2015 Summer Course, IFUSP
March 25th 2015

Water in the climate system

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Outline

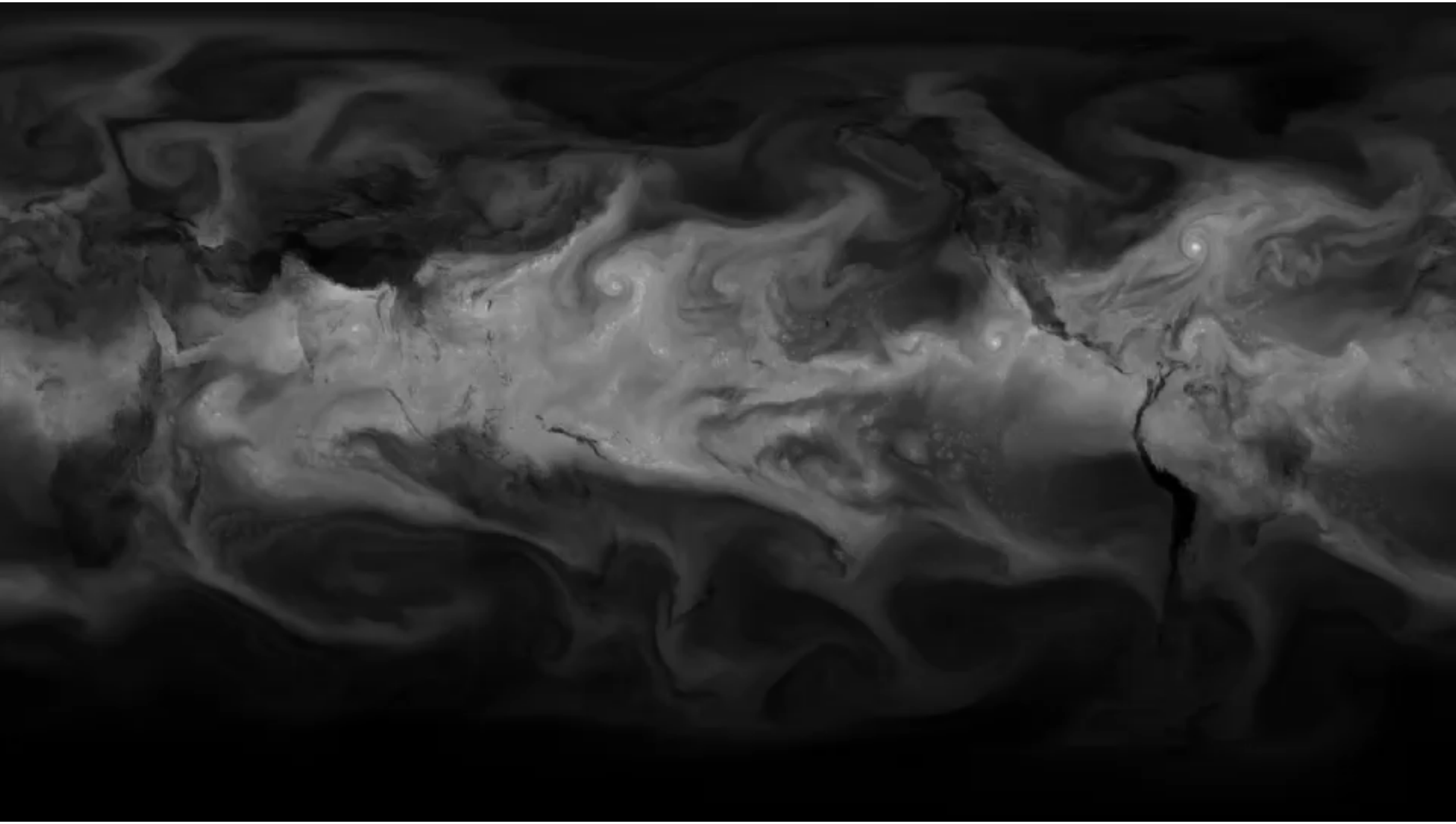
- Review the greenhouse effect
- Why Radiative properties of water matter?
- How Clausis-Clapeyron produce clouds?
- Interaction of clouds and radiation
- Energy budget and global circulation
- Linking moisture transport and hydrological cycle
  - Focusing on my own research

Water in the climate system

Its physical properties determine

- How strong greenhouse effect is;
- Planetary albedo;
- Thermodynamic structure of the troposphere;
- Large scale circulation;
- Hydrological cycle;

Total column water vapor



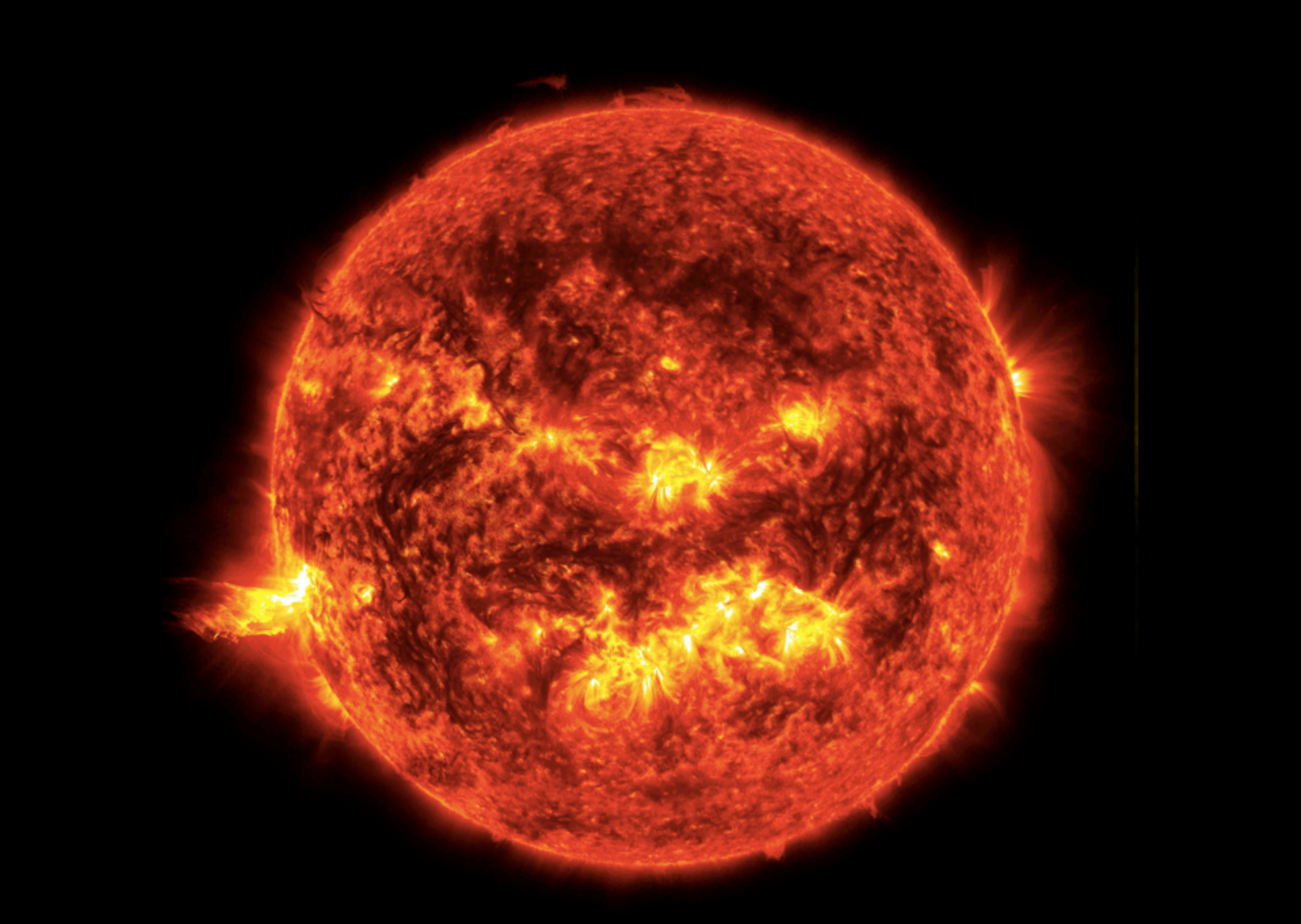
GEOS-5 http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3811

Water is rare

Water in the atmosphere, be it vapor, liquid or solid, is the least likely place to find a water molecule in the climate system.

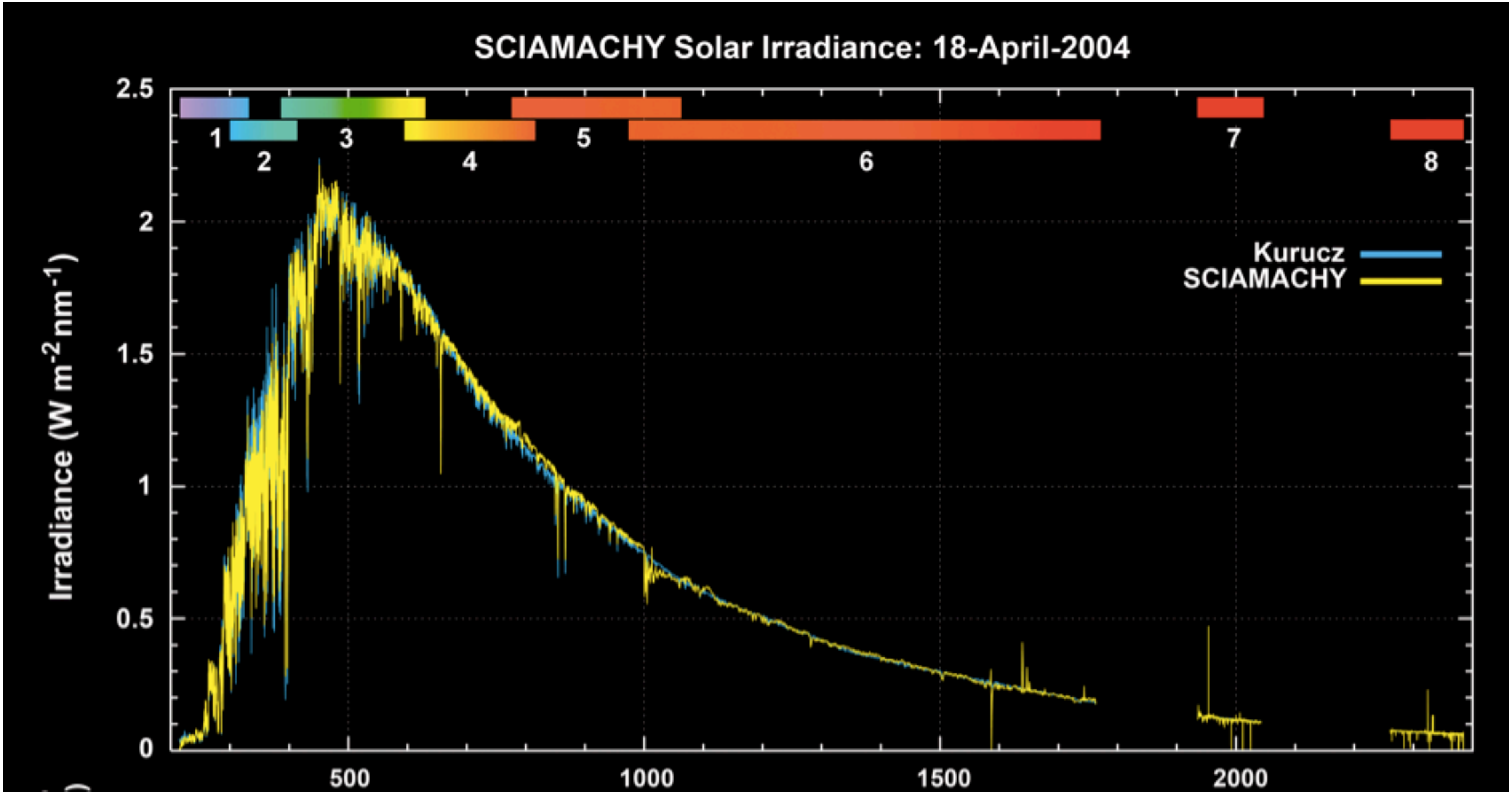
H_2O	Equivalent in meters
Liquid or solid water in the atmosphere	0.0001 m
Vapor in the atmosphere	0.025 m
Water in soil, lakes, rivers and glaciers	50 to 75 m
Oceans	2800 m

Its important role steams from its radiative properties



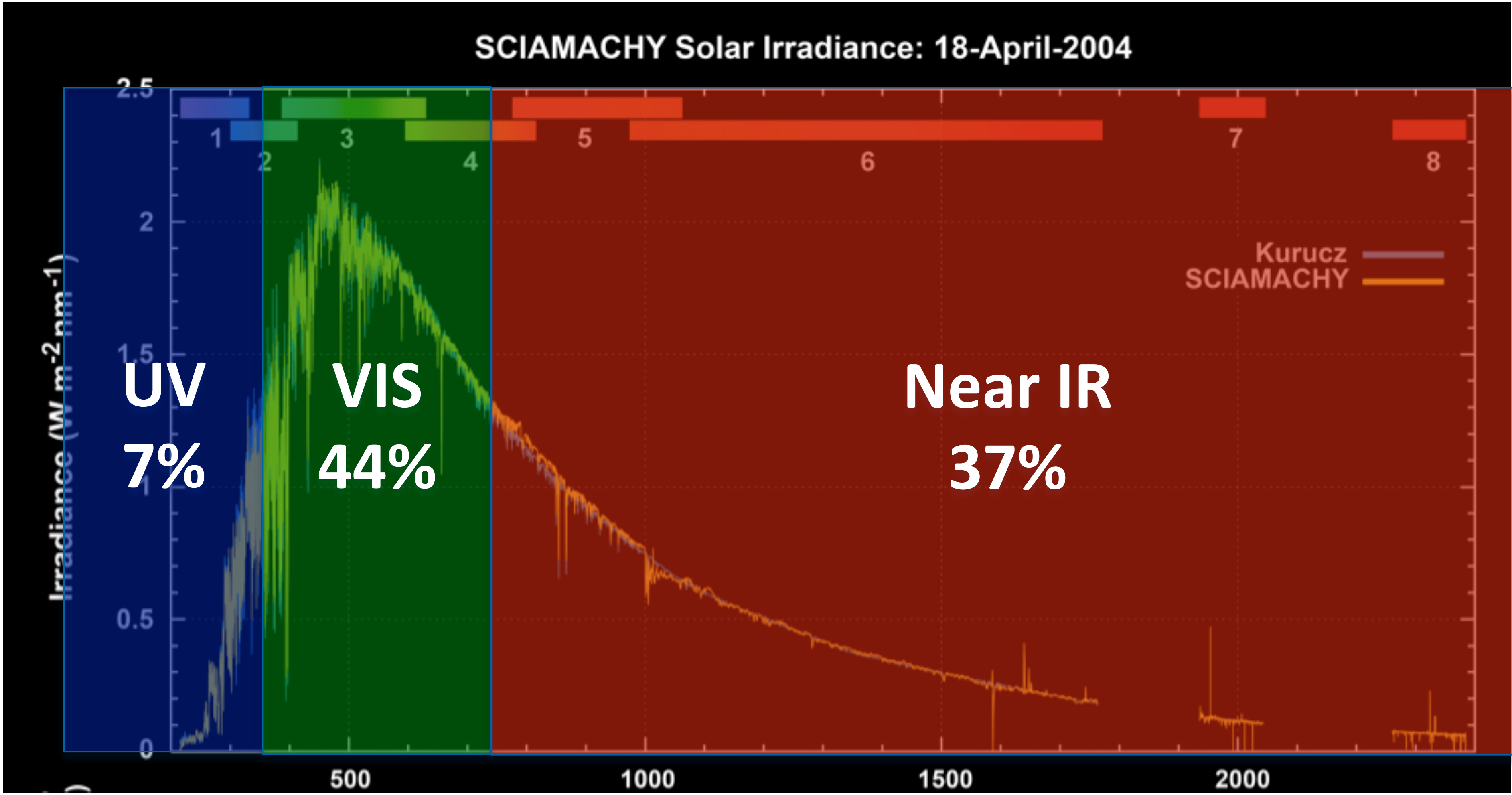
http://svs.gsfc.nasa.gov/vis/a010000/a011200/a011298/June_21_CME_171and304-half.jpg

Observed Solar Spectrum



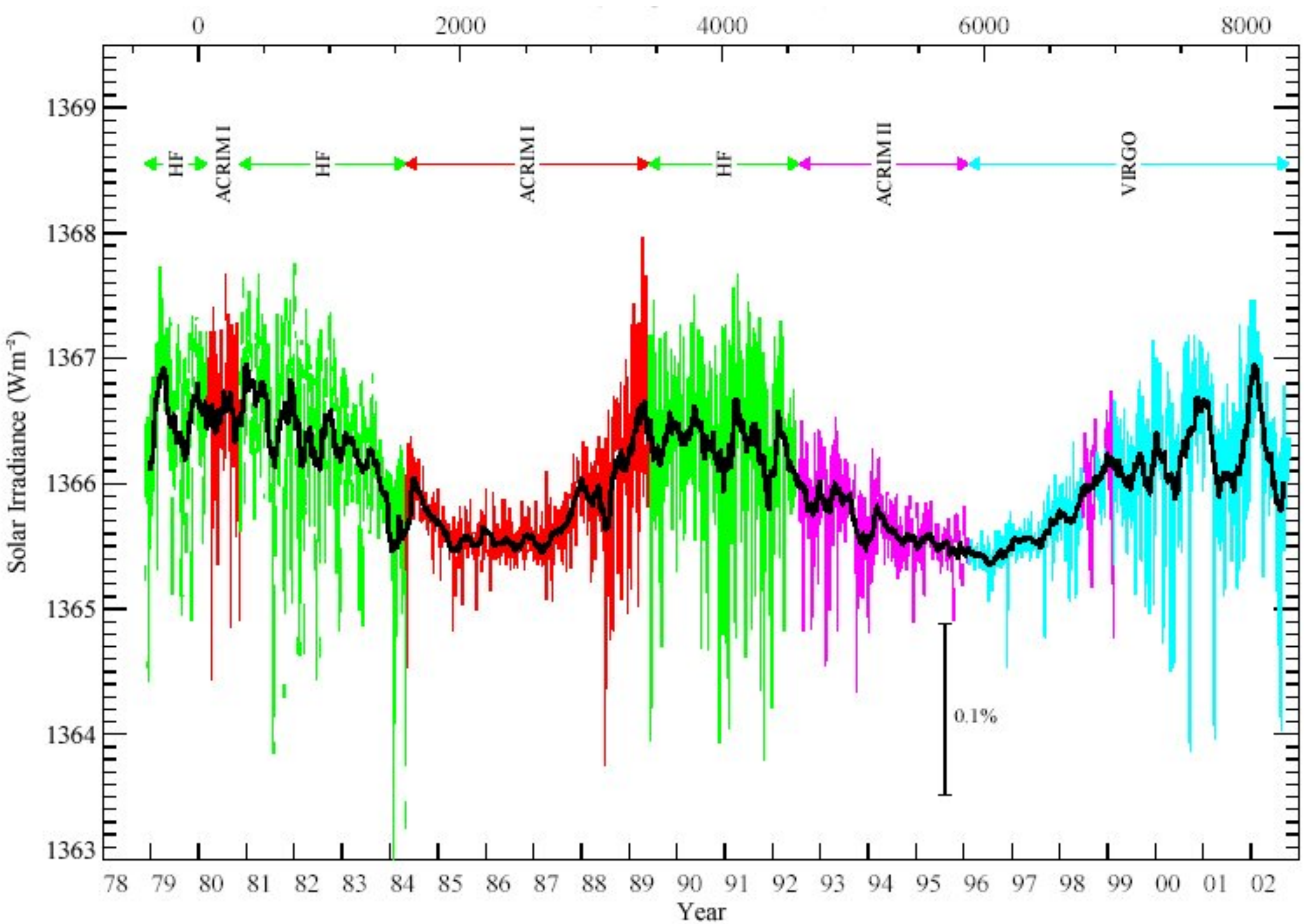
BOOK: SCIAMACHY - Exploring the Changing Earth's Atmosphere
http://atmos.caf.dlr.de/projects/scops/

S_0 ~1365 W/m^2



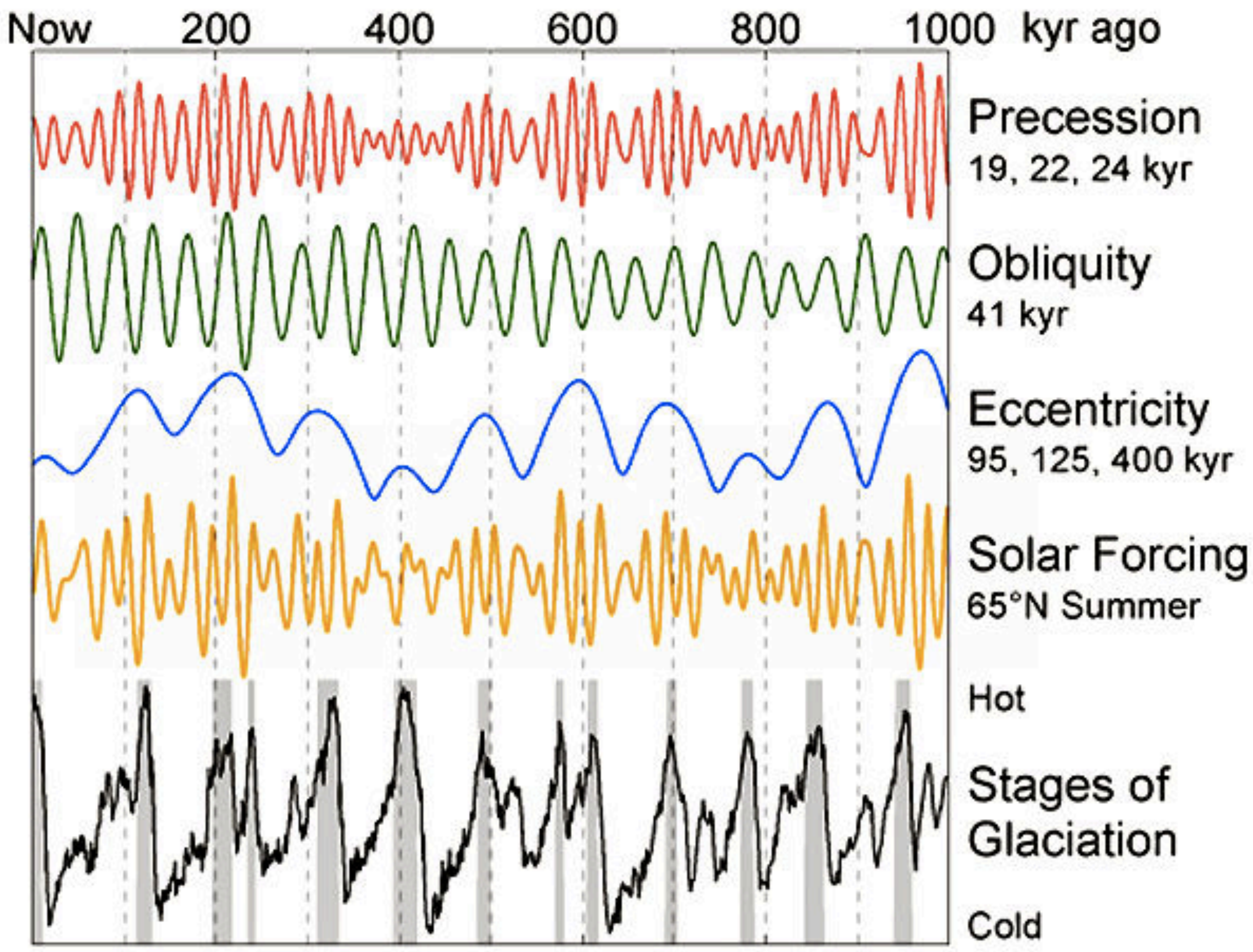
BOOK: SCIAMACHY - Exploring the Changing Earth's Atmosphere
http://atmos.caf.dlr.de/projects/scops/

S_0 measured by different satellites since 1978
Constant climate!

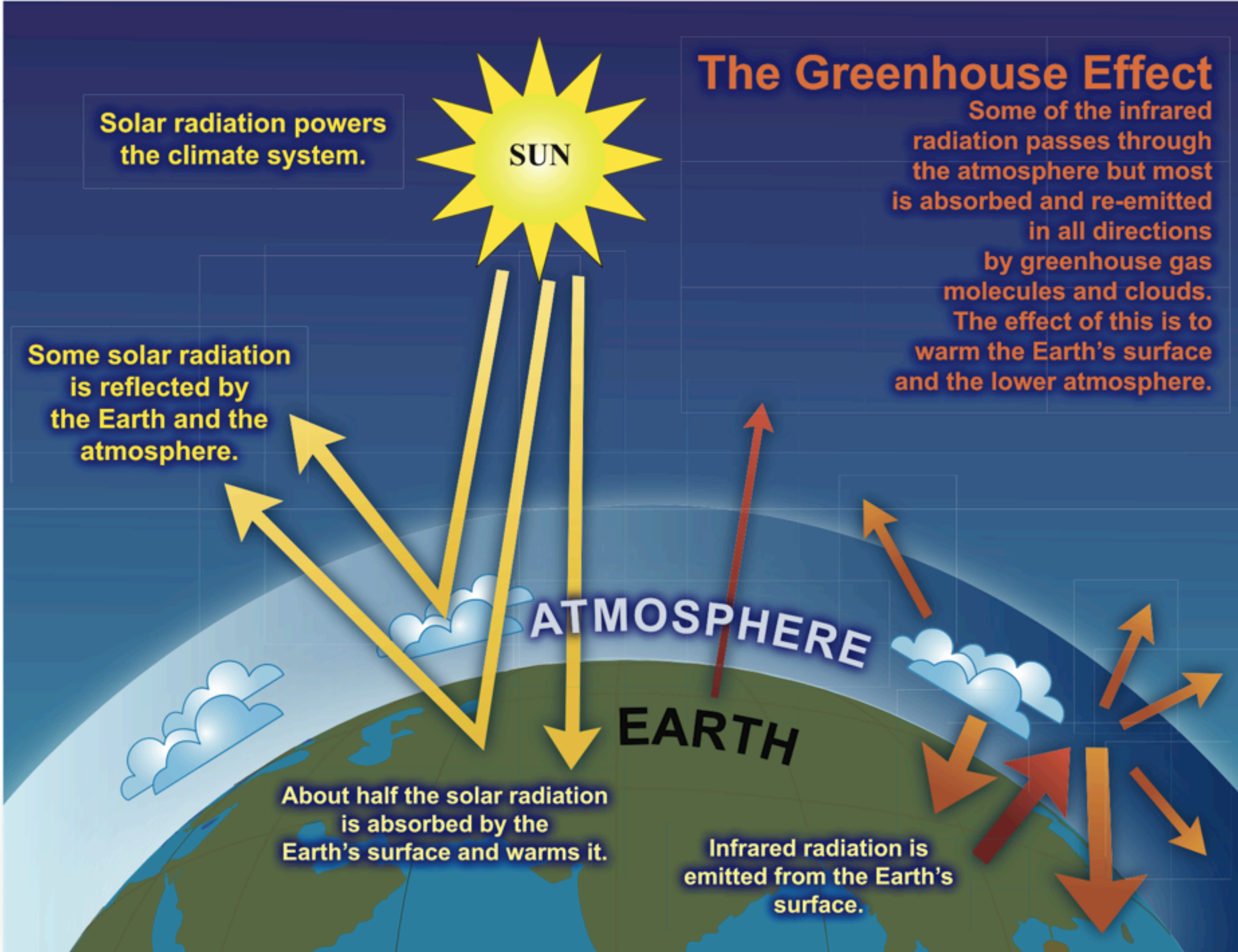


http://science.nasa.gov/media/medialibrary/2003/01/16/17jan_solcon_resources/stitch_big.jpg

…except for changes in Earth's orbit

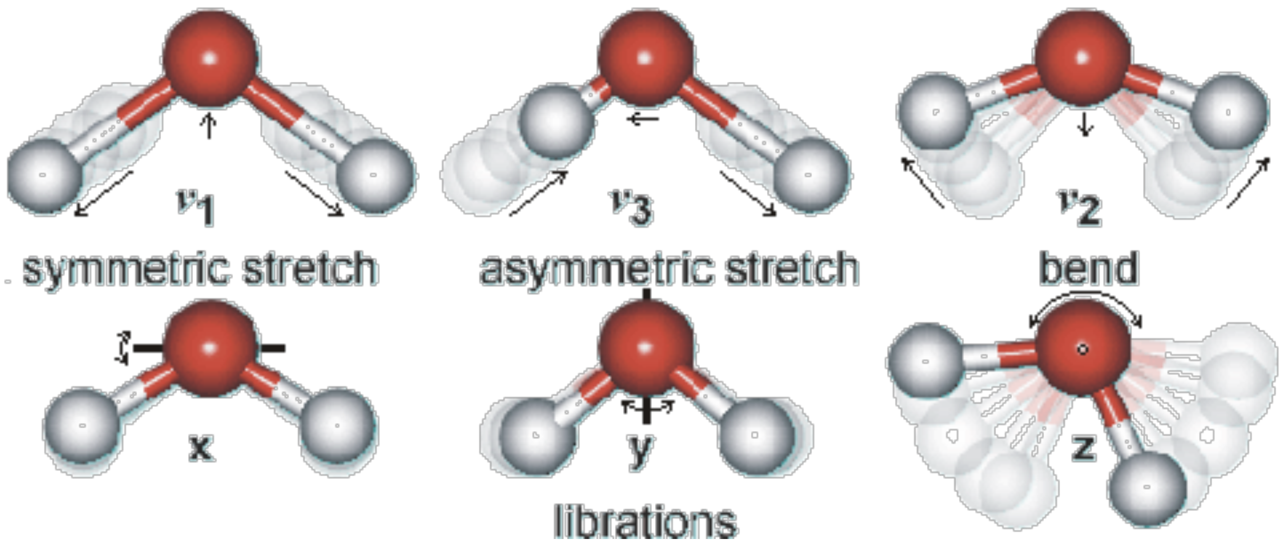


Source: Global Warming Art


The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation powers the climate system.
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

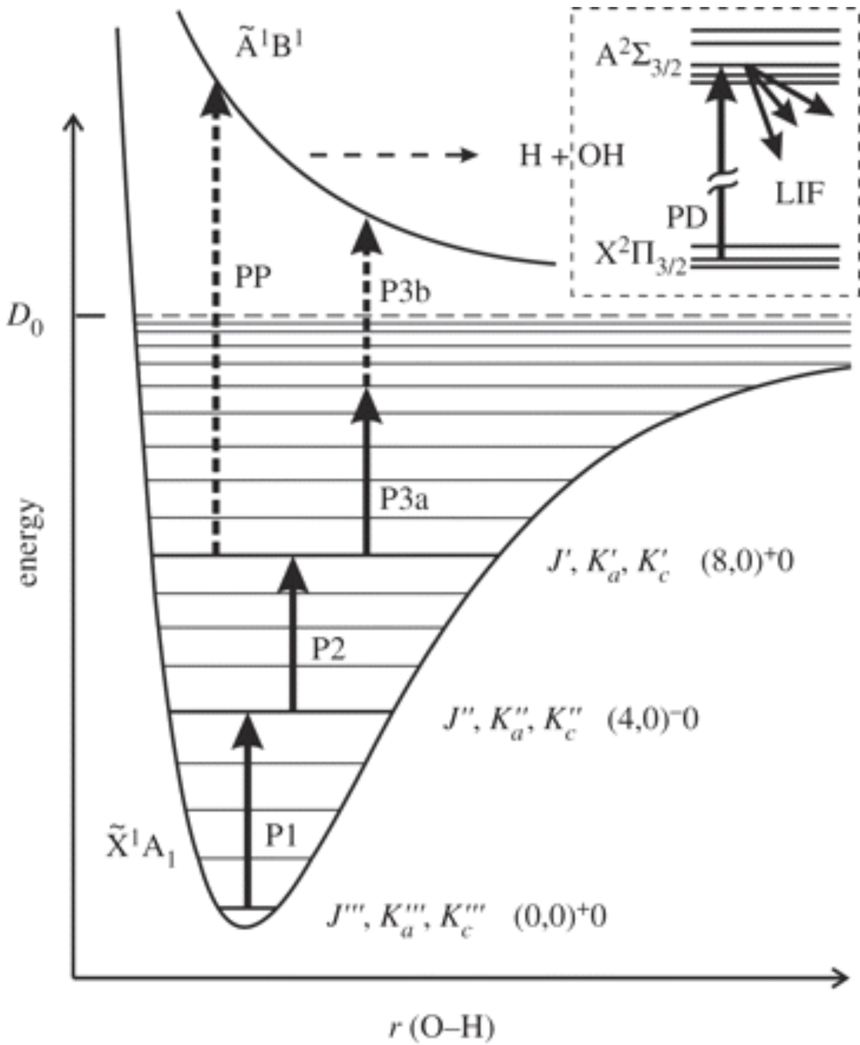
H_2O vibration and rotation

- The water molecule has a very small moment of inertia on rotation which gives rise to rich combined vibrational-rotational spectra in the vapor containing tens of thousands to millions of absorption lines.



http://www1.lsbu.ac.uk/water/water_vibrational_spectrum.html

Energy levels



- Energy-level diagram of double- and triple-resonance vibrational overtone excitation (photons P1–P3a) followed by photodissociation (dashed arrows, photons P3b or PP) and OH fragment

MAKSYUTENKO, Phil. Trans. R. Soc. A (2012) doi:10.1098/rsta.2011.0277

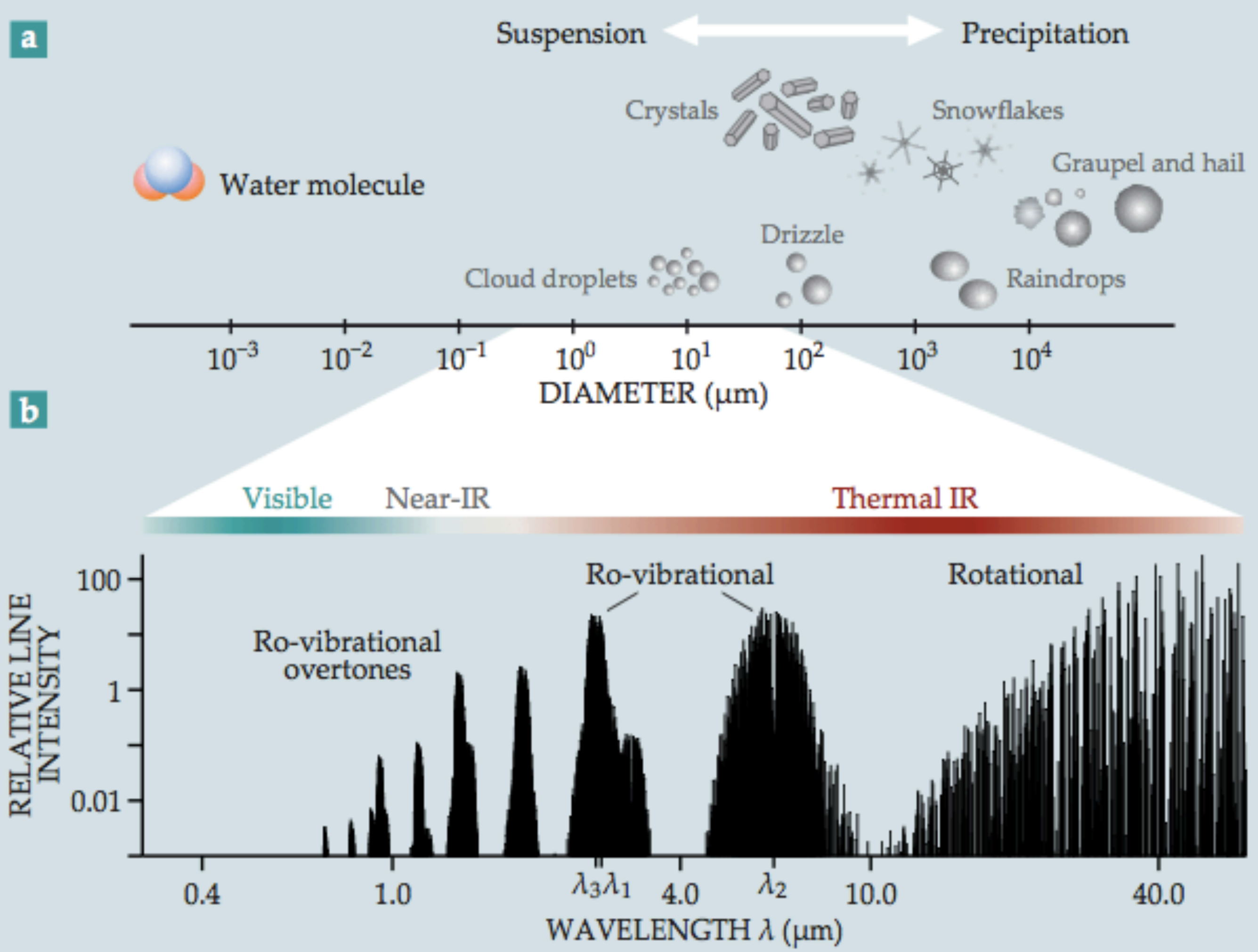


Figure 1. Hydrometeors (a), the condensed forms of water in the atmosphere, come in several sizes. They mostly scatter visible light but absorb over a broad range of the IR. **(b)** The near- and thermal-IR regions of the spectrum excite the molecule and produce its rotational–vibrational (or ro-vibrational) and rotational bands. Specific lines λ_1, λ_2, and λ_3 mark the symmetric stretching mode, bending mode, and asymmetric stretching mode, respectively.

