Water vapour in the climate system Introduction

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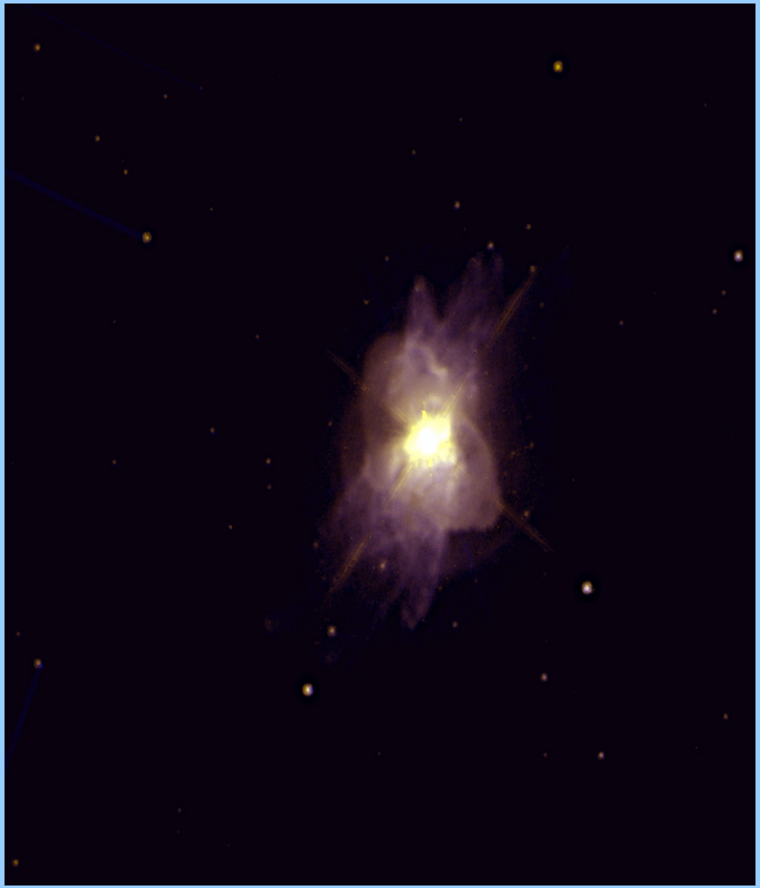
The origin of water

There is plenty of water in the universe, produced from combined hydrogen and oxigen produced and released by supernovae.

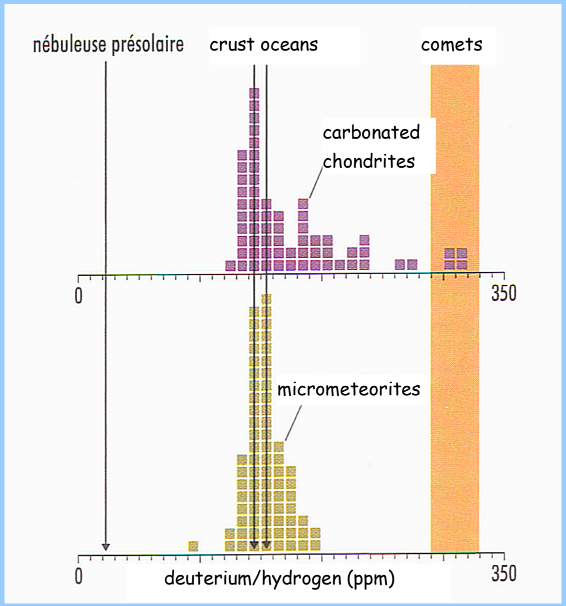
Detail of Eagle nebulae
NASA Hubble telescope
These clouds contain large amount of water.



There is water within the proto-solar nebulae when a new star and planetary system are formed.

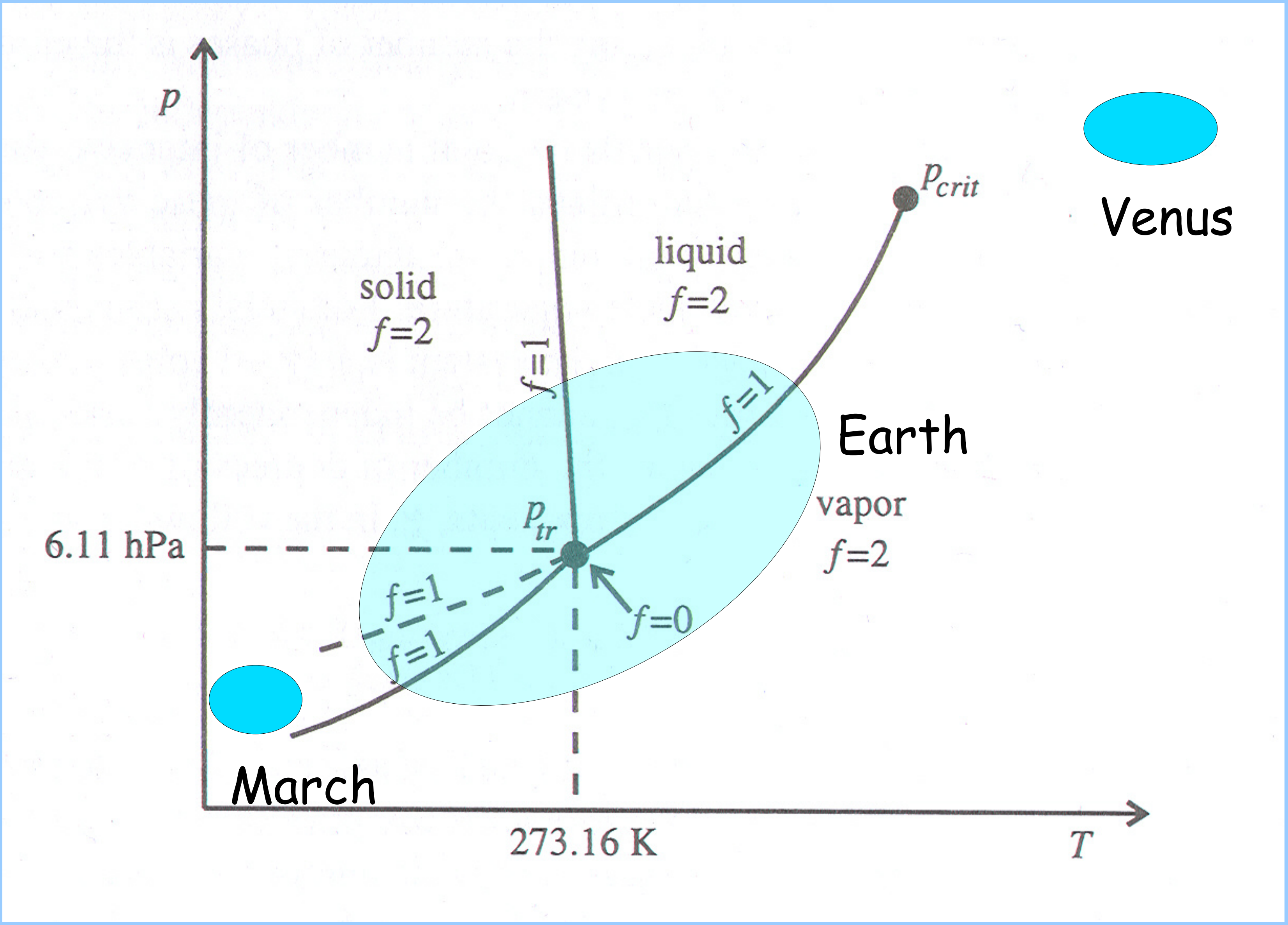
There was water on the Earth during its early stages (formation of zircons 4.3-4.4 By) and oceans were present 150-200 My after the formation of the Earth.
However, most of water was not contained within the accreted cloud.

