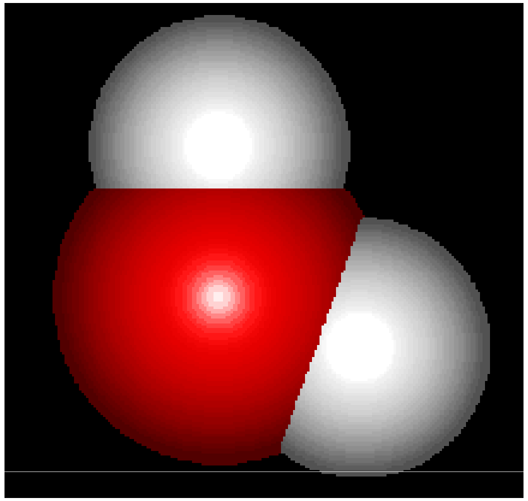
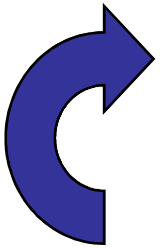
A short course on water vapor and radiation



Rémy Roca
Chargé de Recherche CNRS
Laboratoire de Météorologie Dynamique
roca@lmd.jussieu.fr

Scope of the lecture

- The water vapor radiative feedback is the most important feedback in the Earth climate system and doubles the climat sensitivity

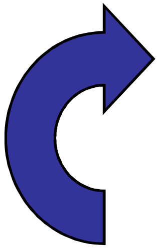


1. Initial increase in Temperature (e.g. due to CO_2)
2. If RH=cte then specific humidity increases
3. Greenhouse effect increases

- This « infernal » loop yield to run away conditions

Scope of the lecture: provide the basis to understand this !

- The water vapor radiative feedback is the most important feedback in the Earth climate system and doubles the climat sensitivity



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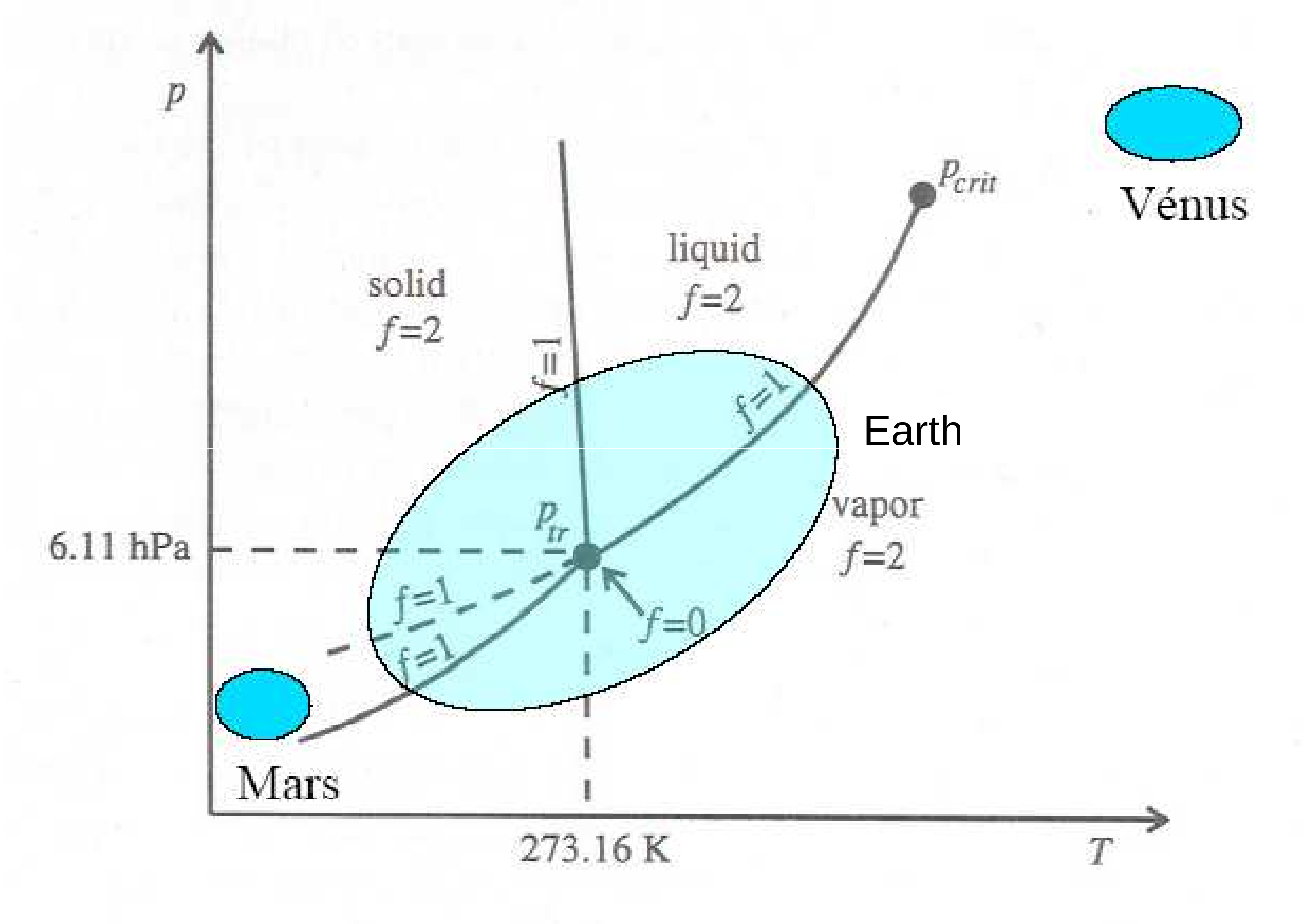
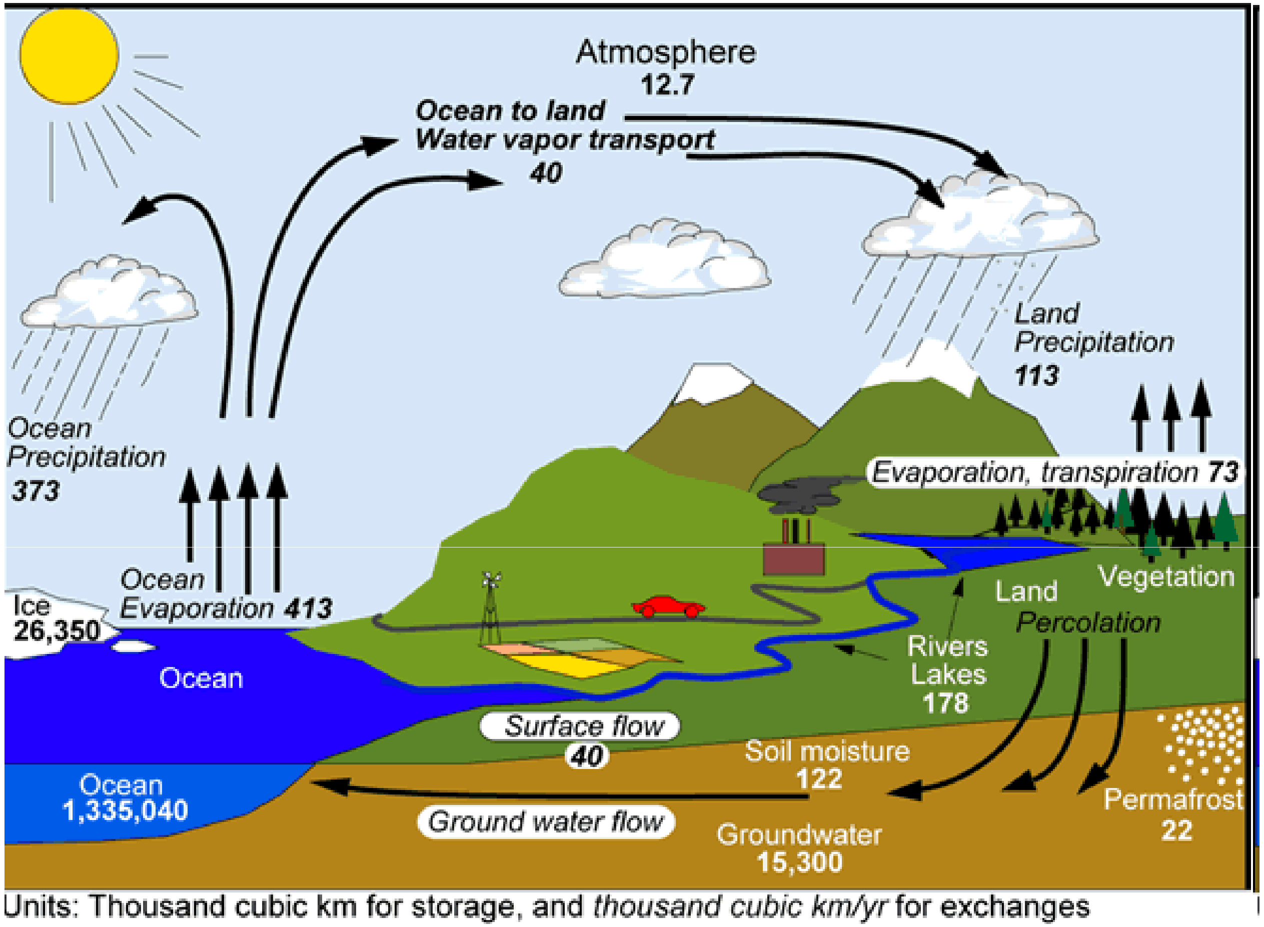
Planet Earth



On Earth the 3 phases of water are there.

The hydrological cycle



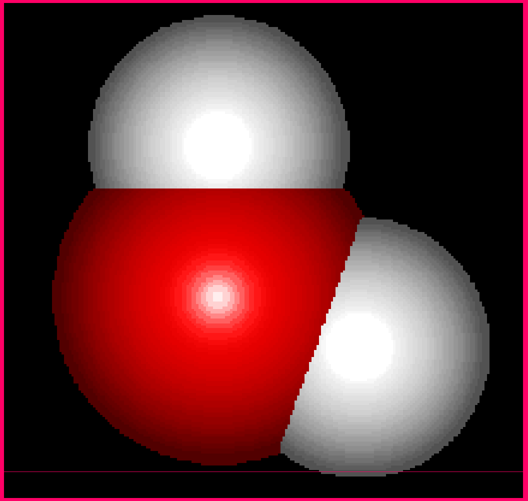
(from Trenberth)

Water vapor storage in annual global mean= 35 mm
Rainfall in annual global mean = 3.5 mm/day
Water resides ~ 10 days in the atmosphere in the form of vapor

Outline of the lecture

- Water vapor in the atmosphere
  - Basis
  - Climatology
- Long wave Radiation in the atmosphere
  - Basis
  - Water vapor and radiation
- The water vapor feedback
  - Classical views
  - Key regions

A short course on water vapor and radiation



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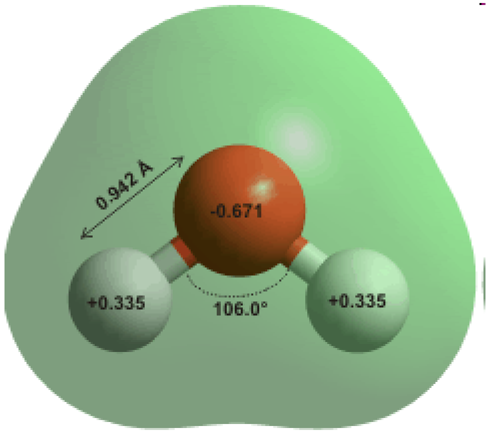
Laboratoire de Météorologie Dynamique
roca@lmd.jussieu.fr

Outline of the lecture

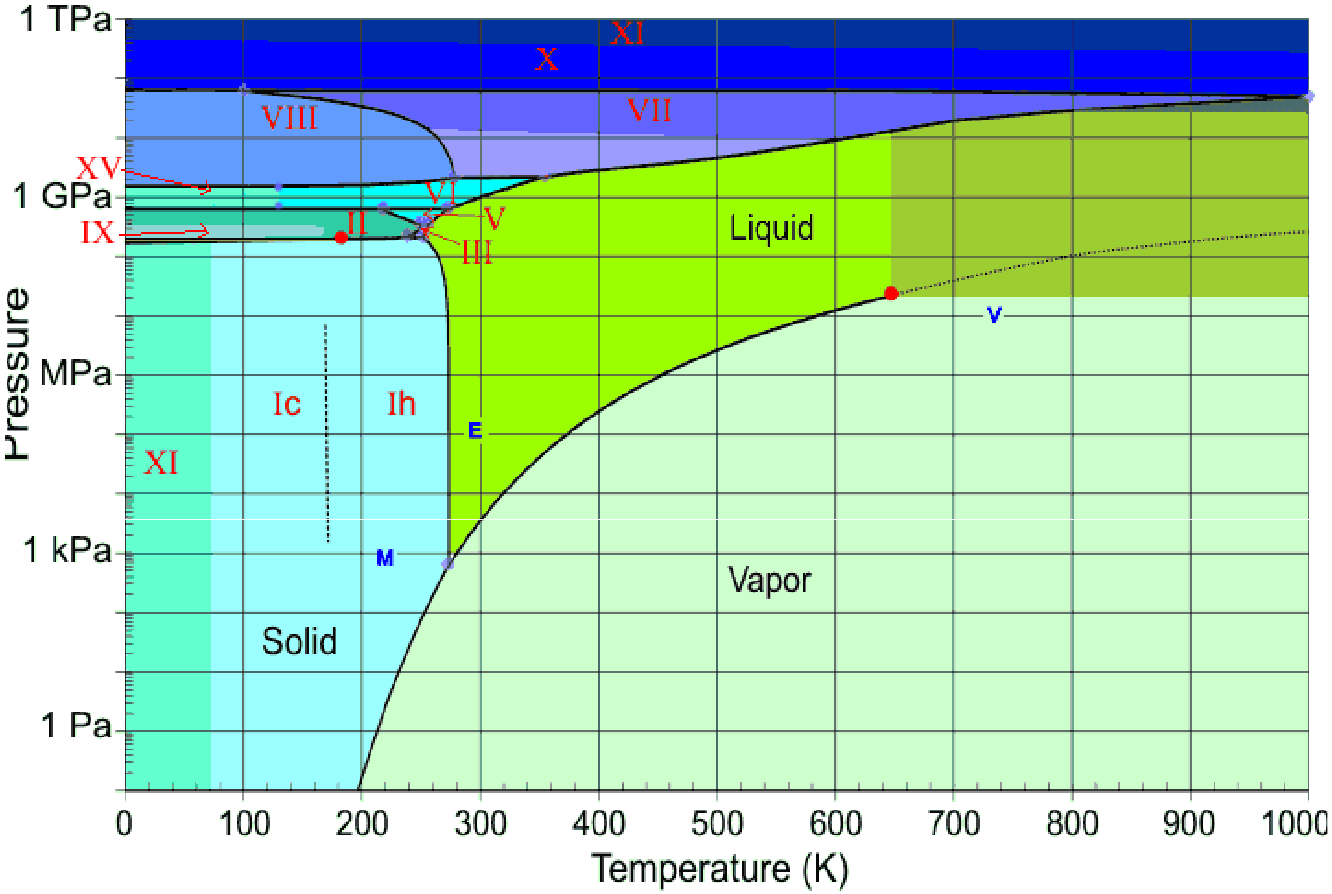
- Water vapor in the atmosphere
  - Units and definitions
  - Saturation vapor pressure
  - Climatology and variability

- Long wave Radiation in the atmosphere
- The water vapor feedback

The water molecule



From Martin Chaplin



On Earth,

H_2O exists in three phases

- Water liquid
- Water solid (ice)
- Water vapor

Isotopologues (e.g., $H_2{}^{18}O$)

Moist thermodynamics in 1 slide !

- Moist air is considered as a mixture of dry and vapor both assumed ideal gas

Ideal gas law dry air

Density

Temperature

$$p_d = \rho_d R_d T$$

Pressure

Gas Constant for dry air = 287 J Kg^{-1} K^{-}

Water Vapor

$$e = \rho_v R_v T = \rho_v \frac{R_d}{\varepsilon} T$$

Vapor pressure

vapor density

Gas constant for Vapor = 461 J Kg^{-1} K^{-1}

0.622

From Bechtold and Tompkins

Moist thermodynamics in 1 slide !

$$p = p_d + e; \qquad p_d = pN_d; e = p\,N_v$$

$$\Rightarrow \frac{dp}{p} = \frac{dp_d}{p_d} = \frac{de}{e}$$

Partial pressures add if both gases occupy same volume V.

N_x are the mol masses

$$\left.\begin{array}{l} p_d V = m_d R_d T \\ eV = m_v R_v T \end{array}\right\} \Rightarrow pV = T(m_d R_d + m_v R_v)$$

From Bechtold and Tompkins

Water vapor units and definition

1. Vapour Pressure Pa e

$\varepsilon = R_d / R_v = 0.622$

2. Absolute humidity $kg\ m^{-3}$ $\rho_v = \frac{m_v}{V}$

3. Specific humidity $kg\ kg^{-1}$

Mass of water vapour per unit moist air

$$q = \frac{m_v}{m_d + m_v} = \frac{\rho_v}{\rho} = \varepsilon \frac{e}{p - (1-\varepsilon)e} \approx \varepsilon \frac{e}{p}$$

4. Mixing ratio $kg\ kg^{-1}$

Mass of water vapour per unit dry air

$$r = \frac{m_v}{m_d} = \frac{\rho_v}{\rho_d} = \varepsilon \frac{e}{p - e} \approx \varepsilon \frac{e}{p}$$

$$q = \frac{r}{1+r} \qquad r = \frac{q}{1-q}$$

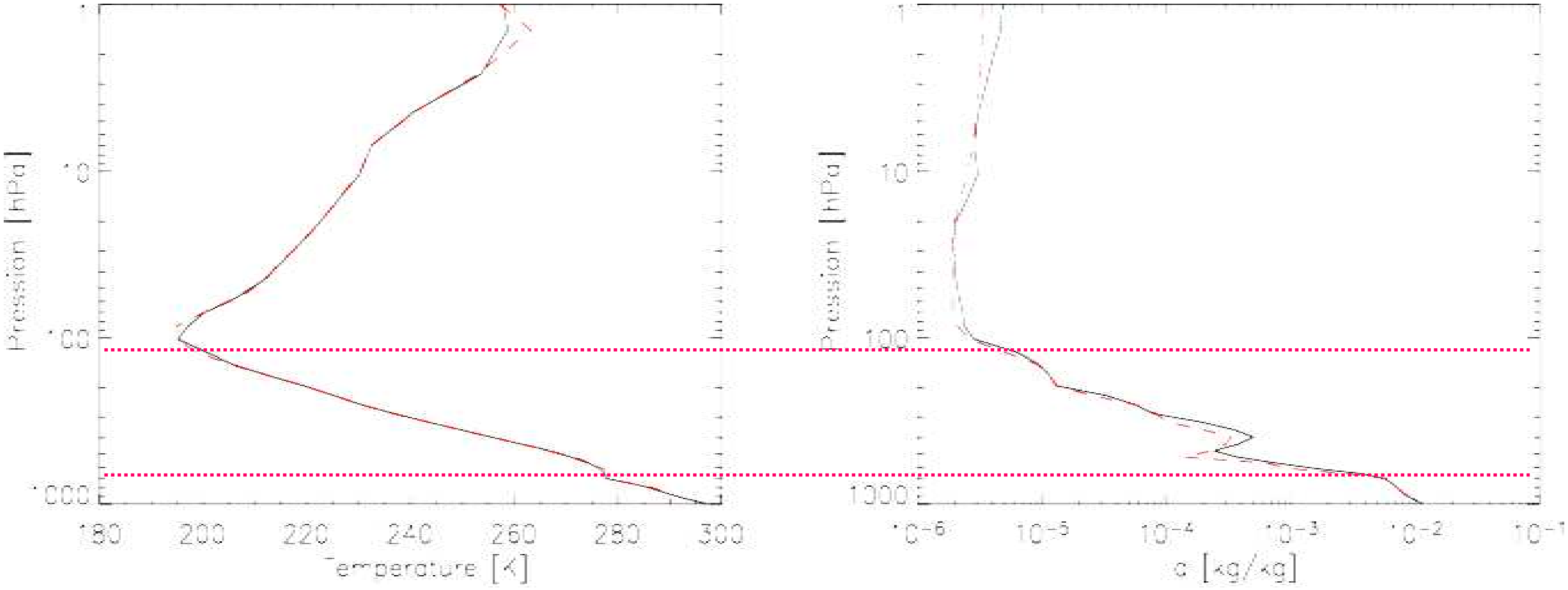
For atmospheric conditions

q~r

Bechtold and Tompkins

Water vapor in the atmosphere and P_{wat}

One profile of T and q, the specific humidity in the atmosphere (from ERAinterim)



An column integrated water vapor quantity
Precipitable water: P_{wat}

$$P_{wat} = \frac{1}{g}\int_0^\infty q(p)dp$$

kg.m^{-2} (mass)
or
mm (volume)

Outline of the lecture

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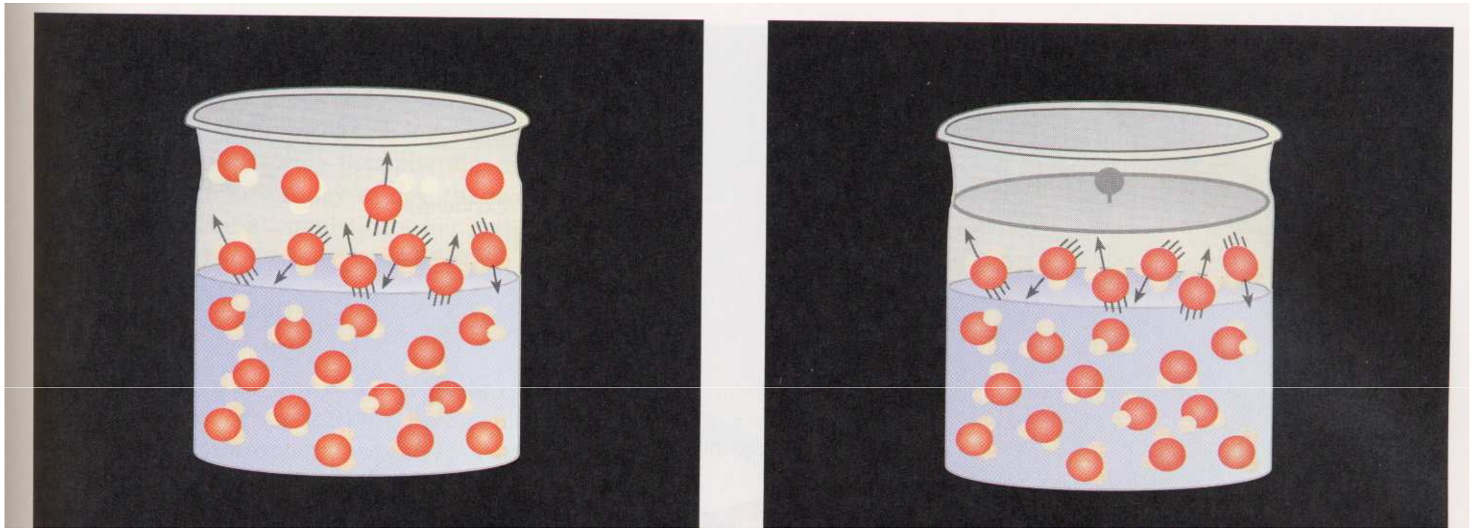
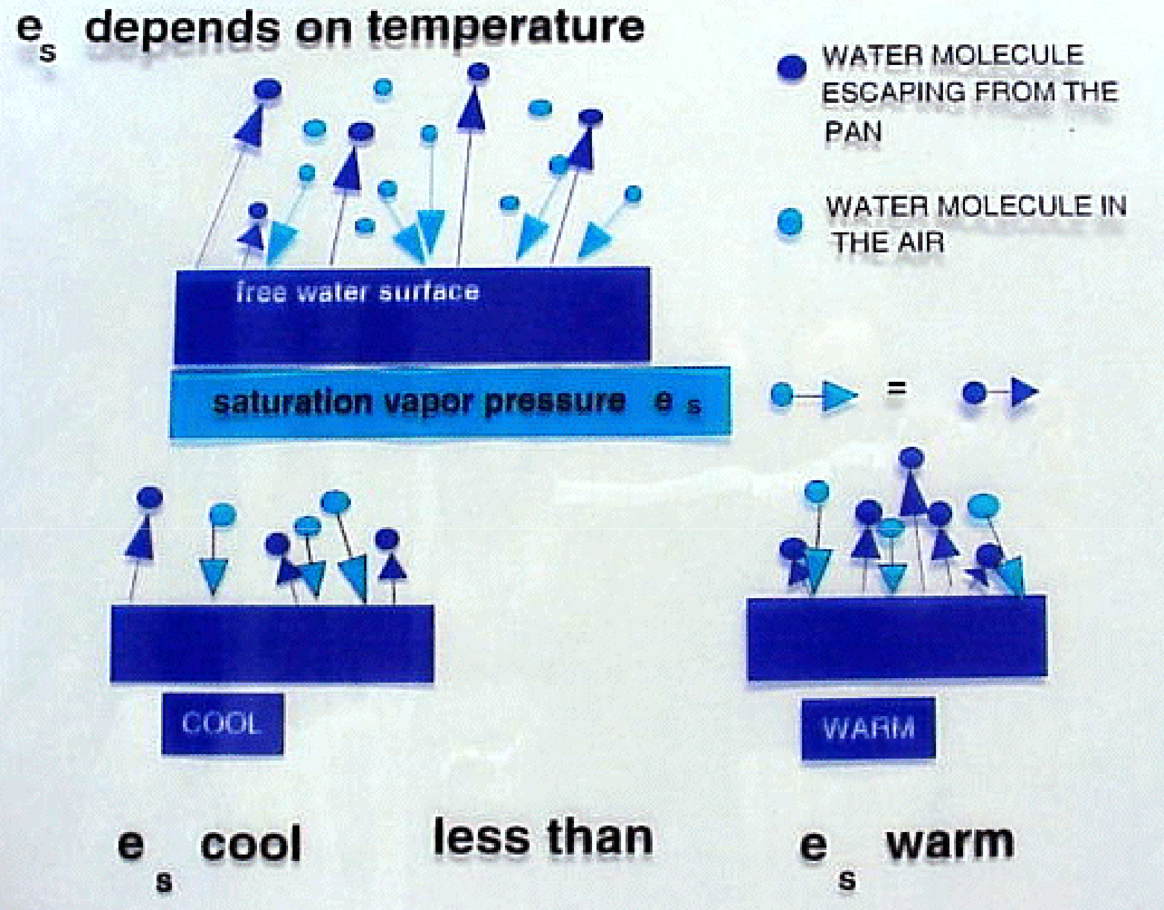
Water vapor saturation



- Water molecules move freely in between the two liquid / vapor phases
- Equilibrium is reached when the rate of exchange in the two directions is equal
  - That point is called the saturation point with respect to liquid water
  - Equilibrium does not mean there is not exchange

Water vapor saturation

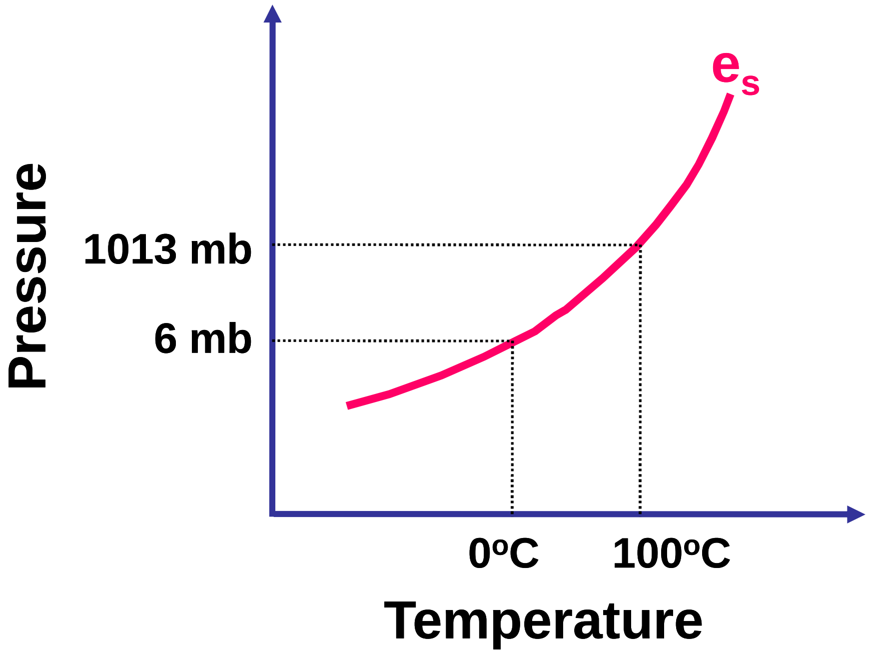


Es increase with temperature

Formulae based on « pan-évaporation »
In the atmopshere pollution, sursaturation, etc…

Water vapor saturation

- Equilibrium Curve that describes this temperature dependence
- From basics thermodynamics principles



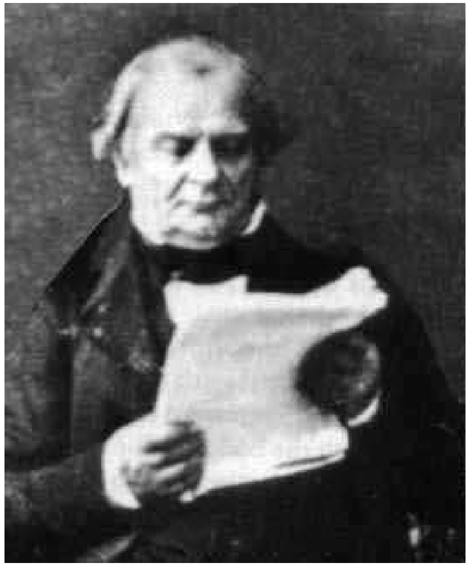
Adapted from Prof. F.Remer
Univ. North Dakota

The Clausius-Clapeyron equation

The Clausius Clapeyron equation describes the non linear relationship between the saturation vapor pressure e_s and temperature

Rudolf Clausius
1822 – 1888

German Mathematical Physicist



Emile Clapeyron
1799 - 1864

French Engineer

The Clausius-Clapeyron equation

The Clausius Clapeyron equation describes the non linear relationship between the saturation vapor pressure e_s and temperature

$$\frac{d \ln e_s}{dT} = \frac{L_{c,s}}{R_V T^2}$$

e_S saturation vapor pressure wrt a plane surface
R_V=gaz constant for water vapor (461 $JK^{-1}kg^{-1}$)
$L_{C,S}$=Latent heat of evaporation/sublimation

$$e_s = e_s(T_0)\exp(\frac{L_{c,s}}{R_V}(\frac{1}{T_0} - \frac{1}{T}))$$

(Assuming L independent of T)

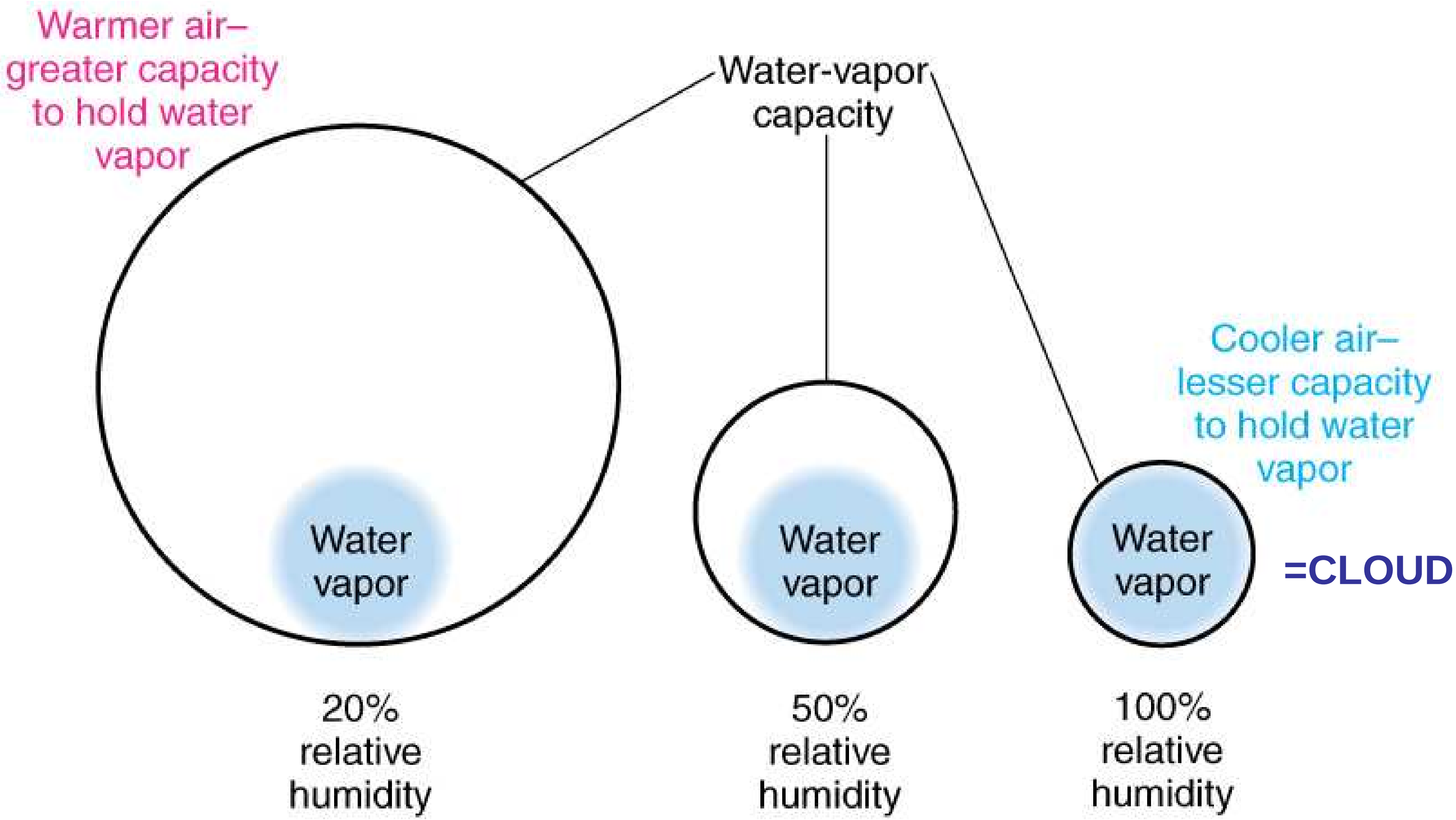
e_s depends only on temperature et increase exponentially

A reference: Es(0℃)=6.11hPa

This formulae is fundamental to Earth (and others planets) climate

Saturaturation vapor pressure and relative humidity

$$\text{Relative Humidity} = \frac{\text{Actual water vapor content of air}}{\text{Maximum water vapor } \textit{capacity} \text{ of air}} \times 100$$



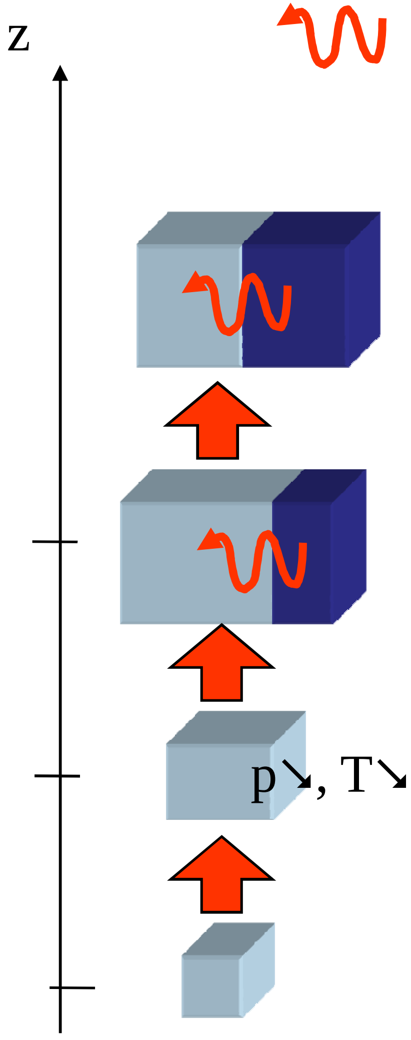
=CLOUD !

