4 May 2021 14h40 — **TRAINING**
Thematic introduction, a few papers/links

→

6 May 2021 14h40 — **SYNTHESIS**
Preparation of 4-5 slides by each working group

→

7 May 2021 13h40 — **PRESENTATION**
Plenary presentations of the slides (each presentation will have 5 minutes plus discussion)

GOAL OF PROJECT: How are clouds distributed on Earth, and why?

SLIDES

Part 1: Synthesis of the theme and tools proposed during the training session

* General context : What is the goal of the project ?
* Introduction to cloud types and cloud physics
* Spatial distribution and link with the large scale atmospheric motion

Part 2: Your project

* Links to satellite visualizations
* Your presentation

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Ecole Normale Supérieure Paris

What are clouds ?

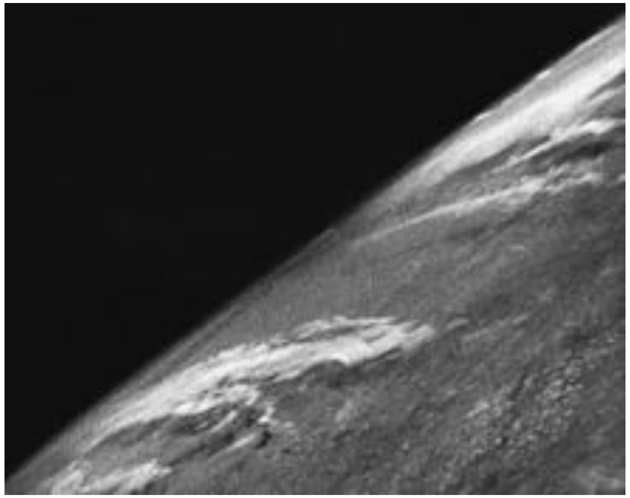
Clouds and atmospheric convection

and clouds

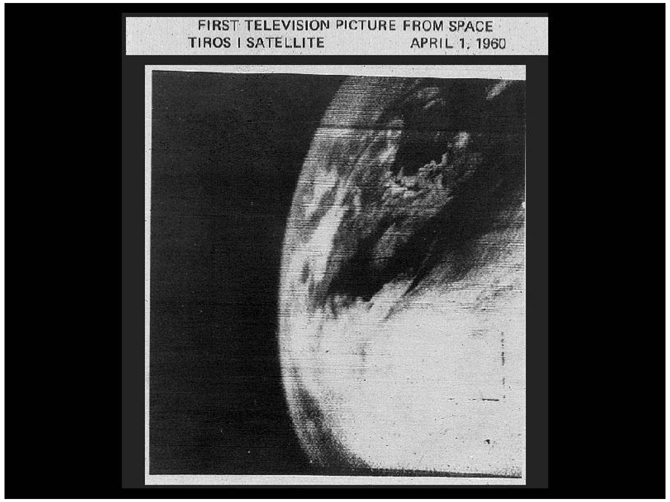
"How inappropriate to call this planet Earth, when clearly it is Ocean." - *Arthur C. Clark*

What are clouds ?

Earth from rocket 1946



Earth From Weather Satellite 1960

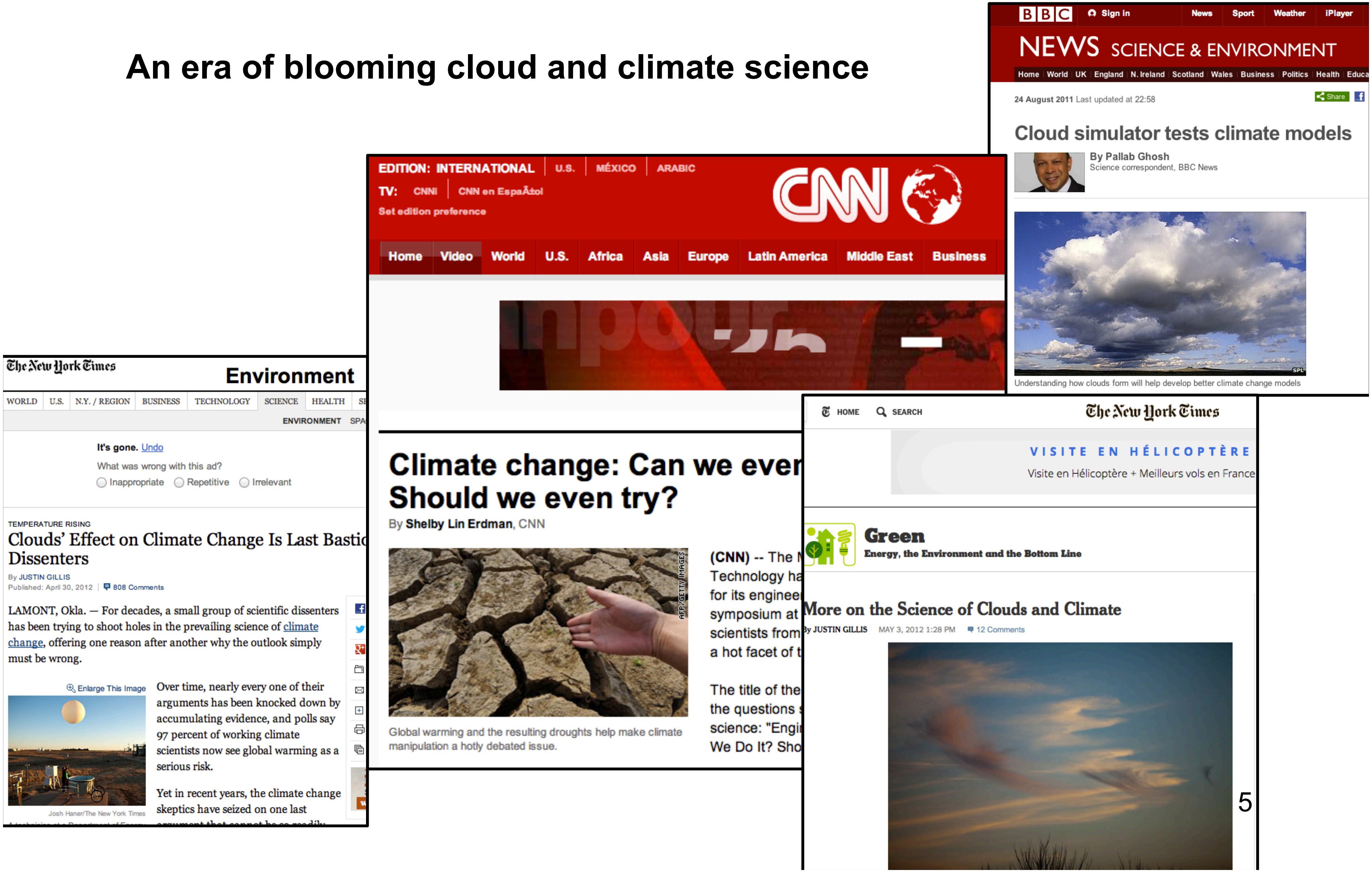


Blue Marble 1972

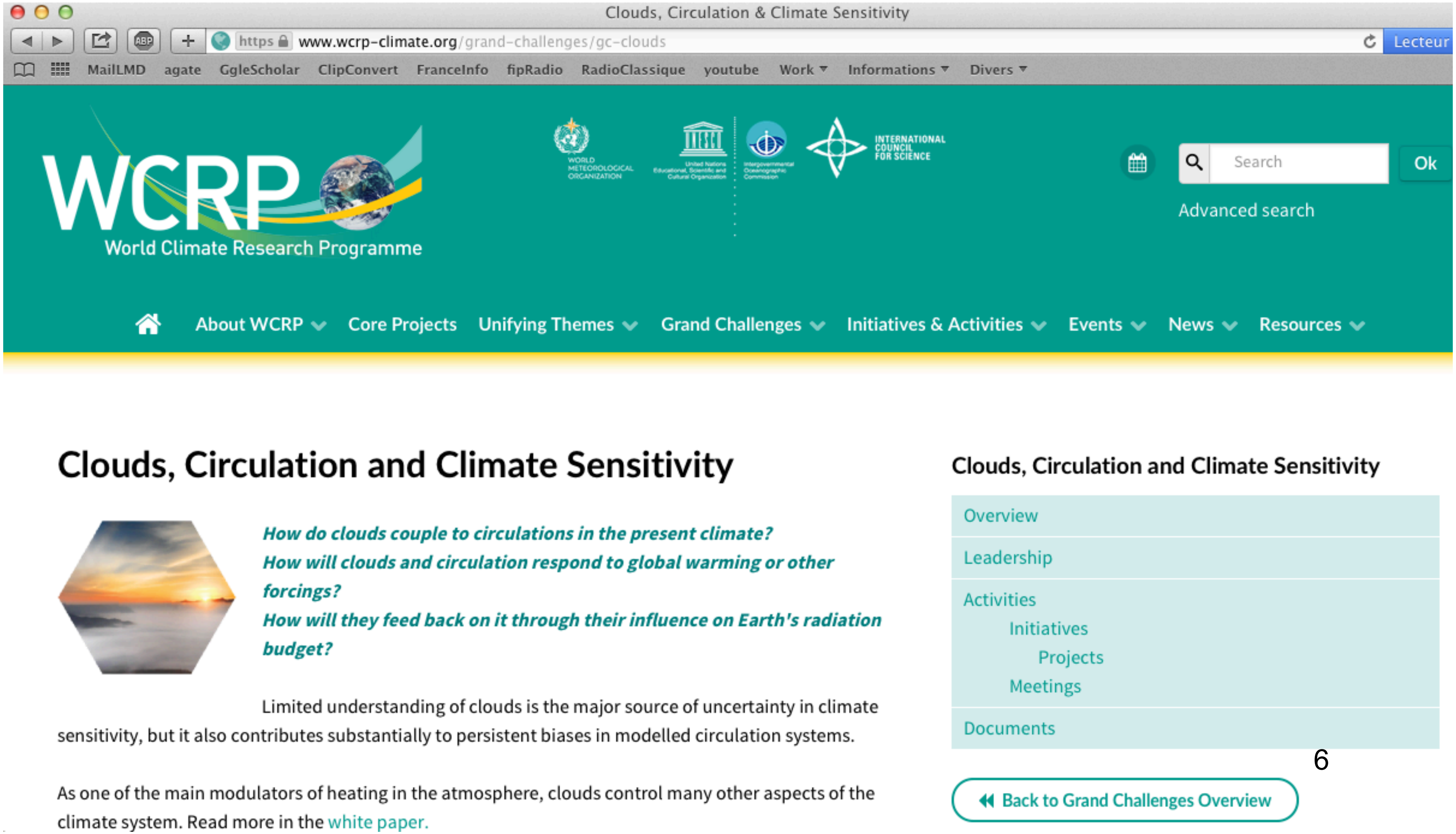
Tintin on the moon 1952

What are clouds? Key actors of climate

An era of blooming cloud and climate science

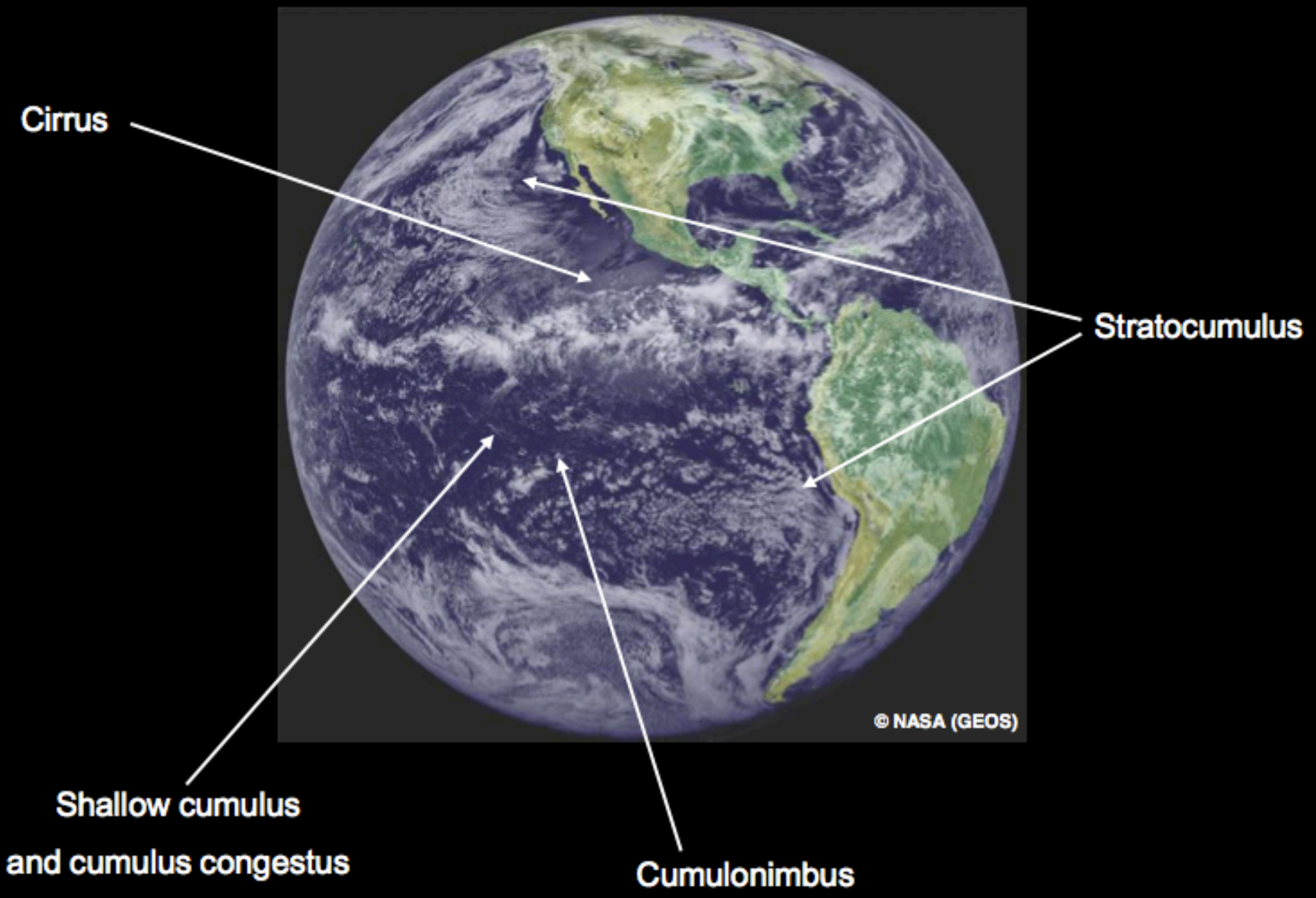


What are clouds? A Grand Challenge



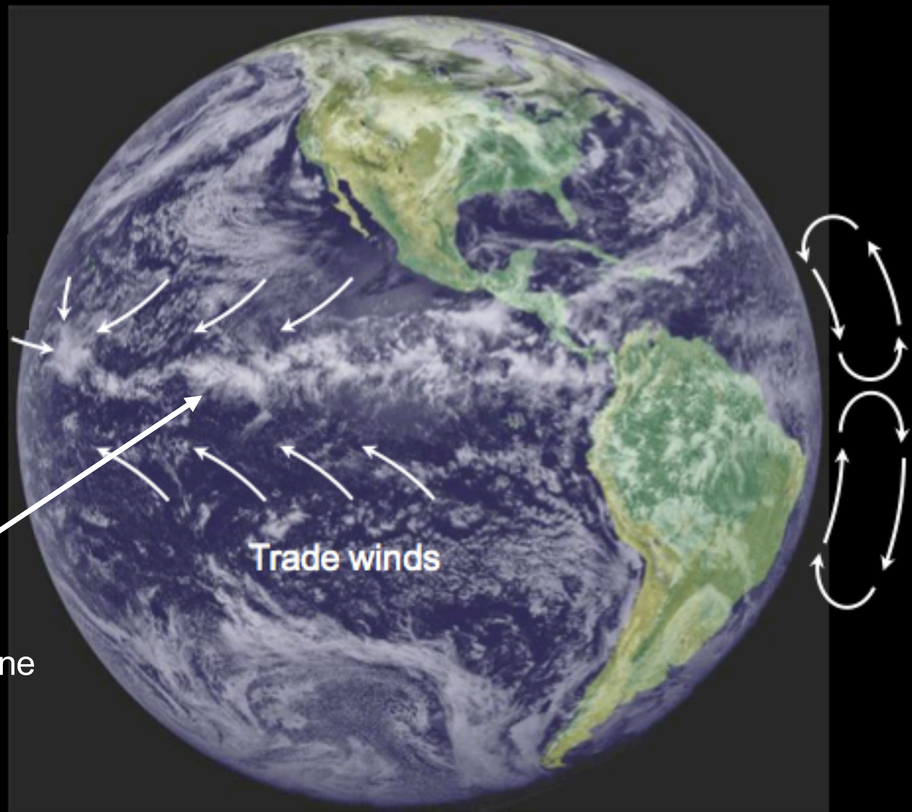
Clouds and atmospheric convection

clouds are diverse, ...



Clouds and atmospheric convection

… and coupled to circulations.



Clouds and atmospheric convection

GOAL OF PROJECT: How are clouds distributed on Earth, and why?