There are geochimical evidences that most of surface water came with bombing of early Earth by meteorites and comets. This also explains the abundancy of noble (siderophil) metals in the crust. 0,3% of Earth mass was added this way.



Magritte, Zeno

Thermodynamical constrains



Earth conditions are such that water is present at the surface and in the atmosphere under its three phases.

Moisture condensation

Atmospheric water vapour is characterized by its partial pressure e, and its mass mixing ratio

$r = \rho_v/\rho_d = (e/p_d)(R_d/R_v)$

where d refers to dry air.

Sometimes, use volume mixing ratio e/p_d

Saturated pressure ratio depends exponentially on temperature (Clausius-Clapeyron law). Empirical fits (T in K):

$e_s^{liquid} = 6{,}112 \exp(17{,}67\ (T-273.15)/(T-29.65))$

$e_s^{ice} = \exp(23{,}33086-6111{,}72784/T + 0{,}15215\ \mathrm{Ln}(T))$

Exemples of saturated ratio

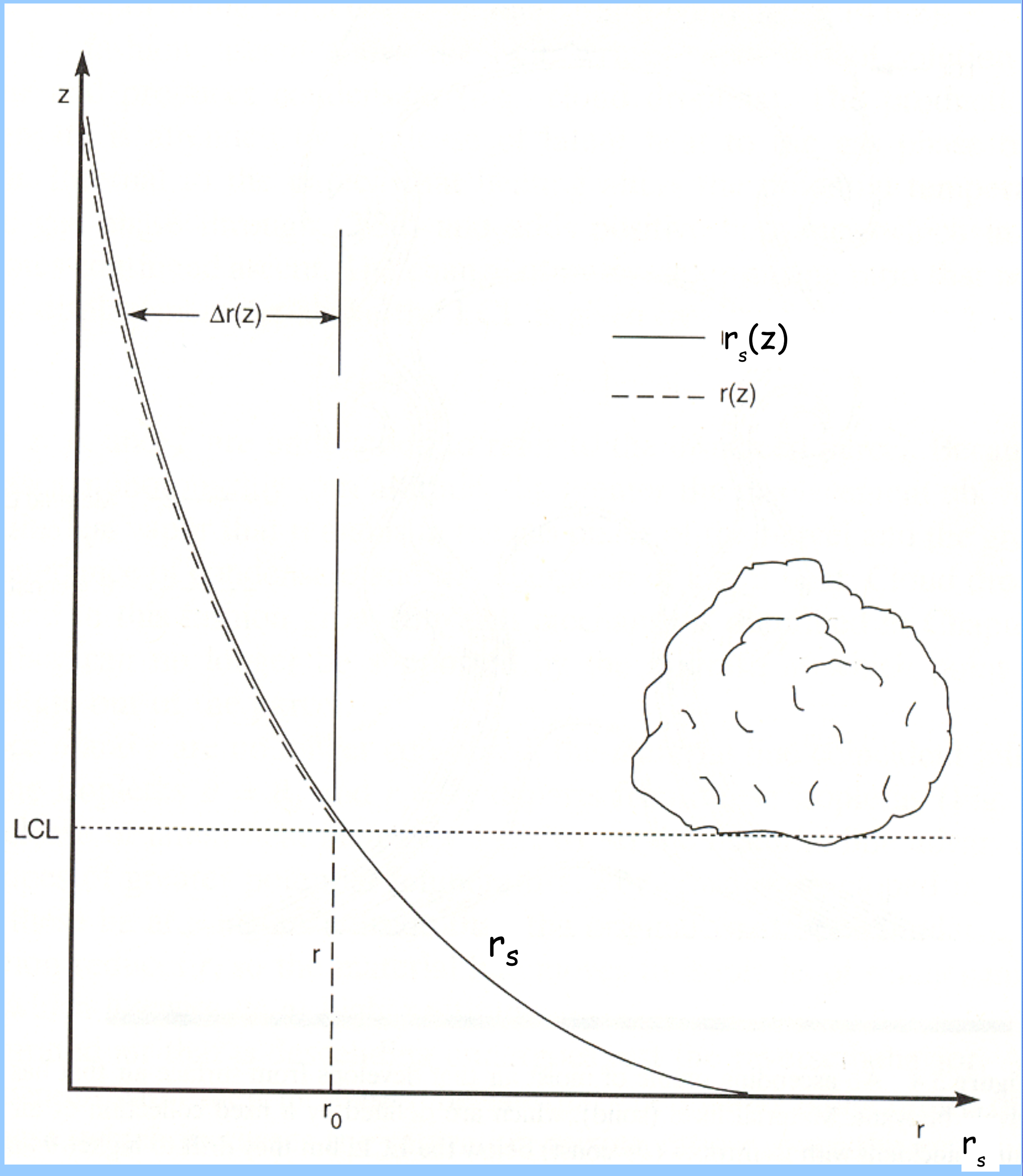
at 1000hPa and T=20°C: r_s = 14,5 g/kg,

at 800 hPa (2000m) et T = 7°C: r_s =7,8 g/kg,

at 500 hPa and T=-30°C: r_s =0,47 g/kg,

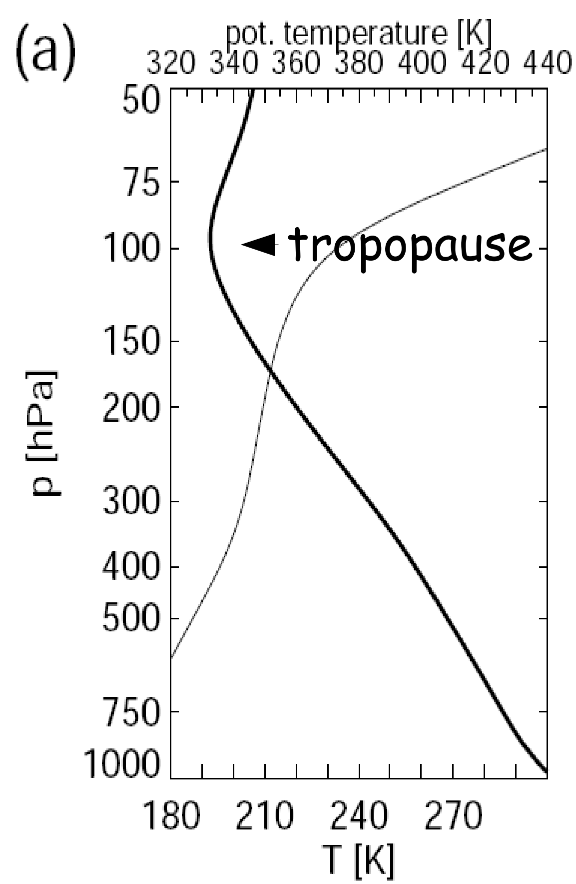
at 100 hPa and T =-80°C: r_s =0,003 g/kg,

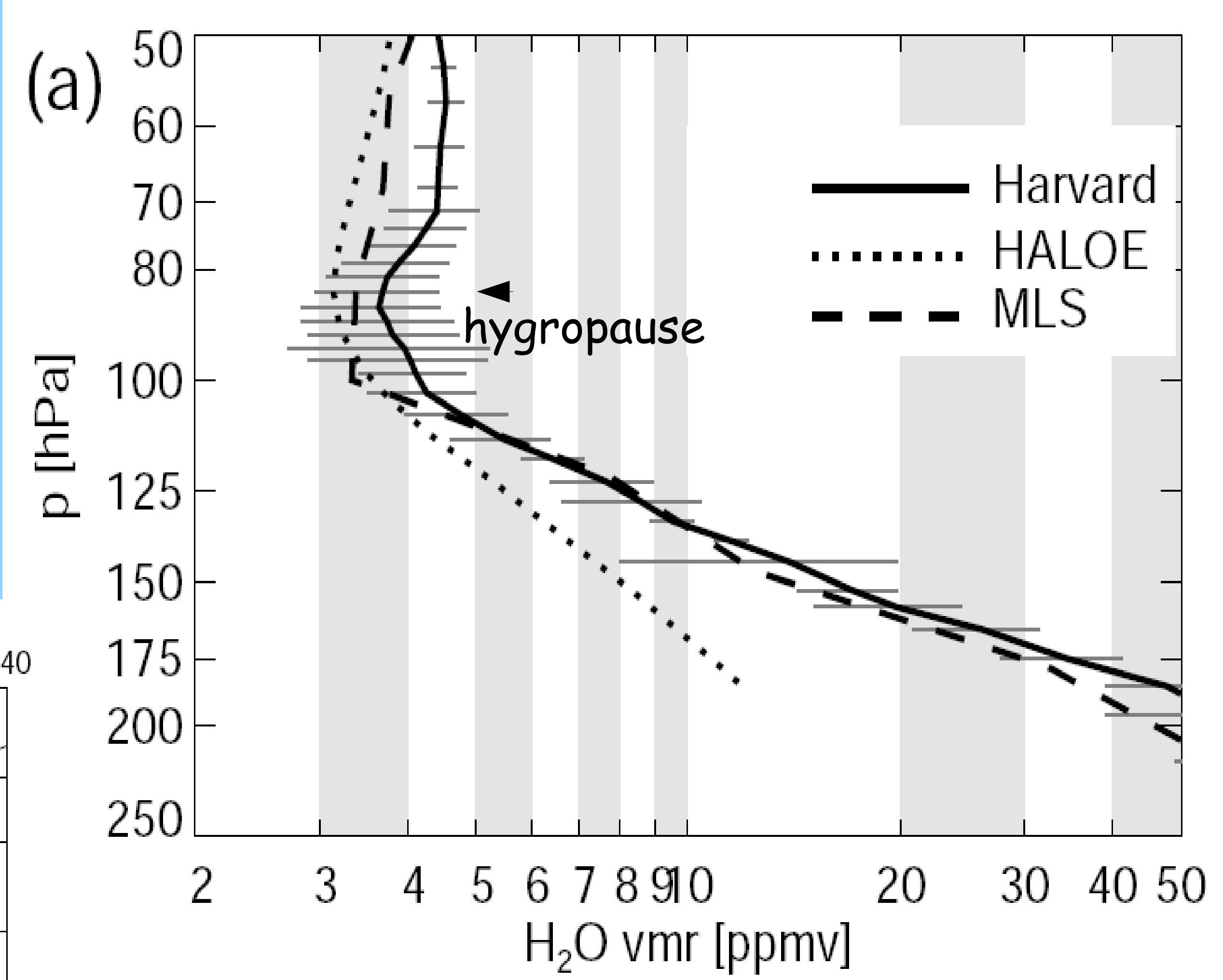
(le contenu en eau de l'atmosphère est divisé par presque quatre ordres de grandeur entre le sol et 100 hPa)