Stevens & Bony, Physics Today 2013

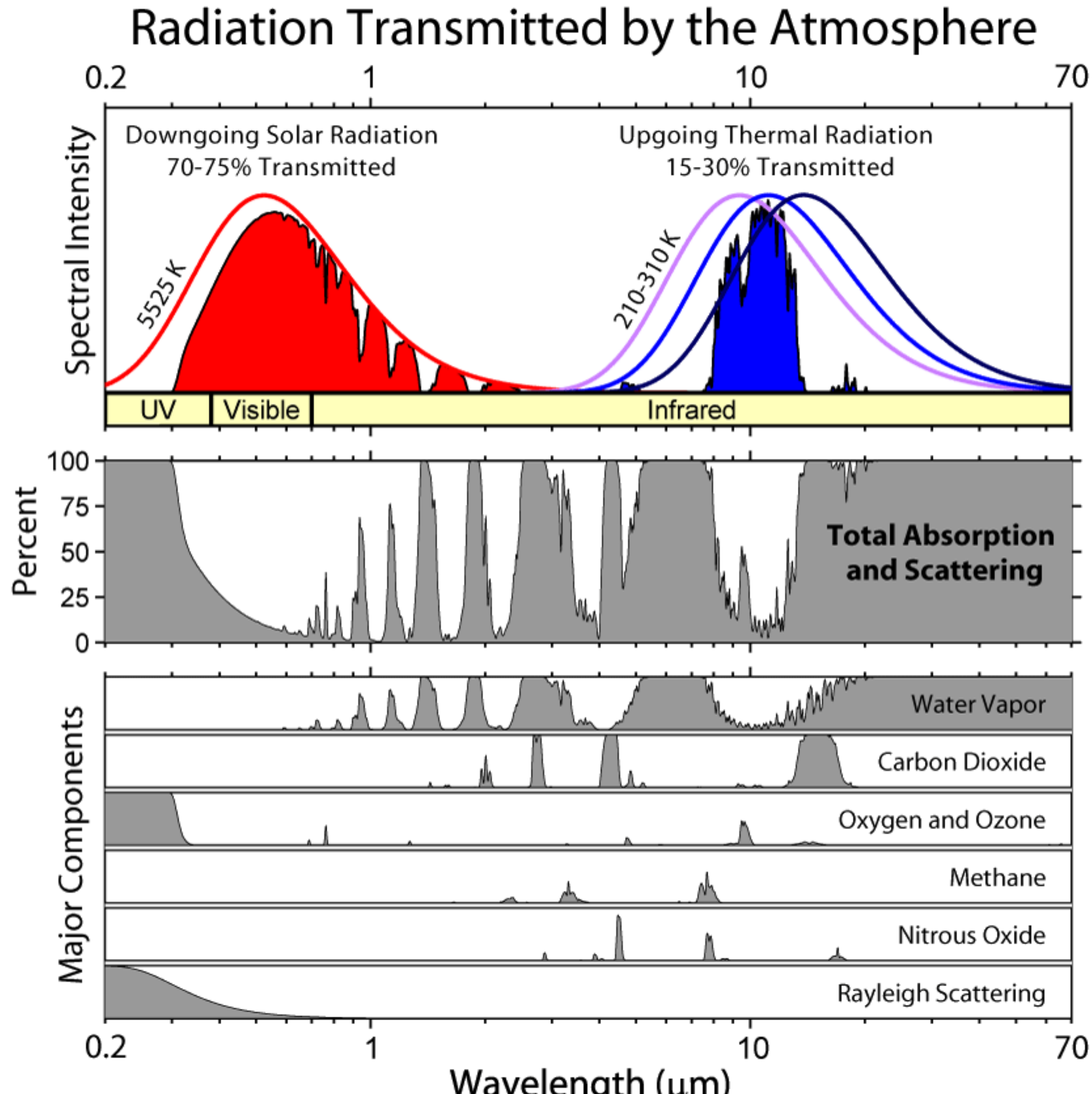
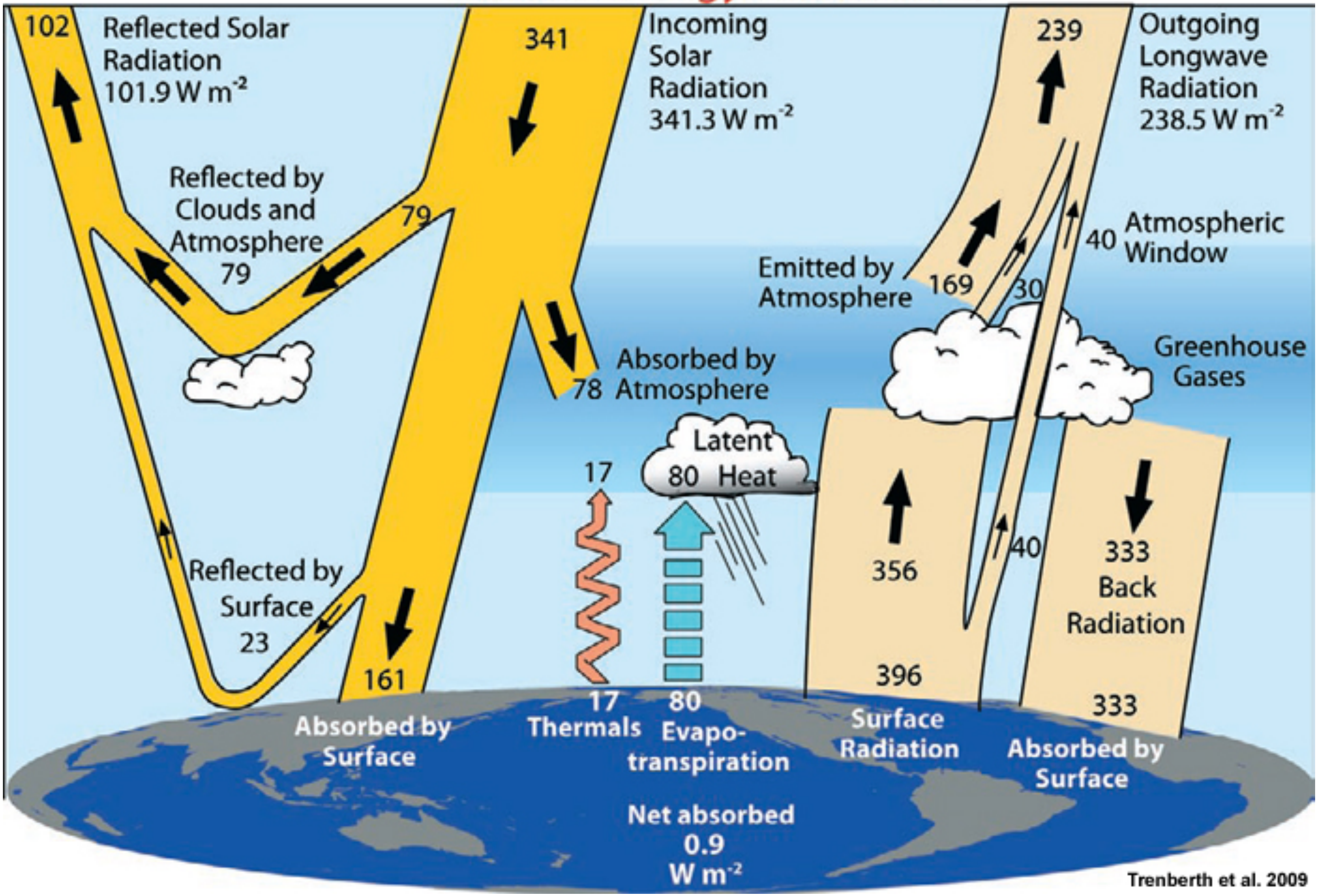


Image by:
Robert A. Rohde
Global Warming Art.

Global Energy Flows W m^{-2}

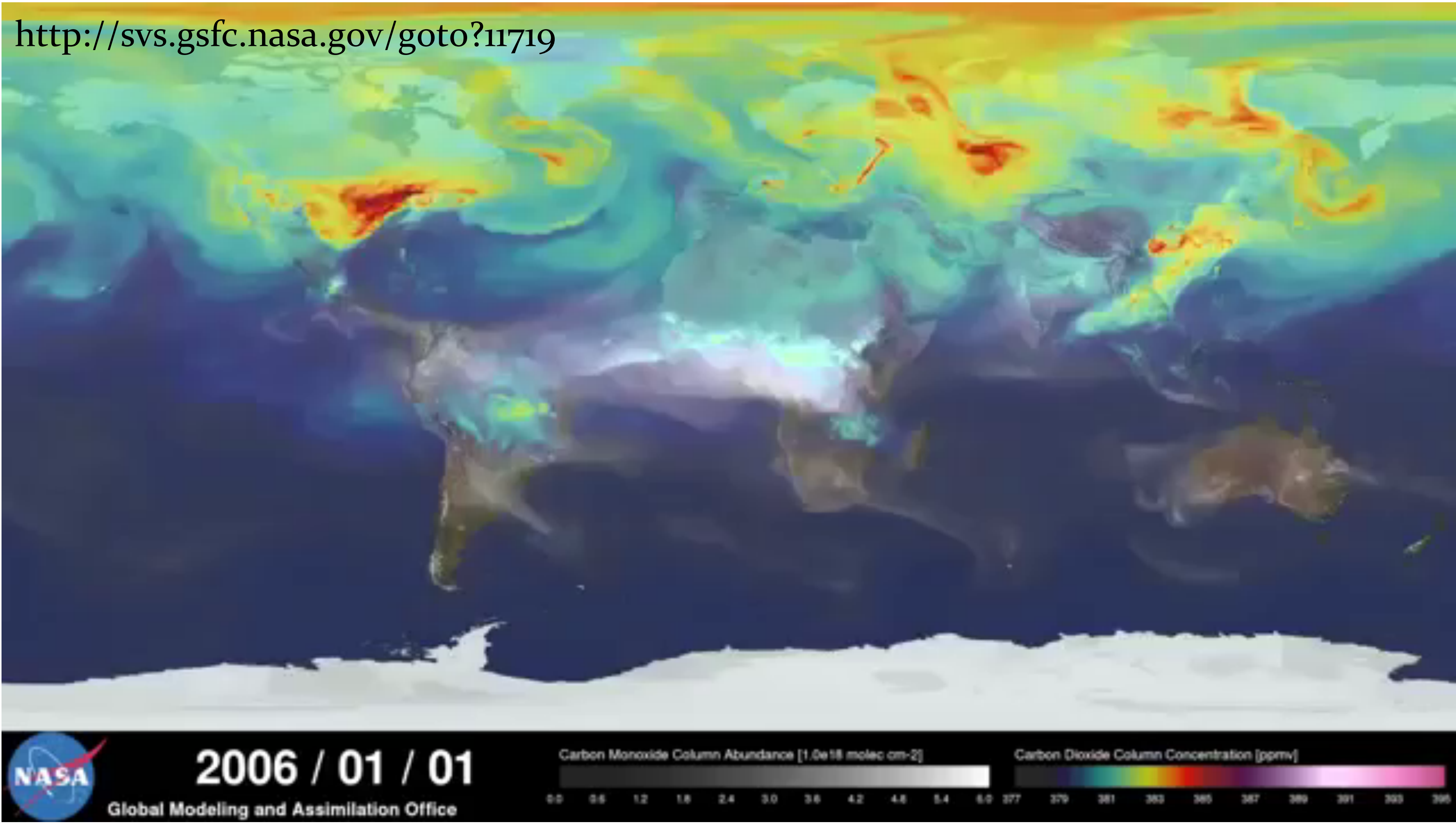


Natural Greenhouse effect

	Radiative efficiency ($W\ m^{-2}/ppb$)	Pre industrial conc.	Natural Greenhouse effect ($W\ m^{-2}$)		Concentration in 2011	Antrop. Forcing ($W\ m^{-2}$)
H_2O			75	**51**		
CO_2	$1.37\ 10^{-5}$	278±2 ppm	32	**24**	390.4±0.2 ppm	1.82
O_3			10	**7**		0.35
CH_4	$3.63\ 10^{-4}$	722±25 ppb	8	**4**	1803.2±1.2 ppb	0.48
N_2O	$3.03\ 10^{-3}$	270±7 ppb			324.3±0.1 pbb	0.17
CF_4	0.1	34.7±0.2 ppt			79.0±0.1 ppt	0.0041
Outros						0.01
Total			125	**86**		2.83

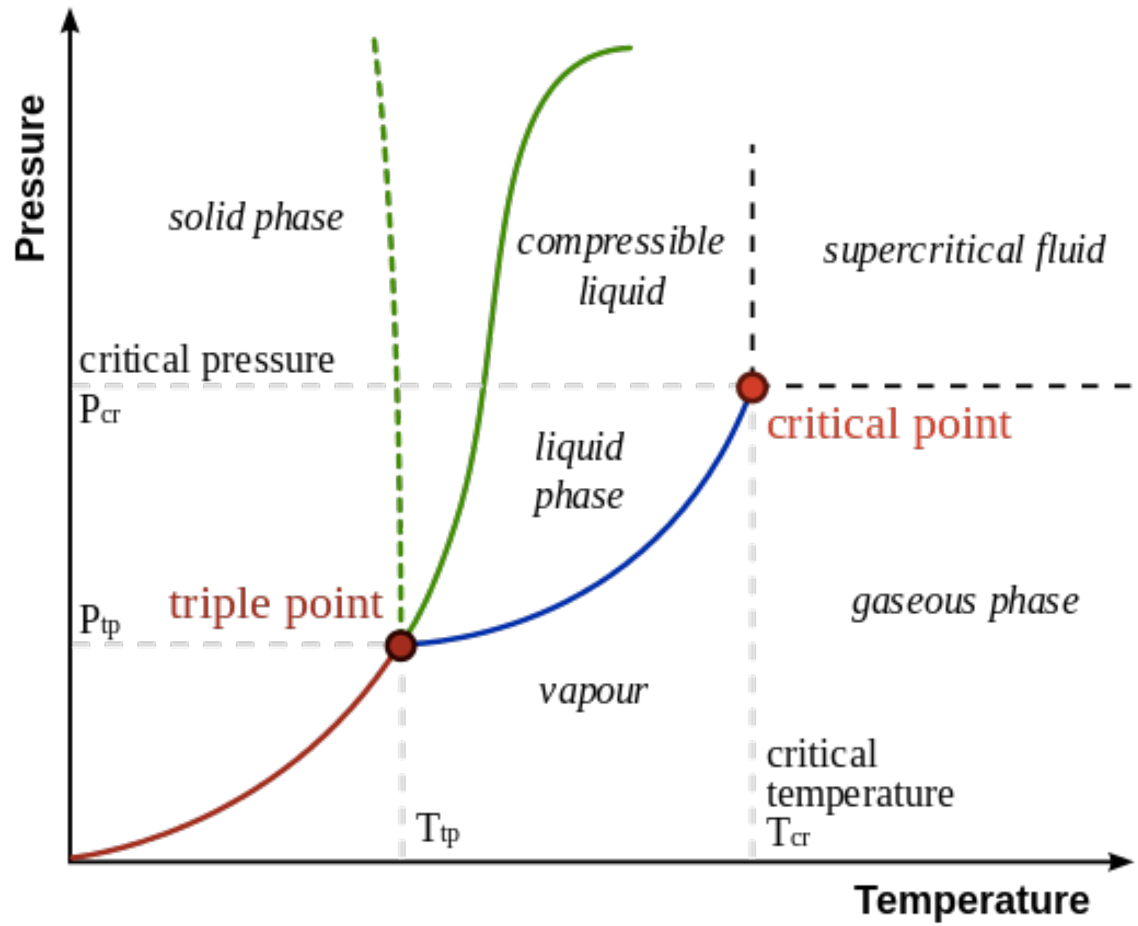
Hartmann et al, IPCC (WG-I) 2013
Kiehl and Trenberth, BAMS, 1997

H_2O is not a forcing because it is not directly emitted as CO_2



Vapor phase diagram

- Vapor refers to a gas phase at a temperature where the same substance can also exist in the liquid or solid state, below the critical temperature of the substance.
- $T_{cr}(H_2O) = 374\ °C$
- $T_{tp}(H_2O)=0.01\ °C$



Water vapor partial pressure

Clausius-Clapeyron:

$$\frac{\mathrm{d}e_s}{\mathrm{d}T} = \frac{L_v(T)e_s}{R_vT^2}$$

Saturation vapor pressure:

$$e_s(T) = 6.1094\exp\left(\frac{17.625T}{T+243.04}\right)$$

http://earthsci.org/processes/weather/weaimages/weaimages.html

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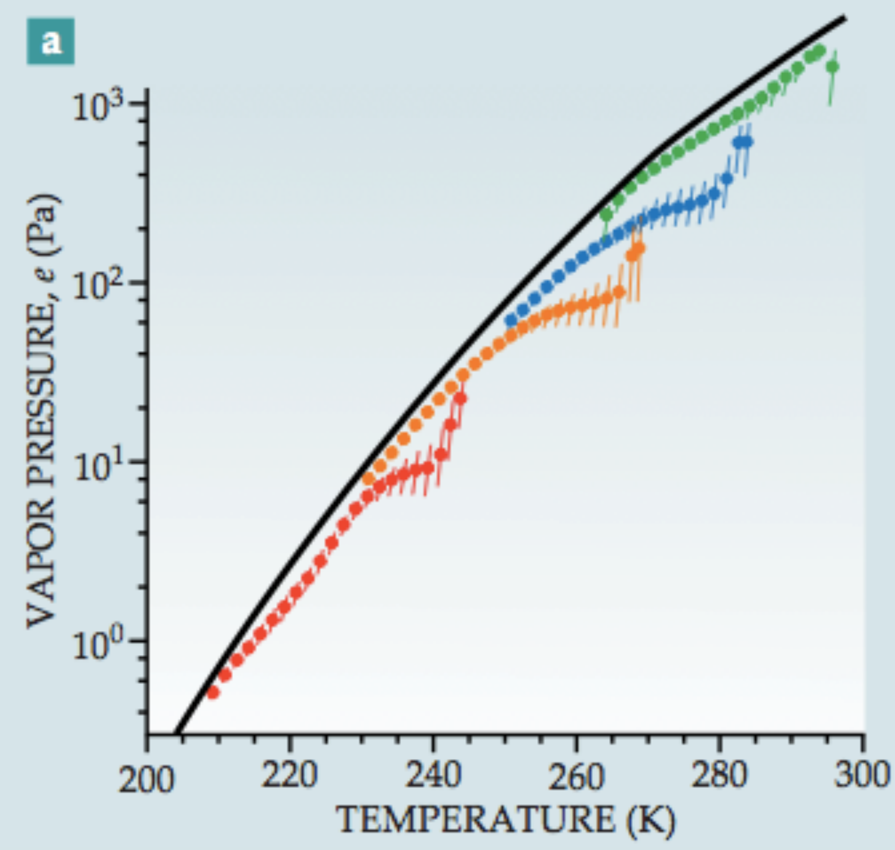
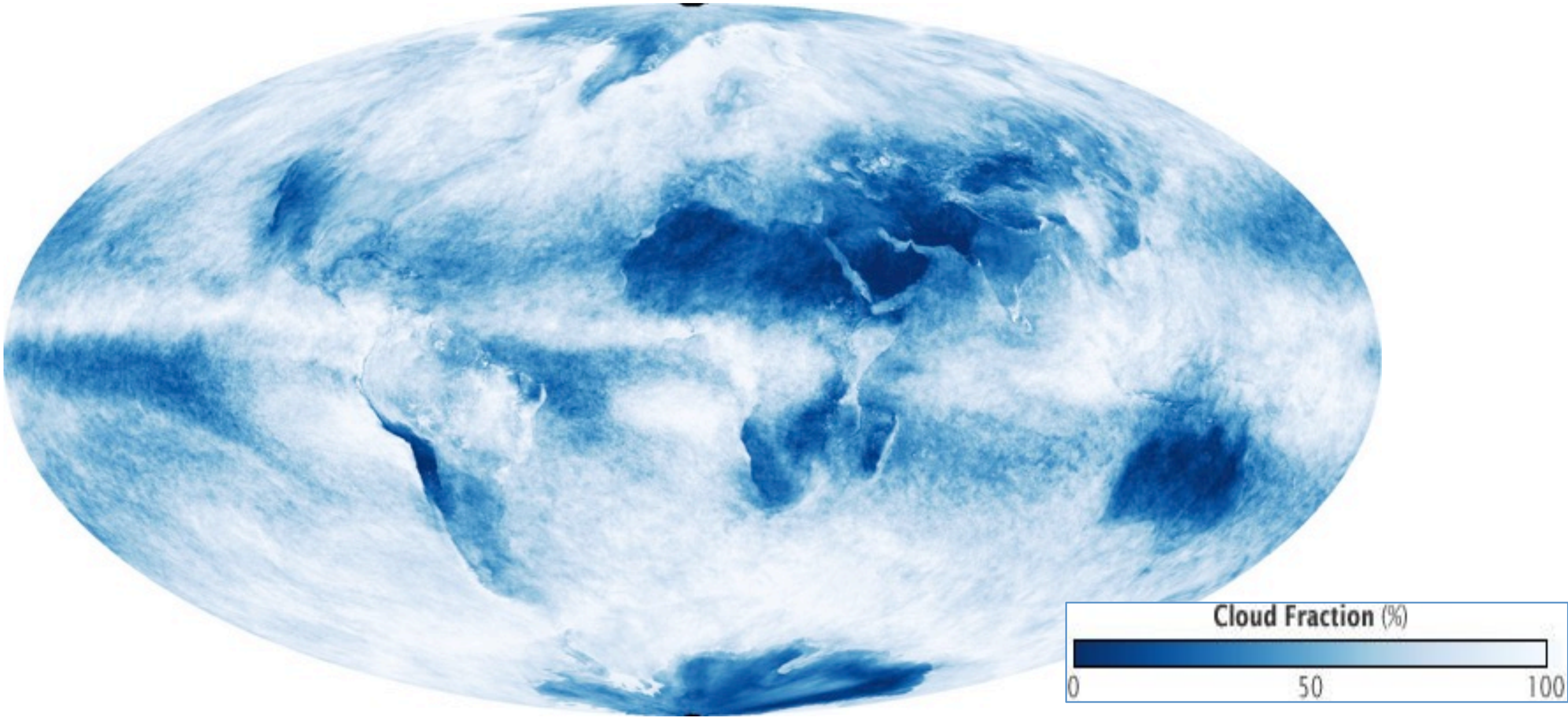


Figure 2. The atmospheric vapor pressure as a function of temperature **(a)** is bounded by the atmosphere's vapor pressure when saturated with water (solid line). The data are shown as the median (dot) and range (error bar) of 228 monthly values at different isobaric levels—900 hPa (green), 700 hPa (blue), 500 hPa (orange), and 300 hPa (red). (Data are provided by the European Centre for Medium-Range Weather Forecasts.) **(b)** Based on satellite measure-

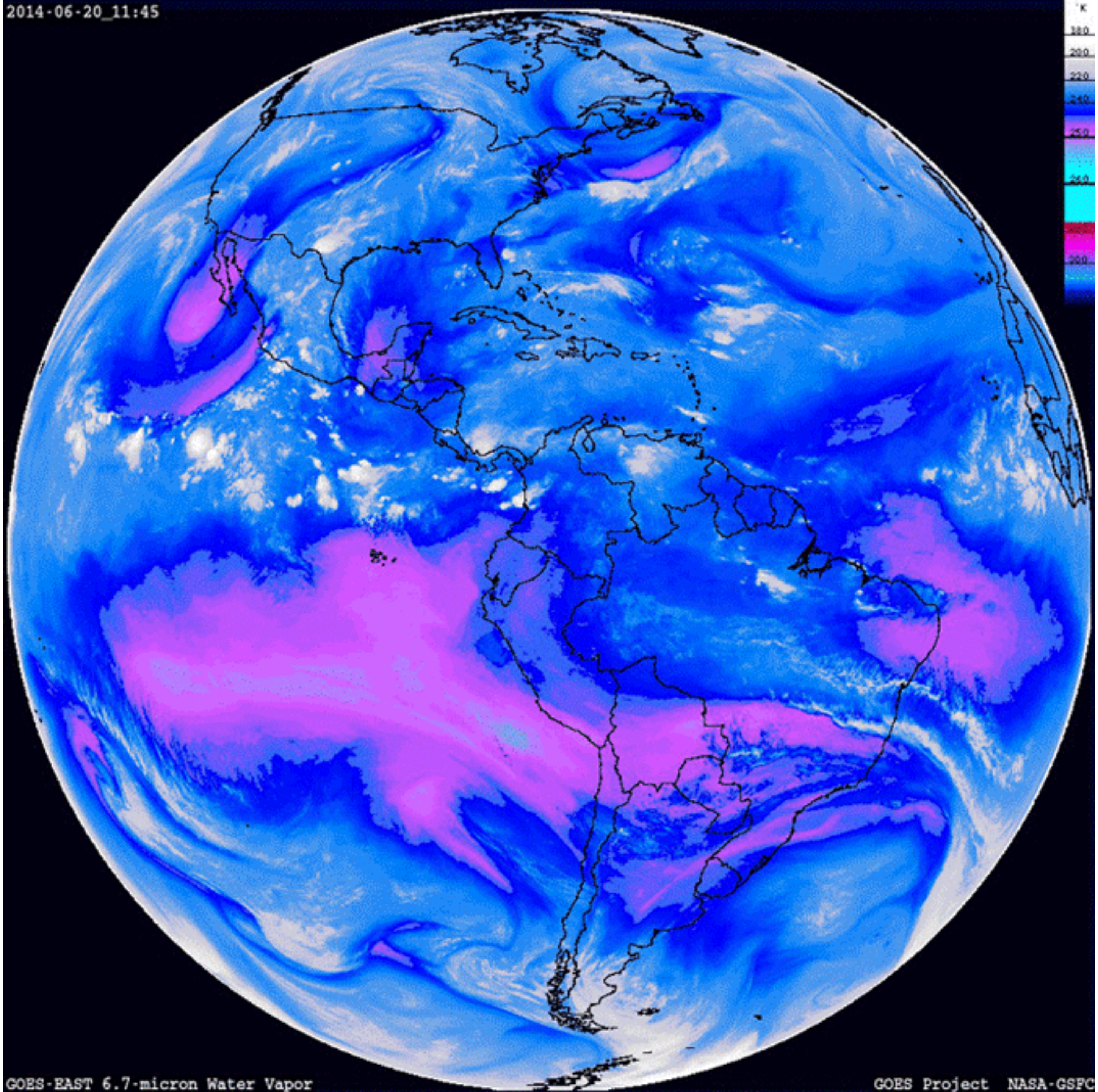
Stevens & Bony, Physics Today 2013

http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MODAL2_M_CLD_FR



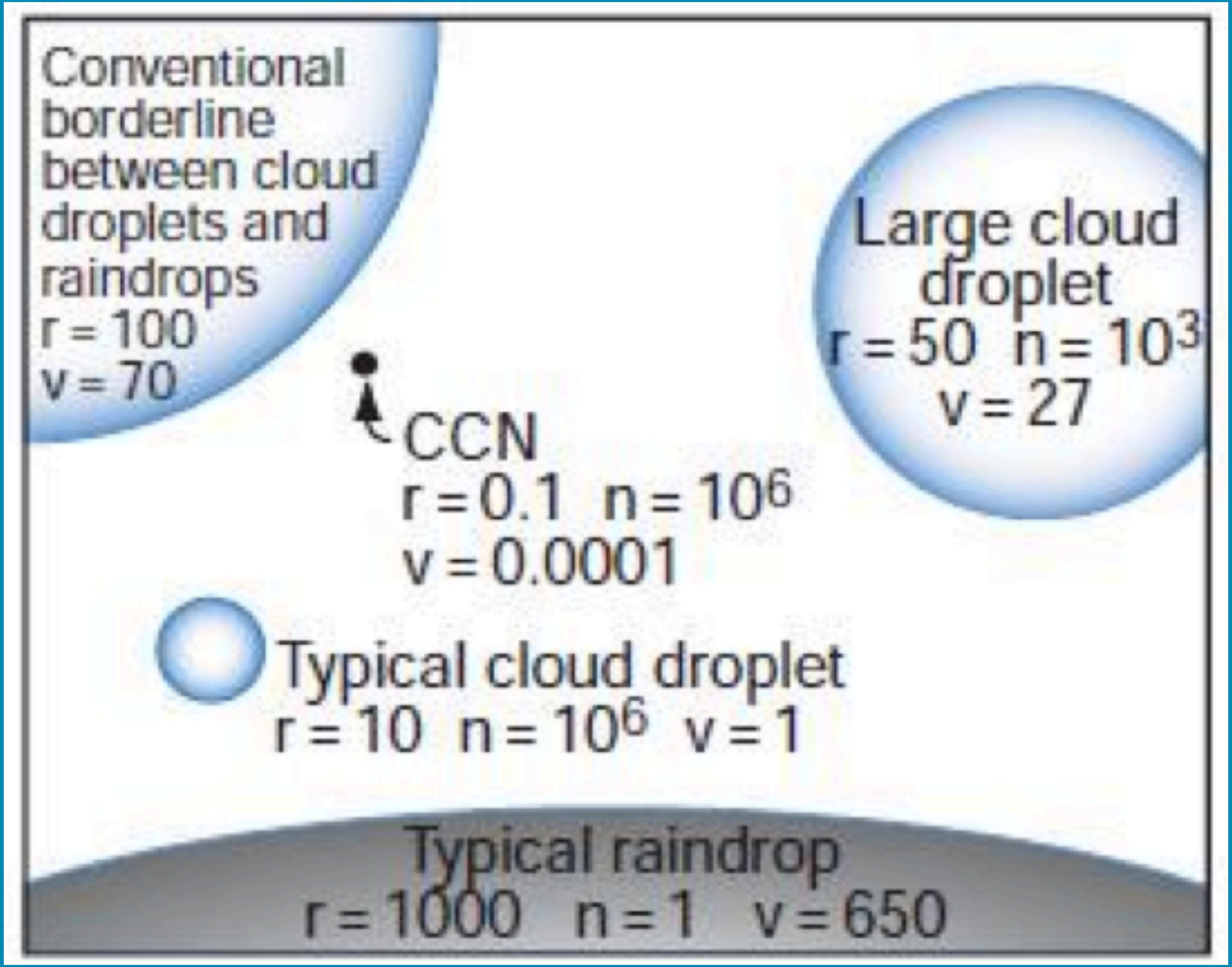
	Cloud density			
	Thin	Thick	Opaque	
Cloud level	$N\varepsilon < 0.5$	$0.5 < N\varepsilon < 0.95$	$N\varepsilon > 0.95$	All densities
	$\sigma_{vis} < 1.4$	$1.4 < \sigma_{vis} < 6$	$\sigma_{vis} > 6$	
High (<440 mb)	15%	15%	3%	33%
Middle (440–700 hPa)	7%	10%	9%	26%
Low (>700 hPa)		2%	47%	49%
Total	20%	23%	32%	75%

NOAA HIRS 1979-2001, Wylie et al, J. Clim. 2005 http://www.nasa.gov/content/goddard/a-new-view-nasanoaa-water-vapor-animations-over-oceans

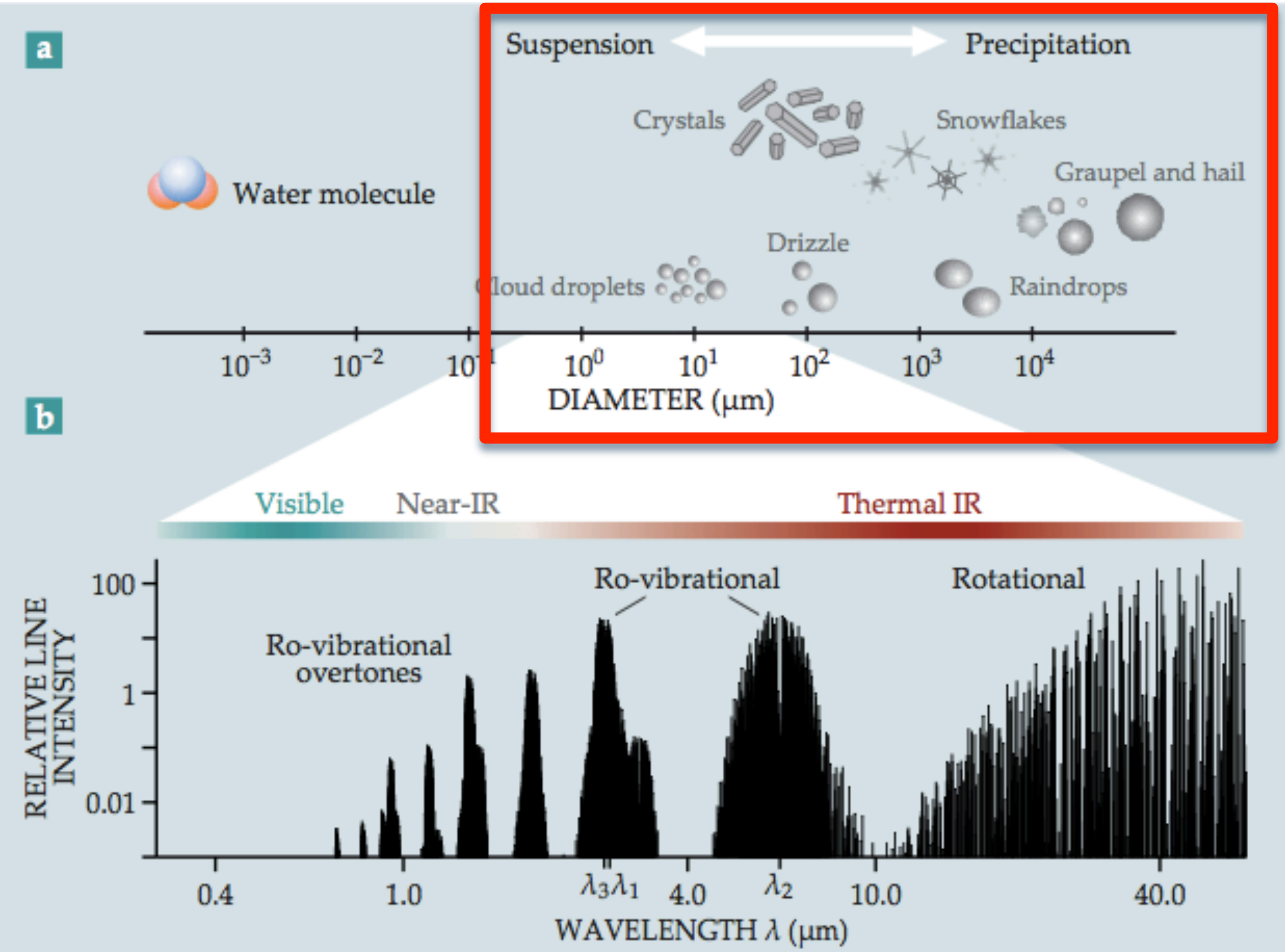


CPTEC - INPE

6 orders of magnitude in volume



Clouds (liq/ice) strongly interact with SW and LW radiation



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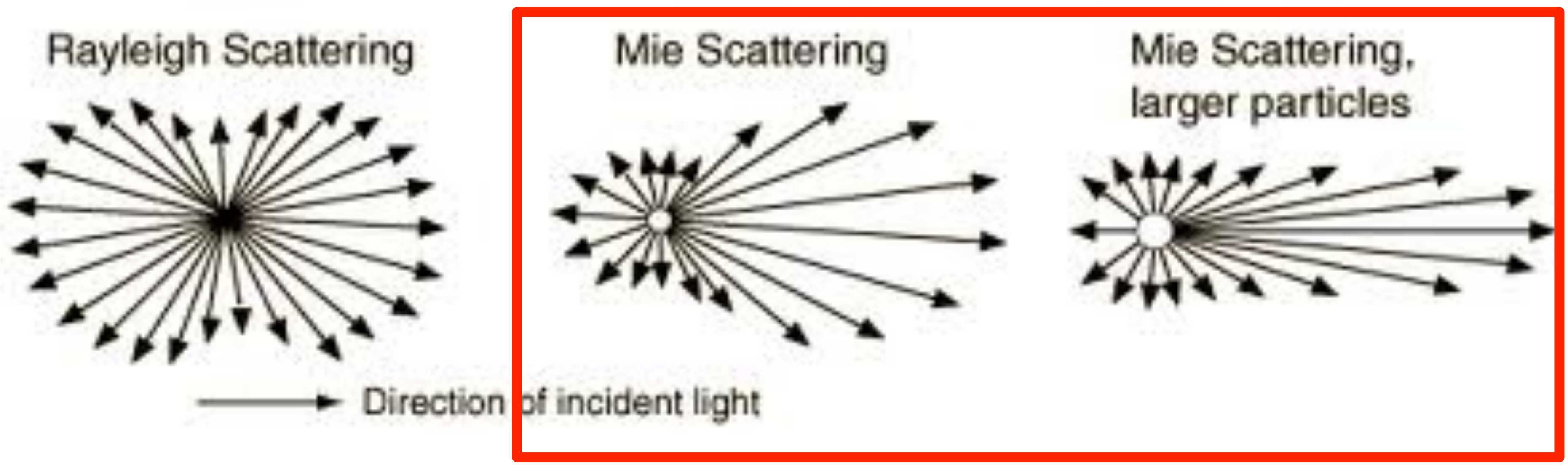
Stevens & Bony, Physics Today 2013

