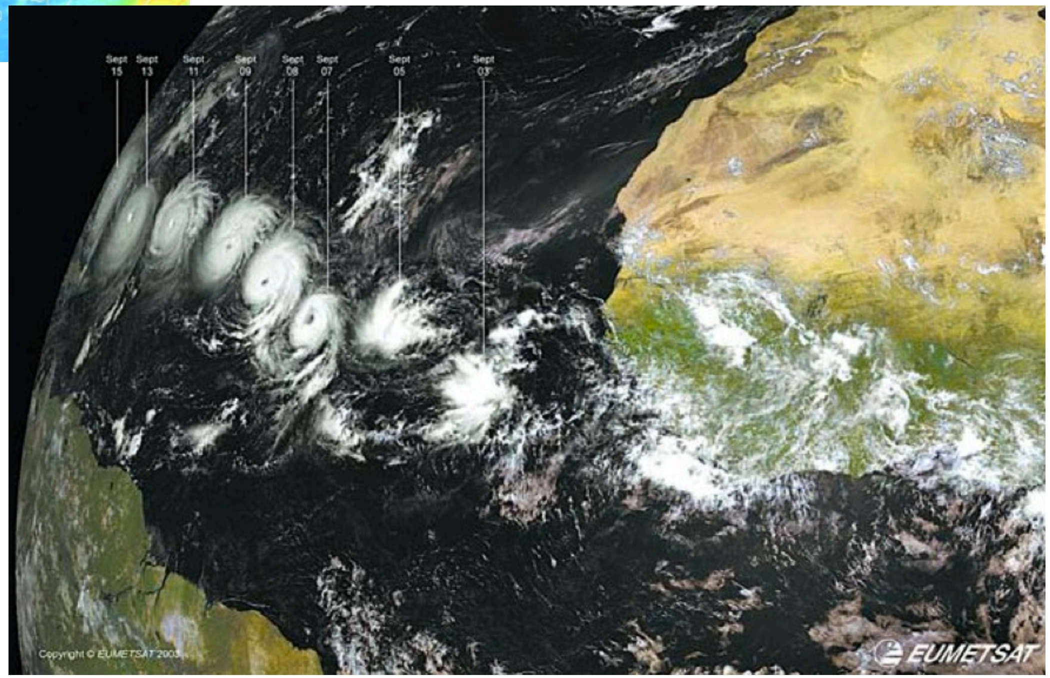




Convective organization

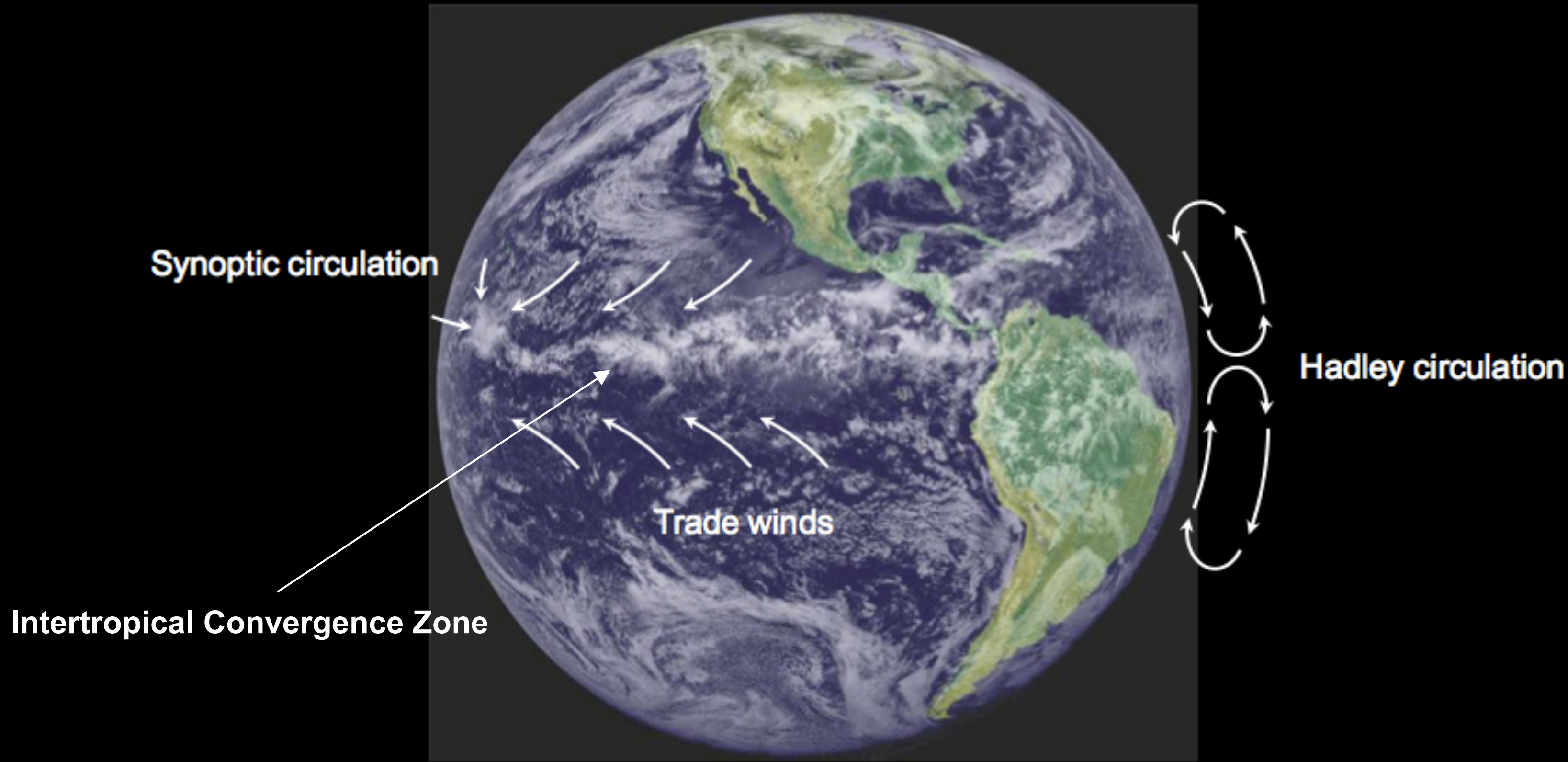


Hurricane Isabel off the coast of Africa

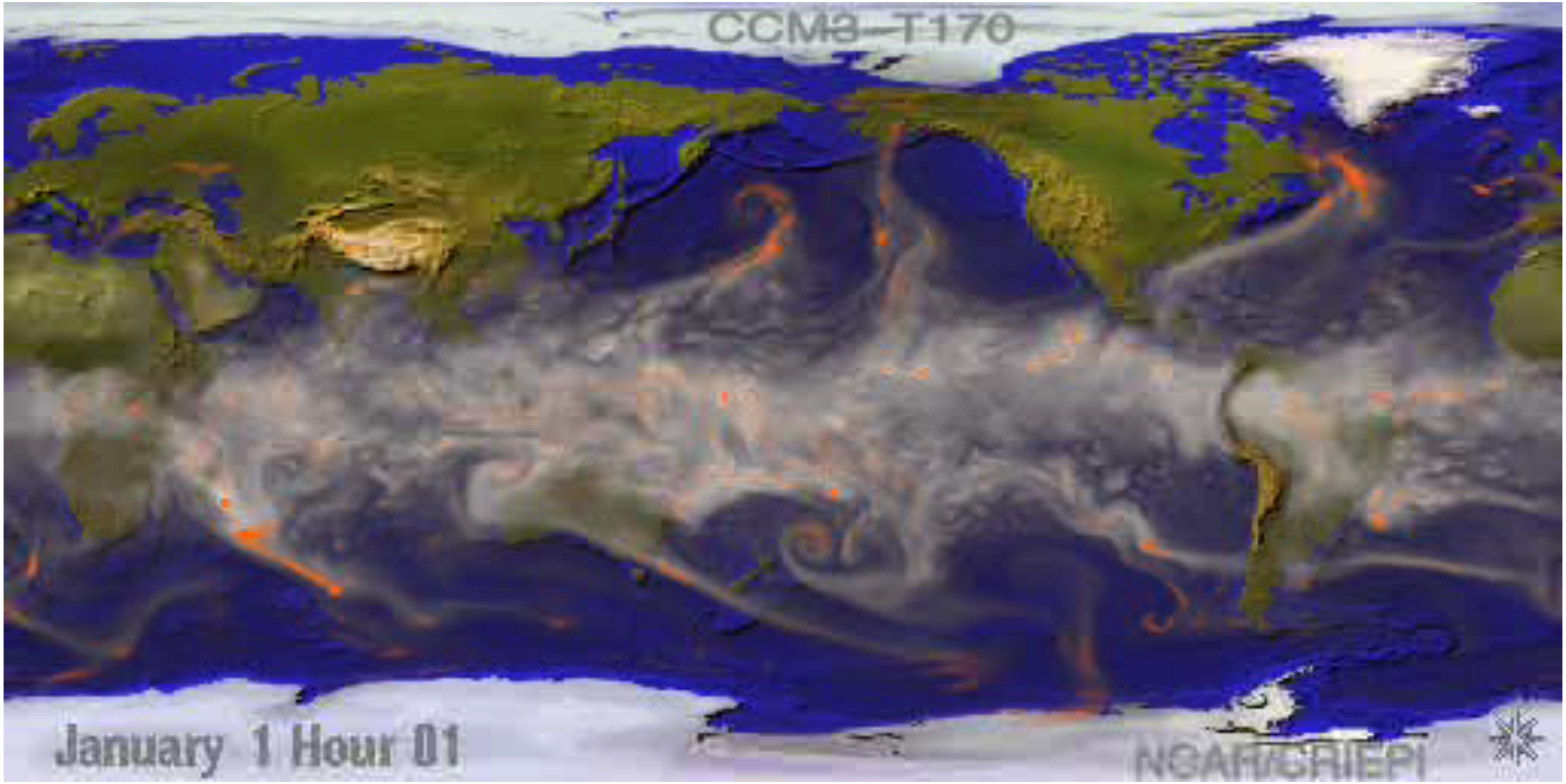


Coupling with circulation

… and coupled to circulations.