LCL (lifting condensation level): condensation leval of parcels lifted from the ground

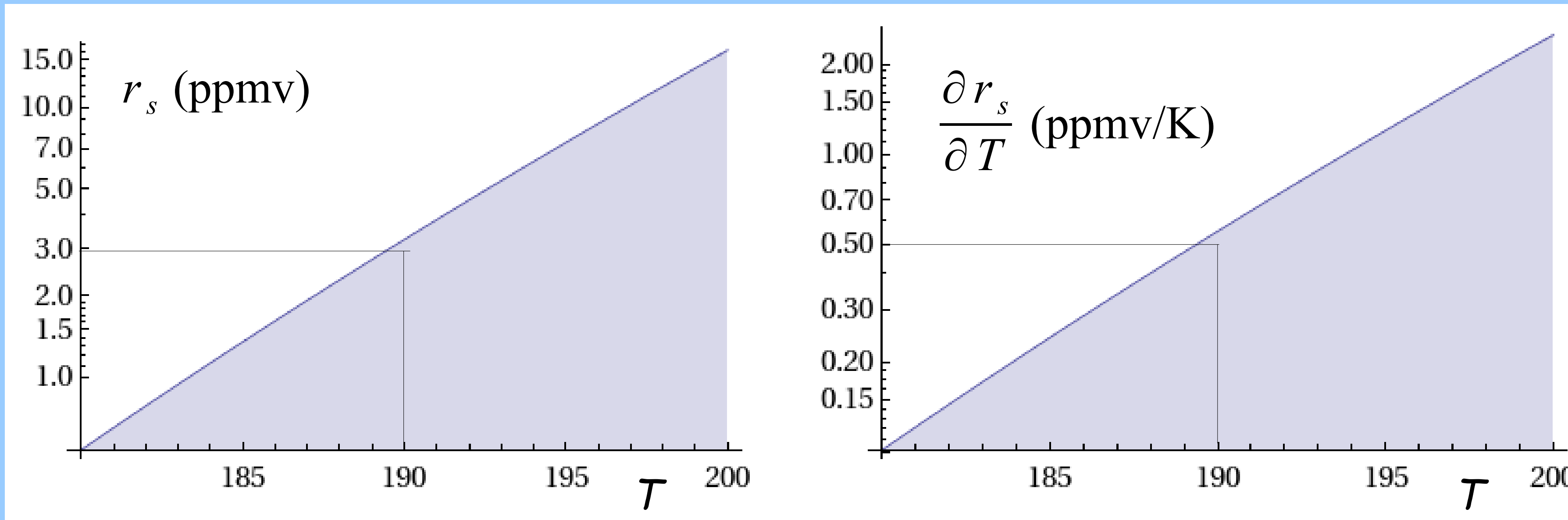
Water vapour drops to very low values (3-4 ppmv, 2-3 mg/kg) at the tropical tropopause due to cold point near 190K.





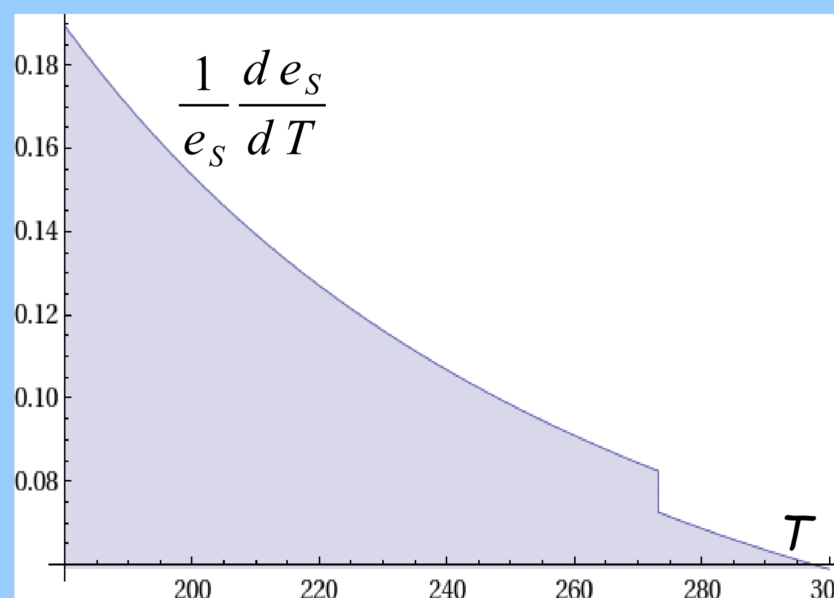
Fueglistaler et al., Rev. Geophys., 2009

Saturation mixing ratio at the tropical tropopause



Volume mixing ratio near 3 ppmv at 100hPa and 190K.
Sensitivity to temperature is 0.5 ppmv K^{-1}

Relative variation of saturation vapour pressure is larger at high altitude and low temperature.