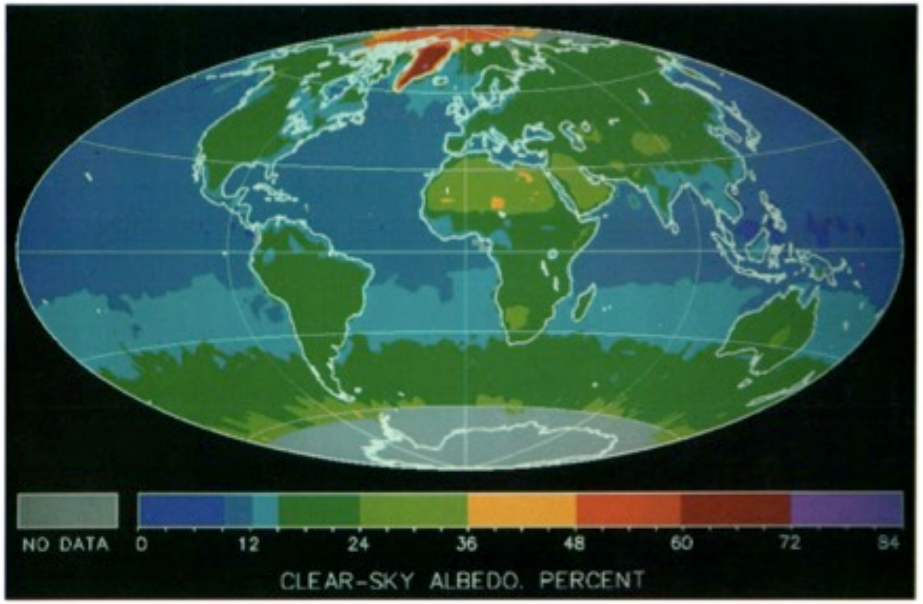
Particles are very complicated

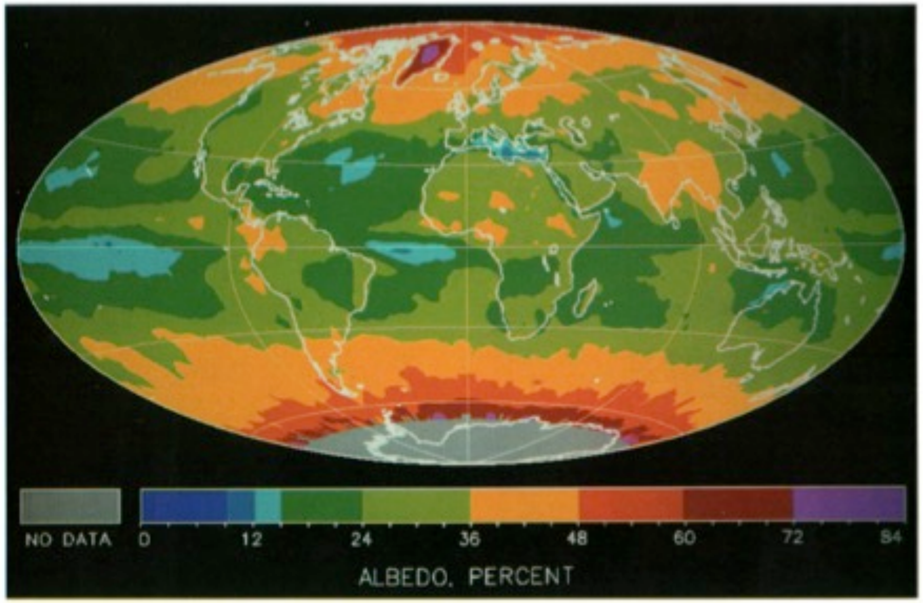
- Classical electromagnetism
  - Rayleigh scattering - molecules
  - Mie scattering – aerosol and droplets



Size << λ **Size ≈ λ** **Size > λ**

Effects on SW radiation



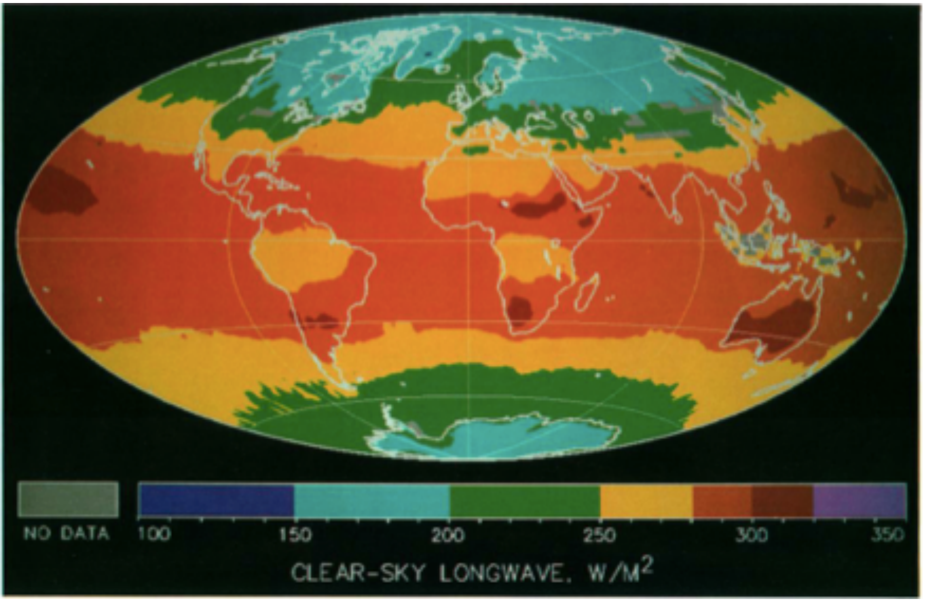


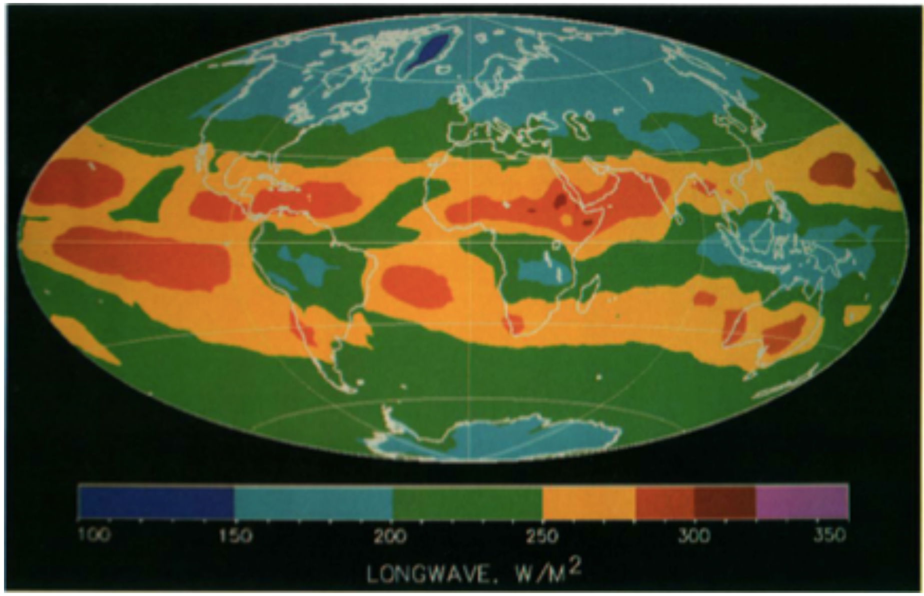
Harrison et al, JGR 1990

TABLE 1. Summary of Cloud Radiative Forcing Parameters (W/m^2)

Date	Longwave	Clear-Sky Longwave	Longwave Cloud Forcing	Shortwave Absorbed	Clear-Sky Shortwave Absorbed	Shortwave Cloud Forcing	Net Cloud Forcing
April 1985	234.5	265.8	31.3	236.5	281.6	−45.1	−13.8
July 1985	237.5	267.6	30.1	234.4	281.1	−46.7	−16.6
Oct. 1985	234.1	266.3	32.2	243.0	293.1	−50.1	−17.9
Jan. 1986	231.9	262.5	30.6	243.3	295.0	−51.7	−21.1
Annual	234.5	265.6	31.1	239.3	287.7	−48.4	−17.3

Effects on LW radiation





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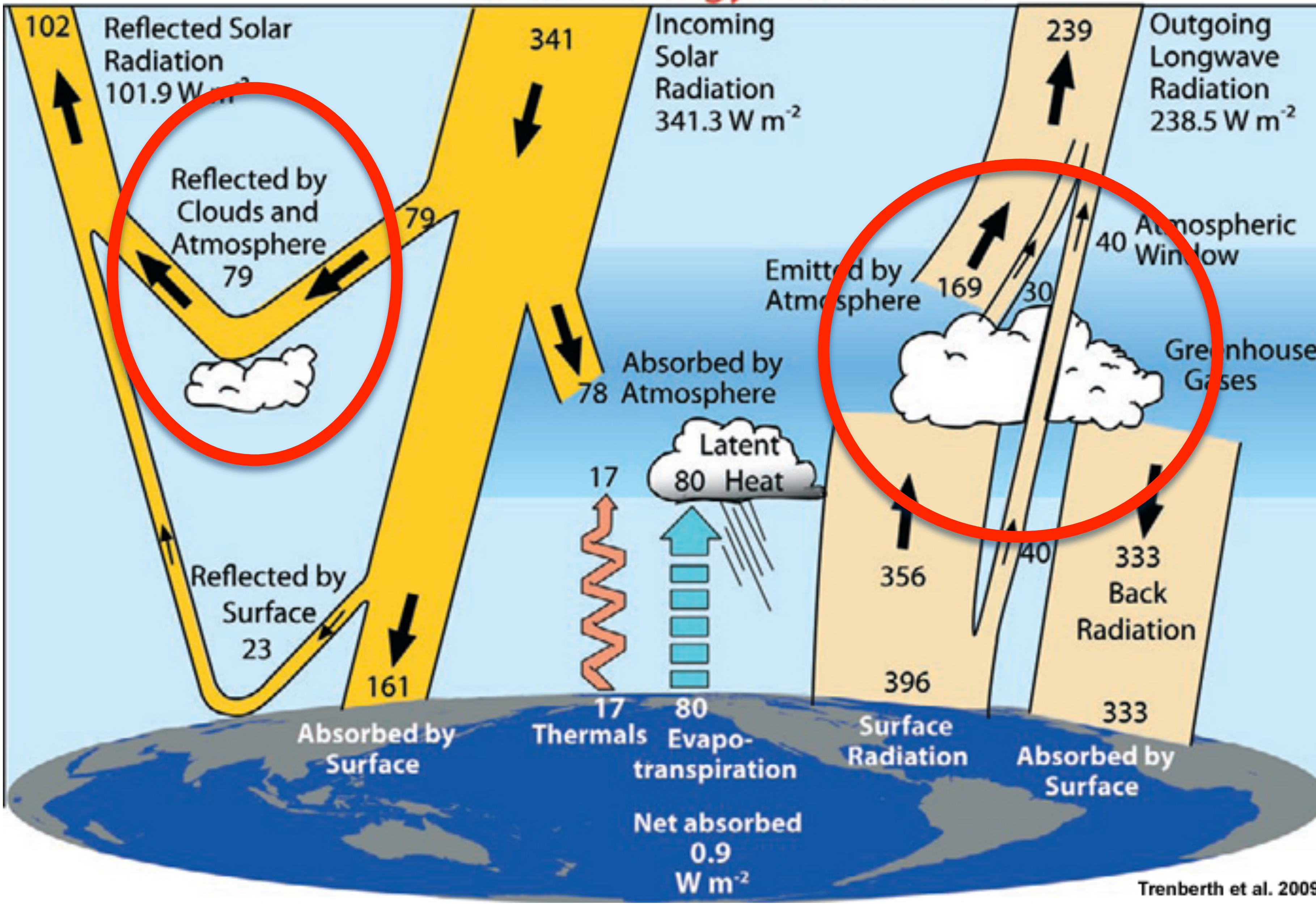
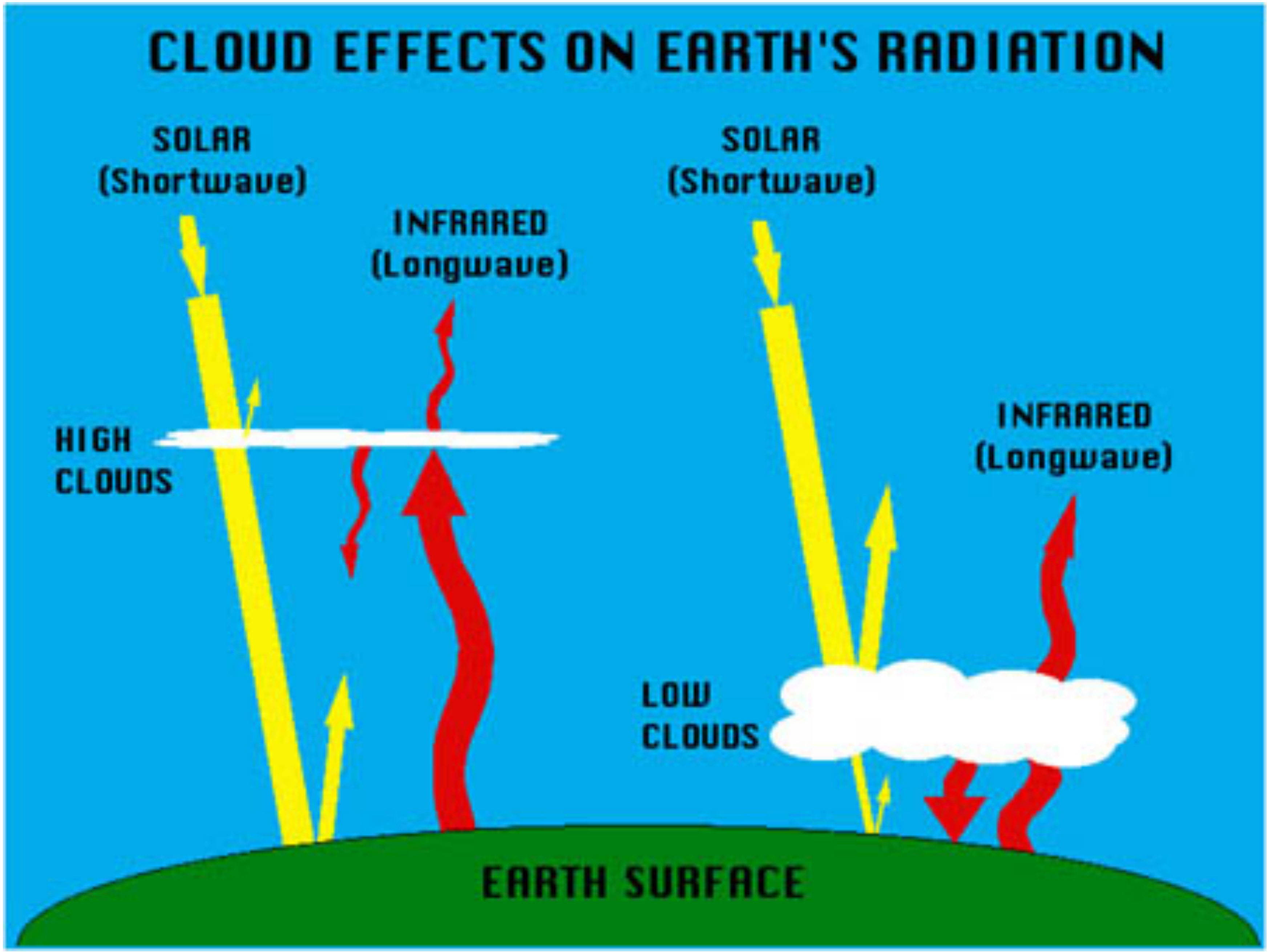
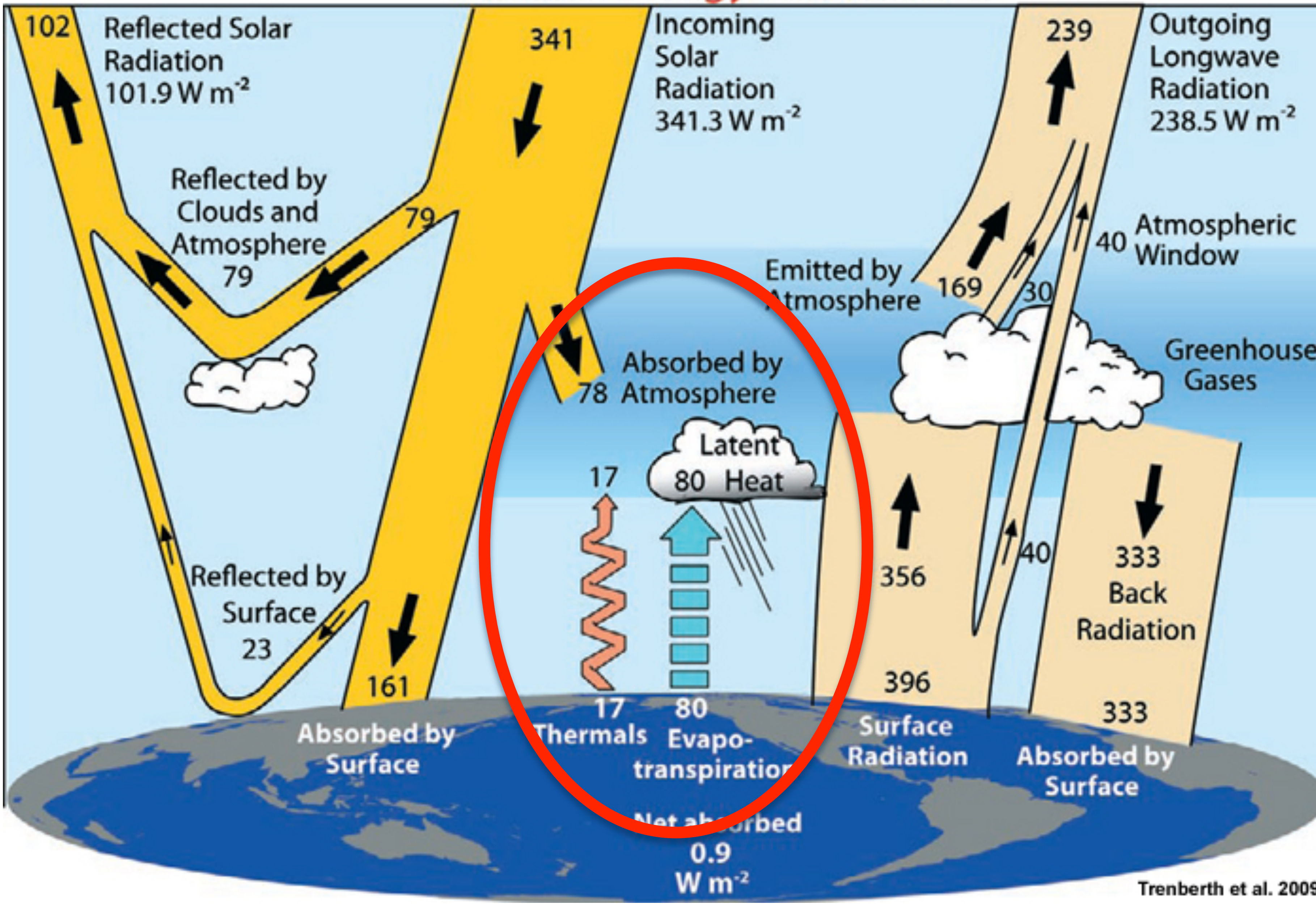
Global Energy Flows W m⁻²

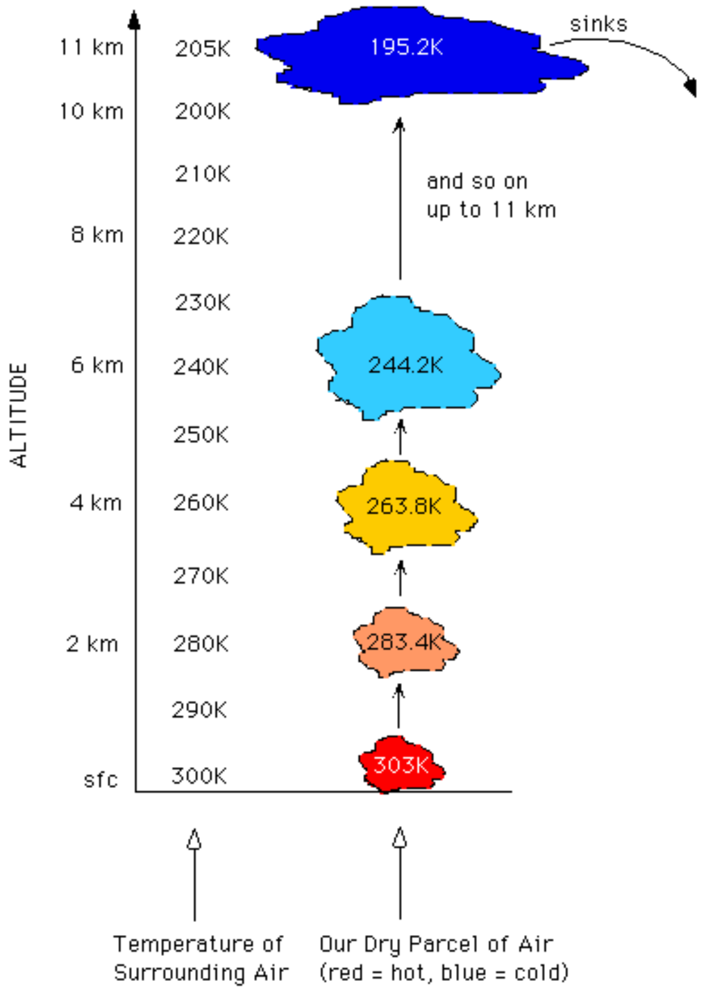


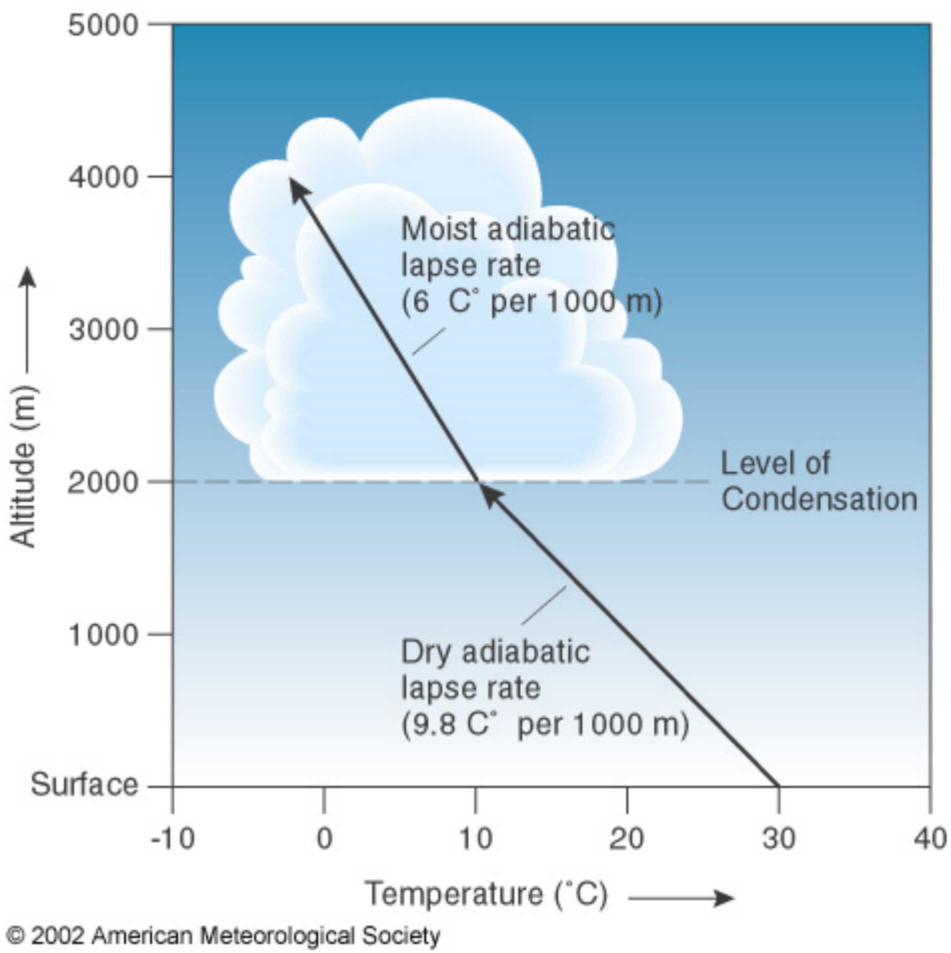

CLOUD EFFECTS ON EARTH'S RADIATION
SOLAR
(Shortwave)
INFRARED
(Longwave)
HIGH
CLOUDS
SOLAR
(Shortwave)
INFRARED
(Longwave)
LOW
CLOUDS
EARTH SURFACE

Global Energy Flows W m^{-2}

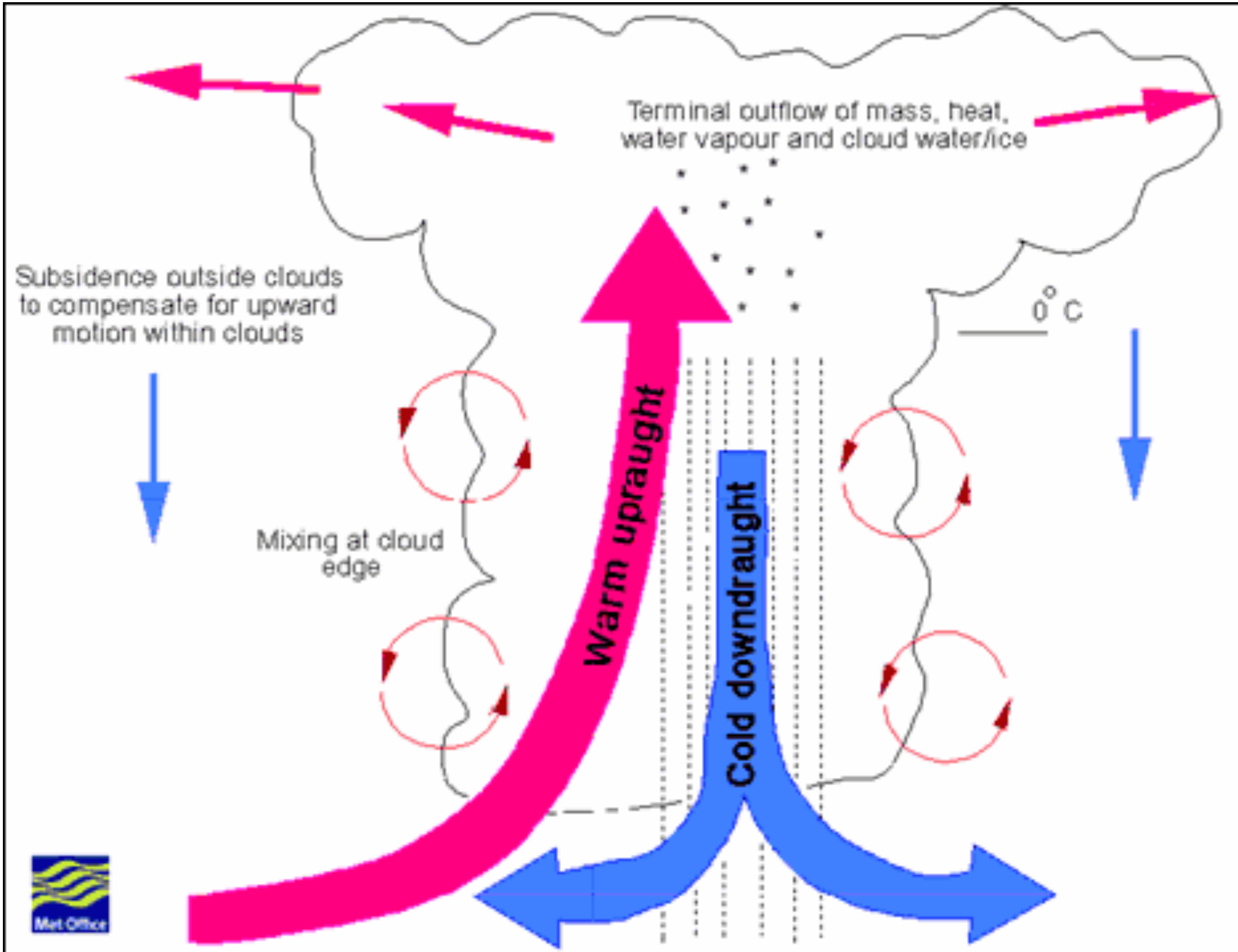


Heat Exchange





Lawrence Berkeley National Laboratory.


Terminal outflow of mass, heat, water vapour and cloud water/ice
Subsidence outside clouds to compensate for upward motion within clouds
0° C
Warm upraught
Cold downdraught
Mixing at cloud edge
Met Office

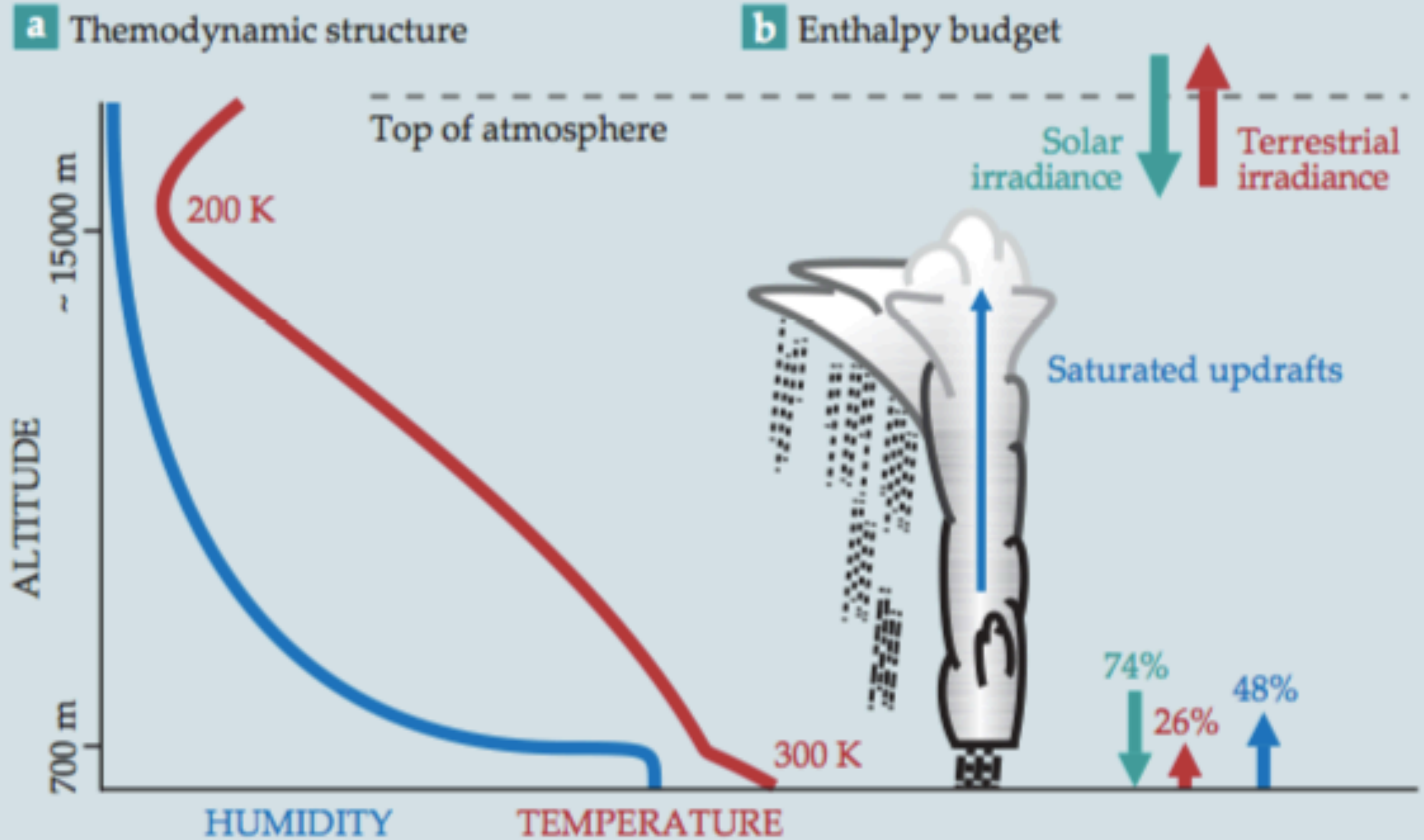


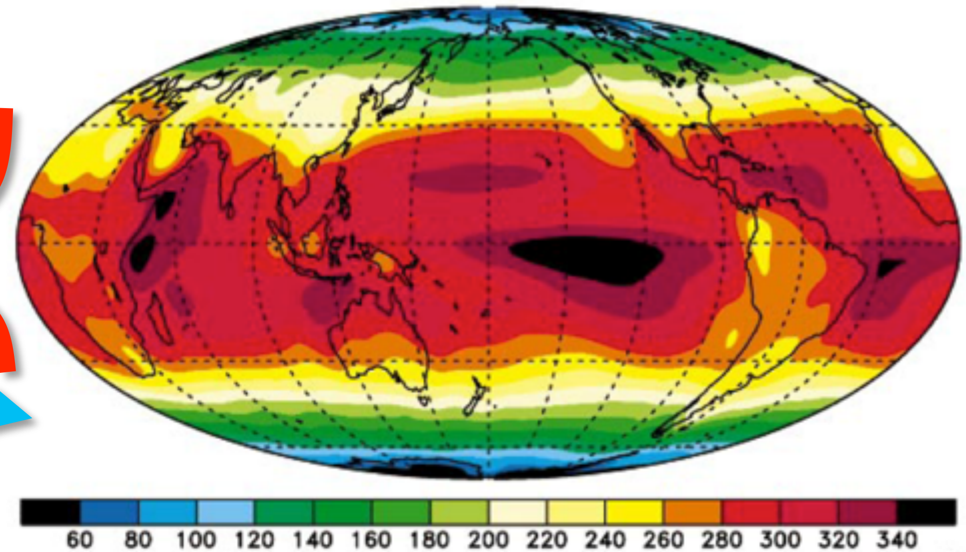
Figure 3. The thermodynamic structure and enthalpy budget of the atmosphere. **(a)** The atmosphere's temperature (red) and its absolute humidity (blue) are closely coupled. **(b)** At the top of the atmosphere solar and terrestrial irradiances balance one another. According to calculations, most (74%) of the incoming solar irradiance reaches the surface, but the net terrestrial irradiance at the surface is only a small fraction (26%) of its value at the top of the atmosphere. The radiative deficit (48%) is balanced by surface turbulent fluxes of enthalpy, arising mostly from evaporation, that transport warm water vapor from the surface to the troposphere, where it cools and condenses.

