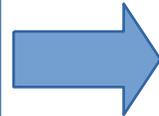


4 May 2021 14h40

TRAINING

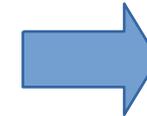
Thematic introduction, a few papers/links



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

What are clouds ?



Clouds and atmospheric convection

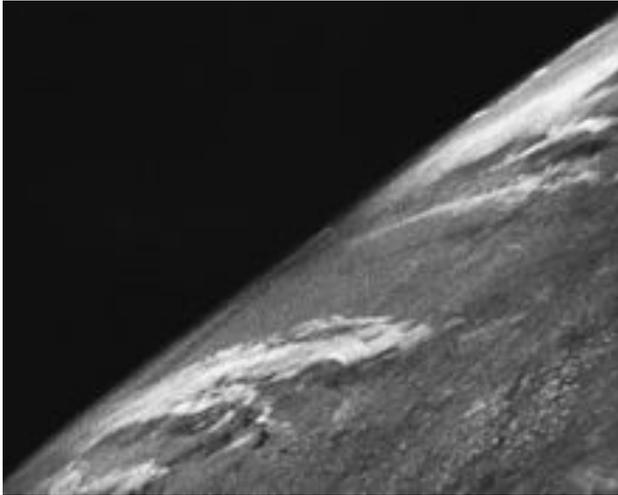


and clouds

"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

The New York Times Environment

WORLD U.S. N.Y. / REGION BUSINESS TECHNOLOGY SCIENCE HEALTH SPA

ENVIRONMENT SPA

It's gone. [Undo](#)

What was wrong with this ad?

Inappropriate Repetitive Irrelevant

TEMPERATURE RISING

Clouds' Effect on Climate Change Is Last Bastion of 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.



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

Josh Haner/The New York Times

EDITION: INTERNATIONAL U.S. MÉXICO ARABIC

TV: CNN CNN en Español

Set edition preference

Home Video World U.S. Africa Asia Europe Latin America Middle East Business



Climate change: Can we ever 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 Technology has for its engine symposium at scientists from a hot facet of

The title of the the questions science: "Engi We Do It? Sho

BBC Sign In News Sport Weather iPlayer

NEWS SCIENCE & ENVIRONMENT

Home World UK England N. Ireland Scotland Wales Business Politics Health Educa

24 August 2011 Last updated at 22:58 [Share](#) [f](#)

Cloud simulator tests climate models

By Pallab Ghosh
Science correspondent, BBC News



Understanding how clouds form will help develop better climate change models

HOME SEARCH **The New York Times**

VISITE EN HÉLICOPTÈRE
Visite en Hélicoptère + Meilleurs vols en France

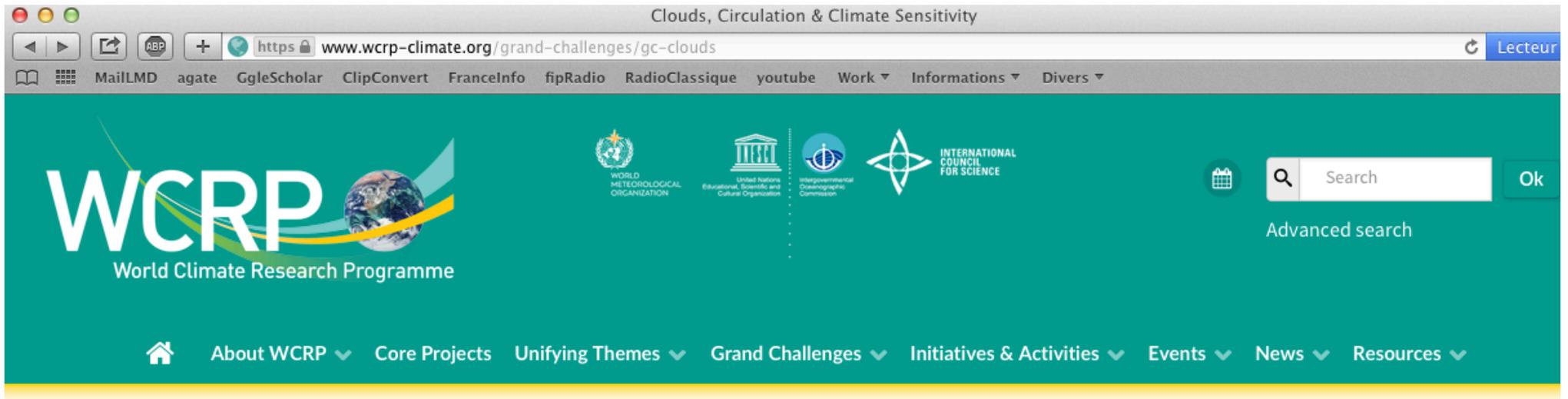
Green
Energy, the Environment and the Bottom Line

More on the Science of Clouds and Climate

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



What are clouds? A Grand Challenge



The screenshot shows a web browser window with the URL <https://www.wcrp-climate.org/grand-challenges/gc-clouds>. The page features the WCRP logo (World Climate Research Programme) and logos for partner organizations: World Meteorological Organization, United Nations Educational, Scientific and Cultural Organization, Intergovernmental Oceanographic Commission, and International Council for Science. A search bar with the text 'Search' and an 'Ok' button is visible. The navigation menu includes: Home, About WCRP, Core Projects, Unifying Themes, Grand Challenges, Initiatives & Activities, Events, News, and Resources.

Clouds, Circulation and Climate Sensitivity



*How do clouds couple to circulations in the present climate?
How will clouds and circulation respond to global warming or other forcings?
How will they feed back on it through their influence on Earth's radiation budget?*

Limited understanding of clouds is the major source of uncertainty in climate sensitivity, but it also contributes substantially to persistent biases in modelled circulation systems.

As one of the main modulators of heating in the atmosphere, clouds control many other aspects of the climate system. Read more in the [white paper](#).

Clouds, Circulation and Climate Sensitivity

Overview

Leadership

Activities

Initiatives

Projects

Meetings

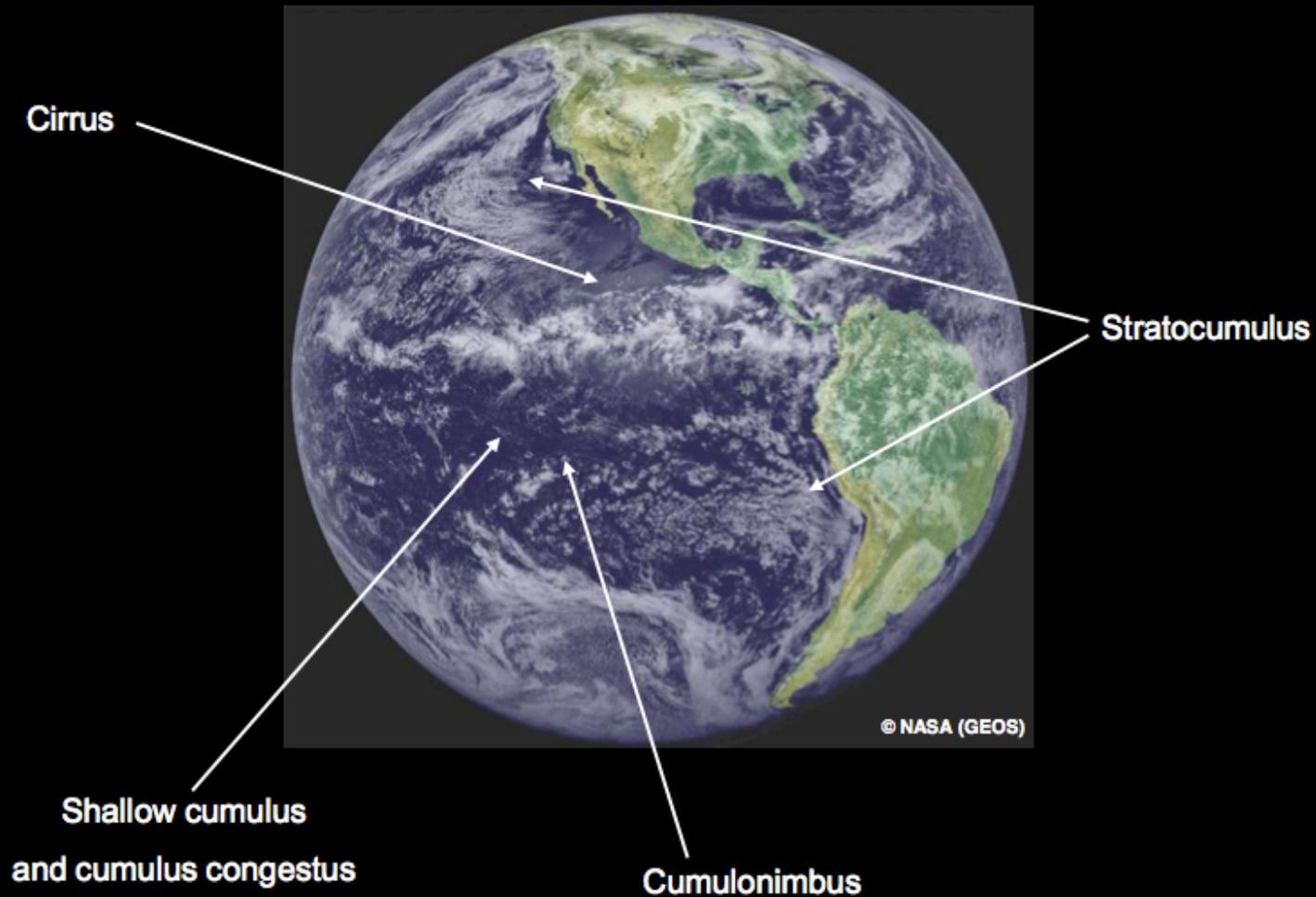
Documents

6

[← Back to Grand Challenges Overview](#)

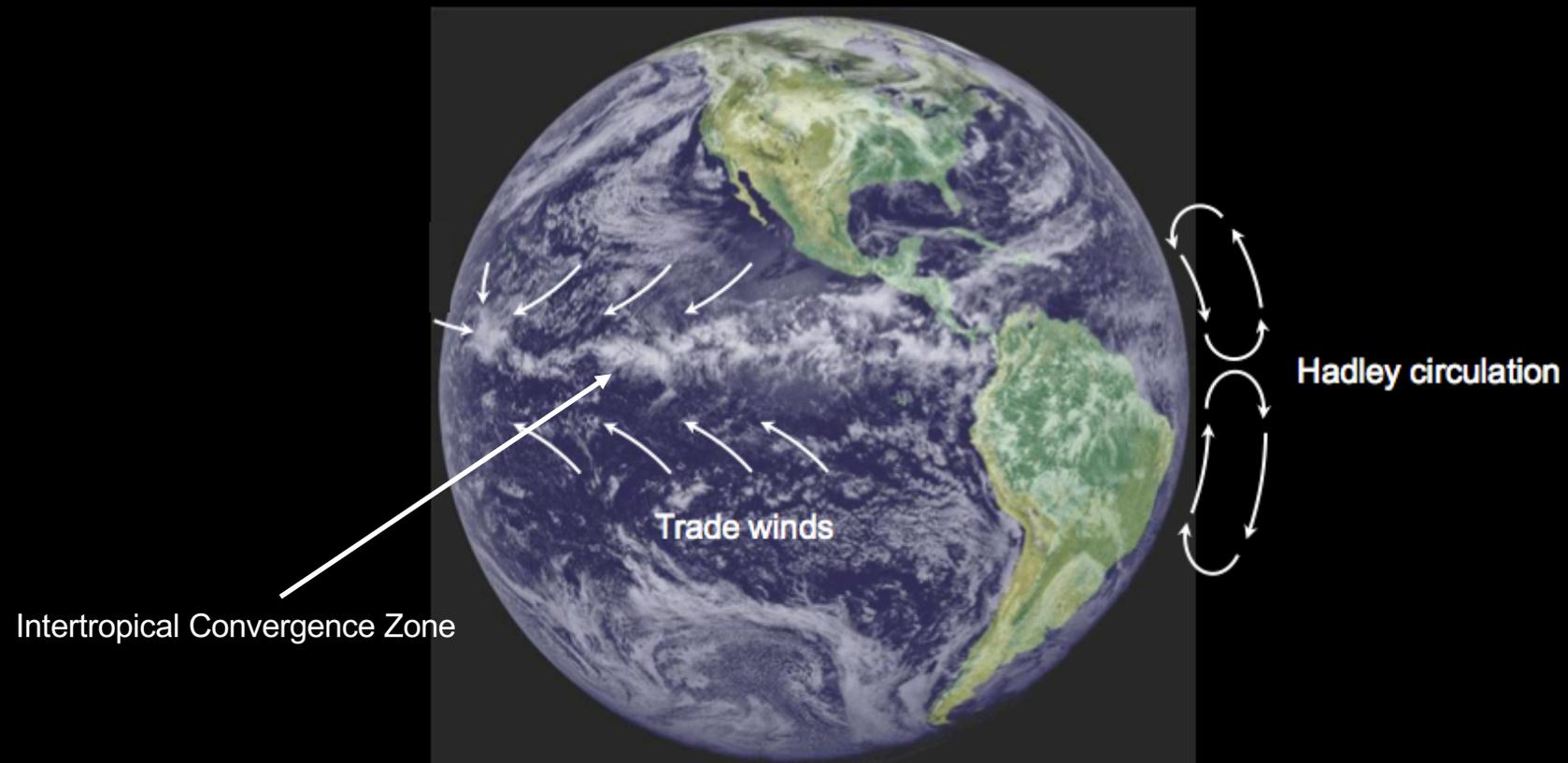
Clouds and atmospheric convection

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

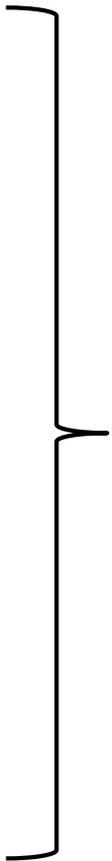
Cumulus: heap, pile

Stratus: flatten out, cover with a layer

Cirrus: lock of hair, tuft of horsehair

Nimbus: precipitating cloud

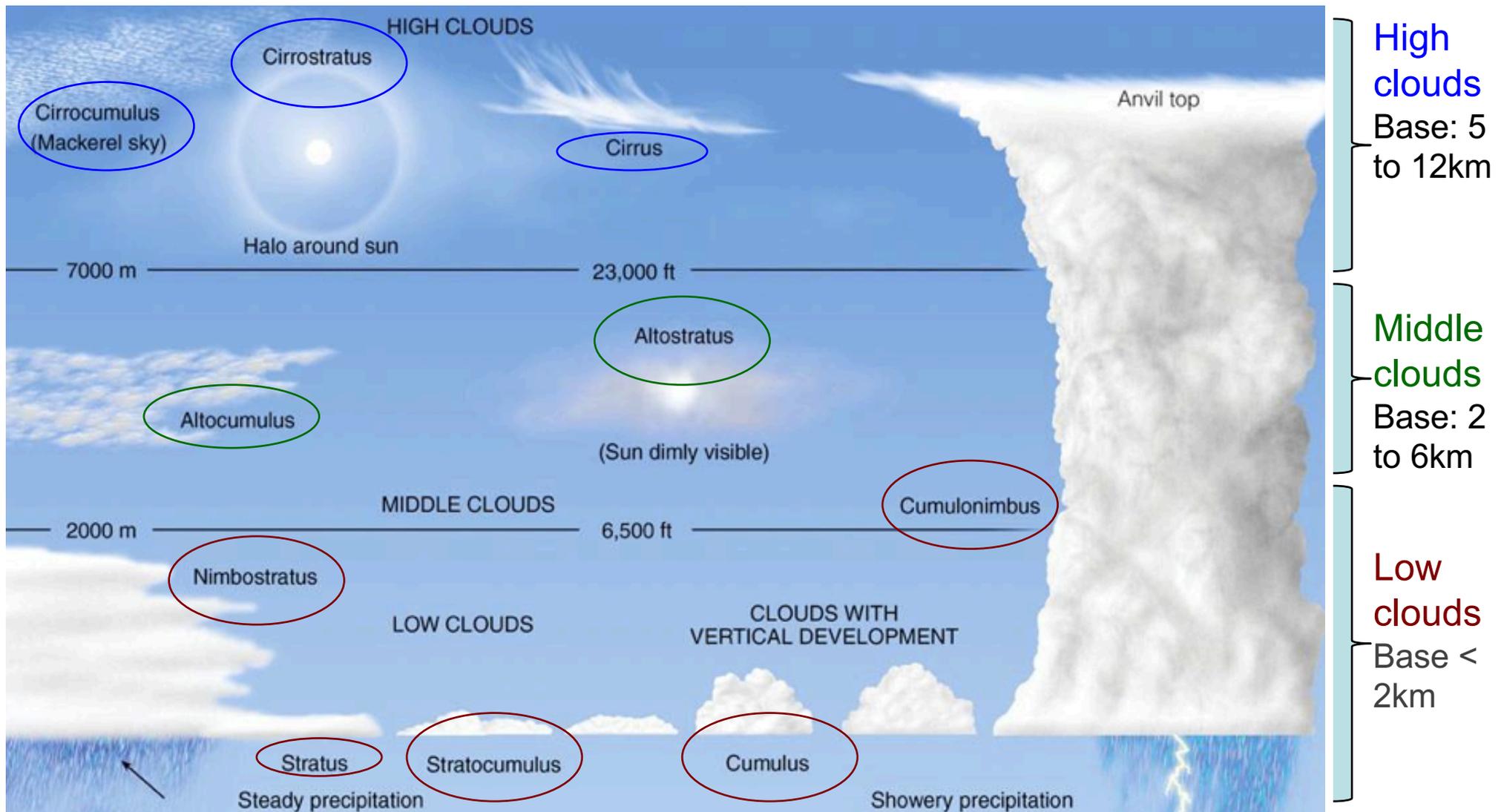
Altim: height



Combined to define
10 cloud types

1. Cloud types

Clouds are classified according to height of cloud base and appearance



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

Alto cumulus

Heap-like clouds with convective elements in mid levels

May align in rows or streets of clouds



1. Low Clouds

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

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



Stratocumulus

Hybrids of layered stratus and cellular cumulus

Stratus

Uniform and flat, producing a gray layer of cloud cover

Nimbostratus

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



1. Low Clouds

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

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

Cumulus (humili)