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

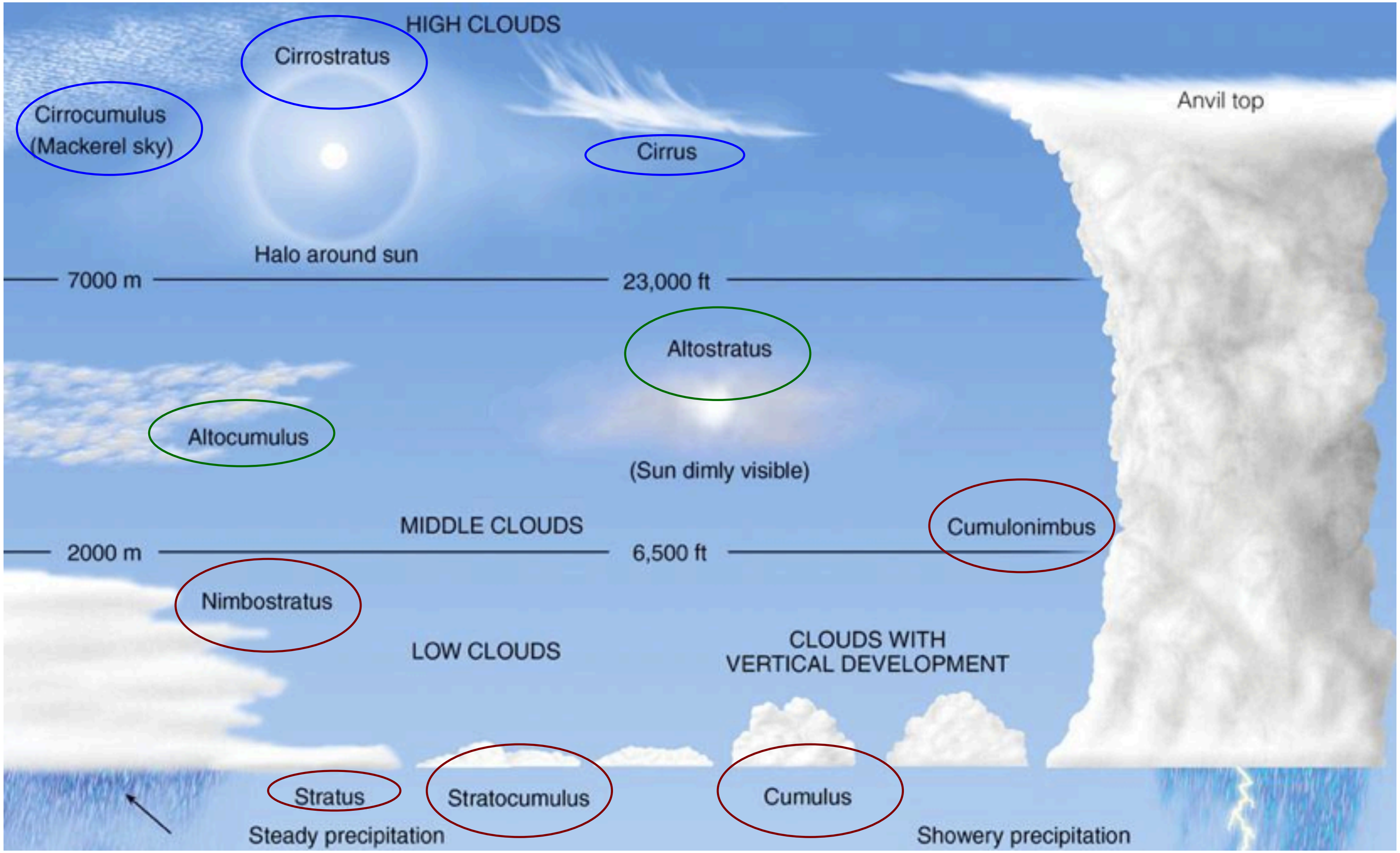
Nimbus: precipitating cloud

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

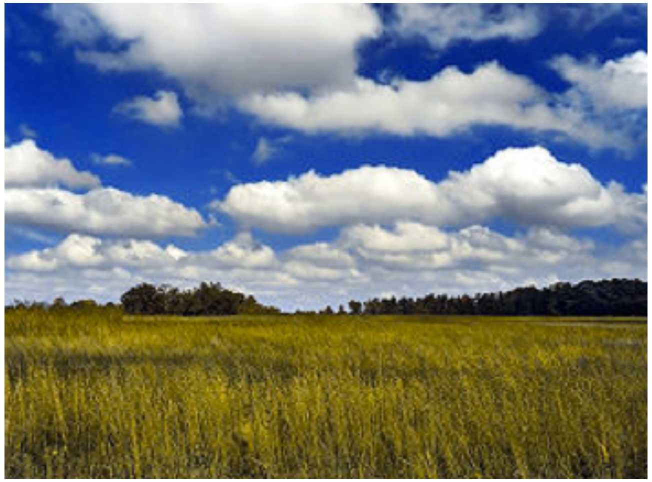
Thick, dense stratus or stratocumulus clouds producing steady rain or snow

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"

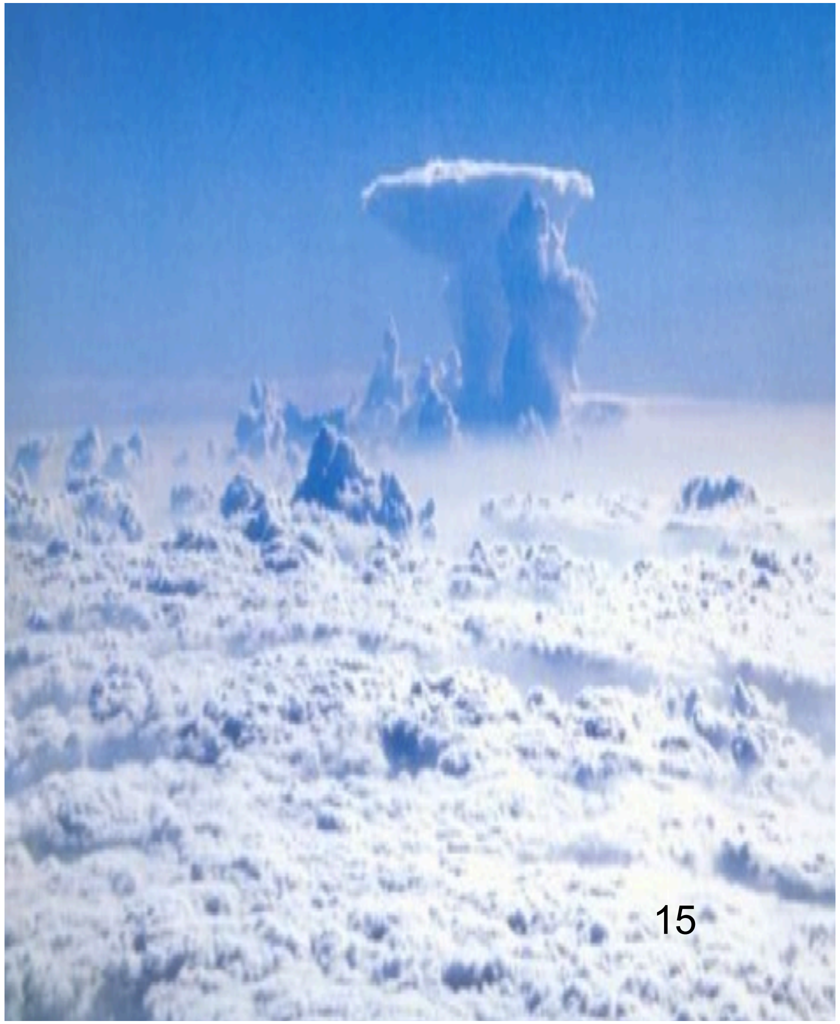


Cumulus (congestus)

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…

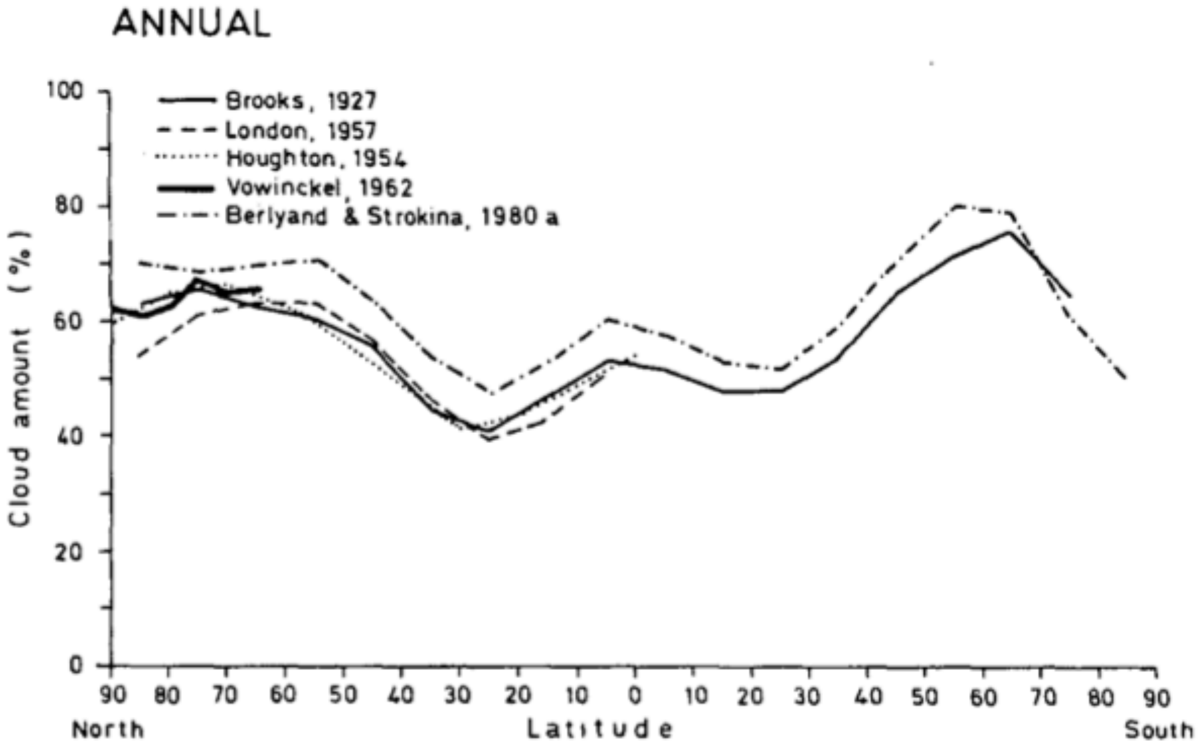
Mammatus clouds (typically below anvil clouds)

Shelf clouds (gust front)

Lenticular clouds (over orography)

Question: Global cloud cover (%)?

Distribution of cloud amount

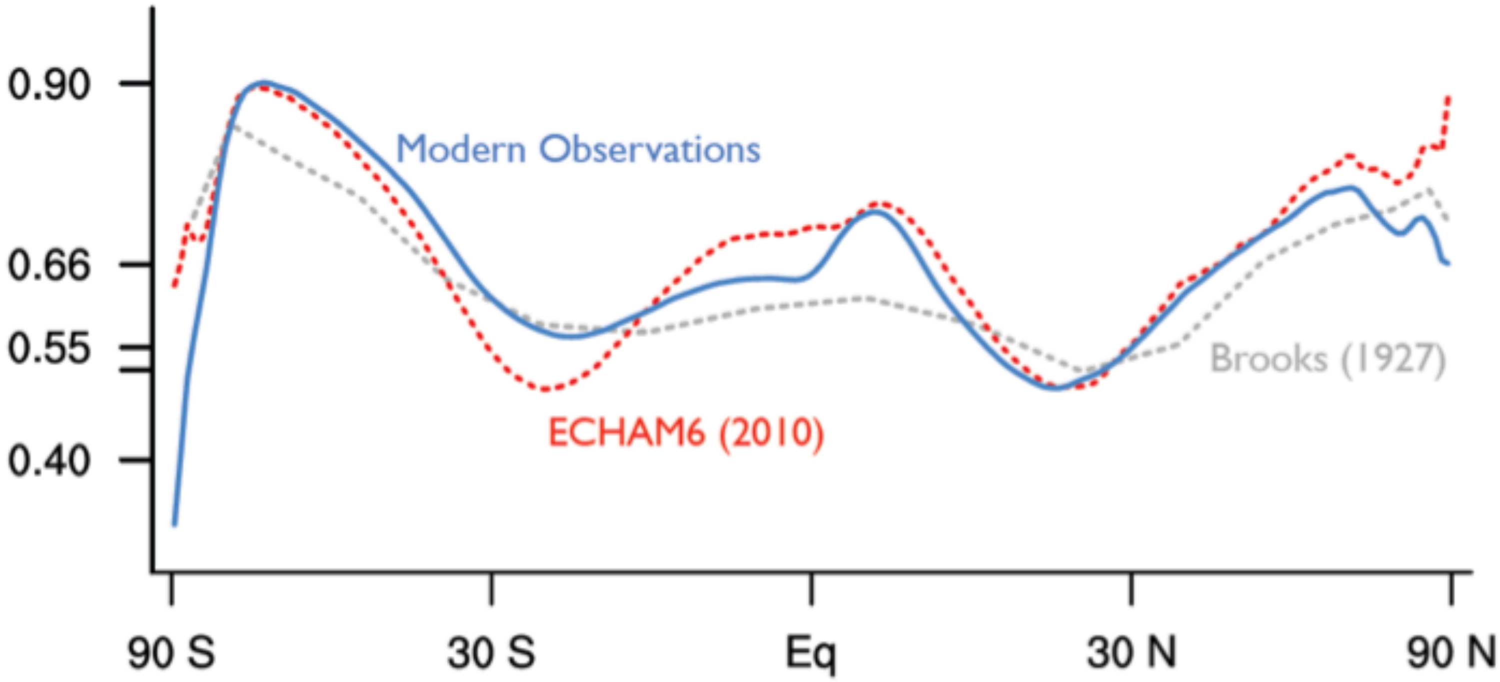


[Hughes 84]

1. Cloud types

Cloud amount was underestimated

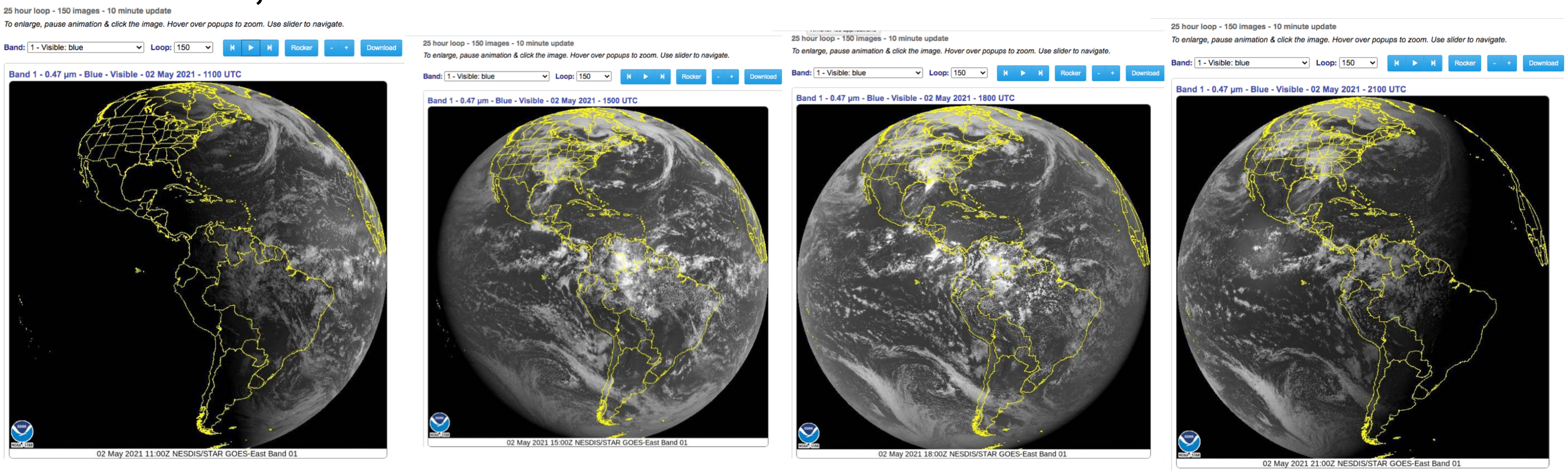
Also note the latitudinal distribution



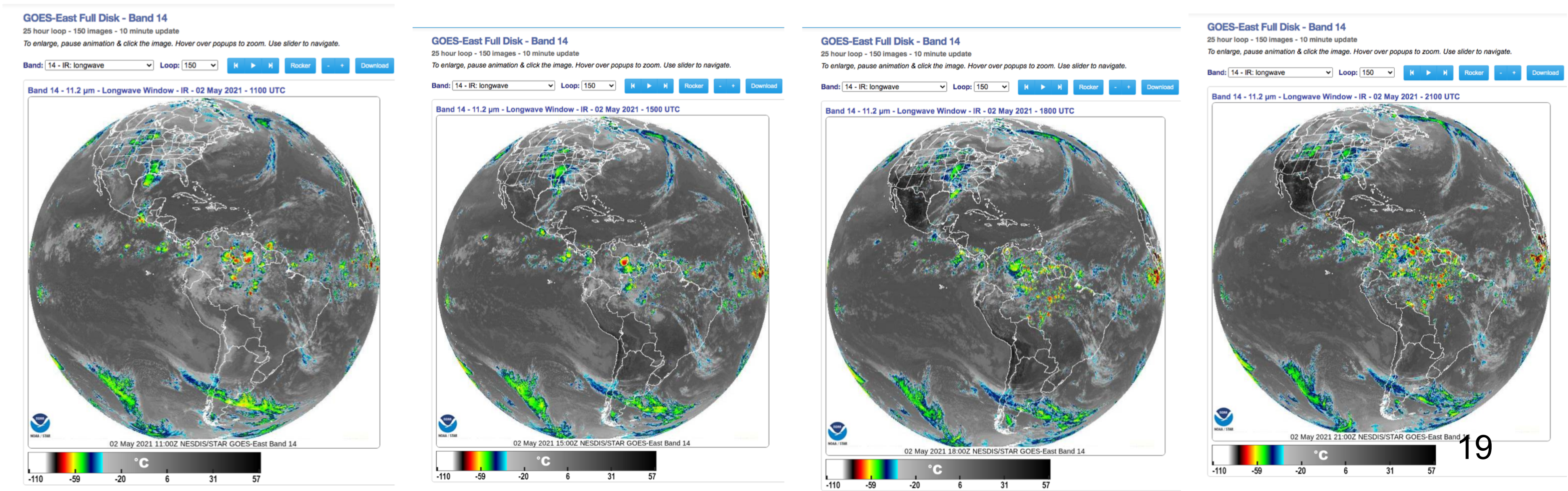
Courtesy Bjorn Stevens

GOES satellite imagery May 2nd @ 11,15,18,21 UTC

Shortwave, or visible

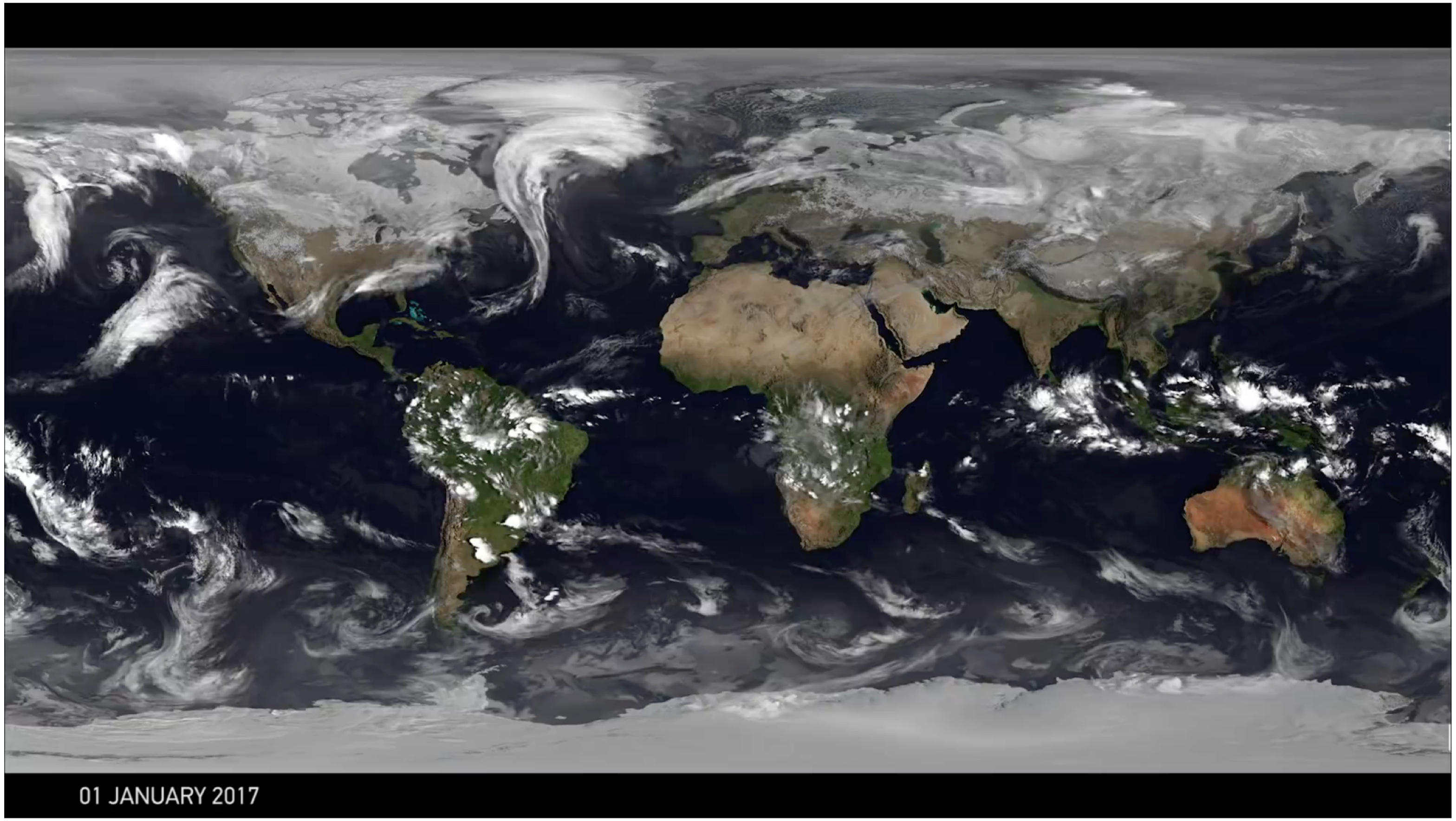


Longwave, or infrared (emission temperature)