Water vapour varies by four order of magnitude between the surface and the tropical tropopause.
Evaporation supply is not limiting the water vapour content above the boundary layer.
The water vapour content is strongly (exponentially) dependent on temperature.

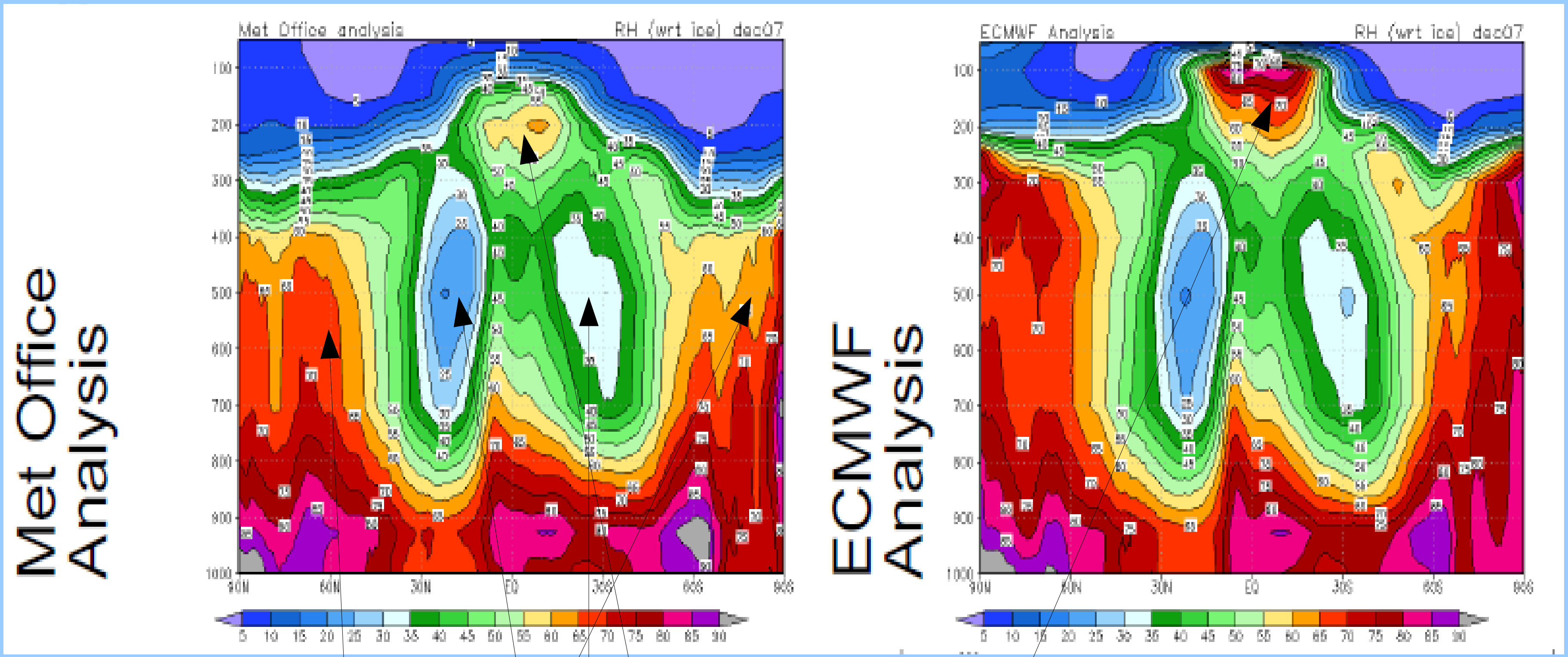
Relative humidity e/eS within a small volume depends on the temperature history of all the parcels that mix within this volume.

It depends also on the evaporation of condensates along the paths of these parcels, hence on the microphysical properties of liquid drops and ice crystals.

Occurence of sursaturation (especially for ice) offsets the equilibrium law by up to 160% under upper troposphere conditions.

Distribution of water vapour and atmospheric circulation

Distribution of relative humidity in the toposphere according to analysis of weather centers