Water vapor in an ascending air mass

p *Total pressure*

p_a, e *Partial pressure*

e_w *Saturation vapor pressure*



Latent heat release

Dry air + water vapor (r_w↘)
+ liquid water (r_l↗)
$$p = p_a + e_w$$

Dry air + water vapor (r_w)
+ liquid water (r_l) $e = e_w$
$$p = p_a + e_w$$

Dry air + water vapor (r)
$$p = p_a + e$$

Dry air+ water vapor (r)
$$p = p_a + e$$

Condensation level

Saturated air mass

$r = r_c$ *Cloudy air*

Unsaturated air mass

Specifique humidity

$$q = \frac{m_v}{m} \approx \frac{m_v}{m_a} = r < r_c$$

Saturaturation vapor pressure and relative humidity

Relative humidity

$$RH \equiv 100\frac{w}{w_s}$$

w is the mixing ratio

$$w = \frac{m_v}{m_d}$$

$$ws = \frac{m_{vs}}{m_d}$$

Vapor and dry air perfect gas
ρ’ is partial pressure (Dalton’s law)

$$ws = \frac{\rho'_{vs}}{\rho'_d} = \frac{e_s/(R_v T)}{(p-e_s)/(R_d T)}$$

RH depends upon the number of molecules (w) as well on T through es and on P through ws

$$ws = 0.622\frac{e_s}{(p-e_s)} \approx 0.622\frac{e_s}{p}$$

For atmospheric pressure ranges

RH=100% : formation of clouds

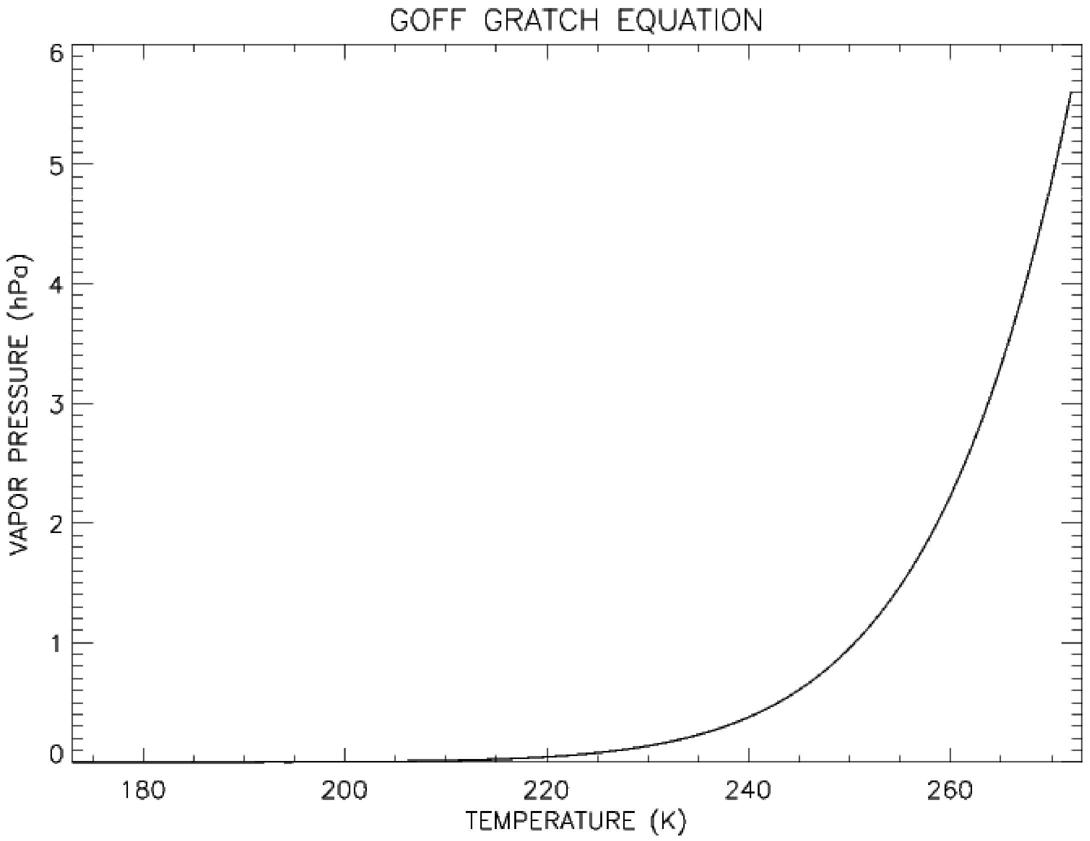
Computation of water vapor pressure over water

One reference is the Goff Gratch equation to compute vapor pressure over liquid water below 0℃.

$$\mathrm{Log}_{10}\, e = -7.90298\,(373.16/T-1) + 5.02808\,\mathrm{Log}_{10}(373.16/T) - 1.3816\mathrm{e}{-7}\,(10^{11.344\,(1-T/373.16)} - 1) + 8.1328\mathrm{e}{-3}\,(10^{-3.49149\,(373.16/T-1)} - 1) + \mathrm{Log}_{10}(1013.246)$$

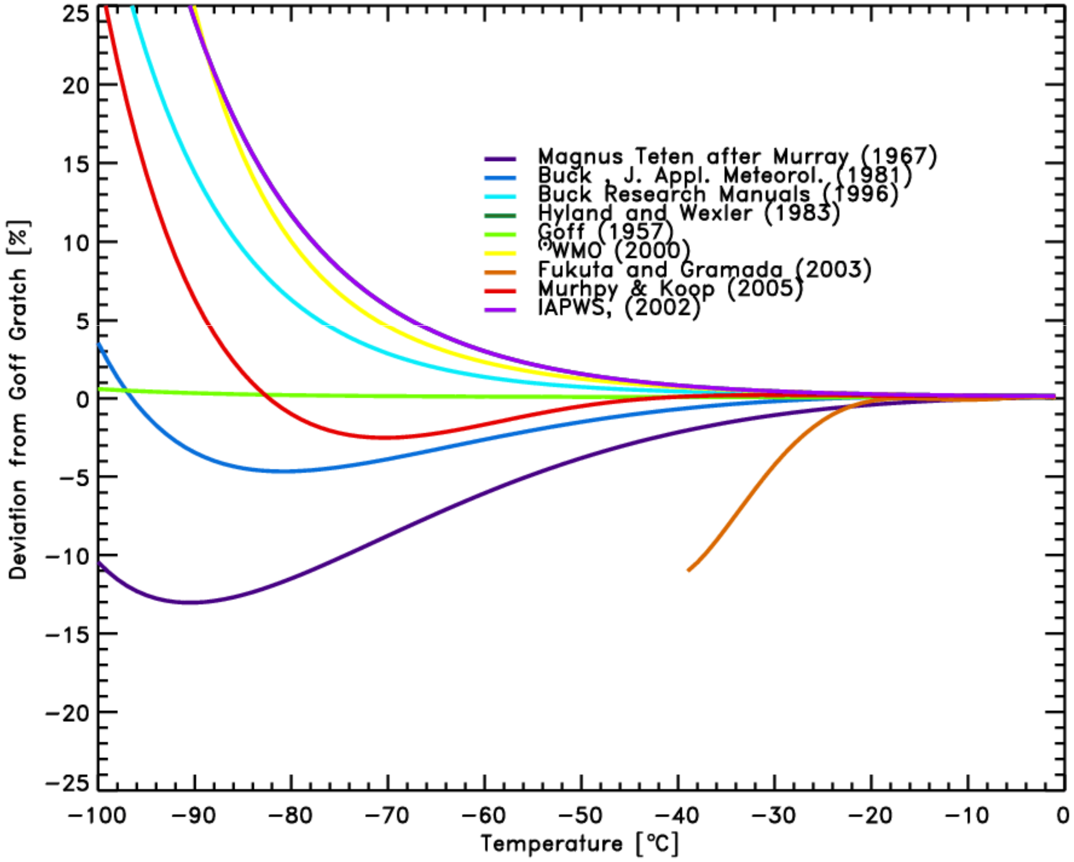
with T in Kelvin and e in hPa.

Note that it is the standard WMO practice to report any radiosondes measurements of moisture using liquid water as a reference independently of the temperature regime



Computation of water vapor pressure over water

- There is a large number of saturation vapor pressure equations used to calculate the pressure of water vapor over a surface of liquid water.



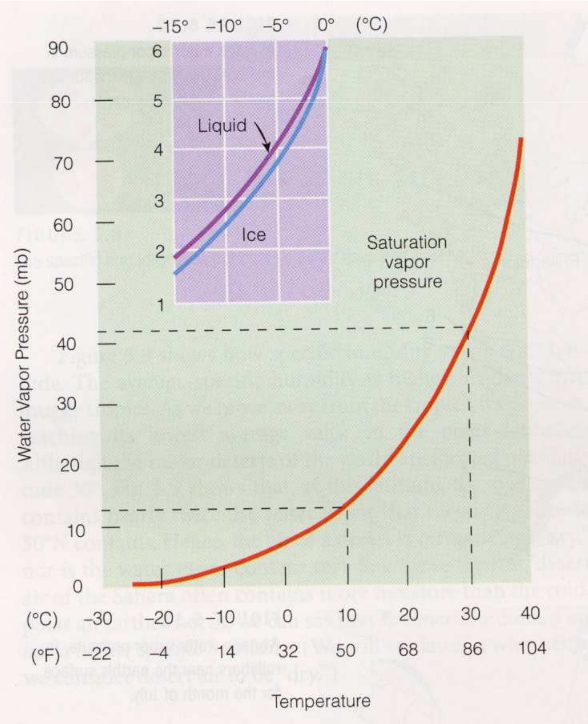
From H. Vömel, CIRES http://cires.colorado.edu/~voemel/vp.html

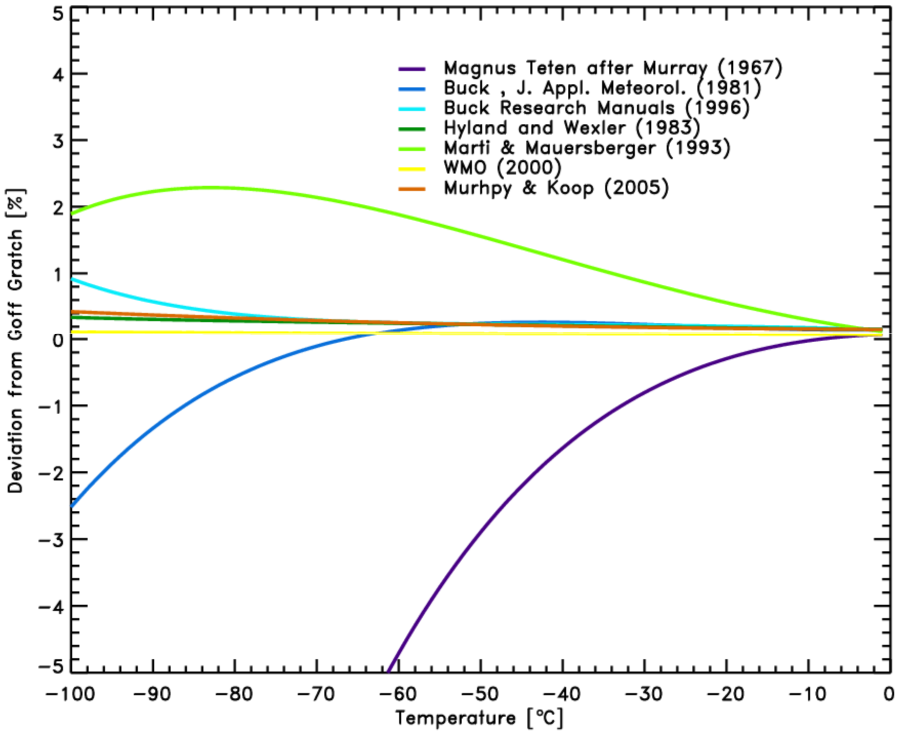
In the upper troposphere, large discrepencies calls for caution when manipulating measurements

Computation of water vapor pressure over ice

In some cold conditions, the vapor pressure is computed relative to an icy surface rather than a liquid water surface

The saturation vapor pressure above solid ice is less than above liquid water





From H. Vömel, CIRES http://cires.colorado.edu/~voemel/vp.html

Less discrepencies for the ice computations

Computation of water vapor pressure in models

Models either climate, met, CRM etc… actually have their own way to compute internally the vapor pressure and to report their relative humidity.

ECMWF and LMDz do follow the same approach and incorporate a mixed layer to account for super-cooled conditions

“*the saturation value over water is taken for temperatures above 0℃ and the value over ice is taken for temperatures below -23℃ using Tetens formulae. For intermediate temperatures the saturation vapour pressure is computed as a combination of the values over water and ice according to the formula*

$$e_{\mathrm{sat}}(T) = e_{\mathrm{sat(ice)}}(T) + [e_{\mathrm{sat(water)}}(T) - e_{\mathrm{sat(ice)}}(T)]\left(\frac{T - T_i}{T_3 - T_i}\right)^2$$

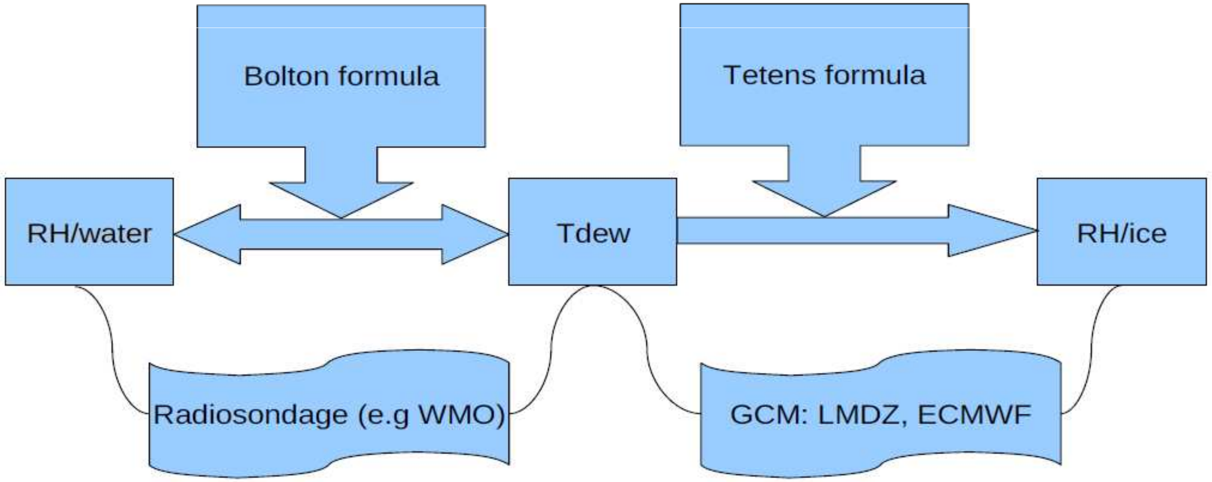
with T_3-T_1*=23K.*”

Other model will have their own implementation of this or simpler version of it.

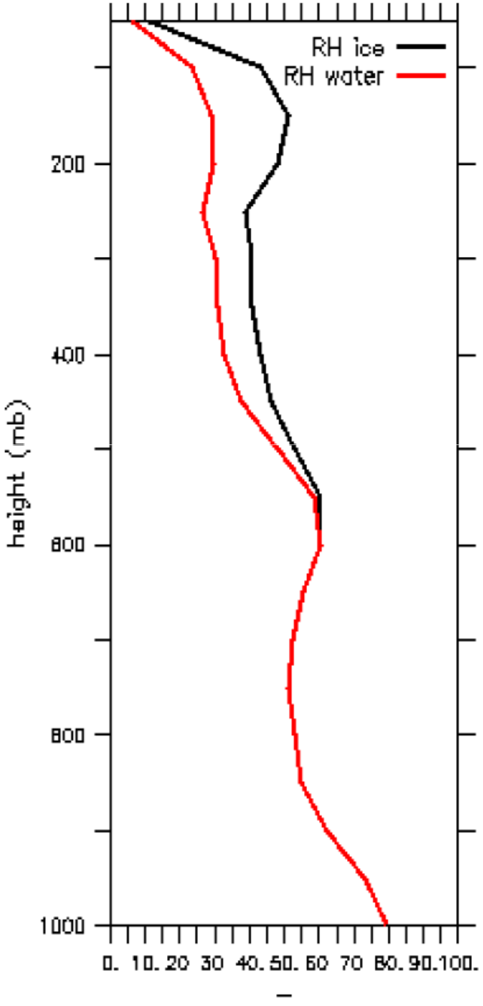
How to compare a radiosonde with a model ?

Need to document the formulae used to report the observations
Need to document the model formulae and assumptions

Example for LMDz and a Vaïsala RS-92 sonde In Africa:



Dakar, Sénégal
Summer 2006



Ly , 2010

RH water vs ice

Comparaison between models and obs RH requires a carefull methodological approach.

Summary

- Three phases on Earth
  - Short residence time in the atmosphere
  - Mainly in the lowest levels (E folding concentration with z)

- Many ways to express humidity
  - Absolute way (e,q,r,etc…)
  - Relative way (RH deficit to saturation)

- Well documented and rooted in thermodynamics laws for saturation
  - Difficulties to actually implement it.
  - Caution with formulae in models and observations

- Sursaturation (RH>100%) is frequent in the UT/LS.
  - More during the week.

Outline of the lecture

- Water vapor in the atmosphere
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- Long wave Radiation in the atmosphere
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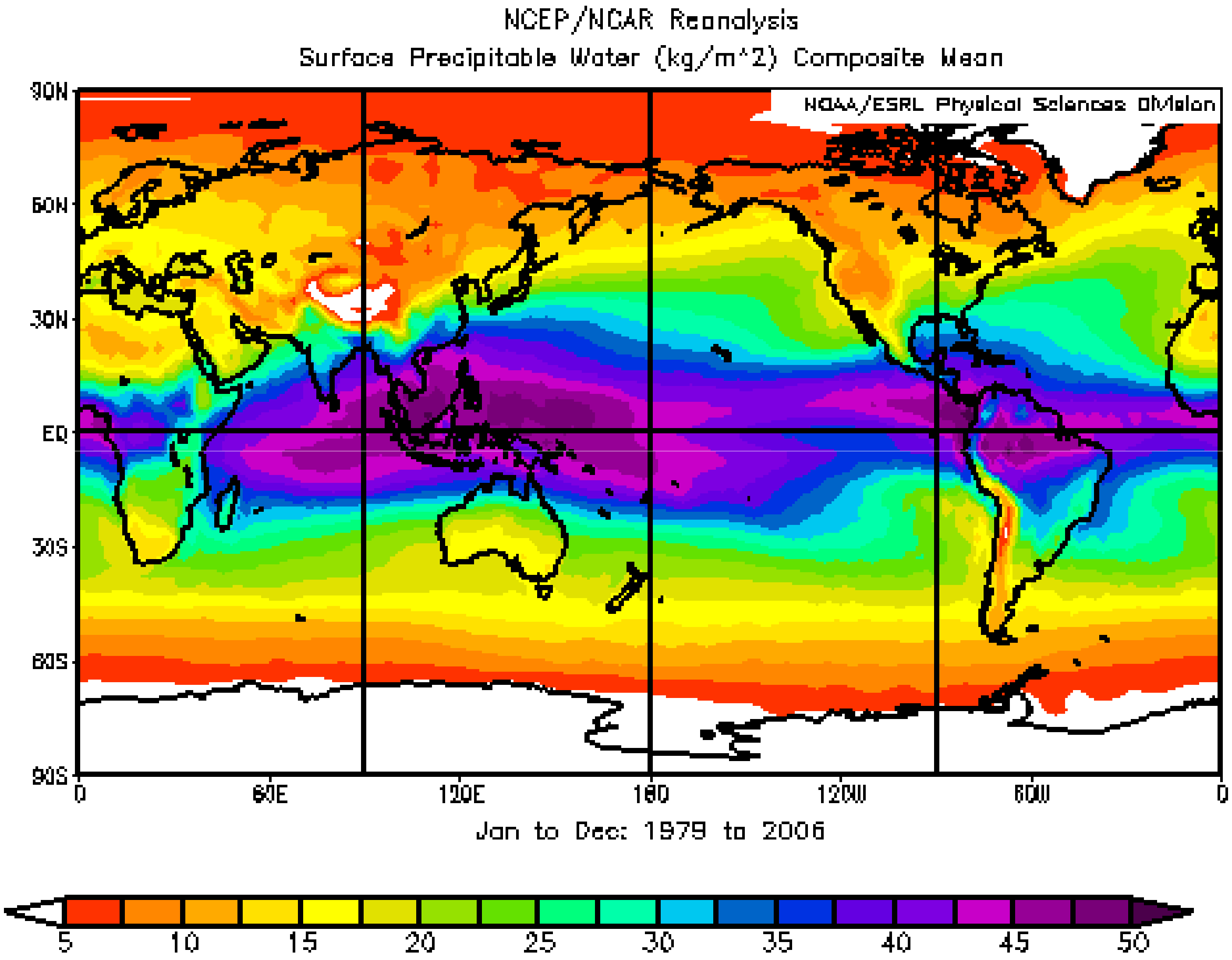
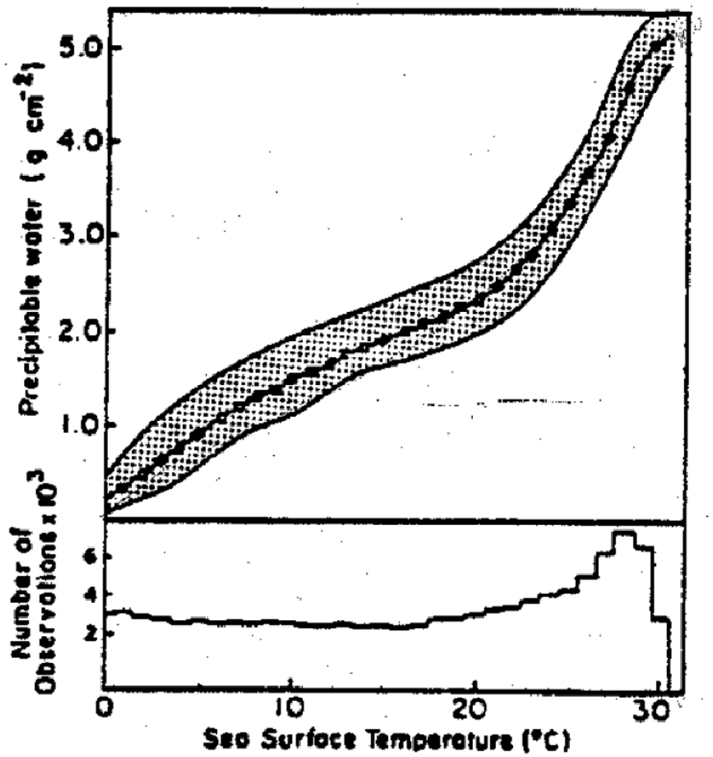
Precipitable water climatology



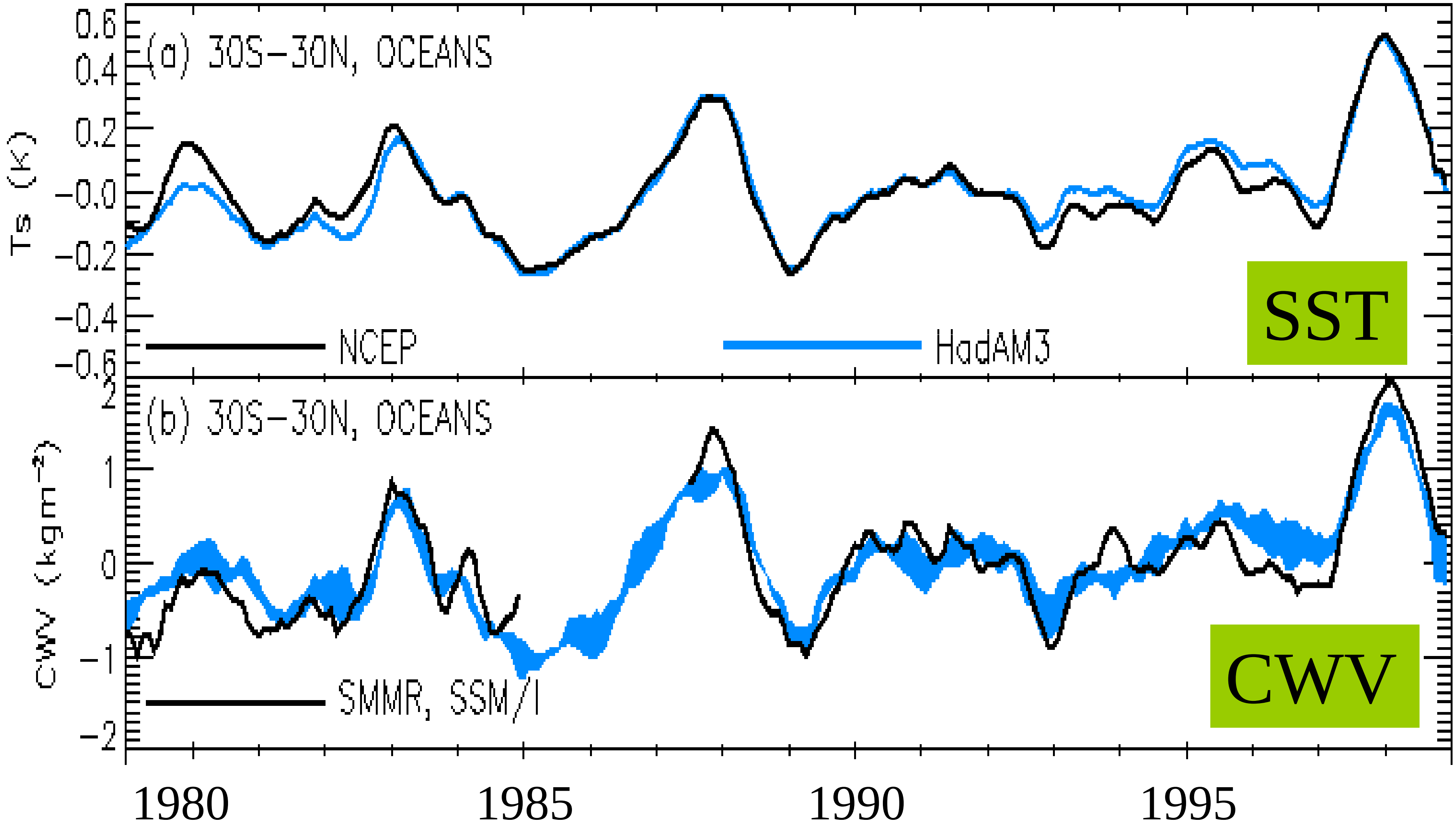
Precipitable water strong link to SST



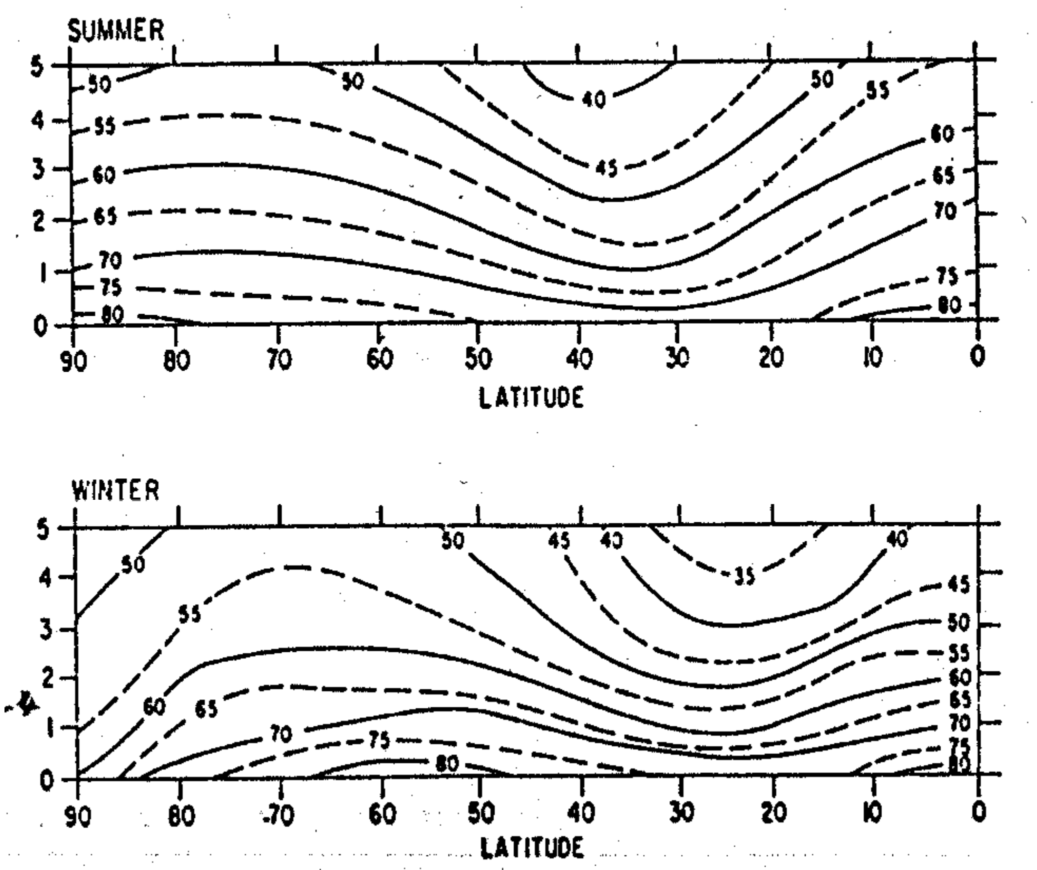
A necessary condition for the existence of water vapor feedback on Earth. Water vapor exists in equilibrium with the oceans in a way that is related to the sea surface temperature largely through the Clausius-Clapeyron relationship. The curve shown is established from thousands of observations of water vapor over the world's oceans (Stephens, 1990).

Precipitable water strong link to SST: interannual scale

Adapted from R Allan



Climatology of water vapor: seasonal variations



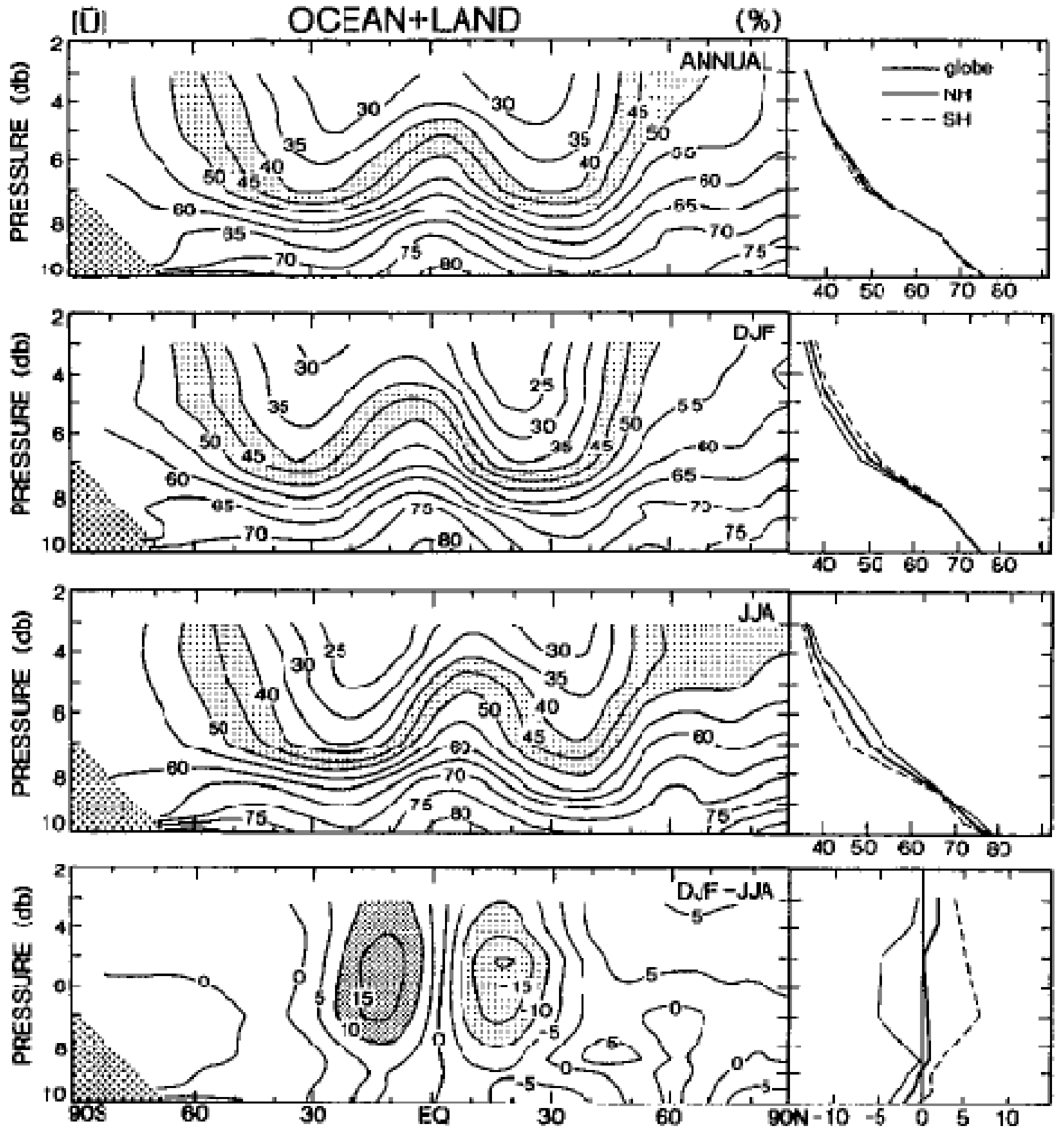
Observations from 1949 up to 5km…

(from Manabe and Wetherald, 1967)

This piece of information
Was once used to argue that
Relative Humidity is almost
constant in time.