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



Cumulus (congestus)

Significant vertical development (but not yet a thunderstorm)



Cumulonimbus

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



1. Other spectacular Clouds...

Mammatus clouds (typically below anvil clouds)



Shelf clouds (gust front)



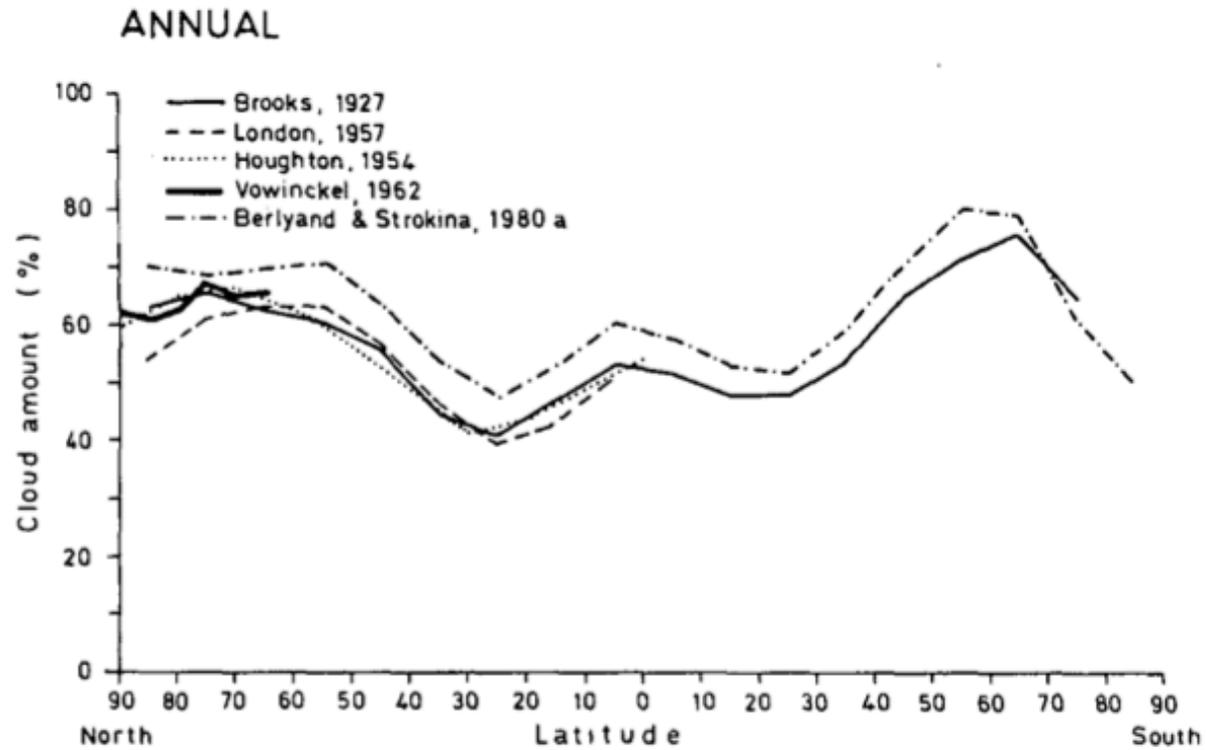
Lenticular clouds (over orography)



Question: Global cloud cover (%)?

1. Cloud types

Distribution of cloud amount

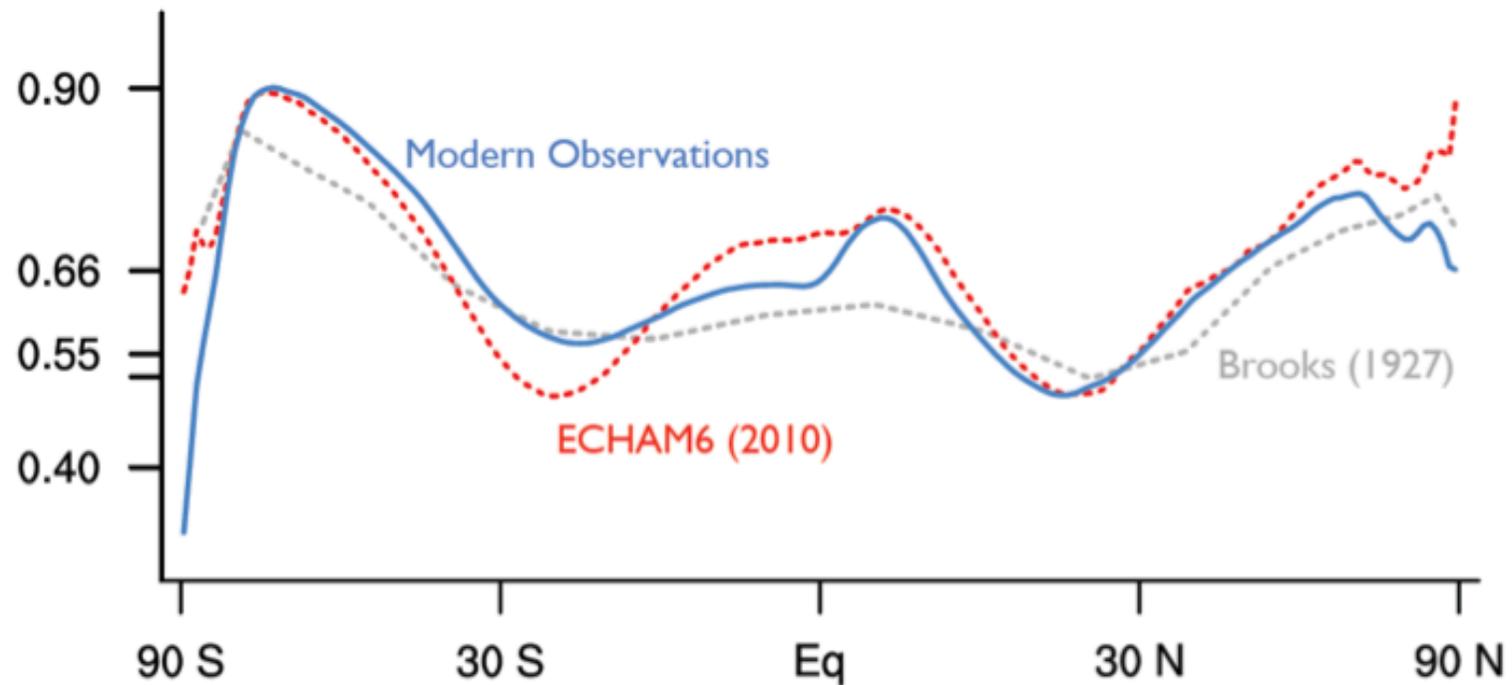


[Hughes 84]

1. Cloud types

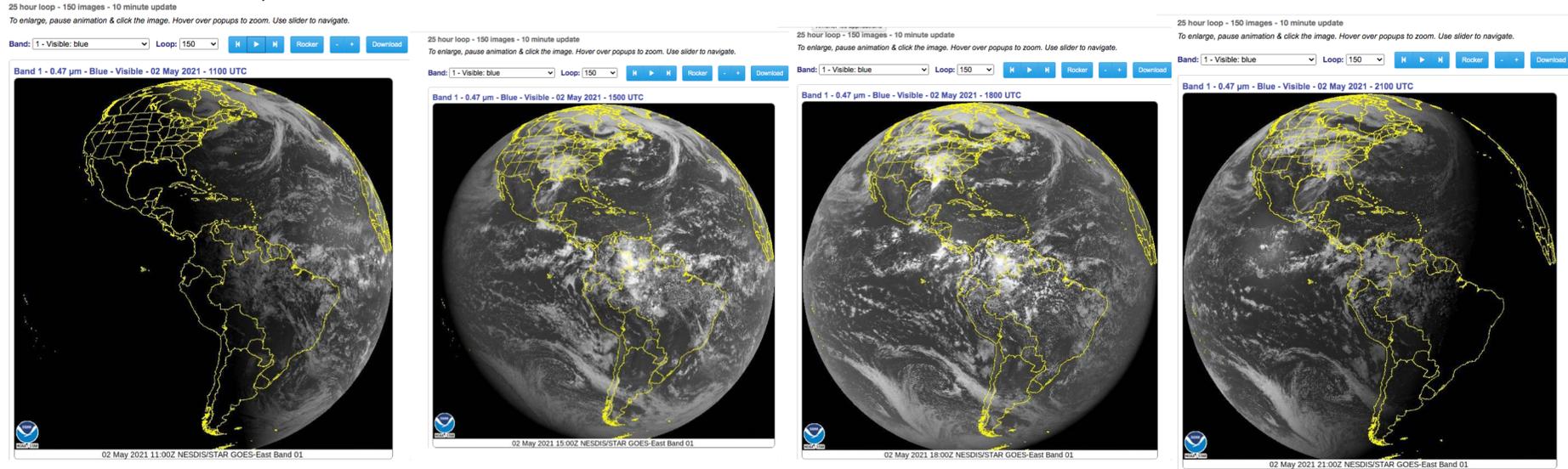
Cloud amount was underestimated

Also note the latitudinal distribution

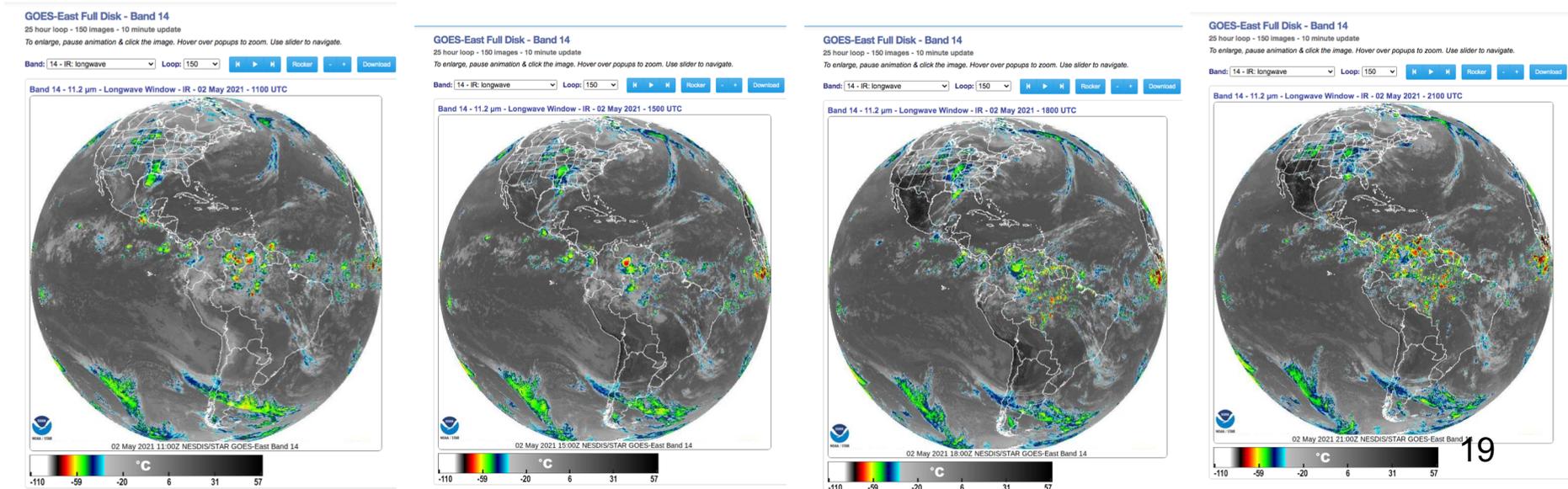


GOES satellite imagery May 2nd @ 11,15,18,21 UTC

Shortwave, or visible

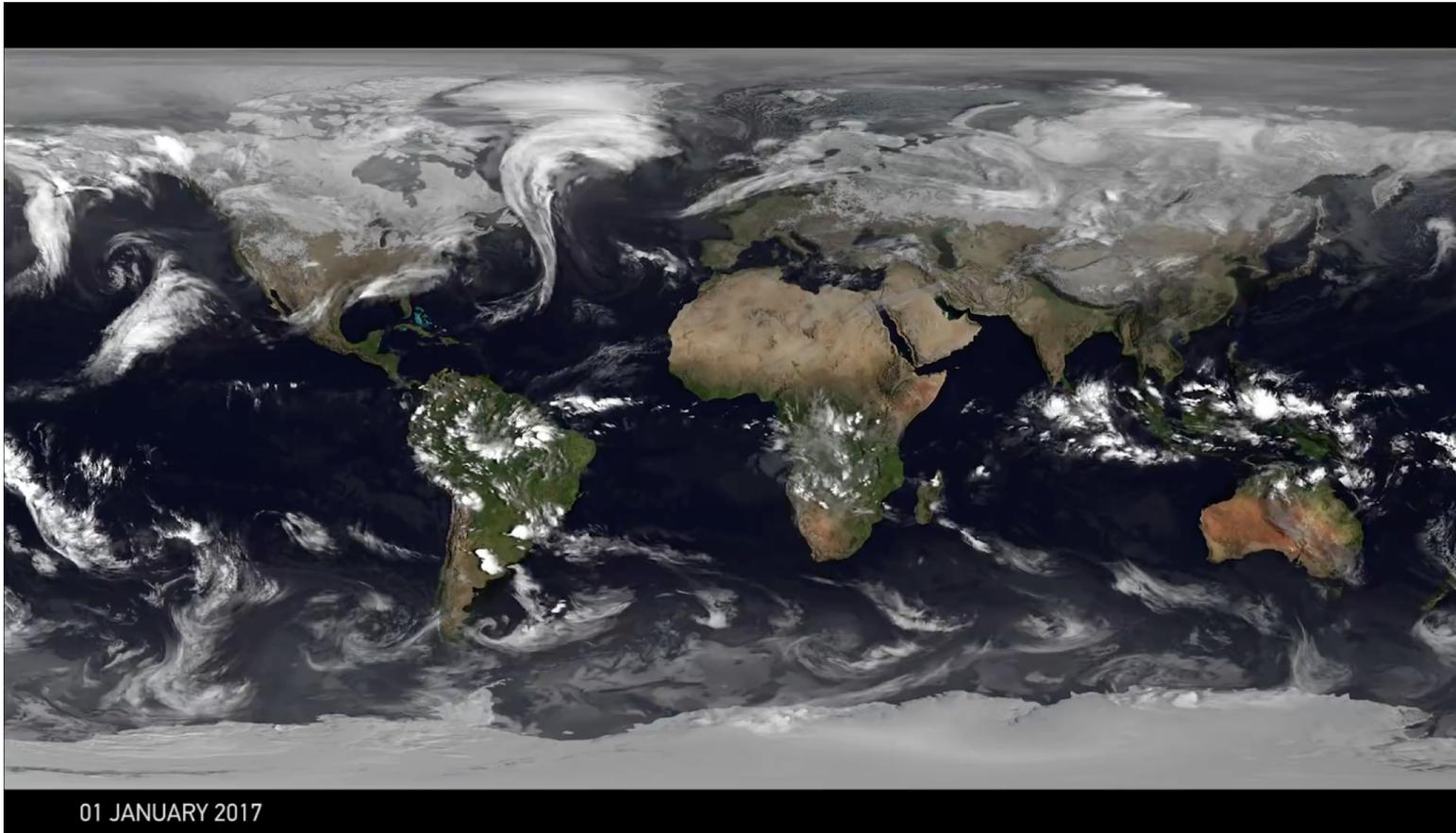


Longwave, or infrared (emission temperature)



1. Cloud types

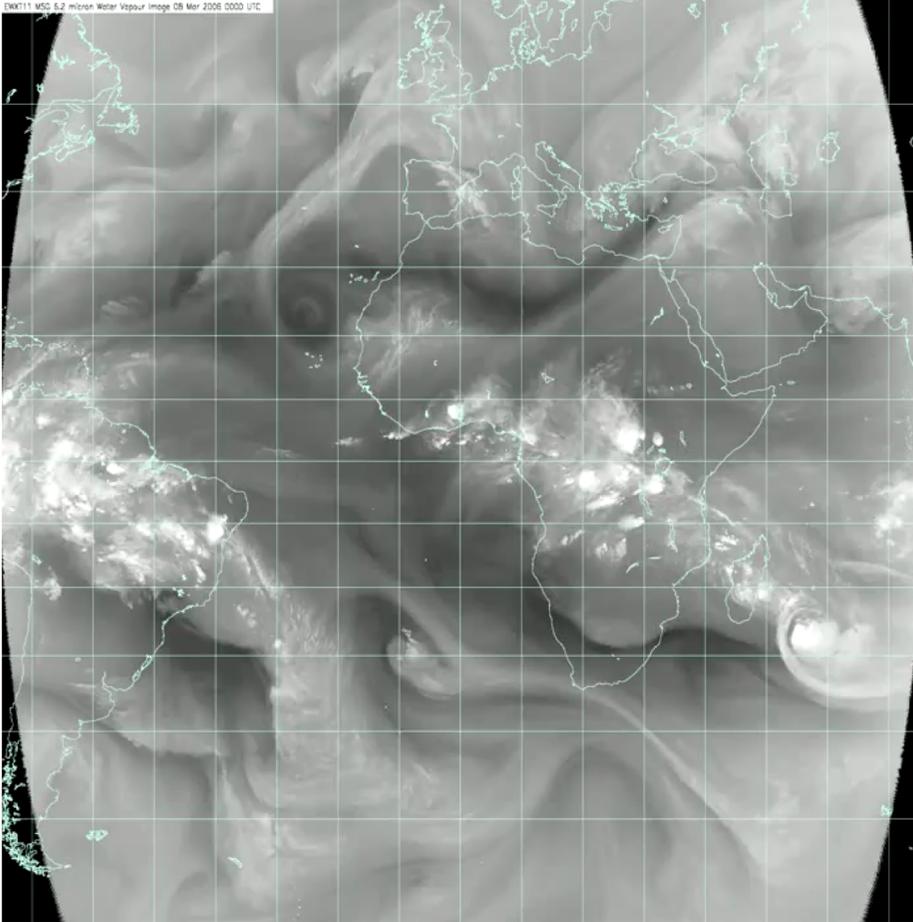
Brightness temperature from satellite (white \Leftrightarrow cold cloud tops)



- Large extratropical storm systems
- subtropics: ~no high clouds
- ITCZ = Intertropical convergent zone