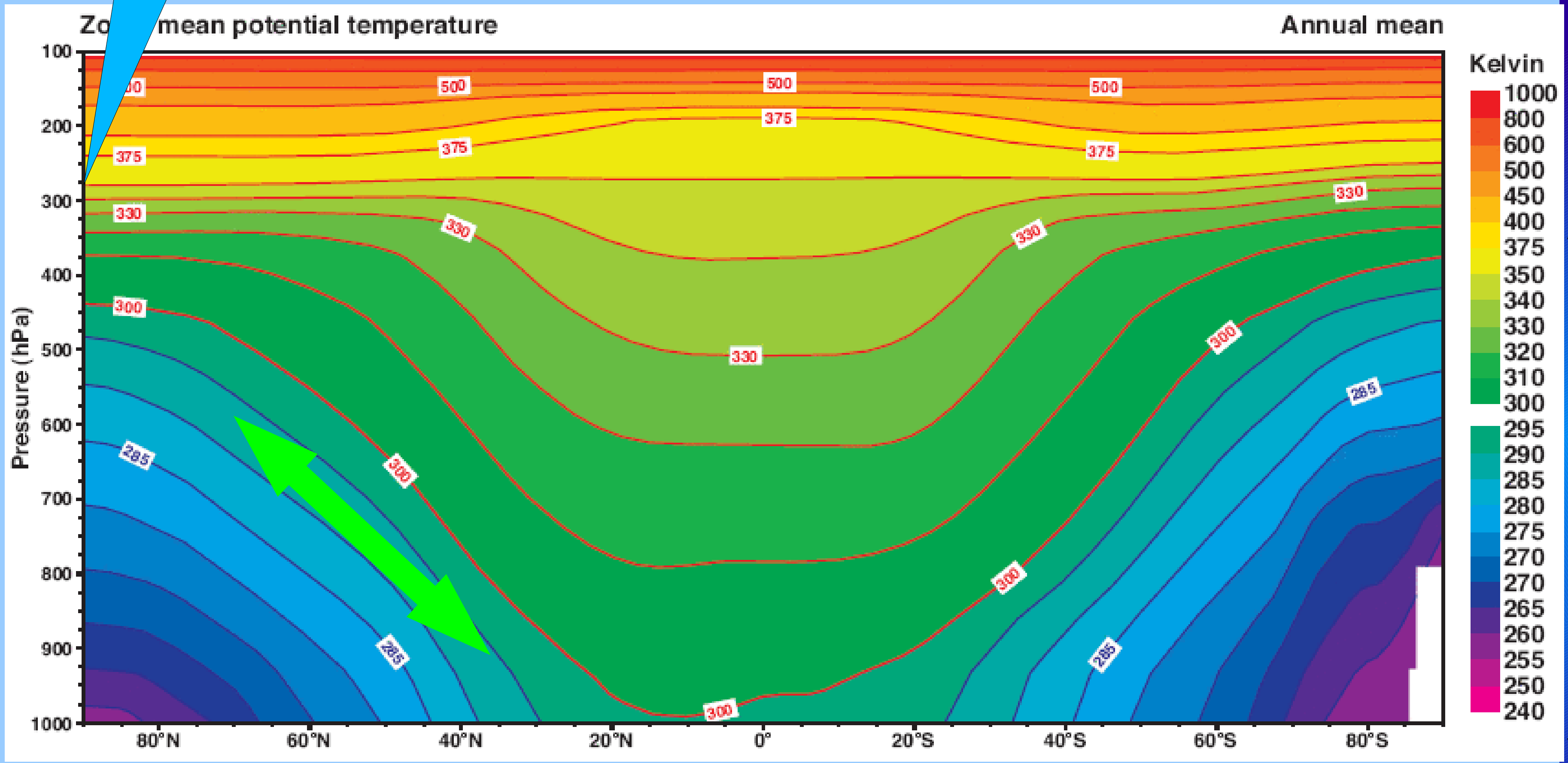
Courtesy of D. Jackson

Detrainment of tropical convection

Subsidence branch of the Hadley cell

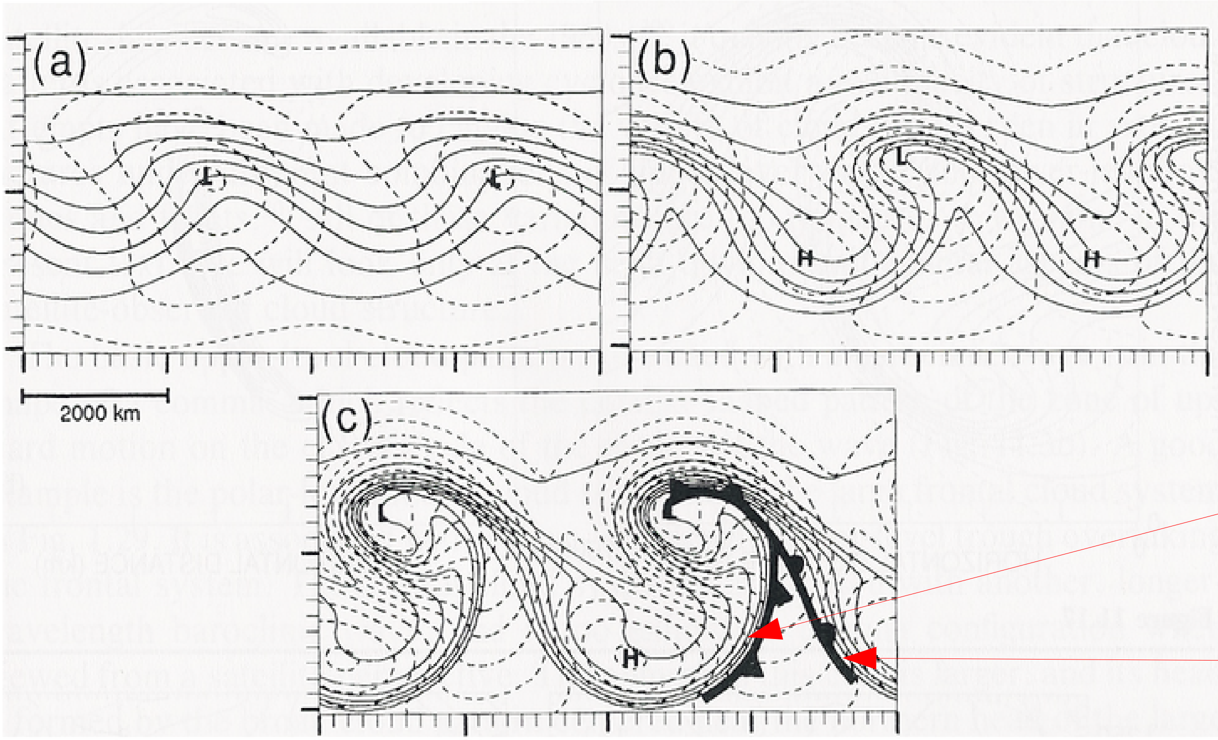
Moistening by sloping motion associated with Rossby waves and baroclinic perturbations

ECMWF ERA-40 atlas



In the mid and high latitudes, poleward isentropic motion is accompanied by upward motion.

In the tropic, vertical upward motion needs heating.