Stevens & Bony, Physics Today 2013

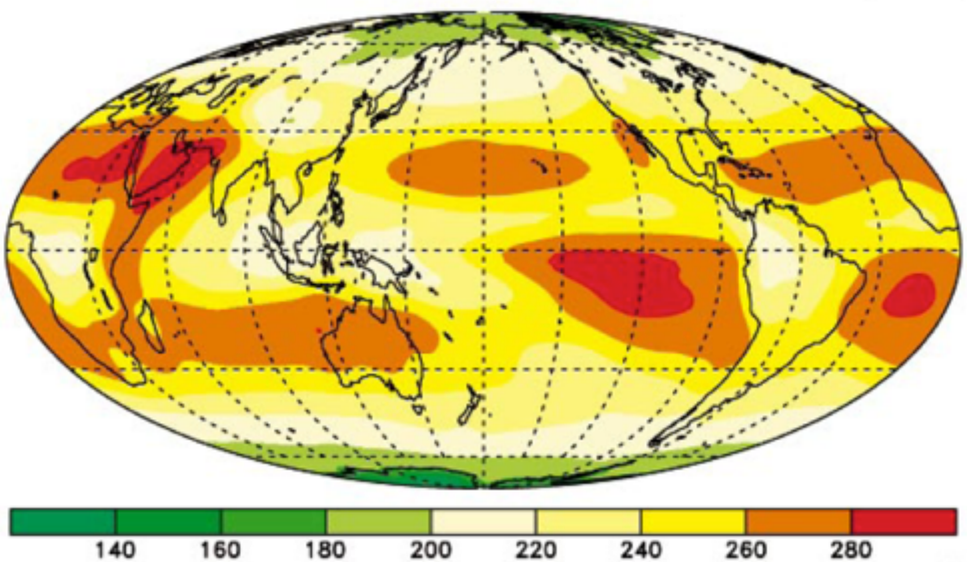
Distribution on the Earth

Hot air rises at the equator

Cold dry air decendes at high latitudes

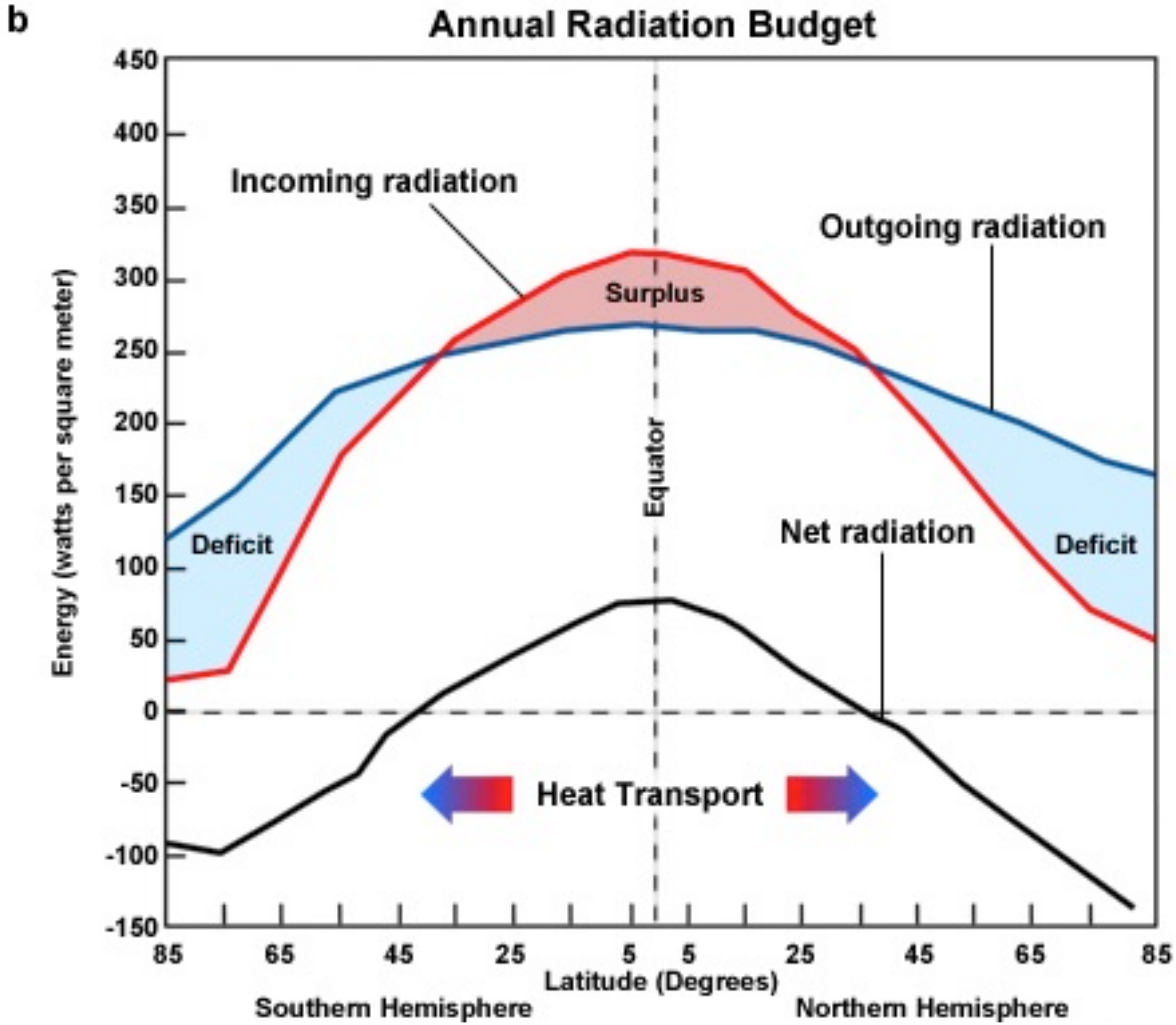


Annual mean solar radiation budget at top (W/m2)

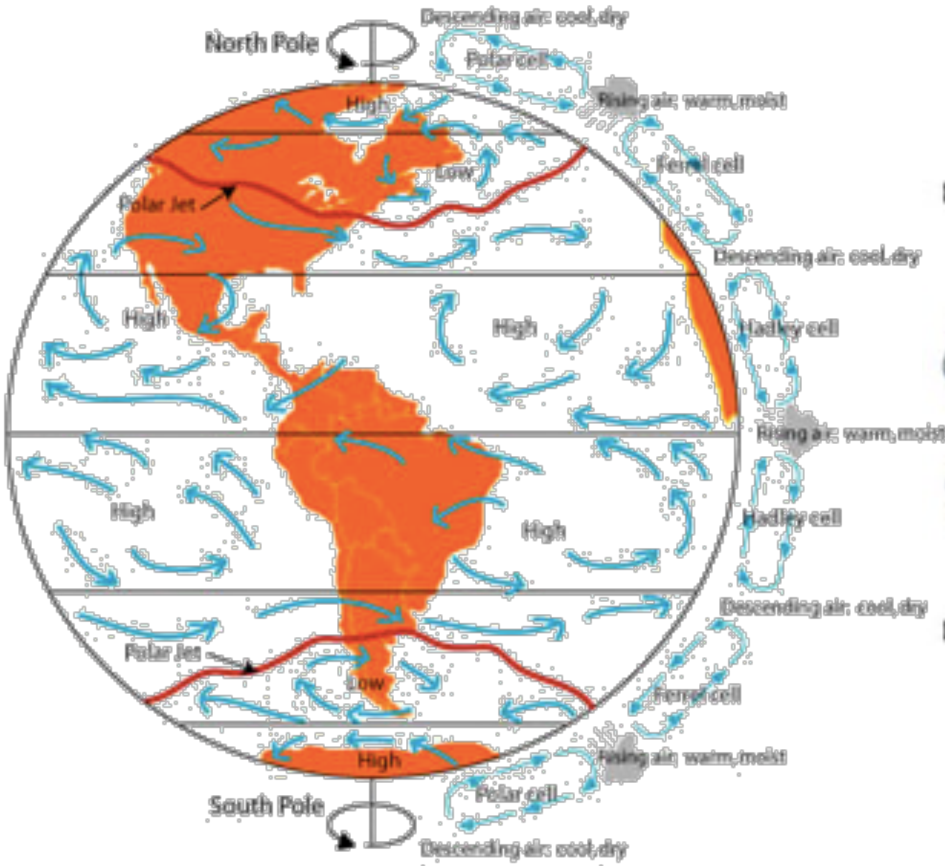


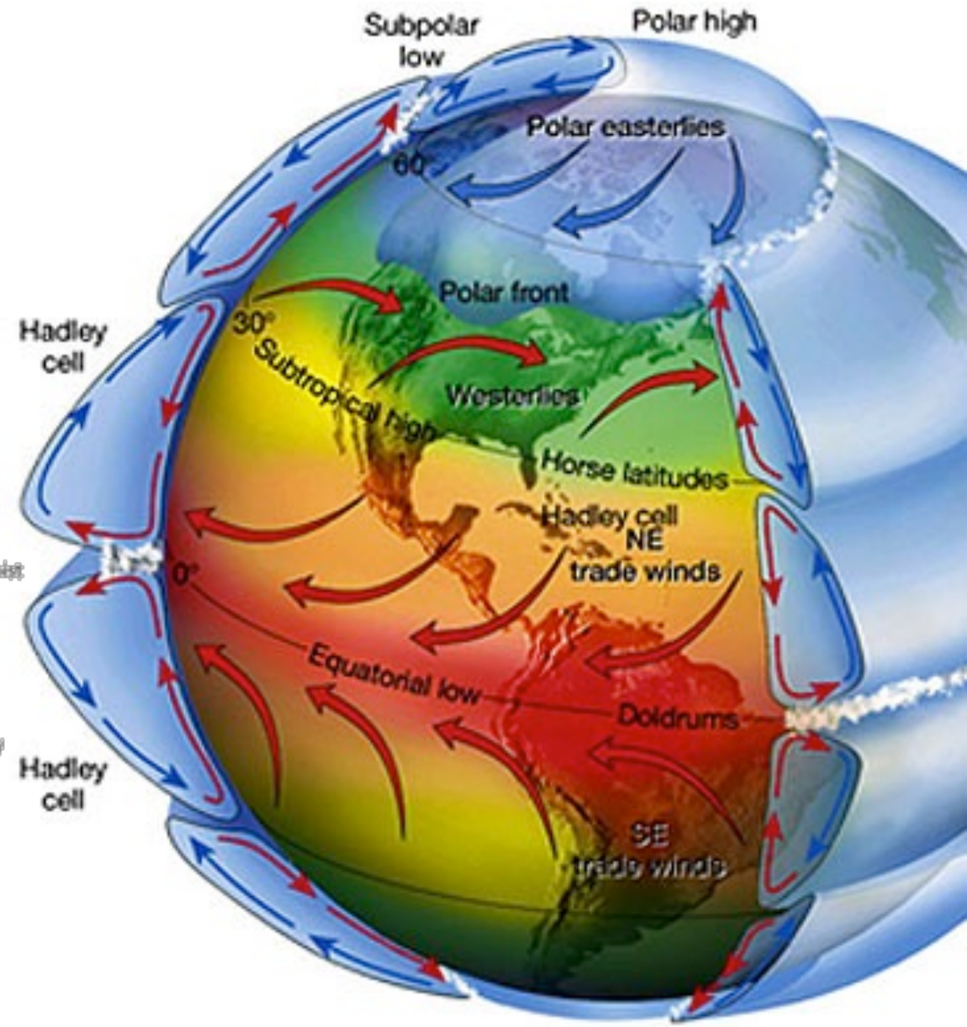
Annual mean outgoing long wave radiation at top (W/m2)

Trenberth and Stepaniak, J. Clim. (2003)

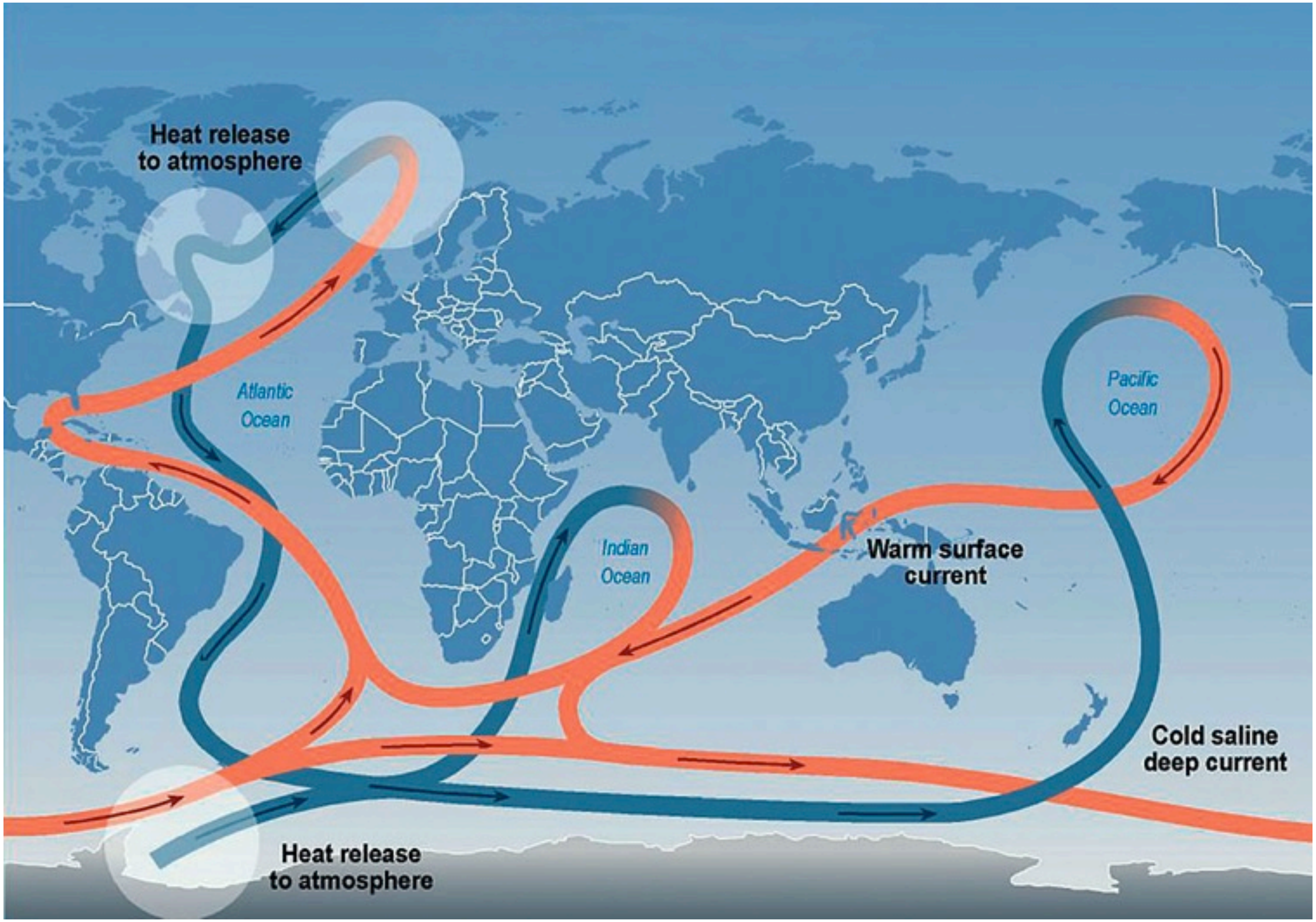

b
Annual Radiation Budget
Incoming radiation
Outgoing radiation
Surplus
Deficit
Deficit
Equator
Net radiation
Heat Transport
Energy (watts per square meter)
450
400
350
300
250
200
150
100
50
0
-50
-100
-150
85
65
45
25
5
5
25
45
65
85
Latitude (Degrees)
Southern Hemisphere
Northern Hemisphere

Atmospheric and Oceanic circulation

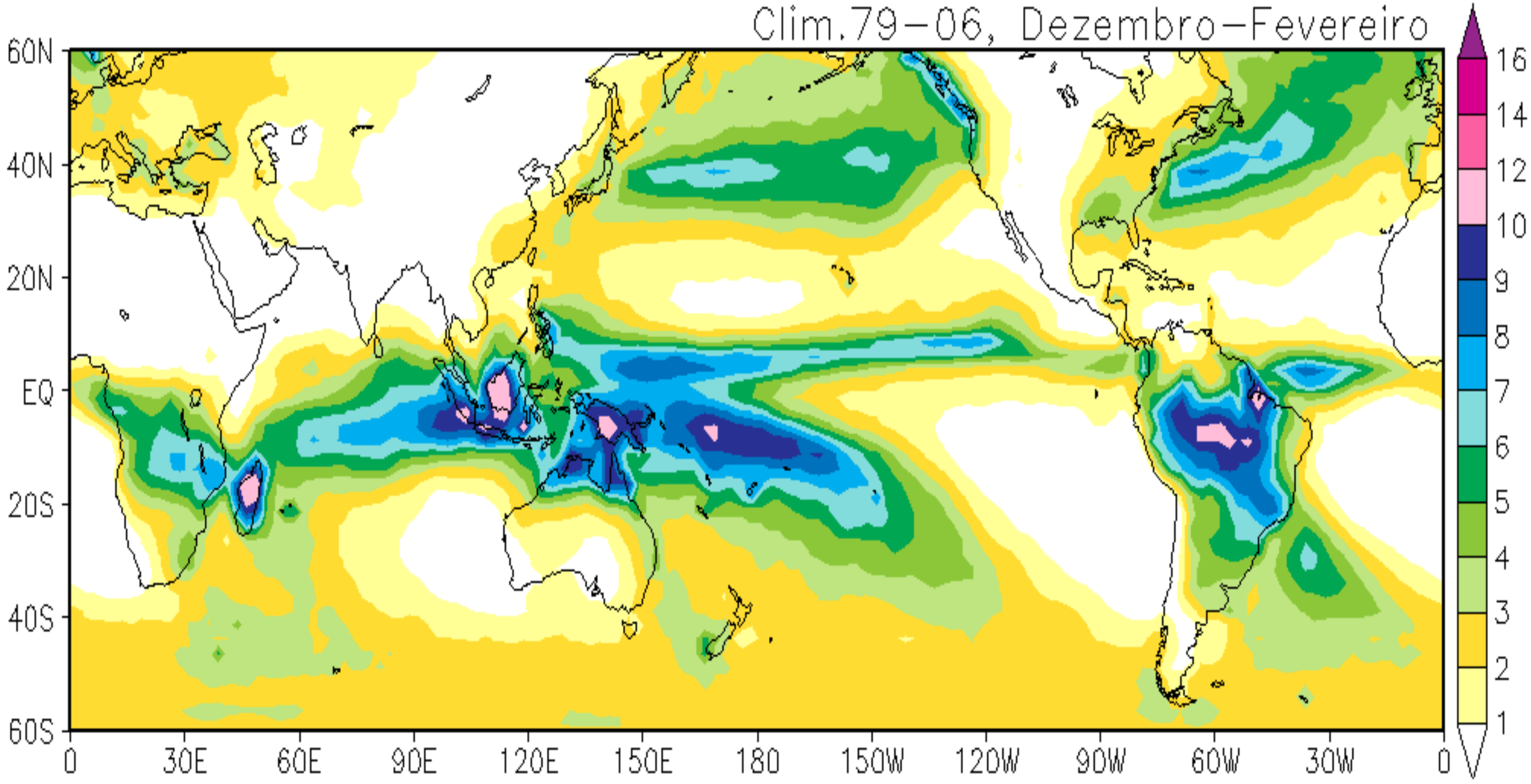


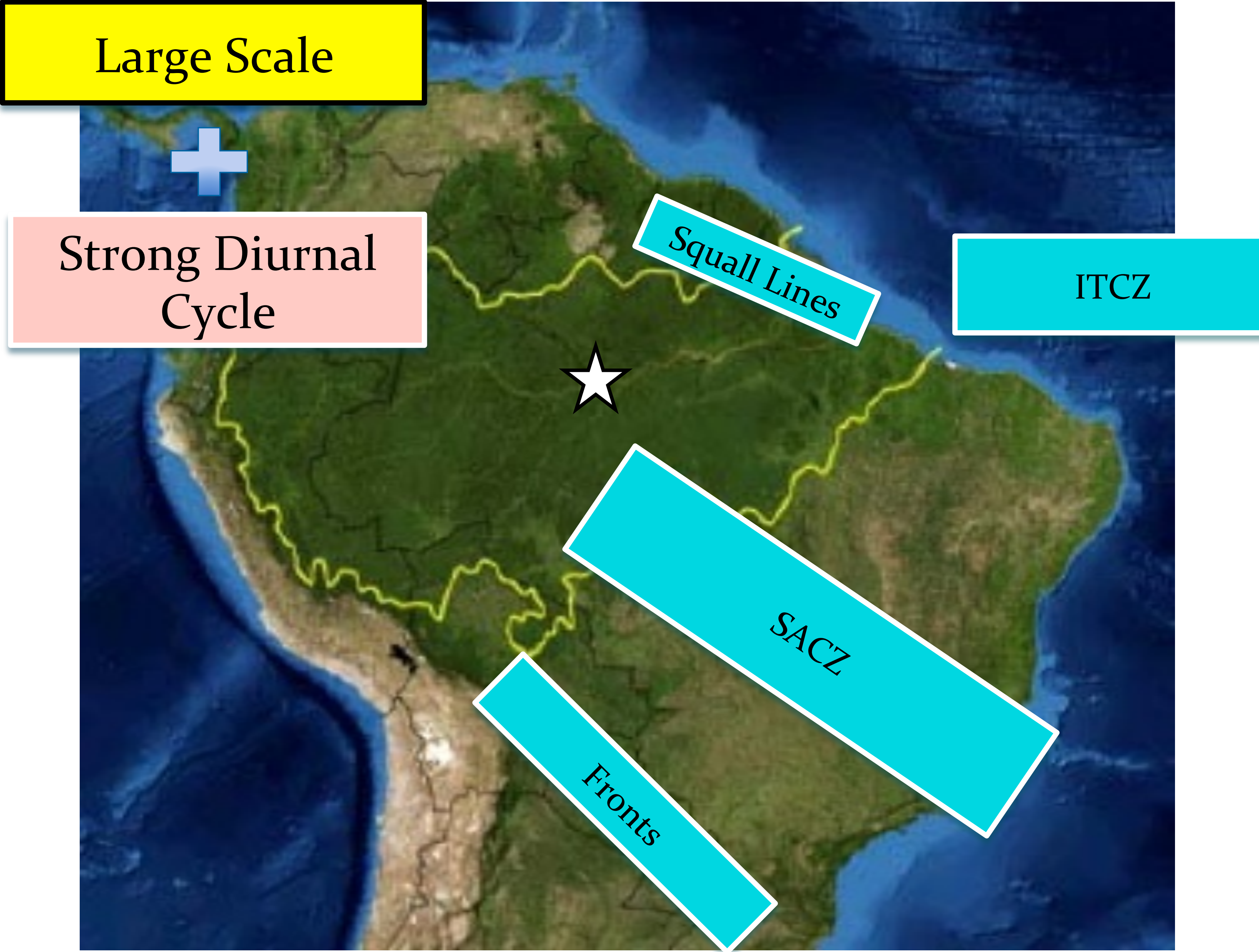


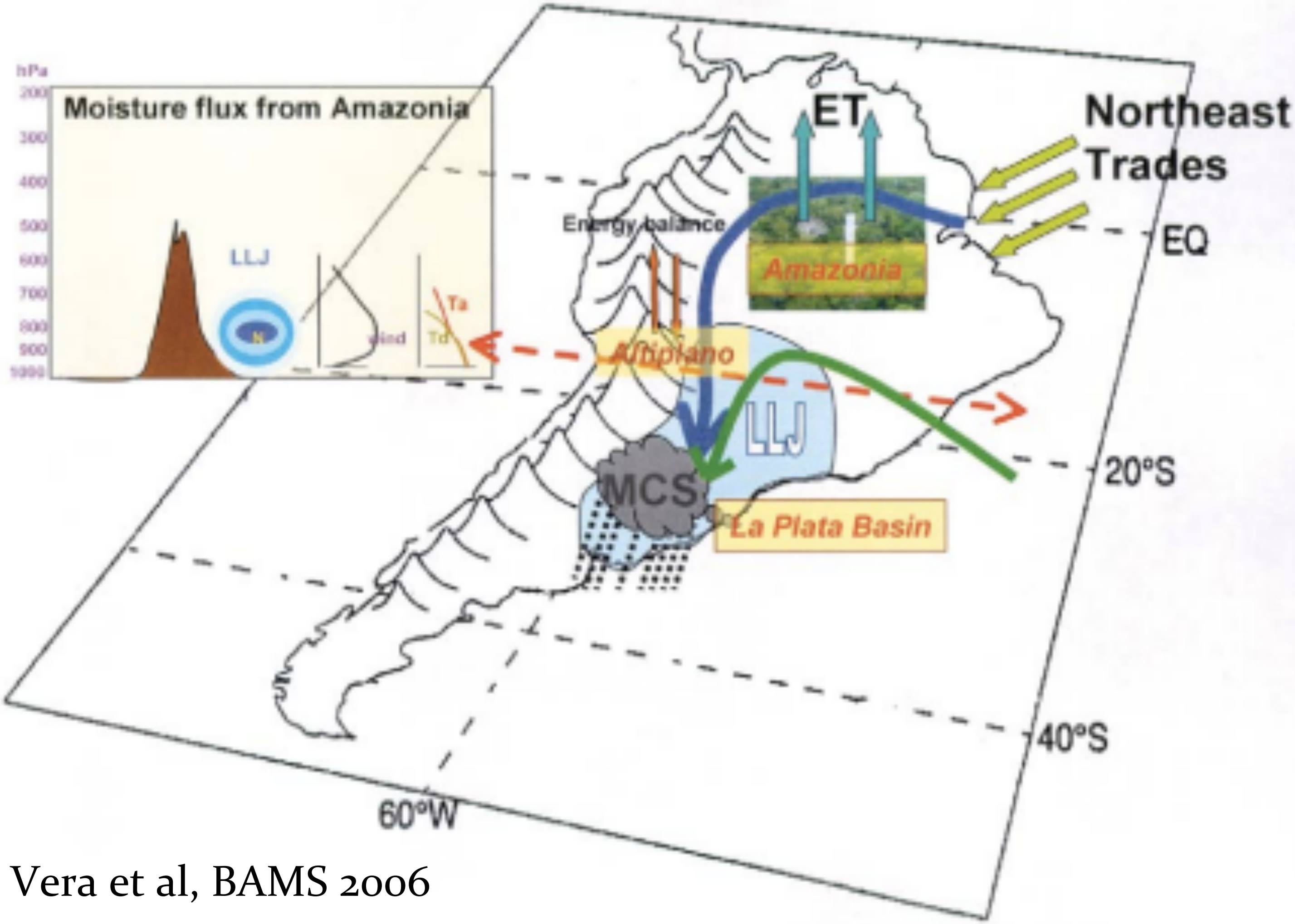
Oceanic circulation



Global Precipitation



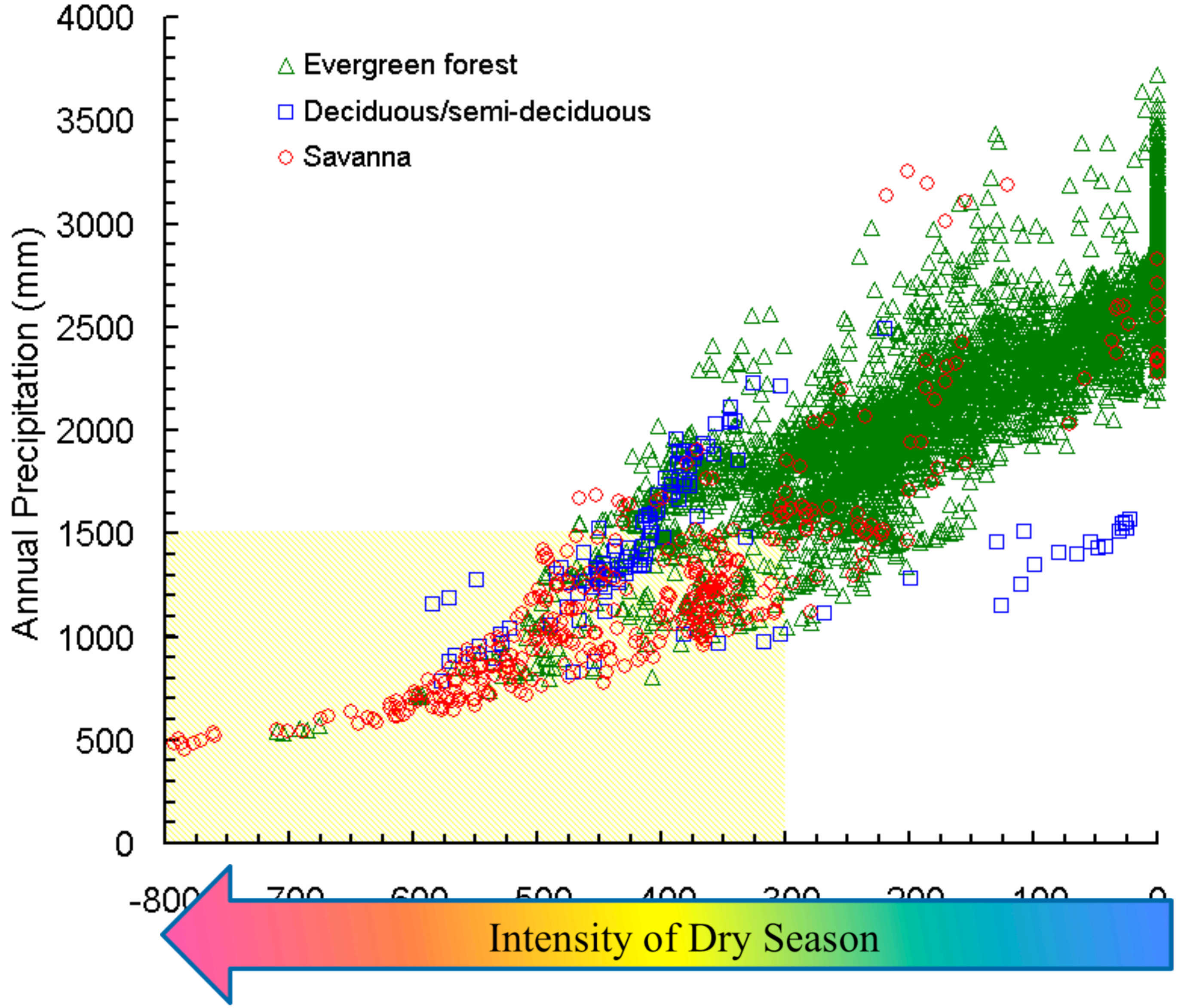

Large Scale
+
Strong Diurnal Cycle
Squall Lines
ITCZ
SACZ
Fronts



Vera et al, BAMS 2006

FIG. 1. Schematic diagram of elements relevant to poleward moisture transport over South America. Blue and green arrows depict the moisture transport into the continent from the tropical and South Atlantic Ocean, respectively. The inset represents a vertical cross section of the northerly flow along the red dashed line displayed in the diagram, including wind and temperature profiles representative of the LLJ core.

A Rainfall Biogeography of Amazonia



Source: Malhi *et al.*, **Exploring the likelihood and mechanism of a climate-change induced dieback of the Amazon rainforest,** *Proceedings of the National Academy of Sciences*, 2010

Precipitation and Vapor transport GPCP + ERA40 1989-2009

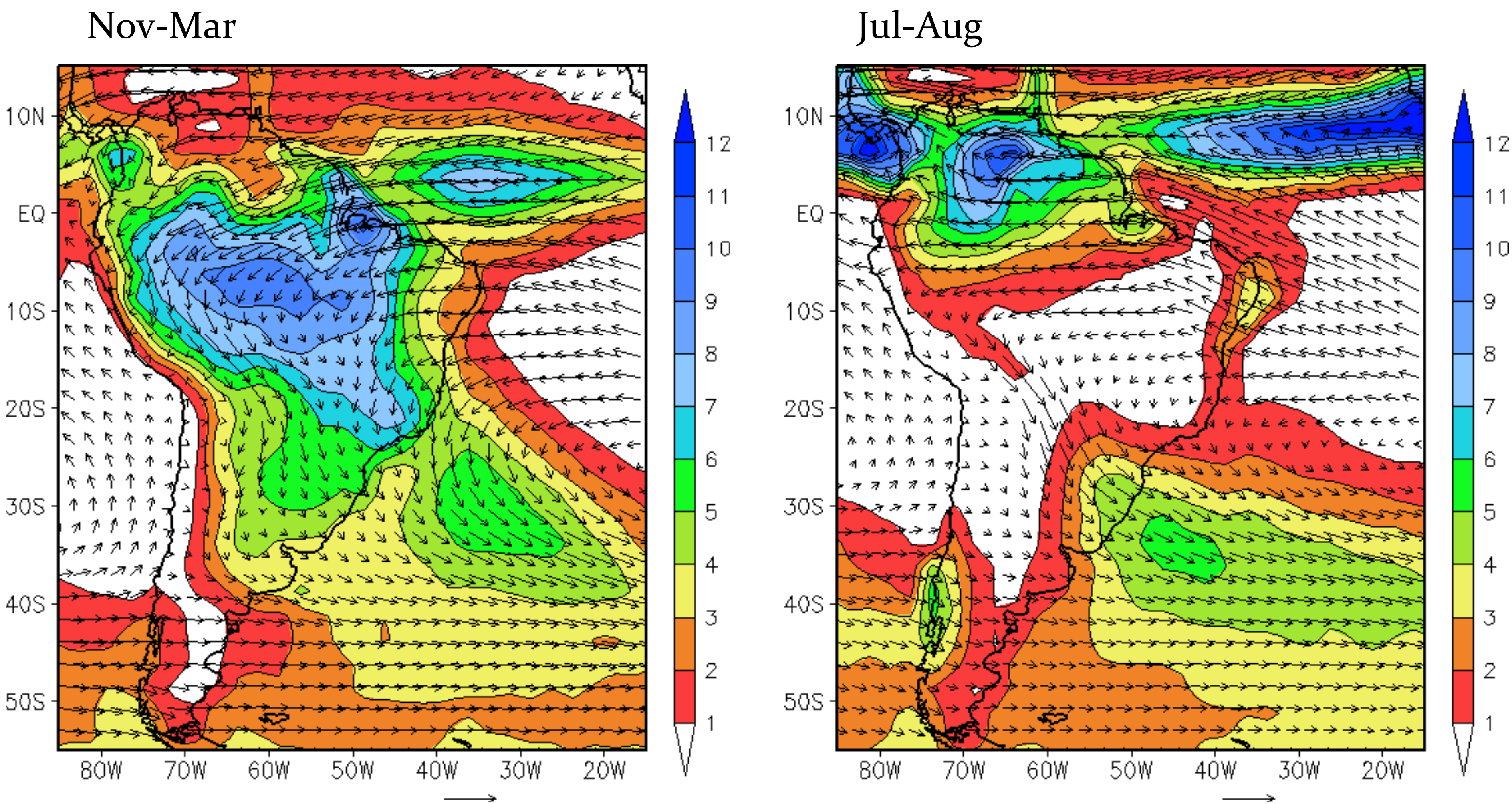


FIG. 1. Mean seasonal precipitation (shaded, mm day^{-1}) and vertically integrated moisture transport (vectors) are shown for NM (Nov–Mar), AJ (Apr–Jun), JA (Jul–Aug), and SO (Sep–Oct).

Arraut et al, J. Clim, 2012

Precipitable water and Vapor transport ERA40 1989-2009

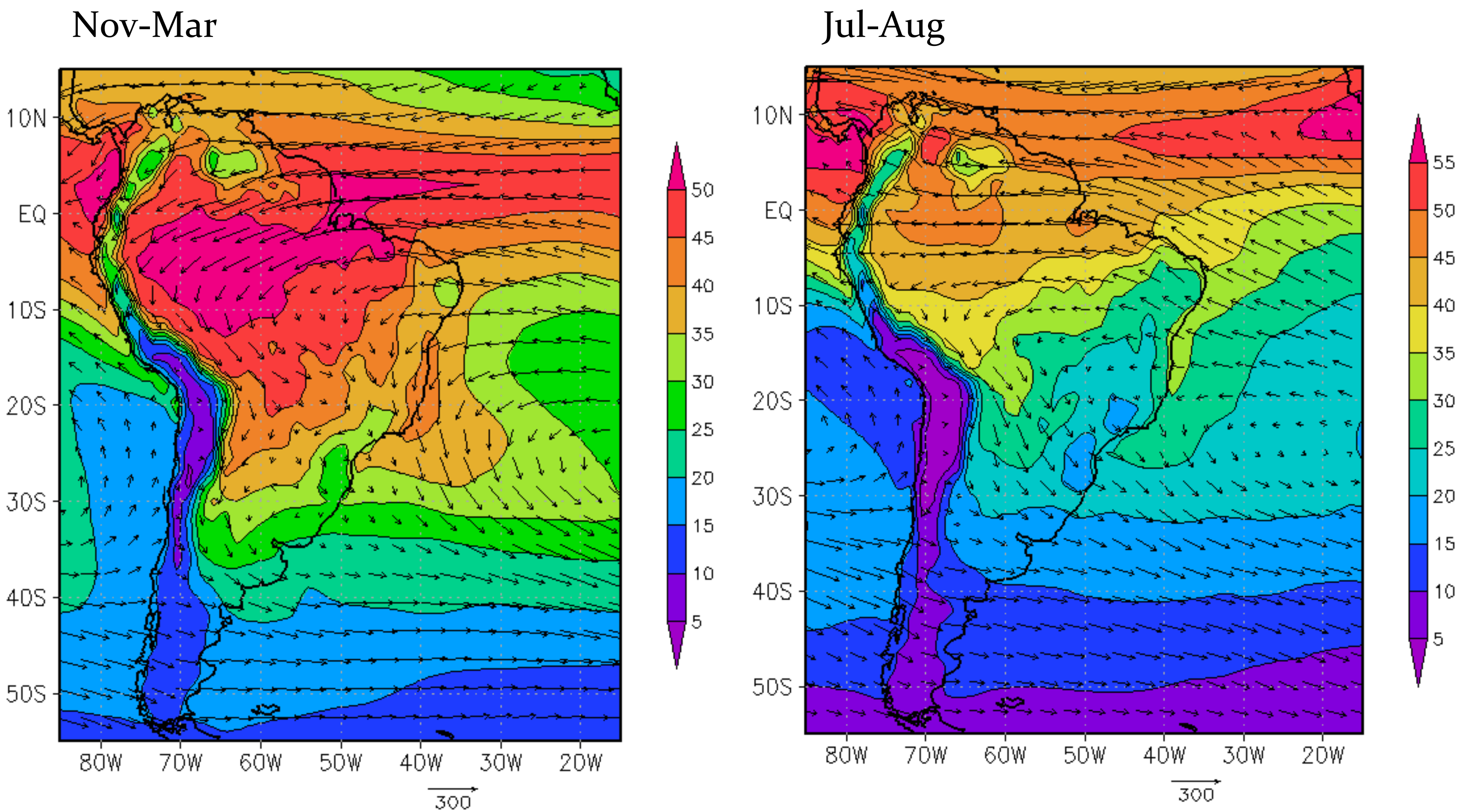


FIG. 2. Magnitude of mean seasonal vertically integrated moisture transport (shaded, kg m^{-1} s^{-1}) and precipitable water (contours, kg m^{-2}) are shown for NM (Nov–Mar), AJ (Apr–Jun), JA (Jul–Aug), and SO (Sep–Oct).

OCEAN-AMAZON, Vapor mix ratio AIRS, ERA, NCEP 2003-2009

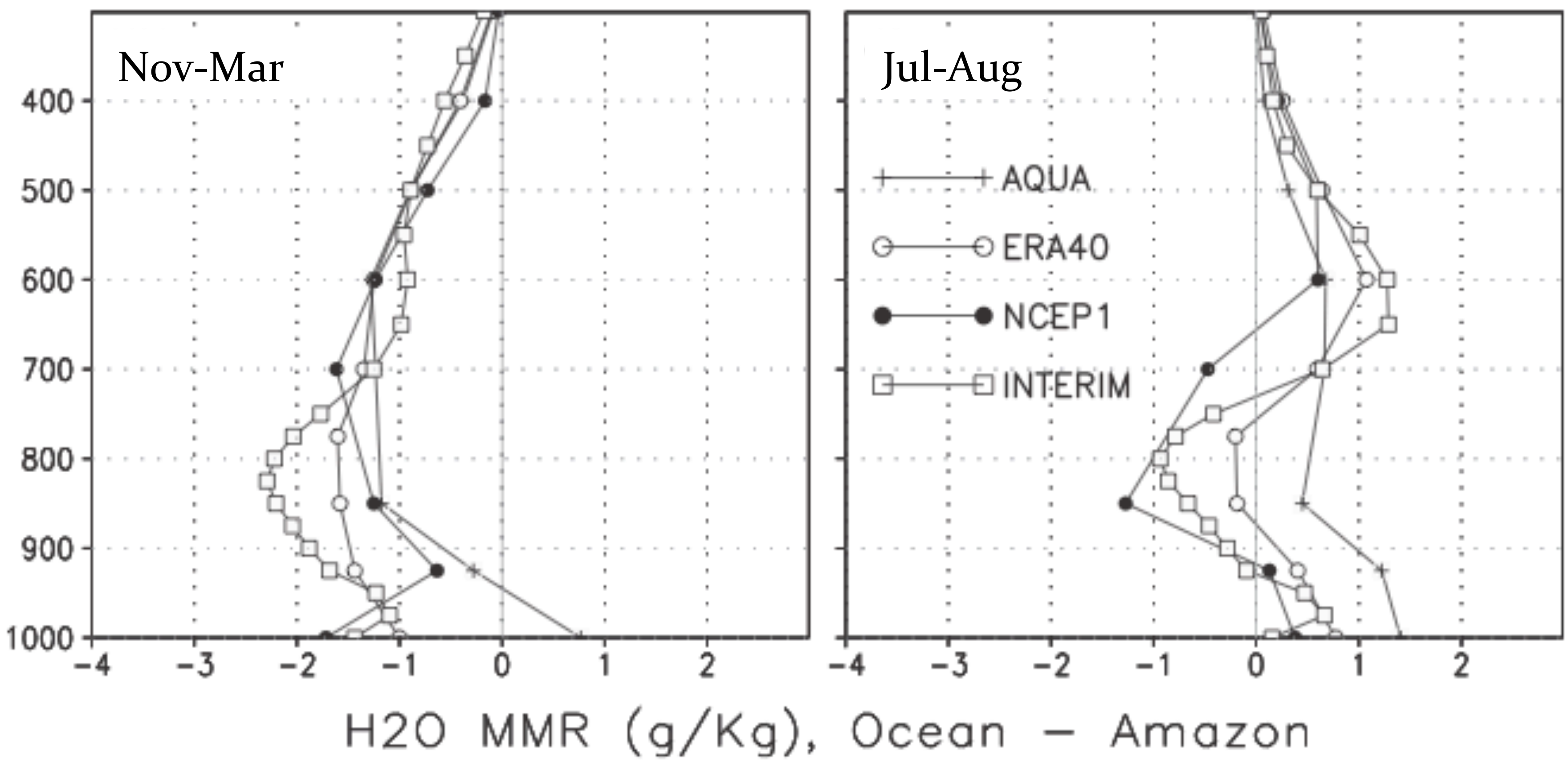


FIG. 4. Mean seasonal differences between the vertical profile of water vapor over the Atlantic (equator–10°N, 50°–30°W) and Amazonia (10°S–equator, 70°–50°W) are shown for AJ, SO, NM, and JA. Data from NCEP (solid circles) and ERA-40 (open circles) are averaged between 1980 and 2001, while ERA-Interim (squares) is averaged between 1989 and 2008, and satellite data from AIRS (crosses) are averaged between 2003 and 2009.