An important statement

Climatology of water vapor: seasonal variations



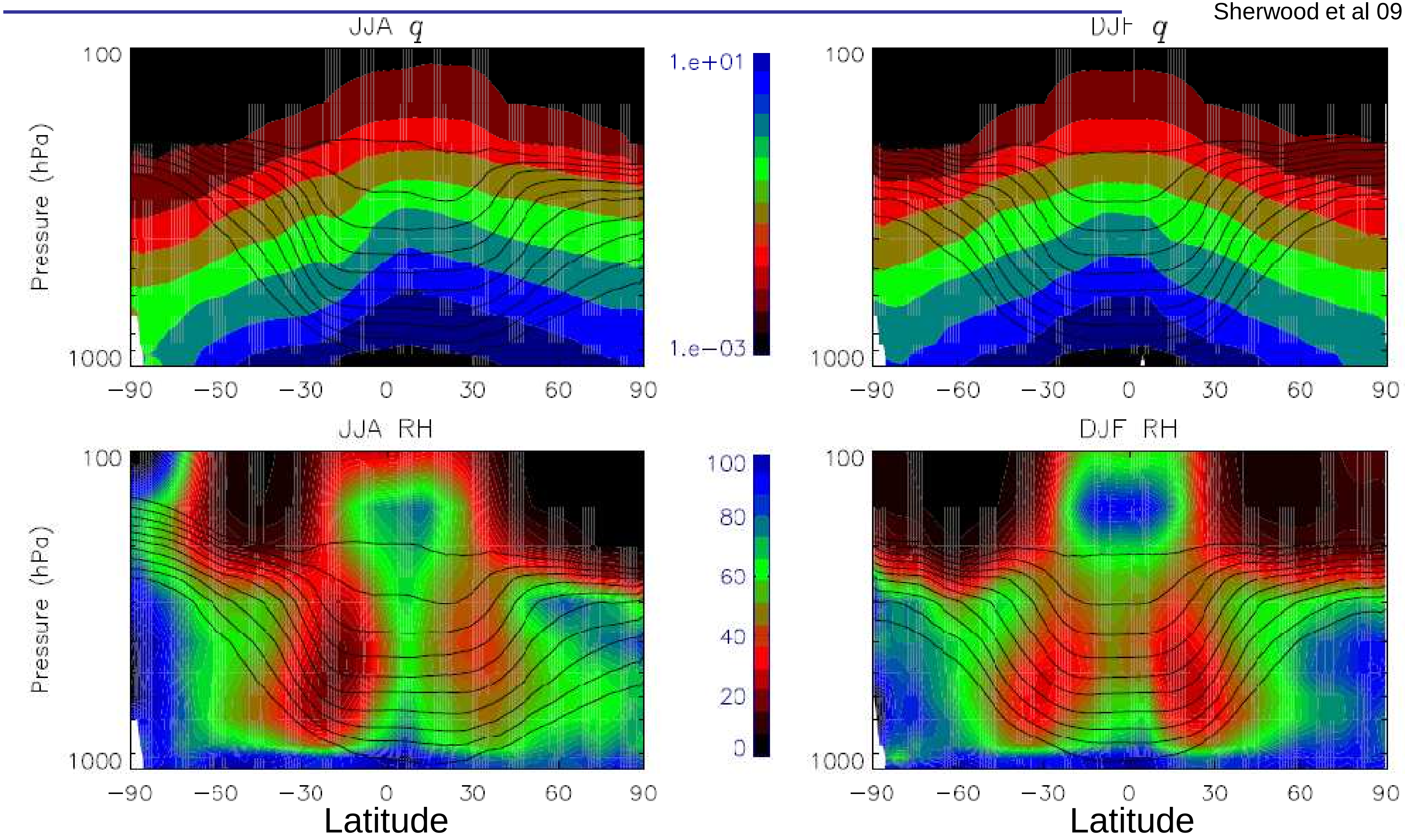
From the radiosondes archive

FIG. 4. Zonal mean cross sections of the relative humidity (%) for annual, DJF, and JJA mean conditions, and for the interseasonal variation, DJF−JJA. Vertical profiles of the hemispheric and global mean values are shown on the right. In the top three diagrams the areas with $40 < \bar{U} < 50\%$ are shaded. In the bottom diagram, areas where the differences are greater than 10% are shaded heavily and those where they are less than −10% are shaded lightly.

Peixoto and Oort 1996

Climatology of water vapor

Sherwood et al 09

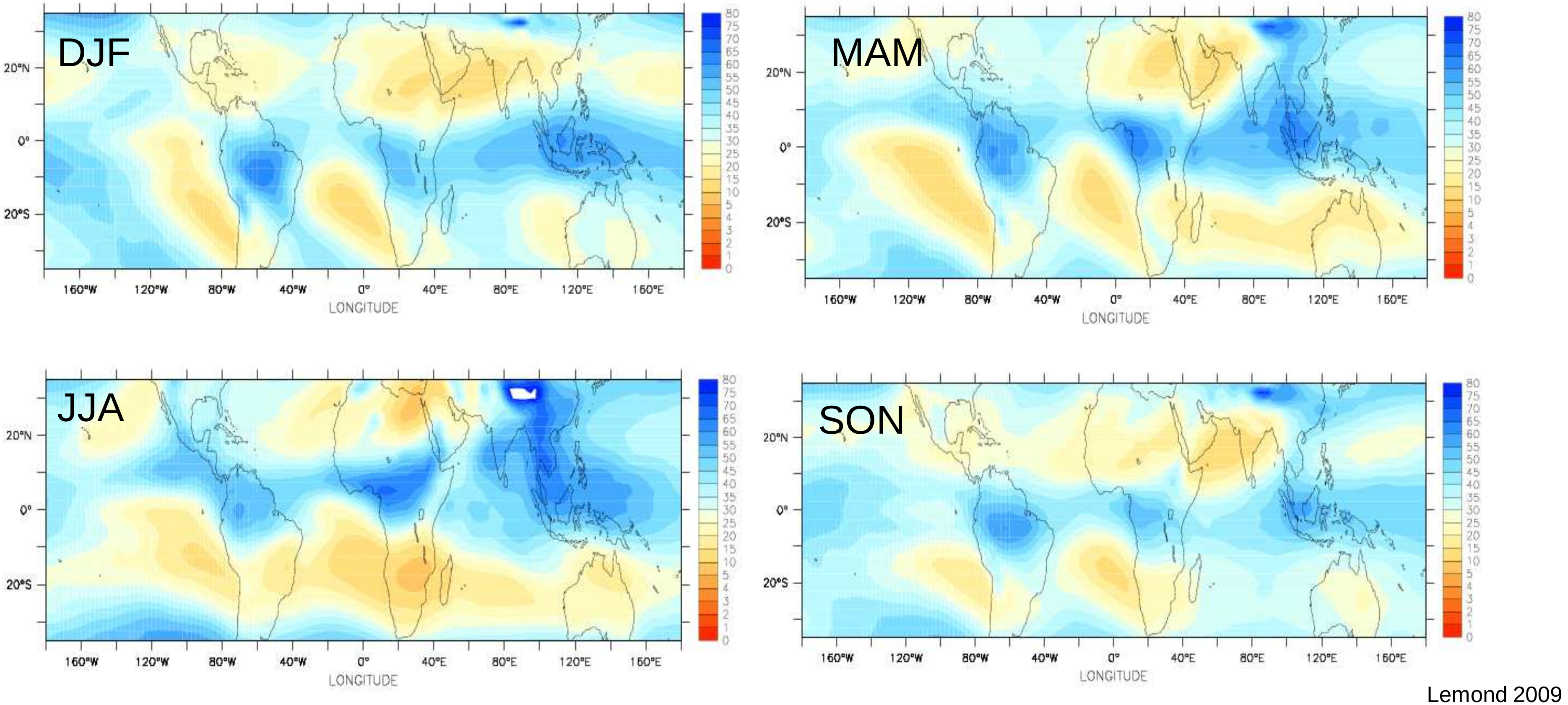


From Hybrid AMSU/AIRS retrievals for boreal summer 2008 and winter 20089

A closer look at the free troposphere

NCEP data **78-07**

Relative Humidity at 500 hPa



Lemond 2009

- •Dry zones below 15%; deserts are dry all year through
- •Moist regions follows the ITCZ seasonal migration and the monsoon
- •Is the seasonal mean well suited to described RH in the troposphere ?

Temperature and humidity dependence of RH

Adapted from
Peixoto and Oort 96

$$rh = \frac{e}{e_s} \approx \frac{q}{q_s}$$

$$\frac{drh}{rh} = \frac{dq}{q} - \frac{dq_s}{q_s}$$

$$\frac{dq_s}{q_s} = \frac{de_s}{e_s} - \frac{dp}{p}$$

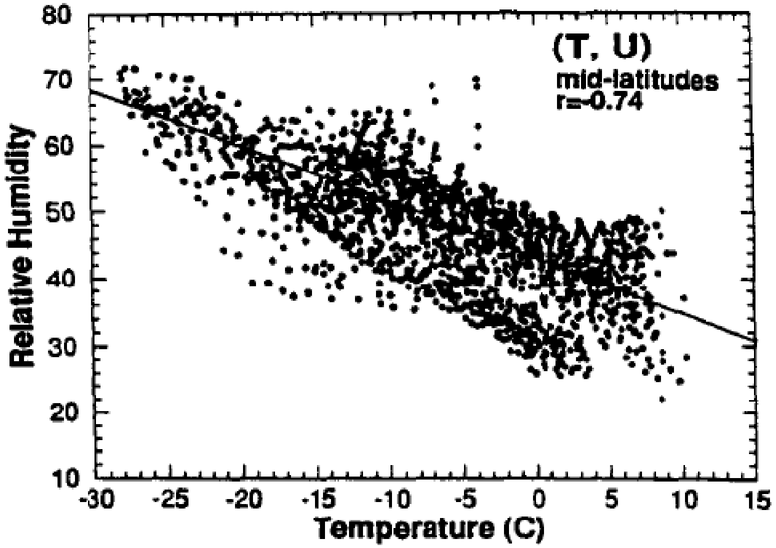
isobar $\frac{dq_s}{q_s} = \frac{de_s}{e_s}$

$$\frac{de_s}{e_s} = \left(\frac{L}{R_v T}\right)\frac{dT}{T}$$

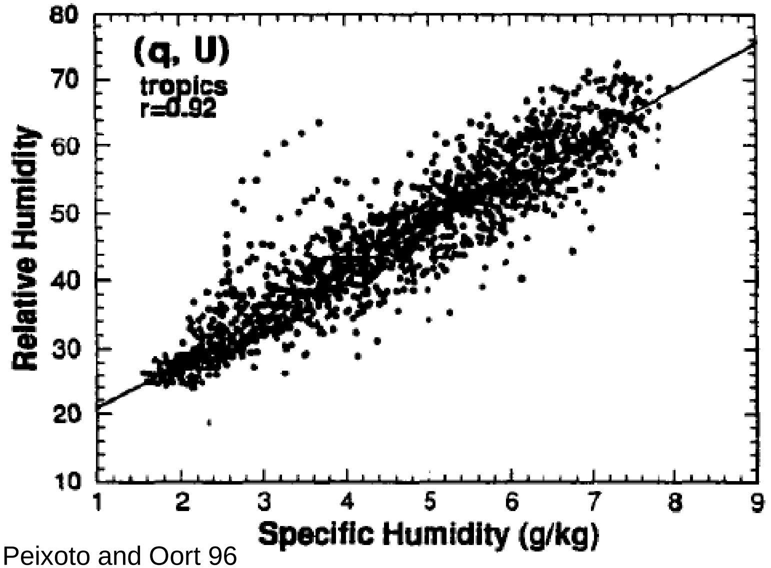
Over T = 260-285K, using L_v=2500 Jg^{-1}
and R_v=466.5$Jkg^{-1}K^{-1}$, L/R_vT 18.9 and 18.9

$$\frac{\Delta rh}{rh} = \frac{\Delta q}{q} - 20\frac{\Delta T}{T}$$

Temperature and humidity dependence of RH



Midlatitudes
ΔRH due to ΔT



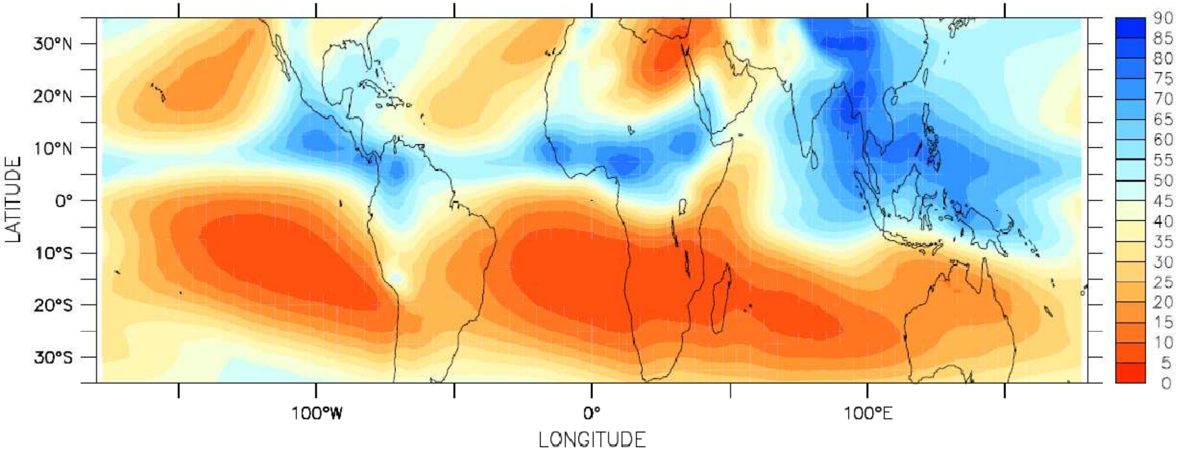
Peixoto and Oort 96

Tropics
ΔRH due to Δq

Importance of the dynamics and the water vapor transport rather than temperature

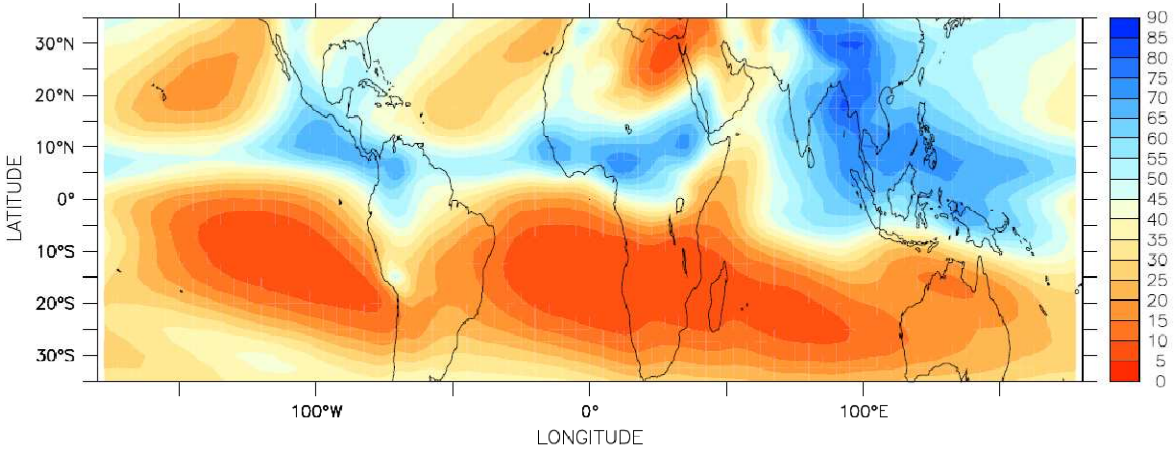
Temperature and humidity dependence of RH

$$RH = \frac{e}{e_{sat}(T)}100$$



MEAN JJA 7902

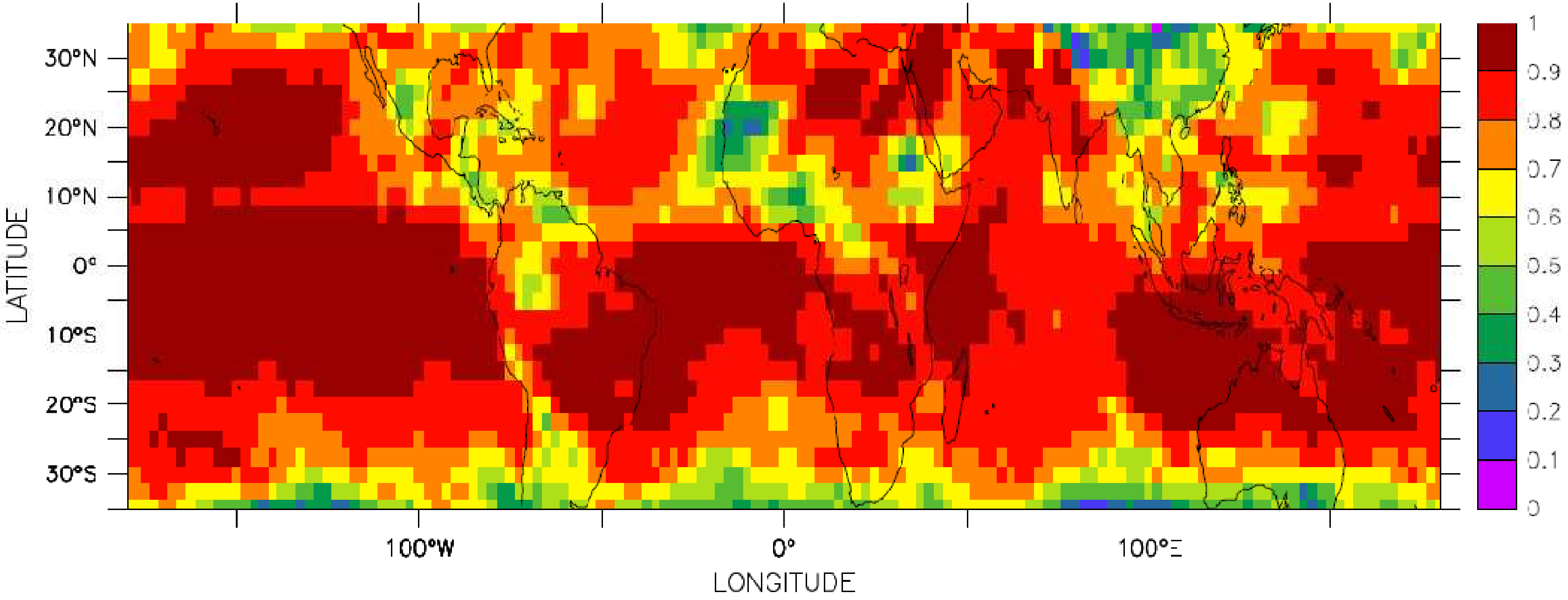
$$RH" = \frac{e}{e_{sat}(\overline{T})}100$$



MEAN RHs 7902

Temperature and humidity dependence of RH

$$RH = \frac{e}{e_{sat}(T)}100 \qquad RH'' = \frac{e}{e_{sat}(\overline{T})}100$$



c) coef.determination JJA 7902

Weak role of temperature anomalies in the RH variability
Need some debate or discussions

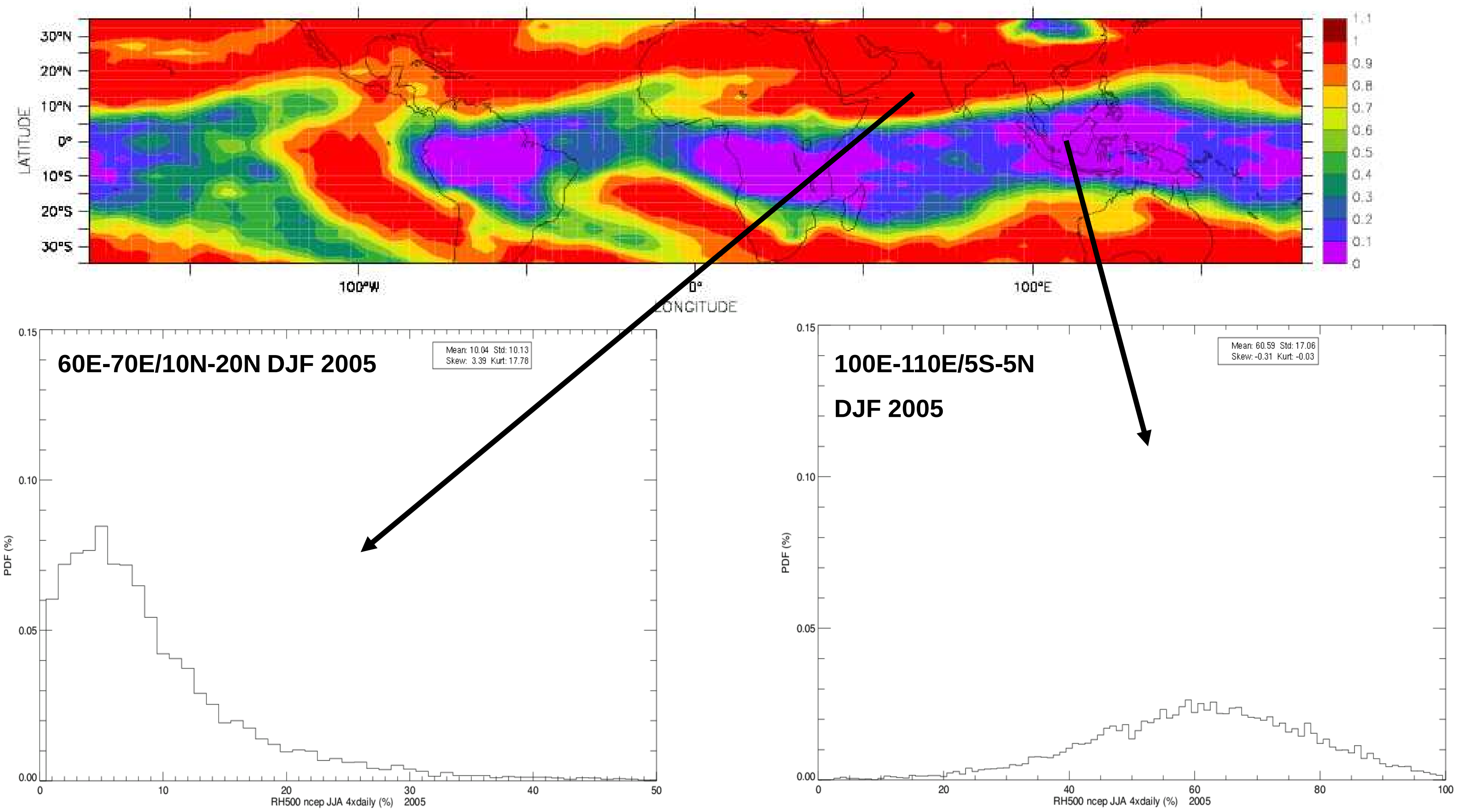
Lémond 2009

PDFs of water vapor

NCEP data

KS test on RH500 DJF 1977-2007 with a 99% confidence level

Lémond 2009



60E-70E/10N-20N DJF 2005

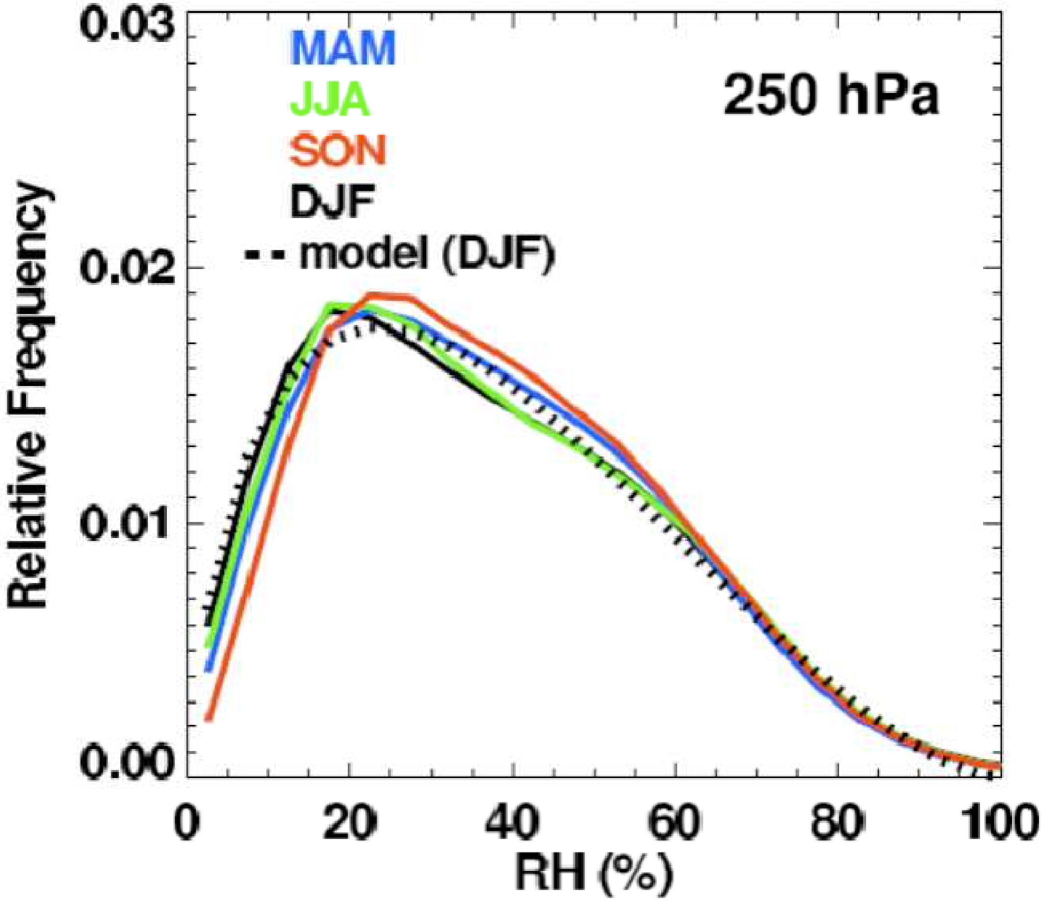
100E-110E/5S-5N

DJF 2005

PDFs of water vapor

AIRS data

Ryoo et al 2008

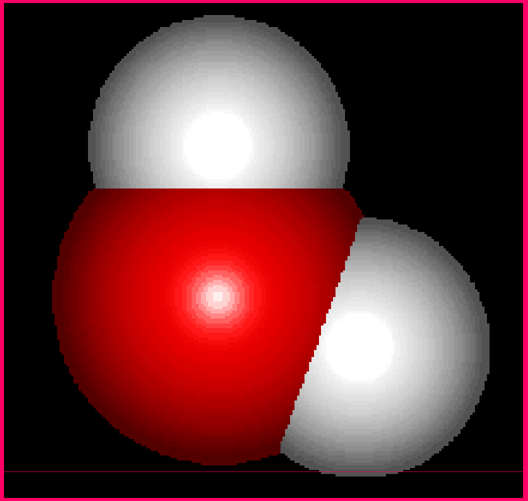


- Need to build some indices to qualifity the full PDF
- Higher order moments might be useful
- Idealized modelling efforts point out to simple power laws

Summary

- Precipitable water
  - Well related to the surface temperature (ocean) at spatial, seasonal, interannual scales
- RH and the Free troposphere
  - Hard to measure and quantify
  - substantial variability in RH
  - Weak role of temperature variability at 500 hPA over subtropics for RH variability despites the CC relationship
  - Non gaussian distribution (log-normal?)

A short course on water vapor and radiation



Rémy Roca
Chargé de Recherche CNRS
Laboratoire de Météorologie Dynamique
roca@lmd.jussieu.fr

Outline of the lecture

- Water vapor in the atmosphere
- Long wave Radiation in the atmosphere
  - Basis of radiation
  - The greenhouse effect
  - The radiative and the radiative convective equilibrium

- The water vapor feedback

Planet Earth

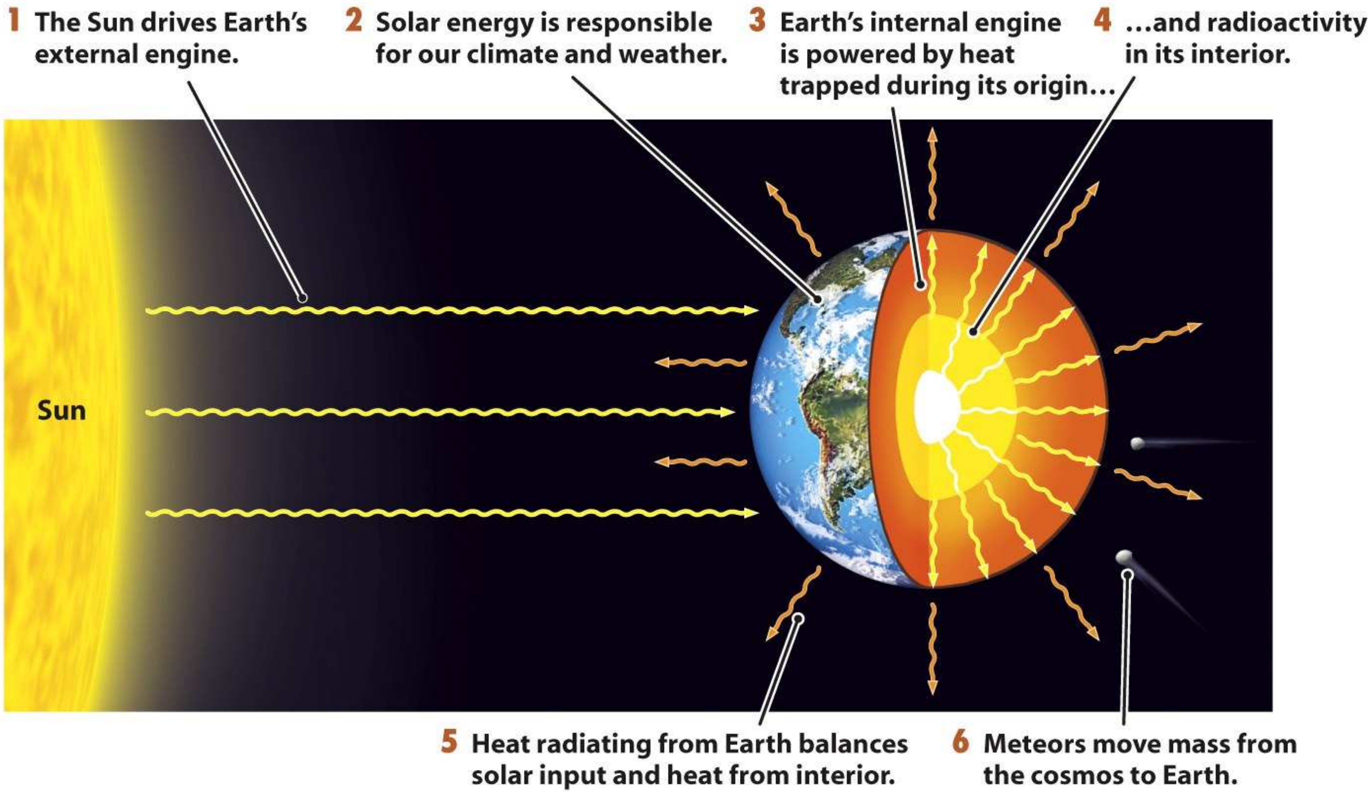


Figure 1-9
Understanding Earth, Fifth Edition
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First Principle of Thermodynamics

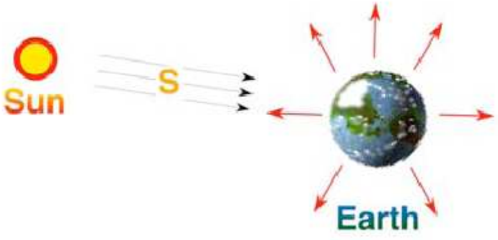
$dQ=dU-dW$

Work from Earth on Space is neglected

Earth exchange energy with space only through radiation

$dQ=dQ_R$

The energy emitted by the Earth is equal to what it got from the Sun



Radiative budget of the Earth

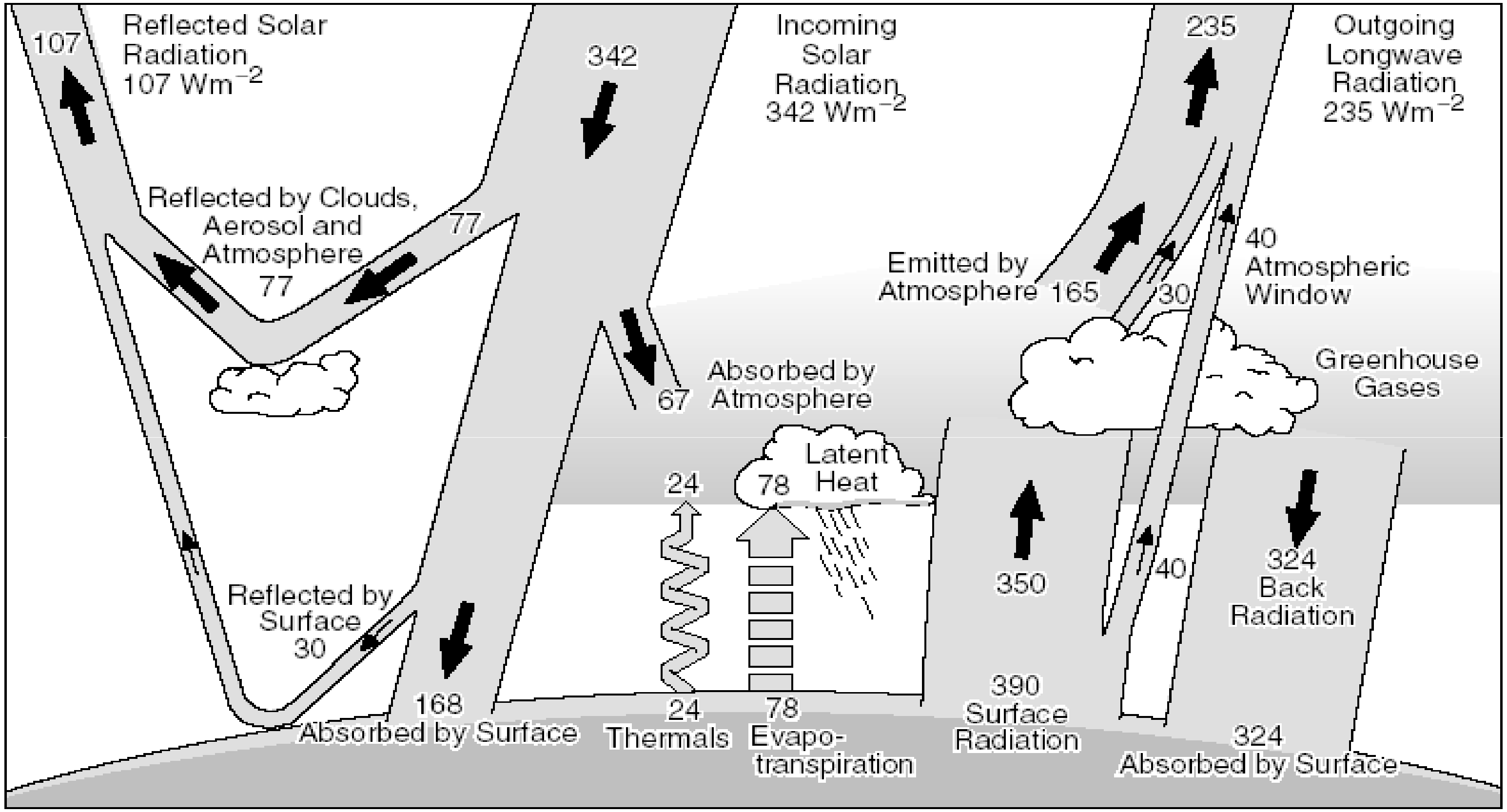
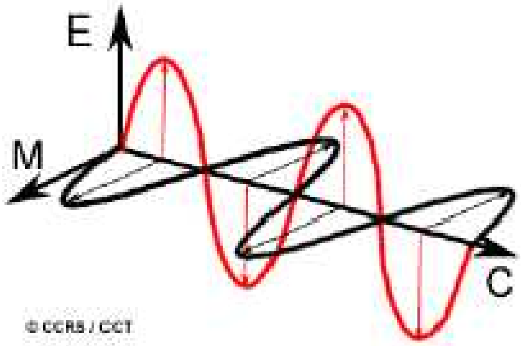
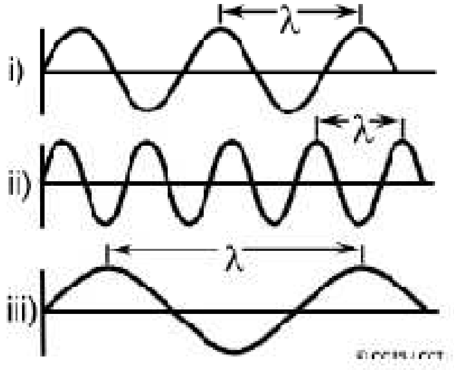


Fig. 1 The Earth's annual global mean energy budget. Units are in W/m^2. [From Kiehl, J. T. and K. Trenberth, 1997: Earth's annual global mean energy budget. Bull Amer. Meteorol. Soc., 78, 197-208.]