1. Cloud types

Brightness temperature from satellite (white ⇔ cold cloud tops)



Large extratropical storm systems

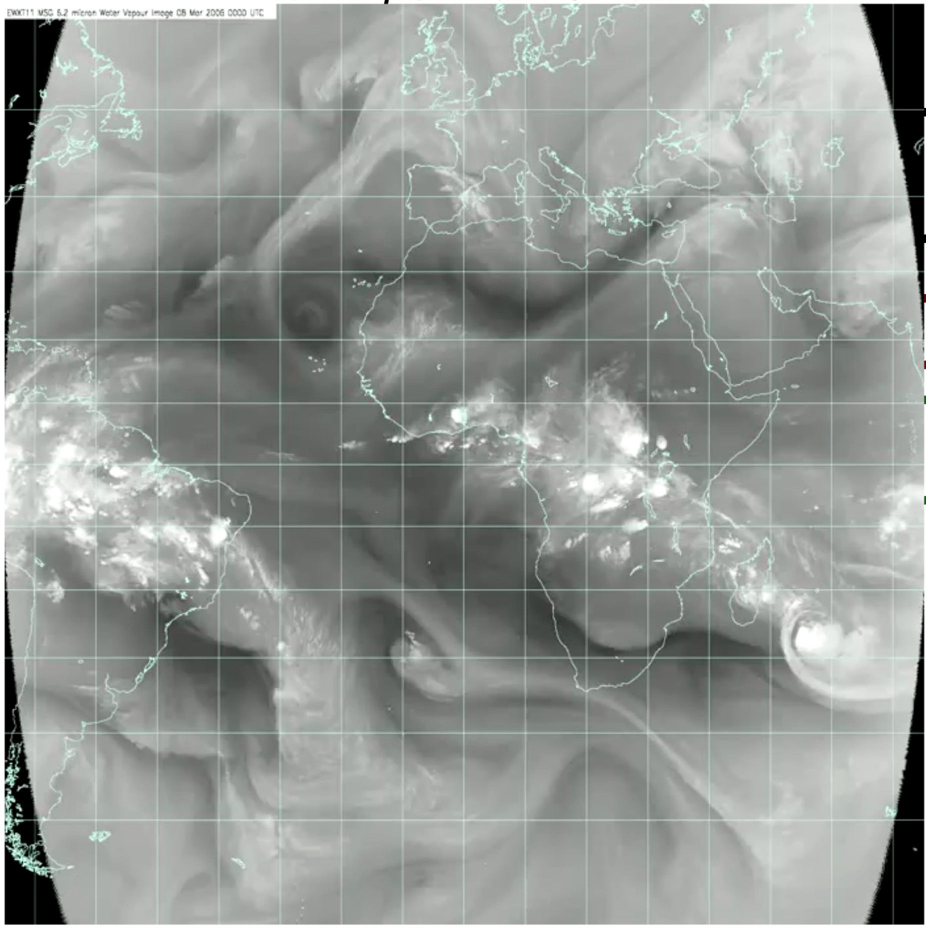
subtropics: ~no high clouds

ITCZ = Intertropical convergent zone

« A year of weather »

1. Cloud types

Water vapor from satellite



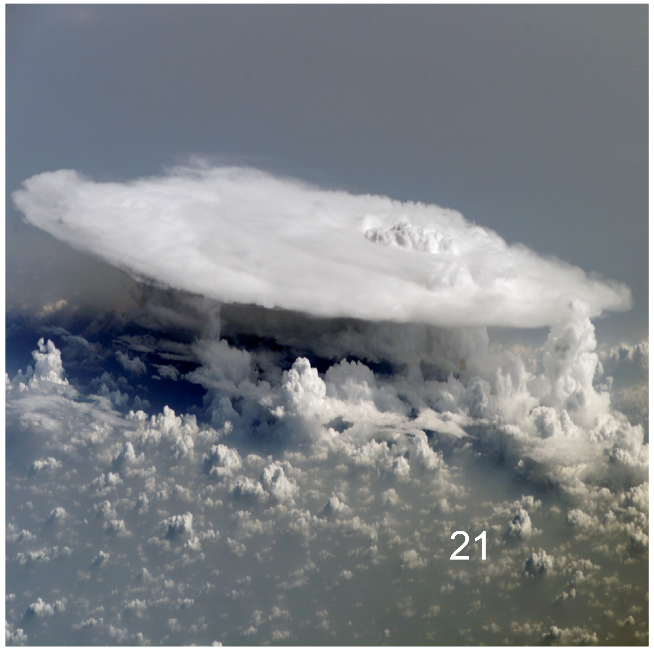
Large extratropical storm systems => Large-scale extratropical convection

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

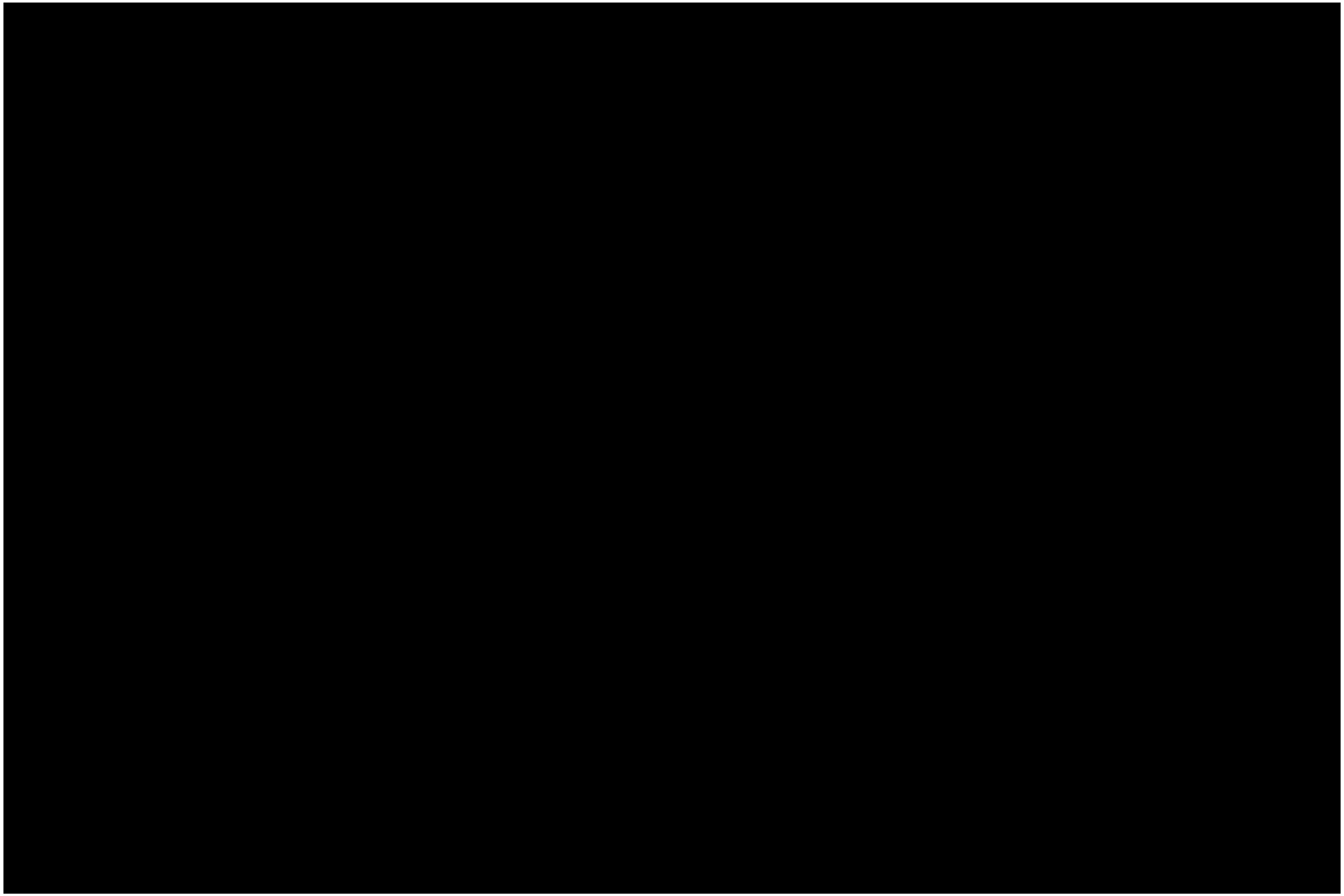
2. Moist thermodynamics and stability

3. Coupling with circulation

Cloud formation

Courtesy : Octave Tessiot

Cloud formation

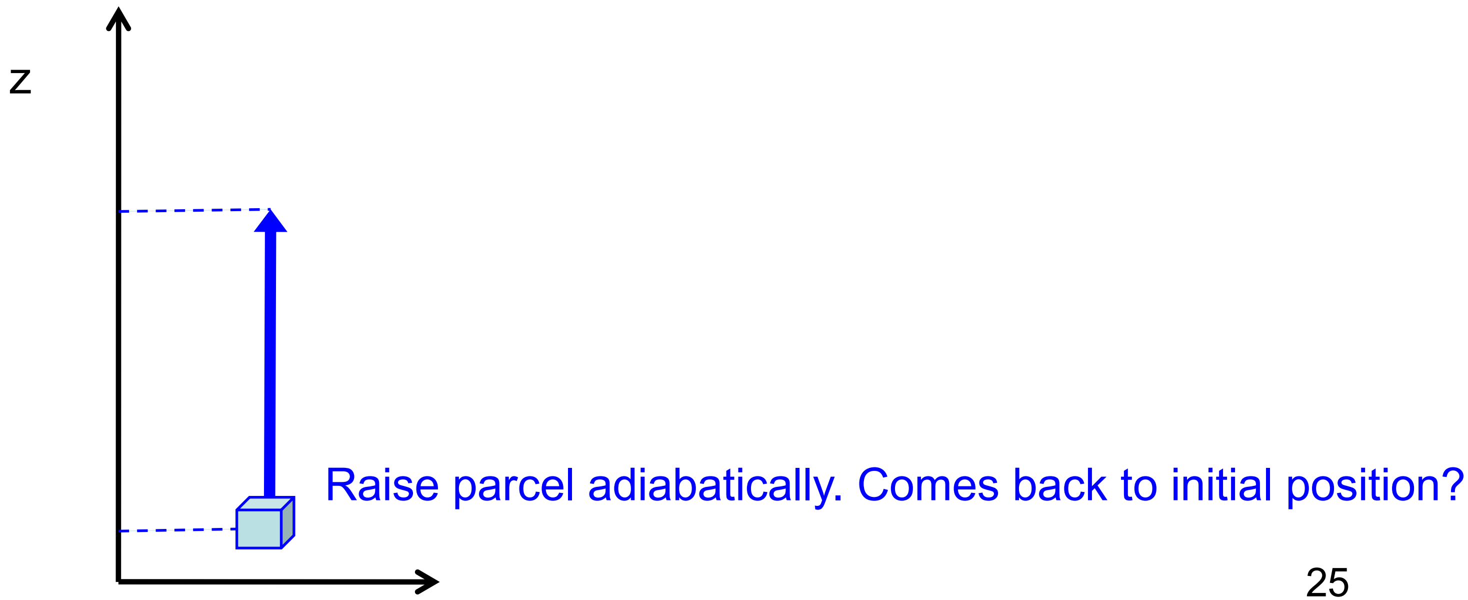


Courtesy : Octave Tessiot

Dry convection

T decreases with height.
But p as well.

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



2. Atmospheric thermodynamics: instability

Dry convection

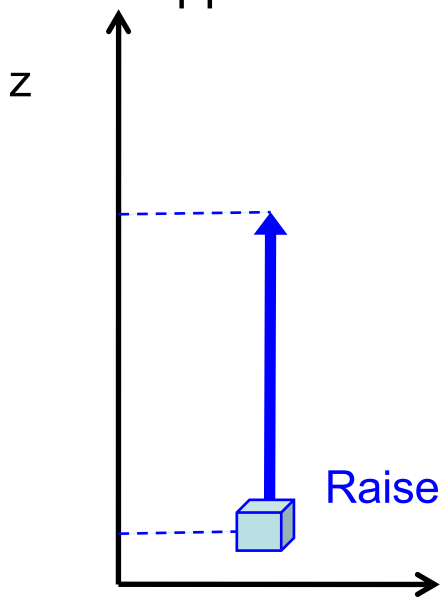
T decreases with height, but p as well. Density = ρ(T,p). How determine stability? The parcel method

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.



Raise parcel adiabatically. Comes back to initial position?

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)

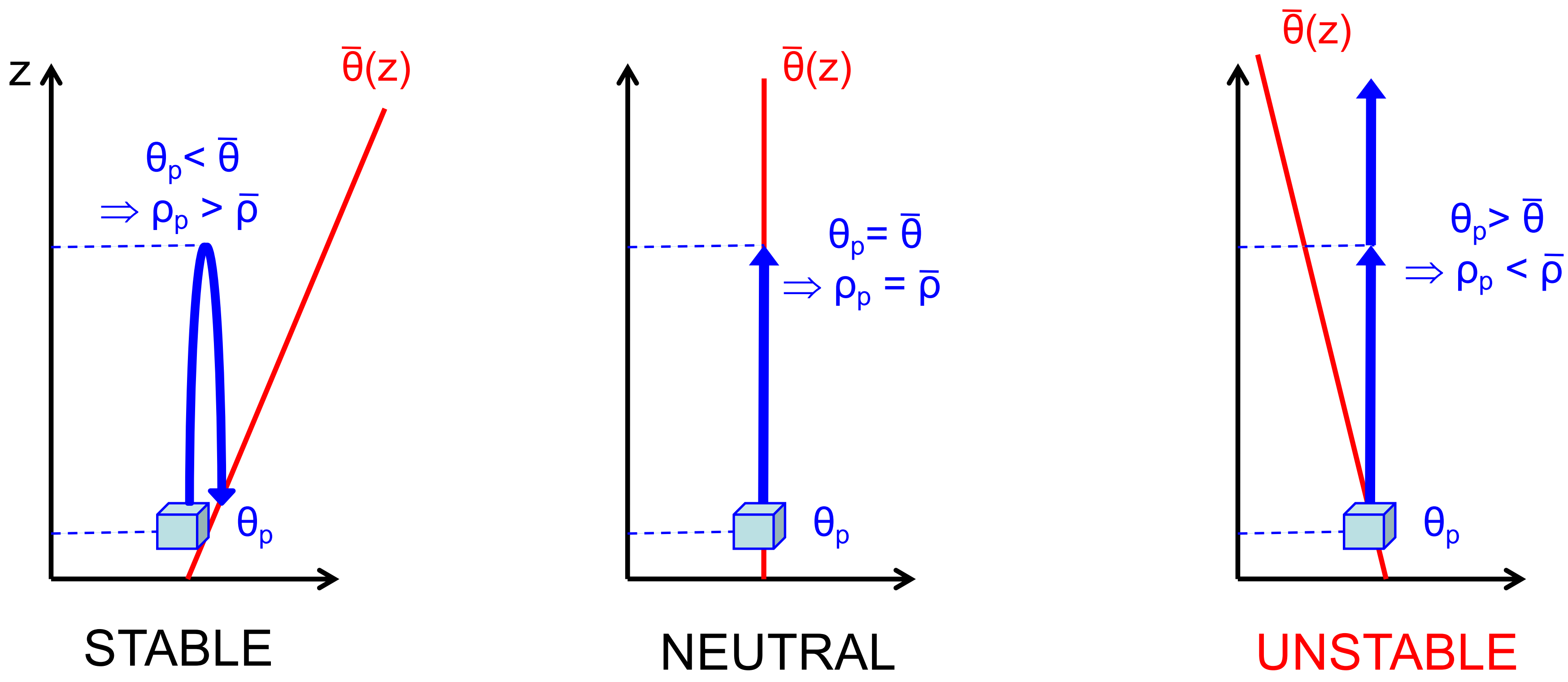
2. Atmospheric thermodynamics: instability

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.