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

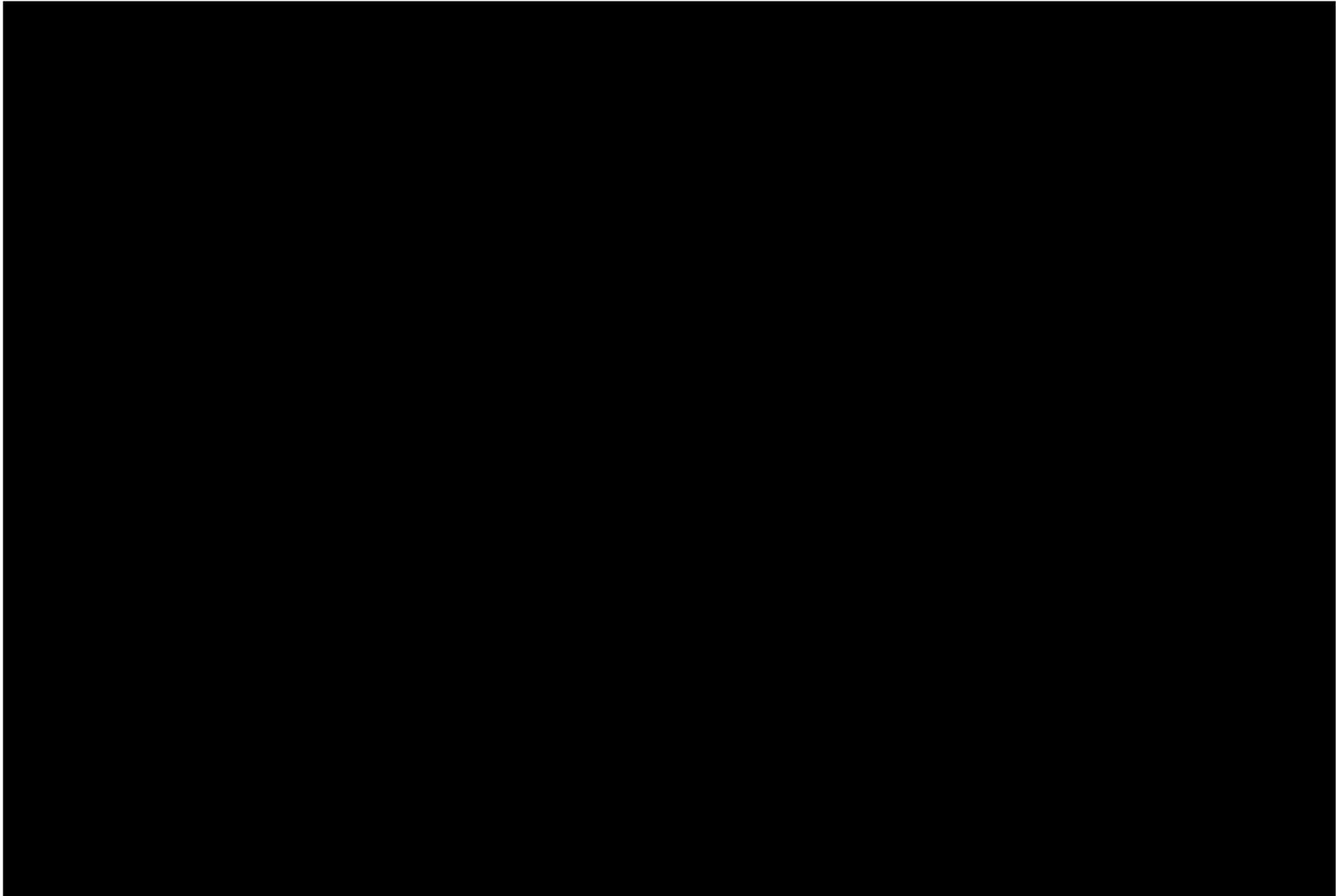
1. Cloud types
2. Moist thermodynamics and stability
3. Coupling with circulation

Cloud formation



Courtesy : Octave Tessiot

Cloud formation



Courtesy : Octave Tessiot

Atmospheric thermodynamics

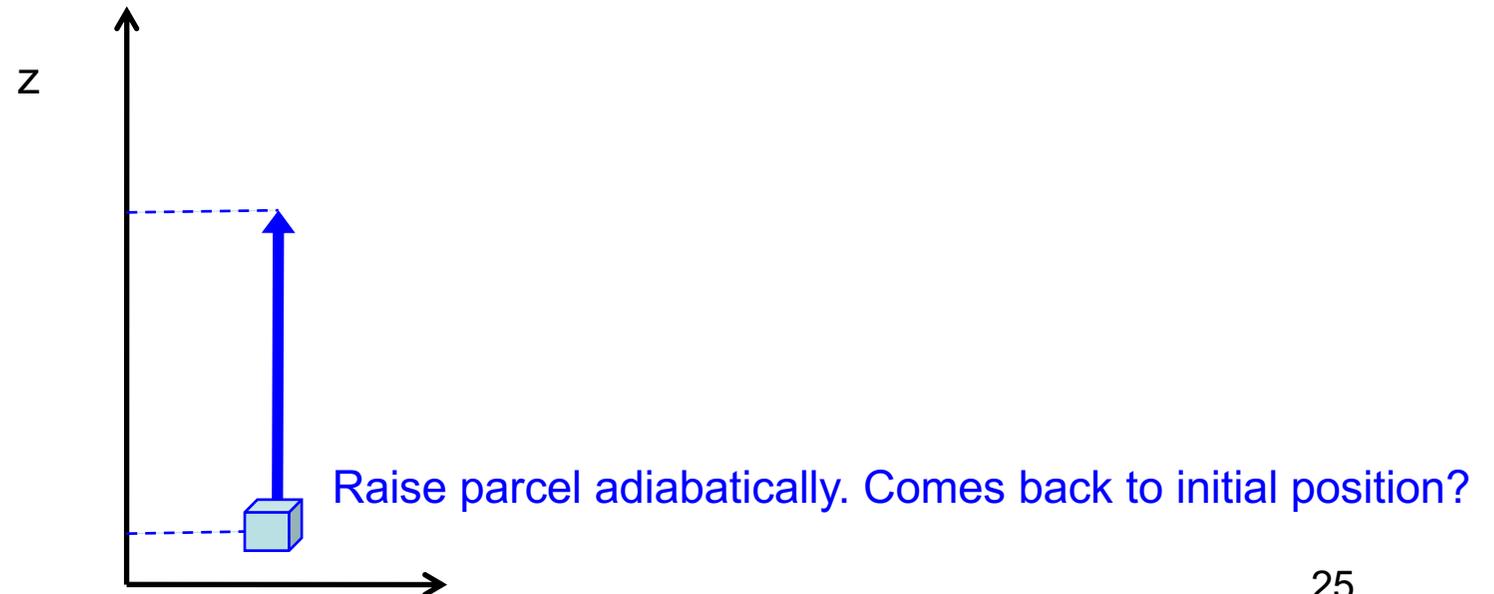
Dry convection

T decreases with height.

But p as well.

Density = $\rho(T,p)$.

How determine stability? The parcel method

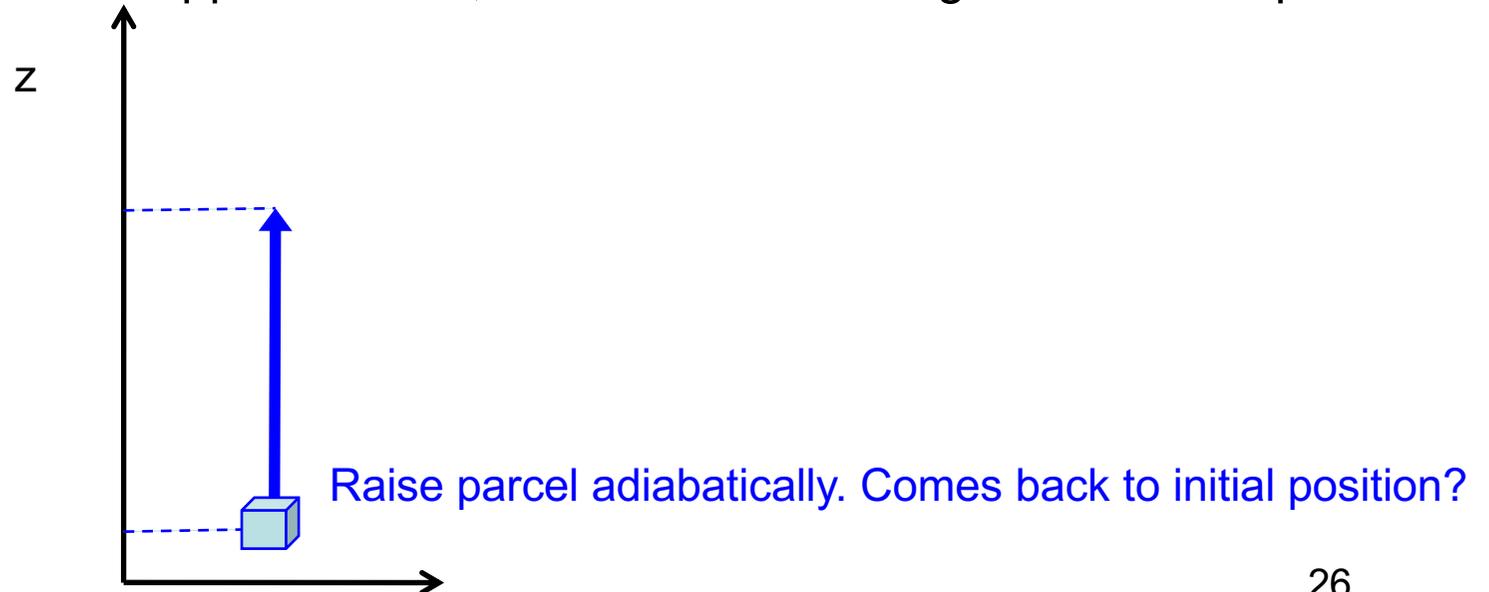


2. Atmospheric thermodynamics: instability

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

Exercise : Temperature profile of a dry adiabat.

- Use the first law of thermodynamics and the ideal gas 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 $\theta = T (p_0 / p)^{R/c_p}$ conserved under adiabatic displacements :

Adiabatic displacement

1st law thermodynamics: $d(\text{internal energy}) = Q$ (heat added) – W (work done by parcel)

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

$$\text{Since } p = \rho R T, \quad c_v dT = - p d(R T / p) = - R dT + R T dp / p$$

$$\text{Since } c_v + R = c_p, \quad c_p dT / T = R dp / p$$

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

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

Hence $\theta = T (p_0 / p)^{R/c_p}$ potential temperature is conserved under adiabatic displacement
(R =gas constant of dry air; c_p =specific heat capacity at constant pressure; $R/c_p \sim 0.286$ for air)

2. Atmospheric thermodynamics: instability

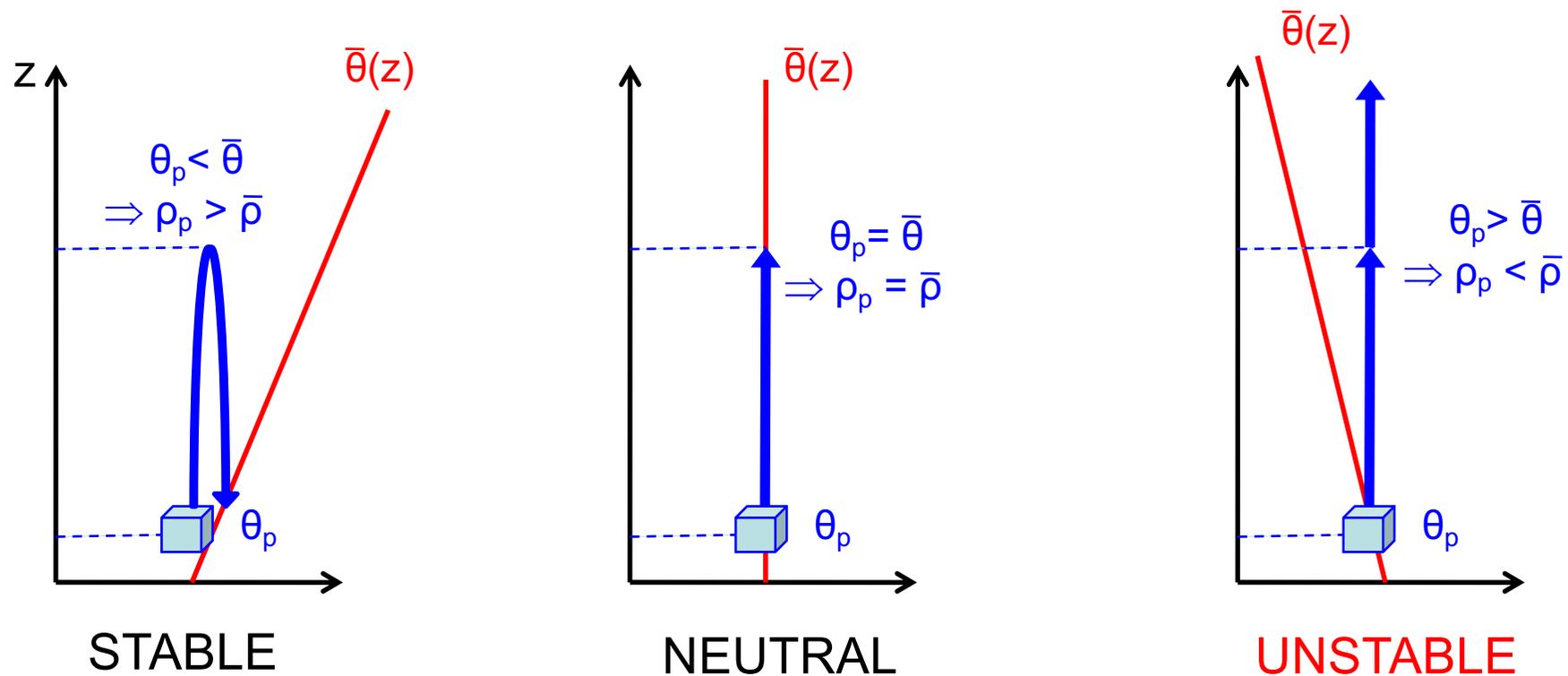
When is an atmosphere unstable to dry convection?

When potential temperature $\theta = T (p_0 / p)^{R/c_p}$ decreases with height !

The parcel method:

Small vertical displacement of a fluid parcel adiabatic ($\Rightarrow \theta = \text{constant}$).

During movement, pressure of parcel = pressure of environment.

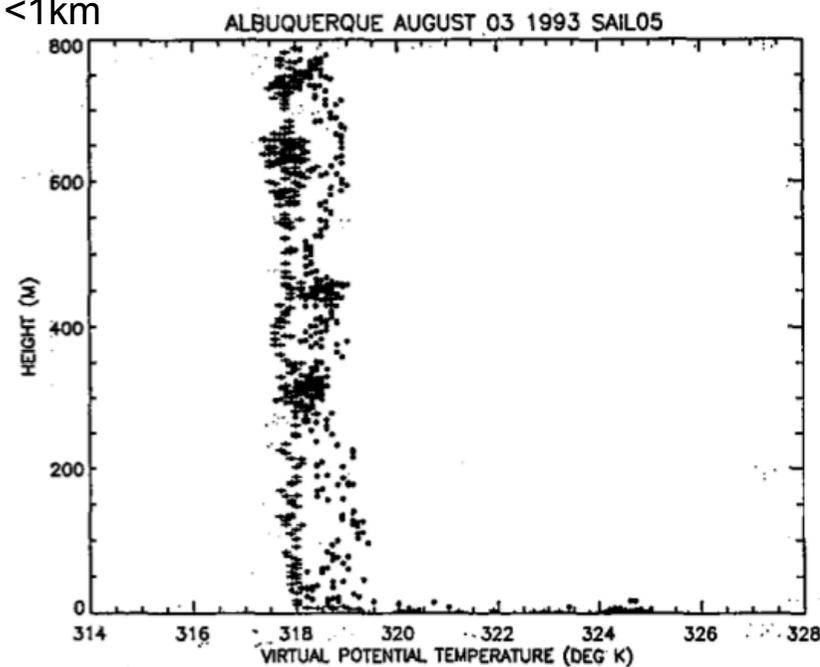


2. Atmospheric thermodynamics: instability

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 $\theta = \text{constant}$. Why?...

Atmospheric thermodynamics: instability

inversion

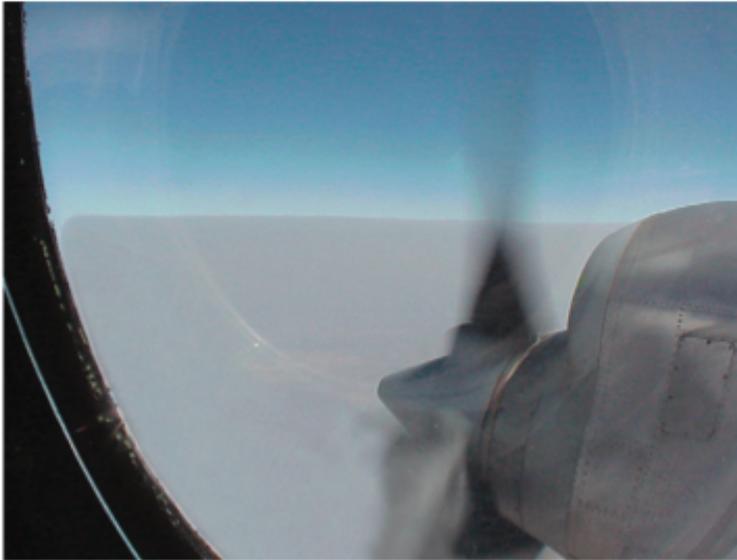


Fig. 3.15 Looking down onto widespread haze over southern Africa during the biomass-burning season. The haze is confined below a temperature inversion. Above the inversion, the air is remarkably clean and the visibility is excellent. (Photo: P. V. Hobbs.)