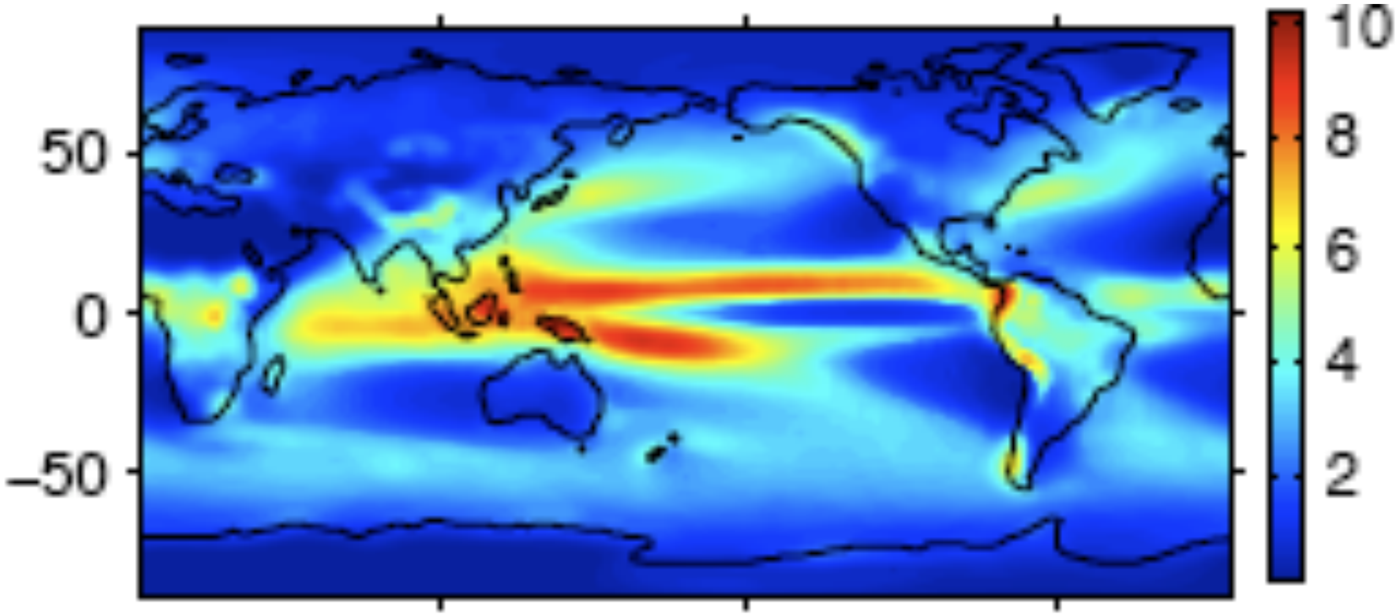


Clouds and Circulation: ITCZ



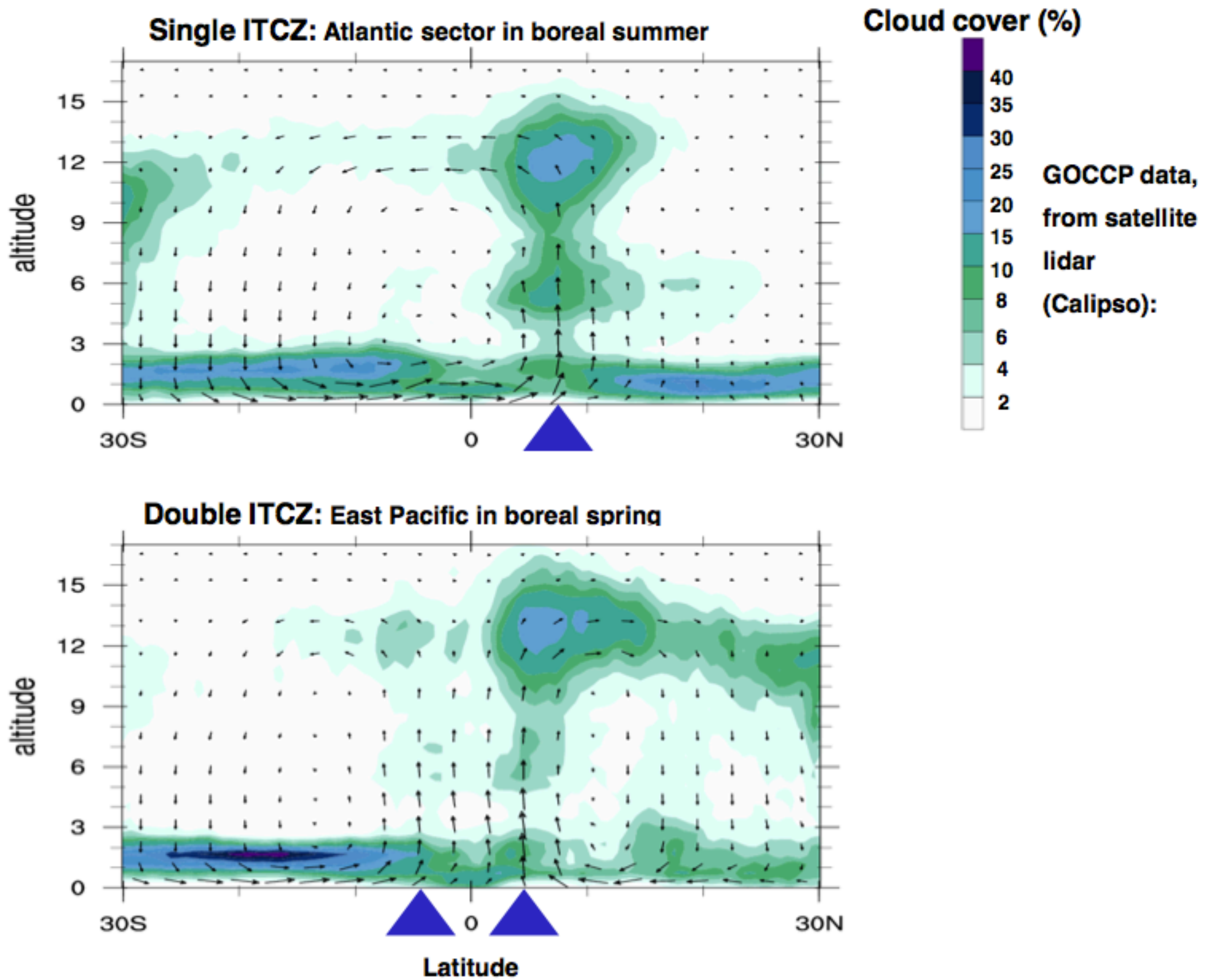
Clouds and Circulation: ITCZ

P (mm/day)
1981-1999 climatology