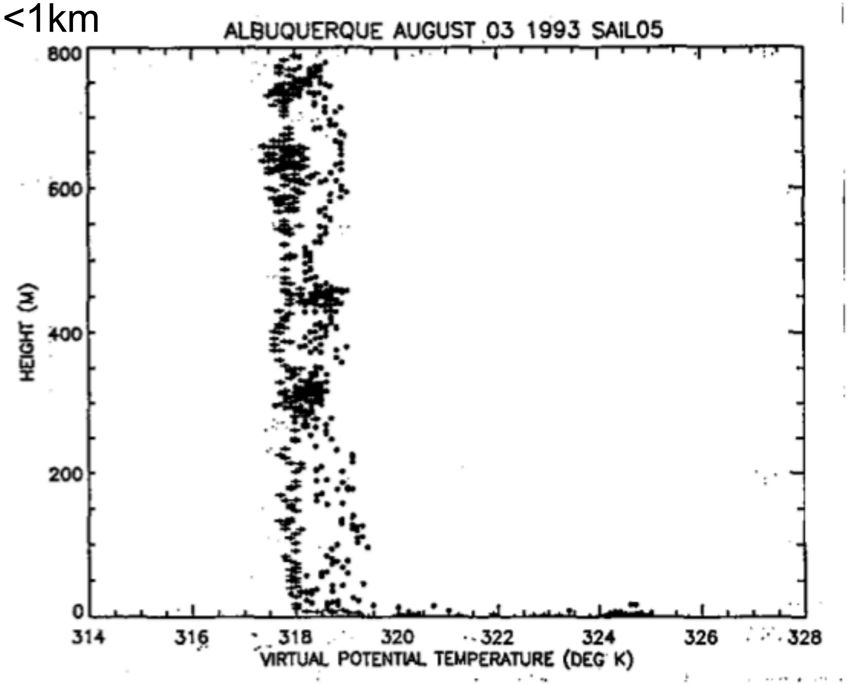
2. Atmospheric thermodynamics: instability

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?…

Atmospheric thermodynamics: instability

inversion

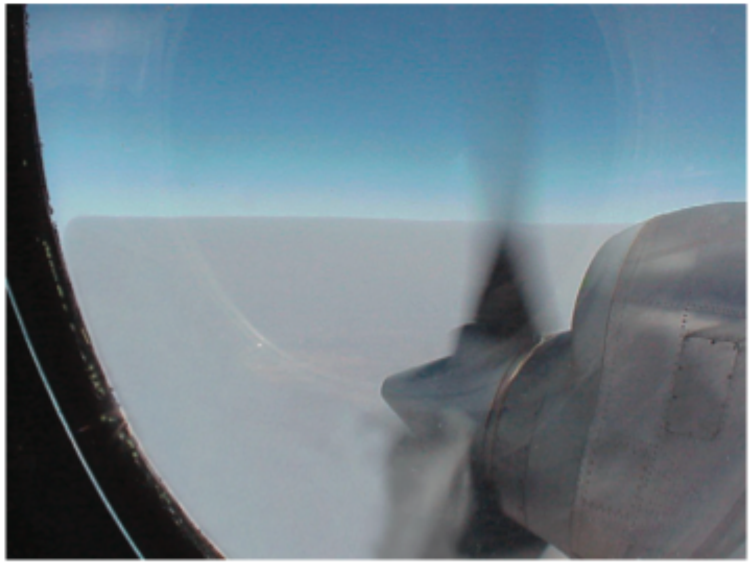


Fig. 3.15 Looking down onto widespread haze over southern Africa during the biomass-burning season. The haze is confined below a temperature inversion. Above the inversion, the air is remarkably clean and the visibility is excellent. (Photo: P. V. Hobbs.)

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

More det

2. Atmospheric thermodynamics: instability

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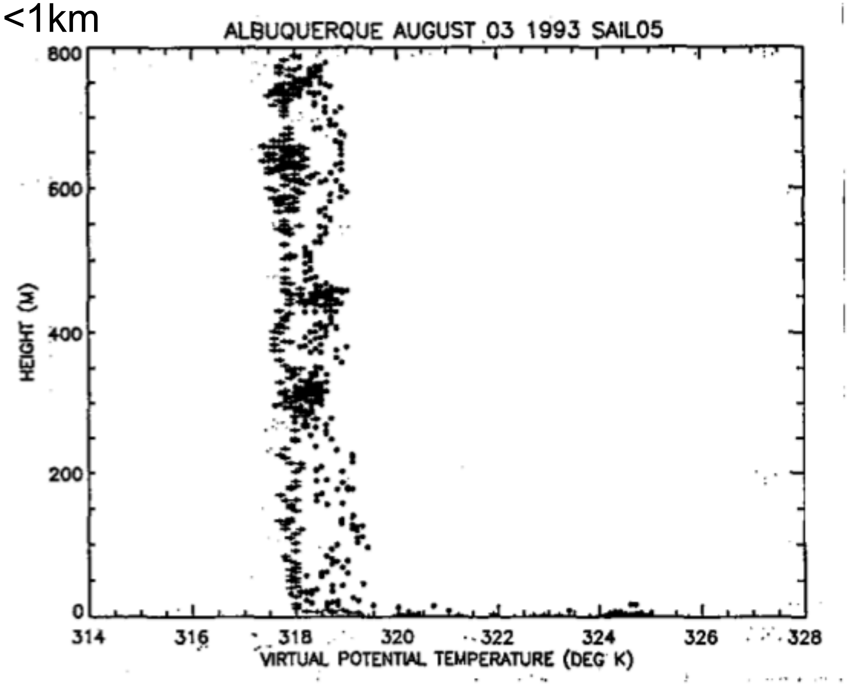


[Renno and Williams, 1995]

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**

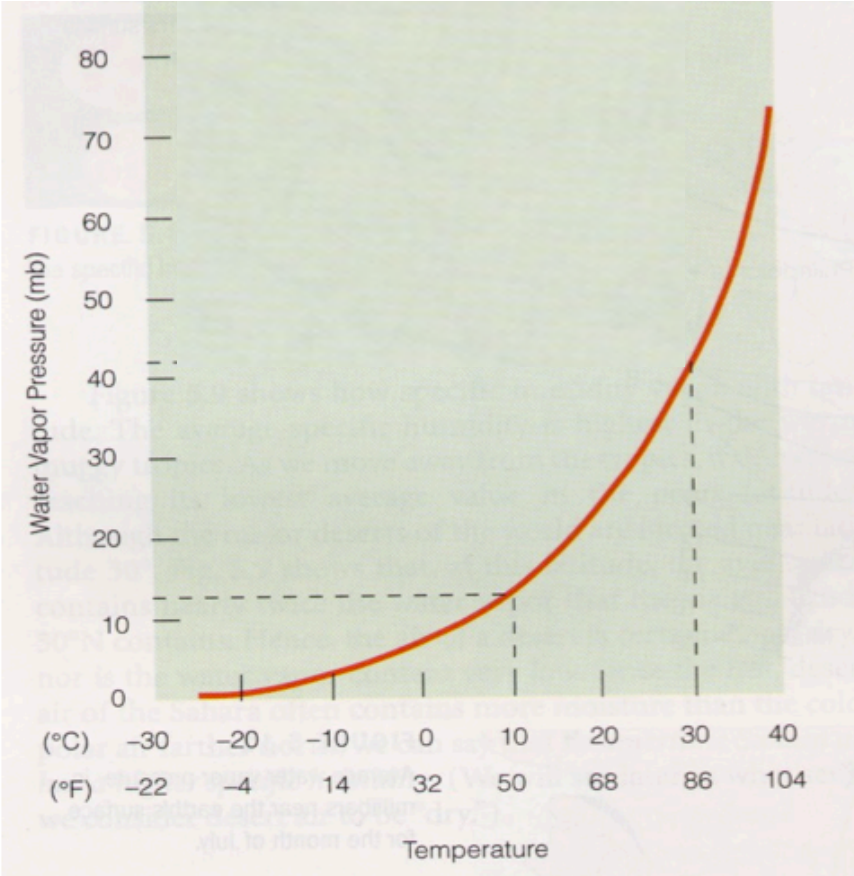
2. Atmospheric thermodynamics: instability

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

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 $L_v = 2.5 \times 10^6$ J kg^{-1}
- water vapor mixing ratio (kg of water vapor per kg of dry air) $q_v = O(10^{-3})$
- temperature $T = O(3 \times 10^2$ 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)

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

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

But $d(q_s / T) = dq_s / T - q_s\, dT / T^2 \approx dq_s / T$ if $dq_s/T >> q_s\, dT/T^2 \Leftrightarrow dq_s/q_s >> dT/T$

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

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

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

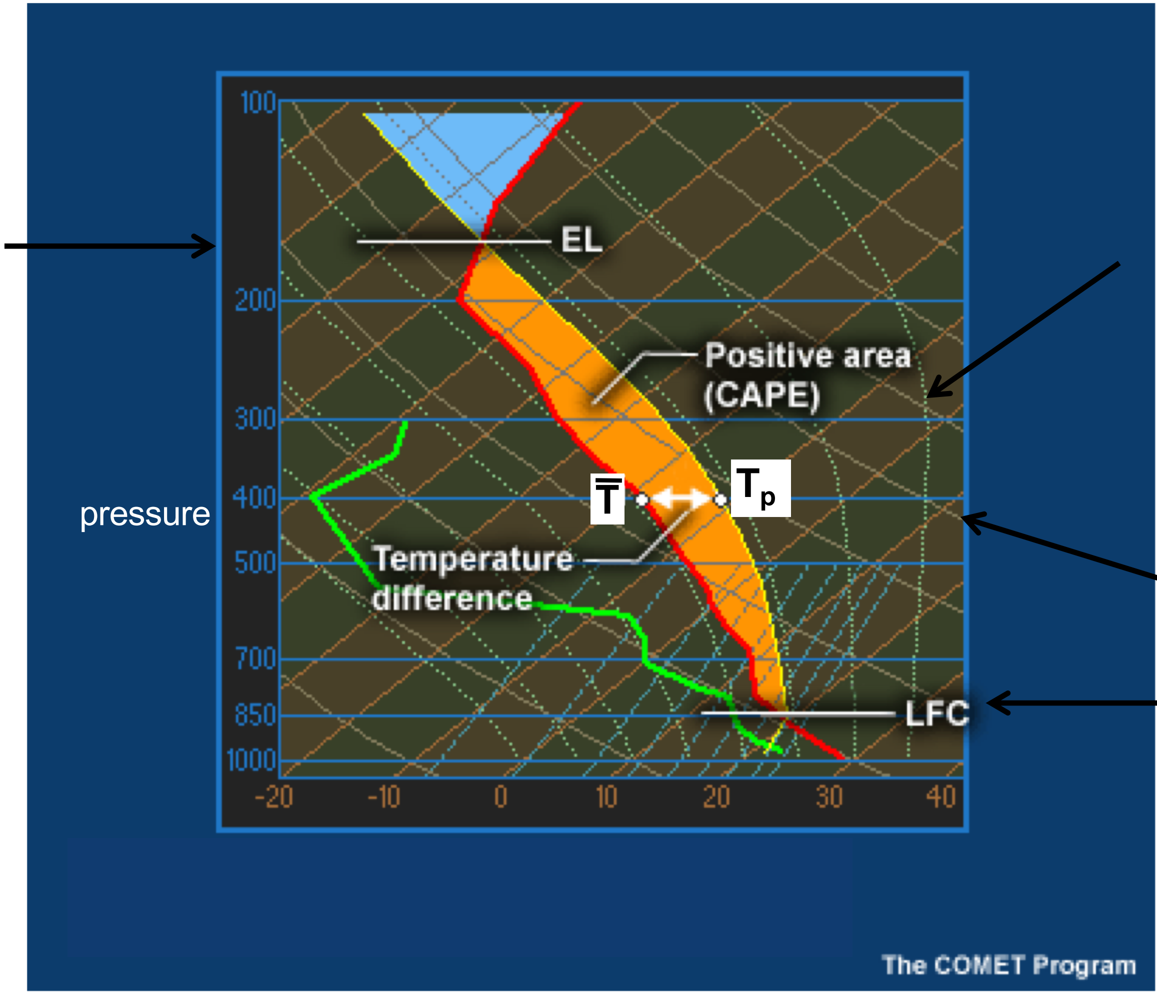
2. Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

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

EL equilibrium level

pressure



Moist adiabat θ_e= cstt

Dry adiabat θ = cstt

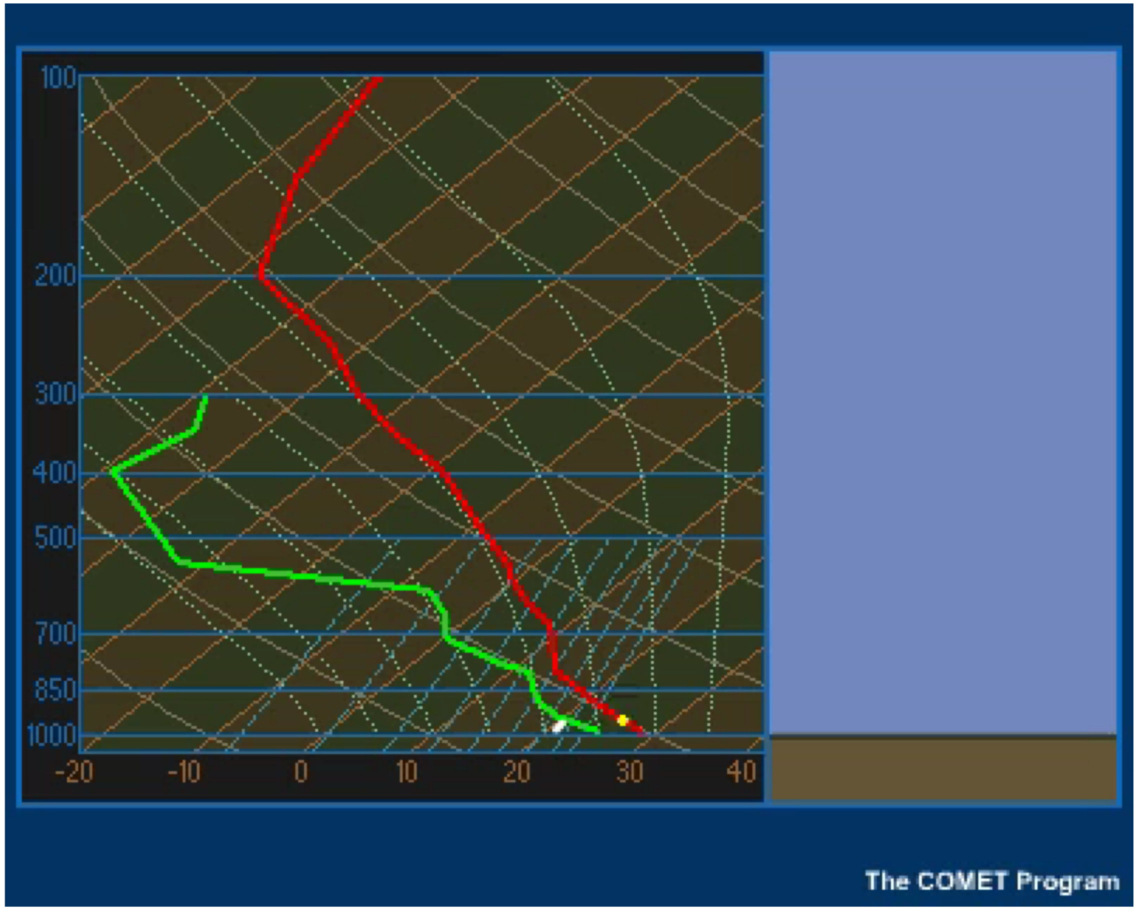
LFC level of free convection (= LCL lifted condensation level for simplicity)