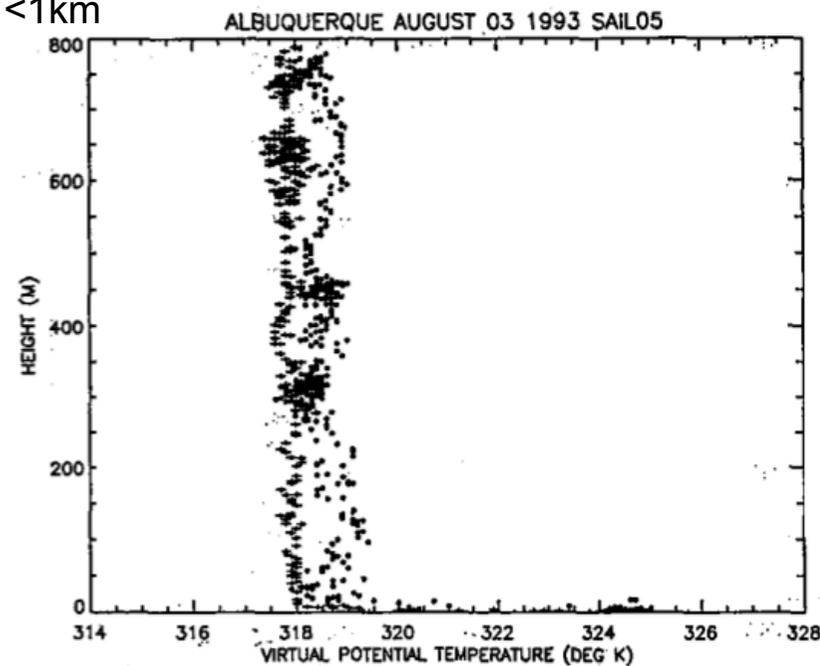
Smoke rising in [Lochcarron, Scotland](#), is stopped by an overlying layer of warmer air (2006).

2. Atmospheric thermodynamics: instability

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 $\theta = \text{constant}$. Why?...

Most atmospheric convection involves phase change of water

Significant latent heat with phase changes of water = **Moist Convection**

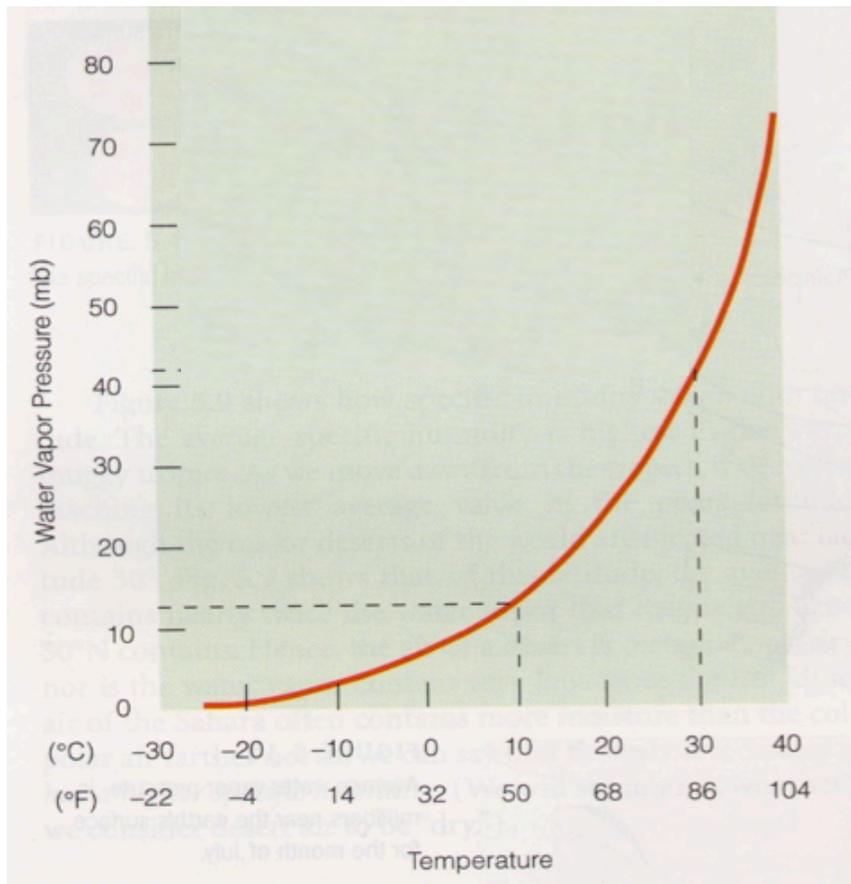
2. Atmospheric thermodynamics: instability

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

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

2. Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

Exercise :

- Show that under adiabatic displacement, a parcel of moist air satisfies $dT / T - R / c_p dp / p = - L_v / (c_p T) dq_v$.
- Deduce that equivalent potential temperature $\theta_e = T (p_0/p)^{R/c_p} e^{L_v q_v / (c_p T)}$ is approximately conserved.

Some helpful values and orders of magnitude :

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

2. Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

Equivalent potential temperature $\theta_e = T (p_0 / p)^{R/c_p} e^{L_v q_v / (c_p T)}$ is conserved under adiabatic displacements :

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

$d(\text{internal energy}) = Q$ (latent heat) – W (work done by parcel)

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

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

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

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

$$\Rightarrow T / p^{R/c_p} e^{L_v q_s / (c_p T)} \sim \text{constant}$$

Note: Air saturated $\Rightarrow q_v=q_s$

Air unsaturated $\Rightarrow q_v$ conserved

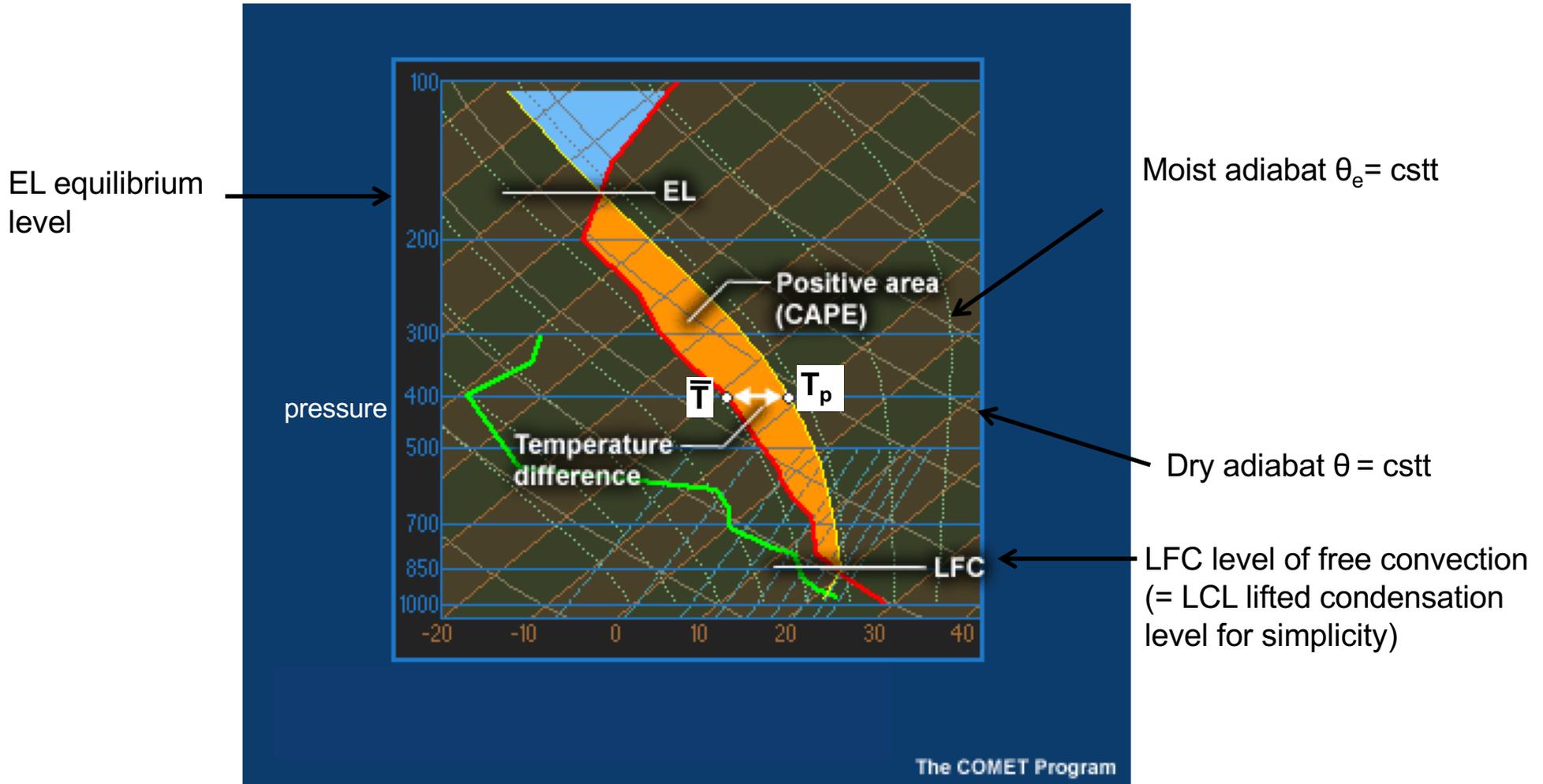
Hence

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

2. Atmospheric thermodynamics: instability

When is an atmosphere unstable to moist convection ?

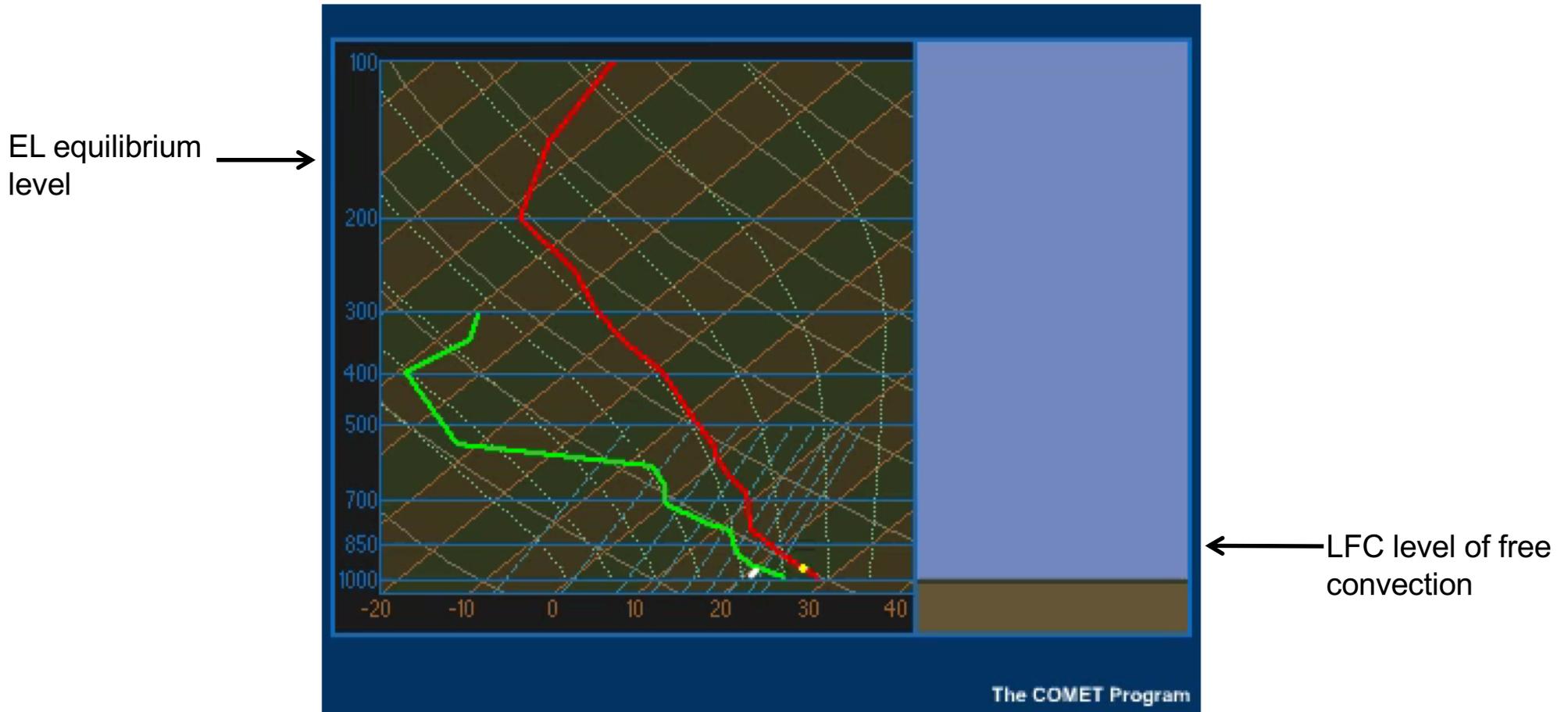
Skew T diagram (isoT slanted), atmospheric T in red



CAPE: convective available potential energy

2. Atmospheric thermodynamics: instability

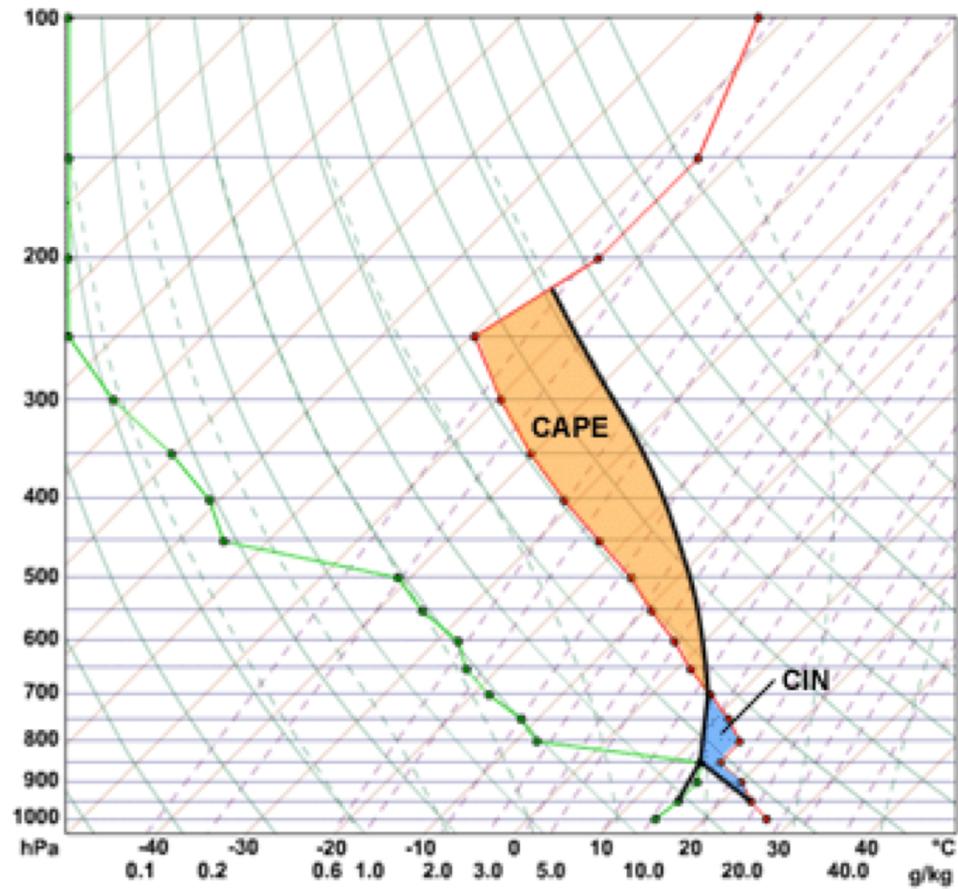
Parcel = yellow dot



CAPE: convective available potential energy

CIN: convective inhibition

Sounding showing CIN and CAPE

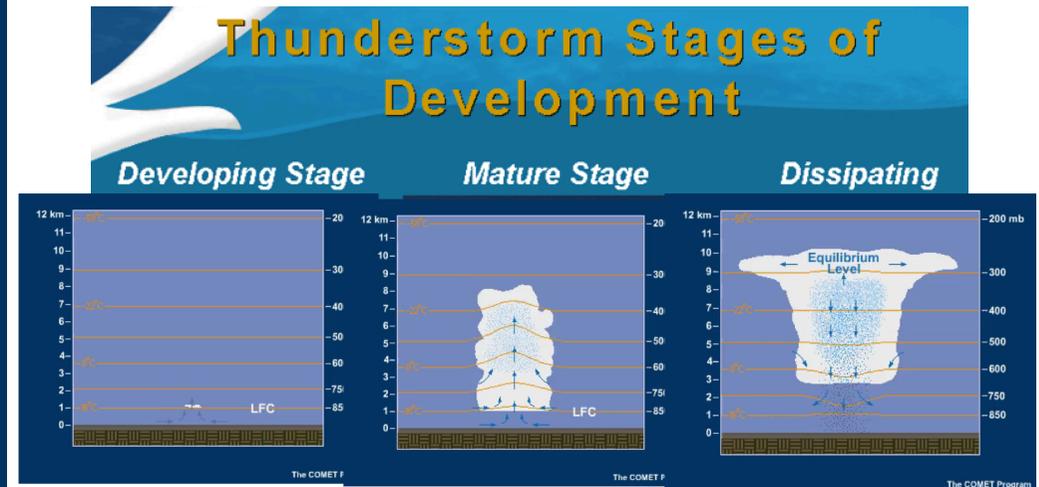
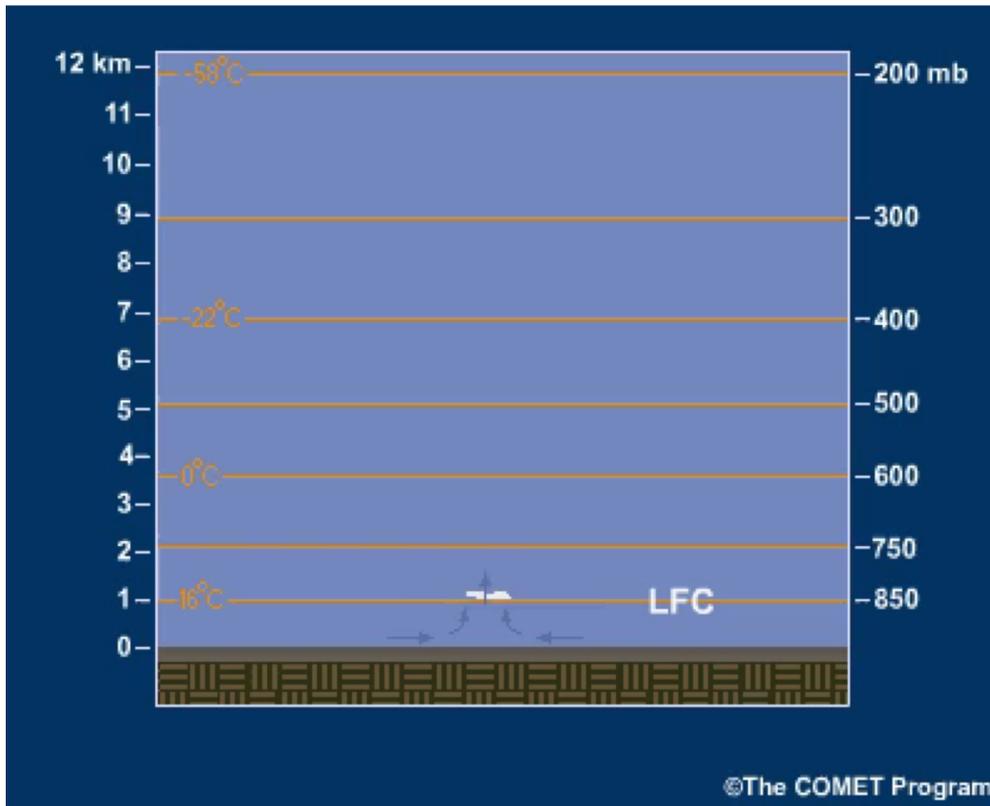


©The COMET Program

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.