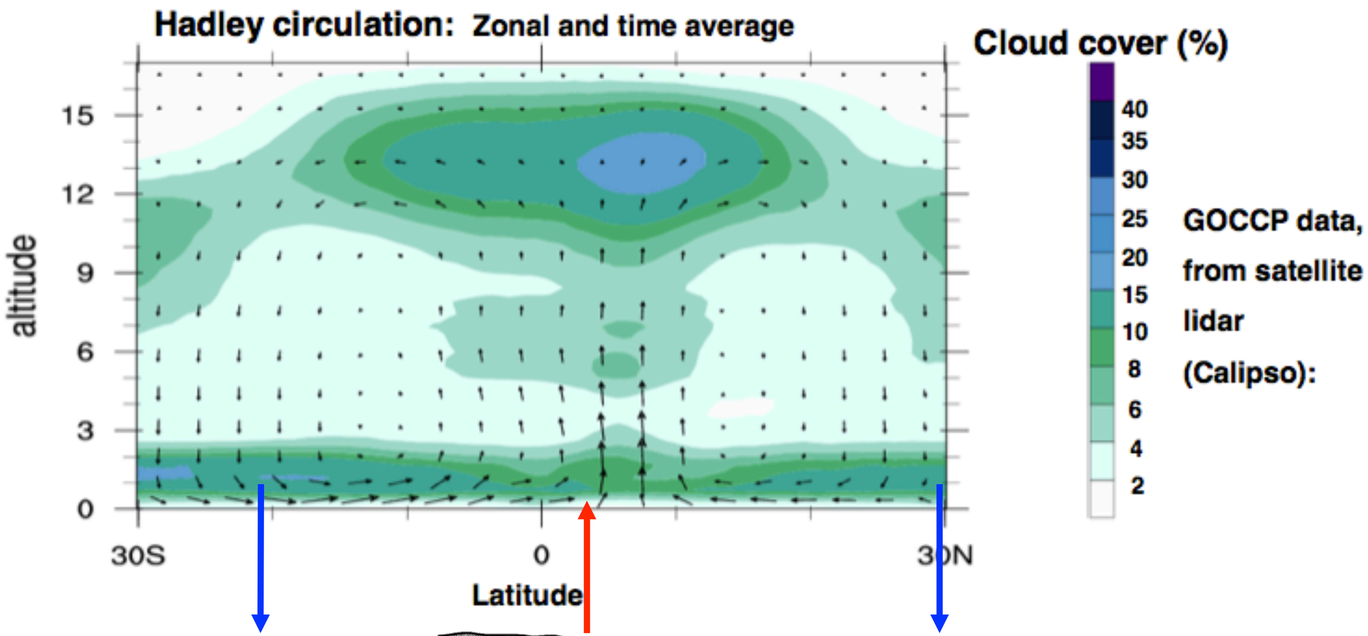
[Muller & O'Gorman, 2011]

Clouds and Circulation: ITCZ

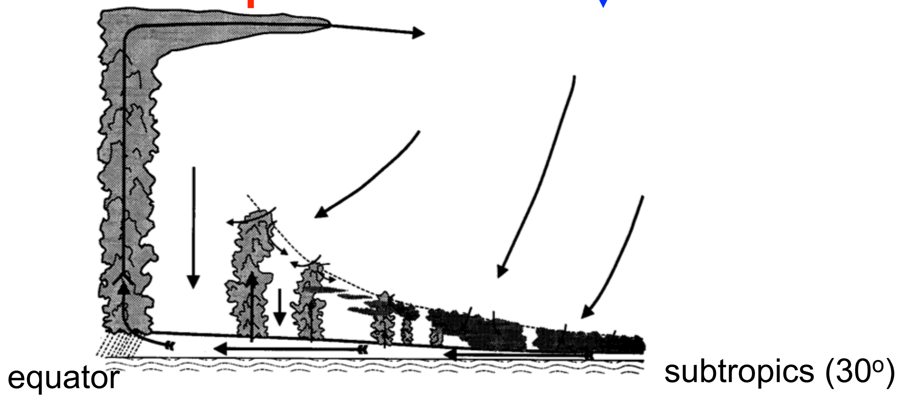


Courtesy Gilles Bellon

Clouds and Circulation: Hadley cell



Cloud types:



Deep cumulonimbus

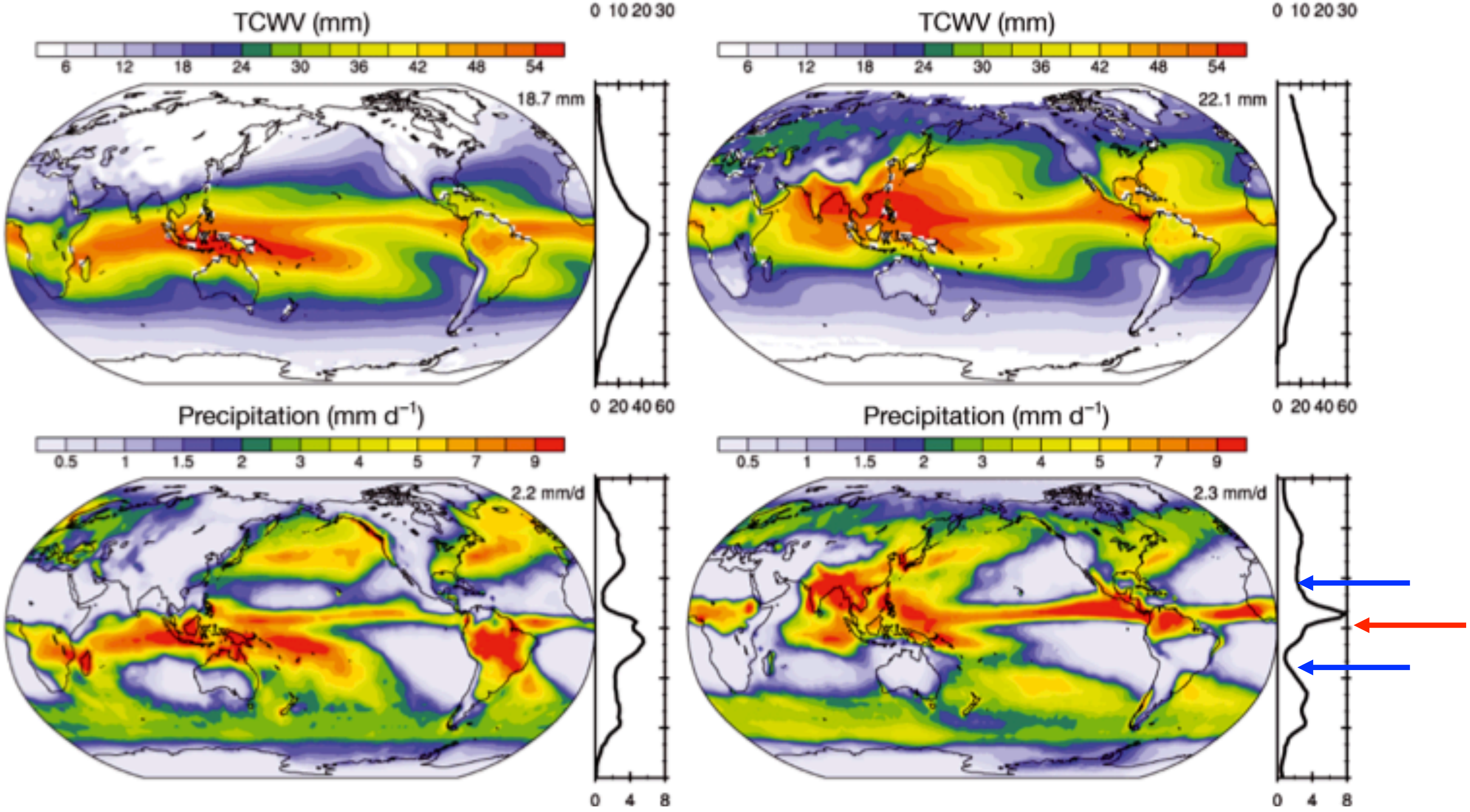
Fair weather cumulus

stratus

Clouds and Circulation: Precipitation

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

January (left) *July (right)*

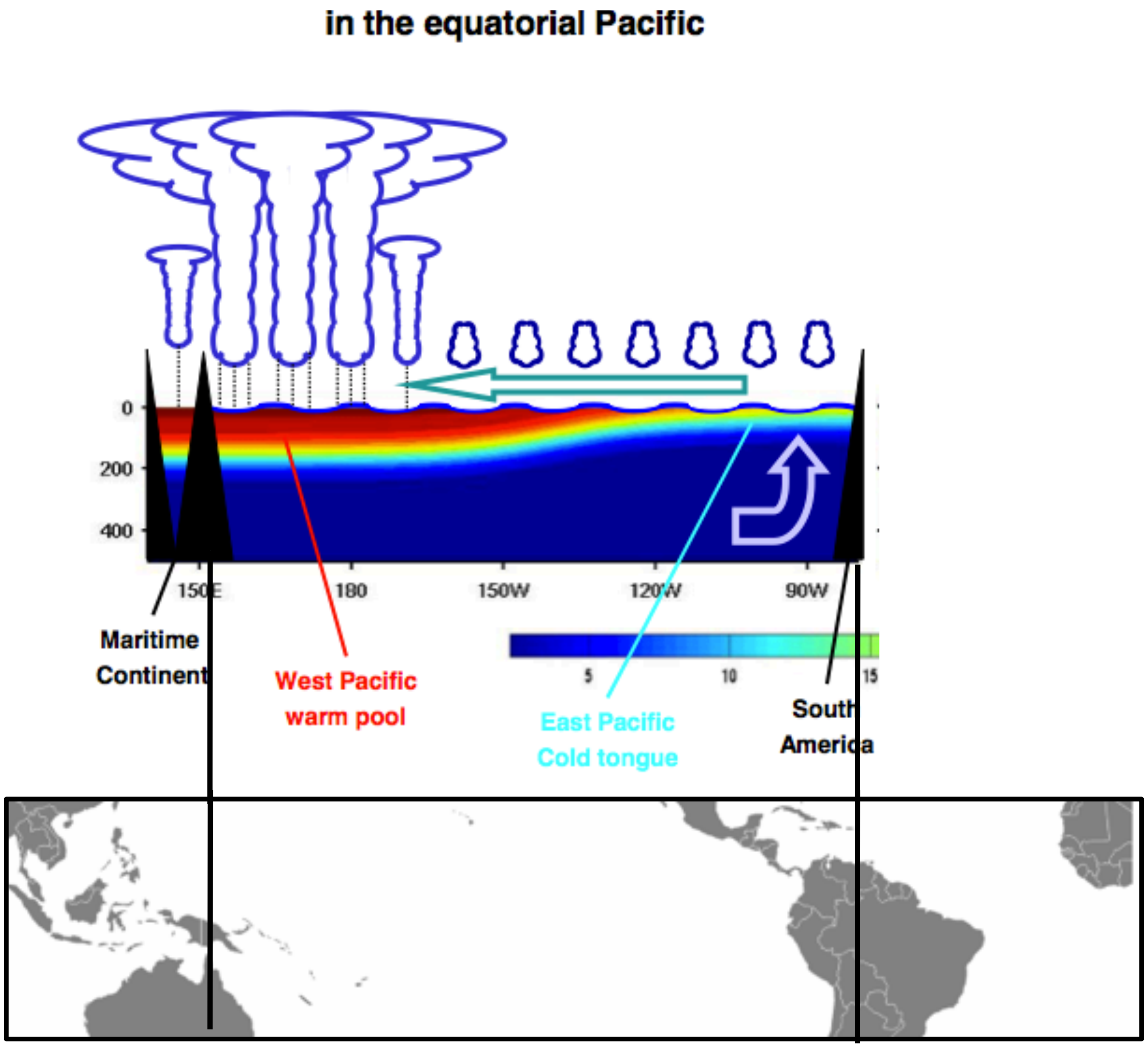


Small in Subtropics (descent)

Large in Tropics (ascent)