Electromagnetic waves





Electromagnetic radiation is generated when an electrical charge is accelerated.

The *wavelength* of electromagnetic radiation (l) depends upon the length of time that the charged particle is accelerated and its frequency (*v*) depends on the number of accelerations per second.

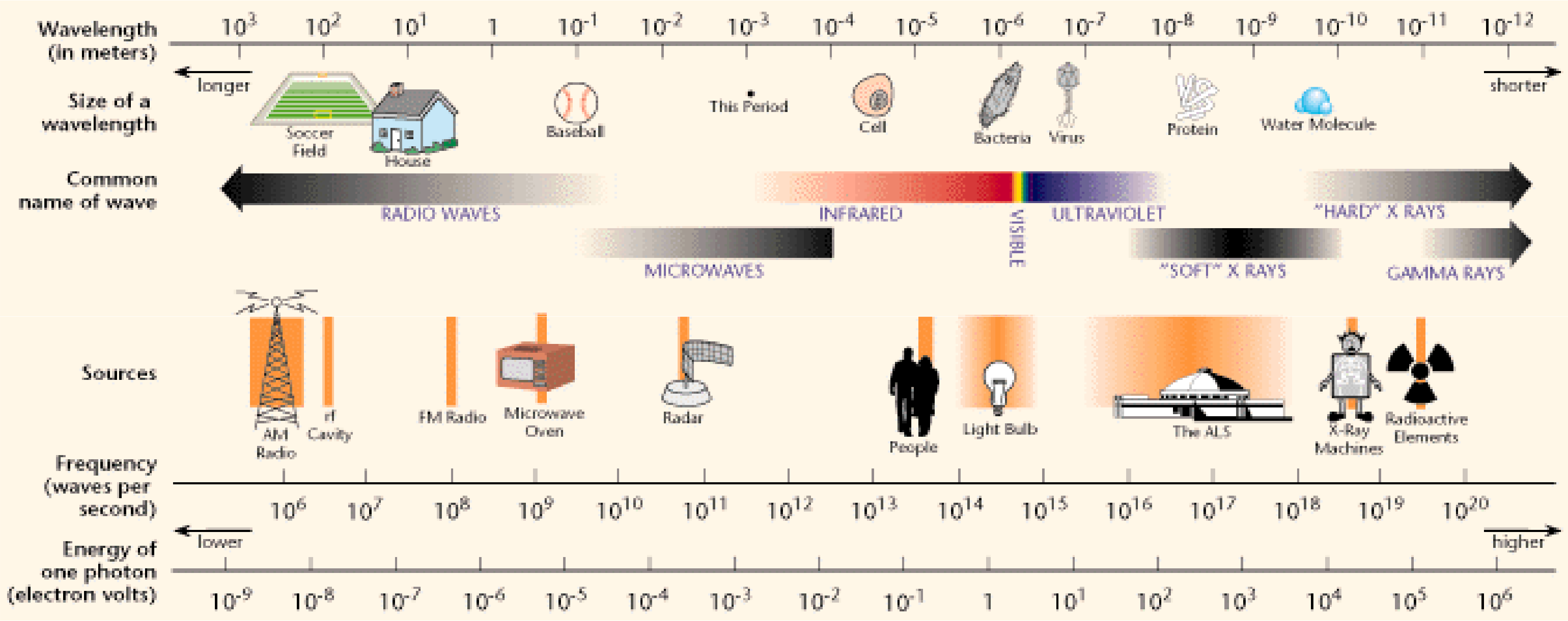
Wavelength is formally defined as the mean distance between maximums (or minimums) of a roughly periodic pattern and is normally measured in micrometers (□m) or nanometers (nm).

Frequency is the number of wavelengths that pass a point per unit time. A wave that sends one crest by every second (completing one cycle) is said to have a frequency of one cycle per second or one hertz, abbreviated 1 Hz.

The relationship between the wavelength, λ, and frequency, ν, of electromagnetic radiation is based on the following formula, where *c* is the speed of light:

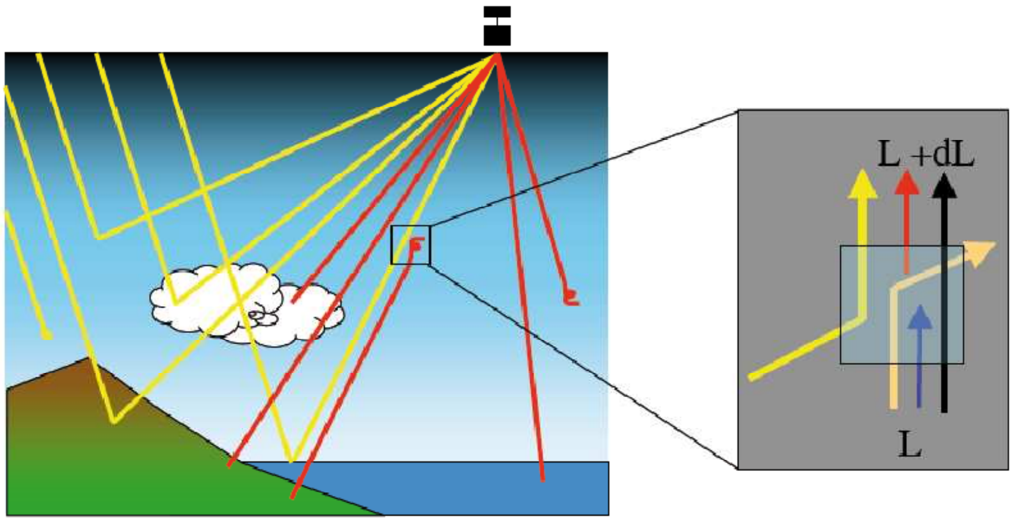
$$\lambda = \frac{v}{c}$$

The electromagnetic spectrum



Radiative transfer in the atmosphere

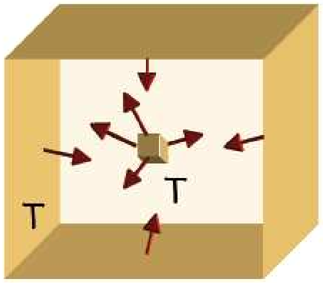
Gas molecules and particules (clouds, aerosols) in the atmosphere modify the radiation under different processes



Source
Diffusion and Emission

Sink
Diffusion and Absorption

Kirchhoff law's: Equilibrium between the emission and Temperature of the object and the wall
The capacity to emit of some material equals its capacity of absorption

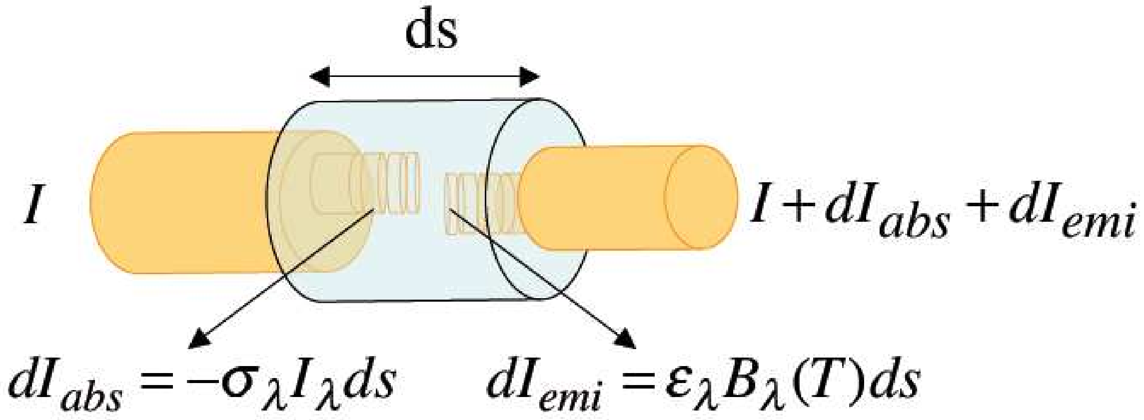


$$\varepsilon_\lambda = \sigma_\lambda$$

σ Is the absorption coefficient

Adapted From Duvel

The equation of radiative transfer (LTE, no diffusion)



$$dI_\lambda = \varepsilon_\lambda B_\lambda(T)\, ds - \sigma_\lambda I_\lambda\, ds$$

Kirchhoff law's: $\varepsilon_\lambda = \sigma_\lambda$

$$dI_\lambda = \sigma_\lambda \left(B_\lambda(T) - I_\lambda\right) ds$$

From Duvel

The equation of radiative transfer (LTE, no diffusion)

At a given wavelength

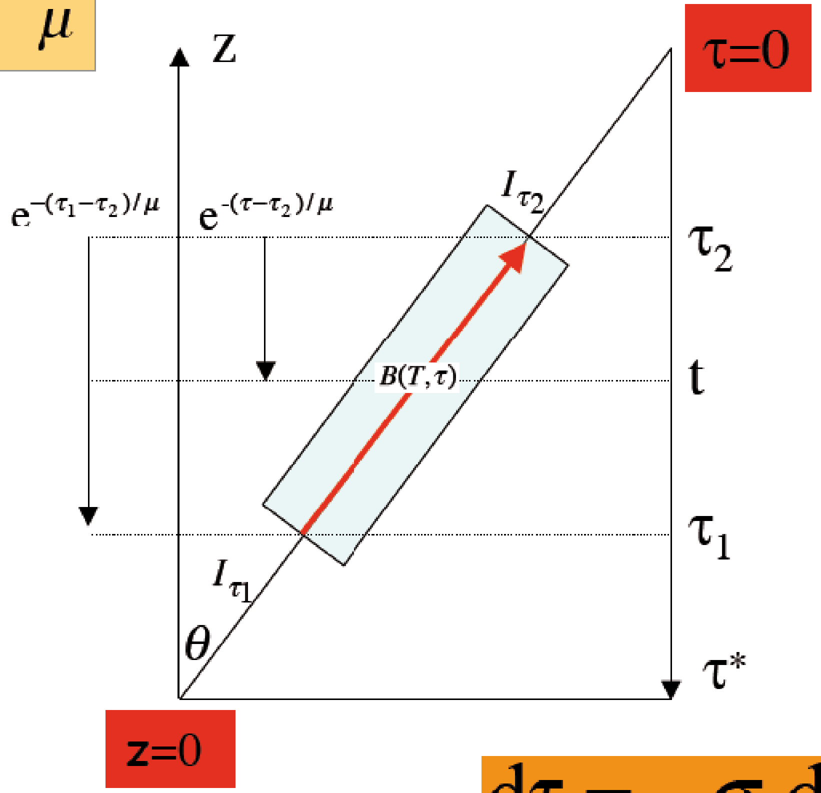
$$I^+_{\tau_2} = I^+_{\tau_1} e^{-(\tau_1-\tau_2)/\mu} - \int_{\tau_1}^{\tau_2} B(T,t) e^{-(\tau-\tau_2)/\mu} \frac{d\tau}{\mu}$$

$$\tau 1 > \tau 2 \ \text{--->}\ d\tau \leq 0$$

- The first term is the absorbed radiation along $\tau 1 - \tau 2$

- The second term is the sum of emission along the path absorbed over $\tau - \tau 2$

Under the LTE (OK for earth atmosphere up to 60km), the source term of emission B is given by the Planck law even if gases are not black body and the Kirchhoff law applies



$$d\tau = -\sigma\, dz$$

From Duvel

The equation of radiative transfer (LTE, no diffusion)

At a given wavelength

$$I^+_{\tau_2} = I^+_{\tau_1} e^{-(\tau_1-\tau_2)/\mu} - \int_{\tau_1}^{\tau_2} B(T,t) e^{-(\tau-\tau_2)/\mu} \frac{d\tau}{\mu}$$

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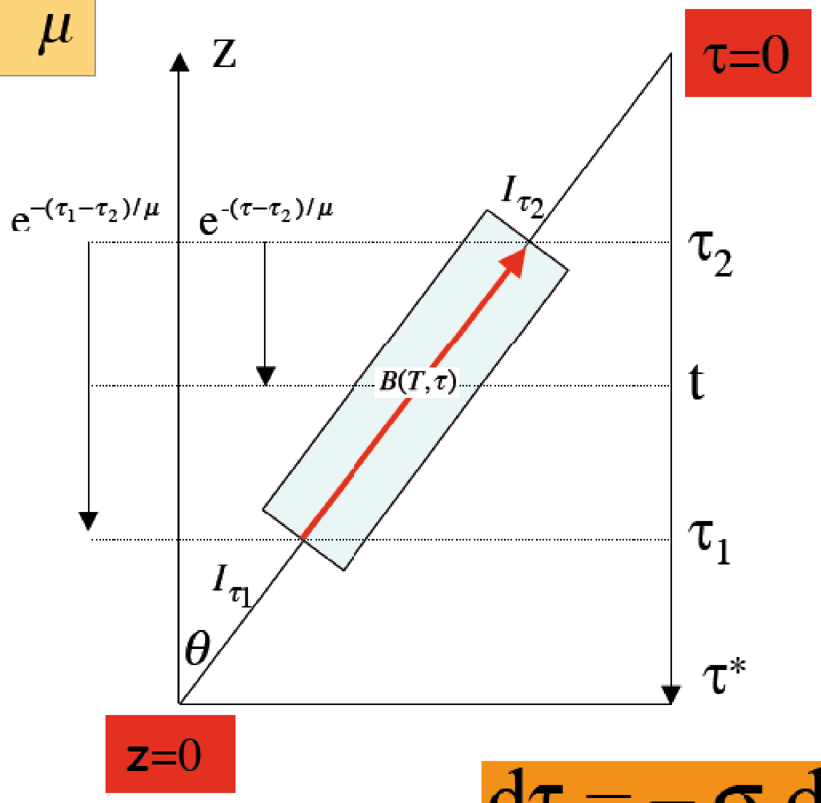
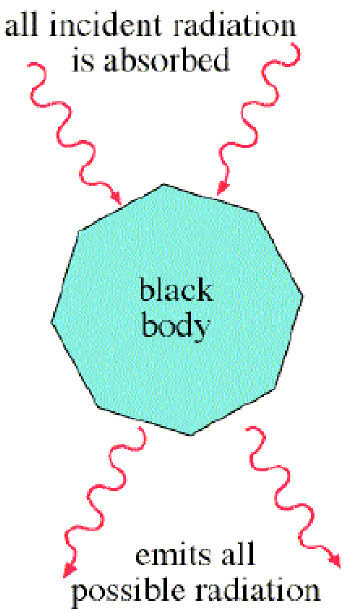


$$d\tau = -\sigma\, dz$$

From Duvel

Black body radiation and Planck Function

Blackbody - is a theoretical object that absorbs all incident radiation arriving on ti and emits the maximum possible radiation for its temperature (according to Planck's Law).



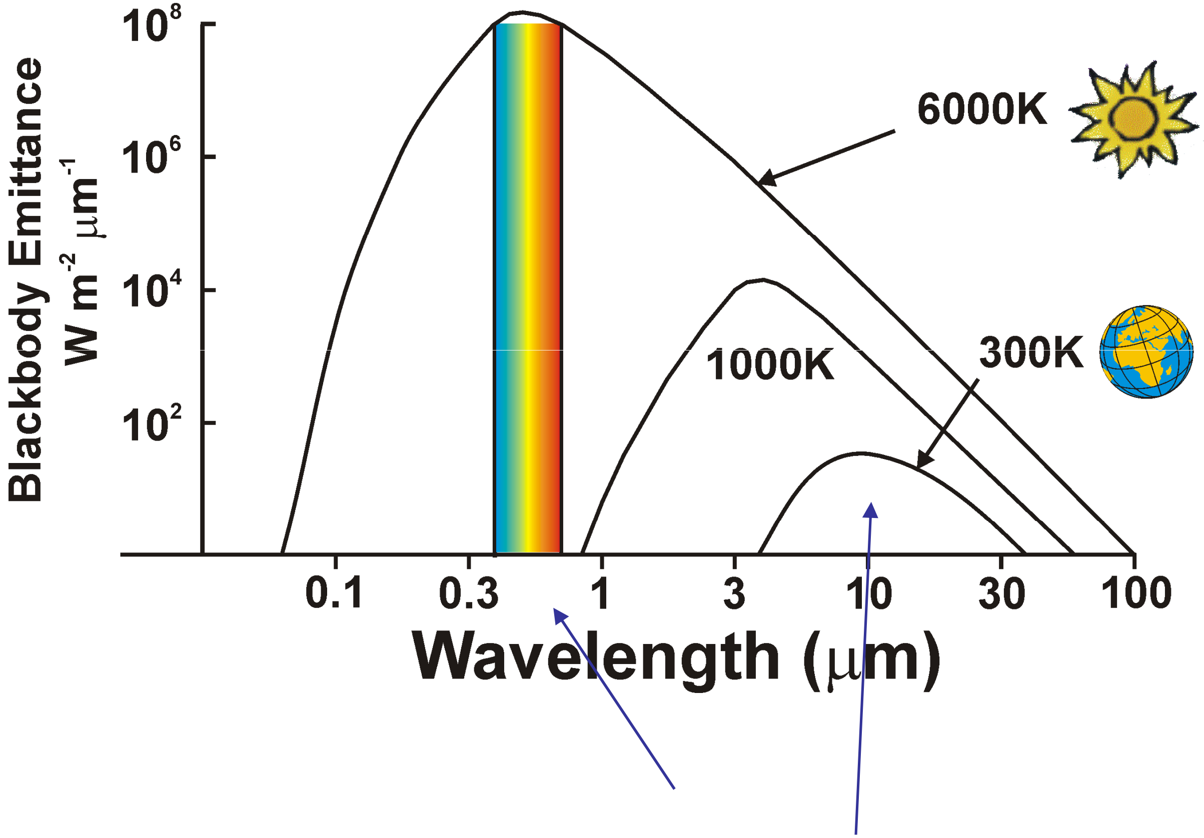
The amount of radiation emitted by a blackbody is described by Planck's Law

$$E_\lambda = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(hc/k\lambda T\right)-1\right]}$$

- k is the Boltzmann constant, and is 1.38x10- 23 J/K
- h is Planck's constant and is 6.626x10-34 Js
- c is the speed of light in a vacuum and is 2.9979x10 8 m s-2.
- T is the temperature of the body
- Blackbody radiation is isotropic

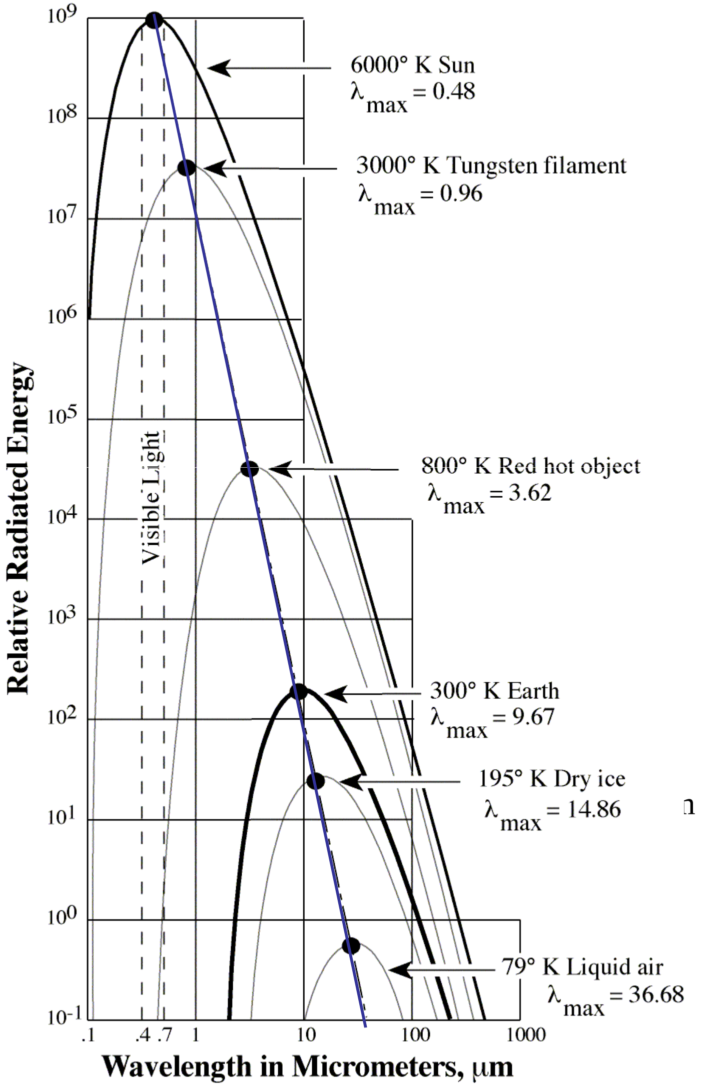
Black body radiation and Planck Function

$$E_\lambda = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(hc/k\lambda T\right)-1\right]}$$



The two main source of radiation for remote sensing of the earth

Wien’s Displacement law



From Jensen 2007

The peak spectral exitance or dominant wavelength (*Lmax*) is described by Wien’s displacement law:

$$\lambda_{\max} = \frac{\mathrm{k}}{\mathrm{T}} = \frac{2898\,(\text{units}: \mu\text{m K})}{\mathrm{T}}$$

E.g. for the Earth

$$\lambda_{\max} = \frac{k}{T} = \frac{2898\ \mu\text{m K}}{300\ \text{K}} = 9.67\mu\text{m}$$

E.g. for a fire ~800K

$$\lambda_{\max} = \frac{k}{T} = \frac{2898\ \mu\text{m K}}{800\ \text{K}} = 3.62\mu\text{m}$$

Hence to detect the fire the most appropriate remote sensing system might be a 3-5 um thermal infrared detector while for the broad Earth observations 8-14 um seems well adapted.

BB radiation Law continued'

The spectrally integrated radiation for a given temperature is given by the Stefan-Boltzman's law

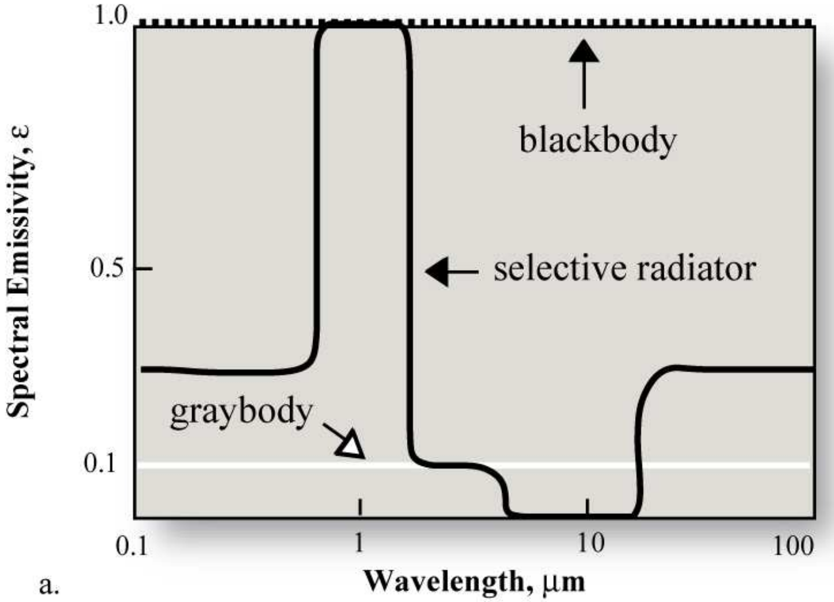
$$B(T) = \int_0^\infty B_\lambda(T)\,d\lambda = \frac{\sigma T^4}{\pi} \quad | W m^{-2} sr^{-1} |$$

Approximation of Rayleigh-Jeans (L infinite)

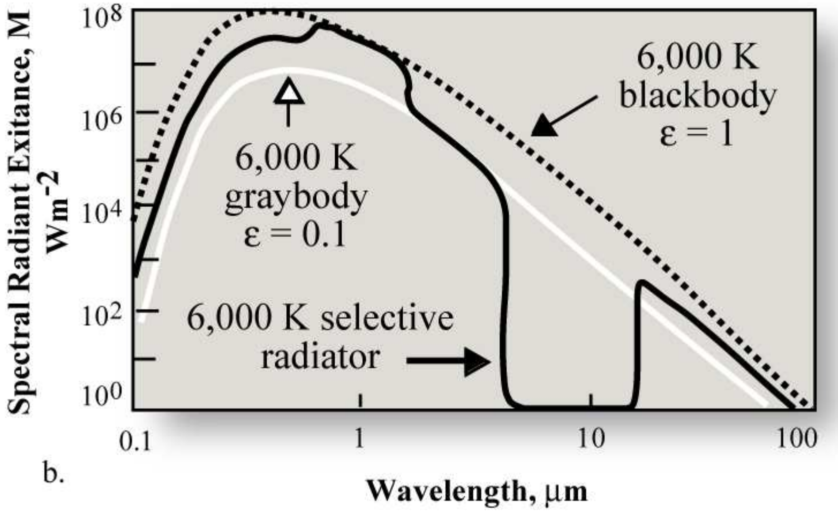
$$\frac{2\pi h c^2}{\pi \lambda^5 (e^{hc/\lambda kT} - 1)} \xrightarrow[\lambda \to \infty]{} 2hc^2 \lambda^{-5} \frac{\lambda kT}{hc} = 2kTc\lambda^{-4}$$

In the microwave part of the spectrum (λ > 1000 µm = 0.1 cm), the emission of the Earth is proportional to its temperature

Non black-body radiation

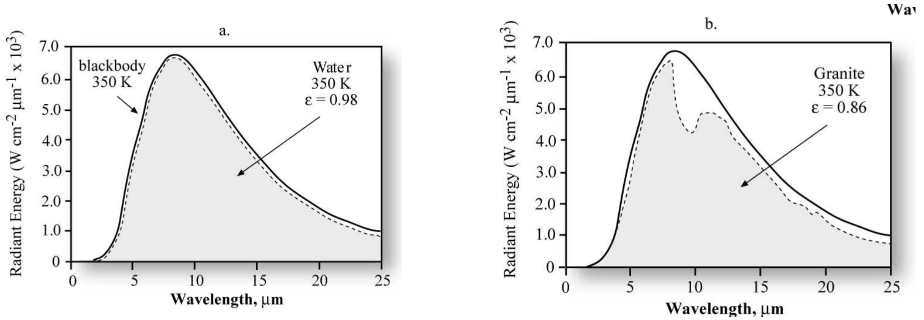


From Jensen 2007



All selectively radiating bodies have emissivity ranging from 0 to <1 that fluctuate depending upon the wavelengths of energy being considered. A gray body outputs a constant emissivity that is less than one at all wavelengths.

$$\varepsilon = \frac{M_{real}}{M_{bb}}$$



From Jensen 2007

Gaseous absorption

- The interaction of radiation with matter is related to 4 phenomenon
  - Absorption
  - Emission
  - Diffusion/Scattering
    - Gas
    - particules
  - Reflection

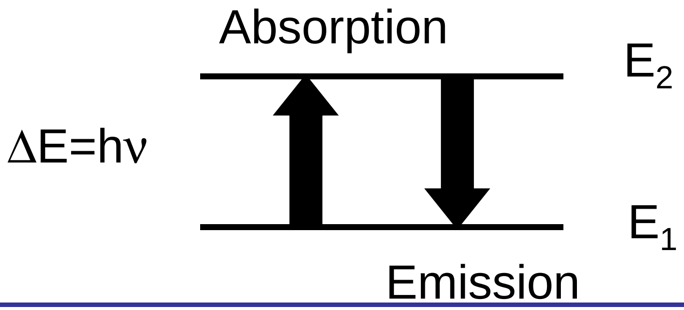
- In the longwave, considering the atmospheric gases only
  - Absorption
  - Emission

$$dI_\lambda = \sigma_\lambda \left(B_\lambda(T) - I_\lambda \right) ds$$

- Note that gas are not black bodies and do not have a continuous spectrum of absorption/emission. These are selective radiators.
- These process are described by molecular spectroscopy

- The absorption coefficient σ_λ summarizes the governing laws

ν is the frequency
λ is the wave lenghth $\lambda = c/\nu$
κ is the wave number $\kappa = 1/\lambda$



Vibration mode of the H_2O molecule

- We focus on molecules rather than atoms for the study of the longwave radiation in the atmosphere

- More complex absorption spectrum due to transitions between levels due to the movements of rotation and vibration of the atoms composing the molecules

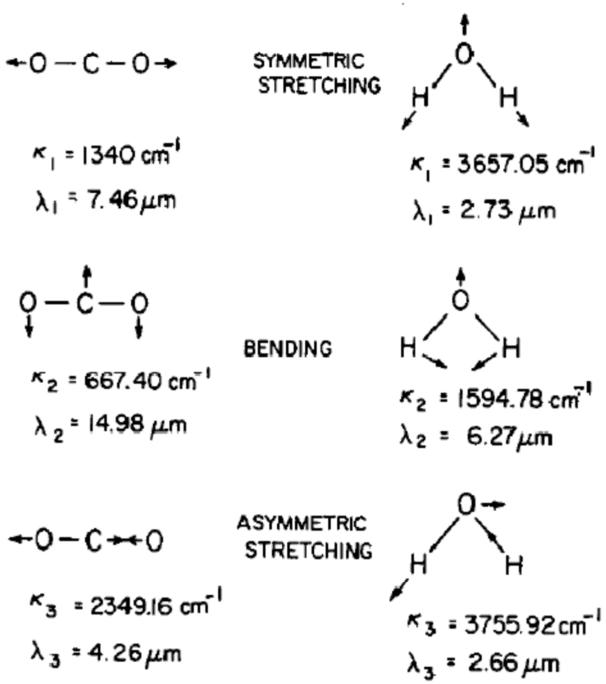
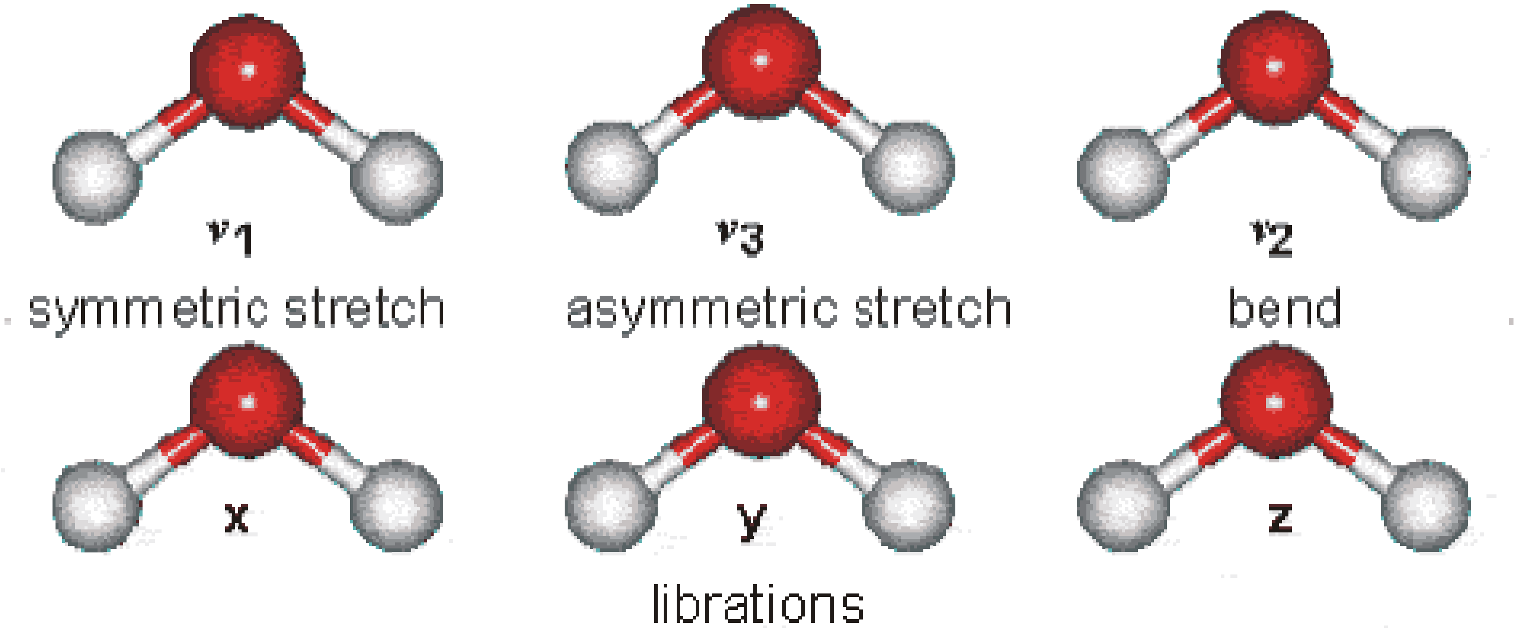


FIGURE 3.15. Vibration modes of carbon dioxide and water vapor.