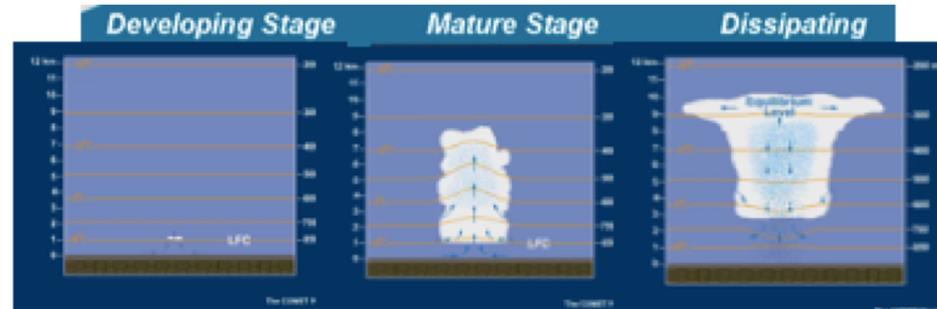


Evaporative driven cold pools

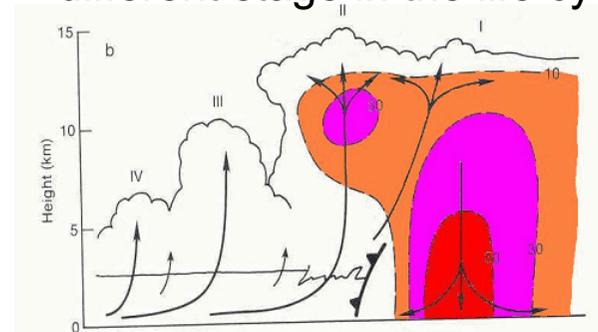
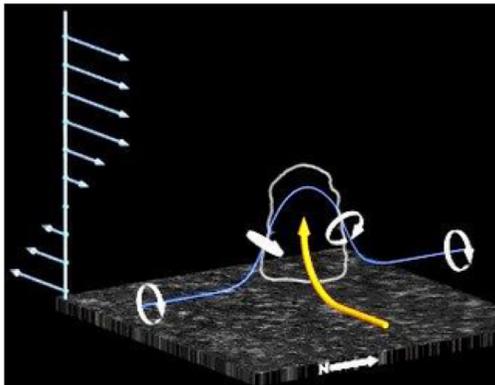
For more: see « atmospheric thermodynamics » by Bohren and Albrecht

Atmospheric thermodynamics: instability

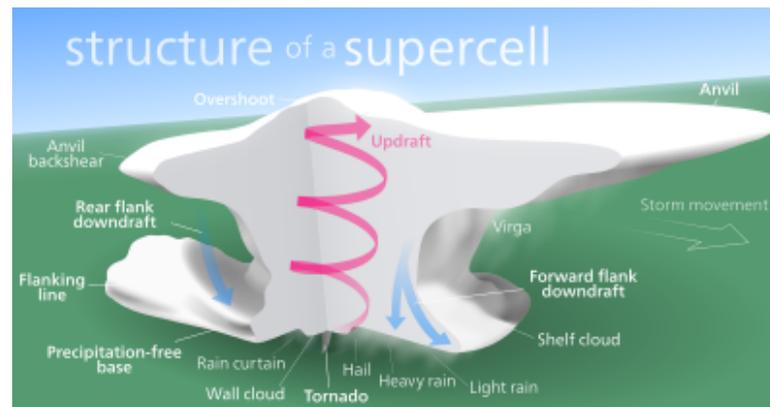
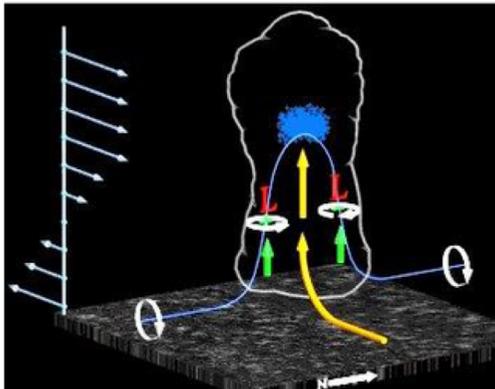
Note that thunderstorms can be : single-cell (typically with weak wind shear)



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)

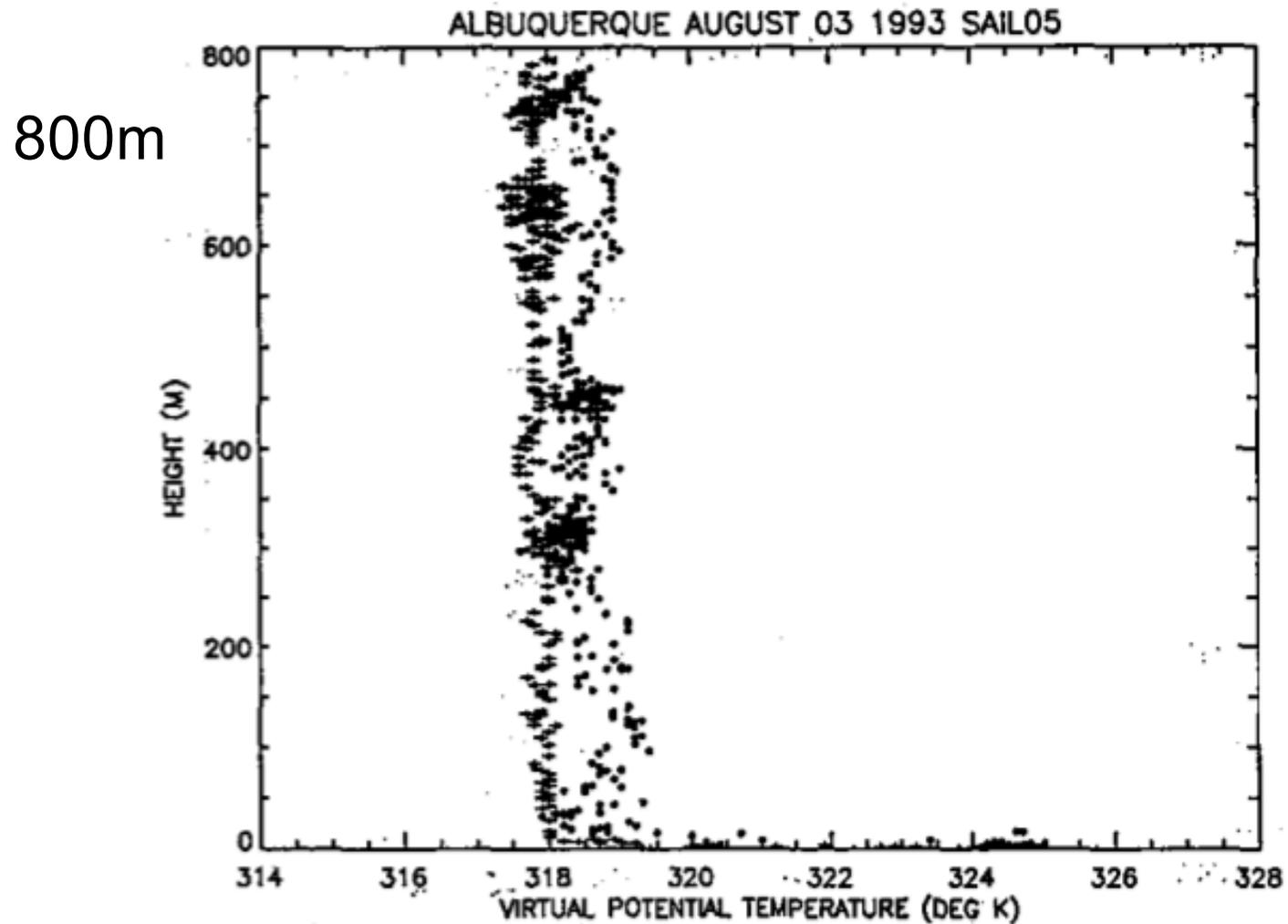
In competition between radiation and convection, convection “wins” and the observed state is much closer to convective neutrality than to radiative equilibrium

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]

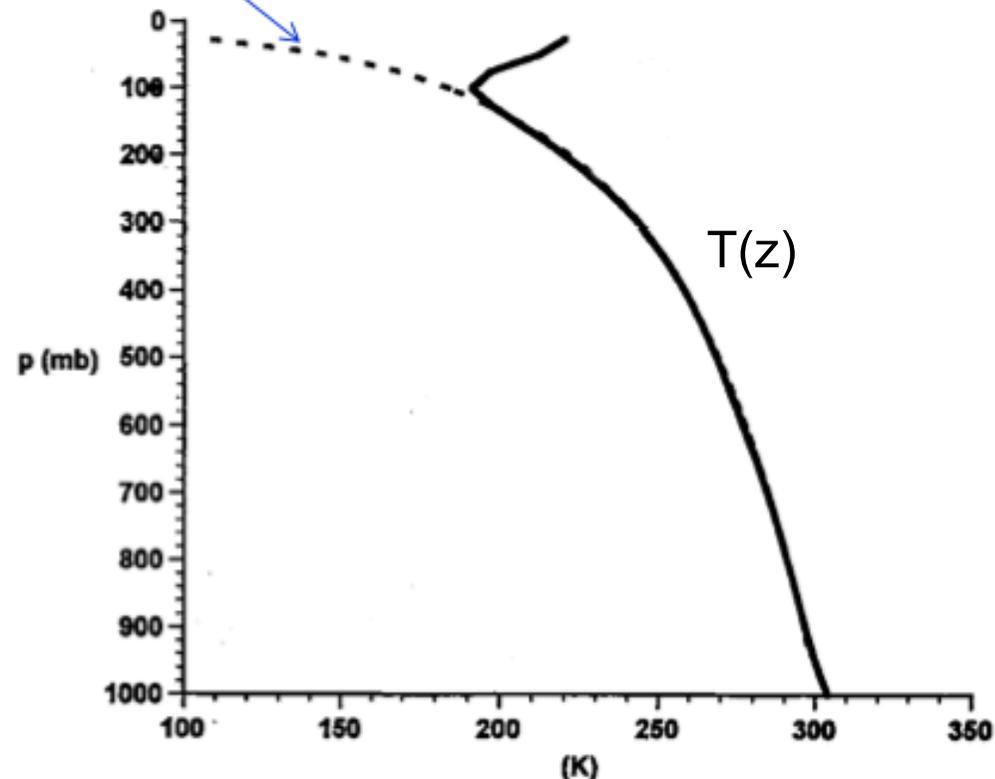


But above a thin boundary layer, most atmospheric convection involves phase change of water: Moist Convection

Radiative Convective Equilibrium

Tropical sounding => moist adiabatic

Constant θ_e



TYPICAL TROPICAL THERMODYNAMIC PROFILE (over oceans)

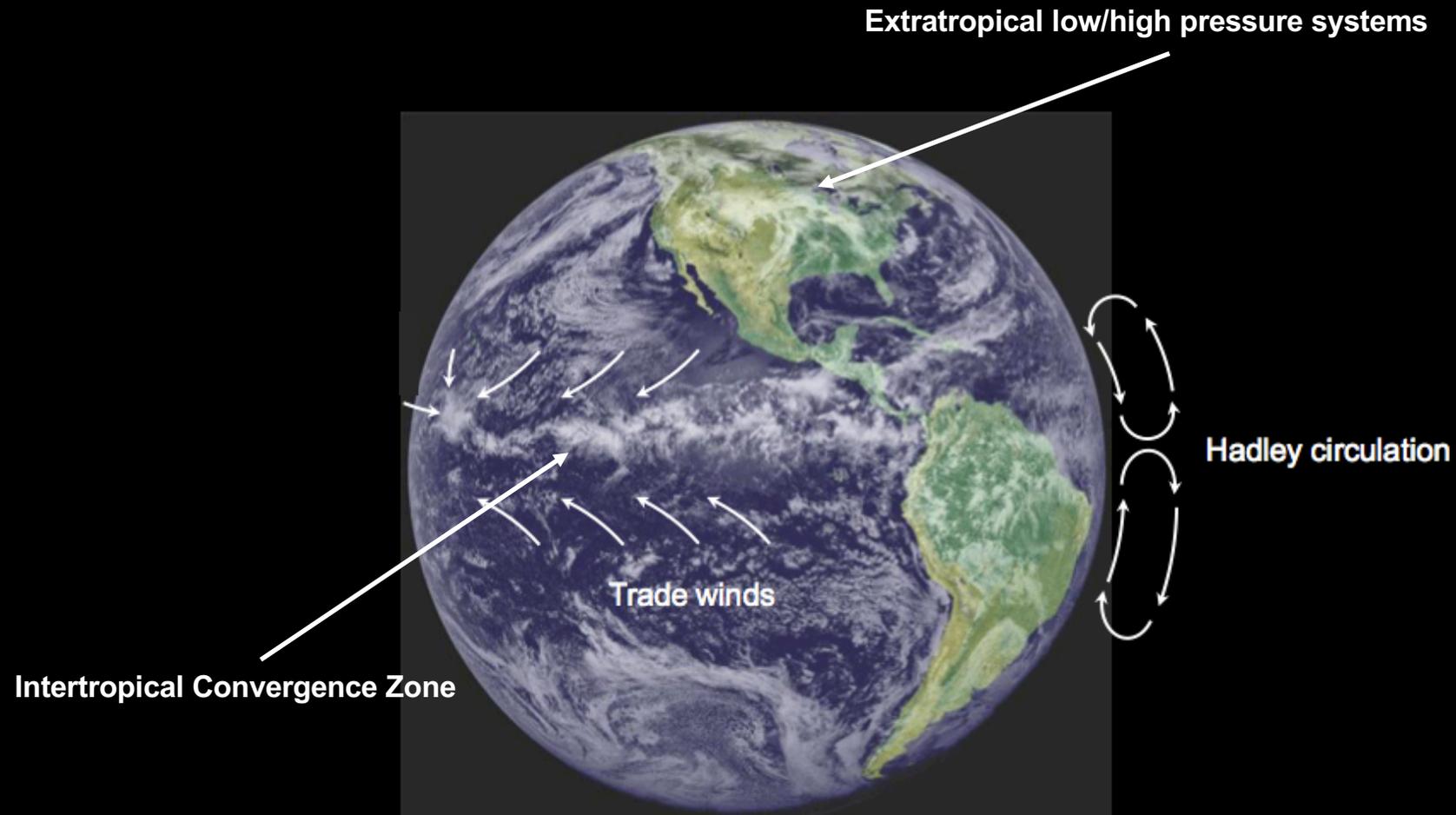
Convection FAST, quickly consumes CAPE.