CAPE: convective available potential energy

2. Atmospheric thermodynamics: instability

Parcel = yellow dot

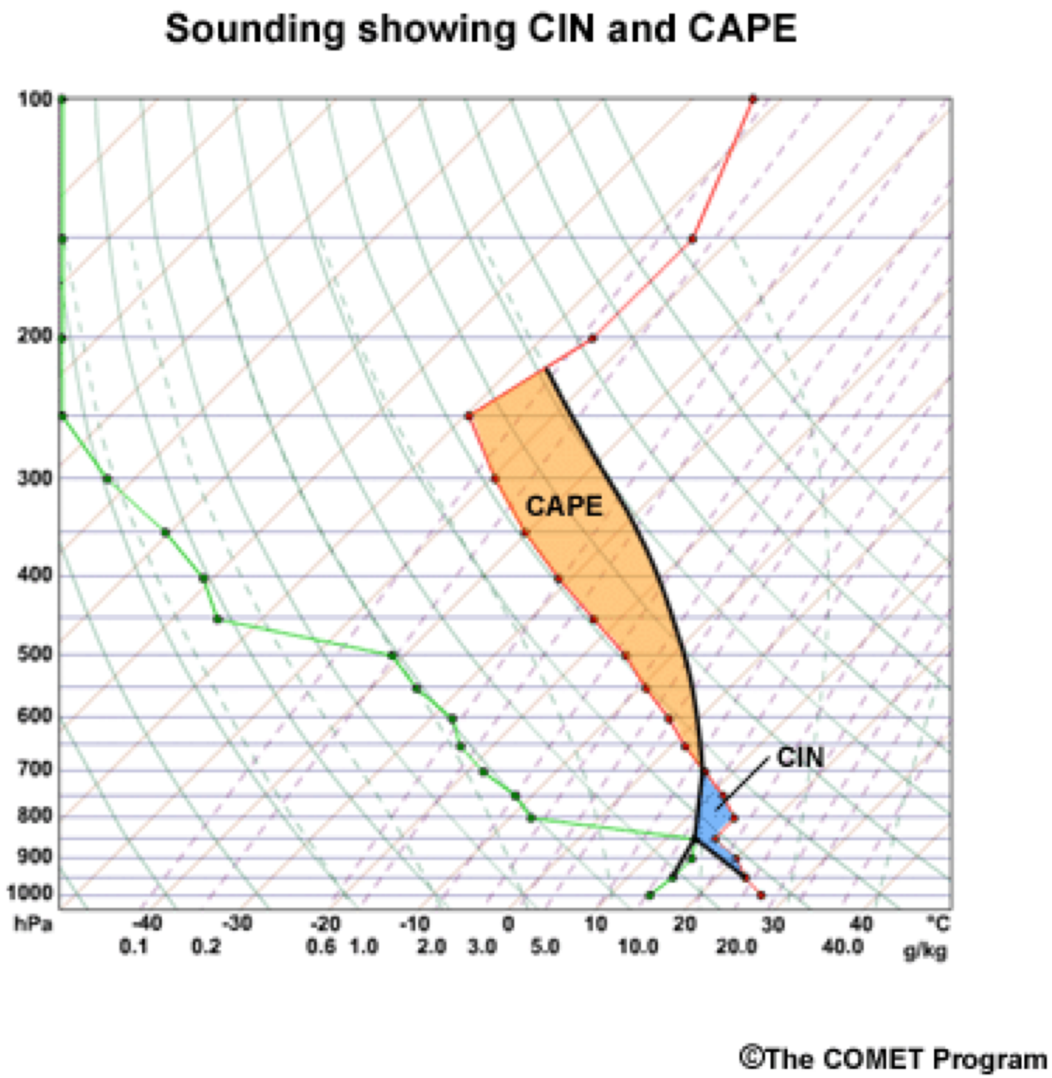
EL equilibrium level



LFC level of free convection

CAPE: convective available potential energy

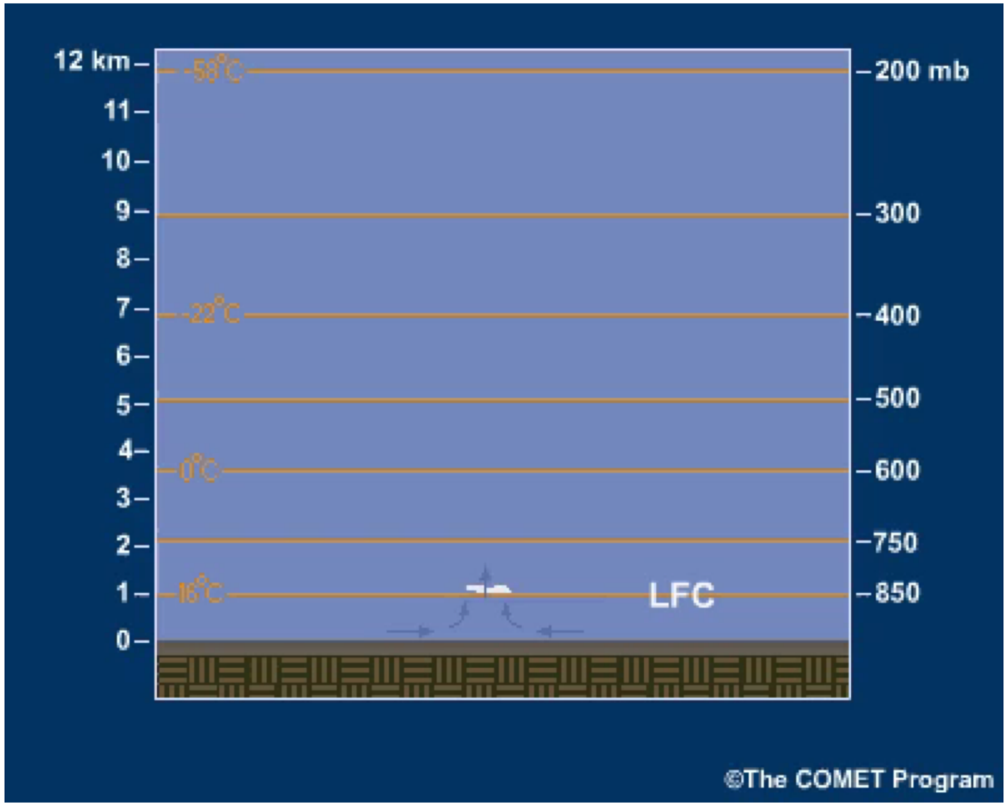
CIN: convective inhibition

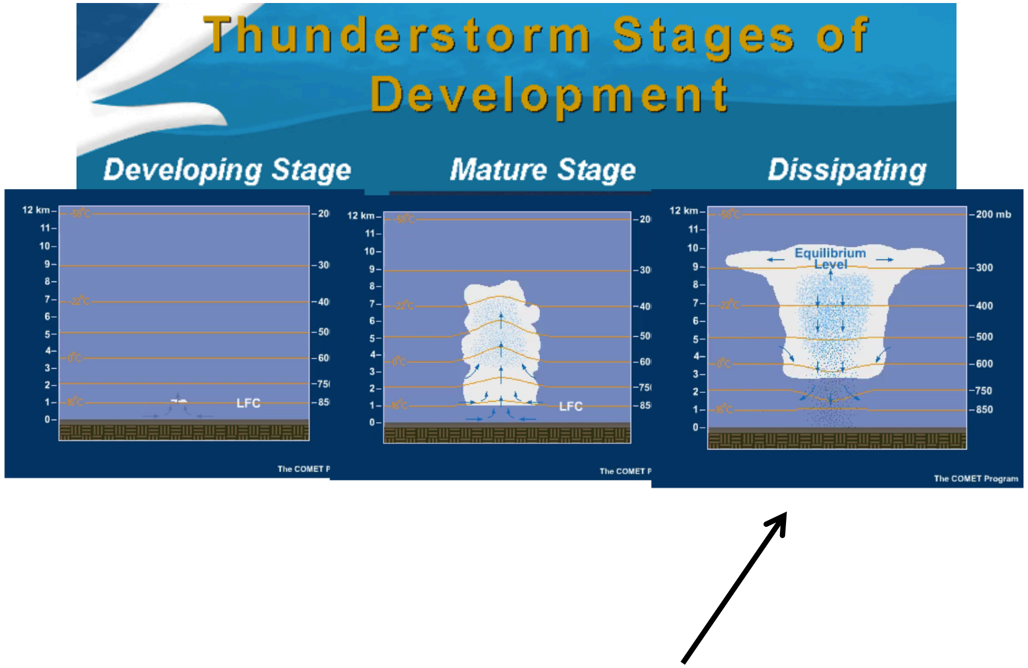


2. Atmospheric thermodynamics: instability

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.





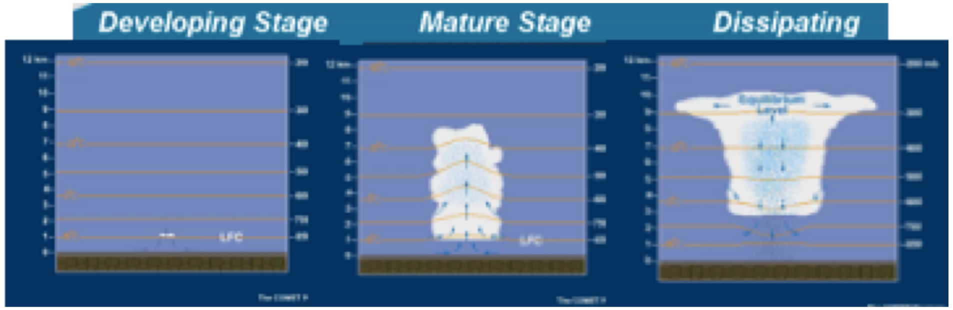
Evaporative driven cold pools

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

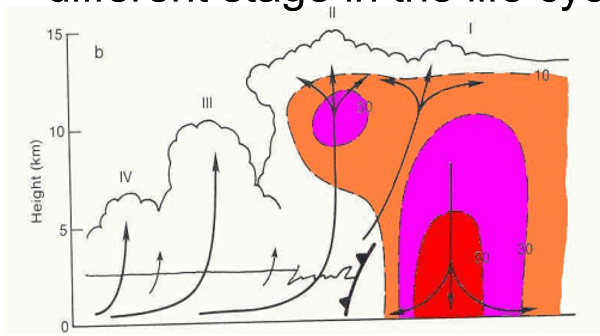
Atmospheric thermodynamics: instability

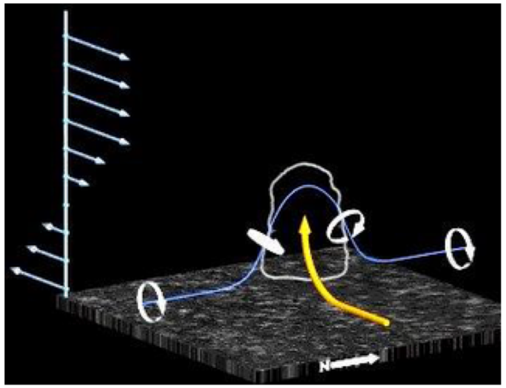
Note that thunderstorms can be :

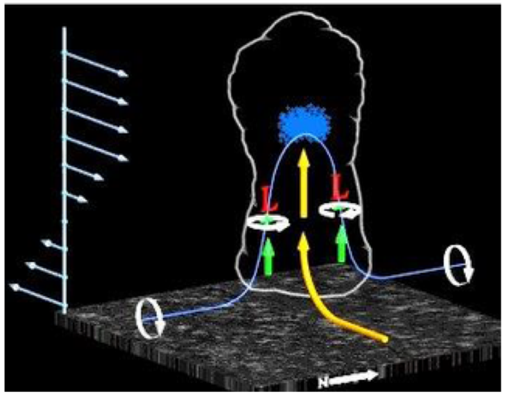
single-cell (typically with weak wind shear)



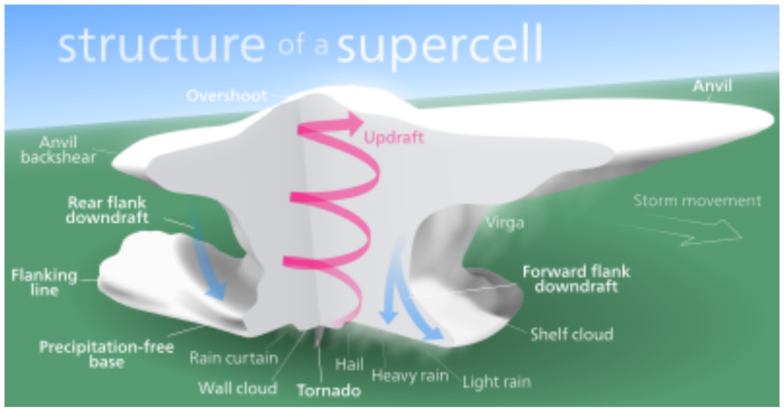
multi-cell (composed of multiple cells, each being at a different stage in the life cycle of a thunderstorm.







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]

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?

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

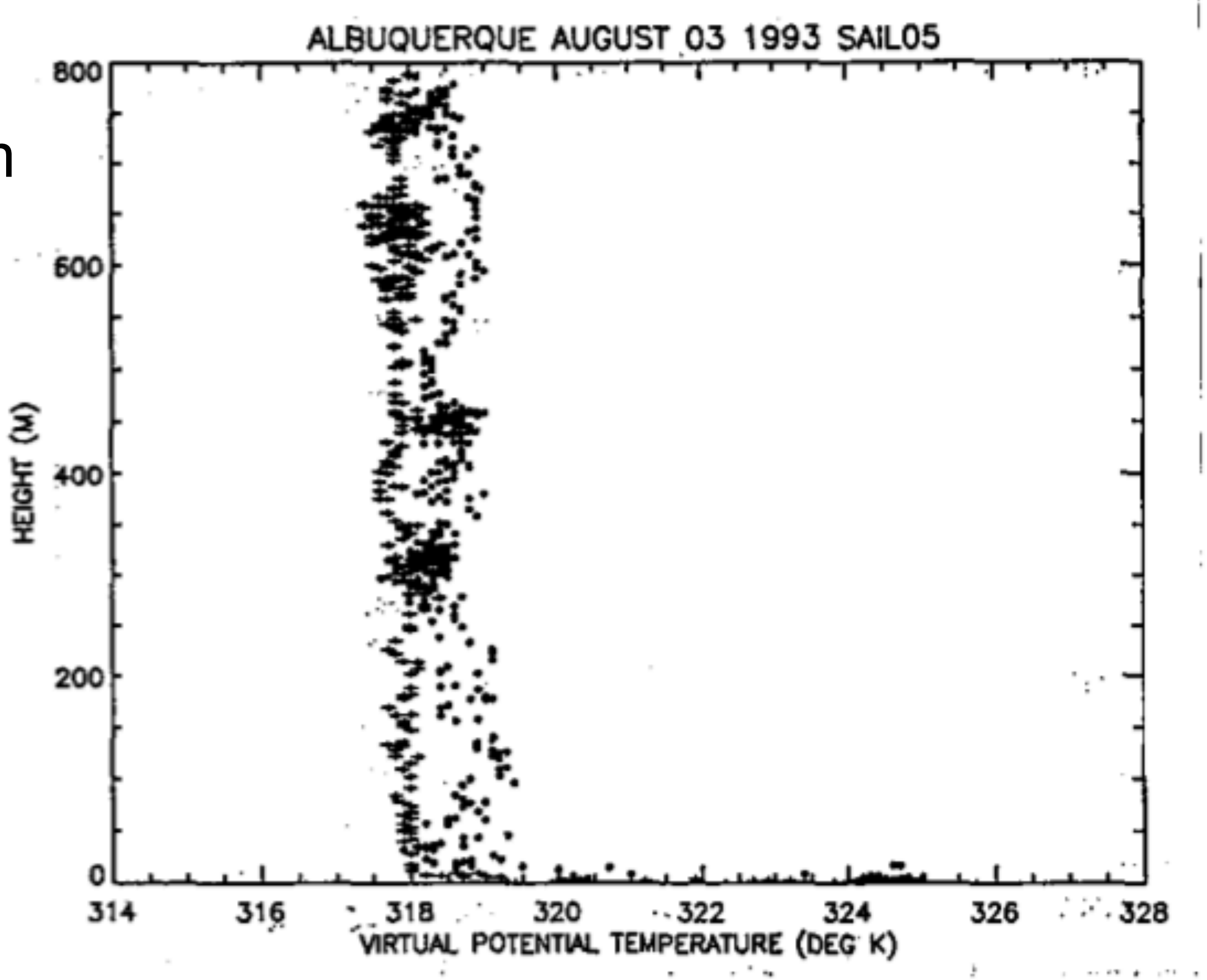
Vertical T profile neutral to dry convection:
θ constant with height

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

Radiative Convective Equilibrium

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

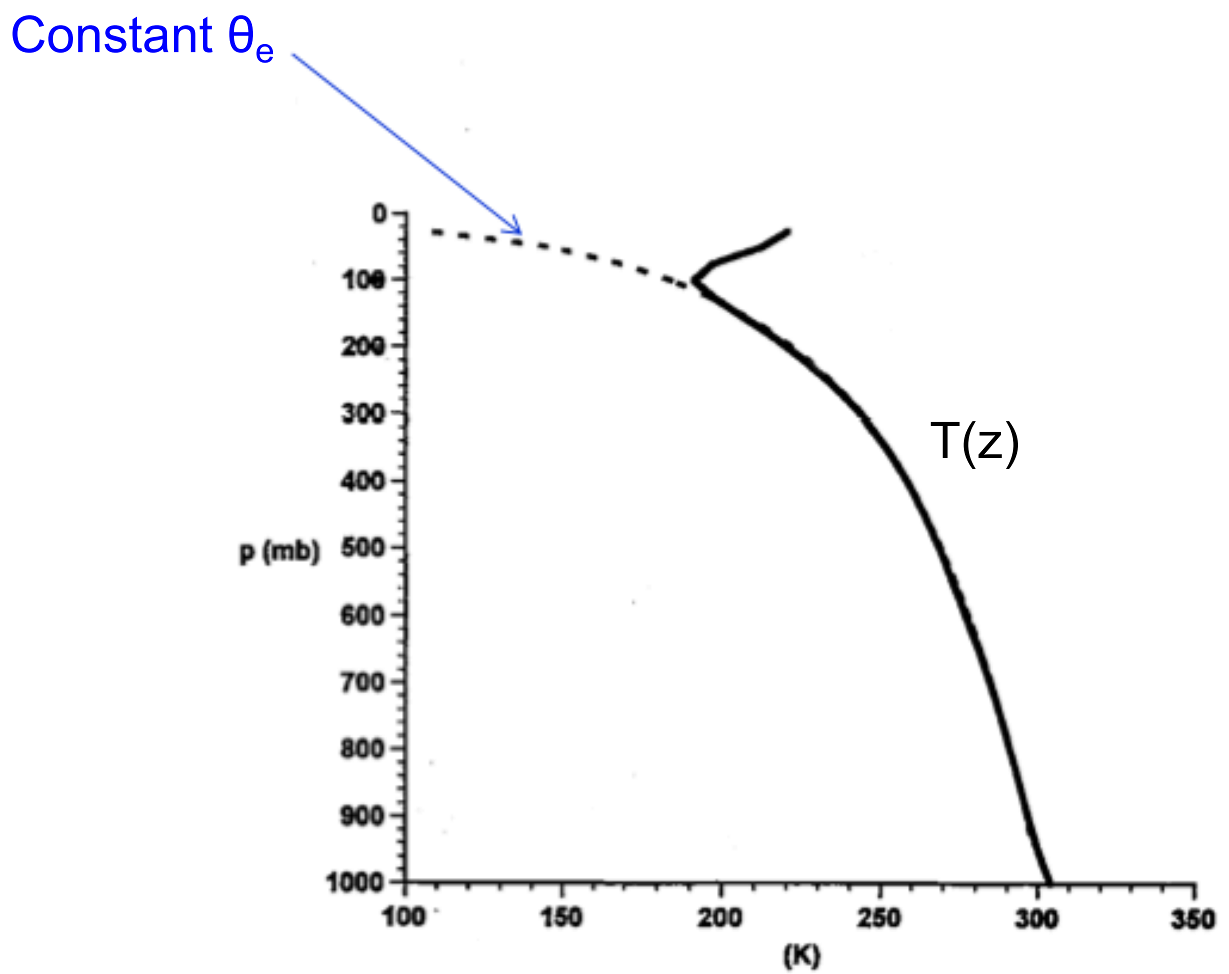
800m



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

Radiative Convective Equilibrium

Tropical sounding => moist adiabatic



TYPICAL TROPICAL THERMODYNAMIC PROFILE (over oceans)

Convection FAST, quickly consumes CAPE.