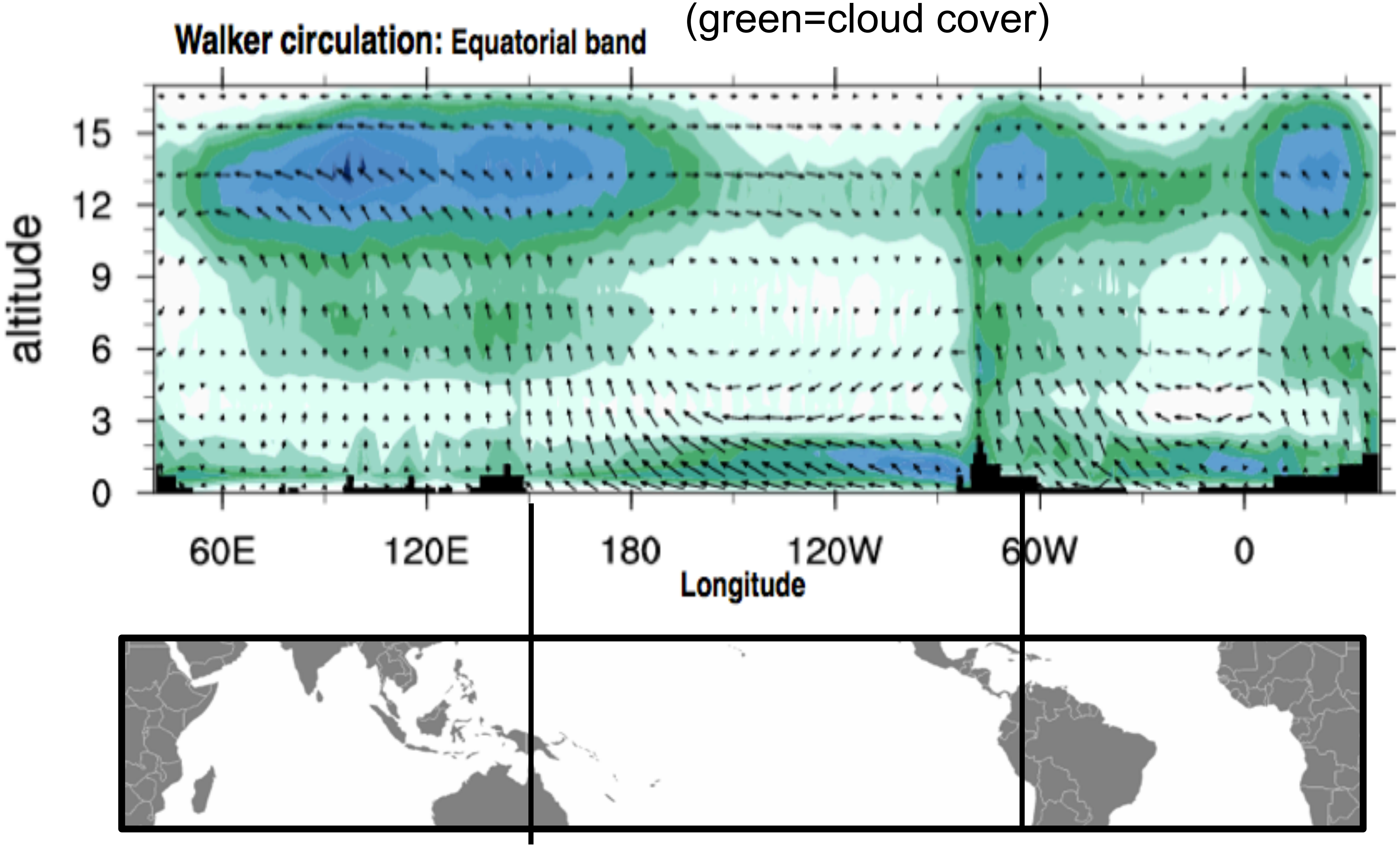
[Trenberth 2011]

Clouds and Circulation: Walker cell



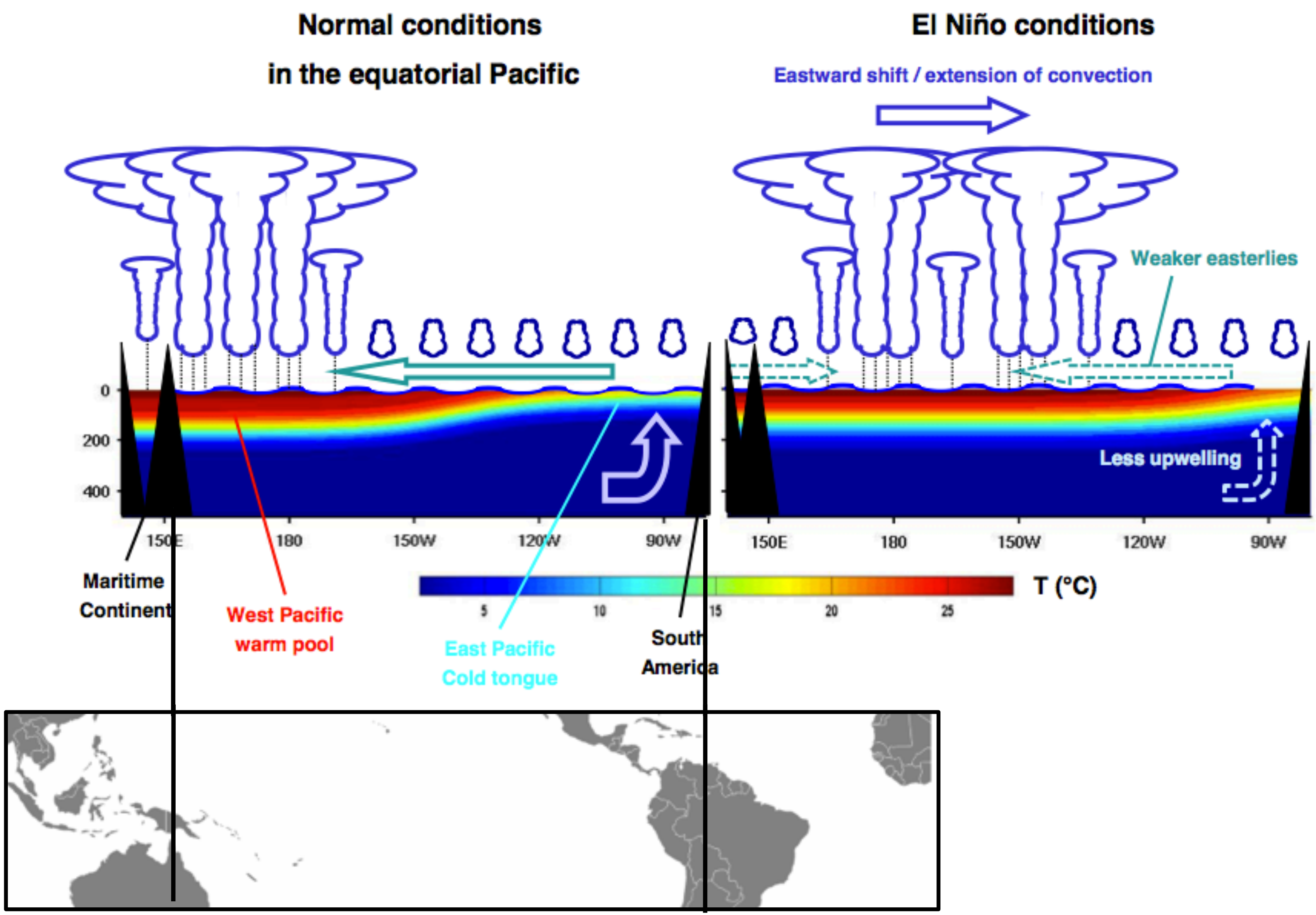
Clouds and Circulation: Walker cell

(green=cloud cover)