Instability (largely CIN) controlled by large scale circulation ⁴³

Clouds and atmospheric convection

1. Cloud types
2. Moist thermodynamics and stability
3. Coupling with circulation

Clouds are coupled with circulation



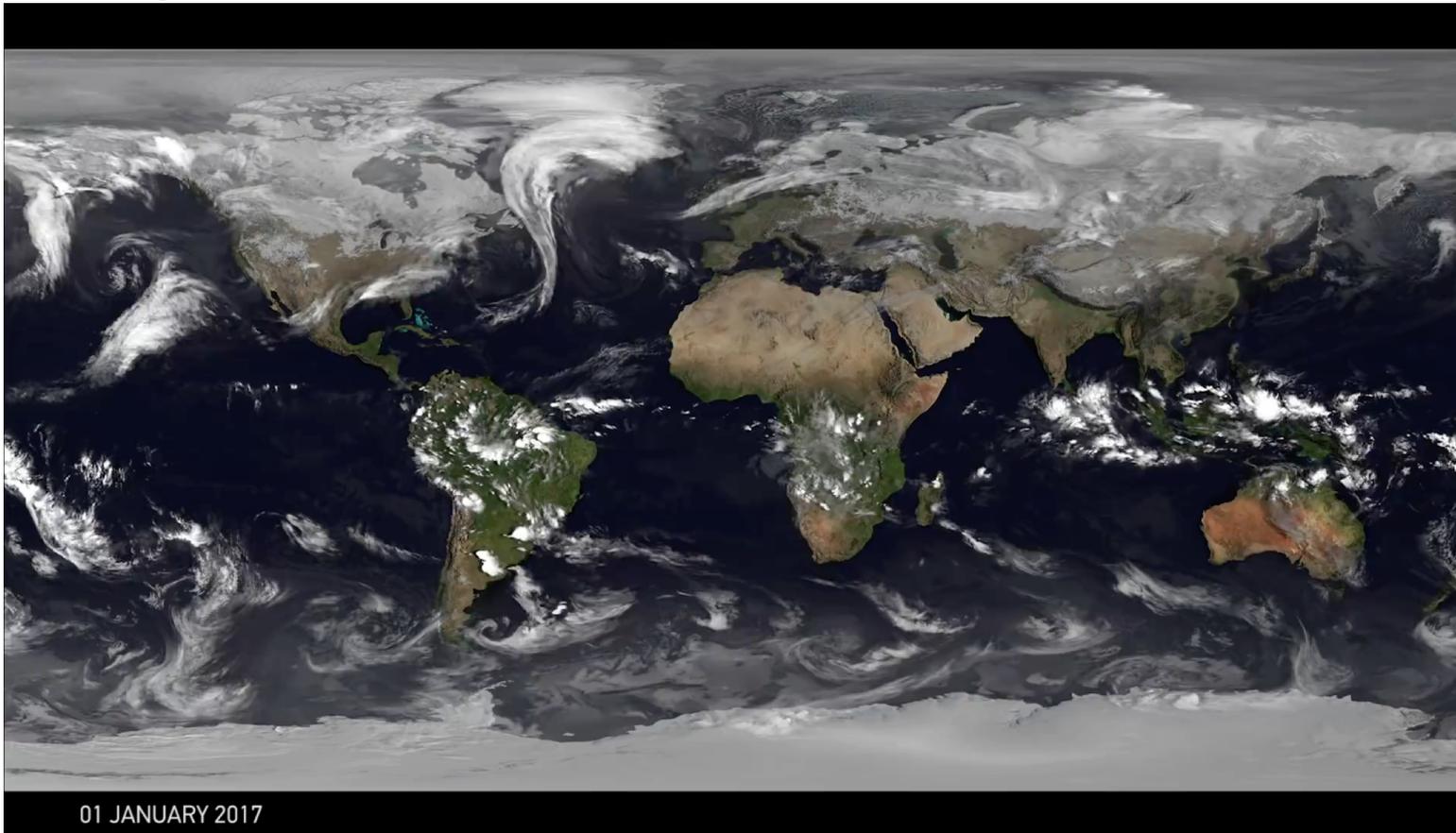
Tropics and Subtropics : ITCZ, Hadley, Walker (ENSO), monsoon

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

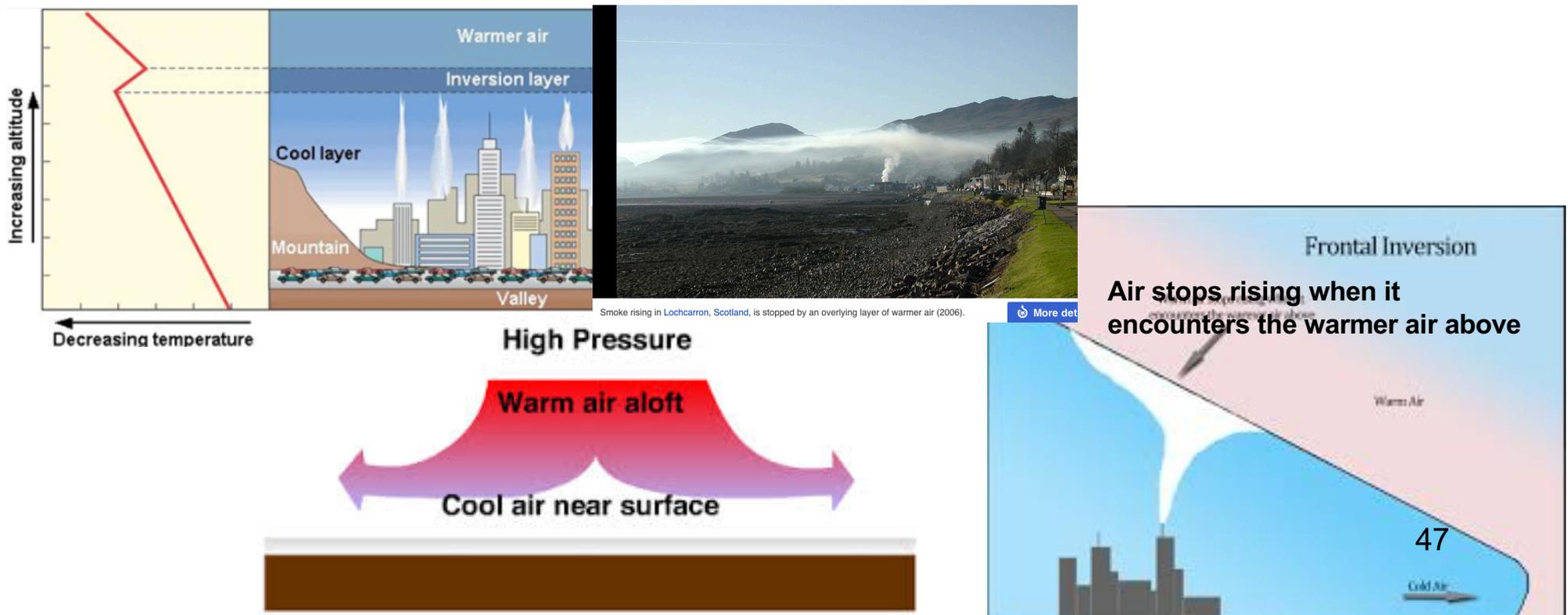
« A year of weather »

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

Clouds and Circulation

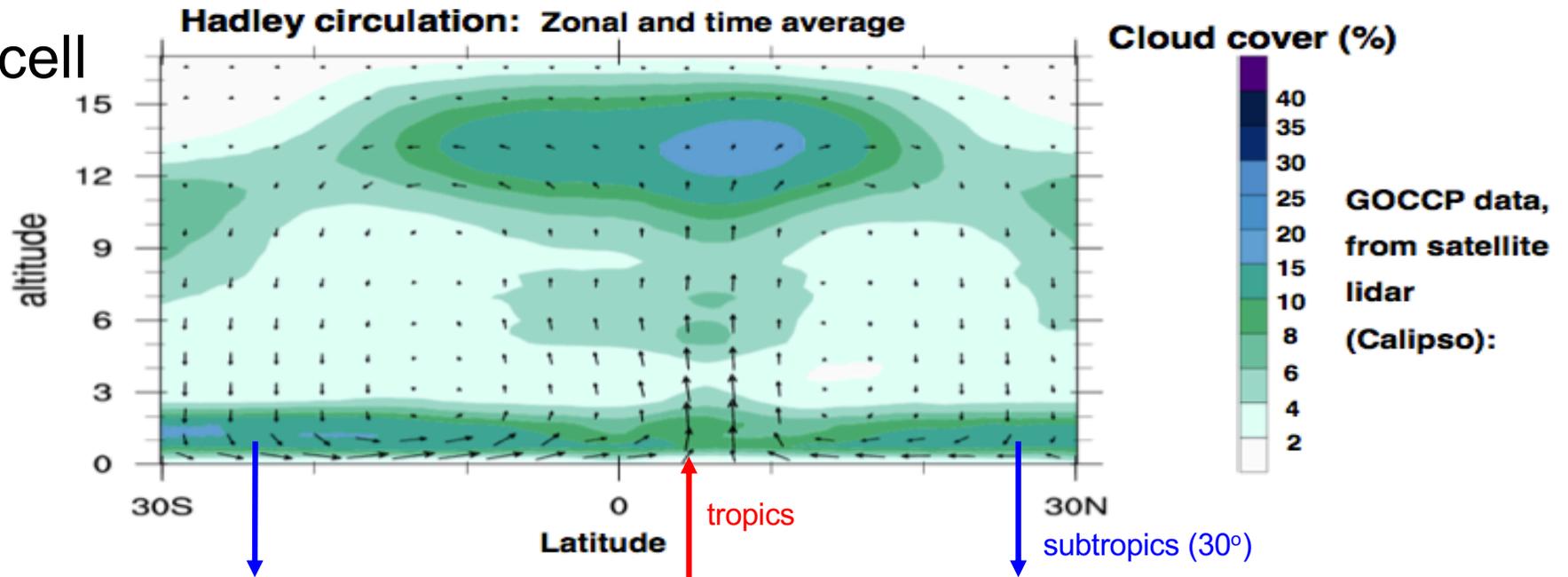
An inversion can develop aloft as a result of air gradually sinking over a wide area and being warmed by adiabatic compression, e.g. associated with subtropical high-pressure areas.

⇒ unstable layer capped by stable layer :
⇒ **Warm, dry** air above **cold** air « T inversion »

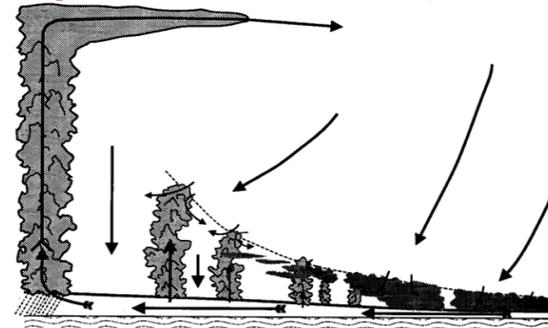


3. Clouds and Circulation: Tropics and Subtropics

Hadley cell



Cloud types:



Deep cumulonimbus

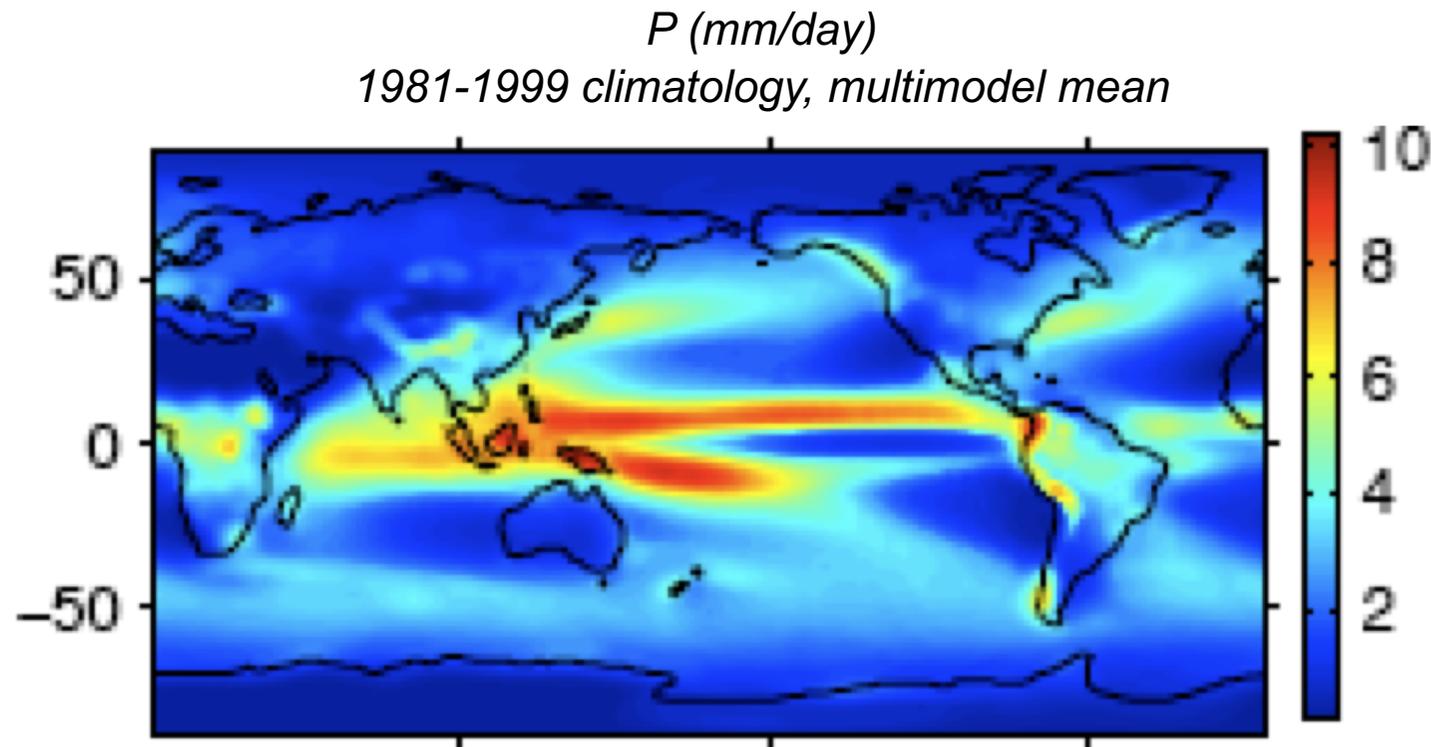
Fair weather cumulus

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



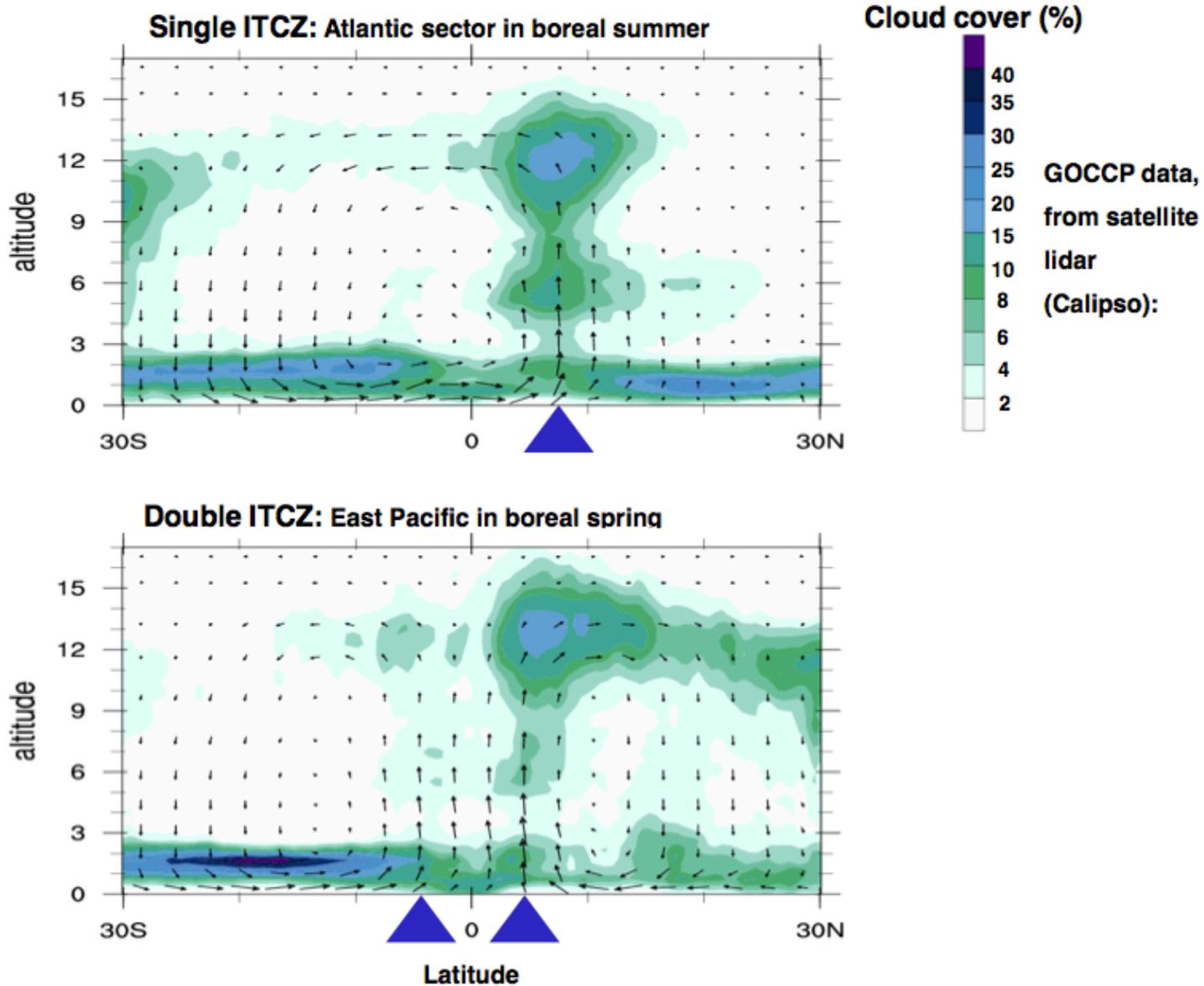
Small in Subtropics (descent)

Large in Tropics (ascent)

[Muller & O’Gorman, 2011]