Instability (largely CIN) controlled by large scale circulation

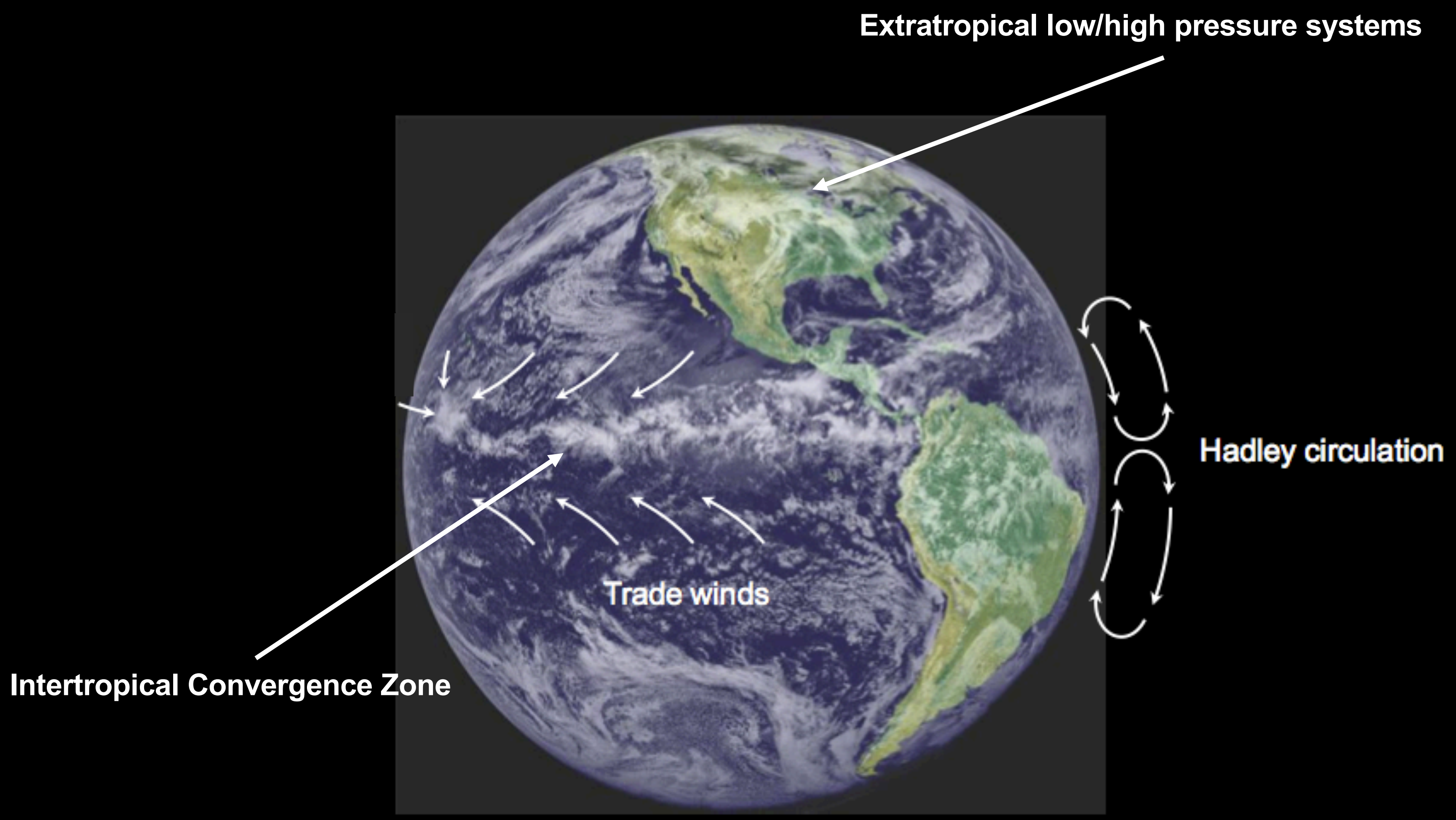
Clouds and atmospheric convection

1. Cloud types

2. Moist thermodynamics and stability

3. Coupling with circulation

Clouds are coupled with circulation



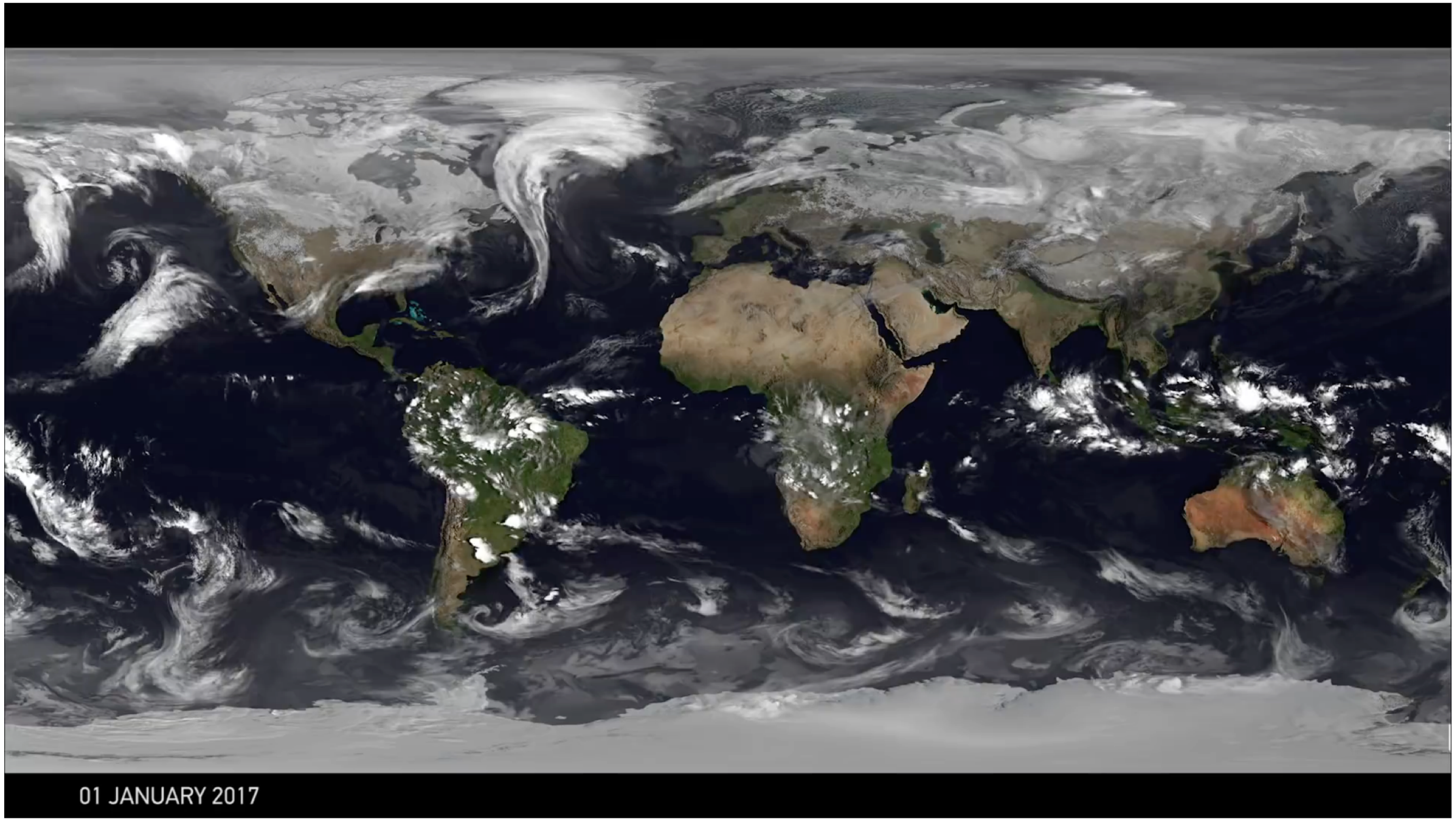
Tropics and Subtropics : ITCZ, Hadley, Walker (ENSO), monsoon

Mid-latitudes : Extratropical frontal systems

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 »

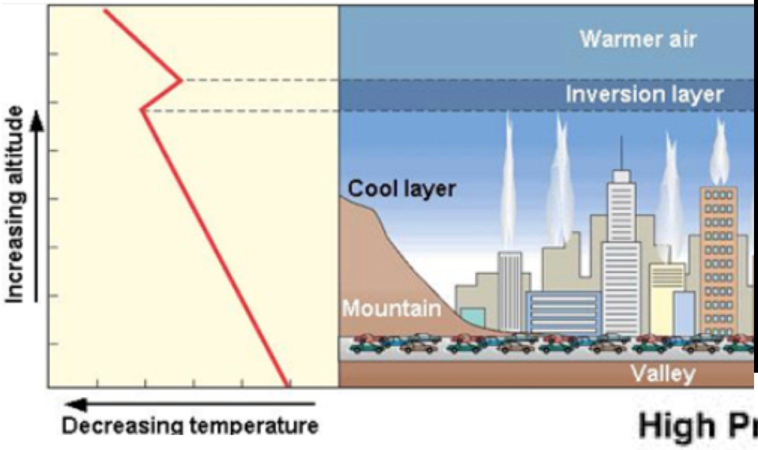
Question: Where are deep clouds more frequent? Why do you think that is?

Clouds and Circulation

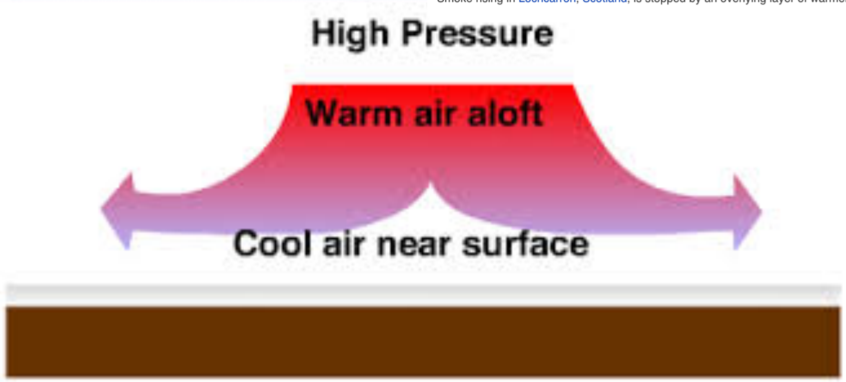
An inversion can develop aloft as a result of air gradually sinking over a wide area and being warmed by adiabatic compression, e.g. associated with subtropical high-pressure areas.

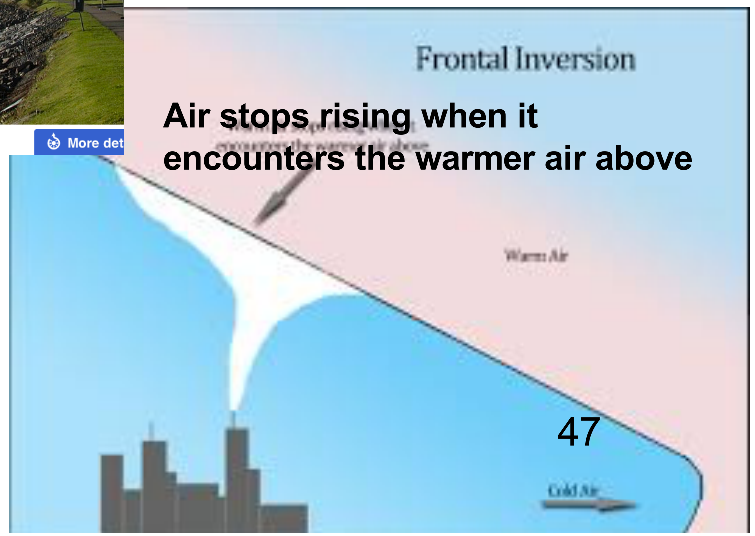
⇒ unstable layer capped by stable layer :

⇒ Warm, dry air above cold air « T inversion »



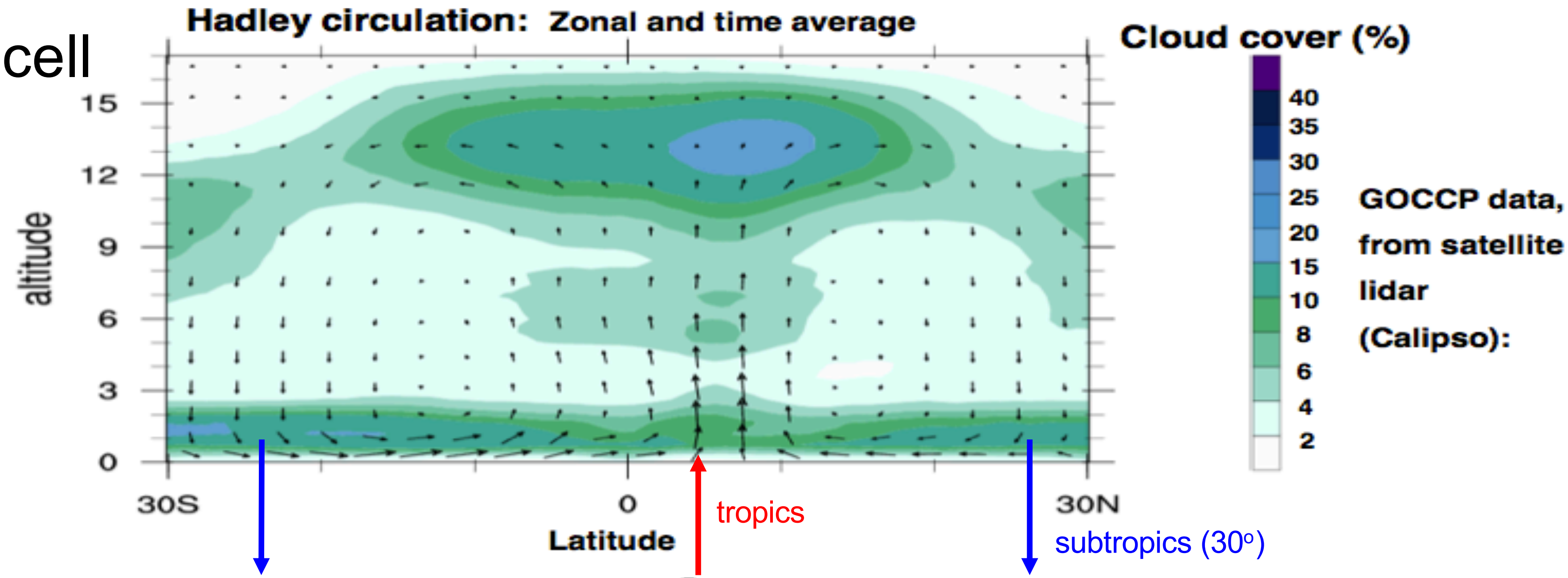
Smoke rising in Lochcarron, Scotland, is stopped by an overlying layer of warmer air (2006).



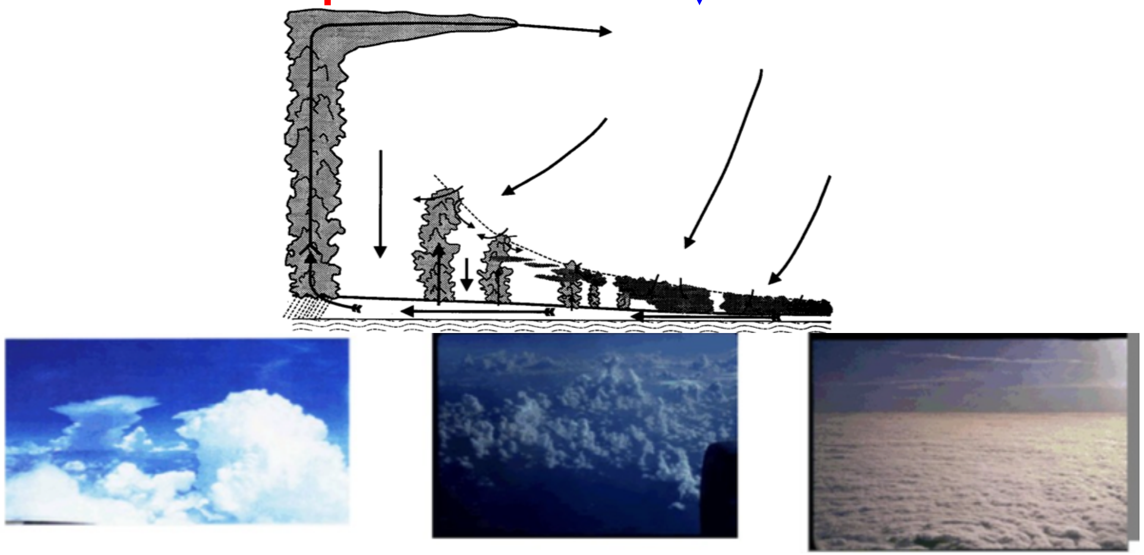


3. Clouds and Circulation: Tropics and Subtropics

Hadley cell



Cloud types:



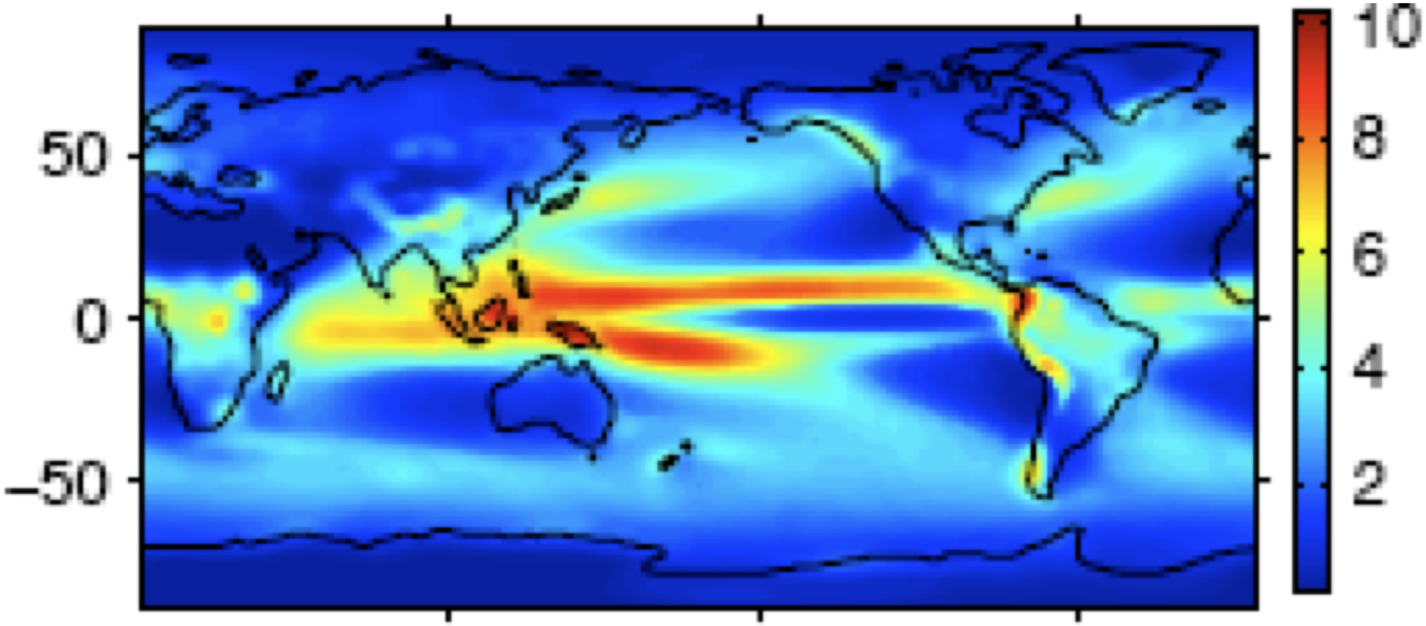
Deep cumulonimbus Fair weather cumulus stratus