OCEAN-AMAZON, Temperature AIRS, ERA, NCEP 2003-2009

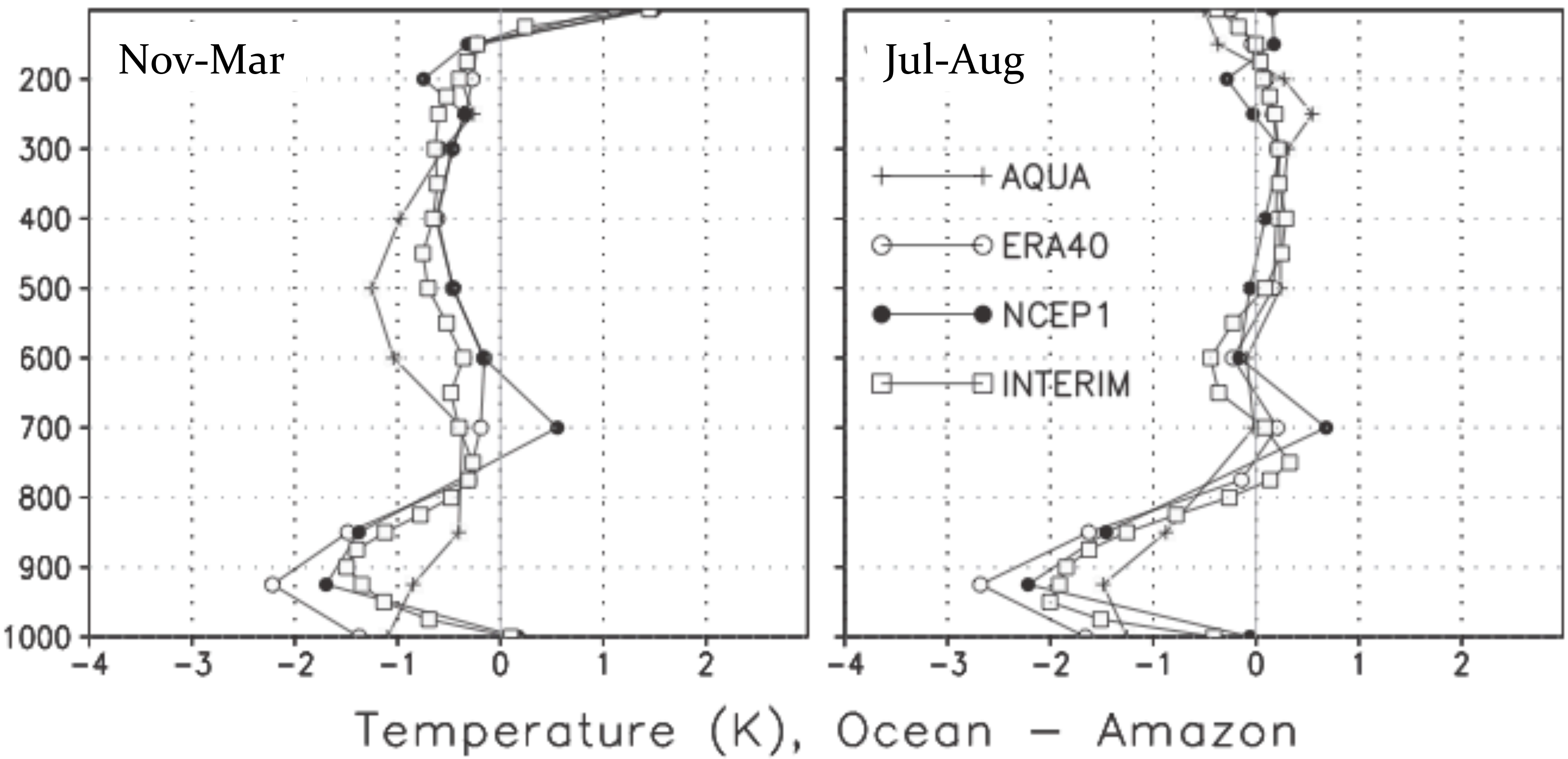
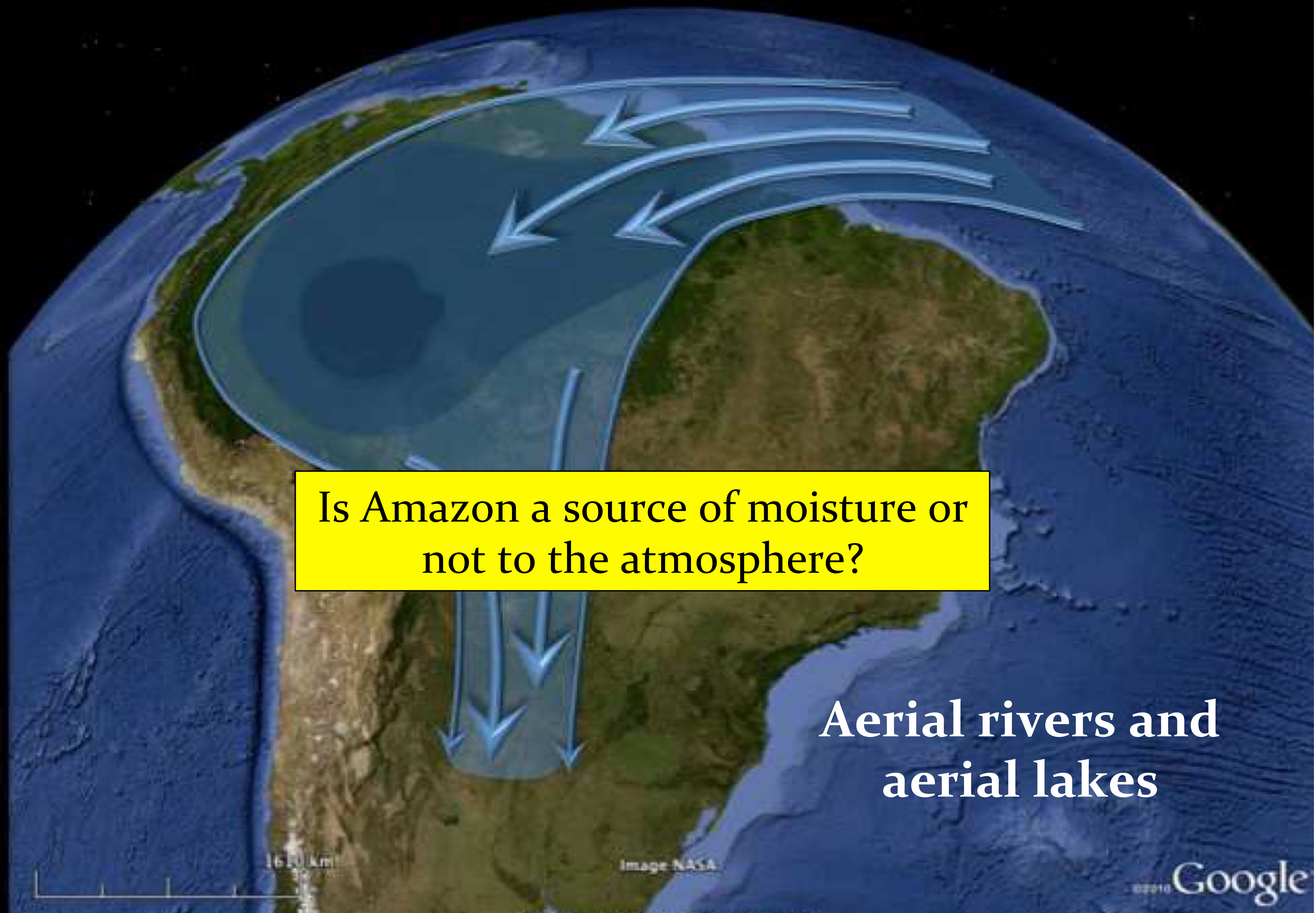


FIG. 5. As in Fig. 4 but for air temperature.

Arraut et al, J. Clim 2012



Is Amazon a source of moisture or not to the atmosphere?

Aerial rivers and aerial lakes

OCEAN-AMAZON, Vapor mix ratio AIRS, ERA, NCEP 2003-2009

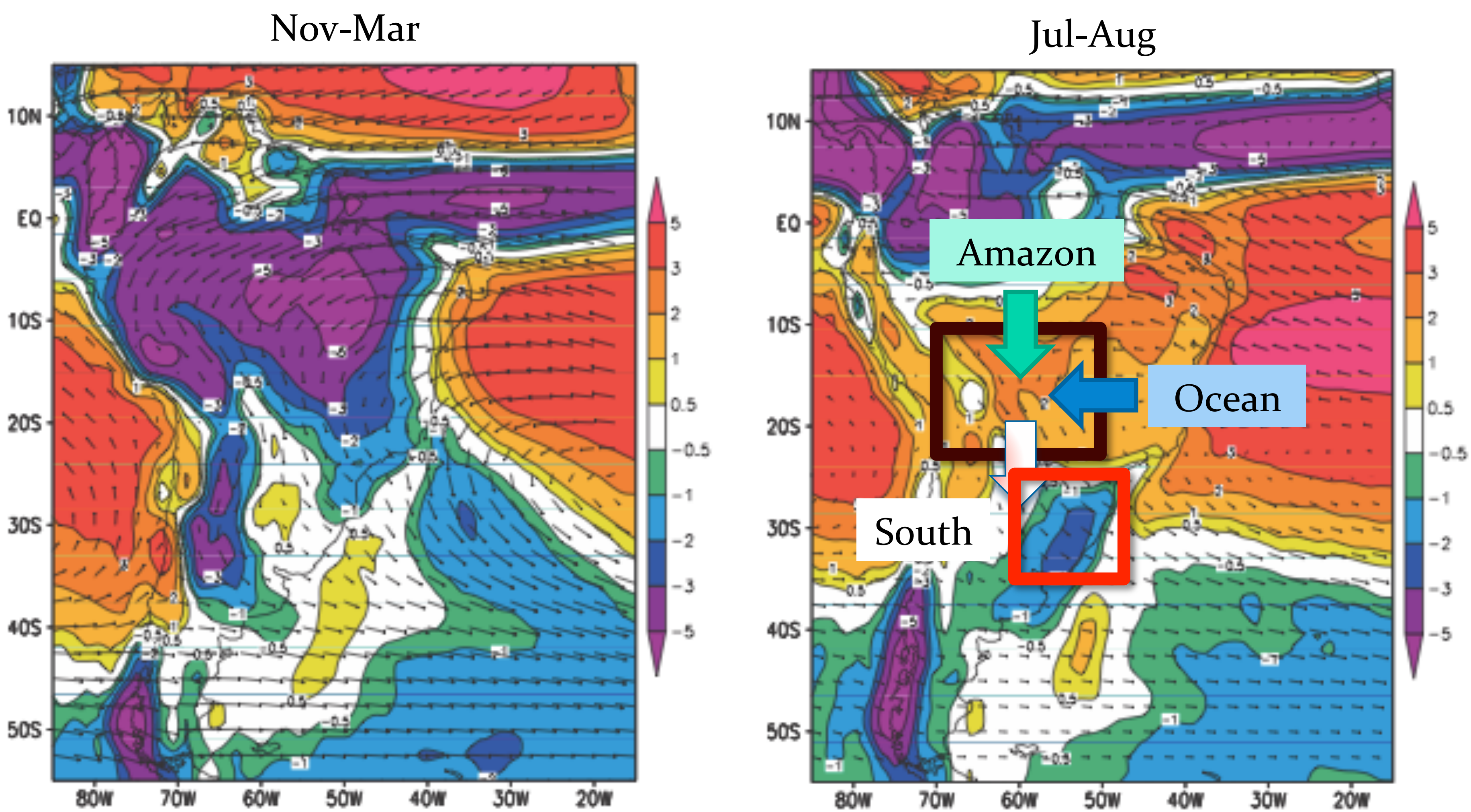


FIG. 6. Mean seasonal vertically integrated moisture transport (arrows) and its divergence (colors, mm day^{-1}) are shown for NM, AJ, JA, and SO.

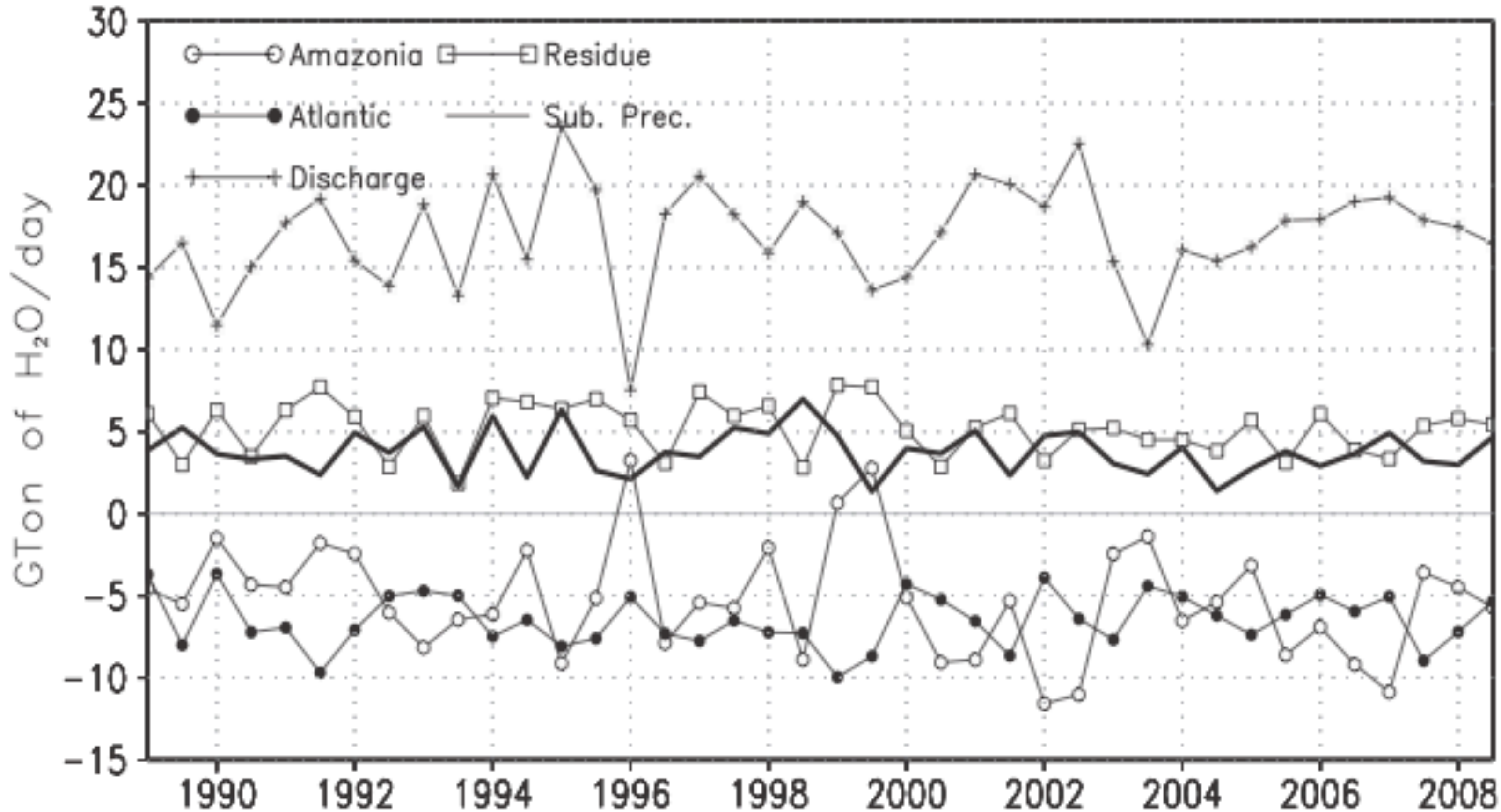


FIG. 7. Water balance (Gt day^{-1}) for the area depicted in Fig. 6 (23°–10°S, 70°–50°W) for the dry months between 1989 and 2008. Inflow is divided into two contributions: Amazonia (open circle) and Atlantic Ocean (filled circle). Discharge (+) is the outflow from this region into the subtropics, and the residue (squares) is the difference between inflows and outflows. The line without symbols is the precipitation averaged over 34°–23°S, 57°–48°W.

Correlation Moisture Flux x Precip.

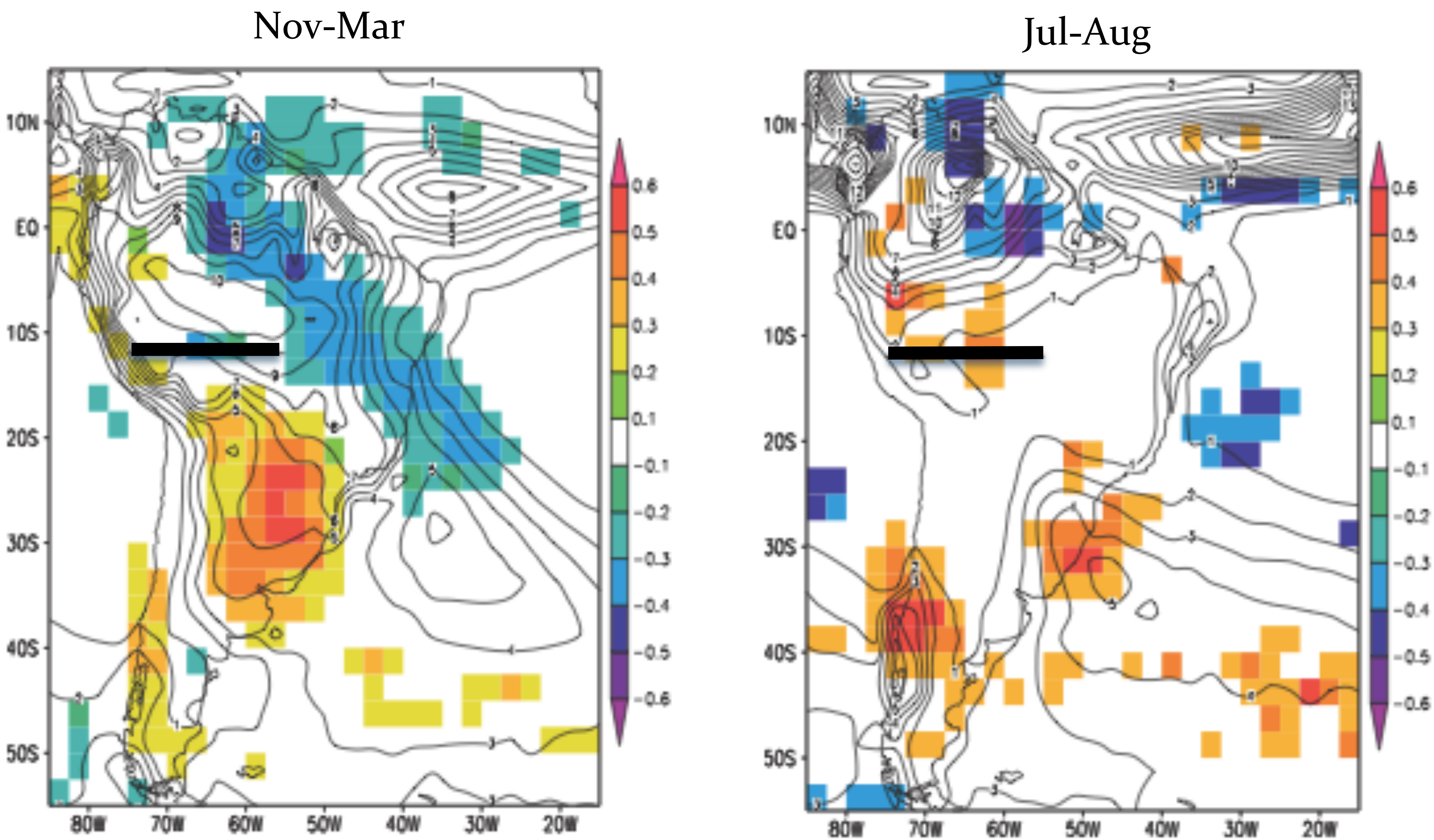
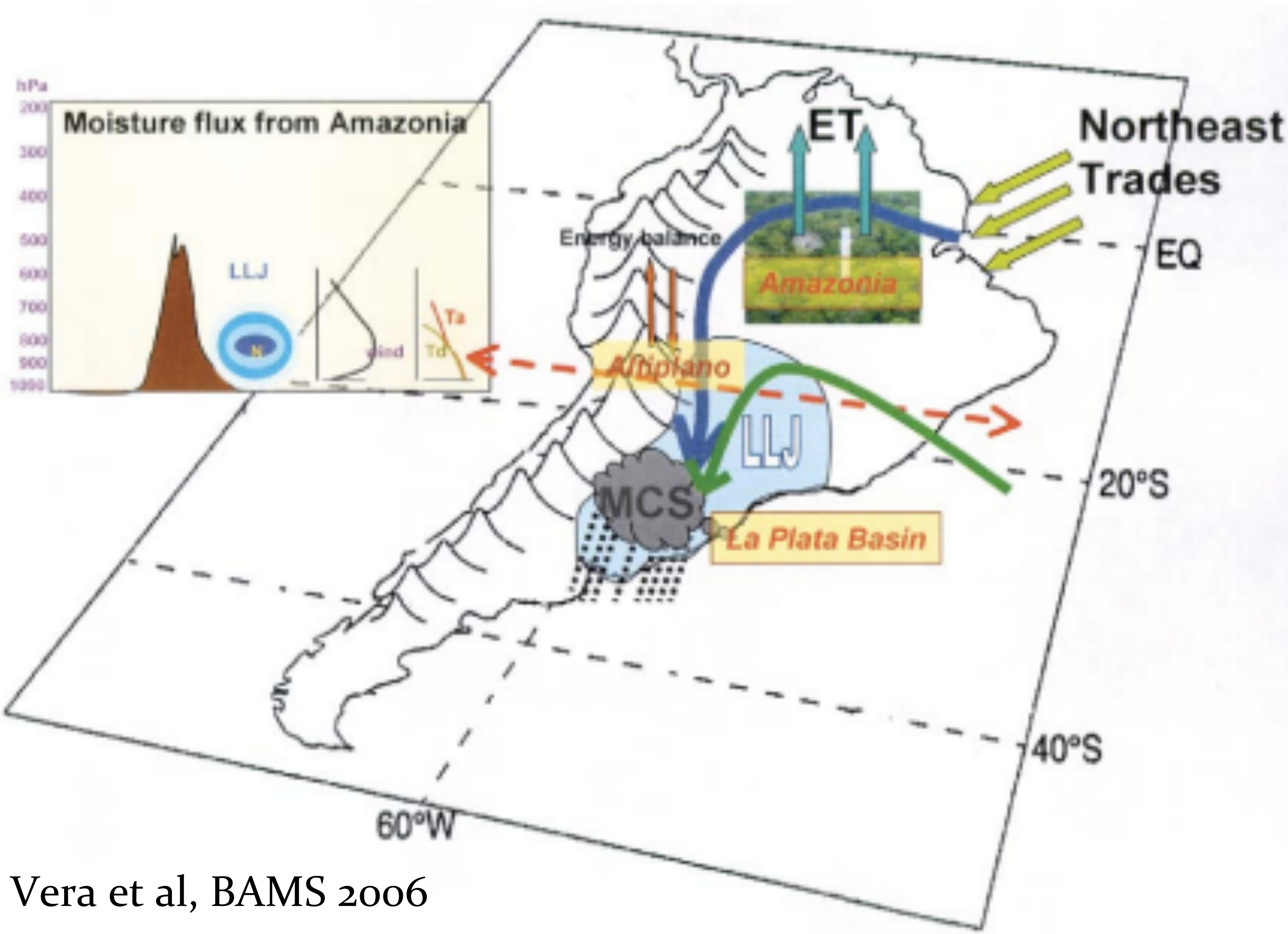


FIG. 8. Colors show correlations between the meridional moisture transport across 12°S between 75° and 55°W (indicated by the grayscale horizontal line) and rainfall at each grid point. Values below the 95% significance level are masked out. Contours show the long-term mean seasonal rainfall, for reference (kg m^{-2}).



Vera et al, BAMS 2006

Ok, so climatologically the water transport from the Amazon to the subtropics is always there… Does it mean the LLJ is not important at al !?!?

Geopotential Height @ 850 hPa(m)

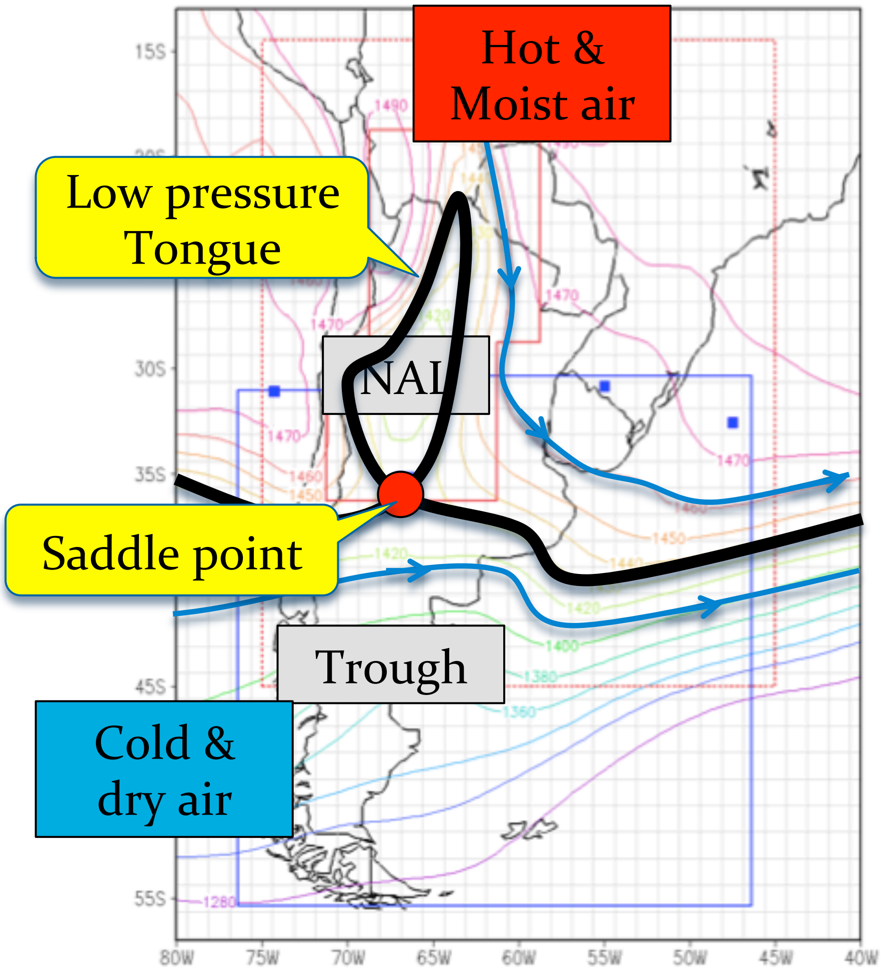
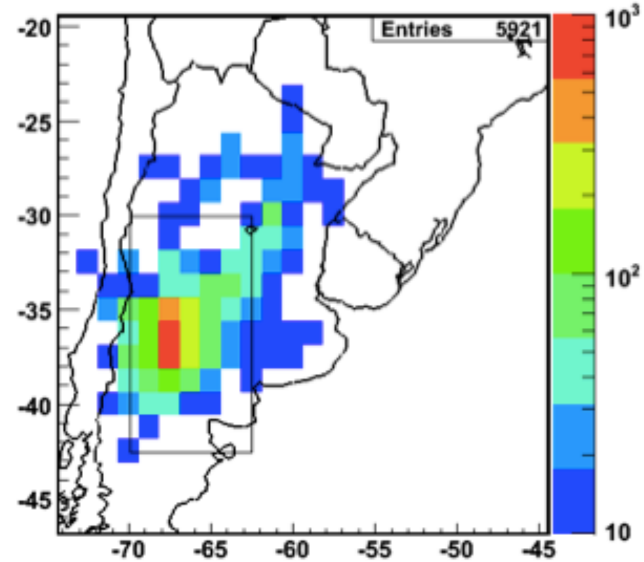
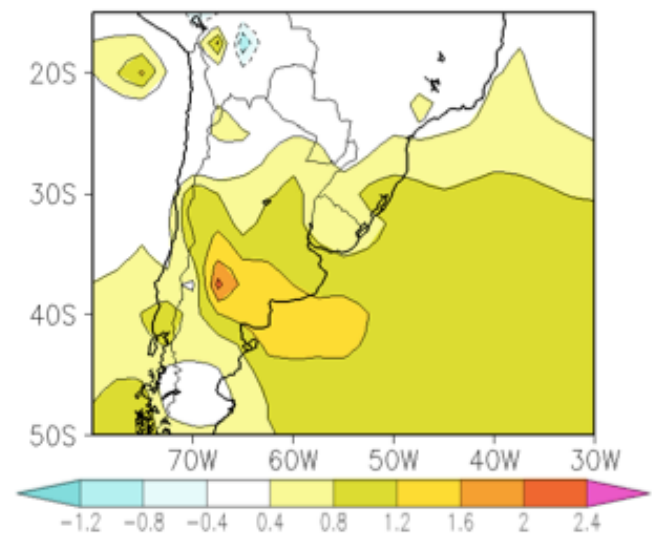


Fig. 1. Contours show ϕ_{850} (m) at 12Z 24th Dec 91. Polygons delimit search regions for: minimums of ϕ_{850} (dotted red); NAL position (red); AC position (blue). Markers indicate: lows (red), NAL (big red), cols (blue), AC (blue square)

Saddle point occurrence

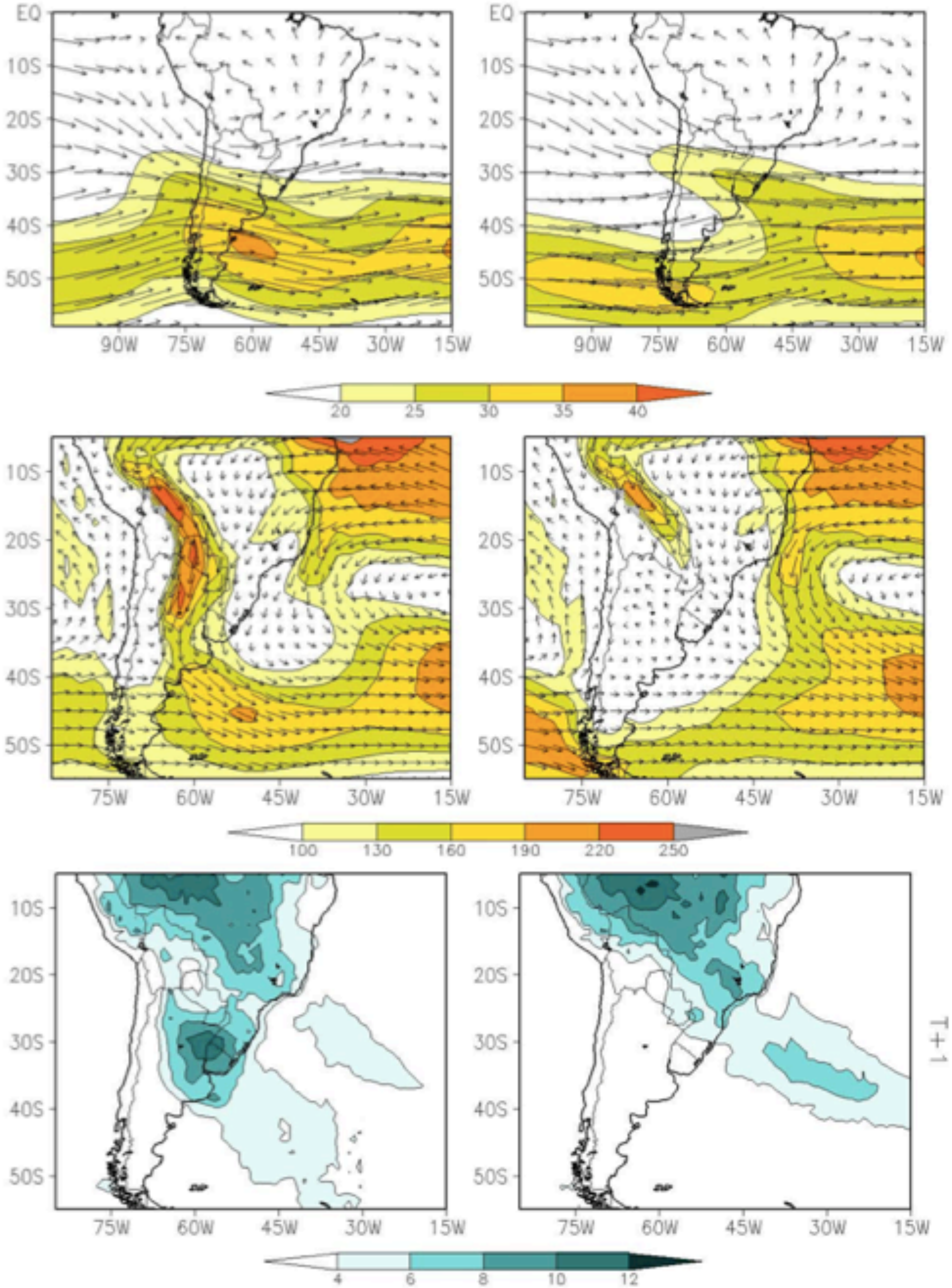




Frontogenesis in θe (K/100km/day)

Barbosa and Arraut, Adv. Geo. 2009

With LPT | Without LPT



Wind at 250hPa
m/s

Moisture transport
Kg/m/s

Precipitation +1 day
mm/day

Fig. 3. Composites for cases with (left) and without (right) AC and LPT inside the selected region. From top to bottom, the panels show geopotential height (m) and FG_3 (K/100 km/day) at 850 hPa, wind vectors and its magnitude (m/s) at 250 hPa, vertically integrated humidity transport and its magnitude (kg/m/s), and precipitation (mm/day) with 1-day lag.

Arraut and Barbosa, Adv. Geo. 2009

That mean precip comes in strong events!