Vibration-rotation mode of the H2O molecule

2.73 µm 2.65 µm 6.27 µm



Yield to many transitions and hence many absorption lines all over the spectrum

Line broadening

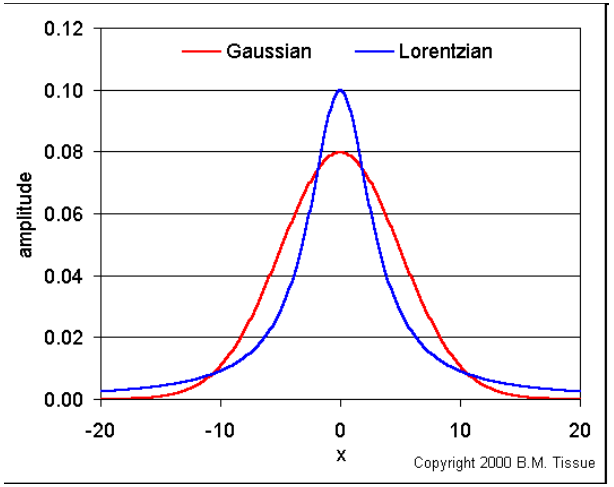
- Natural
  - Heisenberg uncertainty principle: the time and level of energy are not known simultaneously perfectly $\Delta E \sim h/\Delta t$ which turns into $\Delta\nu = \Delta E/h$
  - Small compared to others

- Collision broadening (Lorentz)
  - In the infrared, strong interaction are at play. Collision makes the molecule state jumps from one to another
  - pressure effect
  - Collisions broaden spectroscopic linewidths by shortening the lifetime of the excited states

$$f_L(\nu-\nu_r) \approx \frac{\alpha_L/\pi}{(\nu-\nu_r)^2+\alpha_L^{\,2}}$$

- Doppler Broadening
  - Due to molecular thermal motions
  - Temperature effect
  - Gaussian shape

- Voigt Profile = Collision+Doppler



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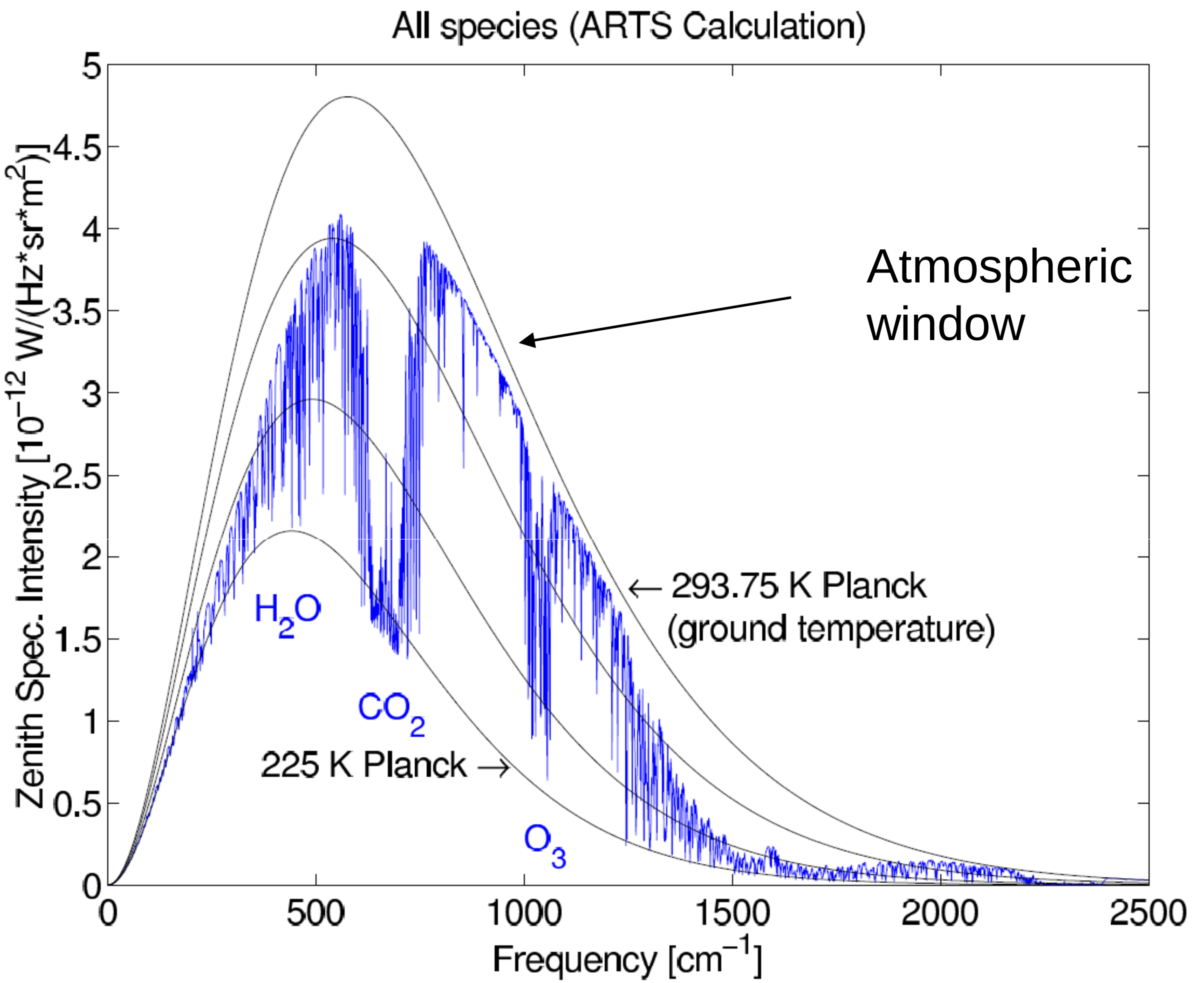
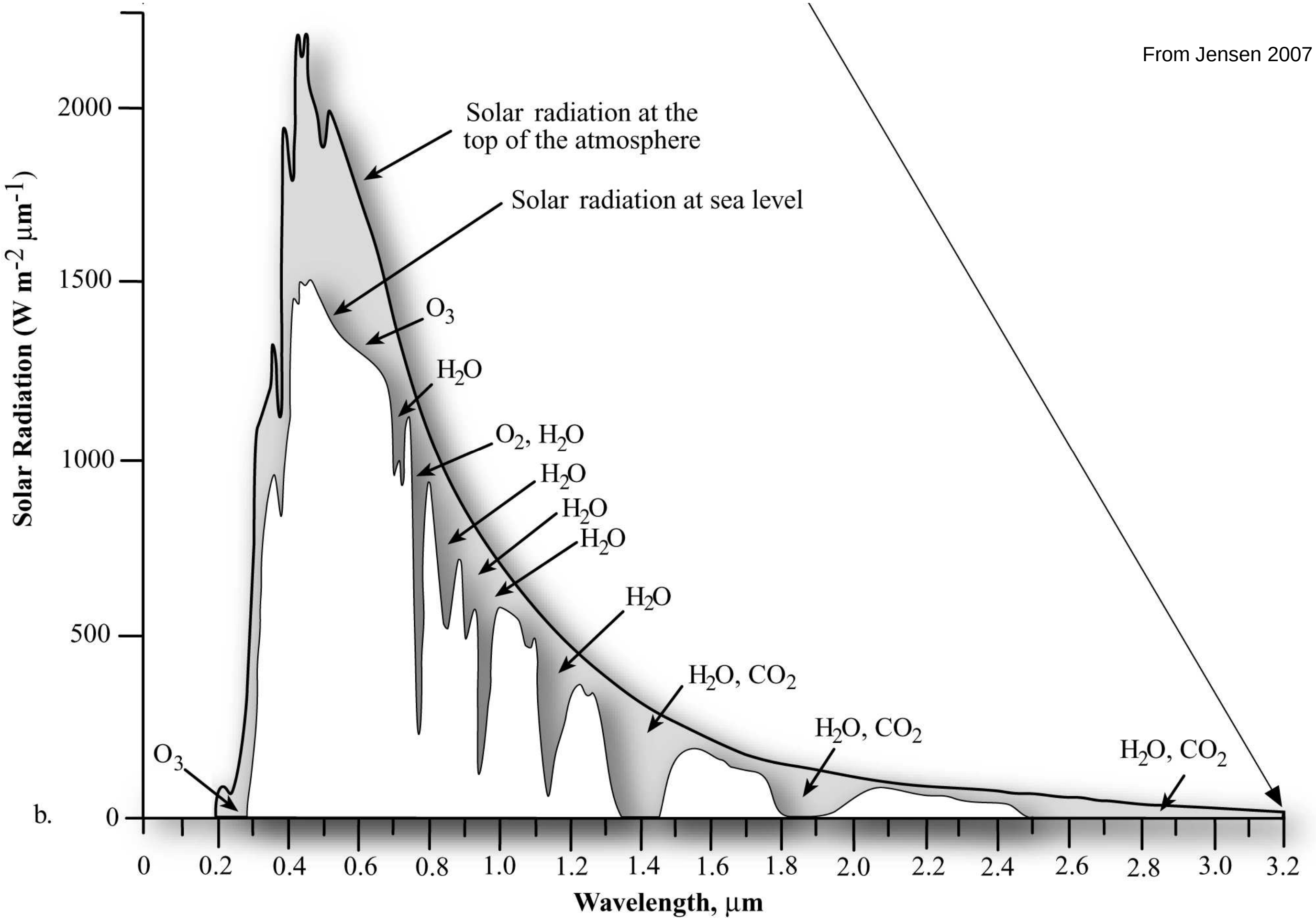
The atmospheric spectrum of longwave radiation



Atmospheric window

Figure 1. A radiative transfer model simulation of the TOA zenith monochromatic radiance for a mid-latitude summer atmosphere. Smooth solid lines indicate Planck curves for different temperatures: 225 K, 250 K, 275 K, and 293.75 K. The latter was the assumed surface temperature. The calculated quantity has to be integrated over frequency and direction to obtain total OLR from (Buehler et al, 2004)

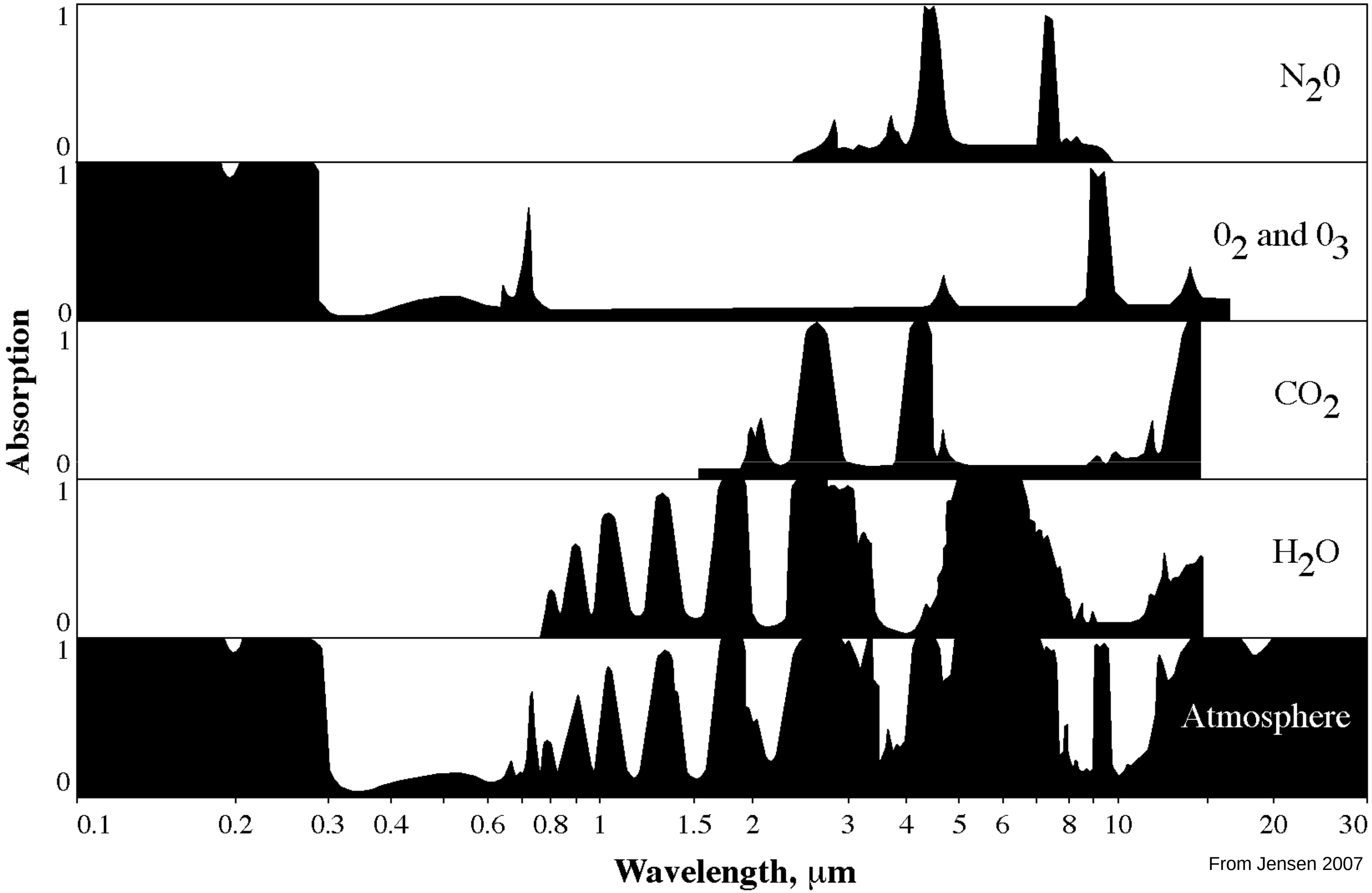
The atmospheric spectrum of shortwave radiation



From Jensen 2007

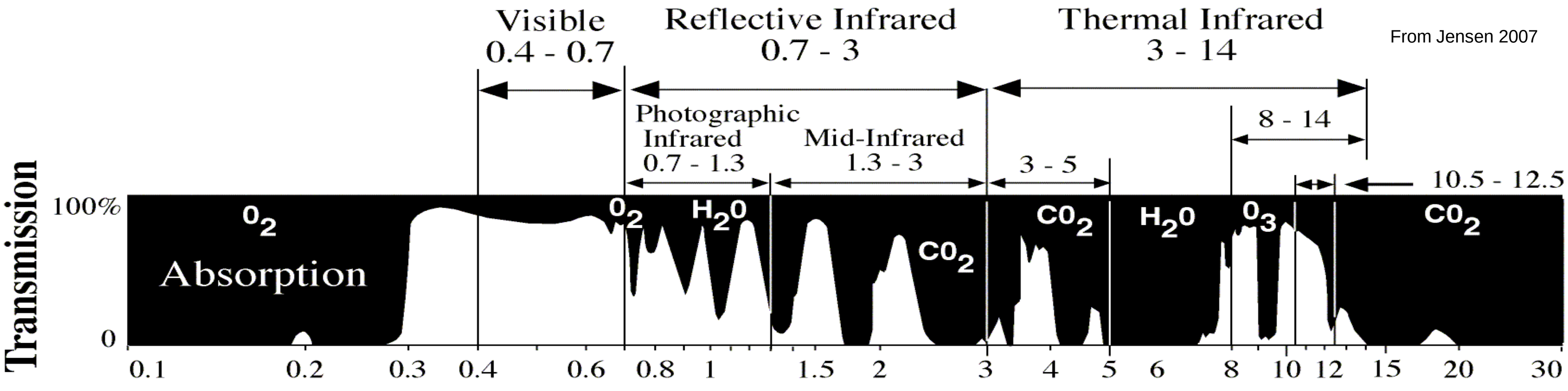
The combined effects of atmospheric absorption, scattering, and reflectance reduce the amount of solar irradiance reaching the Earth’s surface at sea level

Absorption

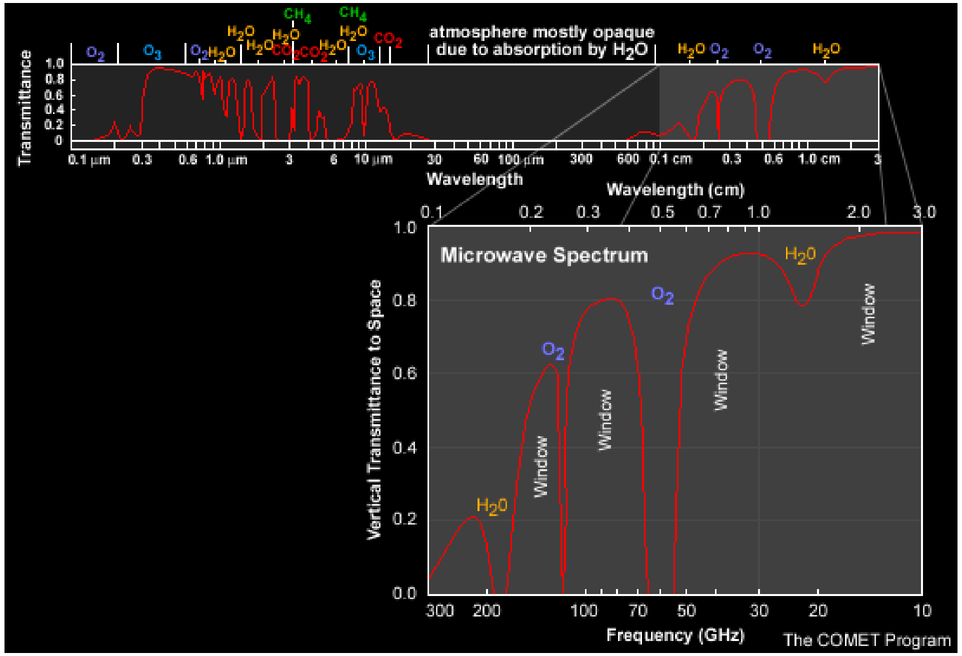


From Jensen 2007

Absorption



From Jensen 2007



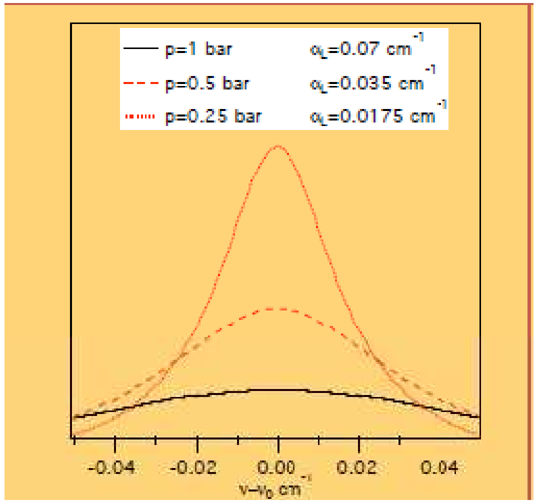
The COMET Program

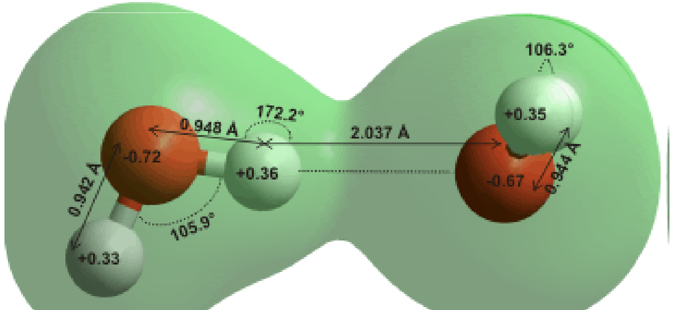
The water vapor continuum

« Atmospheric window » 8-14 microns

Absorption due to a continuum

Sum effects of the far wings of active absorbers on the edges of the windows





Water dimer illustration

From
Martin Chaplin

Isolated water clusters. Typically, in the atmosphere there is about one water dimer for every thousand free water molecules.

Not fully understood but observed and parameterized (e.g., Roberts et al, 1976)

$\sigma_a(\nu)=C(\nu,T)\ [e+\gamma(p-e)]$

Summary

- Atmosphere and radiation interacts through many processes
  - Absorption and emission are important for water vapor feedback

- Basics radiative transfer rooted in quantum mechanics.
  - Planck strong contribution
  - A full theory exists (Chandrasekar)
  - Hard to convey in a few slides

- Elaborated molecular spectroscopy
  - Lines of gaseous absorption
  - Theoretical issues with continuum

- Various models are available to compute all of these effects from band model to so called line-by-line

Outline of the lecture

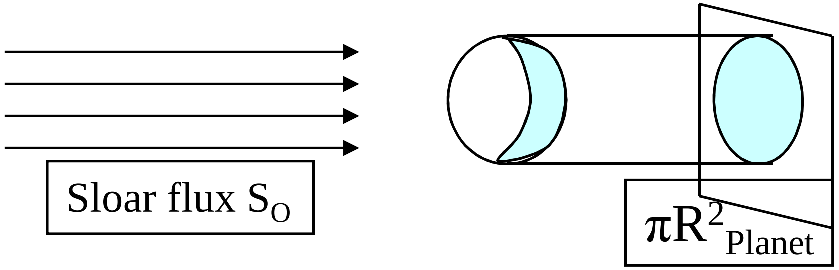
- Water vapor in the atmosphere
- Long wave Radiation in the atmosphere
  - Basis of radiation
  - The greenhouse effect
  - The radiative and the radiative convective equilibrium

- The water vapor feedback

Emission temperature of a planet

Assuming the planet is a black body, we look for T_E the BB equivalent temperature of the planet

absorbed solar radiation absorbé = planetary emitted radiation



*Absorption of the planet= $S_O(1-\alpha)\pi R^2_{planet}$

α is the planet albedo

- Emission of the planet = $\sigma T_E^4 \ . \ 4\pi R^2_{planet}$

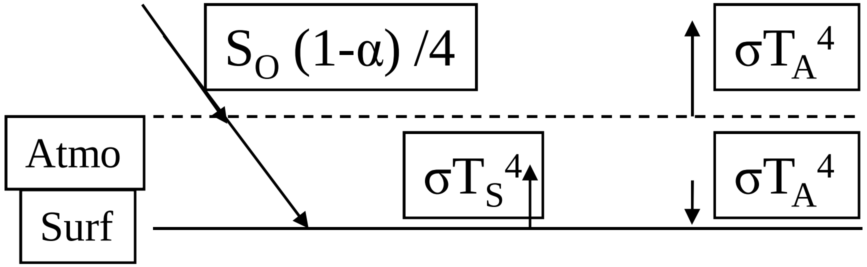
$$\frac{S_O}{4}(1-\alpha) = \sigma T_E^4$$

σ is the Stephan Boltzmann constant=$5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$

T_E only depens upon the incoming solar radiation and of the albedo

Surface temperature of an idealized planet

Let us add to the previous planet, an atmosphere transparent to solar radiation and that behavess like a black body in the longwaves



T_A temperature of the atmosphere
T_S temperature of the surface

TOA budget

$$\frac{S_O}{4}(1-\alpha)-\sigma T_E^4=0$$

$$\sigma T_E^4=\sigma T_A^4$$

Atmo budget

$$\sigma T_S^4-2\sigma T_A^4=0$$

Surface budget

$$\frac{S_O}{4}(1-\alpha)+\sigma T_A^4-\sigma T_S^4=0$$

$$T_S=\left[2\frac{S_O}{4\sigma}(1-\alpha)\right]^{1/4}$$

The greenhouse effect !

Adapted from Stephens G

	Distance from sun (10^4km)	Solar flux S_0 (10^4 erg cm-3 sec-1)	Albedo	T_E (K)	T_s(K) MOD
Venus	108	2.6	0.71	244	285
Earth	150	1.4	0.33	253	301
Mars	228	0.6	0.17	216	257

On Earth: T_E=253°K, Ts=303°K =+30°C,
The difference is due to the greenhouse effect: the trapping of infrared radiation by the atmosphere.

Surface is heated by the presence of the atmosphere (lucky us !).

The greenhouse effect : definitions

The greenhouse effect

$$G = \sigma T_s^4 - OLR$$

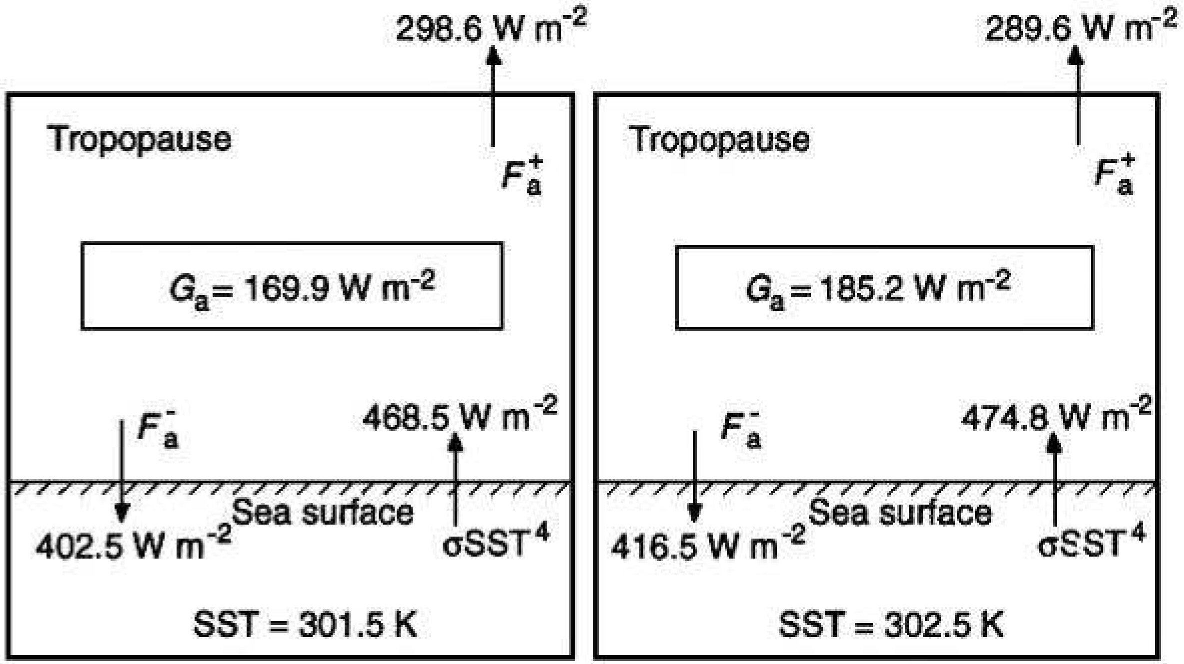
The clear sky greenhouse effect

$$Ga = \sigma T_s^4 - CSOLR$$

The normalized greenhouse effect

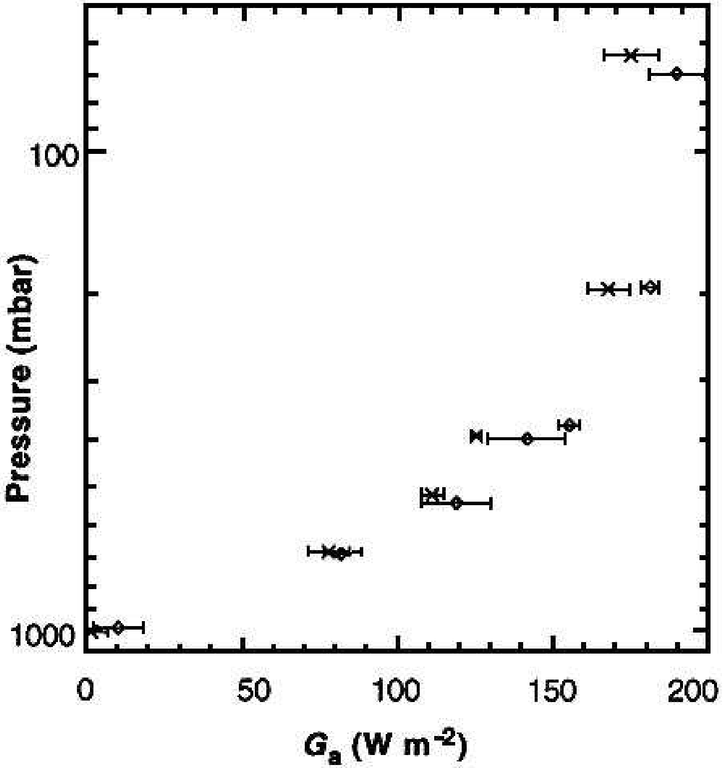
$$ga = Ga / \sigma T_s^4$$

Observation of the greenhouse effect



Valero et al 94

Summary of the measurements of the clearsky water vapor greenhouse effect. The values of Ga, Fa+, and Fa- are shown schematically for SSTs of 301.5 and 302.5 K at sea level and at 69 mbar (tropopause). Ga increases by 15.3 W m-2 K-1, Fa+ by 6.3 W m-2, and Fa- by 14 W m-2 K-1 [23], illustrating that the energy absorbed by the clear sky tropospheric water vapor greenhouse effect is radiated back to the surface, thus contributing to its heating.

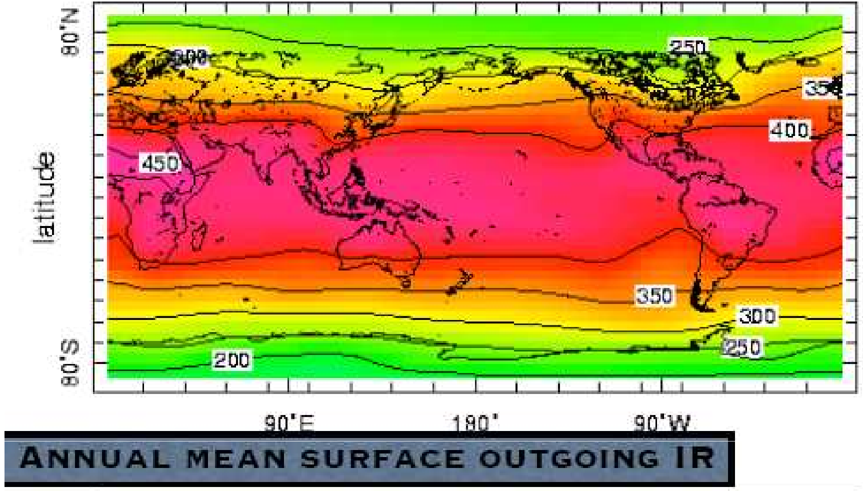


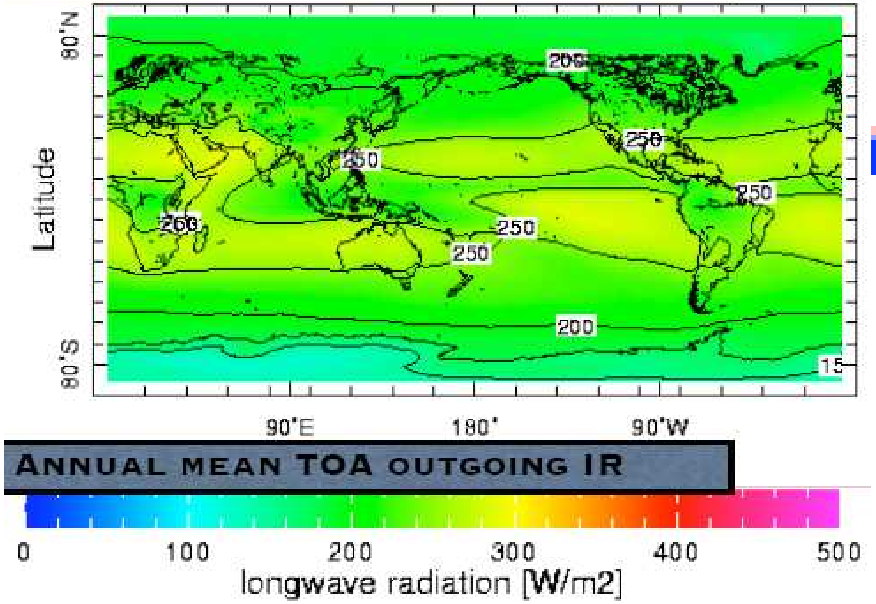
. Vertical profiles of clear sky greenhouse effect east (diamonds) and west (crosses) of the dateline. Bars indicate standard deviations and reflect the change in Ga with SST at each altitude.