⇒**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

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



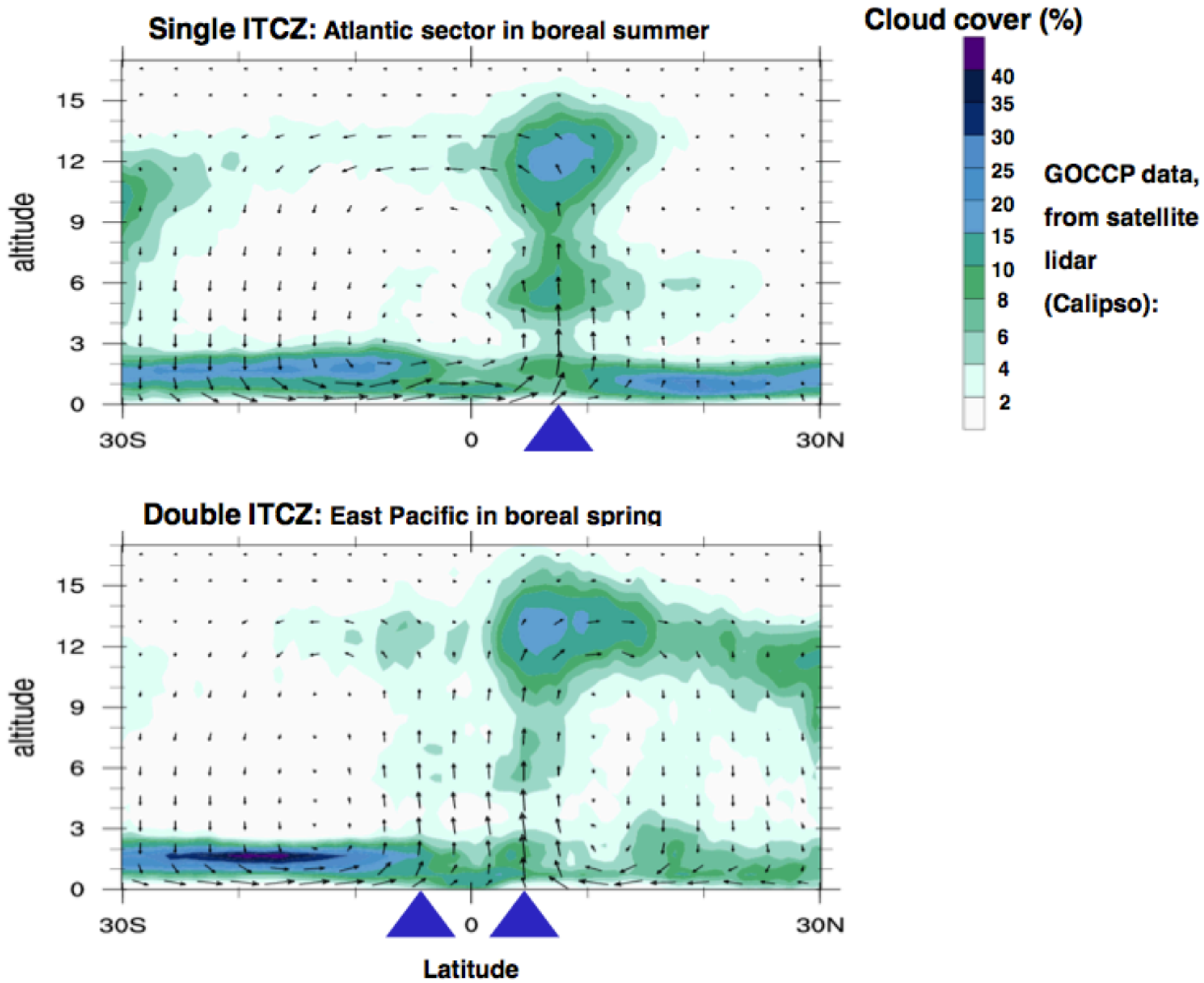
Small in Subtropics (descent)

[Muller & O'Gorman, 2011]

Large in Tropics (ascent)

3. Clouds and Circulation: Tropics and Subtropics

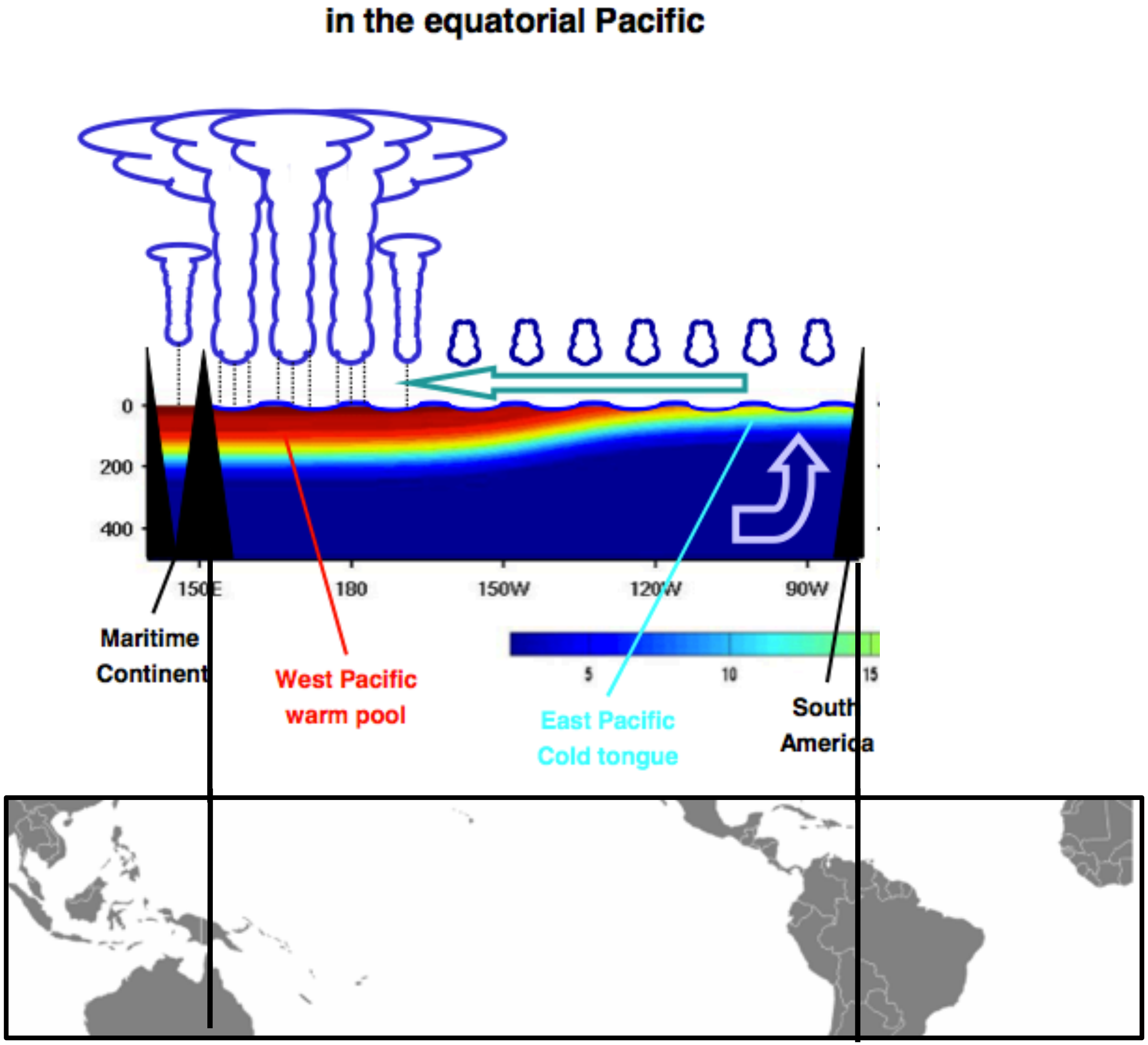
double ITCZ



Courtesy Gilles Bellon

3. Clouds and Circulation: Tropics and Subtropics

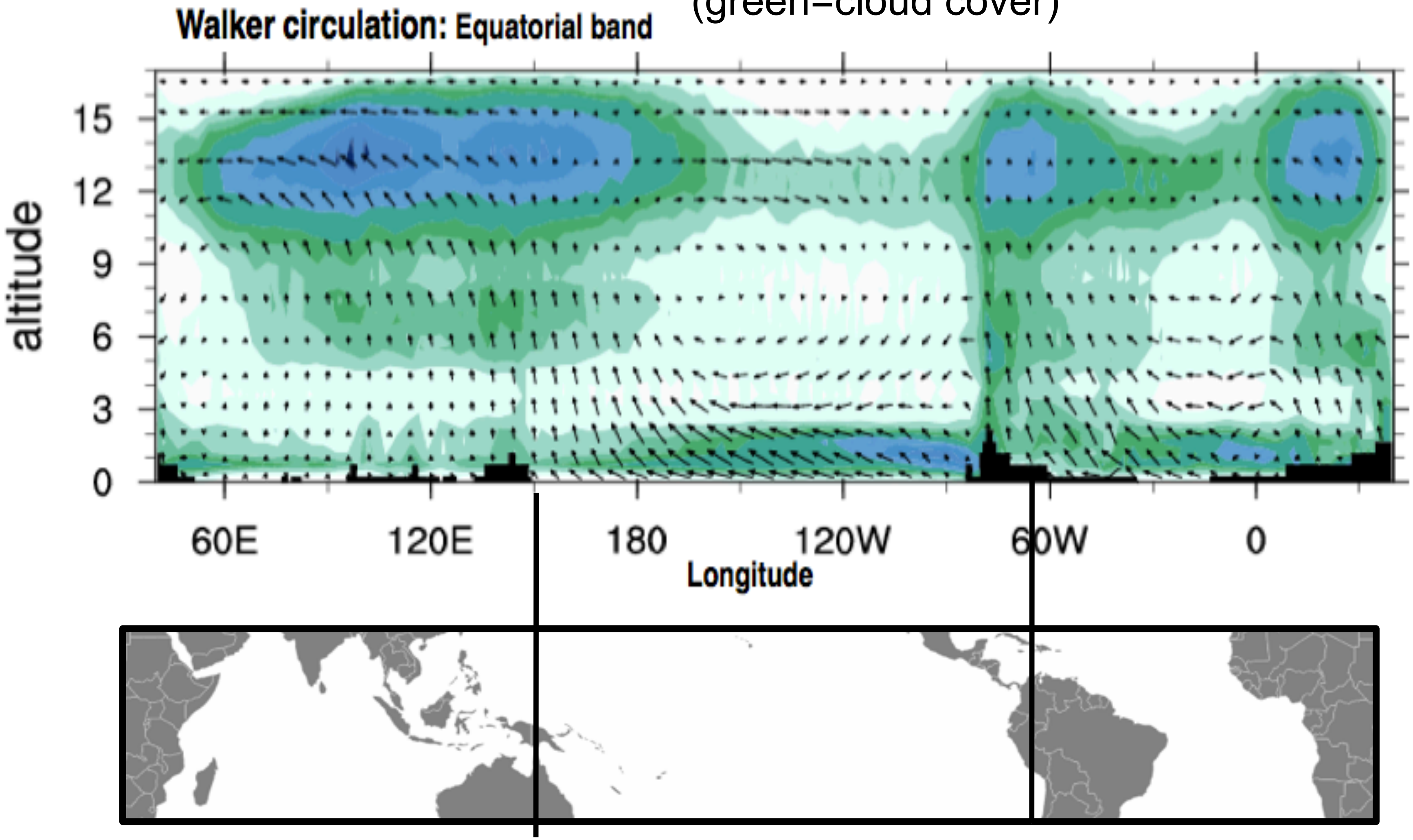
Walker cell



3. Clouds and Circulation: Tropics and Subtropics

Walker cell

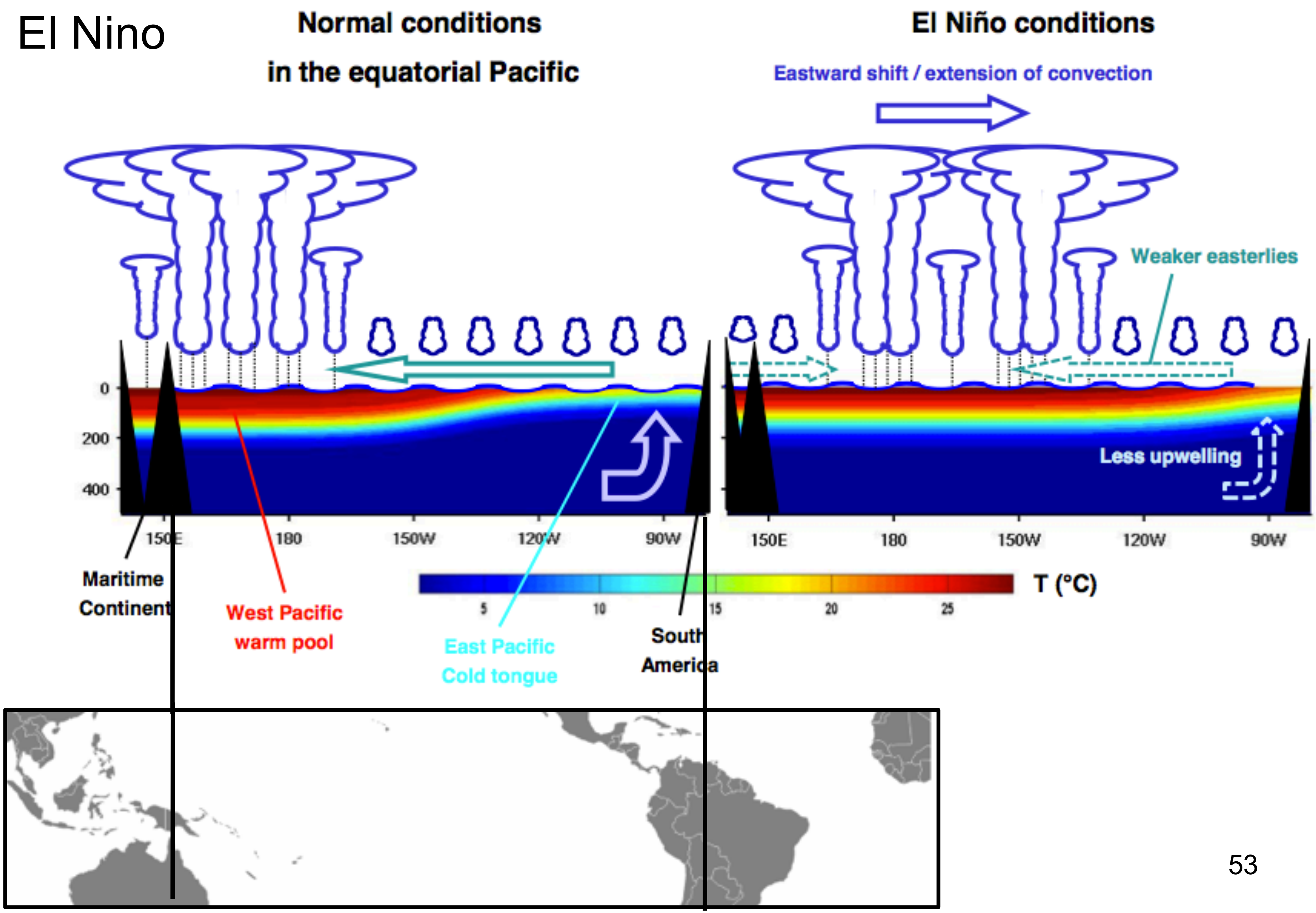
(green=cloud cover)



Courtesy Gilles Bellon

3. Clouds and Circulation: Tropics and Subtropics

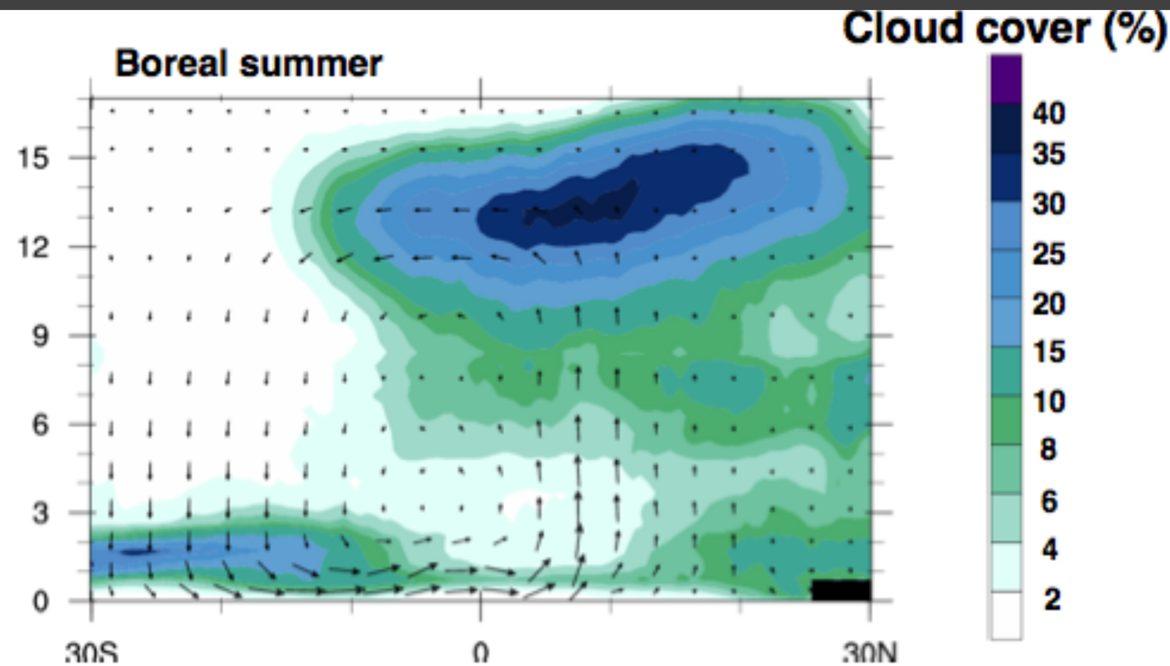
El Nino



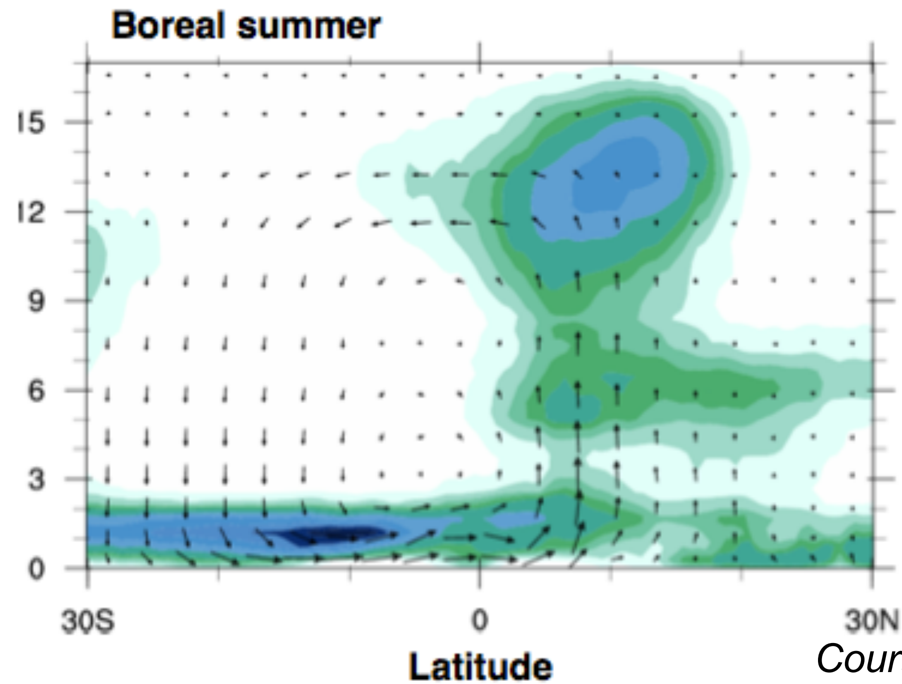
3. Clouds and Circulation: Tropics and Subtropics