Development of an idealized baroclinic perturbation

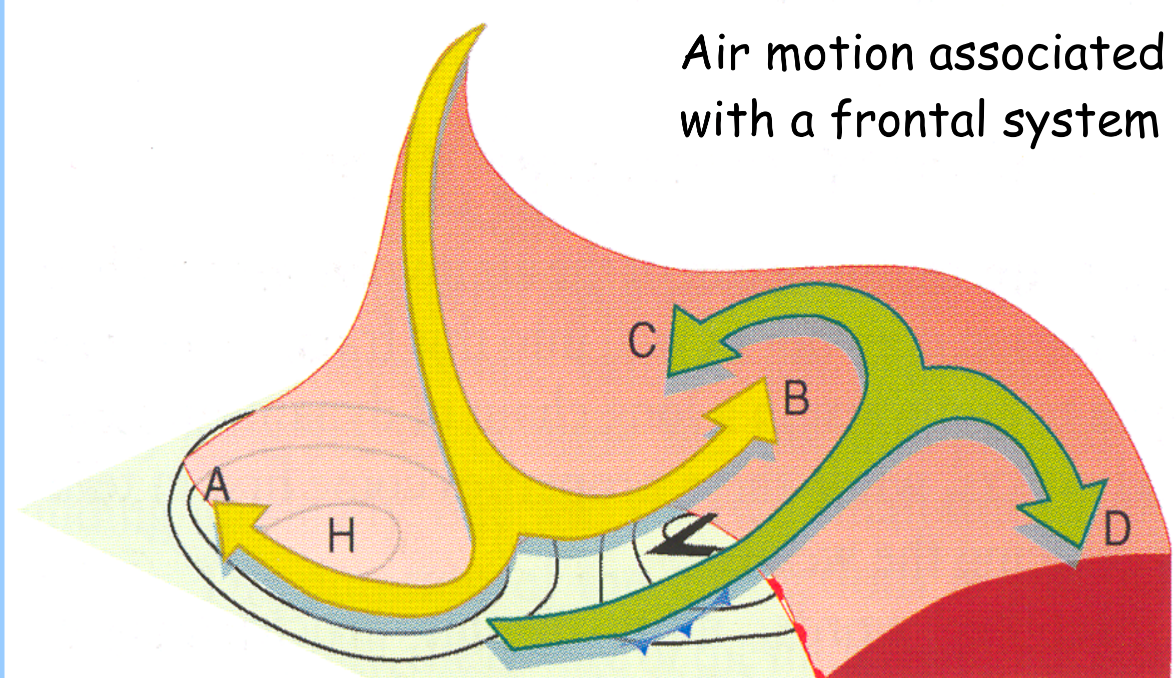
- - - - - = pression

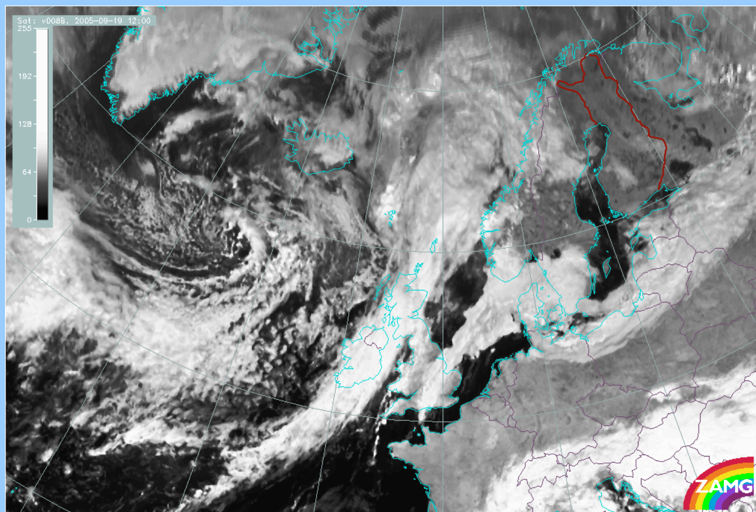
———— = température

Cold front

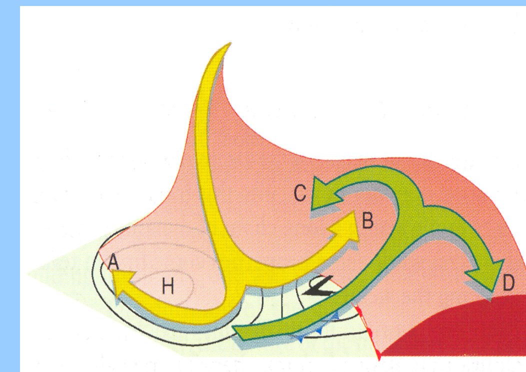
Warm front

Air motion associated with a frontal system .