3. Clouds and Circulation: Tropics and Subtropics

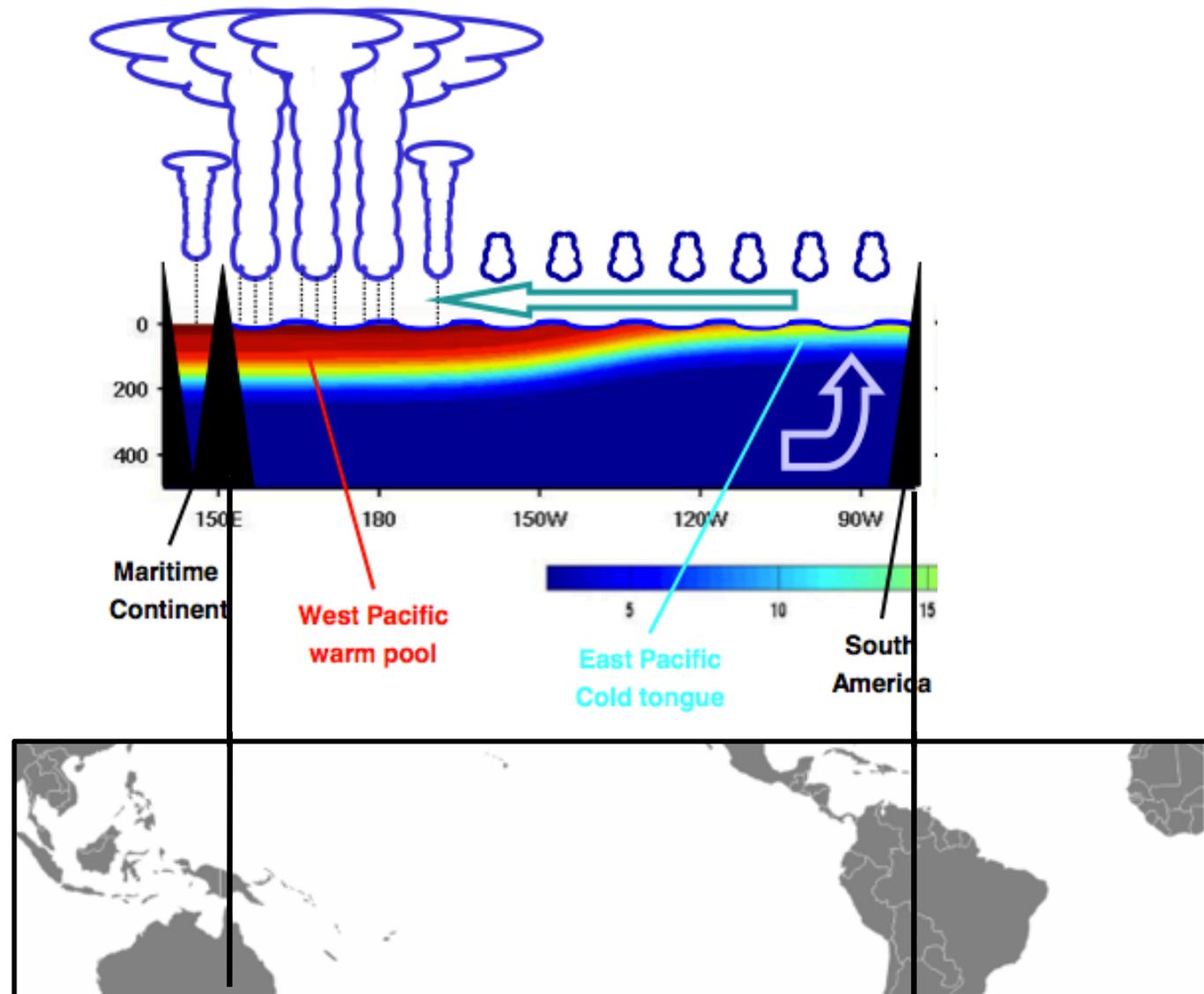
double ITCZ



3. Clouds and Circulation: Tropics and Subtropics

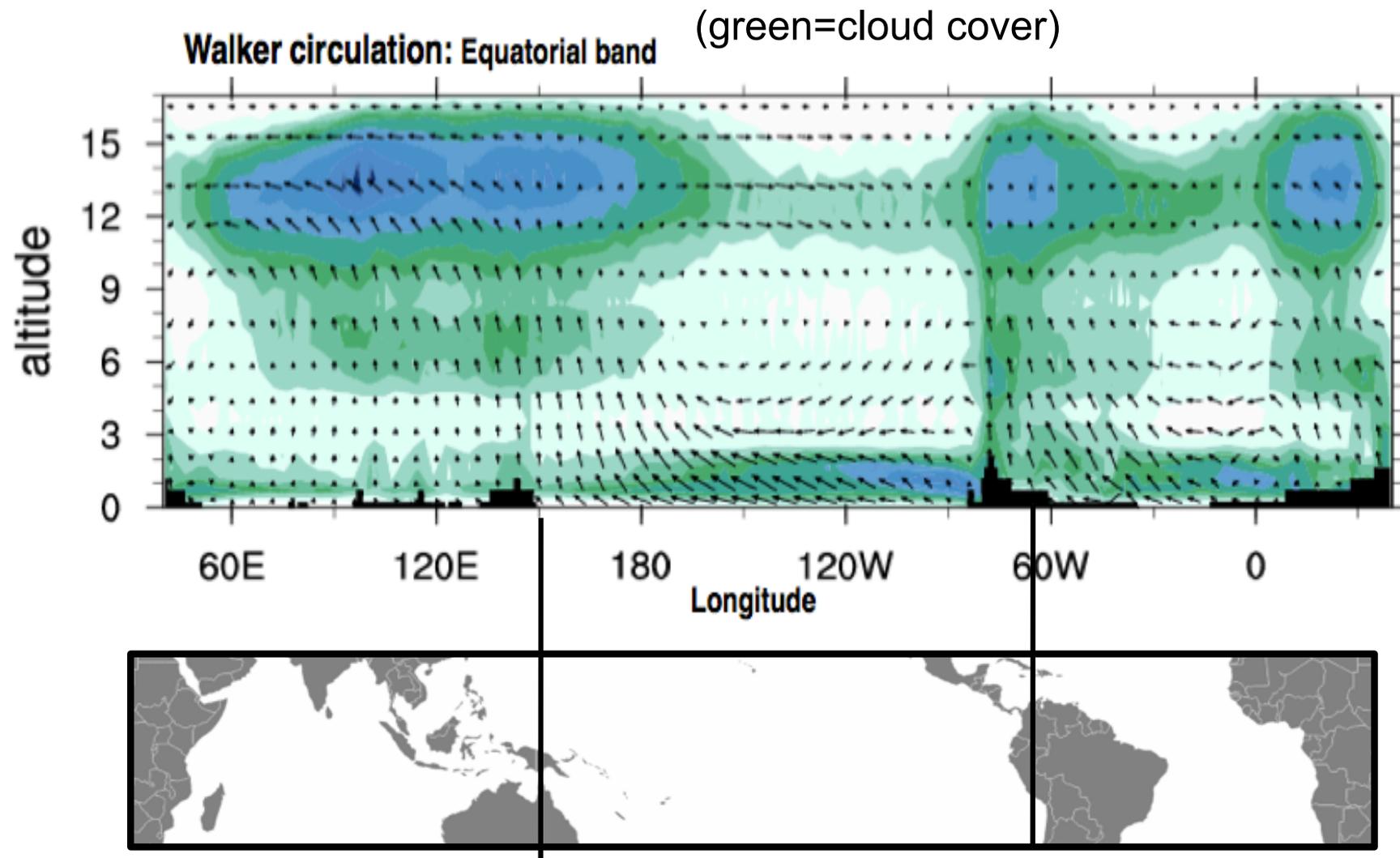
Walker cell

in the equatorial Pacific



3. Clouds and Circulation: Tropics and Subtropics

Walker cell



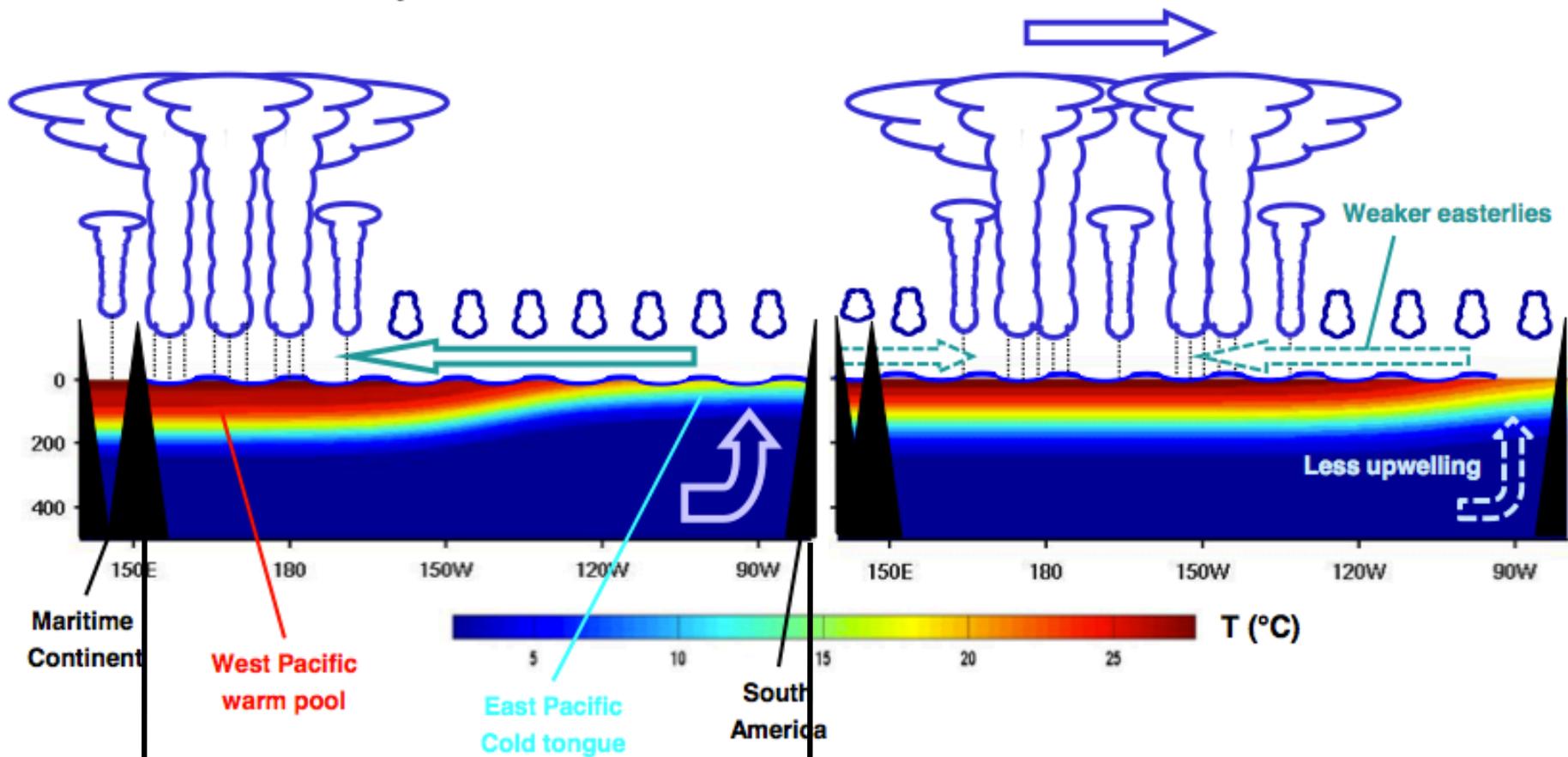
3. Clouds and Circulation: Tropics and Subtropics

El Niño

Normal conditions
in the equatorial Pacific

El Niño conditions

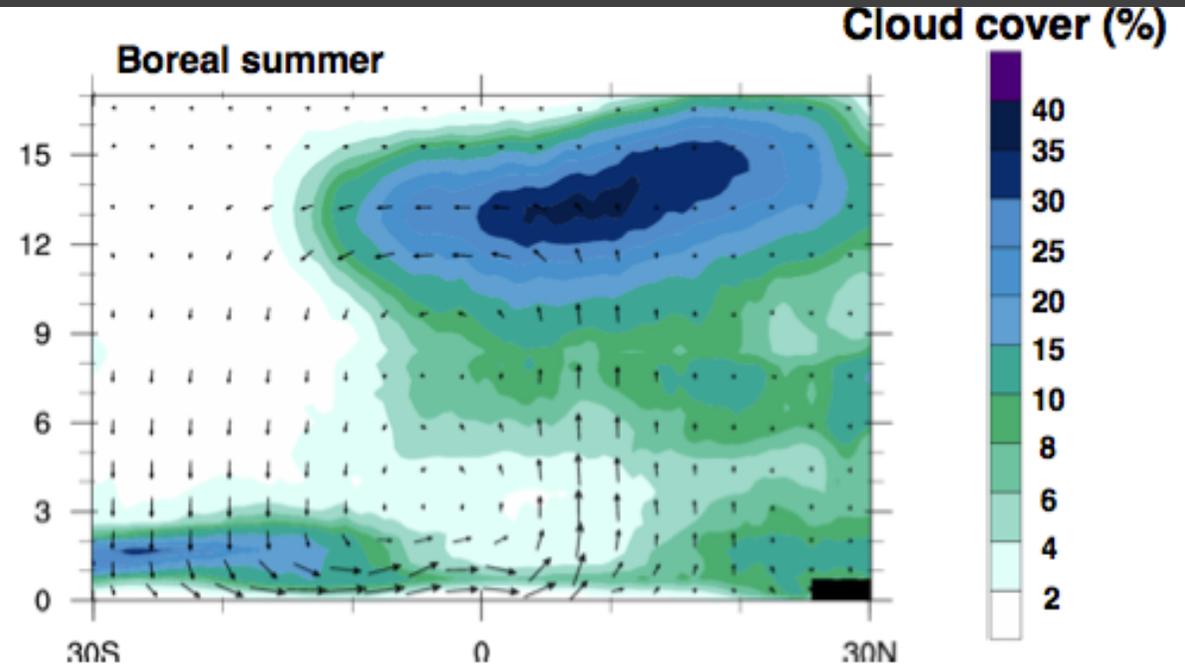
Eastward shift / extension of convection



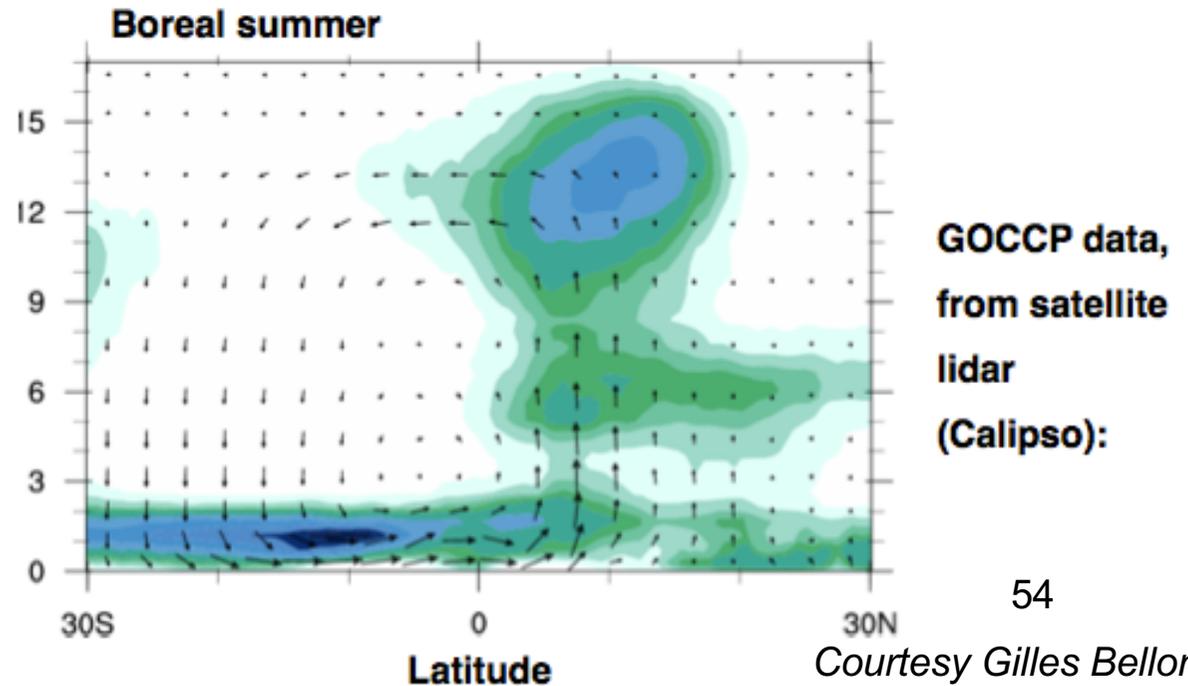
3. Clouds and Circulation: Tropics and Subtropics