Observation of the greenhouse effect

σT_s^4

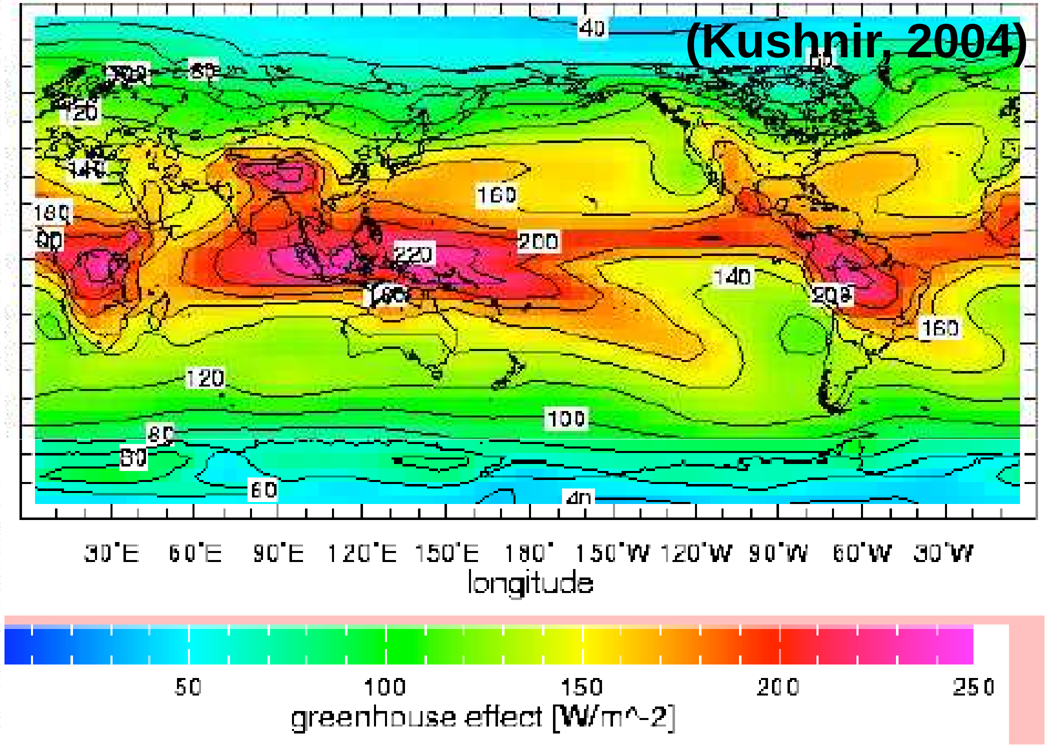
(assuming emissivity 0.95)





$G = \sigma T_s^4 - OLR$

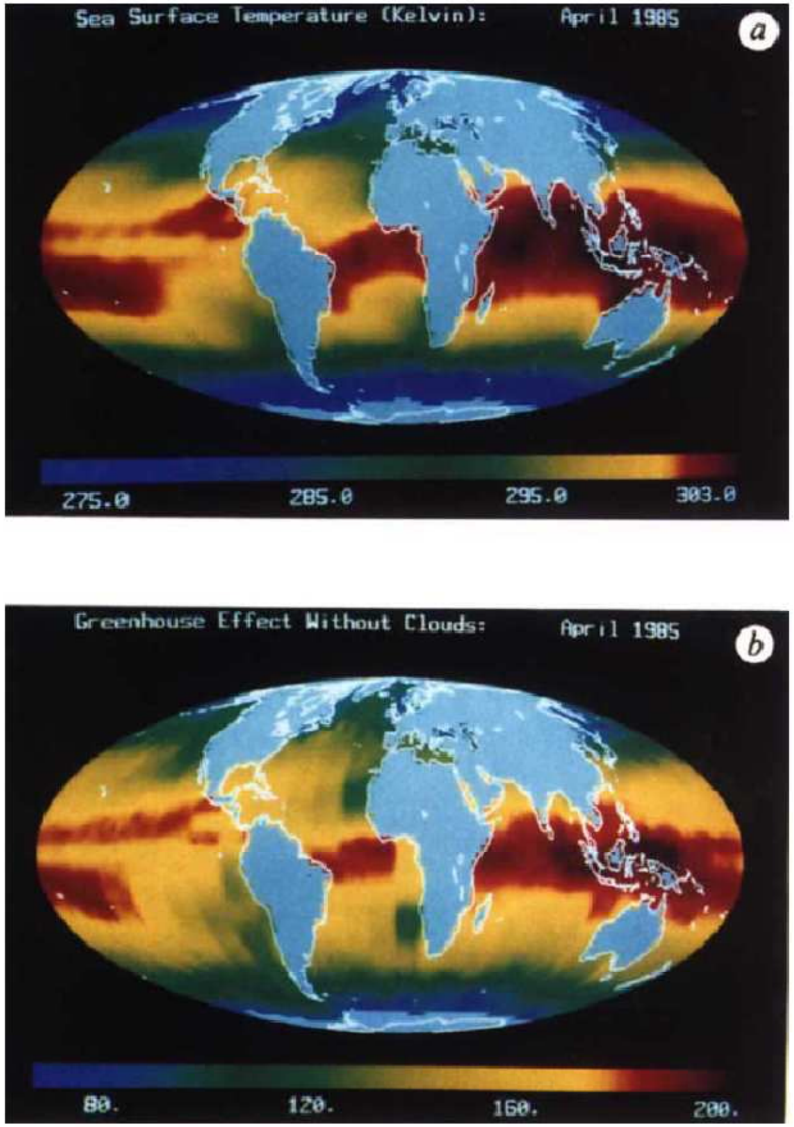
G Effet de serre

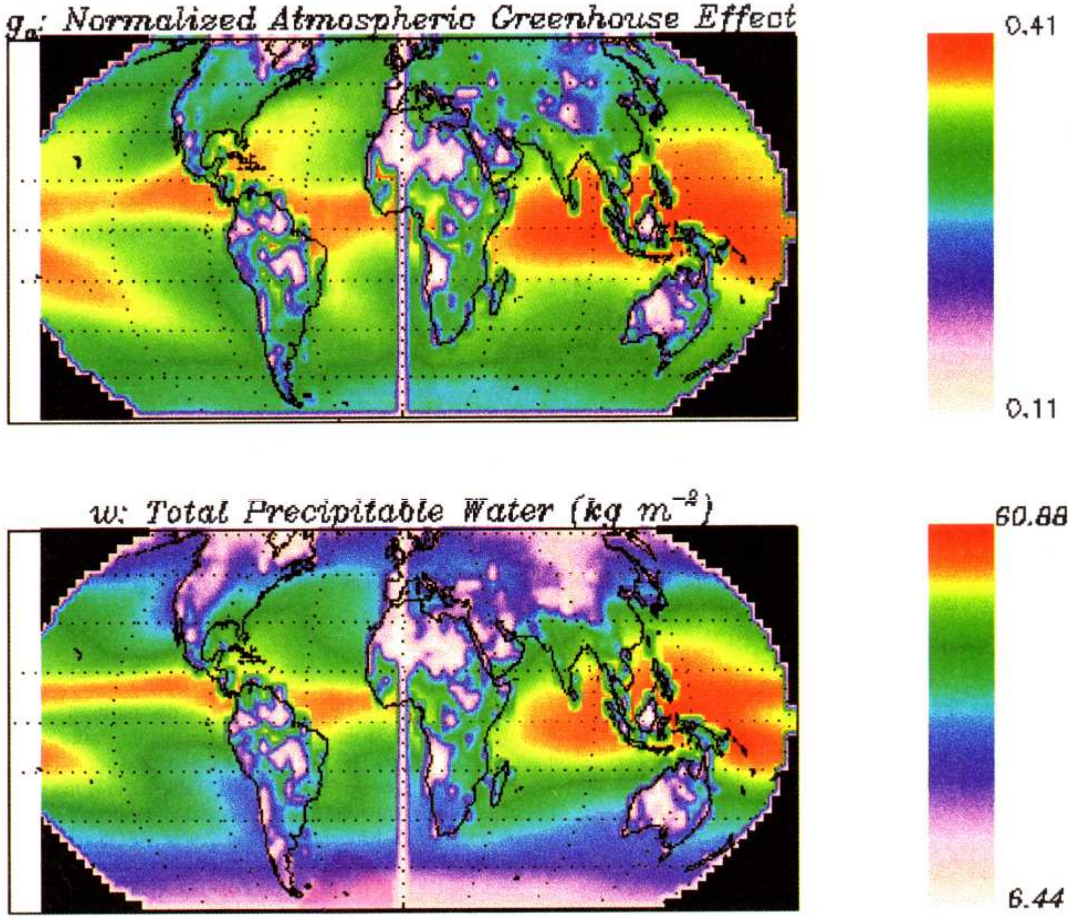


(Kushnir, 2004)

Tropics and monsoon regions reveals a strong greenhouse effect: clouds and water vapor

Observation of the greenhouse effect of water vapor





Inamdar & Ramanathan, 1998

(Raval and Ramanathan, 89)

Radiative and Radiative convective equilibrium

	Albedo	T_E (K)	T_s(K) Mod	Ts(K) Obs
Venus	0.71	244	285	750
Earth	0.33	253	301	288
Mars	0.17	216	257	220

The difference between the real world and this simple radiative equilibrium
Is due to convection !

On Earth it is due to the moist convection

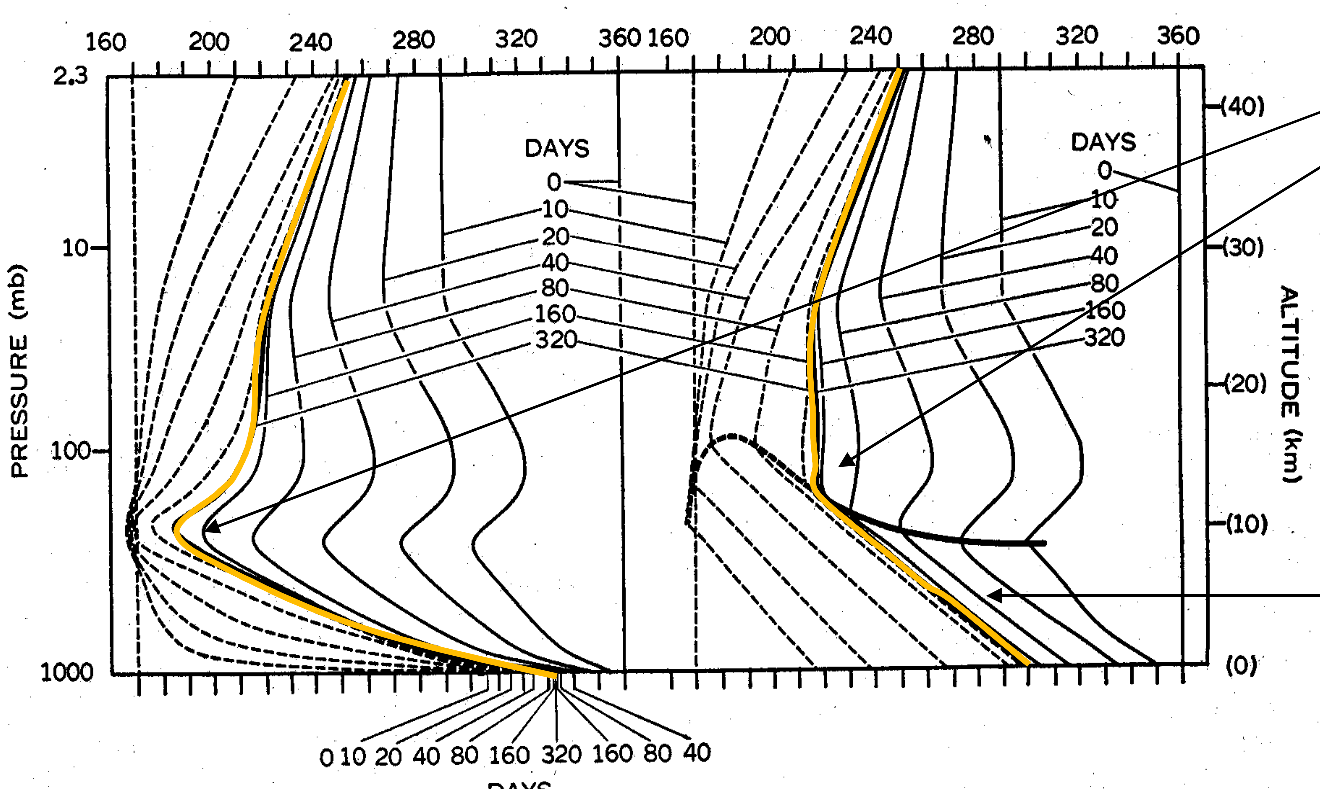
Need to approach reality to shift from radiative equilibrium to radiative convective equilibrium, a very useful framework to understand and discuss the water vapor feedback.

Outline of the lecture

- Water vapor in the atmosphere
- Long wave Radiation in the atmosphere
  - Basis of radiation
  - The greenhouse effect
  - The radiative and the radiative convective equilibrium

- The water vapor feedback

Present climate equilibrium (Manabe and Strickler, 1964)



tropopause

convectif
Adjustement

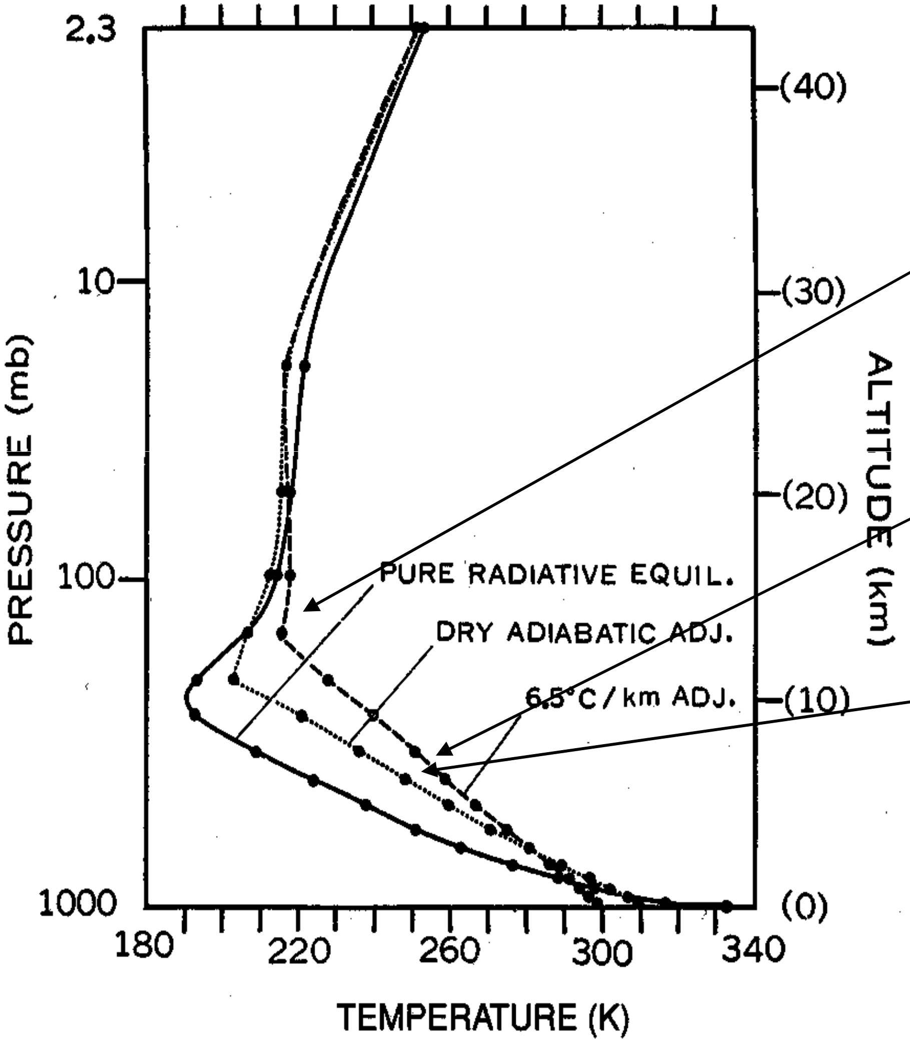
— Equilibrium: left pure radiative; right radiative-convective

— état initial warm

…… État initial cold

Surface temperature is colder in radiative convective equilibrium

Present climate equilibrium (Manabe and Strickler, 1964)



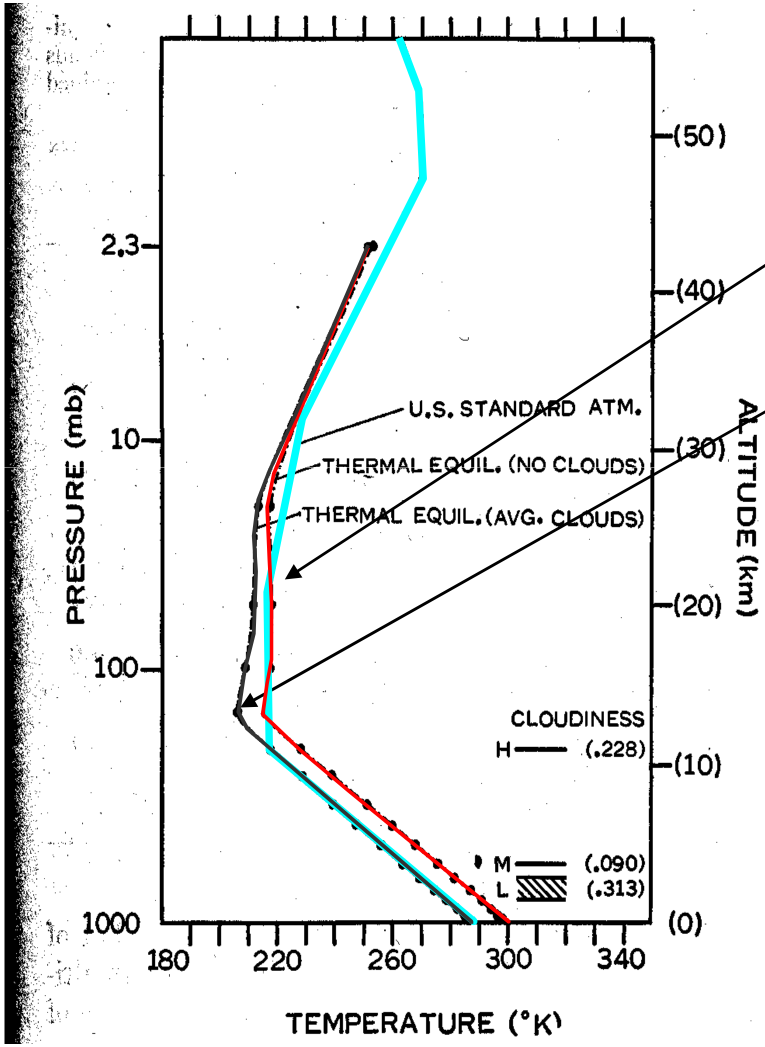
tropopause

Ajustement
Convectif MOIST

Ajustement
Convectif DRY

Surface temperature is colder in moist radiative convective equilibrium

Present climate equilibrium (Manabe and Strickler, 1964)



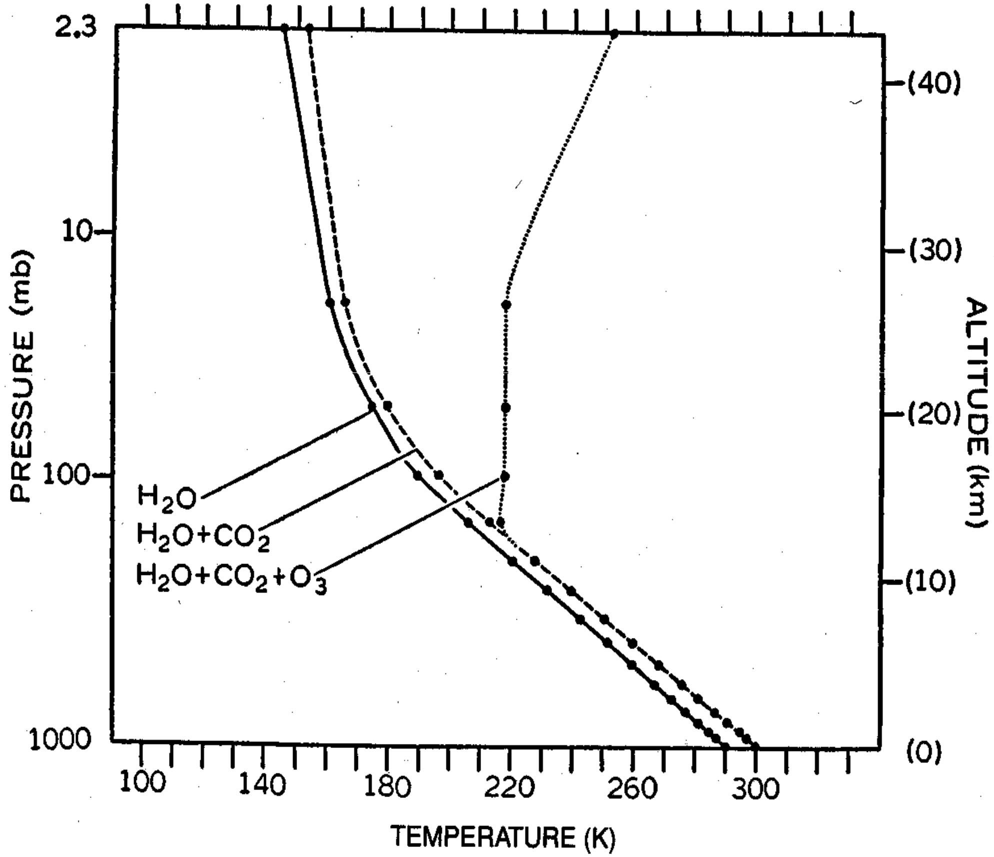
Stratosphère too cold (10K)

Tropopause too high and too cold

Ts=286.9K rather close to surface temperature of the standard atmosphere

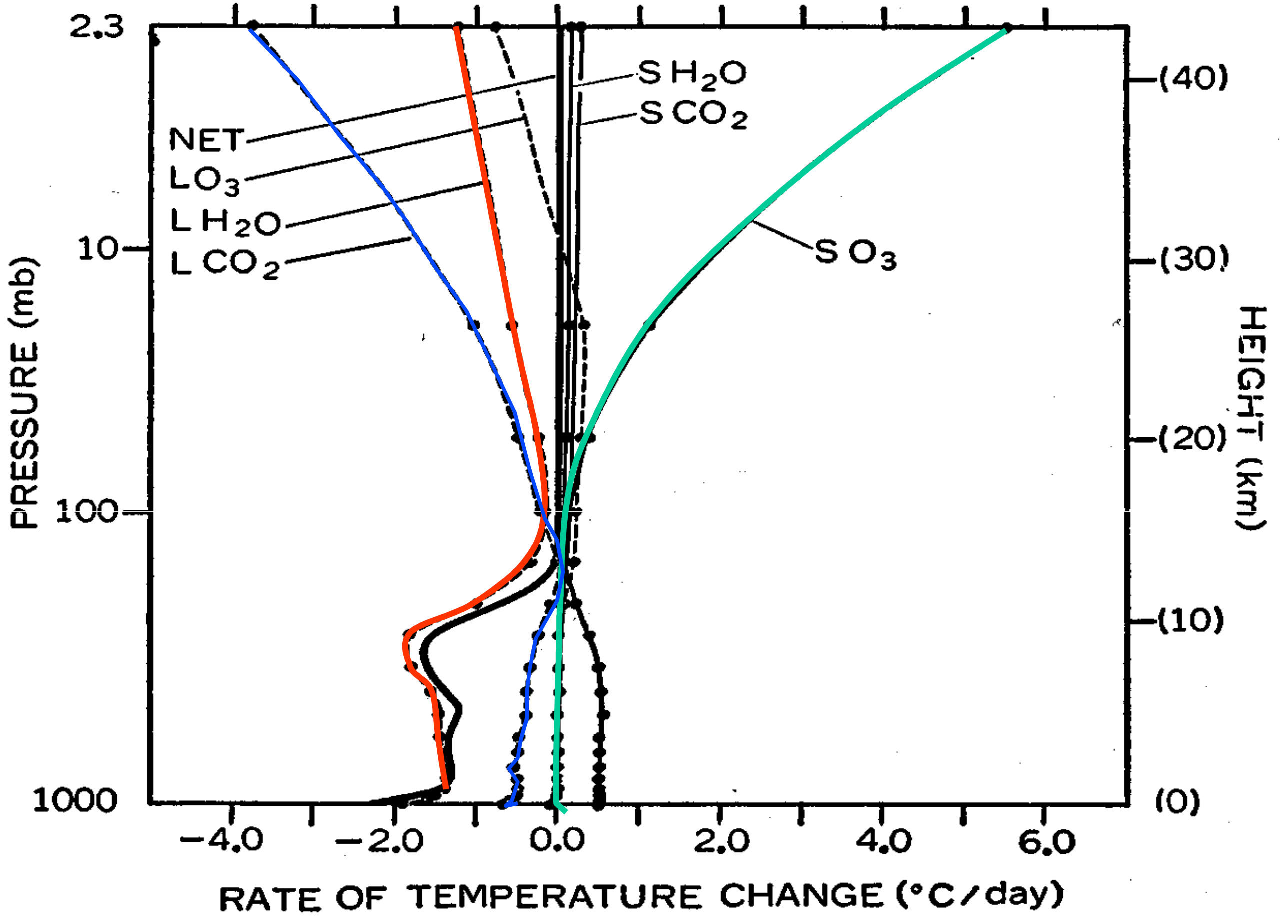
Relative contribution from various absorbers

Clear sky radiative convective equilibrium



Stratosphere temperature is controlled by ozone

Relative contribution from various absorbers

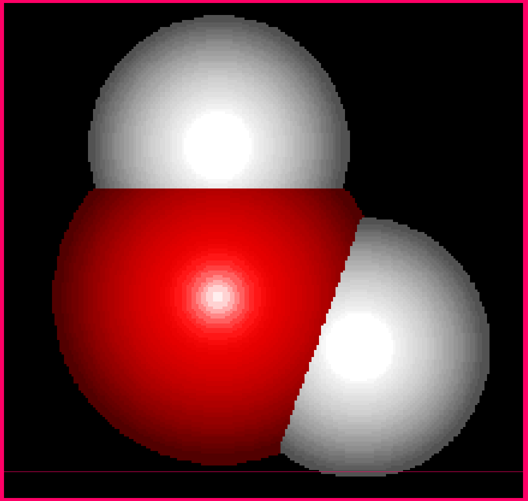


Troposphere cools radiatively. H_2O plays a central role in it. This cooling destabilizes the troposphere hence convective adjustement

Summary

- Greenhouse effect is observed
  - In situ, with satellite
  - It makes the surface temperature warmer than if no atmosphere
- The atmosphere thermal structure and surface temperature requires radiative-convective equilibrium
  - Water vapor plays an important role

A short course on water vapor and radiation

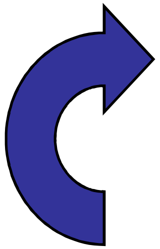


Rémy Roca
Chargé de Recherche CNRS
Laboratoire de Météorologie Dynamique
roca@lmd.jussieu.fr

Outline of the lecture

- Water vapor in the atmosphere
- Long wave Radiation in the atmosphere
- The water vapor feedback
  - The classical view
  - Feedback and runaway greenhouse effect
  - Radiative-convective equilibrium (rh=cte)
  - Relative part of the troposphere to feedback

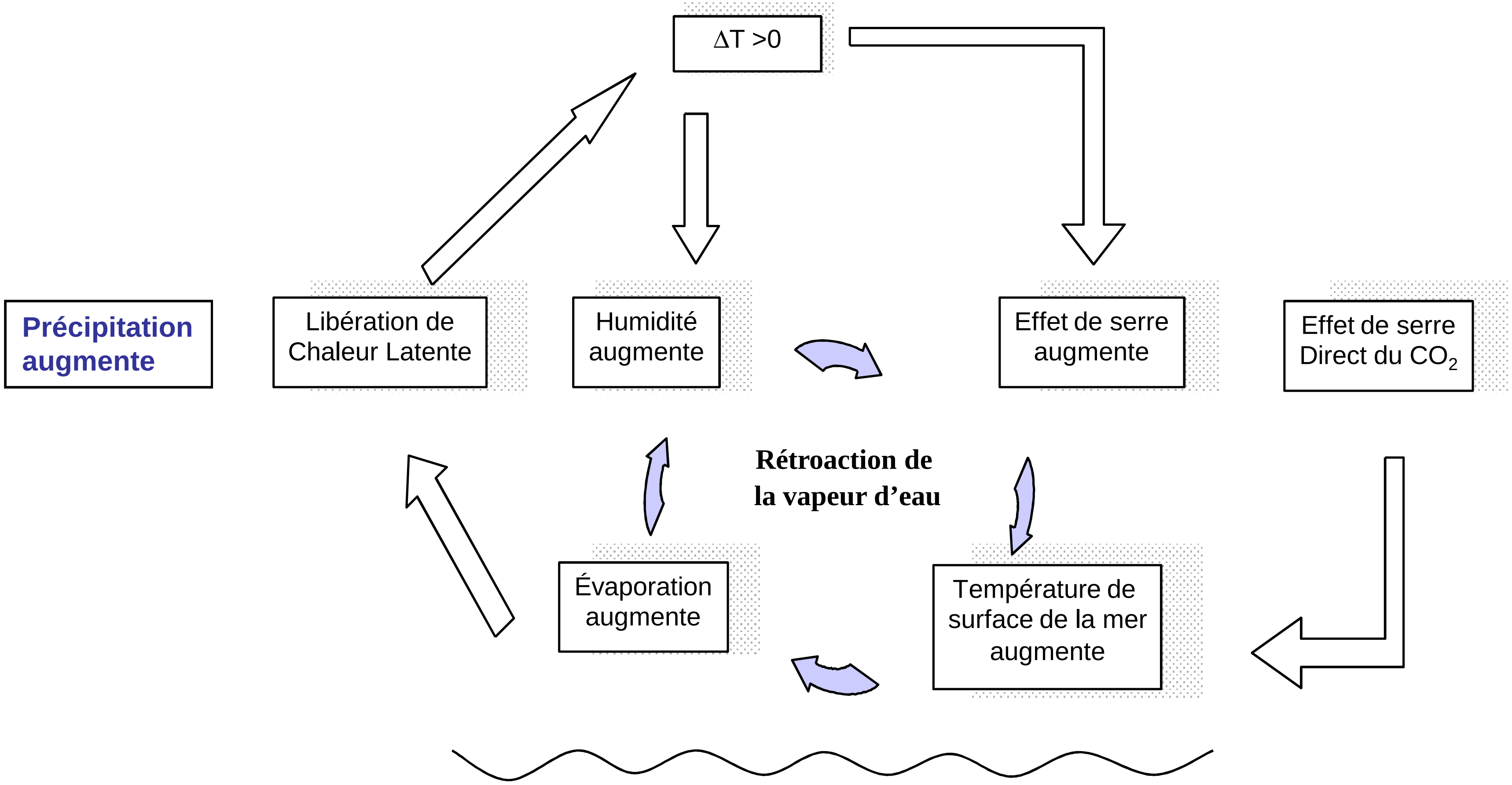
The water vapor feedback



1. Initial increase in Temperature (e.g. due to CO_2)
2. If RH=cte then specific humidity increases
3. Greenhouse effect increases

- This « infernal » loop increases the climate sensitivity
- yield to run away conditions

The water vapor feedback: 0D



$\Delta T > 0$

Précipitation augmente

Libération de Chaleur Latente

Humidité augmente

Effet de serre augmente

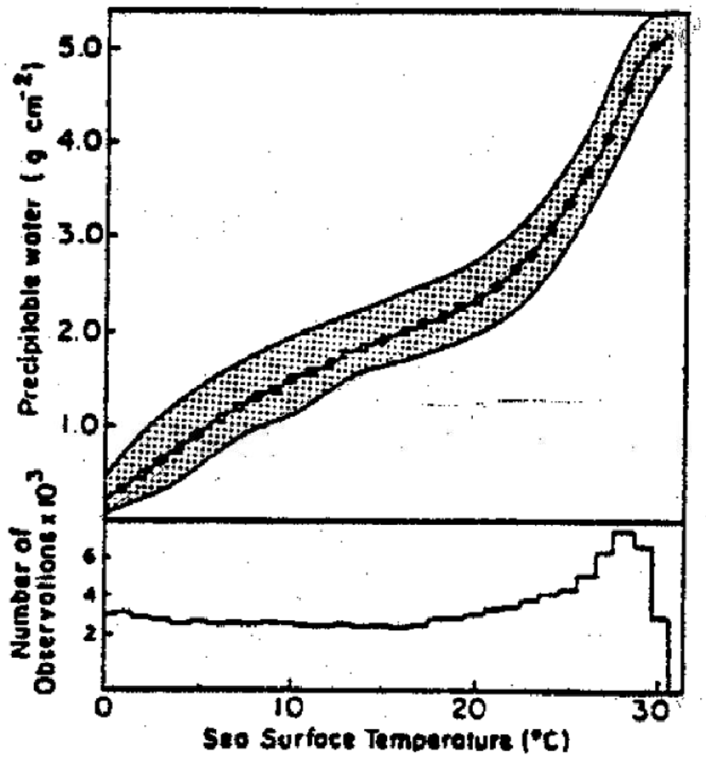
Effet de serre Direct du CO_2

Rétroaction de la vapeur d'eau

Évaporation augmente

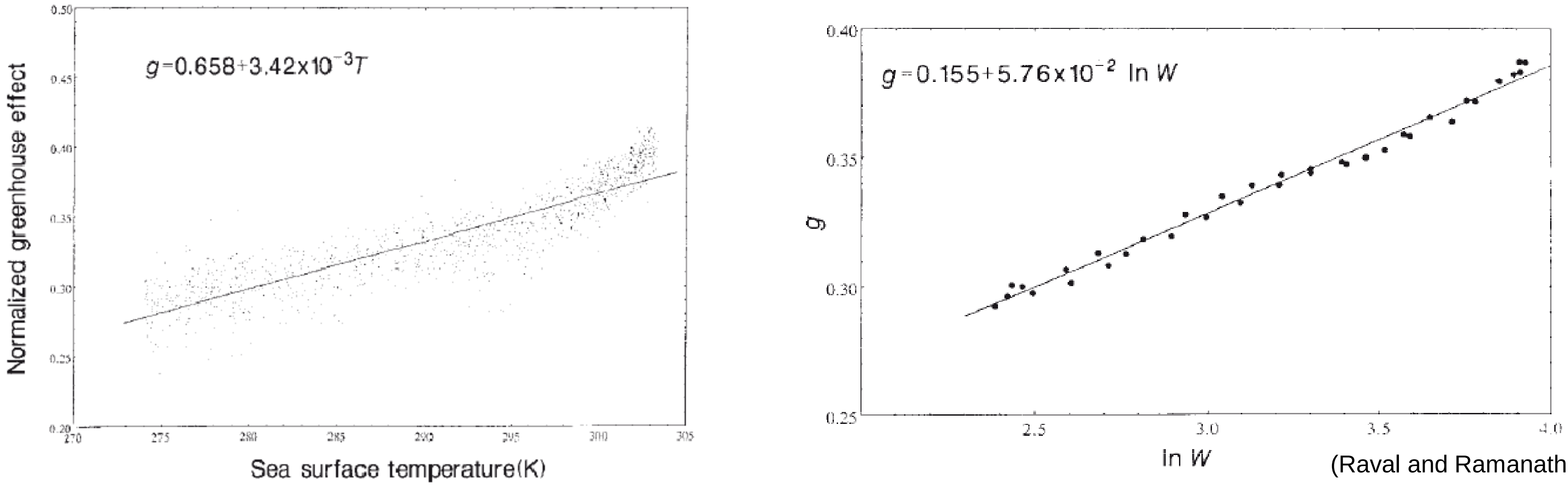
Température de surface de la mer augmente

Observational evidence for the water vapor feedback



A necessary condition for the existence of water vapor feedback on Earth. Water vapor exists in equilibrium with the oceans in a way that is related to the sea surface temperature largely through the Clausius-Clapeyron relationship. The curve shown is established from thousands of observations of water vapor over the world's oceans (Stephens, 1990).