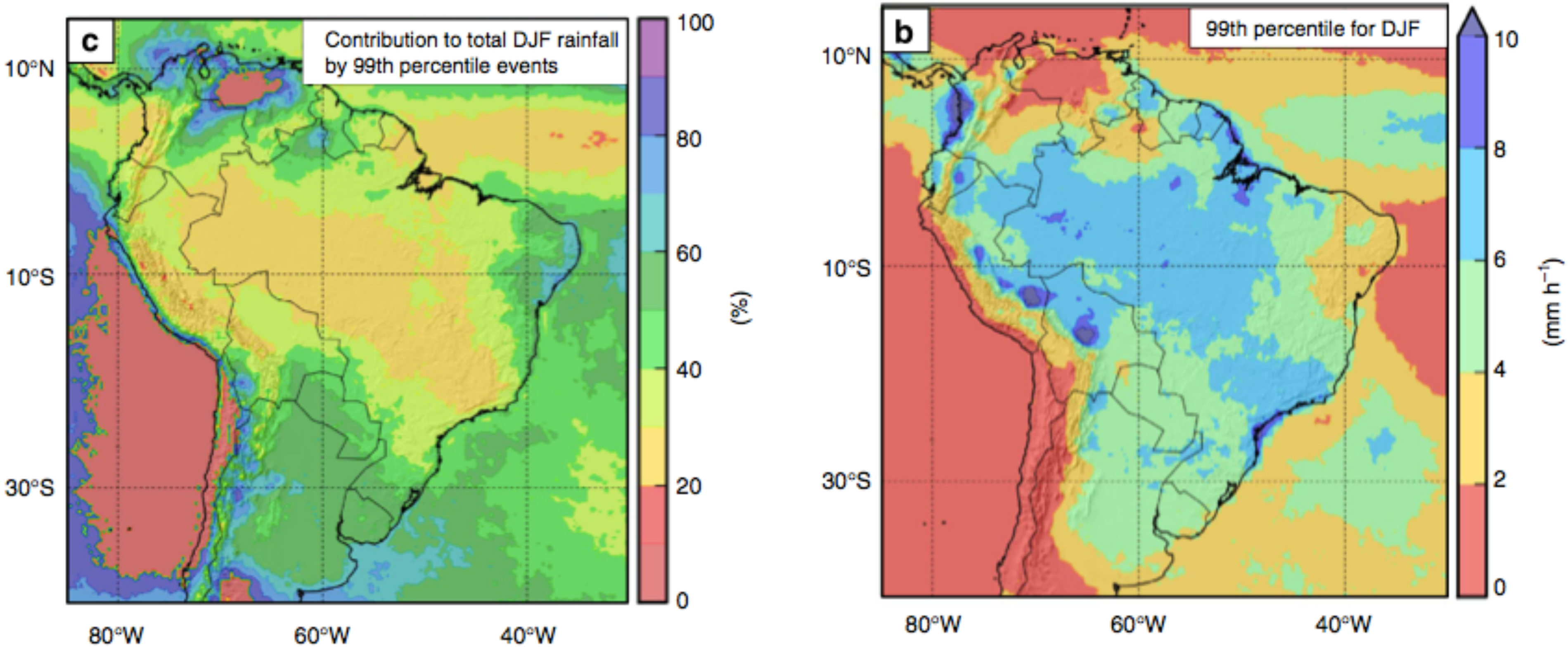
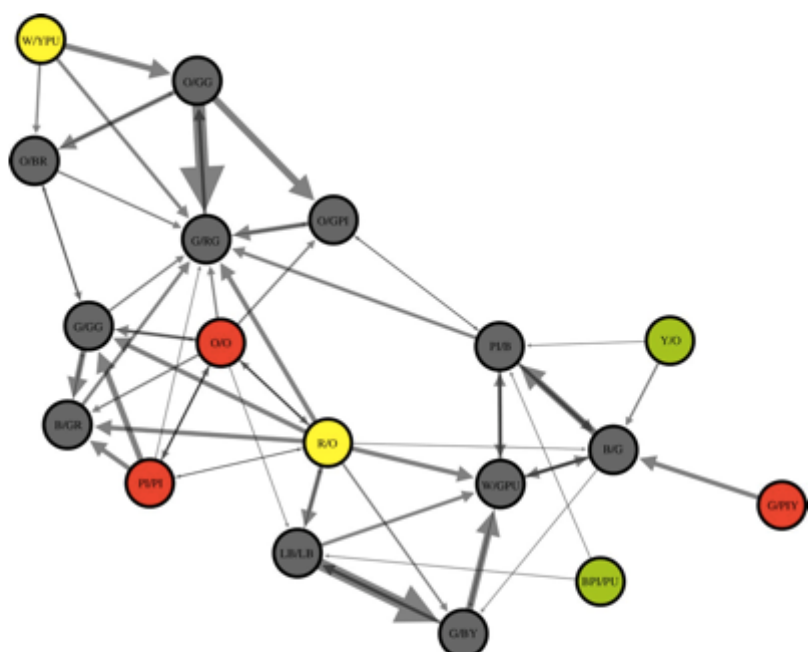


Figure 1 | Geographic and climatic setting. (**a**) Topography and simplified South American Monsoon System mechanisms. The boxes labelled 1 to 7 indicate the climatological propagation path of extreme events as revealed by the network analysis. (**b**) 99th percentile of hourly rainfall during DJF derived from TRMM 3B42V7 (ref. 27 in the spatial domain 85°W to 30°W and 40°S to 15°N, at a horizontal resolution of 0.25° × 0.25° and 3-hourly temporal resolution. (**c**) Fraction of total DJF rainfall accounted for by events above the 99th percentile. (**d**) Trend lines for the number of extreme

Boers et al, Nature Comm. 2014

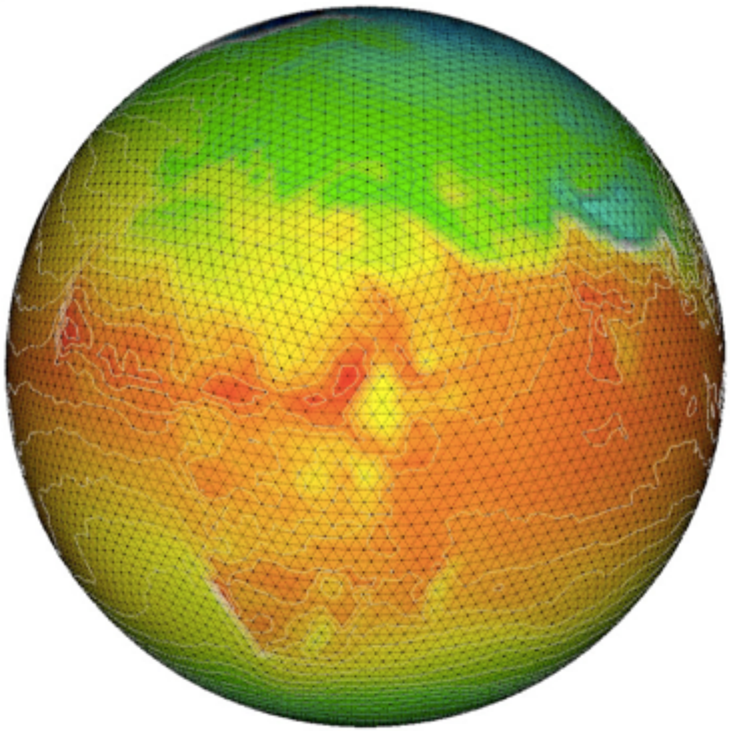
Complex Networks

- In the context of network theory, a complex network is a graph (network) with non-trivial topological features—features that do not occur in simple networks such as lattices or random graphs but often occur in graphs modeling real systems.

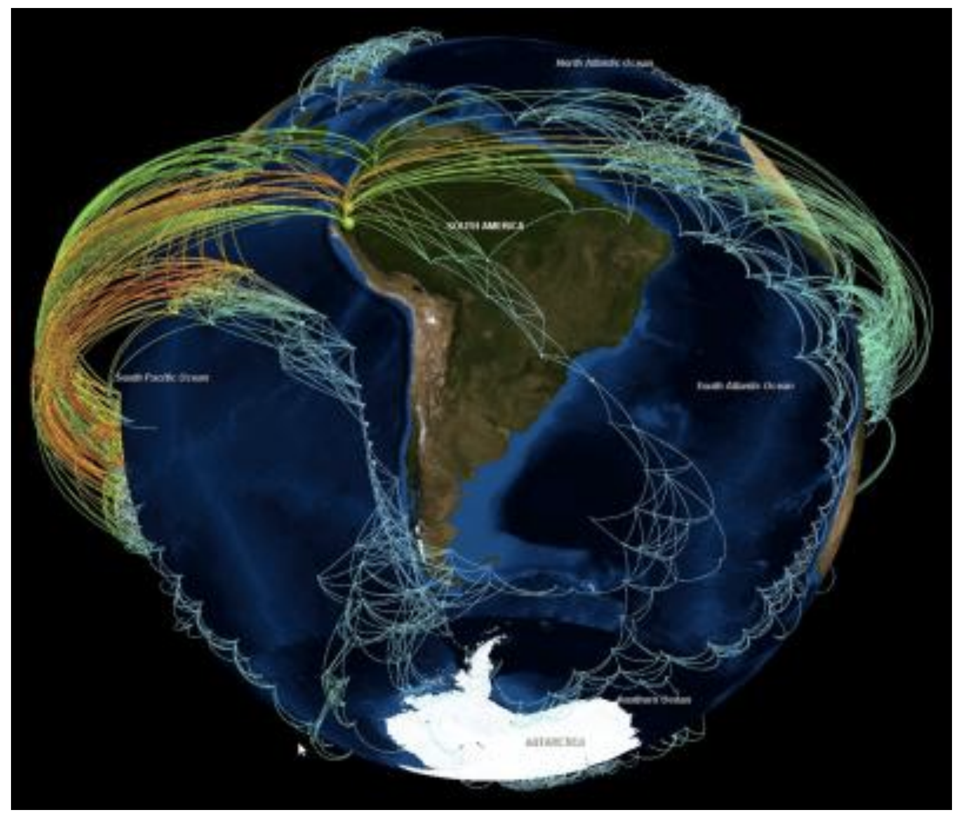


Complex Networks for climate

Ex: times series of global temperatures



But how can I make a map of this complicated correlation??

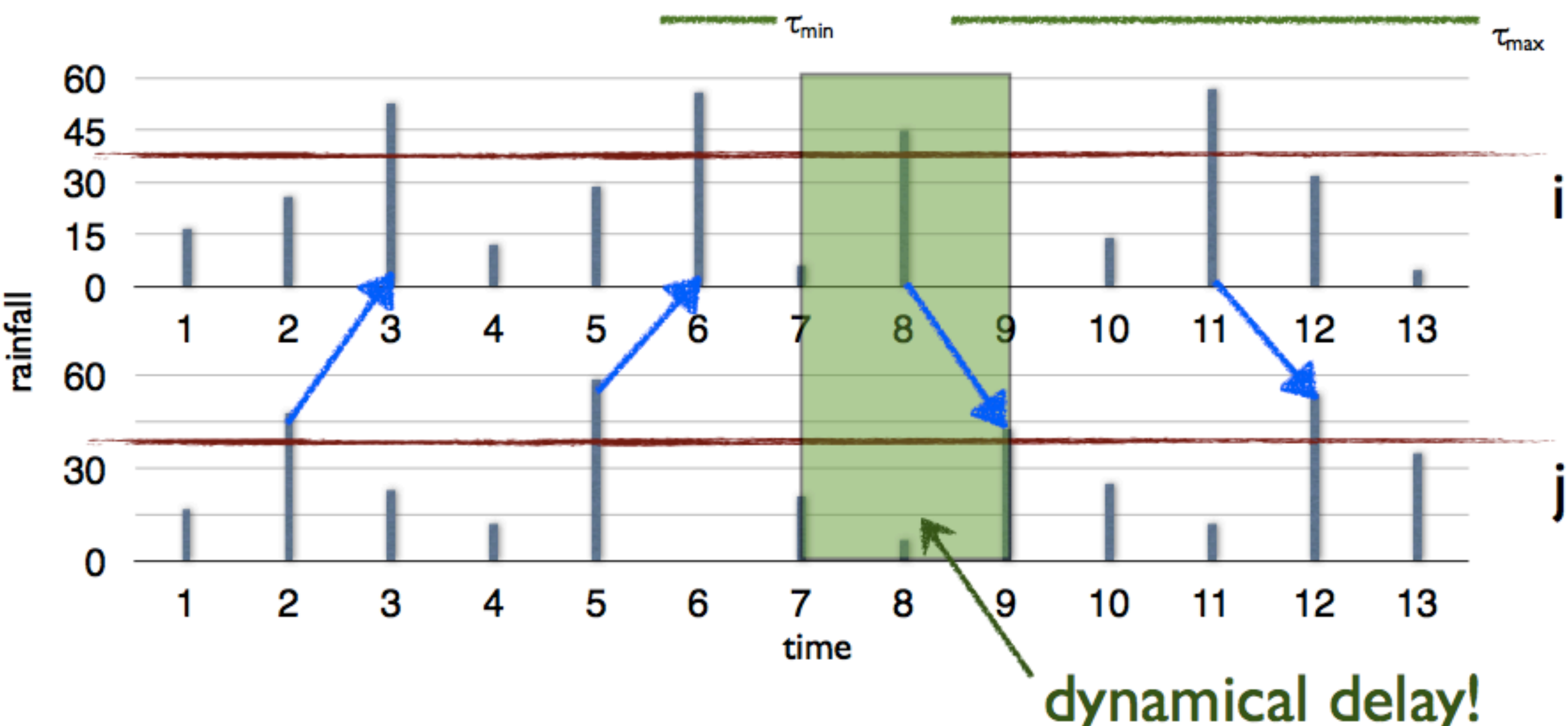


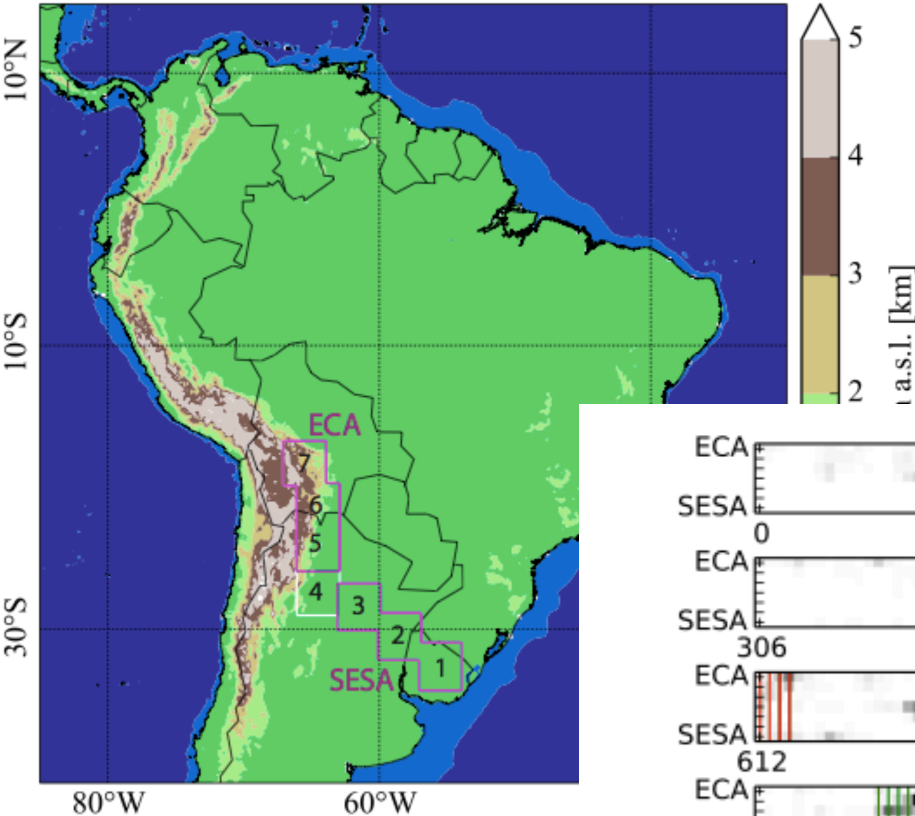
Take the Pearson's **correlation, for each pair** of points:

$$\rho_{i,j,k,l} = \frac{\mathrm{cov}(T_{i,j}, T_{k,l})}{std(T_{i,j})std(T_{k,l})}$$

event synchronization

(extreme events: above 99th percentile of all DJF times)





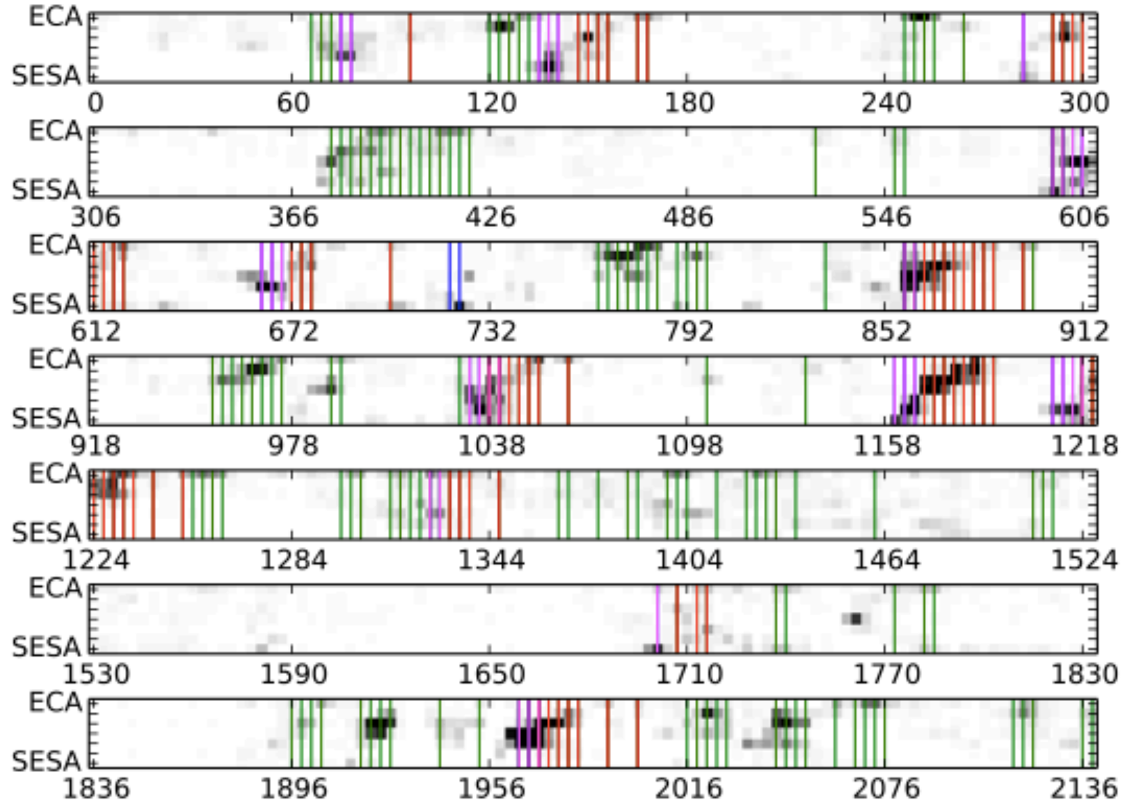
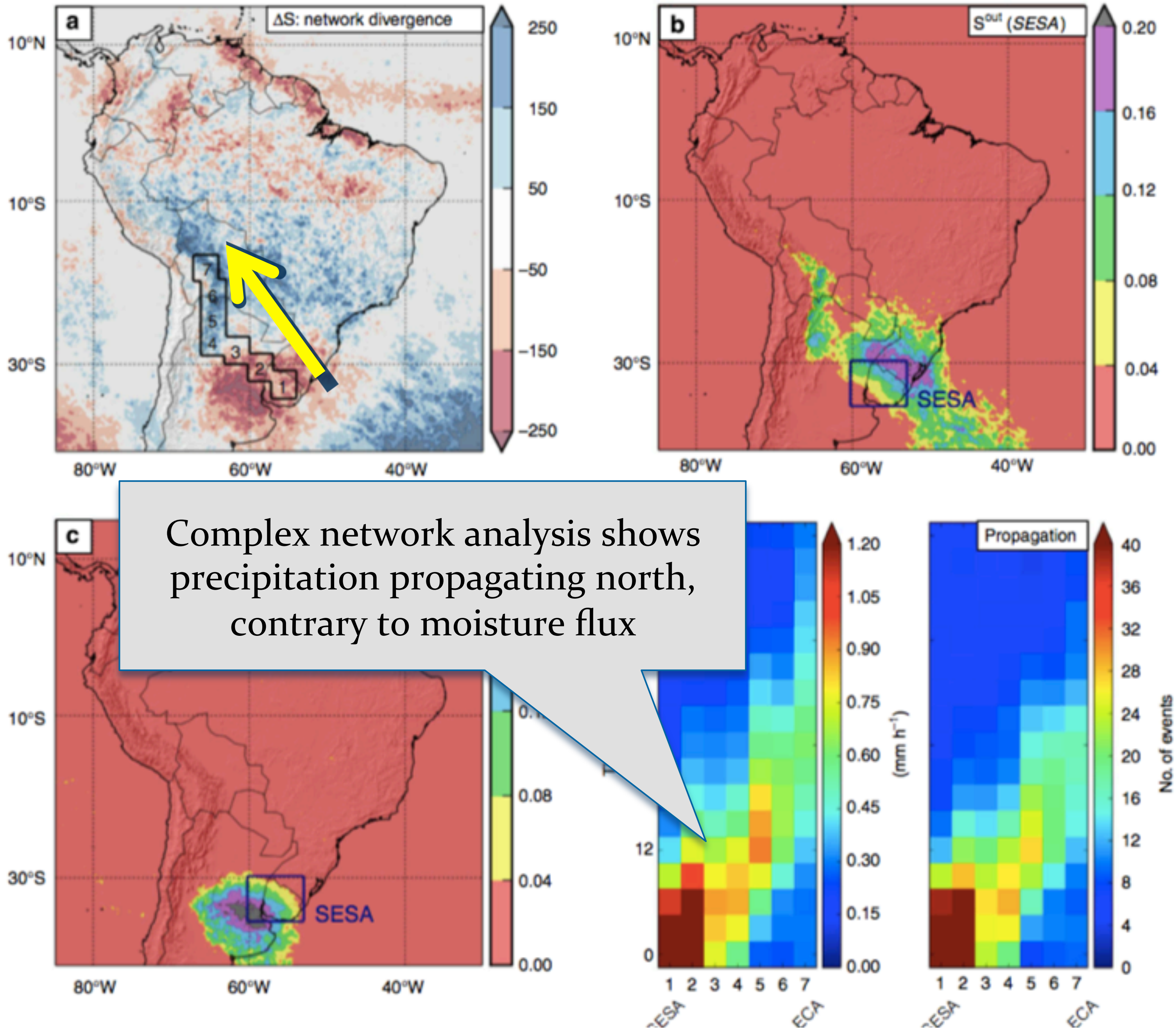


Fig. 2 Rainfall spatially averaged over each of the 7 boxes in Figure 1 for each time step. Here, we show the year 2008 as an example. Magenta (Blue) lines indicate SESA-ECA (SESA-NO-ECA) times, and red (green) lines indicate ECA-SESA (ECA-NO-SESA) times.

- Boers et al, Nature Comm. 2014



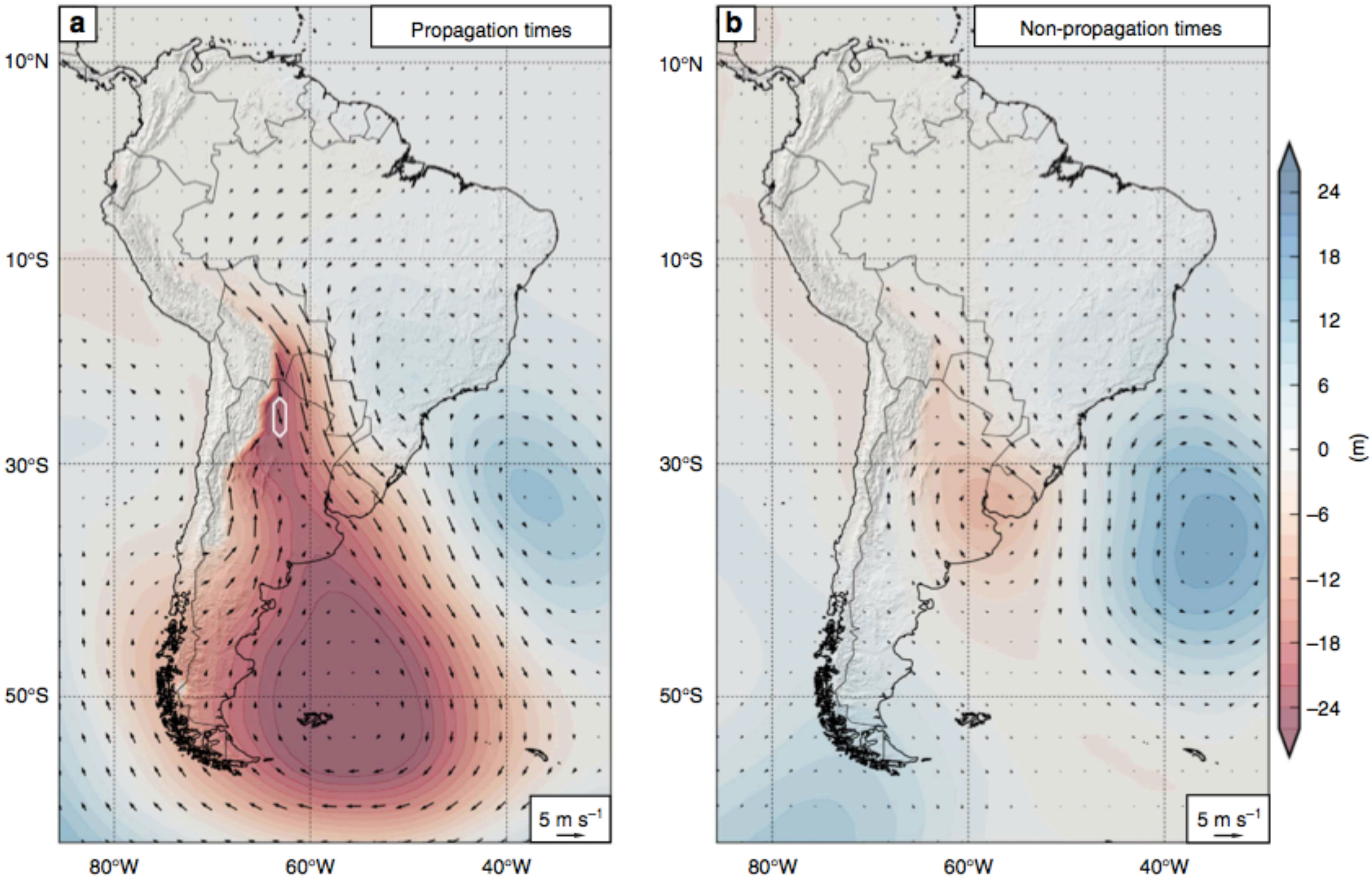
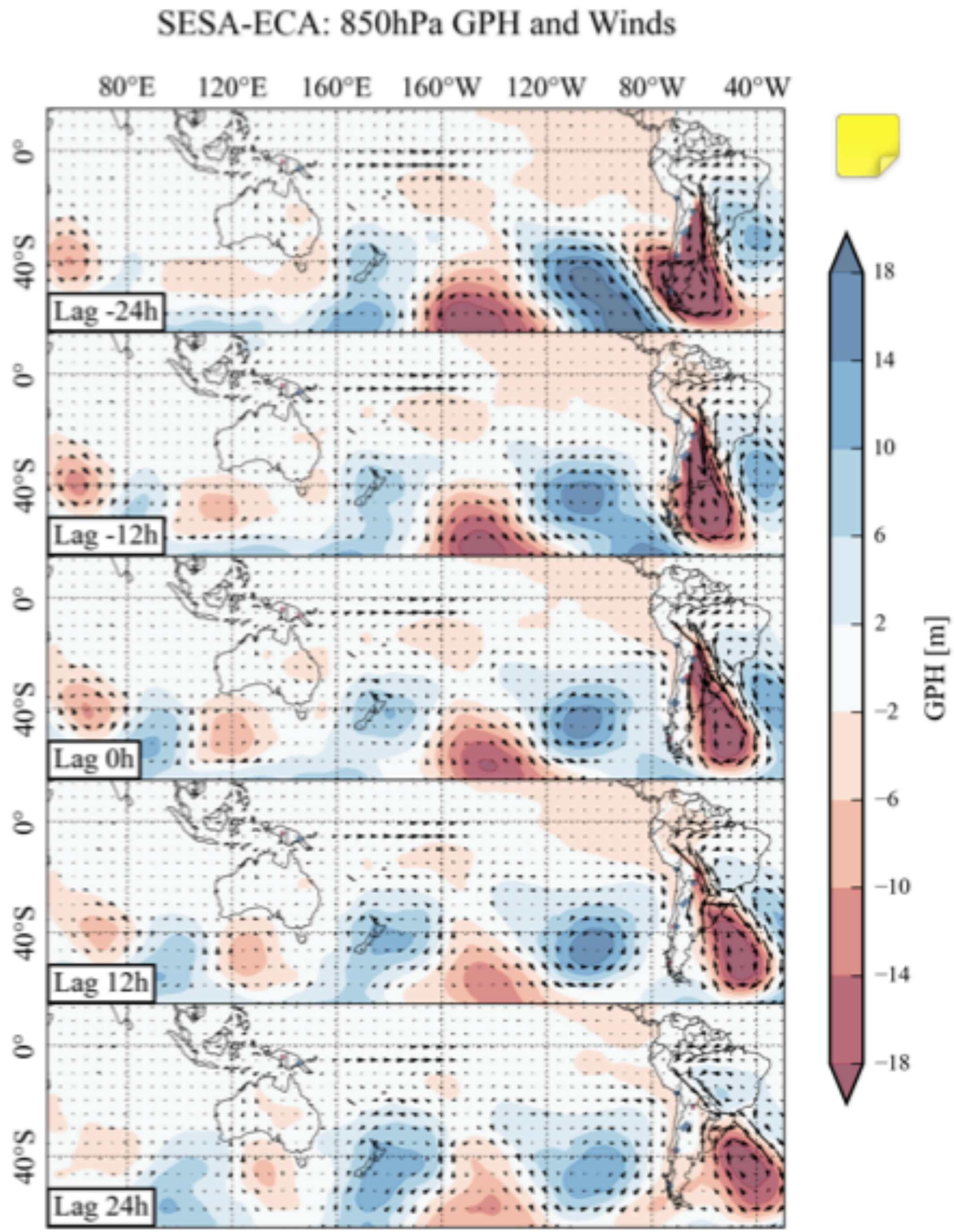


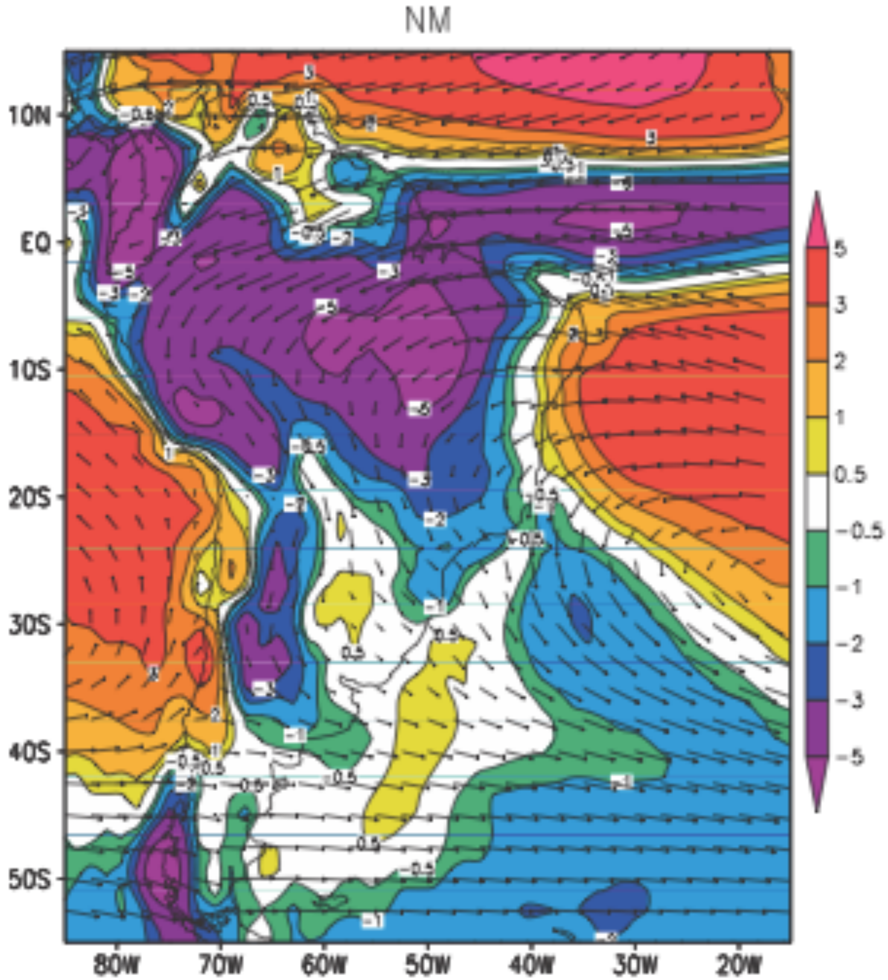
Figure 3 | Atmospheric conditions for propagation and non-propagation times. (**a**) Composite anomalies relative to DJF climatology of 850 mb geopotential height and wind fields from NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA,[29]) for propagation times. Temporal resolution is 3-hourly, spatial resolution is 1.25° × 1.25°. The white polygon delineates the region over which the geopotential height anomalies are computed for the forecast rule. (**b**) The same composite anomalies as for (**a**), but for non-propagation times.

- Besides the
  - Saddle point
  - Low pressure tongue
  - NA Low
  - Through
  - ...

- There is a Rossby wave train propagating from the extra tropics!



Boers, Barbosa et al, JGR (submitted)



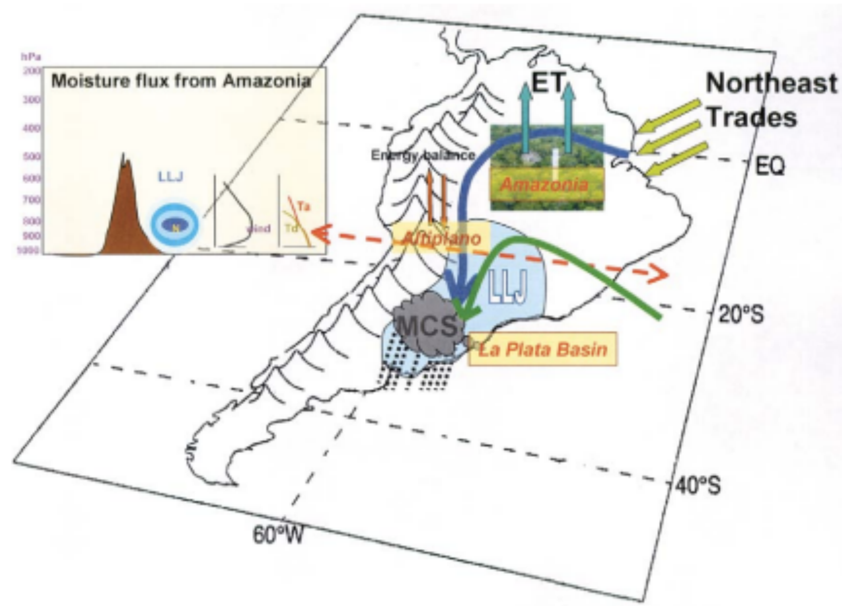
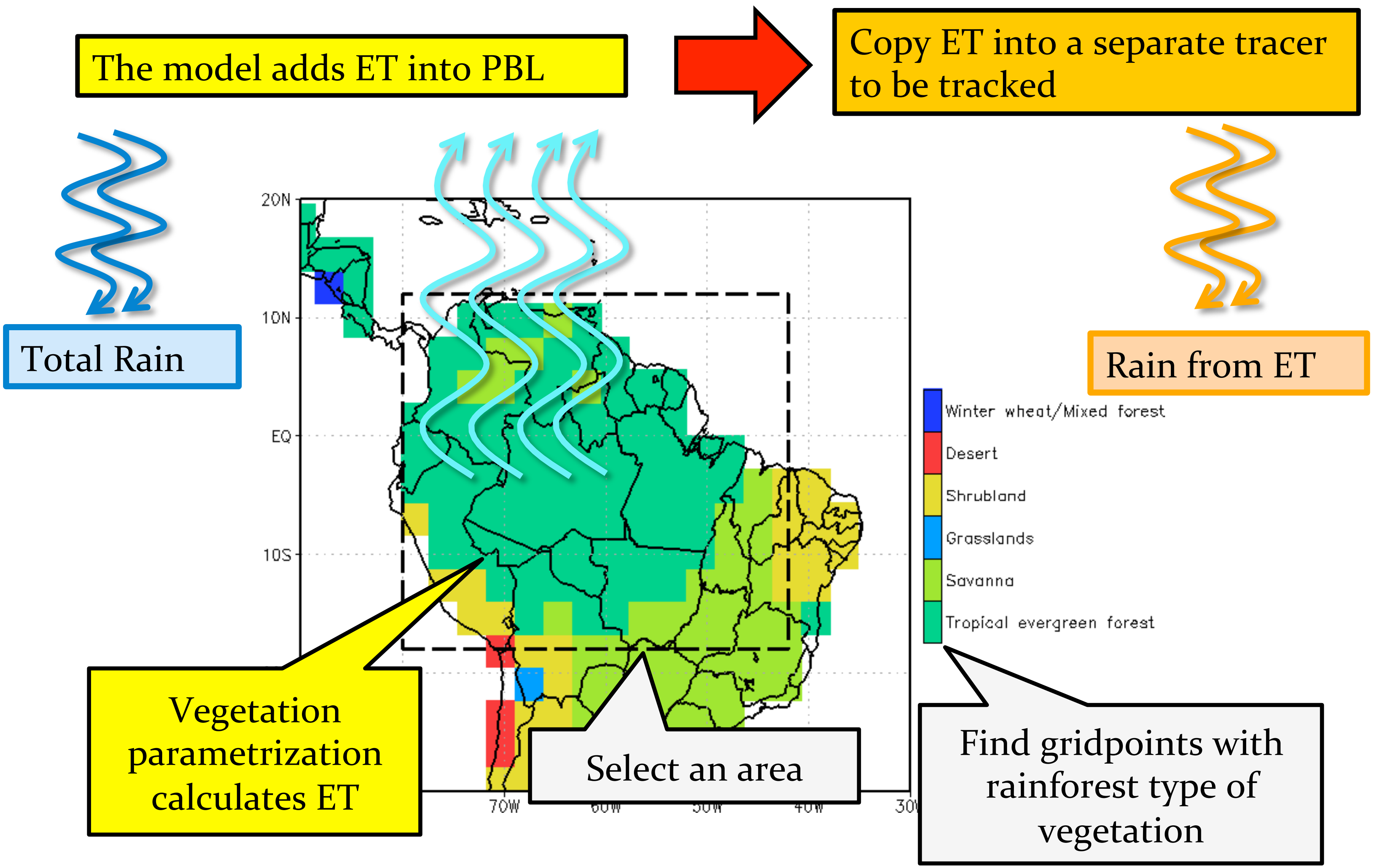


FIG. 1. Schematic diagram of elements relevant to poleward moisture transport over South America. Blue and green arrows depict the moisture transport into the continent from the tropical and South Atlantic Ocean, respectively. The inset represents a vertical cross section of the northerly flow along the red dashed line displayed in the diagram, including wind and temperature profiles representative of the LLJ core.

Ok, LLJ is only a <u>consequence</u>, and the Amazon is a source of moisture <u>only</u> during winter…
But is the rainforest important to water recycling??

Water tracer



Vapor transport, PWC and ET-precip

Roughly 30% of precipitation in Bolivia, Paraguay, North Argentina and southern Brazil comes from Amazon's ET.

WARN: rough estimate depends on the Model's precipitation (parametrized), and resolution was very low.