Monsoons

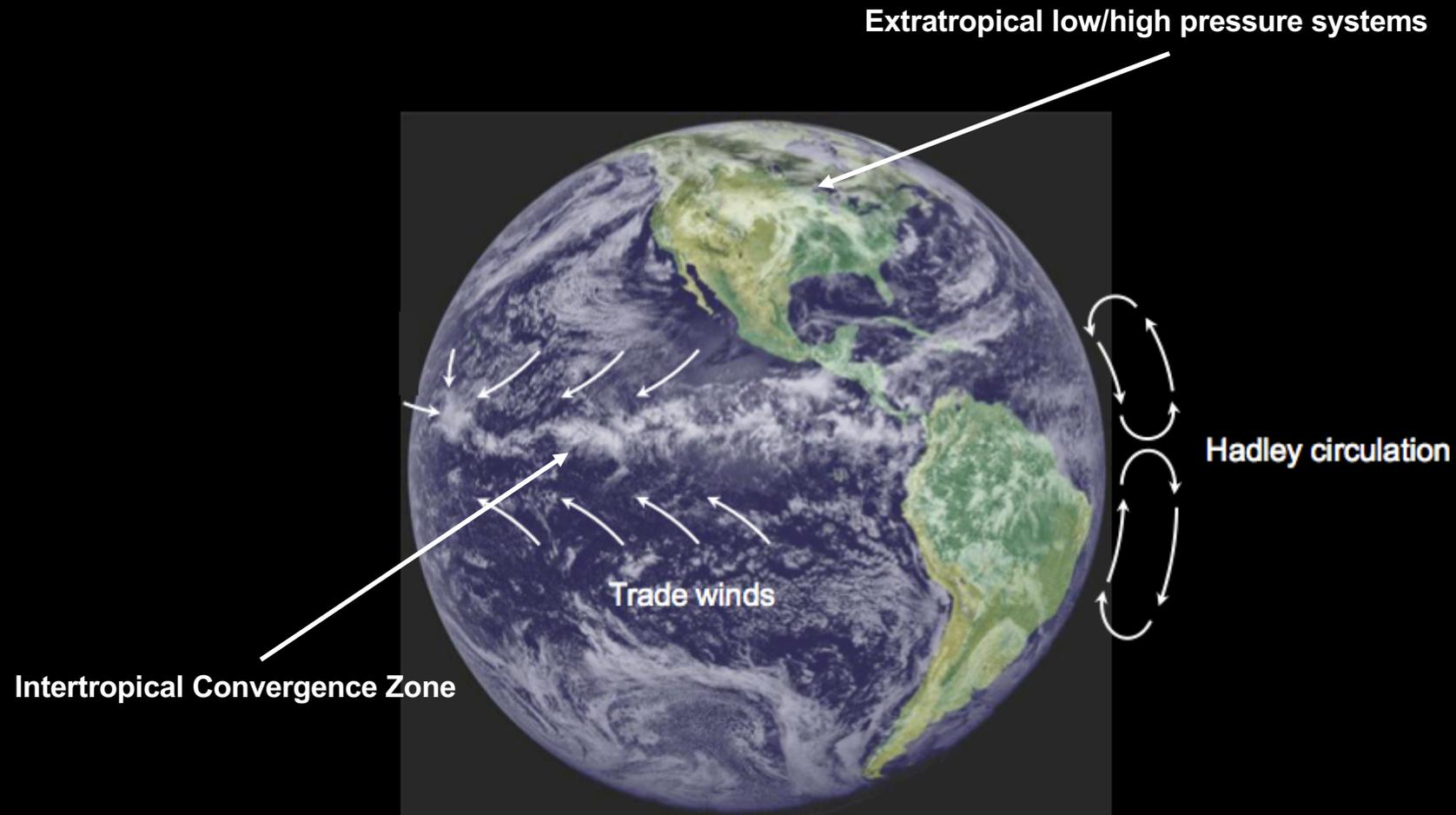
Asian monsoon



West-African monsoon



3. Clouds and Circulation: Extratropics



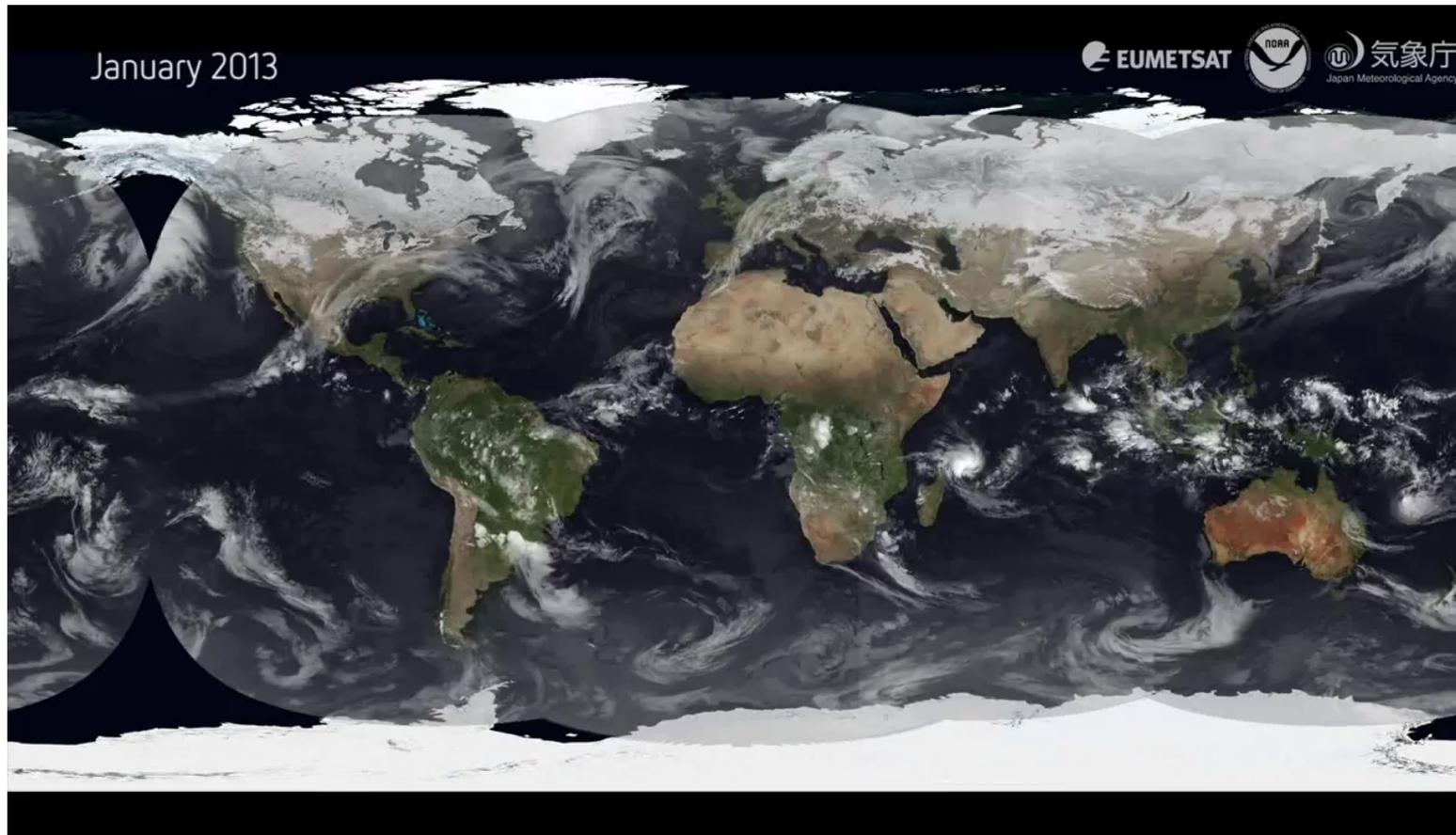
Tropics and Subtropics : ITCZ, Hadley, Walker (ENSO), monsoon

Mid-latitudes : Extratropical frontal systems

3. Clouds and Circulation

Recall : spatial distribution

Brightness temperature from satellite (white \Leftrightarrow cold cloud tops)



Large
extratropical
storm
systems

subtropics: ~no
high clouds

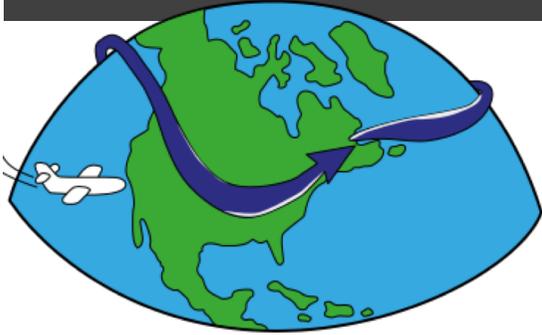
ITCZ =
Intertropical
convergent
zone

« A year of weather »

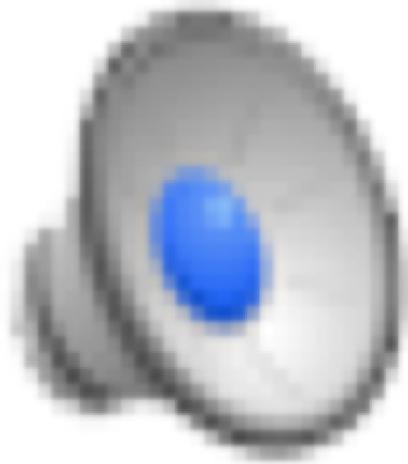
Extratropics: low and high pressure systems within the polar jet

Question: What explains different behaviors between tropics and extratropics?

Distribution of clouds: mid-latitudes



courant-jet polaire

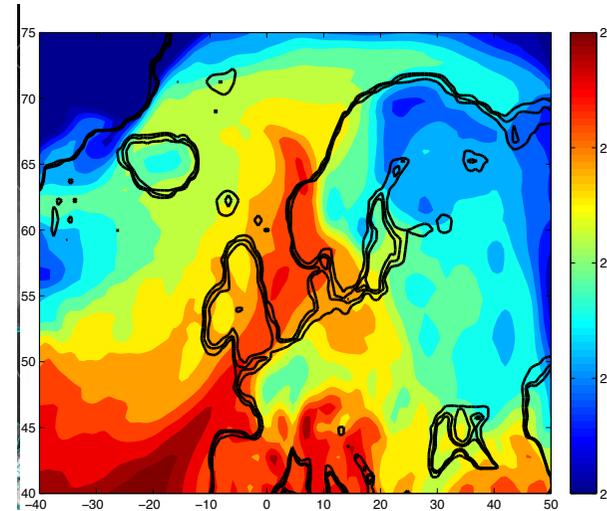
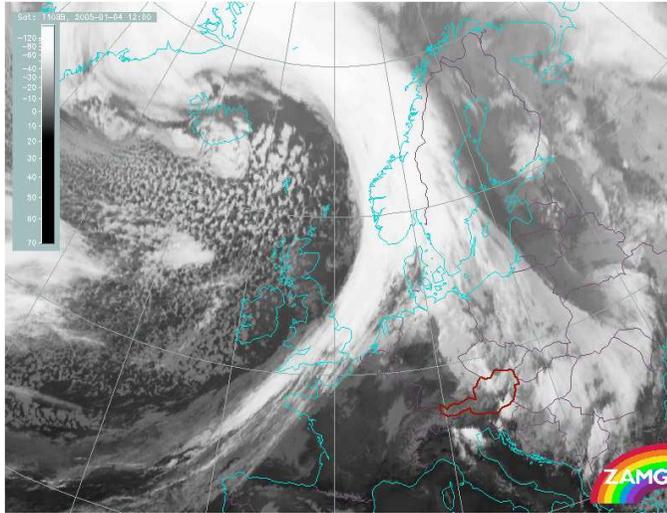


High latitudes => clouds embedded in low/high pressure systems and associated fronts

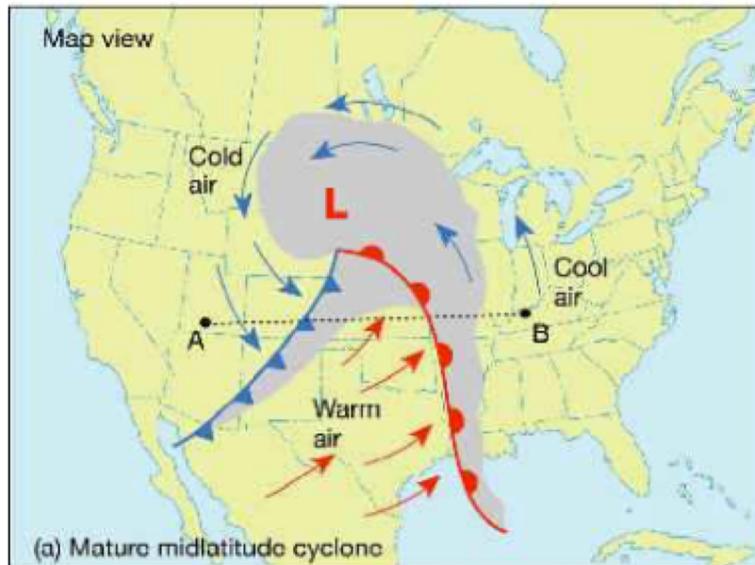
Distribution of clouds: mid-latitudes

Clouds in frontal systems

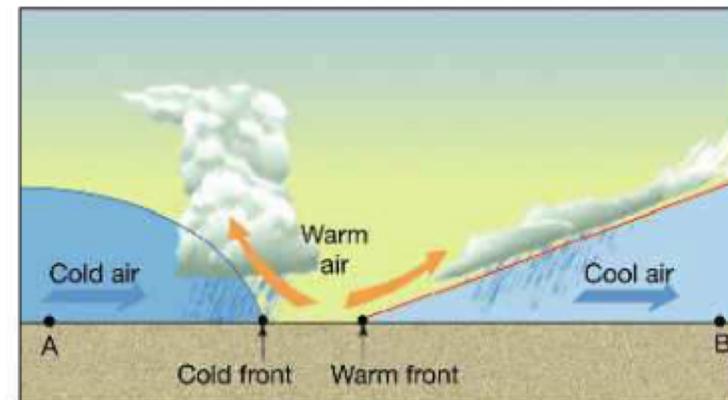
IR



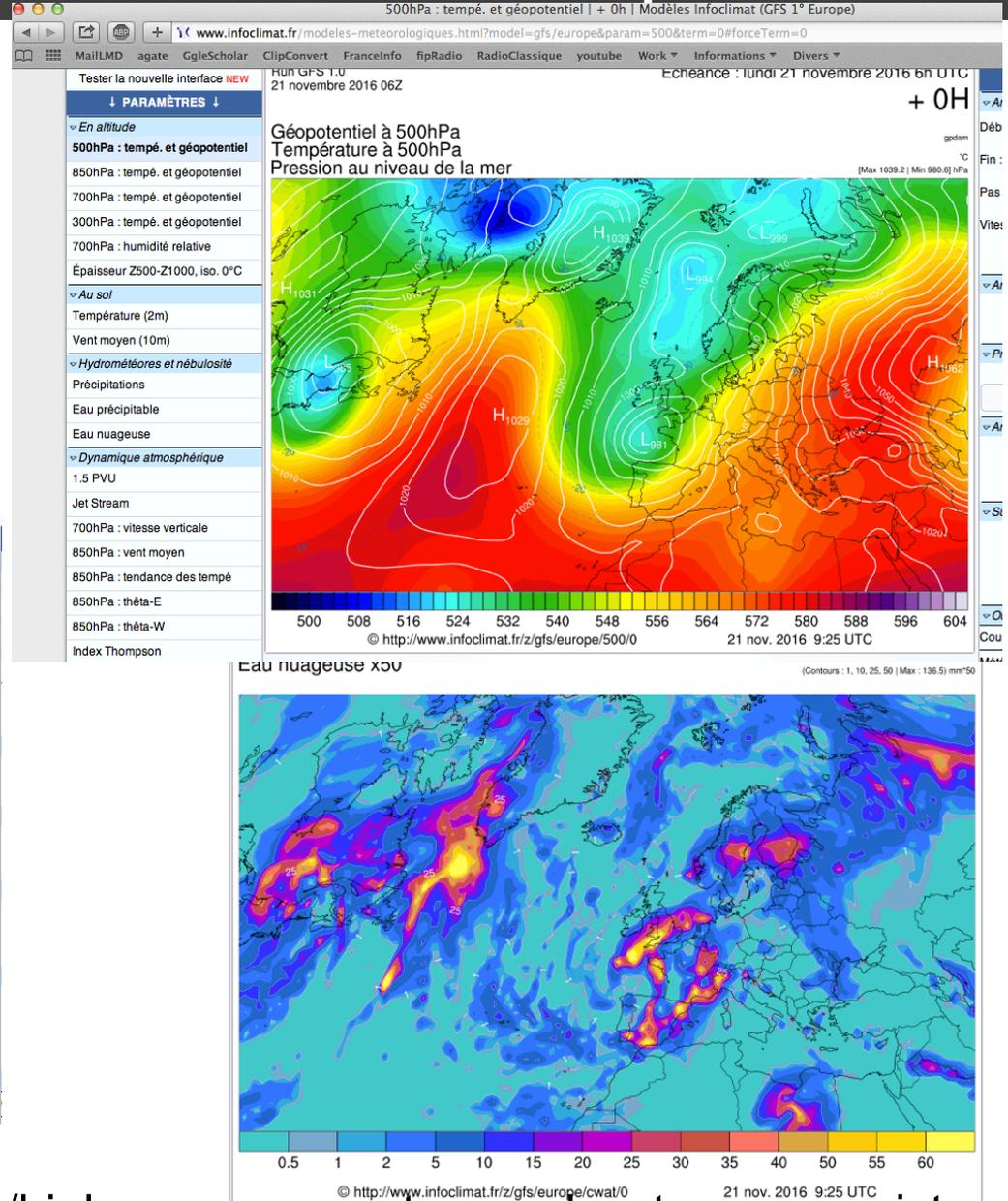
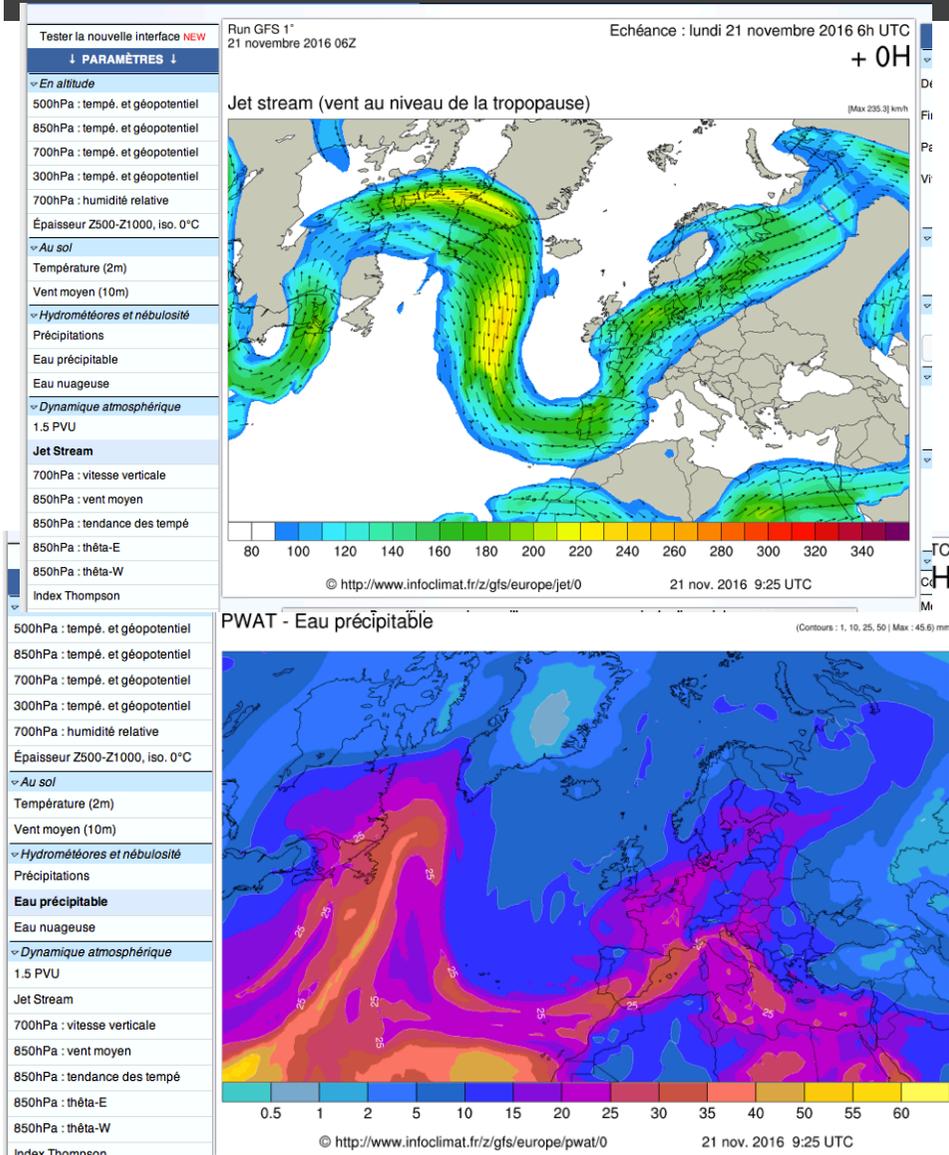
Corresponding T field
Clouds are clearly linked to the dynamics of frontal systems



Cross sectional view



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 useful links:

- « A year of weather » video (available online)
- Online document:
http://www.lmd.ens.fr/muller/DOCS/IPSL_Clouds.pdf