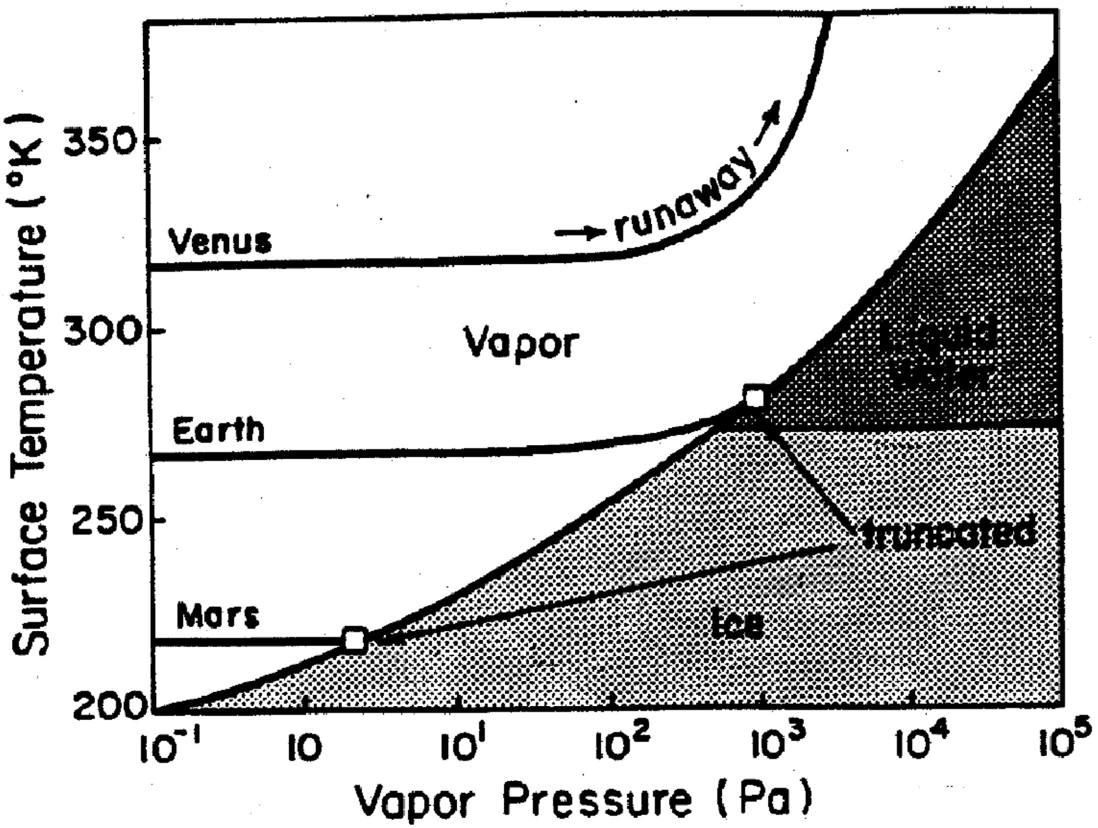
Observational evidence for the water vapor feedback



(Raval and Ramanathan, 89)

Model		**dGa/dTs**($Wm^{-2}K^{-1}$)	**Source**
The first computation	**0D**	**2.9**	Arrhenius (1896)
Rad/convectif RH=cte	**1D**	**3.7**	Manabe and Wetherald (1967)
GCMs	**3D**	**3.0**	Cess et al. (1990)
Observations (**ERBE+SSMI**)	**3D**	**3.3**	Raval and Ramanathan (1989)

The truncated runaway greenhouse effect



After S. I. Rasool and C. DeBergh, 1970 , from Stephens G.

Evolution of the planetary atmosphere and the runaway greenhouse effect

On Earth, the phase change makes the situation more complex and the greenhouse effect is truncated. Not easy to fully understand

But the water vapor feedback is there and strong !

Climatic feedbacks

The feedback processes can amplify (positive feedback) or damp (negative feedback) an initial perturbation.

- The feedback de Stefan-Boltzmann

If Temperature increases then the loss of energy through radiation increases :

negative feedback very strong

- Ice albedo feedback

If Temperature increases then the ice cover decreases hence the absorbed solar incoming radiation and the temperature increases

Positive feedback

- Cloud feedback

If Temperature increases and induced more clouds, more albedo then température decreases. But the greenhouse effect of clouds temperature increases

unclear sign

Runaway greenhouse effect

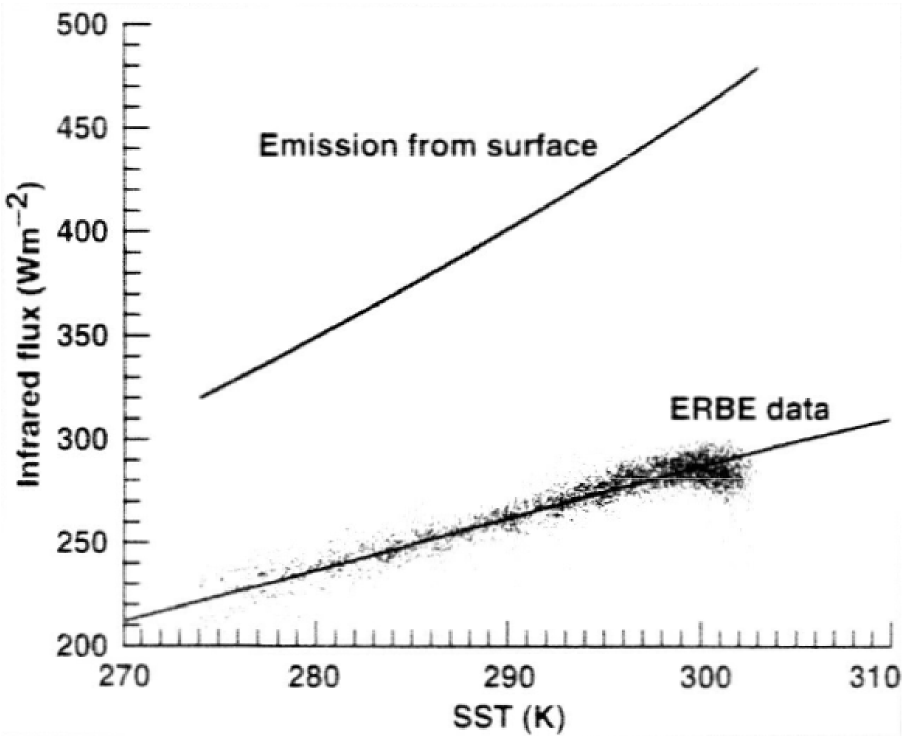
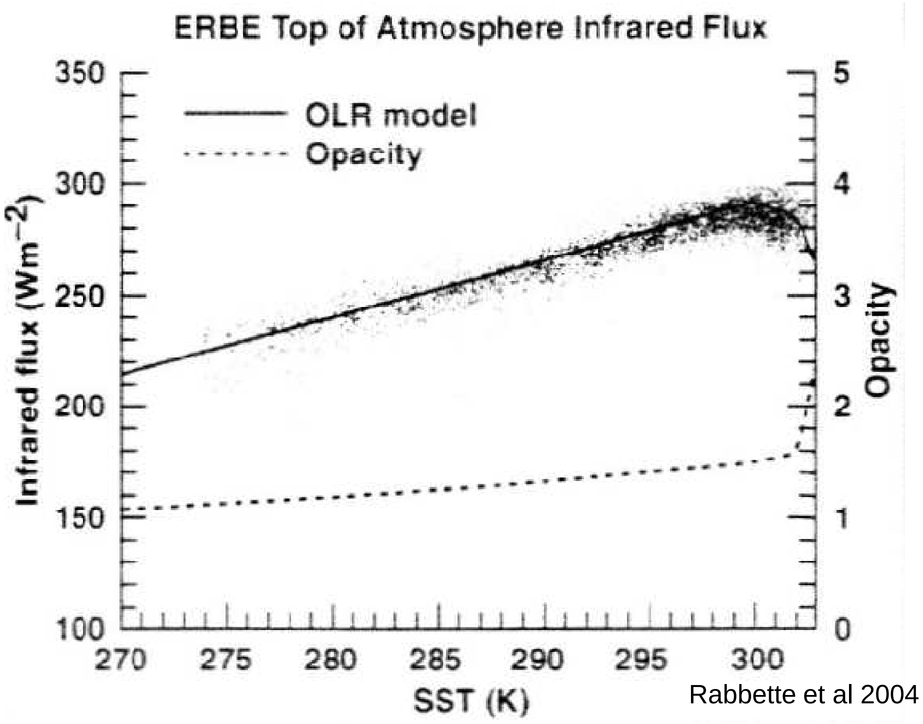


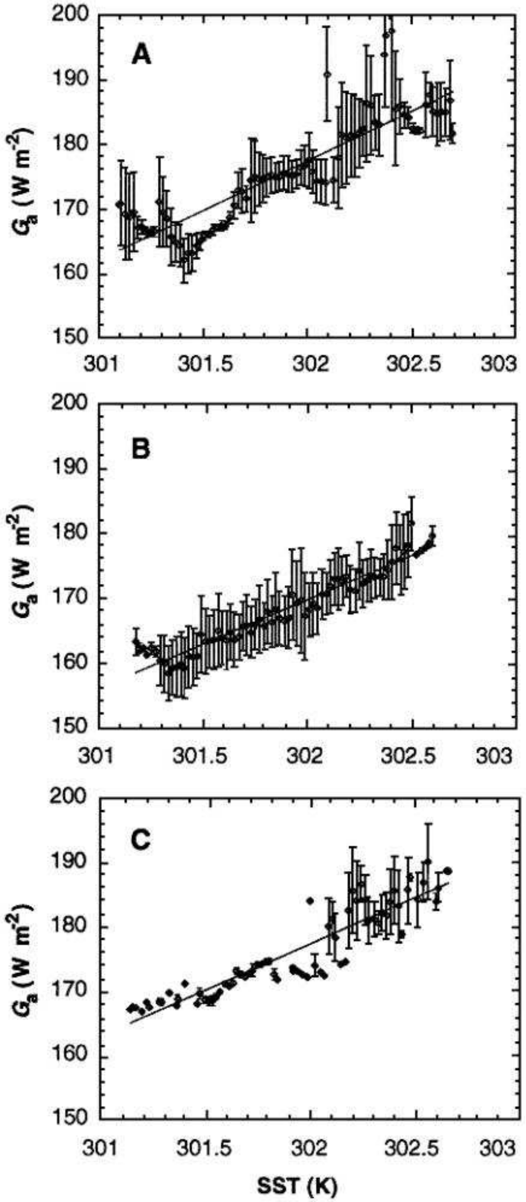
Fig. I. Accordin to Stefan-Boltzmann's law, the amount of heot (upper line). The output from MODTRAN, ;.e., the modeled Top of Atmosphere Emission, is also displayed (lower line). The model incorporates user defined atmospheric pressure profiles and temperature profiles based on o moist adiabdic lapse rde as well as relative humidity profiles. Together these profiles give the bed modeled fit (up to an **SST** of 300 **K)** to the Top of Atmosphere Emission



Rabbette et al 2004

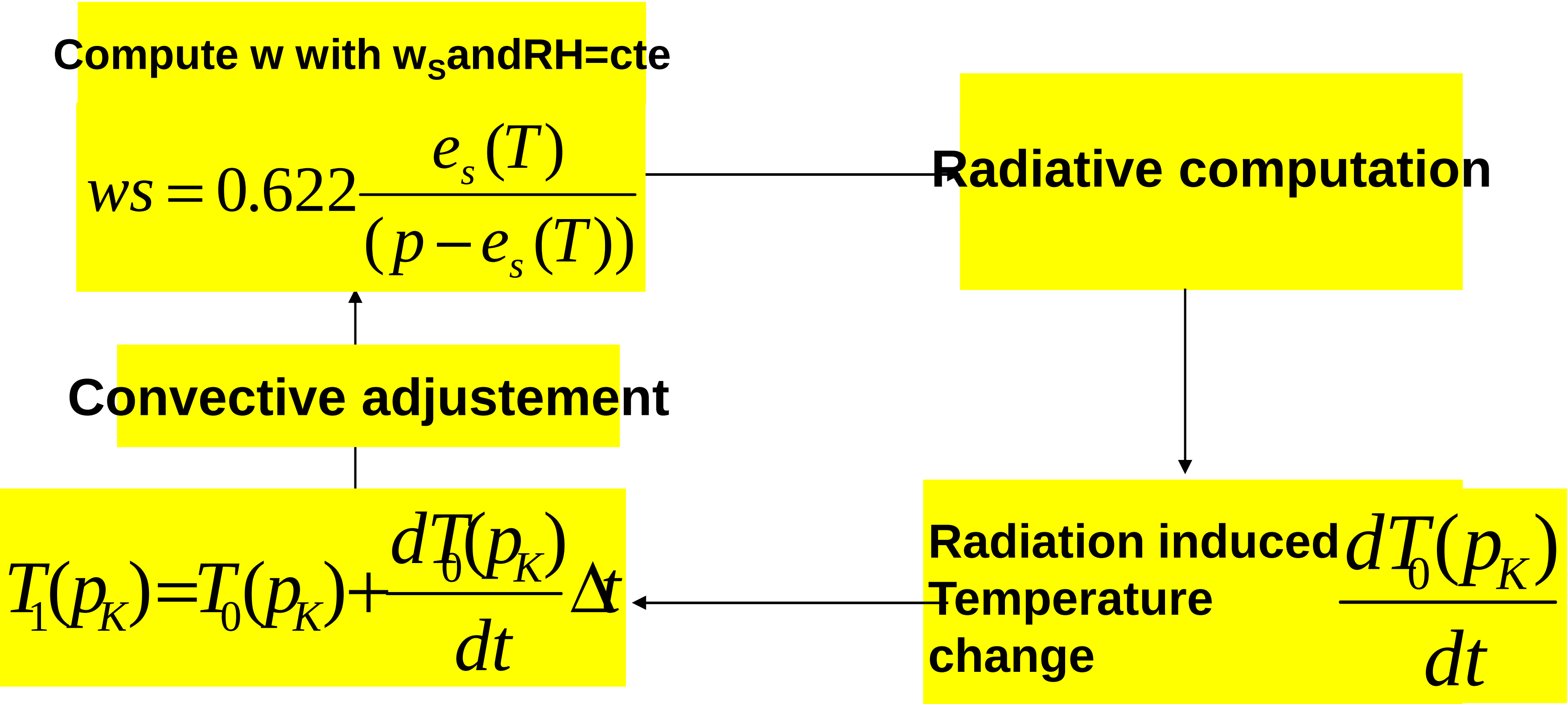
Fig. **2.** The radiative transfer model was then used to reproduce the signature of the potential runaway greenhouse effecf on Eorth. For SST volues 30 1-303 **K,** much higher concentrations of water vapor were introduced into the atmospheric profile. **As** o result, *a* turnoround and decrease in the outgoing longwave radiation model was achieved (solid line through ERBE data points]. ***Also*** shown is the corresponding sharp increase in otmospheric opacity (dashed line)

Runaway greenhouse effect



. Clear sky greenhouse effect versus SST as observed from the ER-2 (69-mbar altitude) and Learjet (191-mbar altitude) aircraft. The plots show data from six flights. Each individual flight covered the full range of SSTs along the 2 degrees S track (Figure 1). Data points represent the average of the clear-sky data points in 0.02 K SST intervals. The standard deviations are indicated by bars. The figures show regressions with data from (A) the IRBBR on the ER-2, correlation factor (R) = 0.871; (B) the IRBBR on the Learjet, R = 0.964; and (C) the NFOV radiometer on the ER-2, R = 0.921.

The radiative convective equilibrium framework: 1D



Compute w with w_s andRH=cte

$$ws = 0.622\frac{e_s(T)}{(p-e_s(T))}$$

Radiative computation

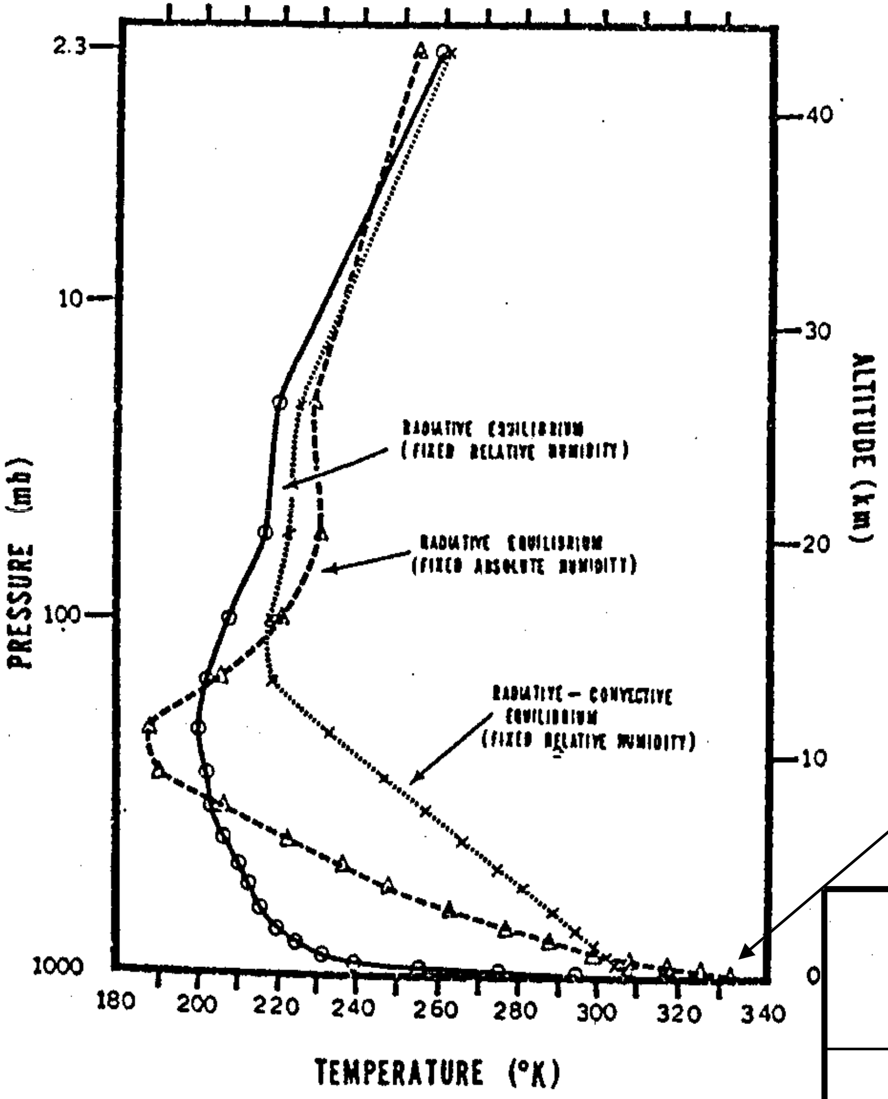
Radiation induced Temperature change $\frac{dT_0(p_K)}{dt}$

$$T_1(p_K) = T_0(p_K) + \frac{dT_0(p_K)}{dt}\Delta t$$

Convective adjustement

The water vapor feedback: 1D

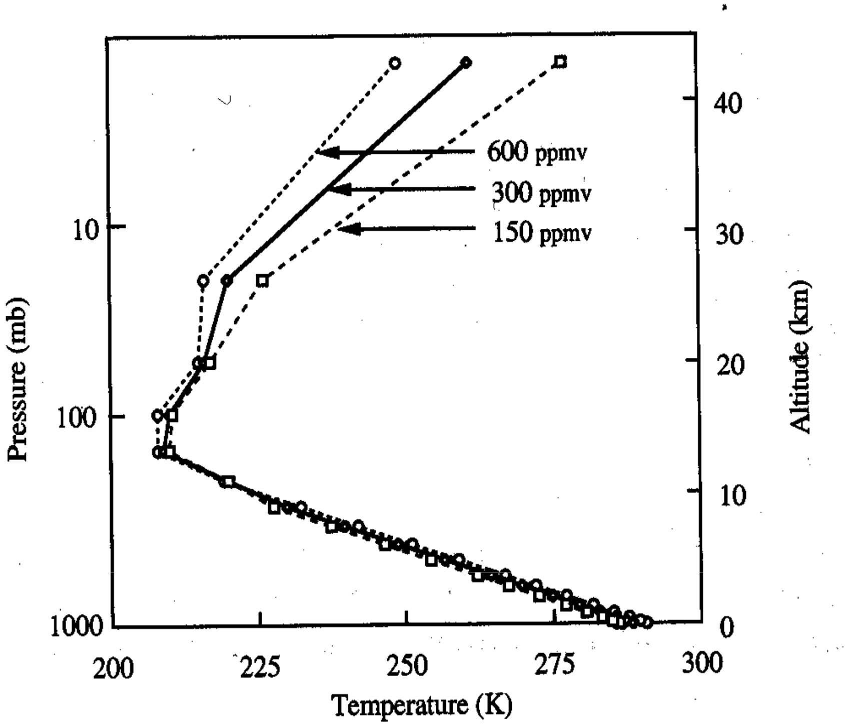
Present climate simulation

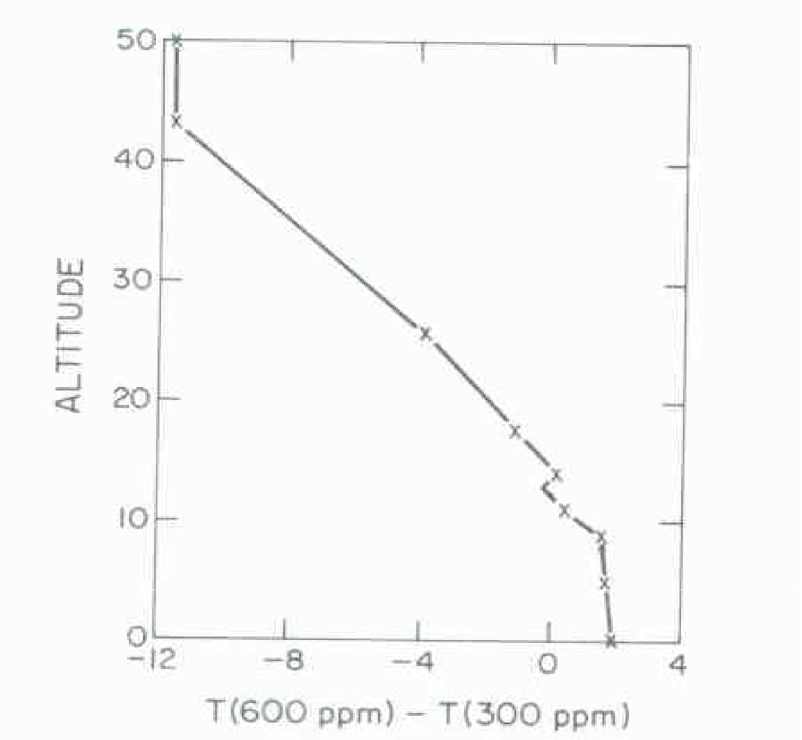


Surface is cooler with fixed RH

Humidité spécifique FIXE	Humidité relative FIXE
291.0 K	288.4 K

The water vapor feedback: 1D





CO_2 change	Specific humidity FIXE	Relative humidity FIXE
300->150	-1.25	-2.28
300->600	+1.33	+2.36

Climate sensitivity is doubled when RH=cte

The relative importance of different parts of atmosphere to the WV feedback

(Held and Soden, 2000)

$$\delta OLR = \sum_{k=1}^{N} \left[\frac{\partial OLR}{\partial T_k} \delta T_k + \frac{\partial OLR}{\partial e_k} \delta e_k \right]$$

Assuming fixed rh and a uniform small perturbation of temperature
Then noting

$$\delta T$$

$$\delta e = rh \frac{de_s}{dT} \delta T$$

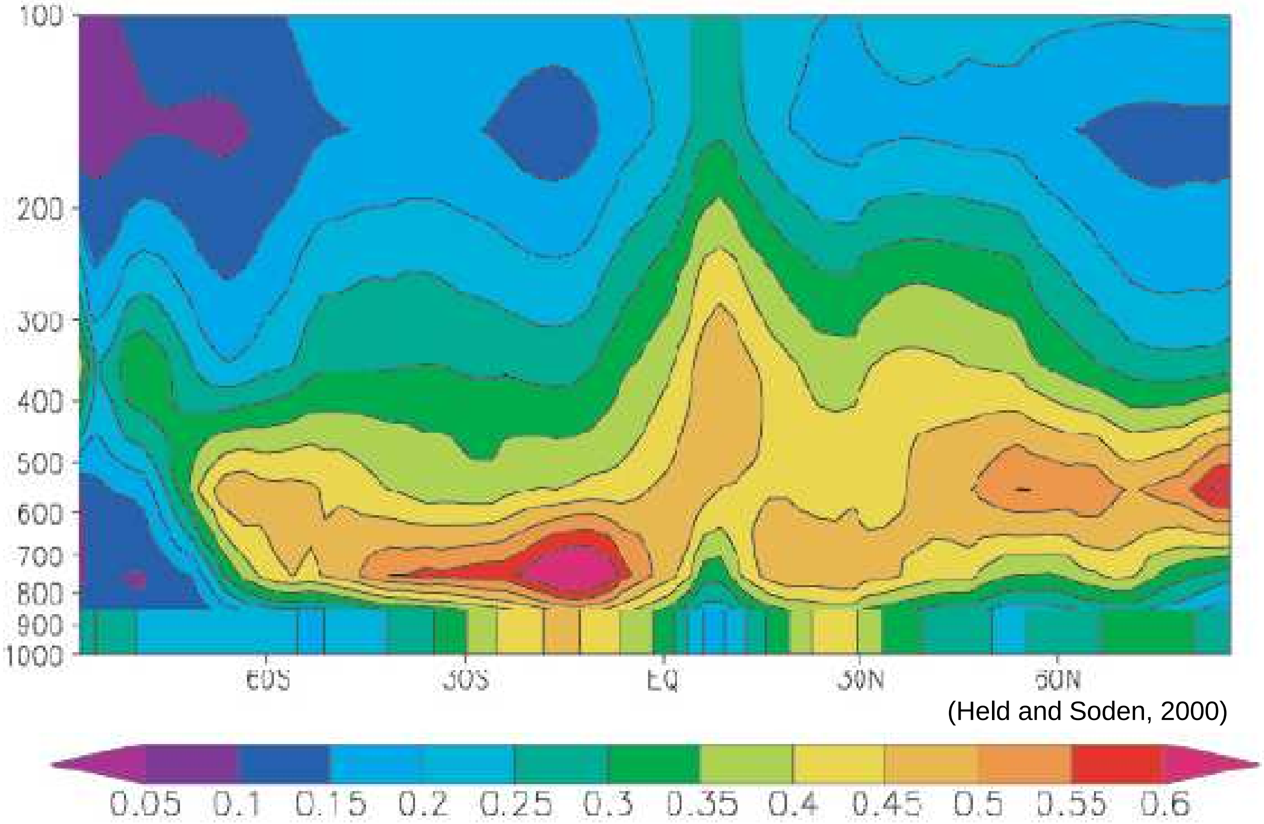
$$Q_e^k = \frac{\partial OLR}{\partial e_k} rh \frac{de_s}{dT} \qquad Q_T^k = \frac{\partial OLR}{\partial T_k}$$

$$\delta OLR = \sum_{k=1}^{N} \left[Q_T^k + Q_e^k \right] \delta T$$

The relative importance of different parts of atmosphere to the WV feedback

All computations July T,q from ECMWF, clouds from ISCCP

$$Q_T^k$$

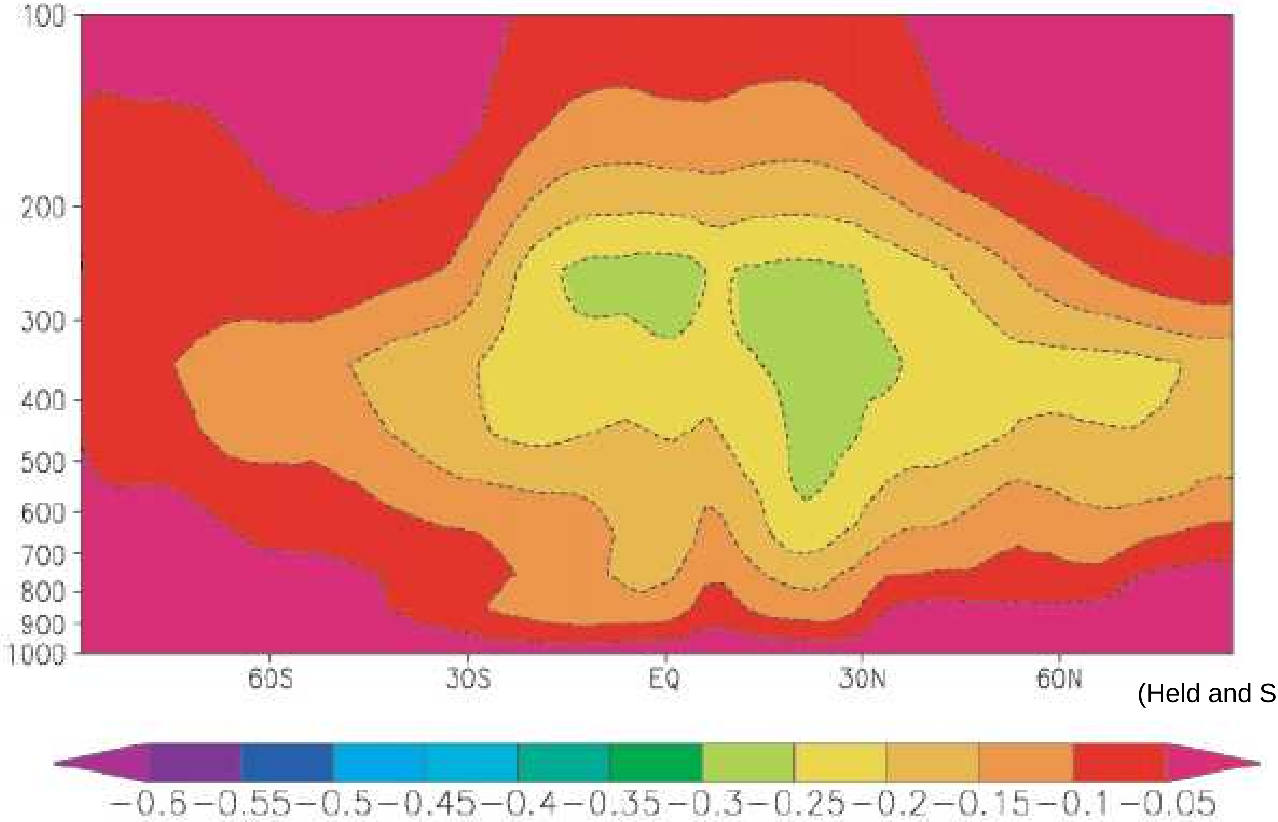


(Held and Soden, 2000)

- Max sensitivity altitude depends on cloud tops
- Away from the deep tropics, lower levels are contributing

The relative importance of different parts of atmosphere to the WV feedback

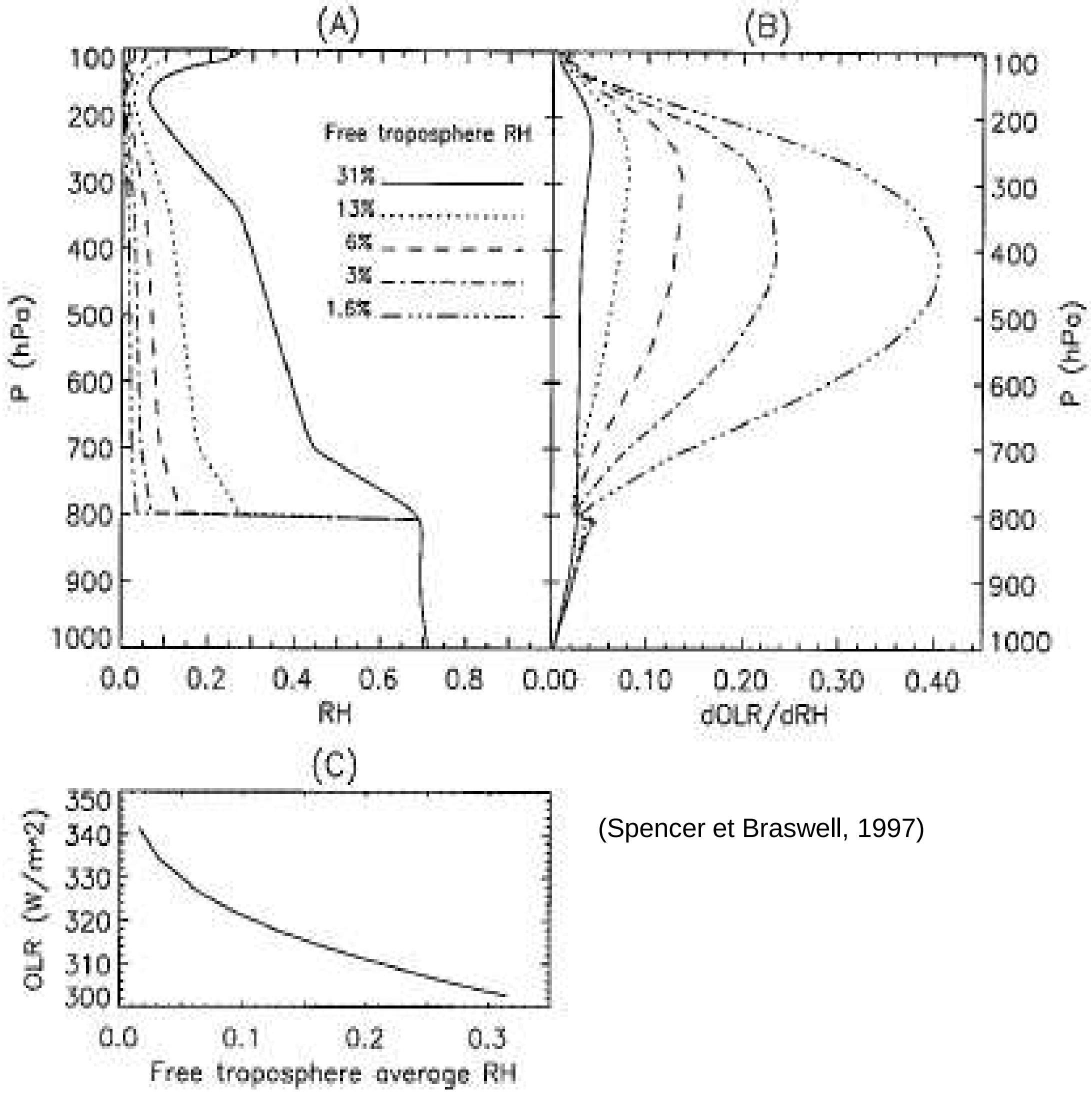
Q_e^k



(Held and Soden, 2000)