Moisture (complex) network

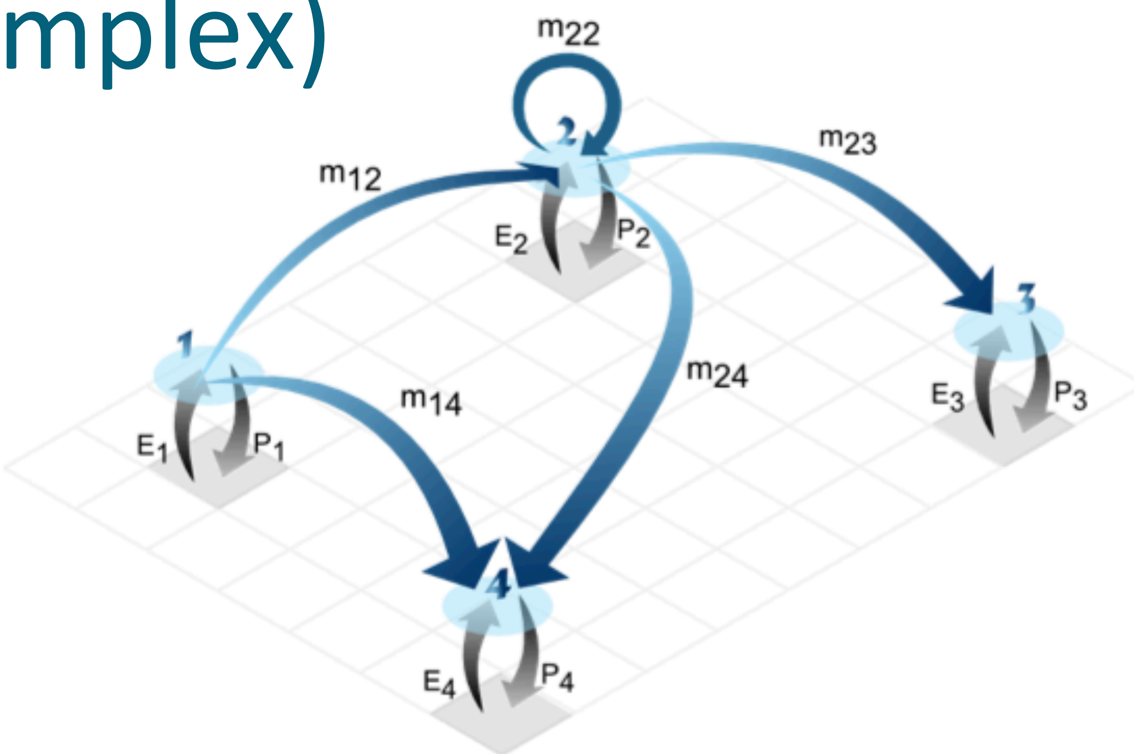


Fig. 1: Scheme of the moisture recycling network. Nodes $1, 2, 3, 4$ represent different grid cells and arrows indicate the direction and amount of moisture originating from evapotransporation in the source cell and contributing o precipitation in the target cell. For example, the total evapotranspiration in 2 (E_2) splits up in three branches: m_{23} precipitates in 3, m_{24} precipitates in 4 and m_{22} is locally recycled. m_{22} contributes together with m_{12} to the total precipitation in 2 (P_2).

Zemp et al, ACP 2014

Cascading

Different paths for water, and possible cascading before getting to “final” destination!

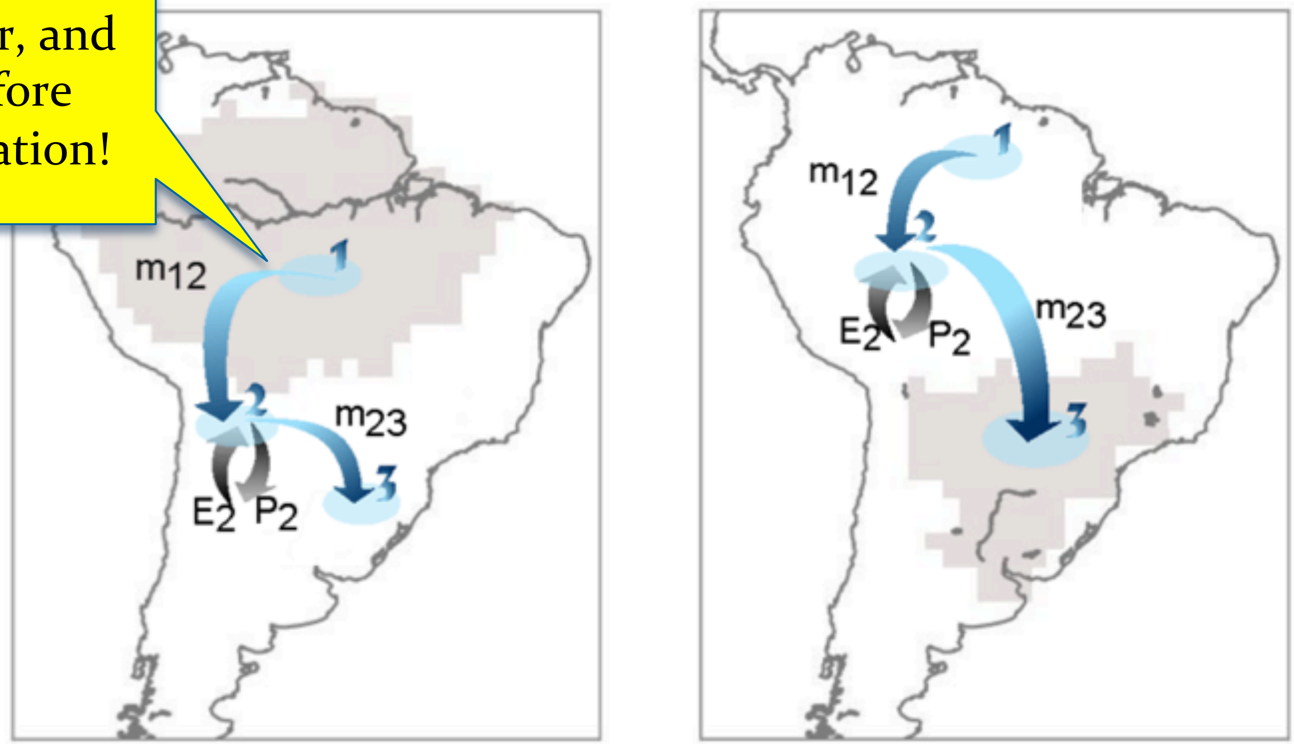
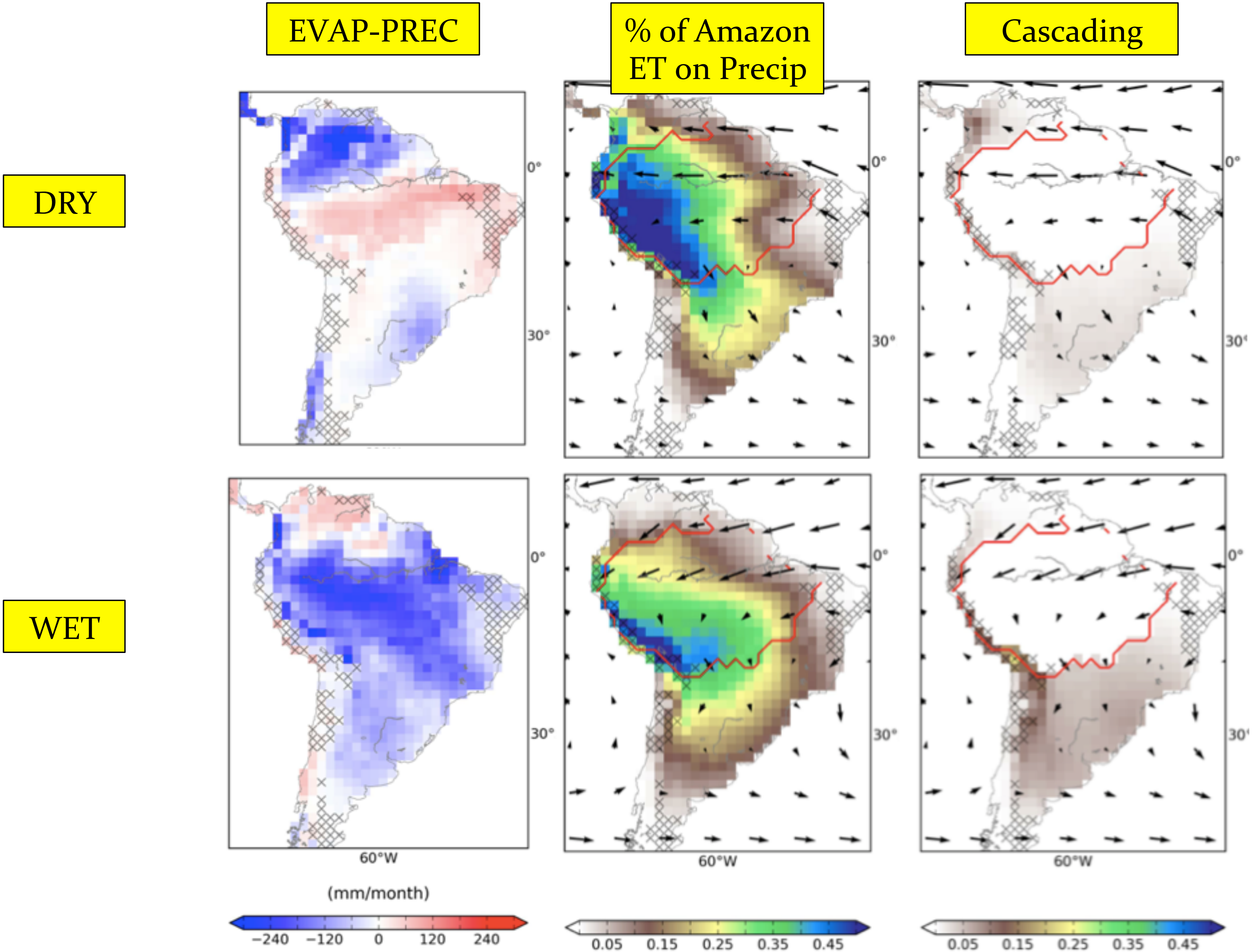
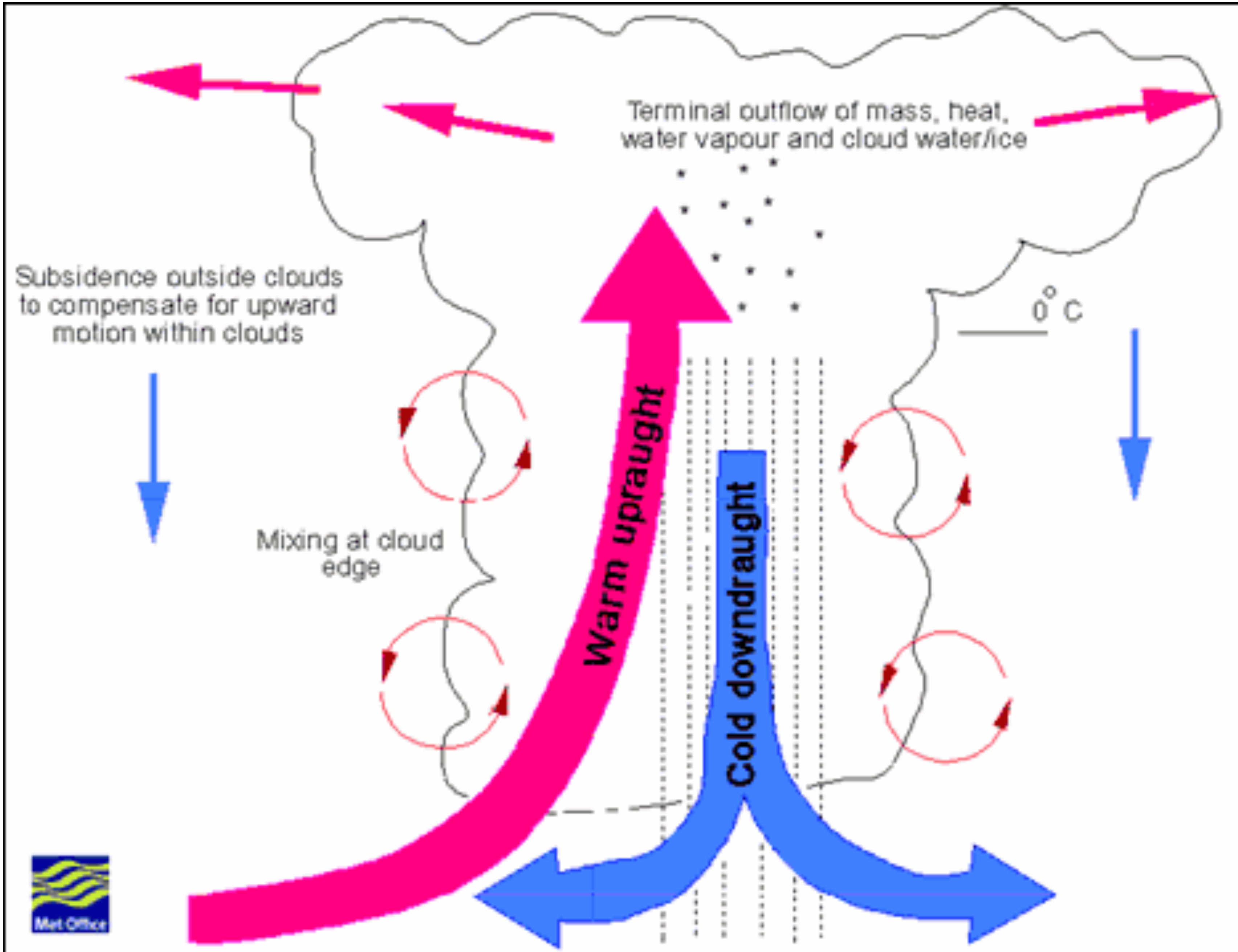


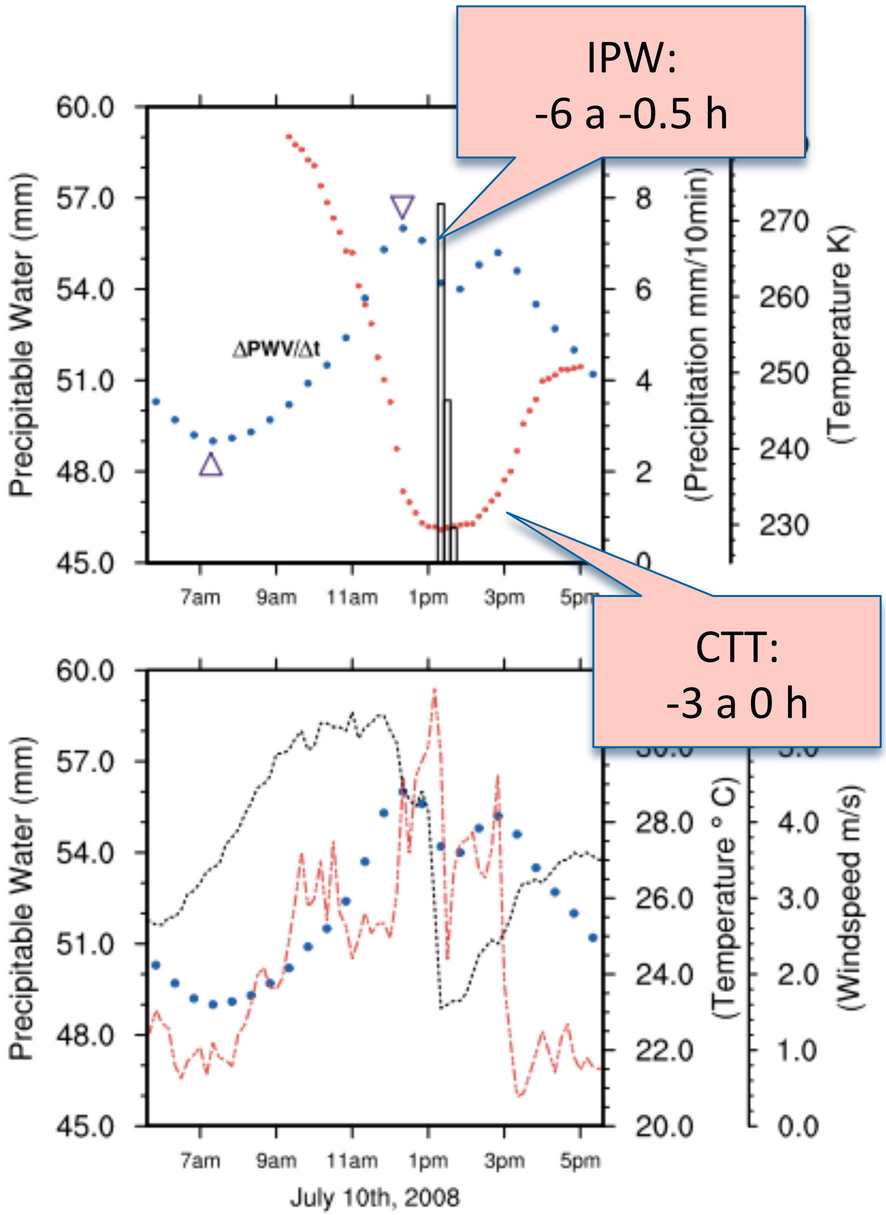
Fig. 2: Scheme of cascading moisture recycling (a) for moisture originating from the Amazon basin and (b) for moisture that has final destination the La Plata basin. In both figures, the amount of precipitation in grid cell 3 that is originating from evapotranspiration in grid cel 1 is $m_{23} \cdot m_{12}/P_2$.



EVAP-PREC
% of Amazon ET on Precip
Cascading
DRY
WET
0°
30°
60°W
(mm/month)
−240
−120
0
120
240
0.05
0.15
0.25
0.35
0.45


Terminal outflow of mass, heat, water vapour and cloud water/ice
Subsidence outside clouds to compensate for upward motion within clouds
0° C
Warm upraught
Cold downdraught
Mixing at cloud edge
Met Office

GNSS Dense Network



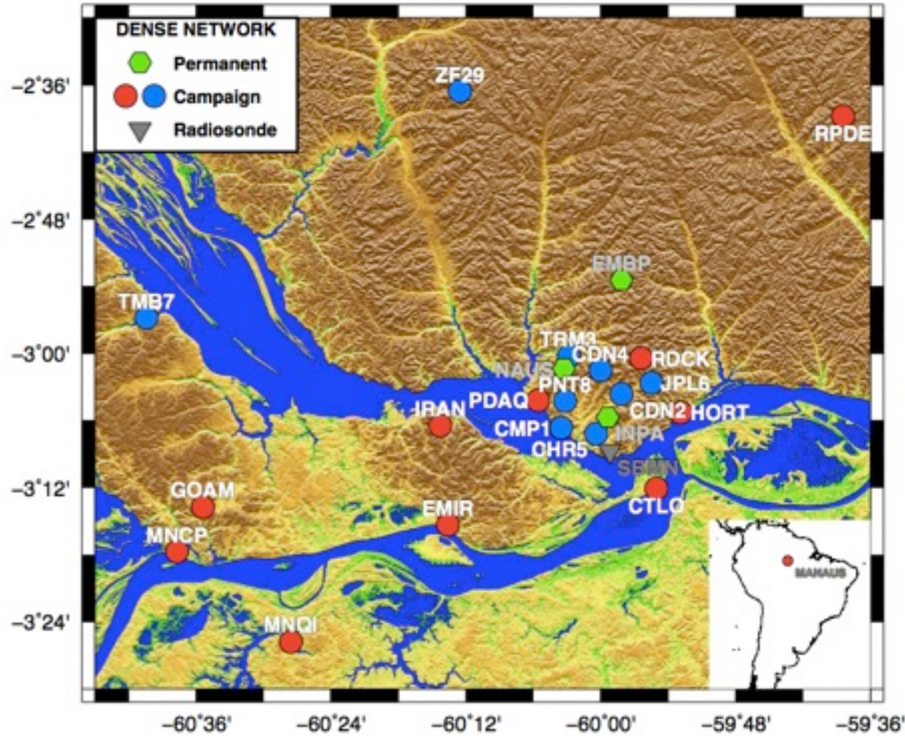
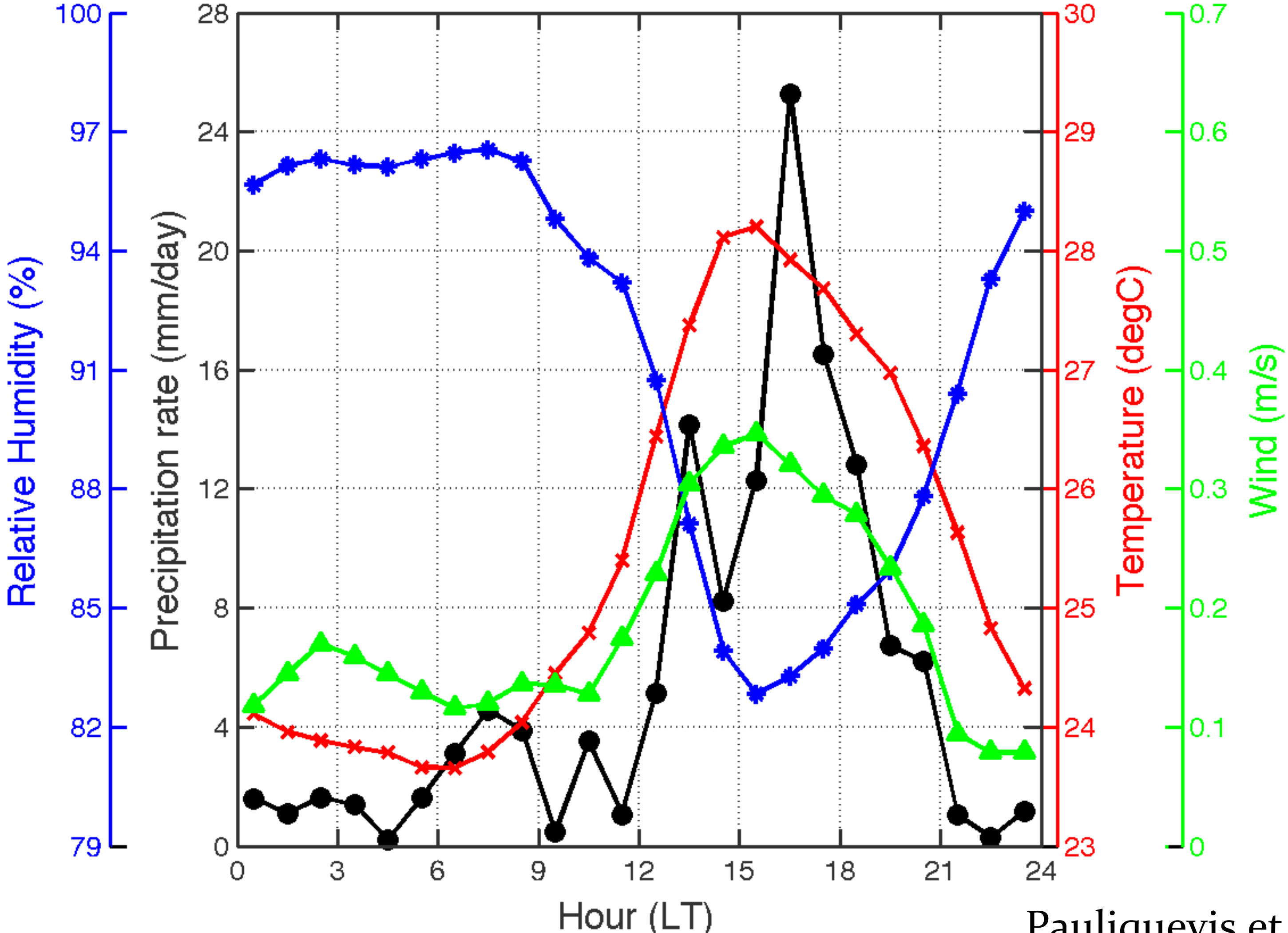


Figure 3. A typical afternoon deep convective event over INPA GNSS/meteorological station. The upper plot contains PWV (blue dots) *versus* average cloud top temperature (red) and precipitation rate (bars). The 'ramp-up' time calculated for the average ΔPWV/Δ*t* (between triangles) represents the timescale of column convergence (see Equation (2) and text for discussion). The bottom graph plots wind speed (red), temperature (black) and PWV(blue) for the deep convective event.

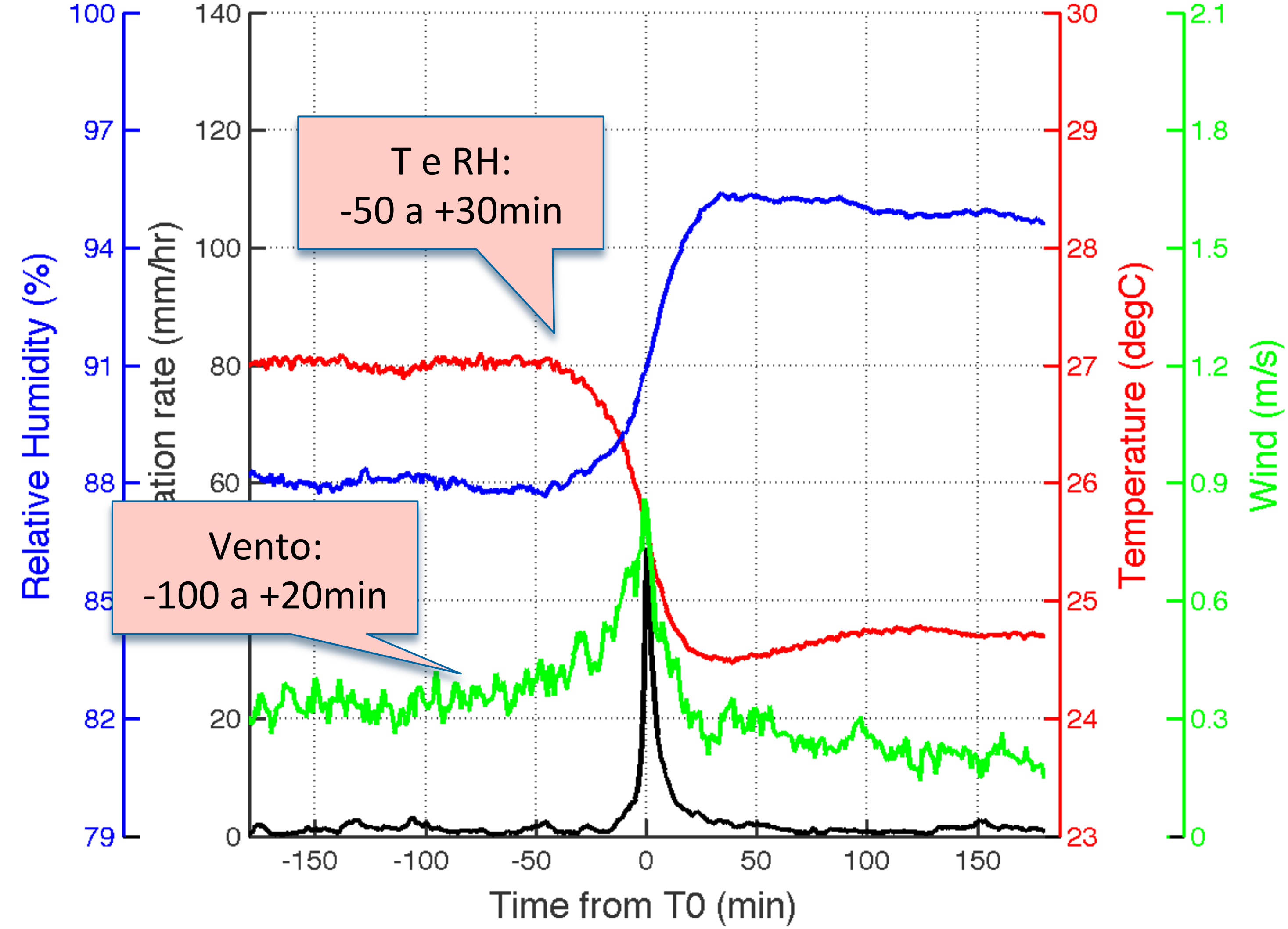
- Adams et al, Atmos. Sci. Let. 2011
- Adams et al, BAMS 2014 (accepted)

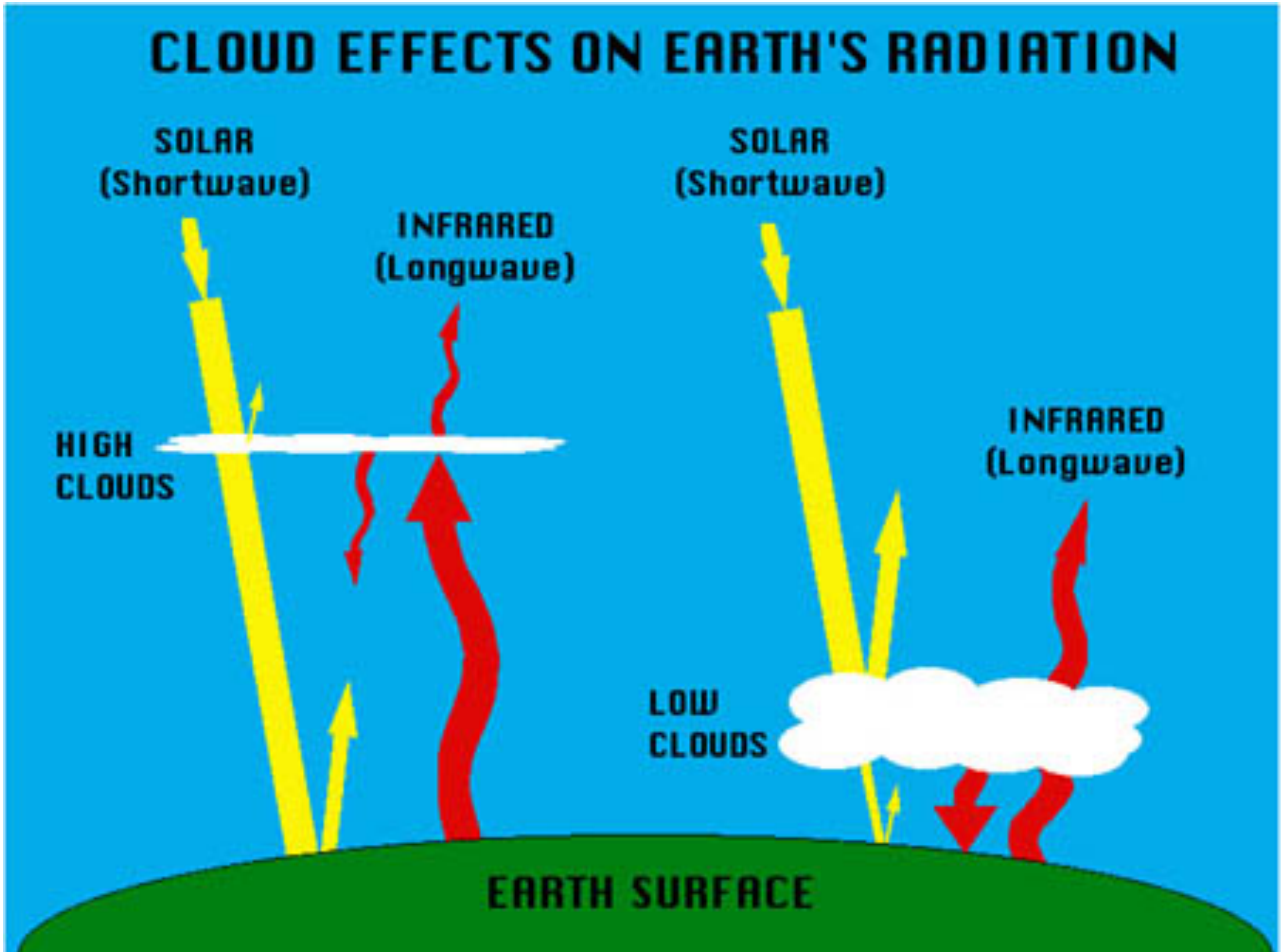
Diurnal Cycle @ Embrapa



Pauliquevis et al., in

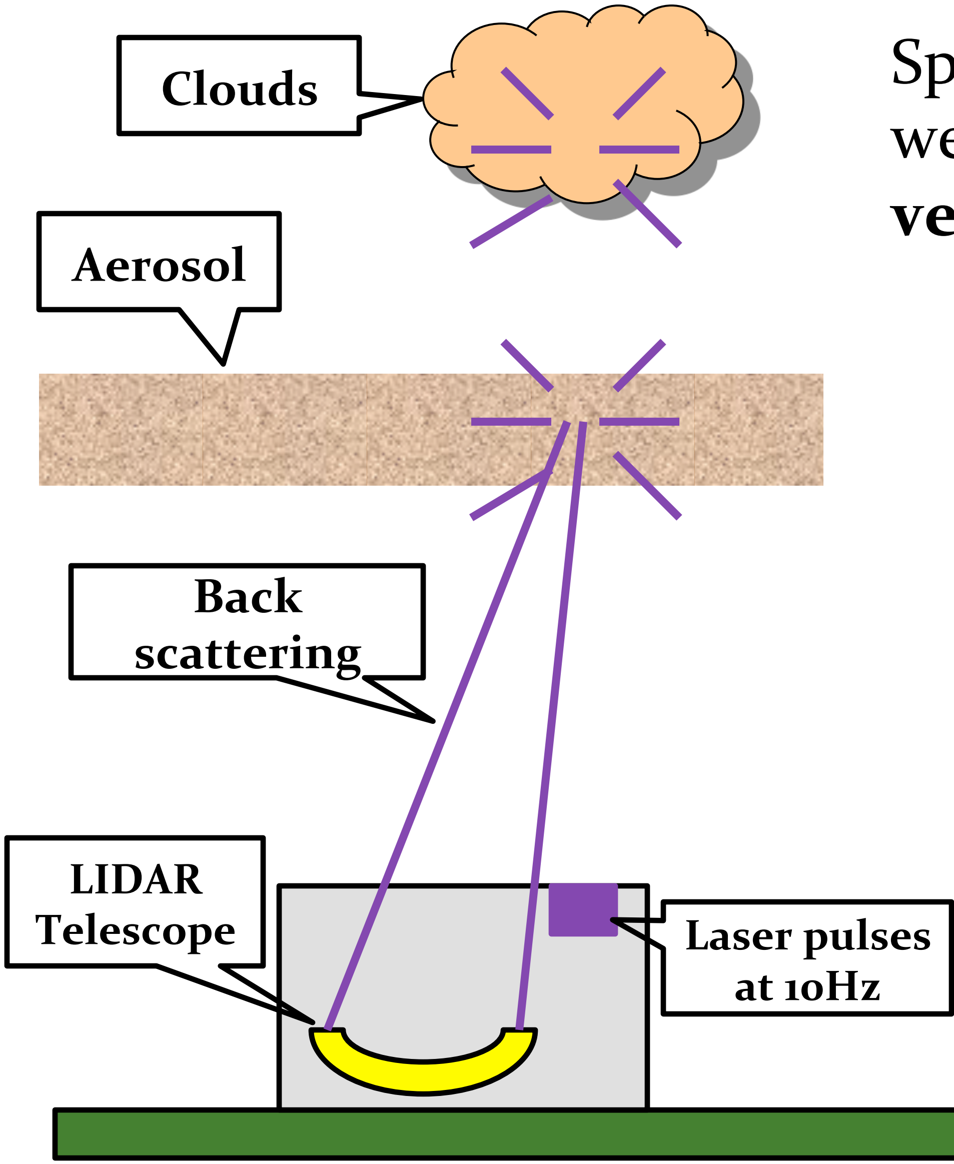
Precipitation Events Life-Cycle @ Embrapa, T0= time of max precip





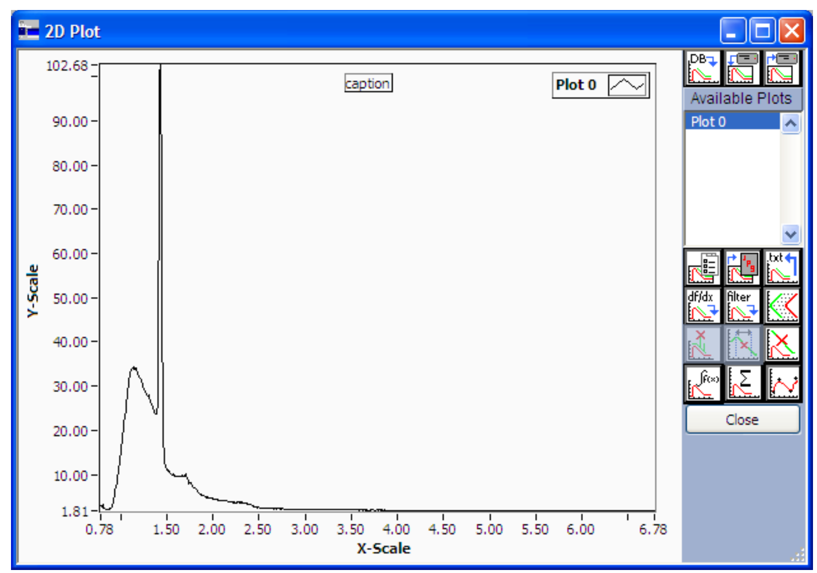
CLOUD EFFECTS ON EARTH'S RADIATION
SOLAR
(Shortwave)
INFRARED
(Longwave)
HIGH
CLOUDS
SOLAR
(Shortwave)
INFRARED
(Longwave)
LOW
CLOUDS
EARTH SURFACE

Lidar

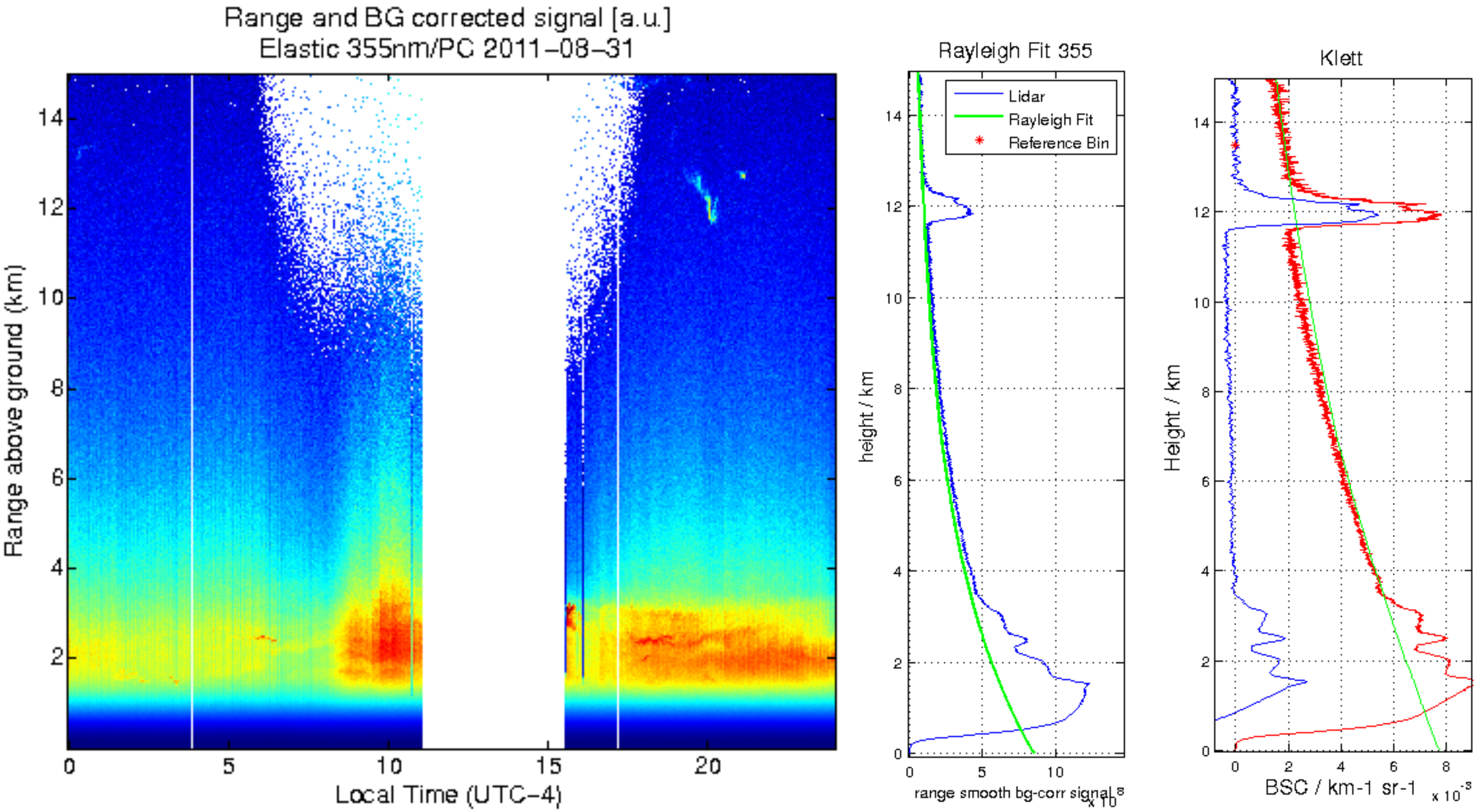


Speed of light is **3 x 10⁸ m/s** and we measure at **20Mhz**, hence **vertical resolution is 7.5m**