Monsoons

Asian monsoon



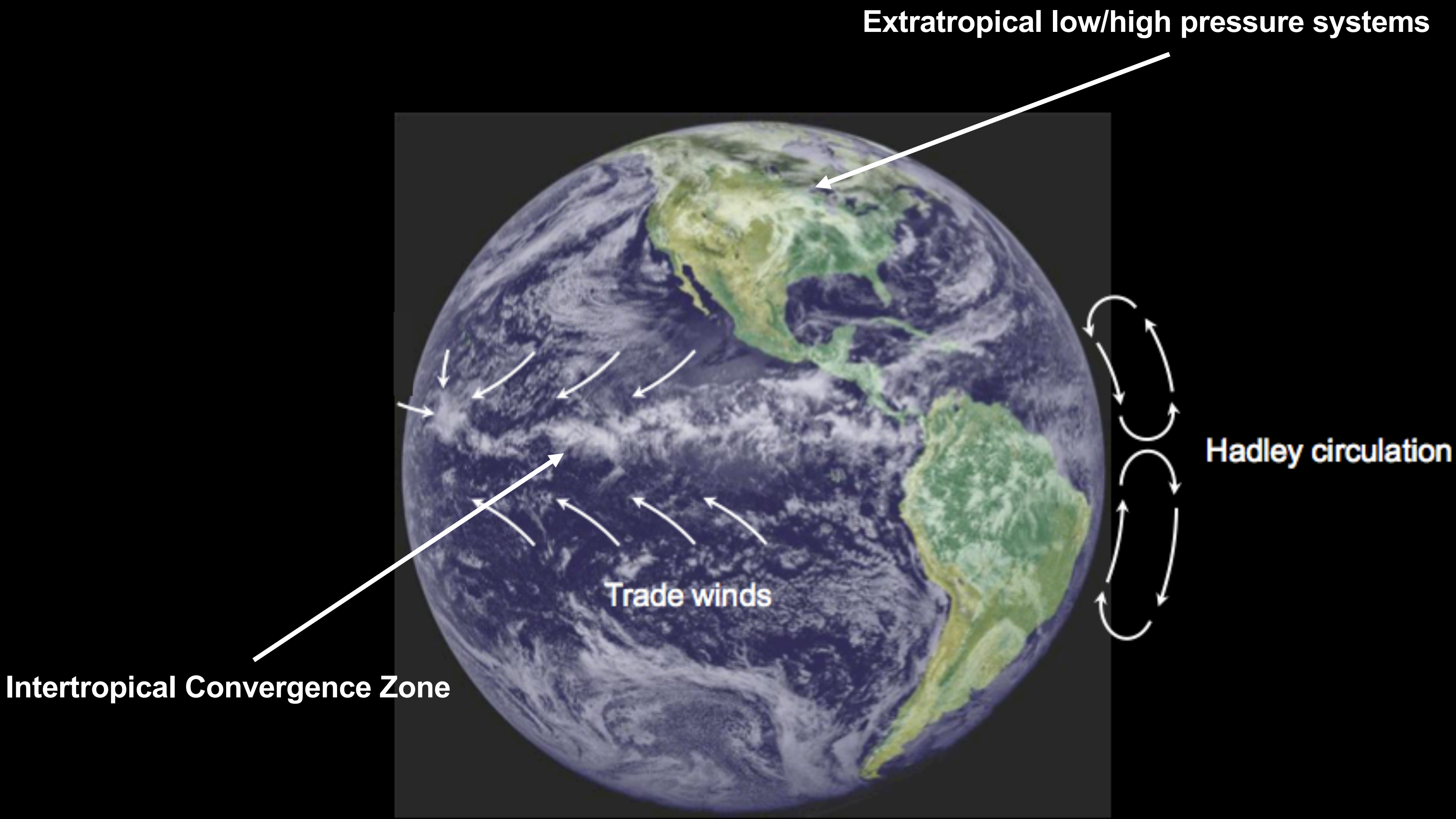
West-African monsoon



GOCCP data, from satellite lidar (Calipso):

Courtesy Gilles Bellon

3. Clouds and Circulation: Extratropics



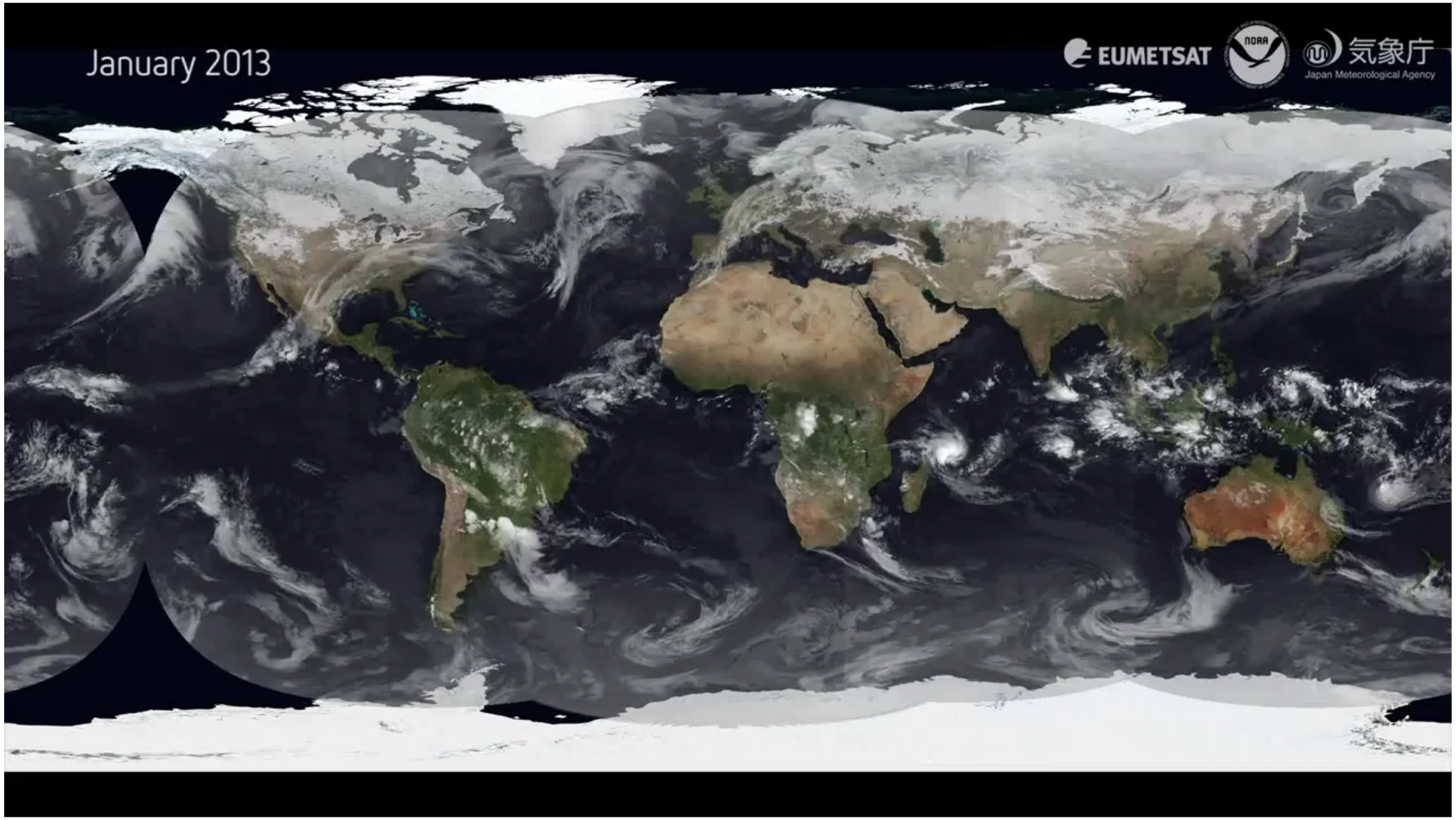
Tropics and Subtropics : ITCZ, Hadley, Walker (ENSO), monsoon

Mid-latitudes : Extratropical frontal systems

3. Clouds and Circulation

Recall : spatial distribution

Brightness temperature from satellite (white ⇔ cold cloud tops)



Large extratropical storm systems

subtropics: ~no high clouds

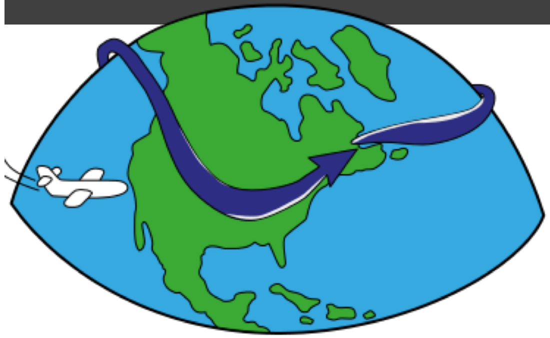
ITCZ = Intertropical convergent zone

« A year of weather »

Extratropics: low and high pressure systems within the polar jet

Question: What explains different behaviors between tropics and extratropics?

Distribution of clouds: mid-latitudes



courant-jet polaire

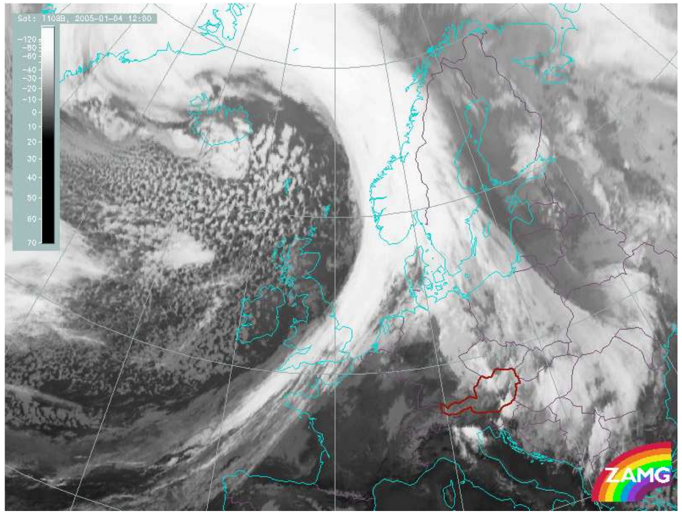
High latitudes => clouds embedded in low/high pressure systems and associated fronts

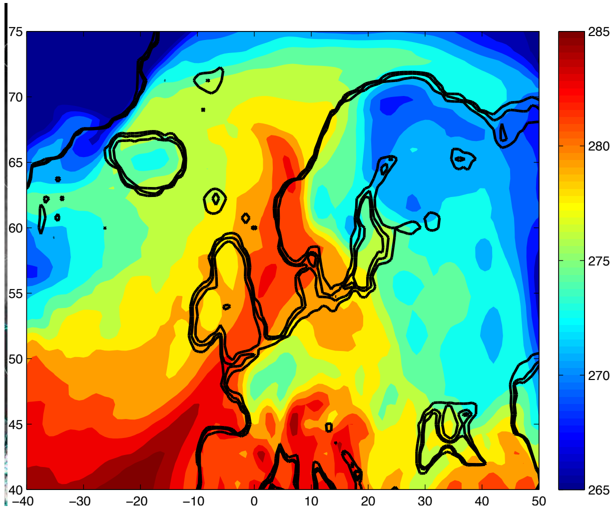
NASA

Distribution of clouds: mid-latitudes

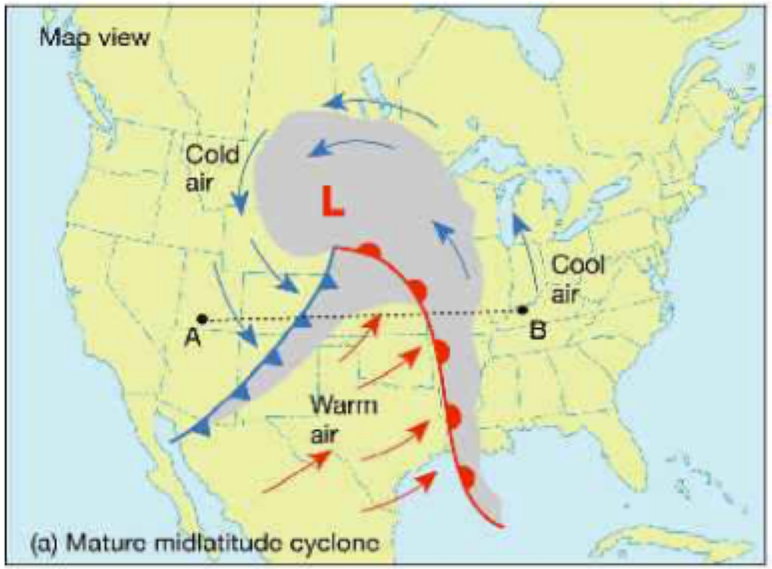
Clouds in frontal systems

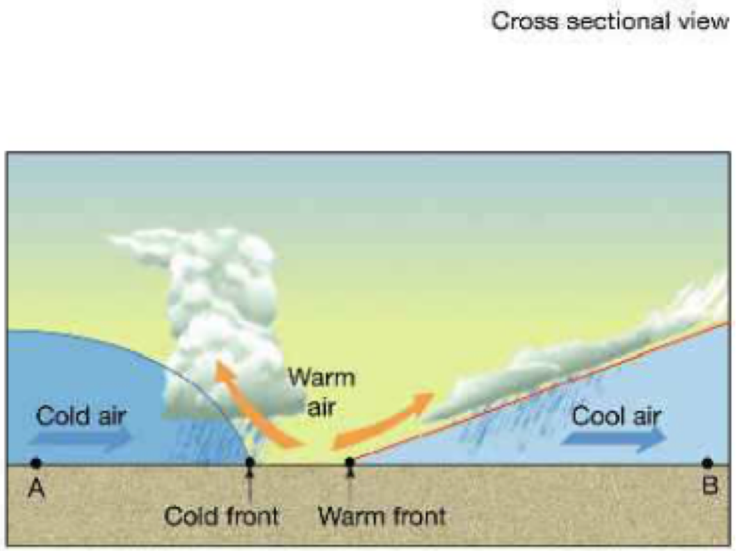
IR



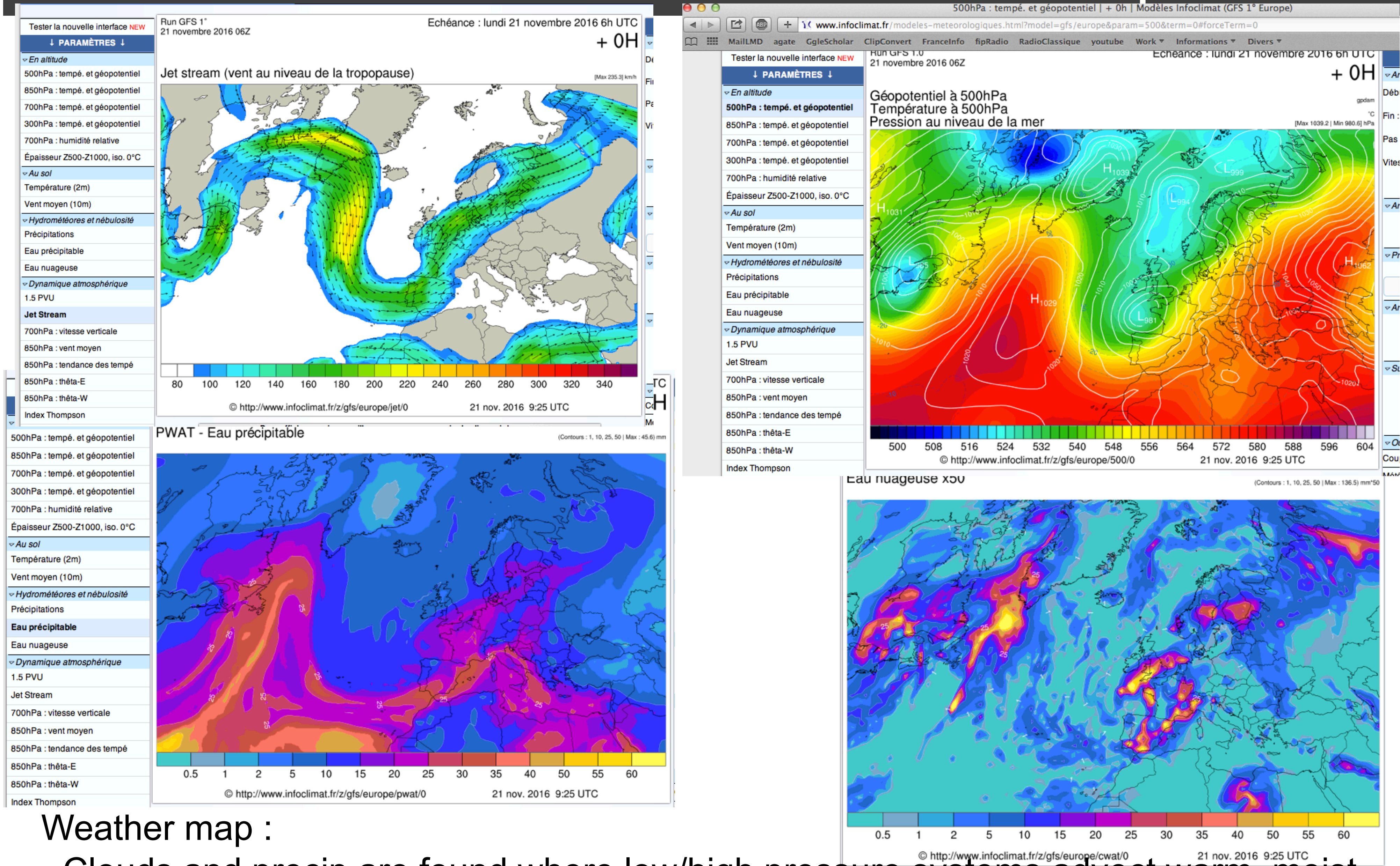


Corresponding T field
Clouds are clearly linked to the dynamics of frontal systems





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

4 May 2021 14h40

TRAINING

Thematic introduction, a few papers/links

→

6 May 2021 14h40

SYNTHESIS

Preparation of 4-5 slides by each working group

→

7 May 2021 13h40

PRESENTATION

Plenary presentations of the slides (each presentation will have 5 minutes plus discussion)

GOAL OF PROJECT: How are clouds distributed on Earth, and why?

SLIDES

Part 1: Synthesis of the theme and tools proposed during the training session

* General context : What is the goal of the project ?
* Introduction to cloud types and cloud physics
* Spatial distribution and link with the large scale atmospheric motion

Part 2: Your project

* Links to satellite visualizations
* Your presentation

Caroline Muller
CNRS, Laboratoire de Météorologie Dynamique
Ecole Normale Supérieure Paris

Your project:

GOAL OF PROJECT: How are clouds distributed on Earth, and why?

To address this question, some uesful links:

- « A year of weather » video (available online)

- Online document:
http://www.lmd.ens.fr/muller/DOCS/IPSL_Clouds.pdf