- •Max sensitivity mid to upper troposphere in the intertropical region
- •Dry free trop important (cloud effect otherwise in the moist regions)
- •90% of the wv feedback (Uniform T, rh=cte) above 800 hPa.
- •55%due to 30s-30n region 2/3 of which (35% total) due to the 100-500 hPa region

The relative importance of different parts of atmosphere to the WV feedback



(Spencer et Braswell, 1997)

Small RH perturbations Emphasizes strongly the dry subtropical free troposphere

$$\delta e \propto e_s$$

Shine and Sina 90s, emphasized the boundary layer

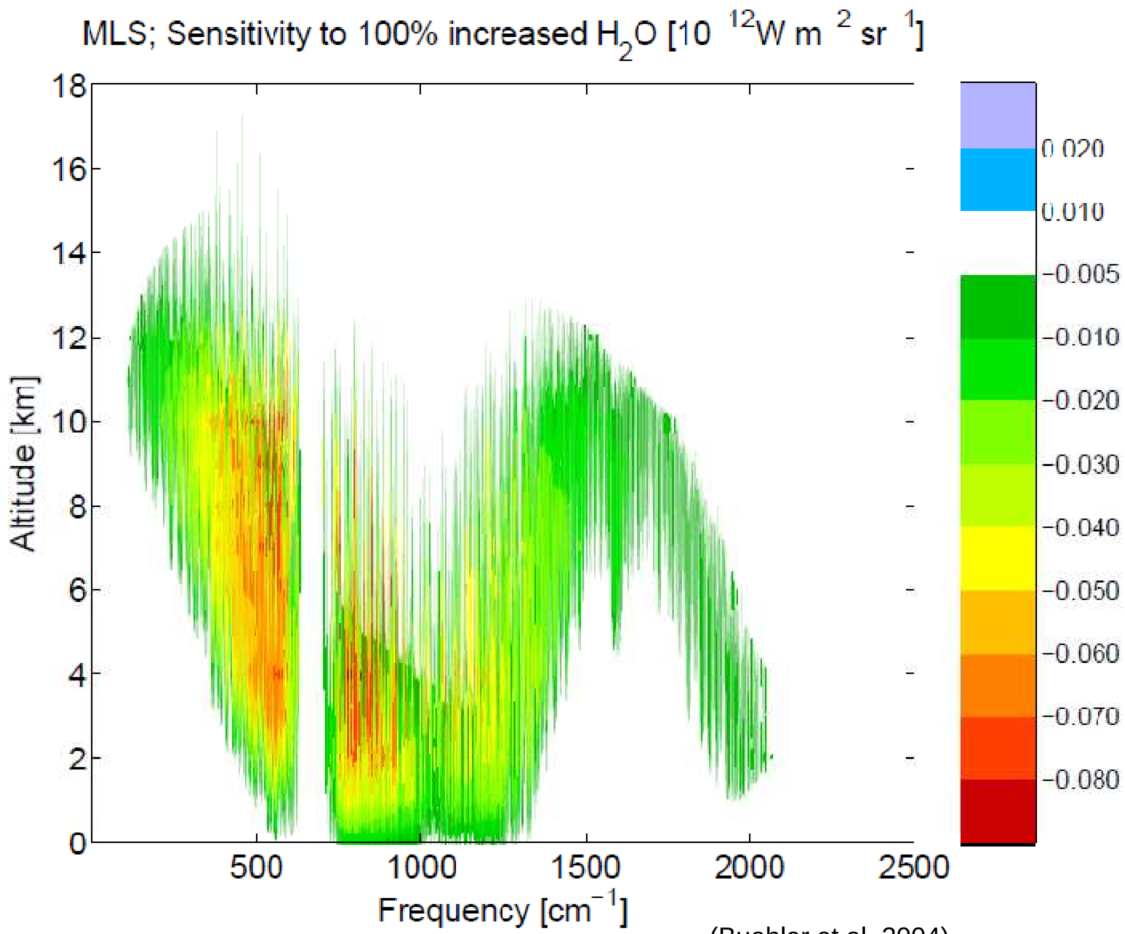
$$\delta e \propto e$$

Held and Soden computations reads

$$\delta e \propto \frac{e}{e_s}\frac{de_s}{dT} \propto \frac{e}{T^2}$$

The relative importance of different parts of atmosphere to the WV feedback

A alternative: the spectraly resolved Jacobian



(Buehler et al, 2004)

The Jacobian of TOA zenith monochromati radiance with respect to humidity in Wsr-^{1}m^{-2} for a midlatitude summer atmosphere. The units correspond to the OLR change for a doubling of the humidity concentration (VMR)at one altitude, decreasing linearly to zero at the adjacent altitudes above and below (triangular perturbations).The grid spacing is 1 km.

The relative importance of different parts of atmosphere to the WV feedback

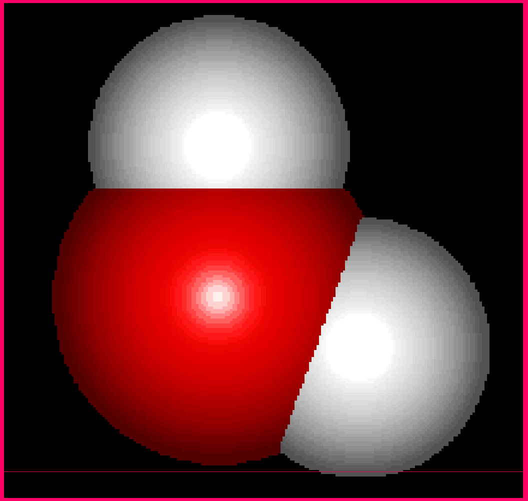
- None of the computations is either correct or wrong.
- They all are consistent radiatively.

- Now, what would the expected change of e be in a changing climate is the question. Held and Soden’s expression is closest to GCM response.

- Tricky spectral dependences to account for

- High non linearity between OLR and wv depends upon the background, location, cloudiness etc…

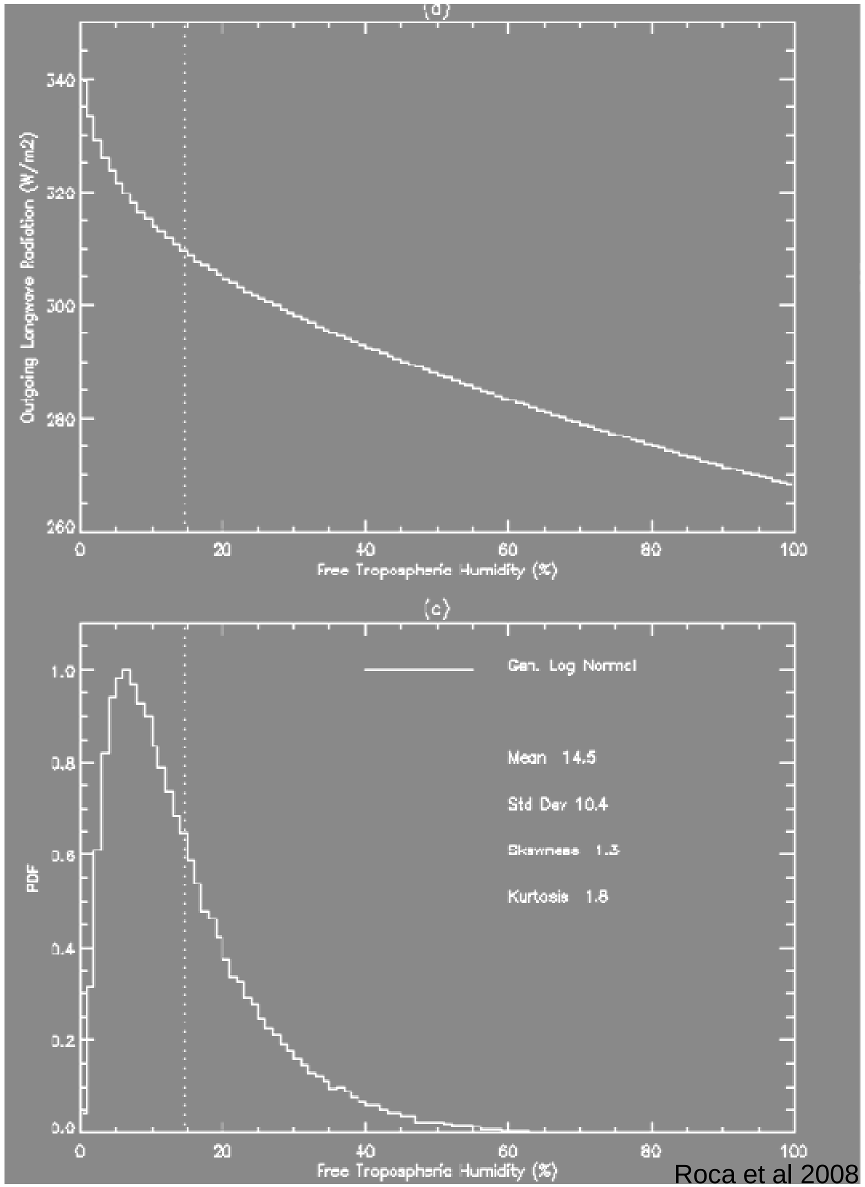
A short course on water vapor and radiation



Rémy Roca
Chargé de Recherche CNRS
Laboratoire de Météorologie Dynamique
roca@lmd.jussieu.fr

Concluding remarks

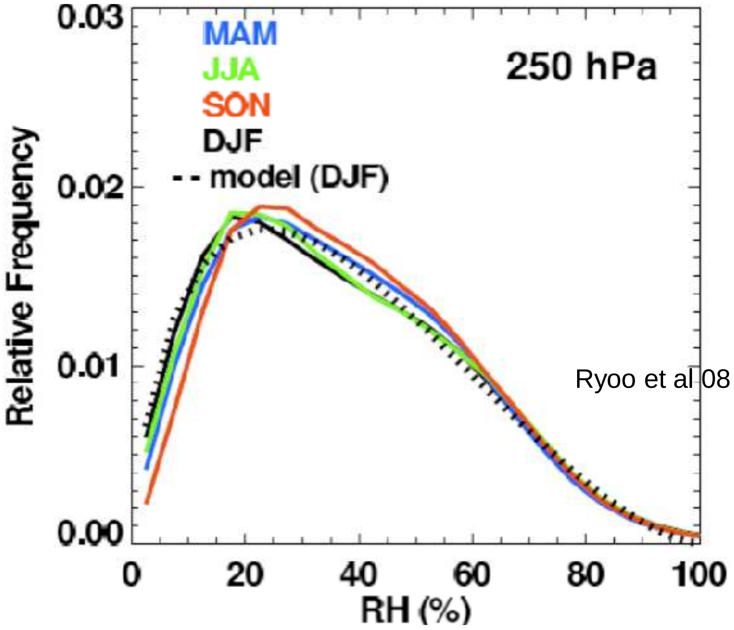
Need to understand the humidity PDF in the troposphere



Roca et al 2008

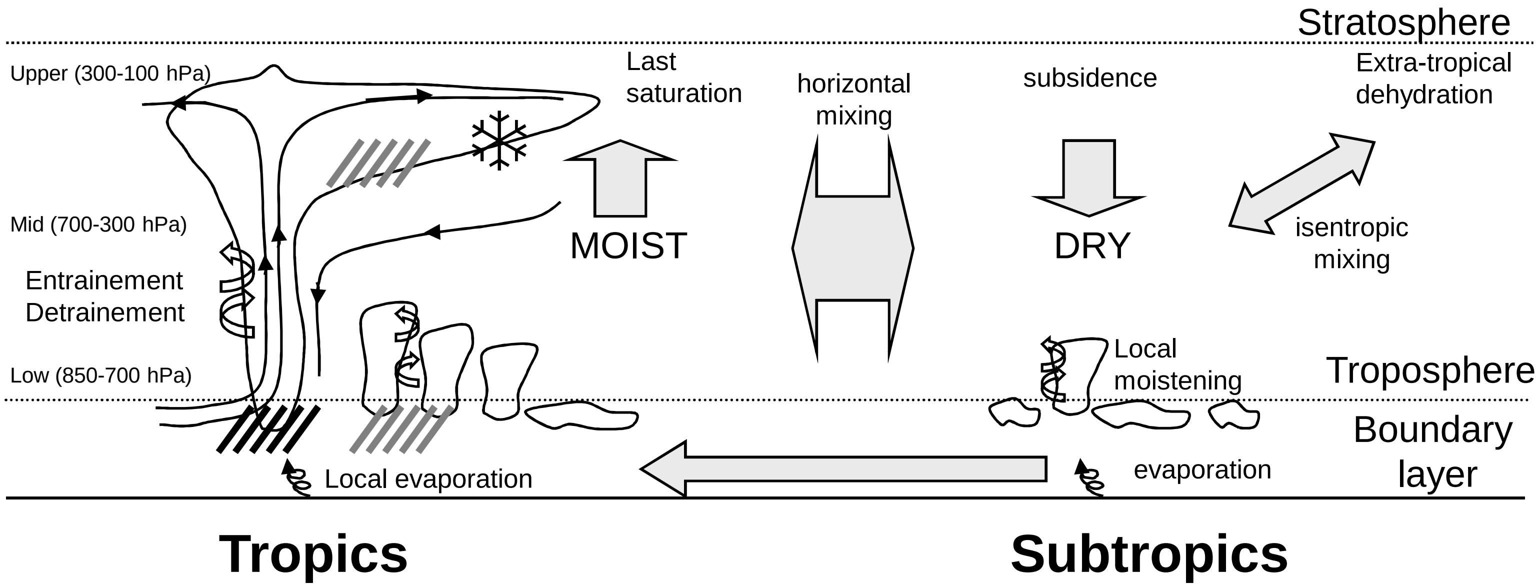
If we assume a constant distribution at 14.5% found in the subtropics. The OLR is worth 309 W/m^2 If we distribute the FTH using a uniform or Gaussian distribution with same mean (and variance of 5%), the resulting average OLR is 309.6 W/m2.If we distribute the FTH using a the bottom figure distribution, the averaged OLR it is worth 312 W/m^2. A generalized log normal distribution is used.

AIRS & Simplified model



Ryoo et al 08

The full picture



Need to check the models against the physical model in order to avoid having the right answer for wrong reasons and therefore a useles derivative

The Megha-Tropiques mission

Overview

Indo-french mission realized by

The Indian Space Research Organisation et the

Centre National d’Etudes Spatiales

Dedicated to the

Water and energy cycle in the Tropics

Low inclinaition on the equator (20°);

865 km height

High repetetivity of the measurements

Launch foreseen in september 2009 March 2010

WEB site http://megha-tropiques.ipsl.polytechnique.fr

The Megha-Tropiques mission

Scientific objectives

Atmospheric energy budget in the intertropical zone and at system scale (radiation, latent heat, …)

Life cycle of Mesoscale Convective Complexes in the Tropics (over Oceans and Continents)

Monitoring and assimilation for Cyclones, Monsoons, Mesoscale Convective Systems forecasting.

Contribution to climate monitoring :

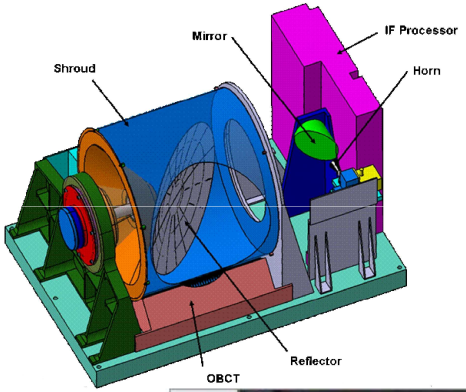
- **Radiative budget (complementary to CERES)**
- **Precipitation (enhanced sampling in the tropics)**
- **Water vapour (enhanced sampling in the tropics),**

The Megha-Tropiques mission

Payloads (1/2)

- **ScaRaB** : wide band instrument for inferring longwave and shortwage outgoing fluxes at the top of the atmosphere (cross track scanning, 40 km resolution at nadir)

- **Saphir** : microwave sounder for water vapour sounding : 6 channels in the WV absoption band at 183.31 GHz. (cross track, 10 km)



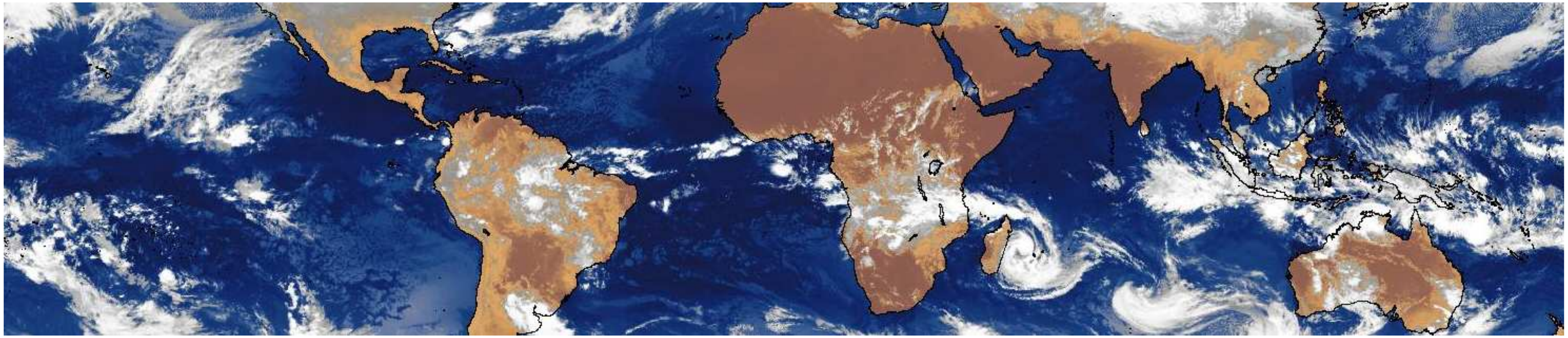
- **MADRAS** : microwave imager for precipitation : channels at 18, 23, 37, 89 and 157 GHz, H and V polarisations. (conical swath, <10 km to 40 km)


MARFEQ RF Hardware

The Megha-Tropiques mission
Payloads (2/2)

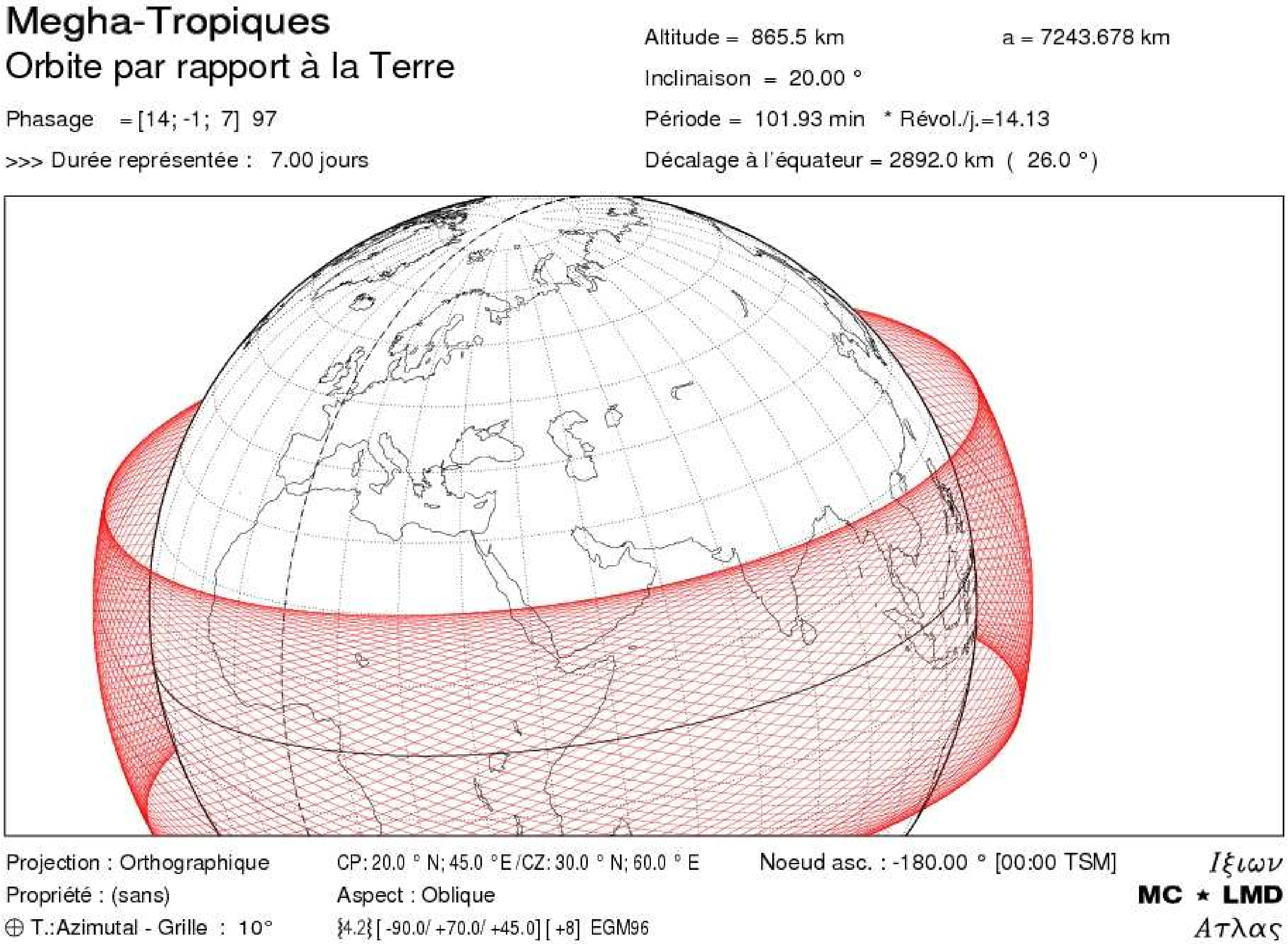
- **GPS RO**: water vapor profile …

- **GEOSTATIONARY DATA**
  - Cloud mask for the MW algo
  - Quicklook for interpreting MT data
  - Basic inputs for MCS tracking algorithm
  - Basic inputs for Level 4 rainfall (radiation) products



The Megha-Tropiques mission

Orbit (1/2)



Megha-Tropiques
Orbite par rapport à la Terre

Phasage = [14; -1; 7] 97

>>> Durée représentée : 7.00 jours

Altitude = 865.5 km a = 7243.678 km

Inclinaison = 20.00 °

Période = 101.93 min * Révol./j.=14.13

Décalage à l'équateur = 2892.0 km (26.0 °)

Projection : Orthographique

Propriété : (sans)

⊕ T.:Azimutal - Grille : 10°

CP: 20.0 ° N; 45.0 ° E / CZ: 30.0 ° N; 60.0 ° E

Aspect : Oblique

{4.2} [-90.0/ +70.0/ +45.0] [+8] EGM96

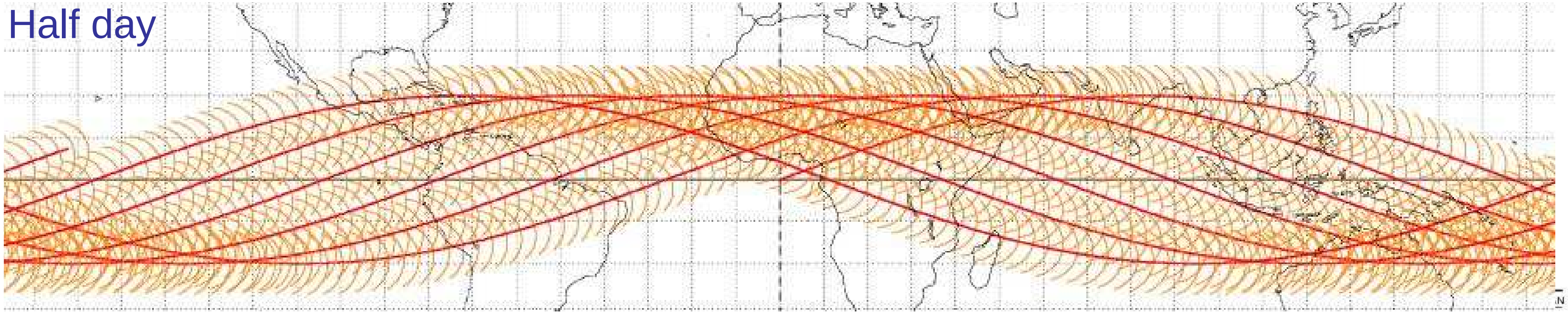
Noeud asc. : -180.00 ° [00:00 TSM]

Ιξιων
MC ⋆ LMD
Ατλας

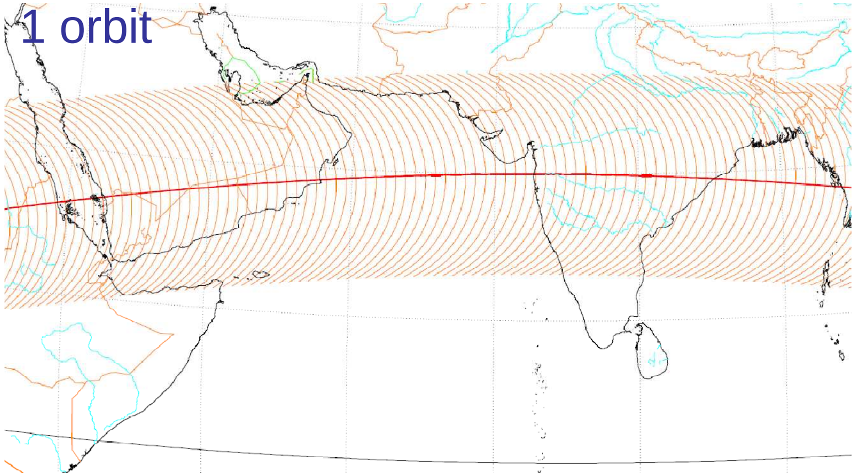
The Megha-Tropiques mission

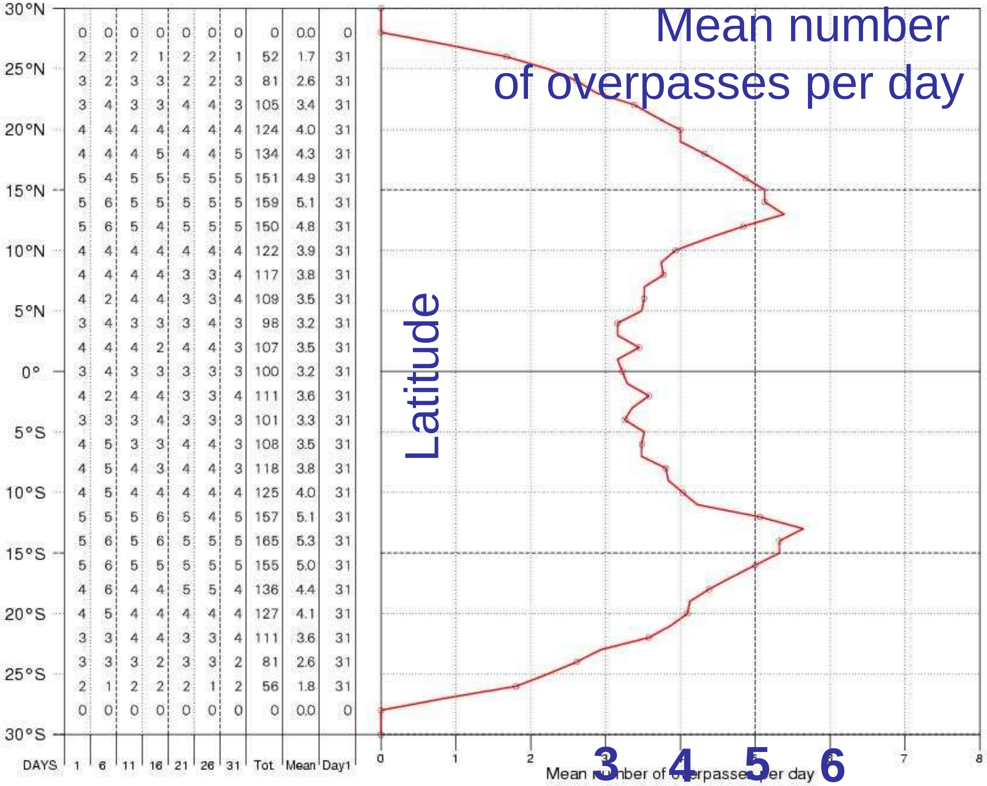
Orbit (2/2)

Half day



1 orbit





DAYS	1	6	11	16	21	26	31	Tot	Mean	Day1
	0	0	0	0	0	0	0	0	0.0	0
	2	2	2	1	2	2	1	52	1.7	31
	3	2	3	3	2	2	3	81	2.6	31
	3	4	3	3	4	4	3	105	3.4	31
	4	4	4	4	4	4	4	124	4.0	31
	4	4	4	5	4	4	5	134	4.3	31
	5	4	5	5	5	5	5	151	4.9	31
	5	6	5	5	5	5	5	159	5.1	31
	5	6	5	4	5	5	5	150	4.8	31
	4	4	4	4	4	4	4	122	3.9	31
	4	4	4	4	3	3	4	117	3.8	31
	4	2	4	4	3	3	4	109	3.5	31
	3	4	3	3	3	4	3	98	3.2	31
	4	4	4	2	4	4	3	107	3.5	31
	3	4	3	3	3	3	3	100	3.2	31
	4	2	4	4	3	3	4	111	3.6	31
	3	3	3	4	3	3	3	101	3.3	31
	4	5	3	3	4	4	3	108	3.5	31
	4	5	4	3	4	4	3	118	3.8	31
	4	5	4	4	4	4	4	125	4.0	31
	5	5	5	6	5	4	5	157	5.1	31
	5	6	5	6	5	5	5	165	5.3	31
	5	6	5	5	5	5	5	155	5.0	31
	4	6	4	4	5	5	4	136	4.4	31
	4	5	4	4	4	4	4	127	4.1	31
	3	3	4	4	3	3	4	111	3.6	31
	3	3	3	2	3	3	2	81	2.6	31
	2	1	2	2	2	1	2	56	1.8	31
	0	0	0	0	0	0	0	0	0.0	0

Mean number
of overpasses per day

Latitude

3 4 5 6

MADRAS sampling over 20°S-20°N
Min 3 per day
Max 5 per day

A few useful references

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- Sherwood, S. C., R. Roca, T. M. Weckwerth and N. G. Andronova, Tropospheric water vapor, convection and climate: A critical review. Reviews of Geophysics, submitted 05/09
- ….

1) Humidity : units, measurements and basis
Mettre la figure de Steve
Clausius Clapeyron
Moist thermodynamics à relire
L'eau precipitable climatology
Le profile
Troposphere only
RH et Peixoto

Transport of water vapor : climatology -> Peixoto plus intro papier.
Bilan d'eau …nuages pluie -> il ya de la vapeur dans l'atmosphere.

Soden and held 2000 a relire
Soden recent aussi ?

2) Radiative transfer basis
Equation du transfer radiatif
Planck,
Wien,
Kirchoff etc… question de Bernard.

3) Water vapor and radiation
Continum lignes far intra red
OLR and Greenhouse effect
decomposition temp/h20

Jacobians de l'OLR et
PW et FTH

LW et concentratino: log ou square root

4) Water vapor radiative feedback
Classical Radiative convective equilibrium
2D a la Ray
Super greenhouse effect

Intégration temporelle du modèle radiatif-convectif pour le profil de température et la température de surface

L’approche “time stepping” consiste à intégrer pas à pas le modèle
Elle est intuitive
Elle est coûteuse en calcul

1. On part d’un profil de température
2. On calcule les taux de refroidissement
3. On calcule le nouveau profil et ainsi de suite….

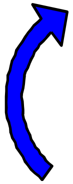
Si au cours du temps, deux couches deviennent supercritiques, alors on applique l’ajustement convectif.
La température de la couche du dessus est fixée de manière à ce que le gradient soit neutre. Les deux couches sont alors en équilibre radiatif-convectif.

Ainsi on corrige le profil de température et on obtient la température de surface à l’équilibre, c.a.d. quand il n’y a plus de couches supercritiques

Différence entre la température d'équilibre aux conditions actuelles et la température d'équilibre pour diverses modifications de la concentration en CO_2

Changement de la concentration en CO_2	**Humidité spécifique FIXE**	**Humidité relative FIXE**
300-150	**FAH** **-1.25**	**FRH** **-2.28**
300-600	**+1.33**	**+2.36**

La sensibilité climatique est doublée lorsque l'humidité RELATIVE est conservée !



- T augmente dans la troposphère à cause du CO_2
- Q, l'humidité spécifique, augmente aussi car RH=cte
- L'effet de serre du CO_2 est renforcé par celui de la vapeur d

la rétroaction POSITIVE de la vapeur d'eau sur la température de la sur

Quels sont les mécanismes qui déterminent la température de la surface de la Terre ?
Quelle est la réponse associée à des perturbations ?

On peut donc répondre à la première question :

Gaz considéré	F (Wm^{-2}) ciel clair	Contribution des gaz omis (%)
$H_2O,CO_2,0_3$	227	
$H_2O,0_3$	247	-9
H_2O,CO_2	232	-2
$CO_2,0_3$	285	-25

Les gaz à effet de serre, en particulier la vapeur d'eau réchauffent la surface
Les nuages refroidissent la surface