We measure light intensity vs time



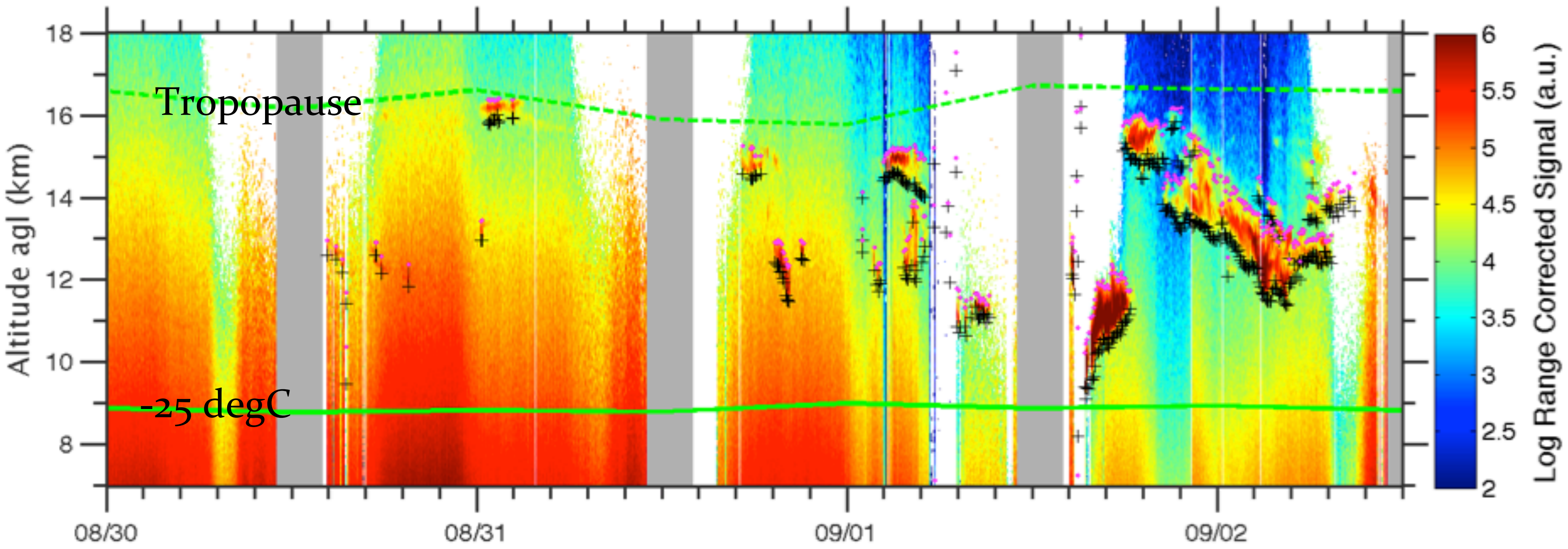
Lidar



Range and BG corrected signal [a.u.]
Elastic 355nm/PC 2011–08–31
Range above ground (km)
Local Time (UTC–4)
Rayleigh Fit 355
Lidar
Rayleigh Fit
Reference Bin
height / km
range smooth bg-corr signal
x 10^8
Klett
Height / km
BSC / km-1 sr-1
x 10^-3

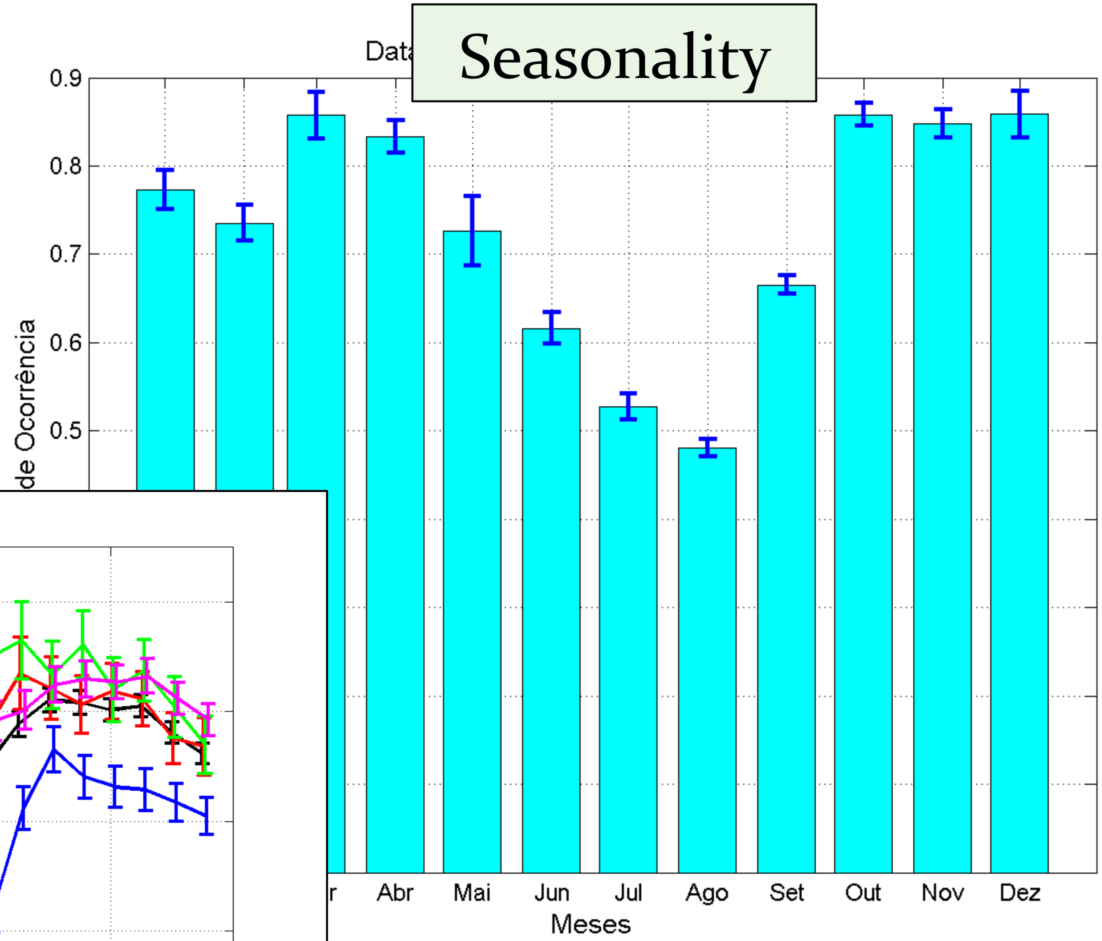
Cirrus Clouds

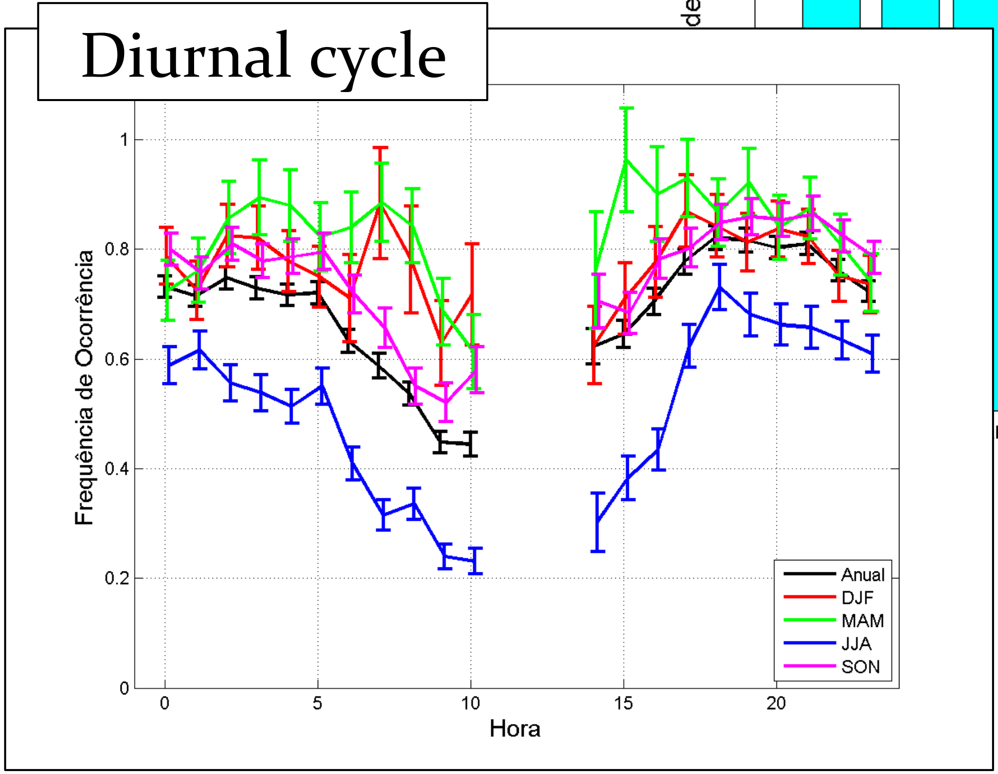
- Cirrus found from 8 to 19.6km
  - Base 12.5±2.4 km
  - Top 14.2±2.2 km



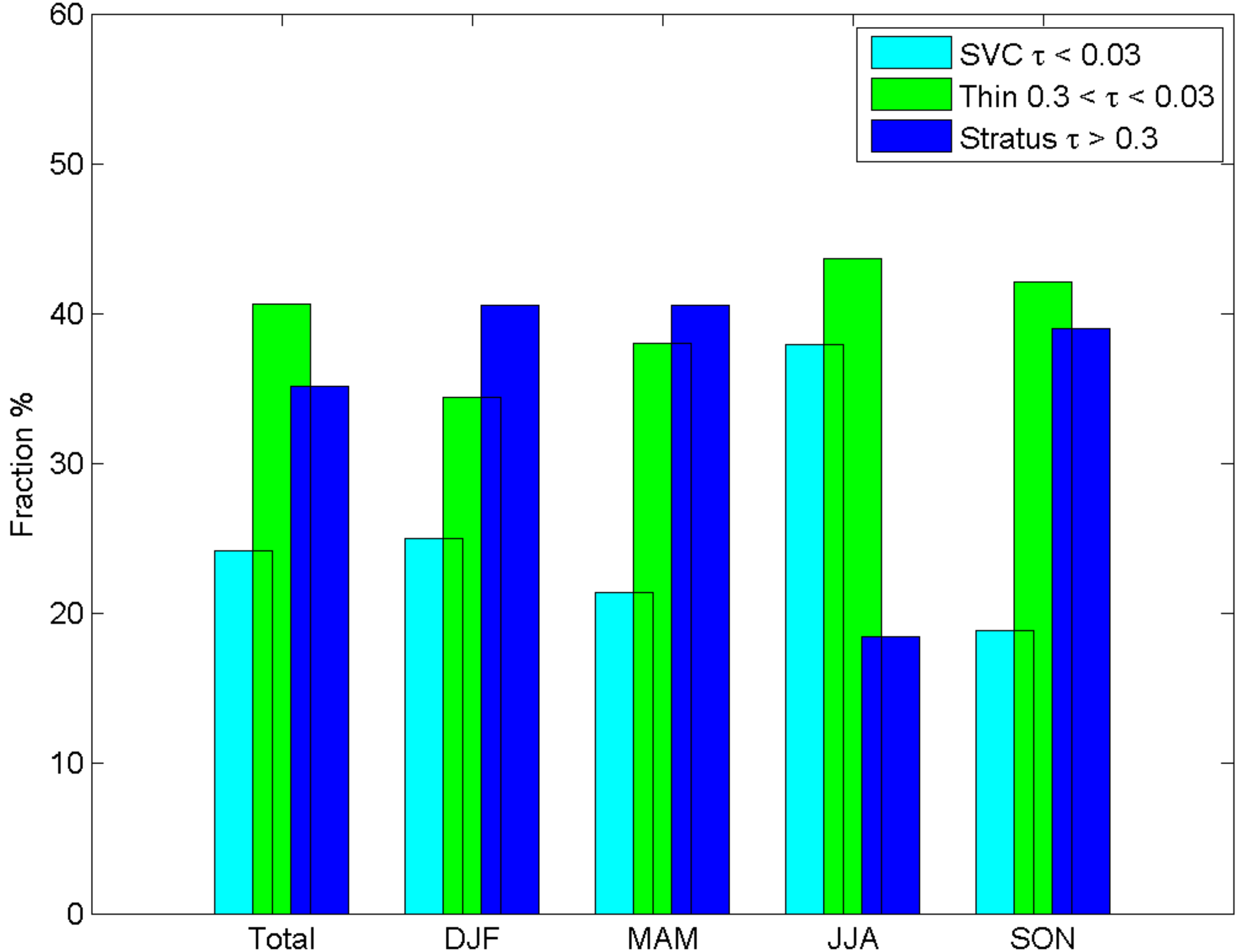
Barja & Gouveia, priv comm

- Cirrus cloud cover at Manaus
  - 83% MAM
  - 52% JJA



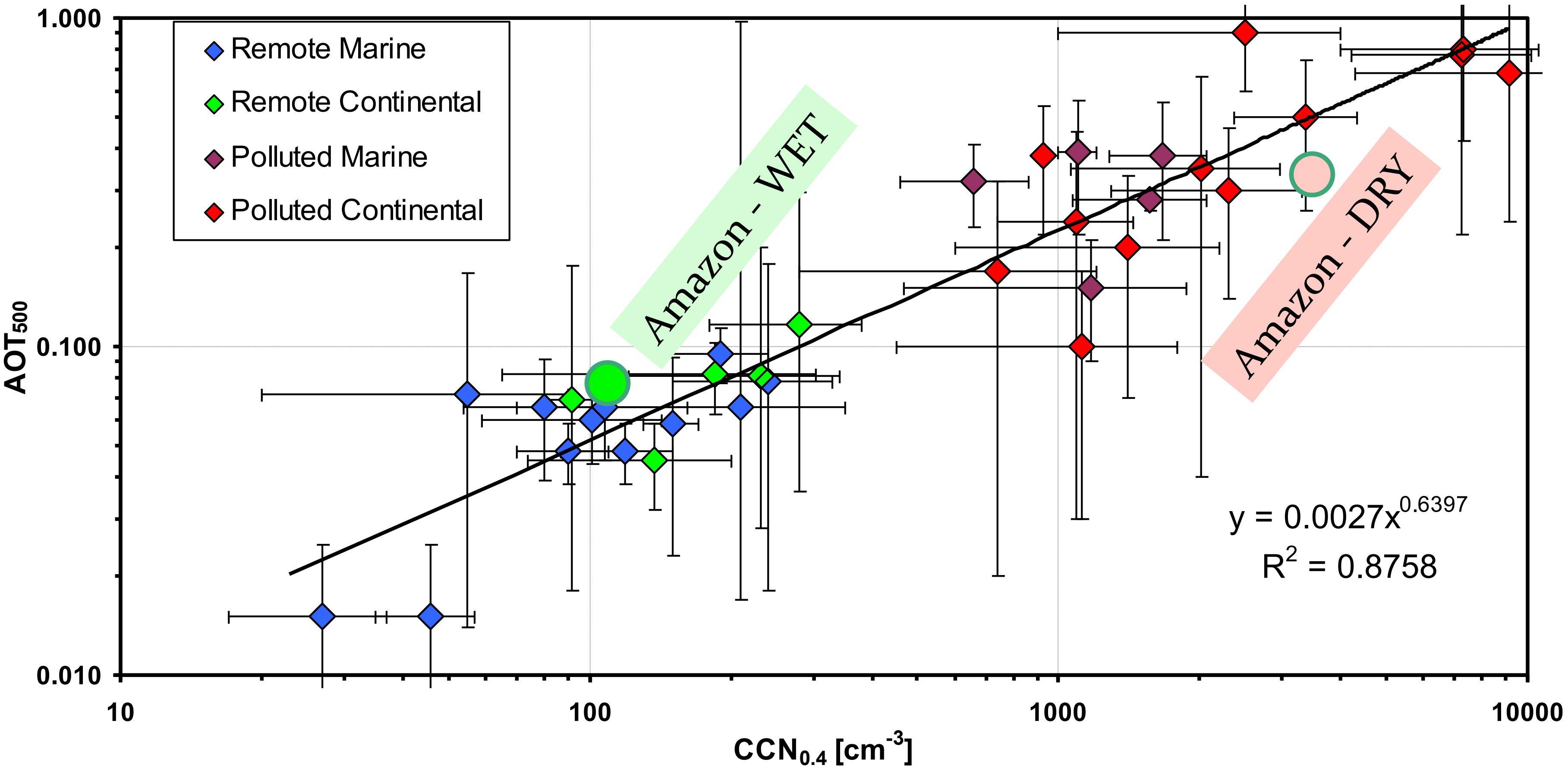


D. Gouveia, Msc dissertation, USP



Frequency 78 % 83 % 52 % 77 %

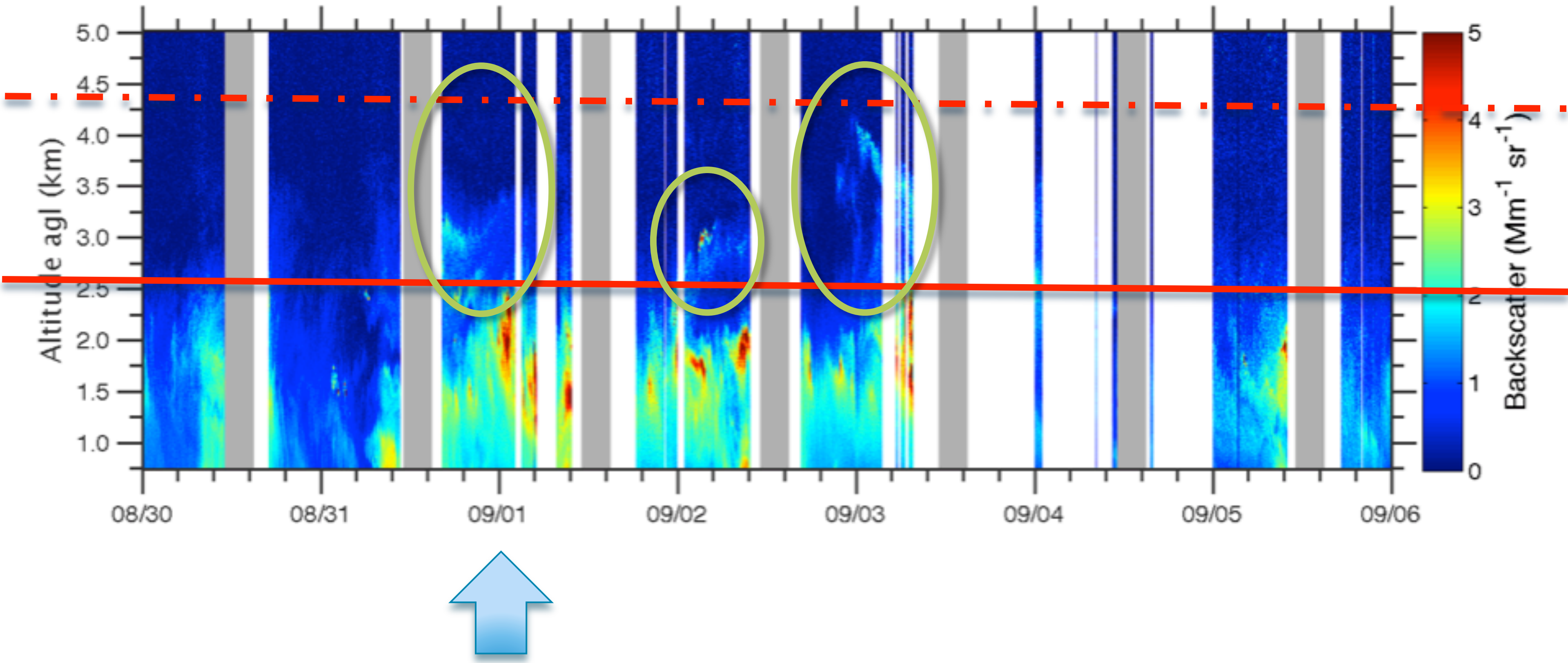
Observations of CCN and AOT



CCN concentrations and AOT over the cleanest continental sites are similar to the cleanest marine sites!

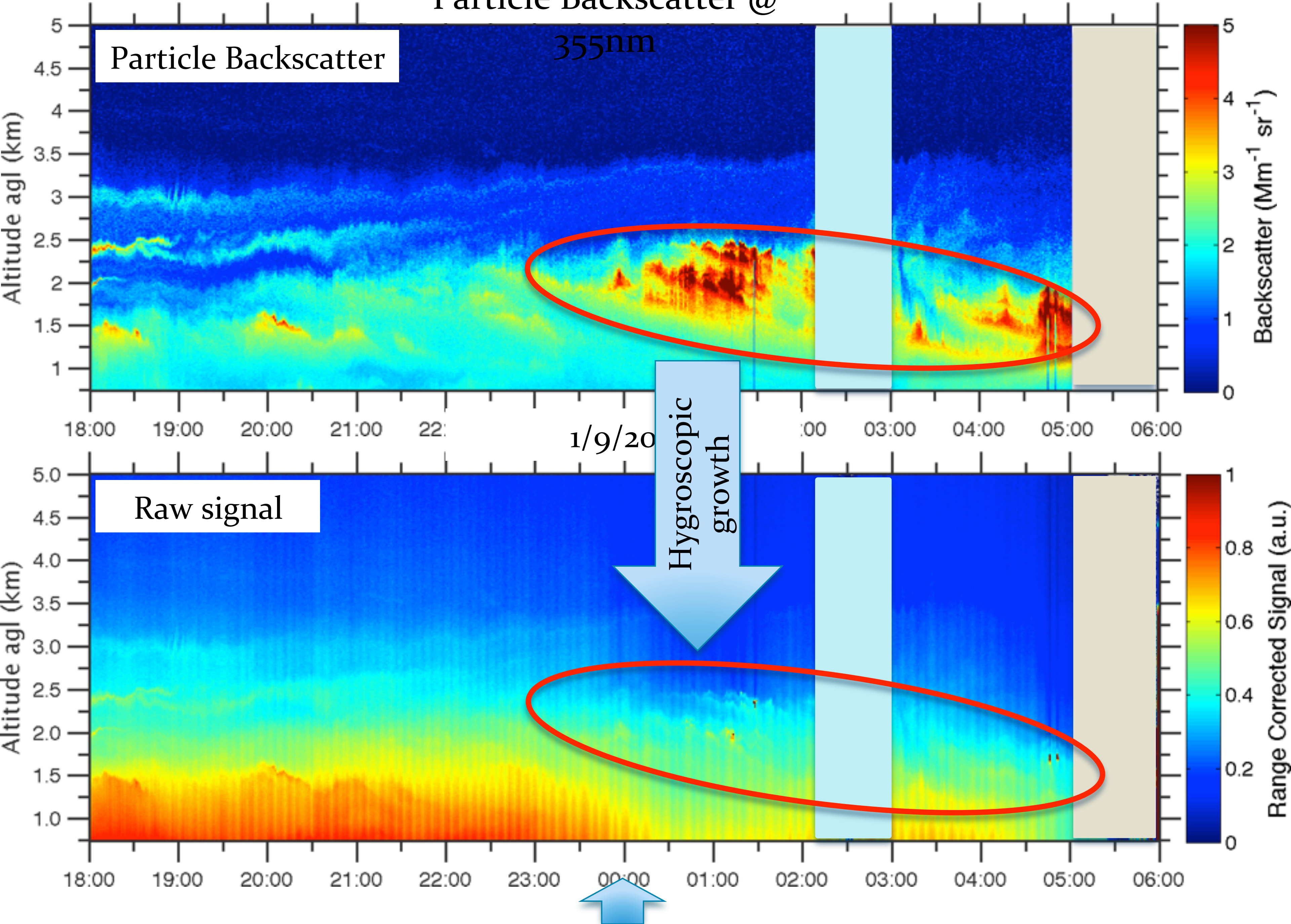
Example of Lidar Measurements

- Particle backscatter coefficient @ 355nm



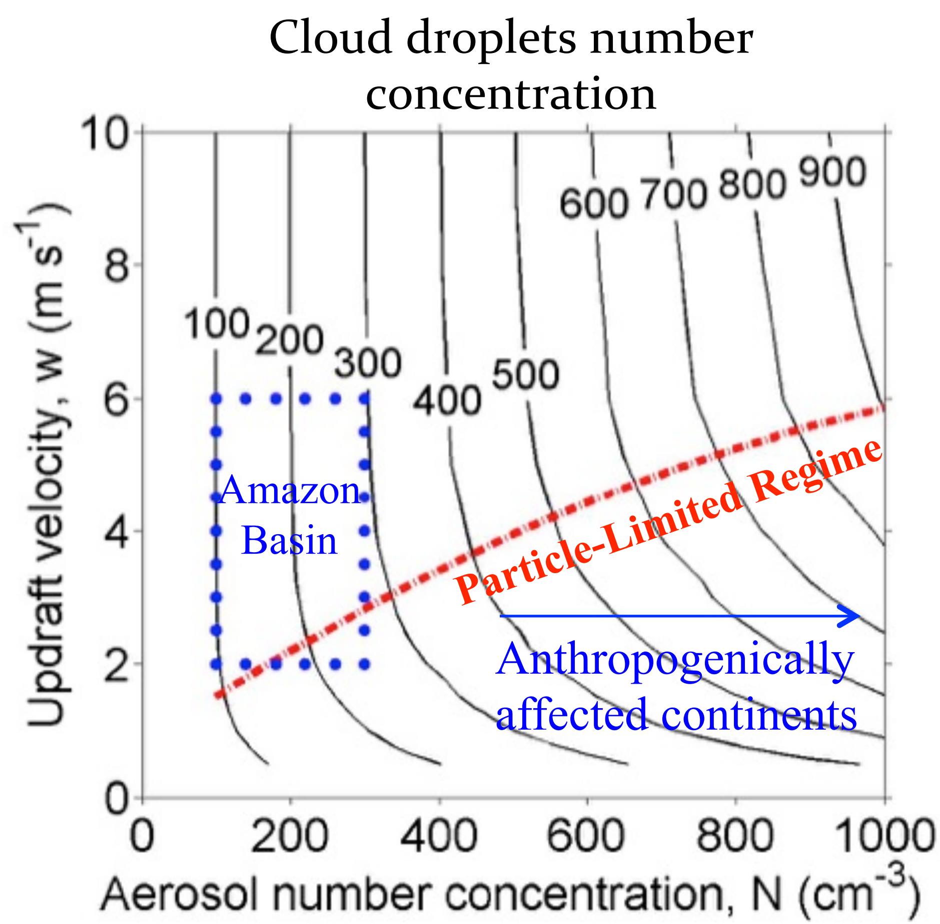
Barbosa et al., AMTD 2014

Particle Backscatter @ 355nm



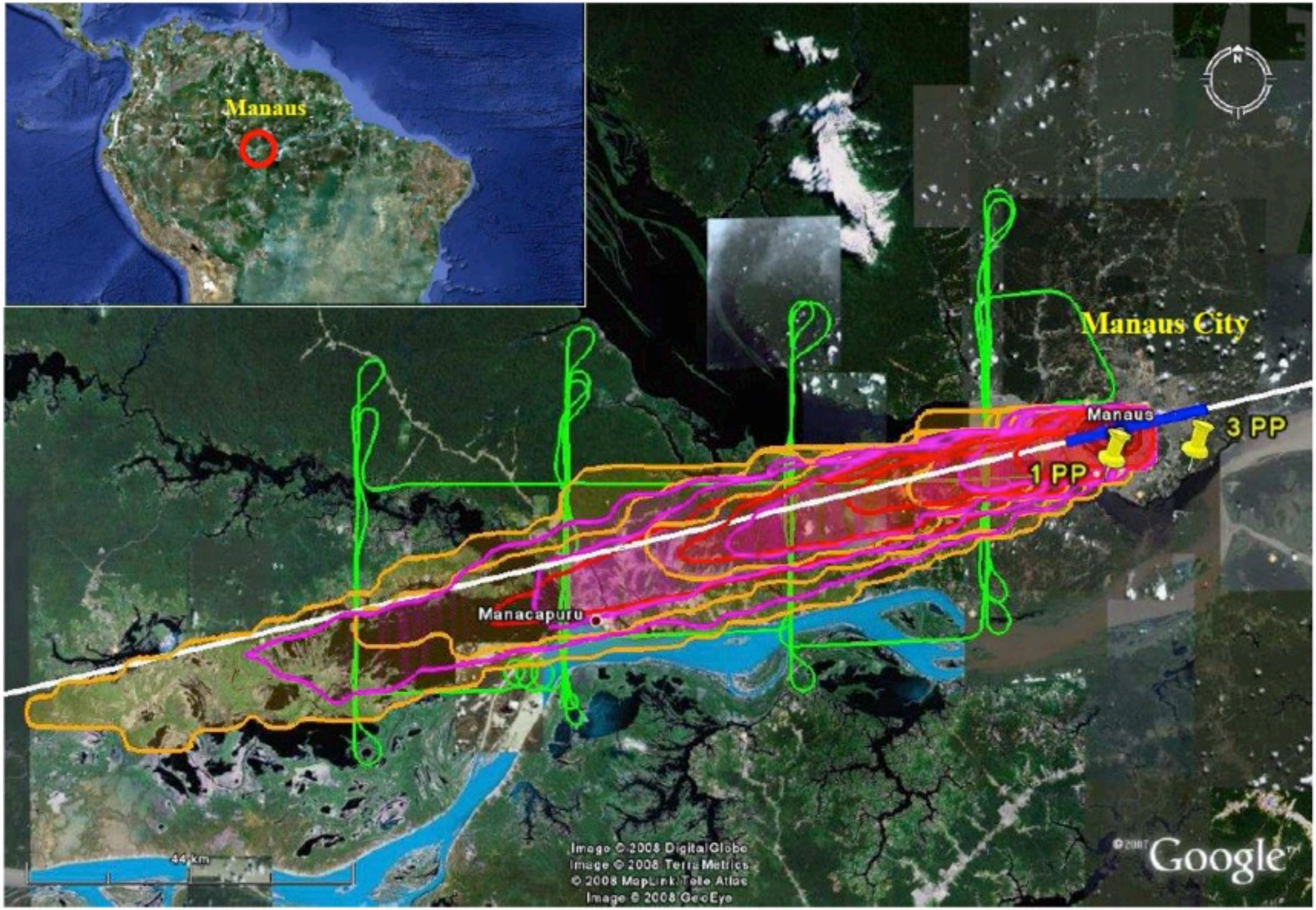
Possible Aerosol Effects

- The Amazon region is particularly susceptible to changes in CN because of the low background concentrations and high water vapor levels, indicating a regime of cloud properties that is highly sensitive to aerosol microphysics.



Poschl et al, Science 2010

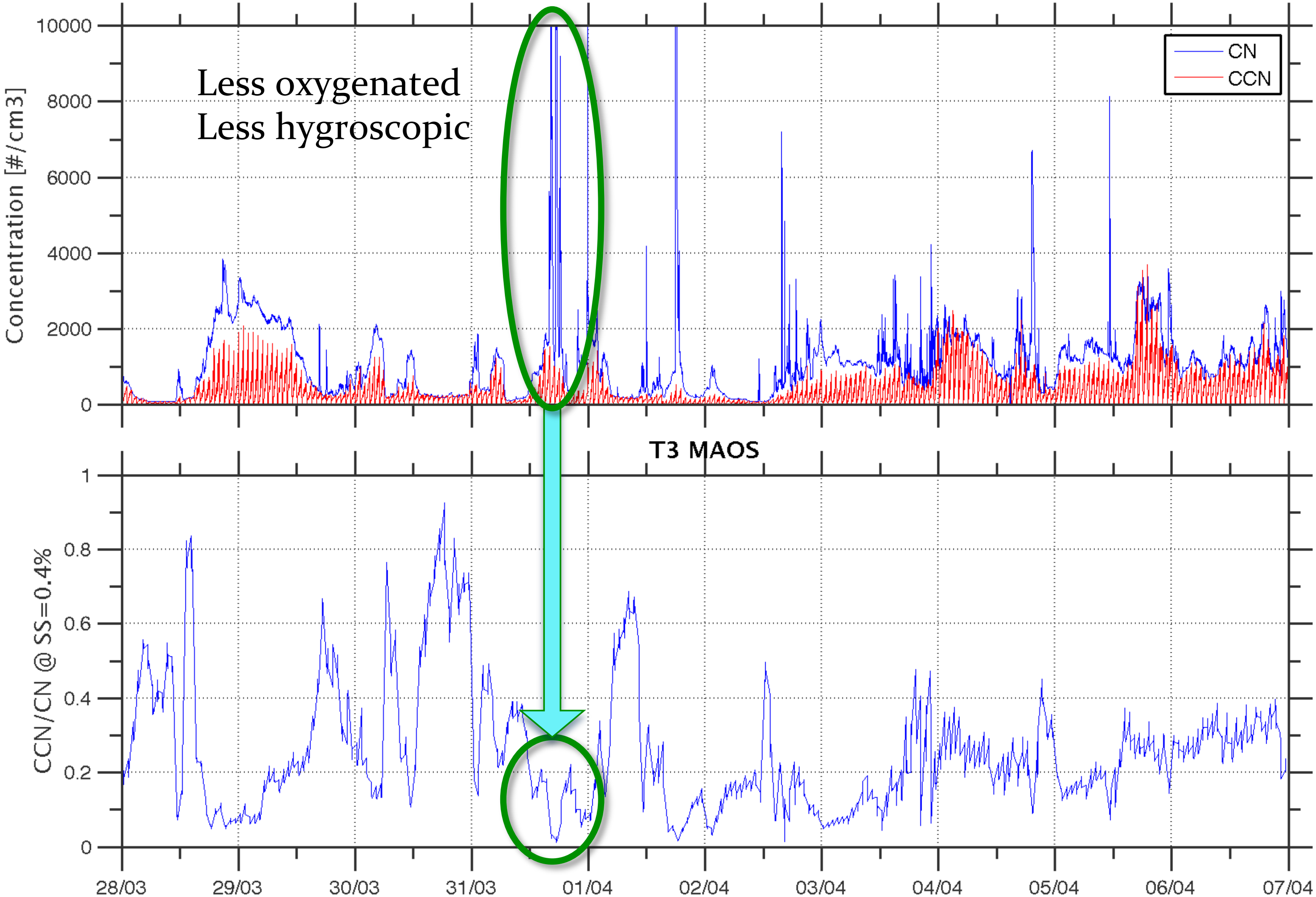
Experimento GoAmazon 2014

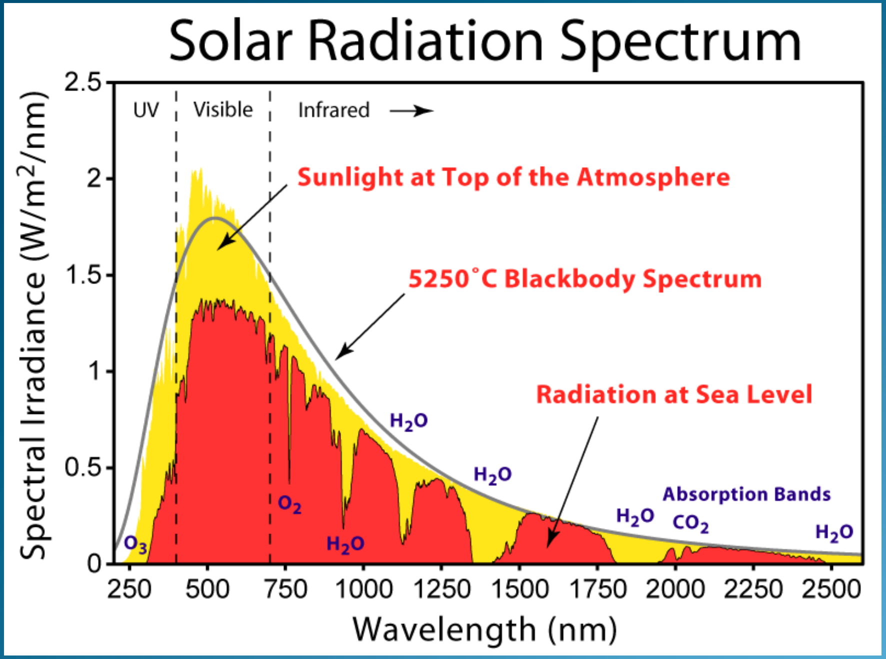


Mira's measurements

- 17-21 March
  - Initial setup
  - Calibration
  - Intercomparison w/ J. Wang at T3
- 22-26 March
  - Moved to ATTO
  - CCNC calibration
  - DMA/UHSAS calibration with PSL's
  - Started data acquis…

CCN/CN Measurements at T3





Thanks!

hbarbosa@if.usp.br

www.fap.if.usp.br/~hbarbosa