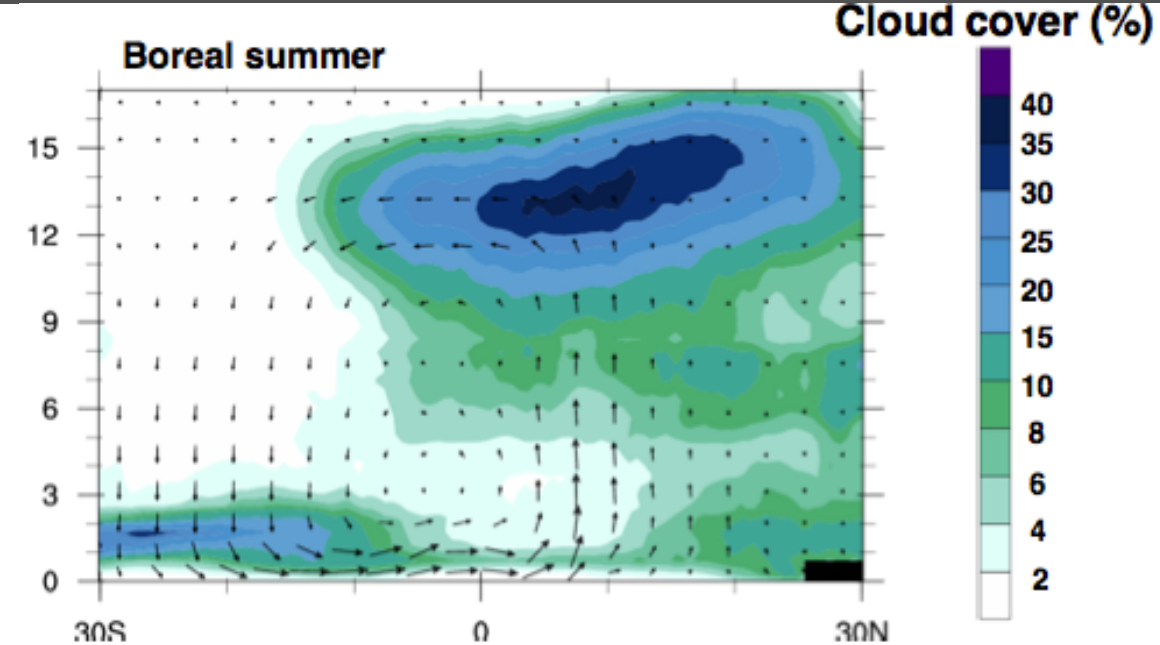
Courtesy Gilles Bellon

Clouds and Circulation: El Nino

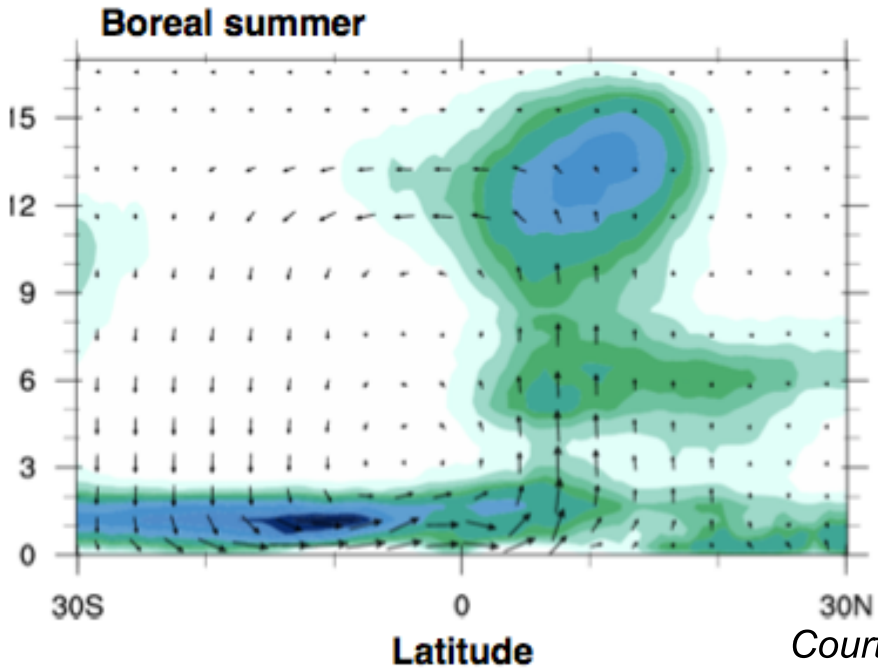


Clouds and Circulation: Monsoon

Asian monsoon



West-African monsoon



GOCCP data, from satellite lidar (Calipso):

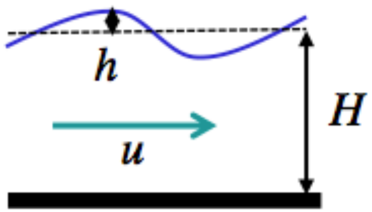
Courtesy Gilles Bellon

Convective organization: equatorial waves

Linearized shallow-water equations on a β-plane:

➢ **Classical formulation:**

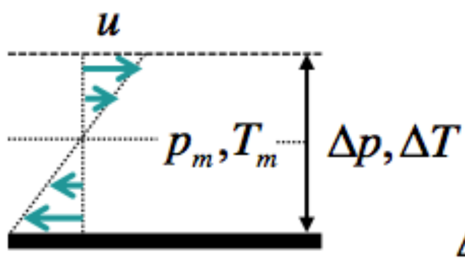
$$\begin{cases} \partial_t u - \beta y v = -g \partial_x h \\ \partial_t v + \beta y u = -g \partial_y h \\ \partial_t h + H(\partial_x u + \partial_y v) = 0 \end{cases}$$



[Matsuno 66]

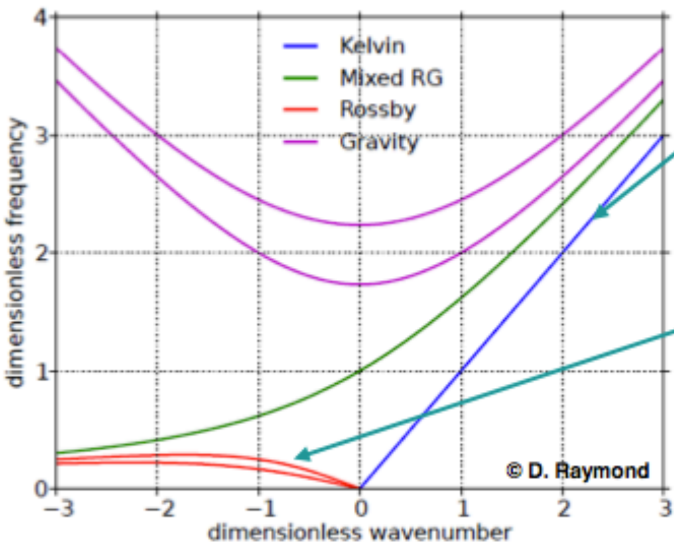
➢ **Tropical atmosphere:**

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

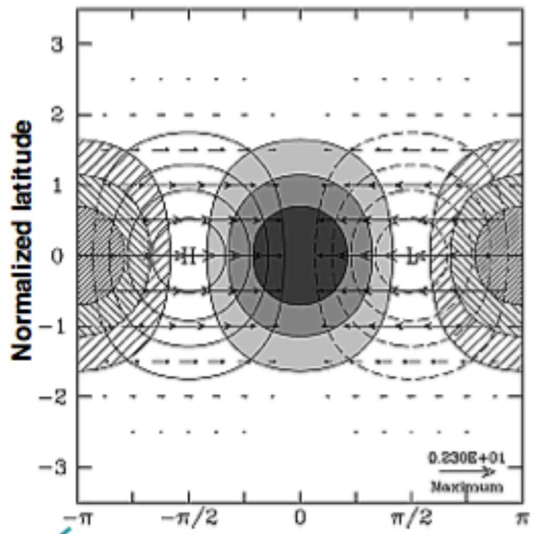


$$\alpha = \frac{\Delta p}{2 p_m} R$$

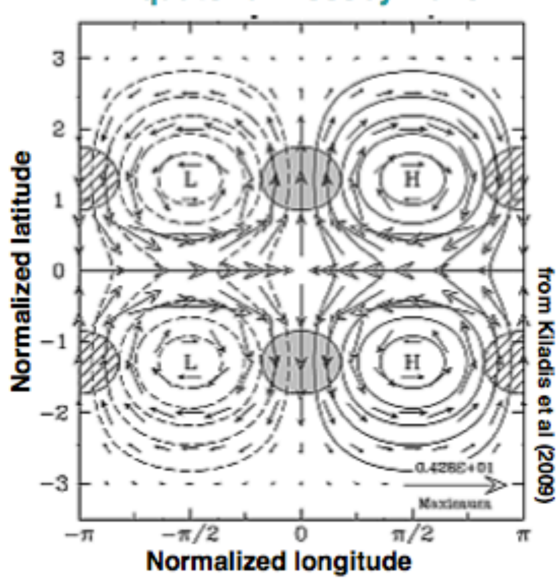
Dispersion diagram:



Kelvin wave



Equatorial Rossby wave



Convective organization: equatorial waves

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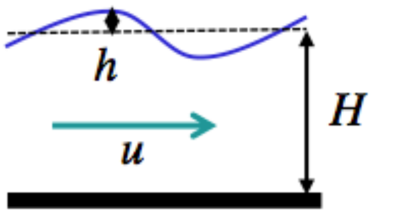

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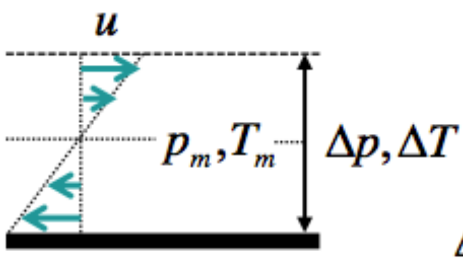
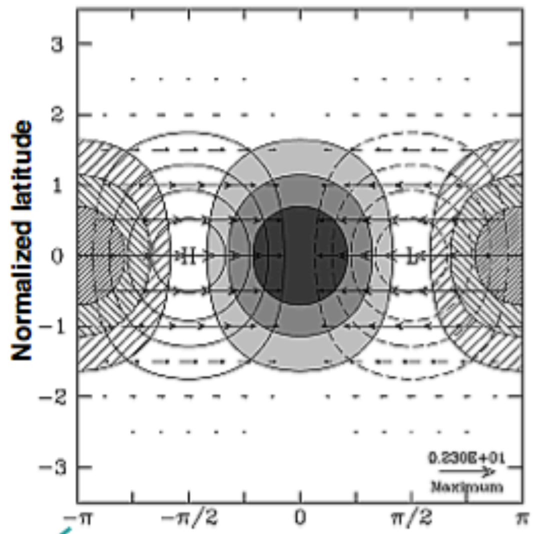
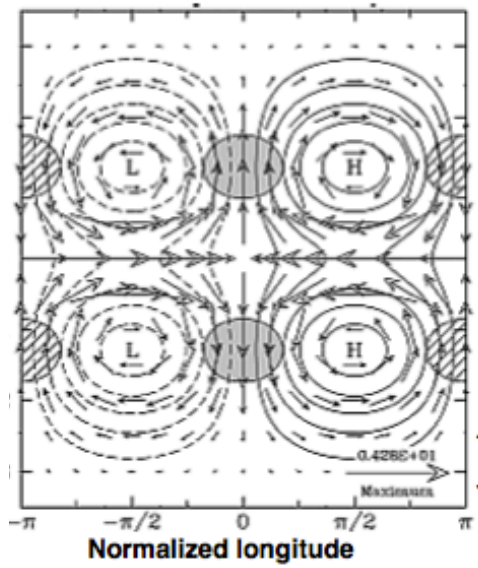


$\alpha = \frac{\Delta p}{\ } R$

Kelvin wave



Equatorial Rossby wave



from Kiladis et al (2009)

Coherence squared (NOAA OLR + ERA Interim winds)

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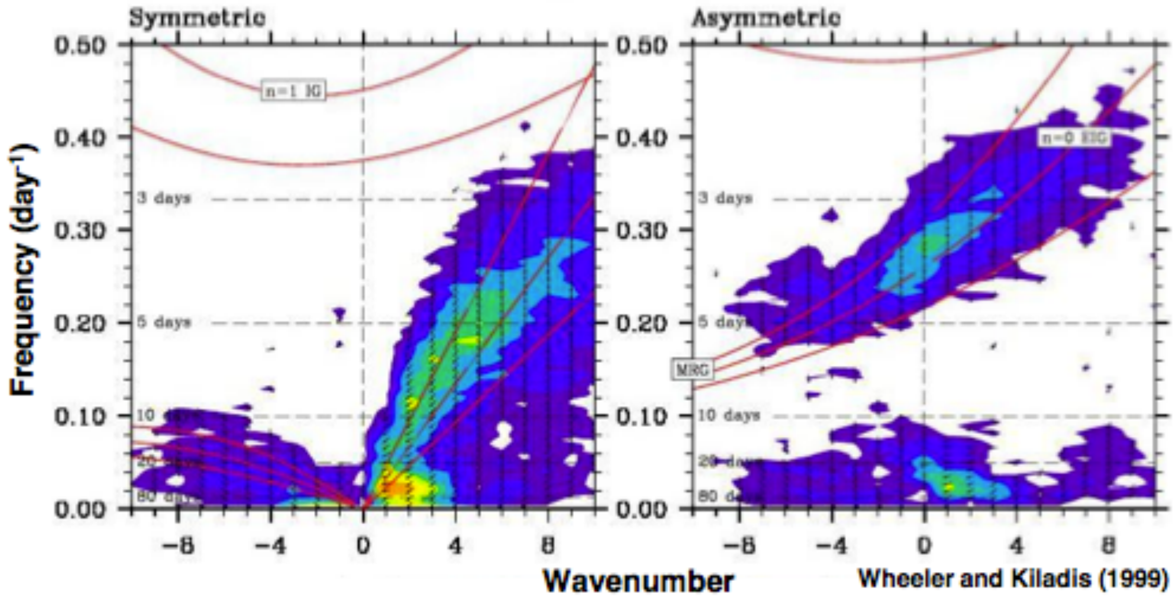
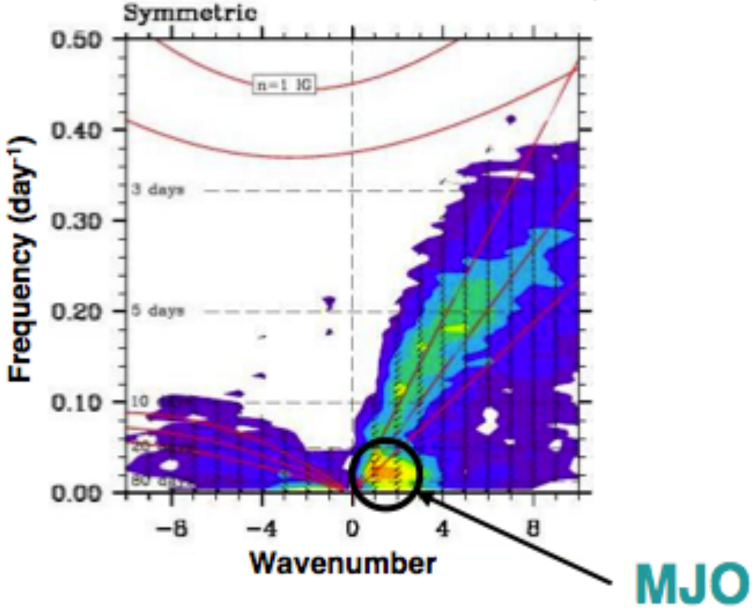


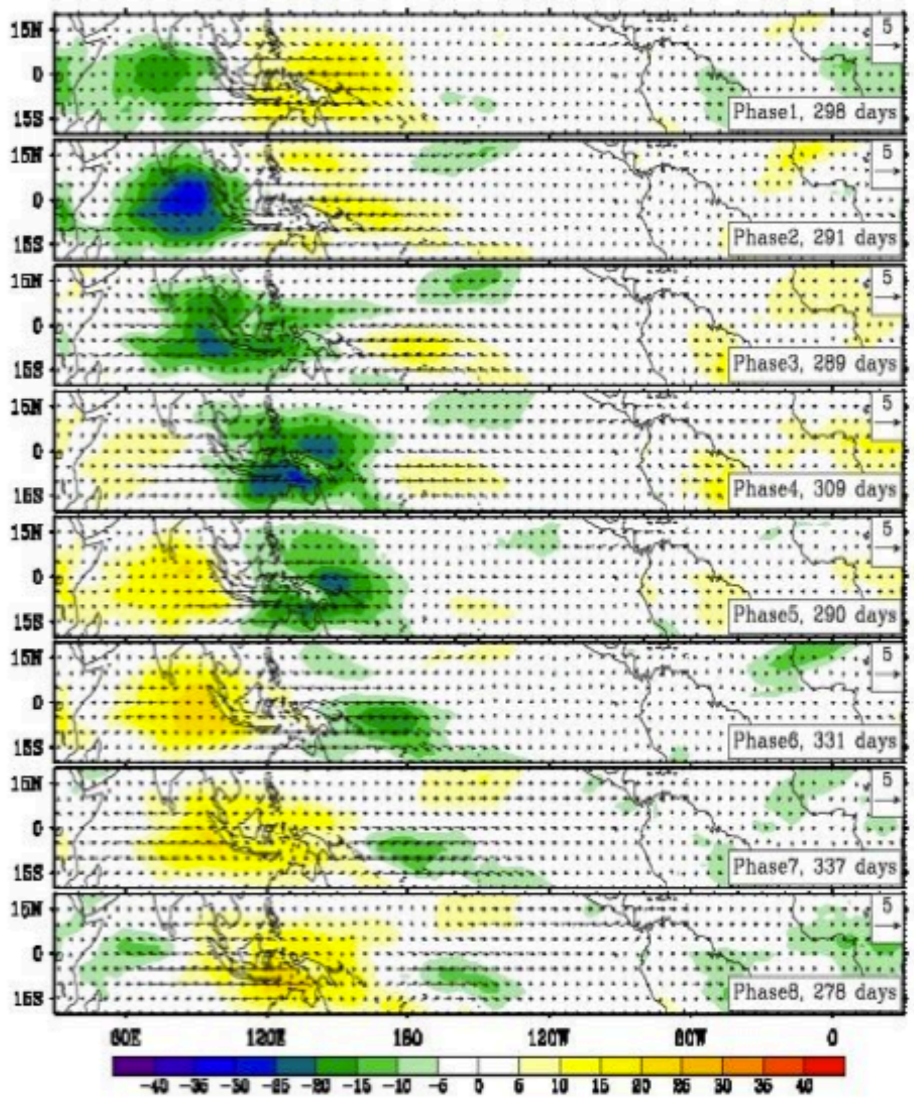
Wheeler and Kiladis (1999)

Convective organization: MJO

Coherence squared
(NOAA OLR + ERA Interim winds)

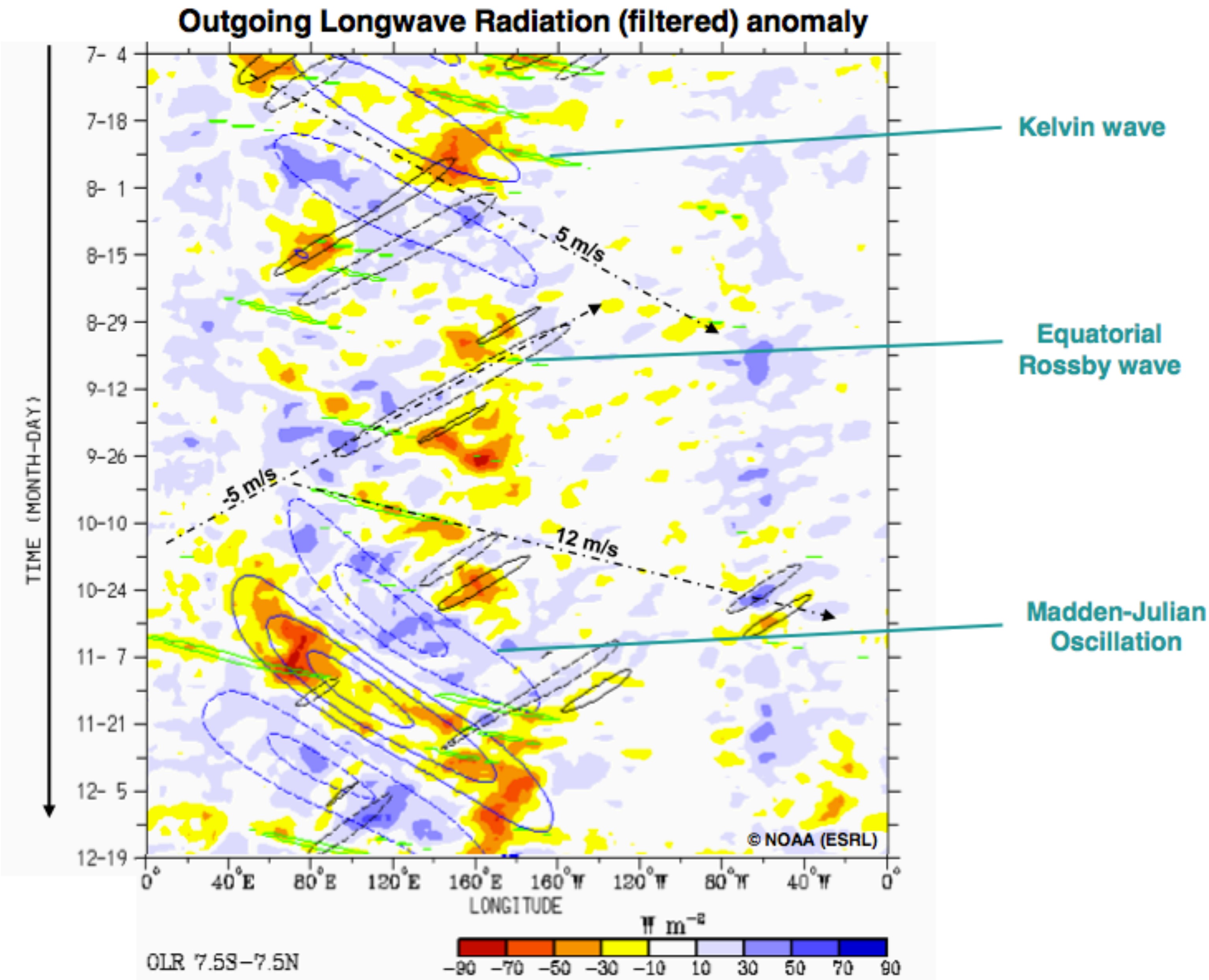


MJO composite life cycle



NOAA OLR anomaly (+ ERA Interim wind anomaly)

Convective organization: equatorial waves



Convective organization: equatorial waves