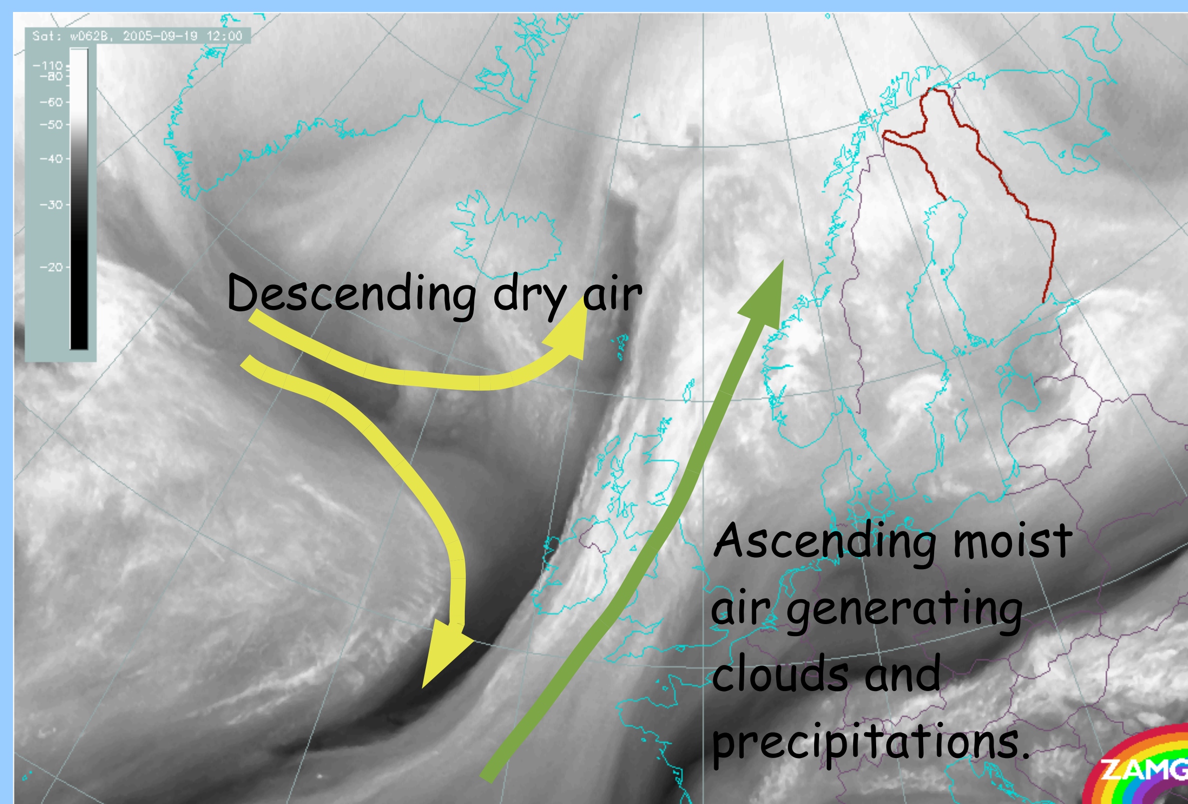




Visible channel
Meteosat

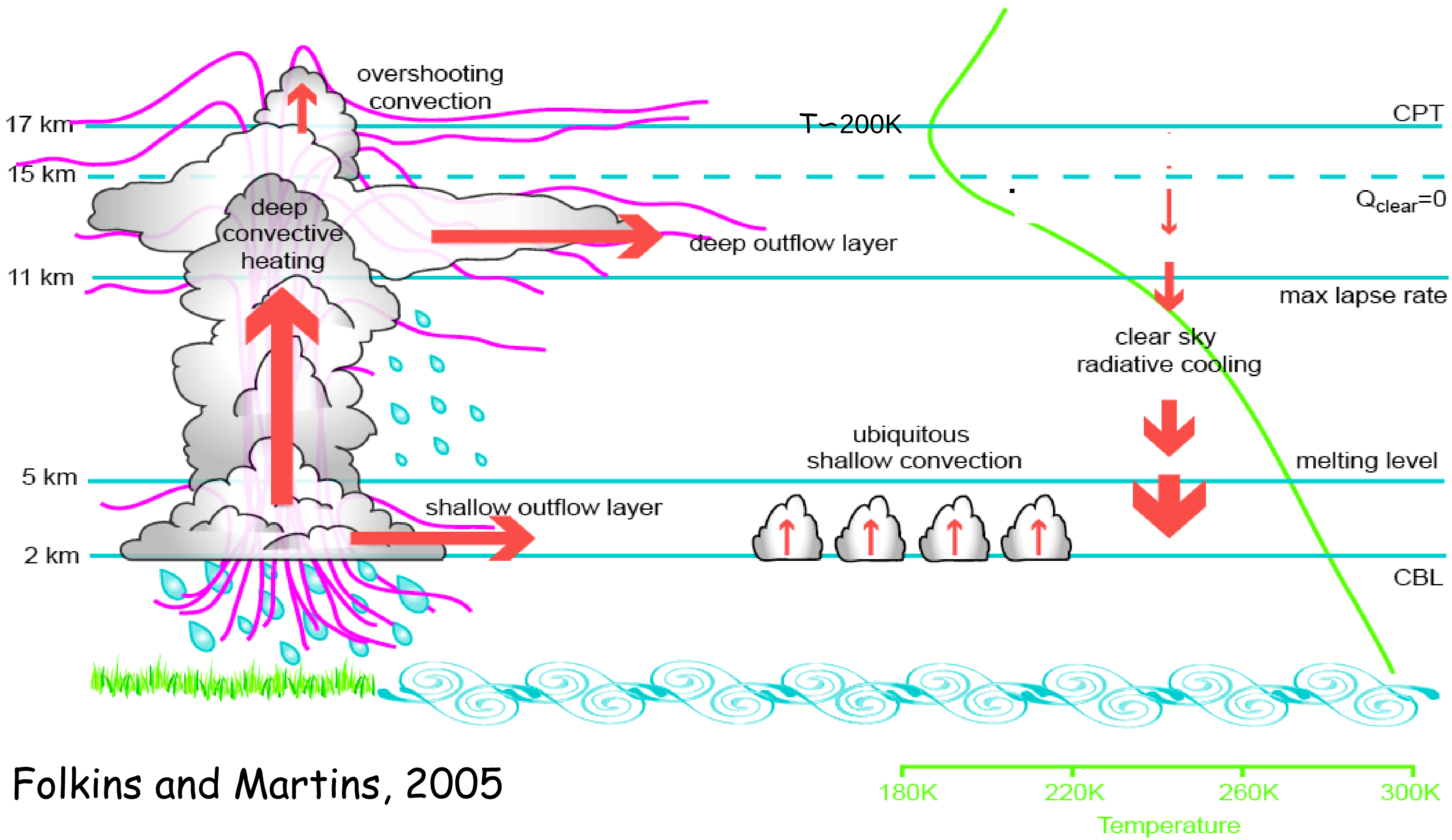


Water vapour channel Meteosat



Although mixing and convective instability do occur during the development, the main ingredient is adiabatic baroclinic instability, that is isentropic motion.

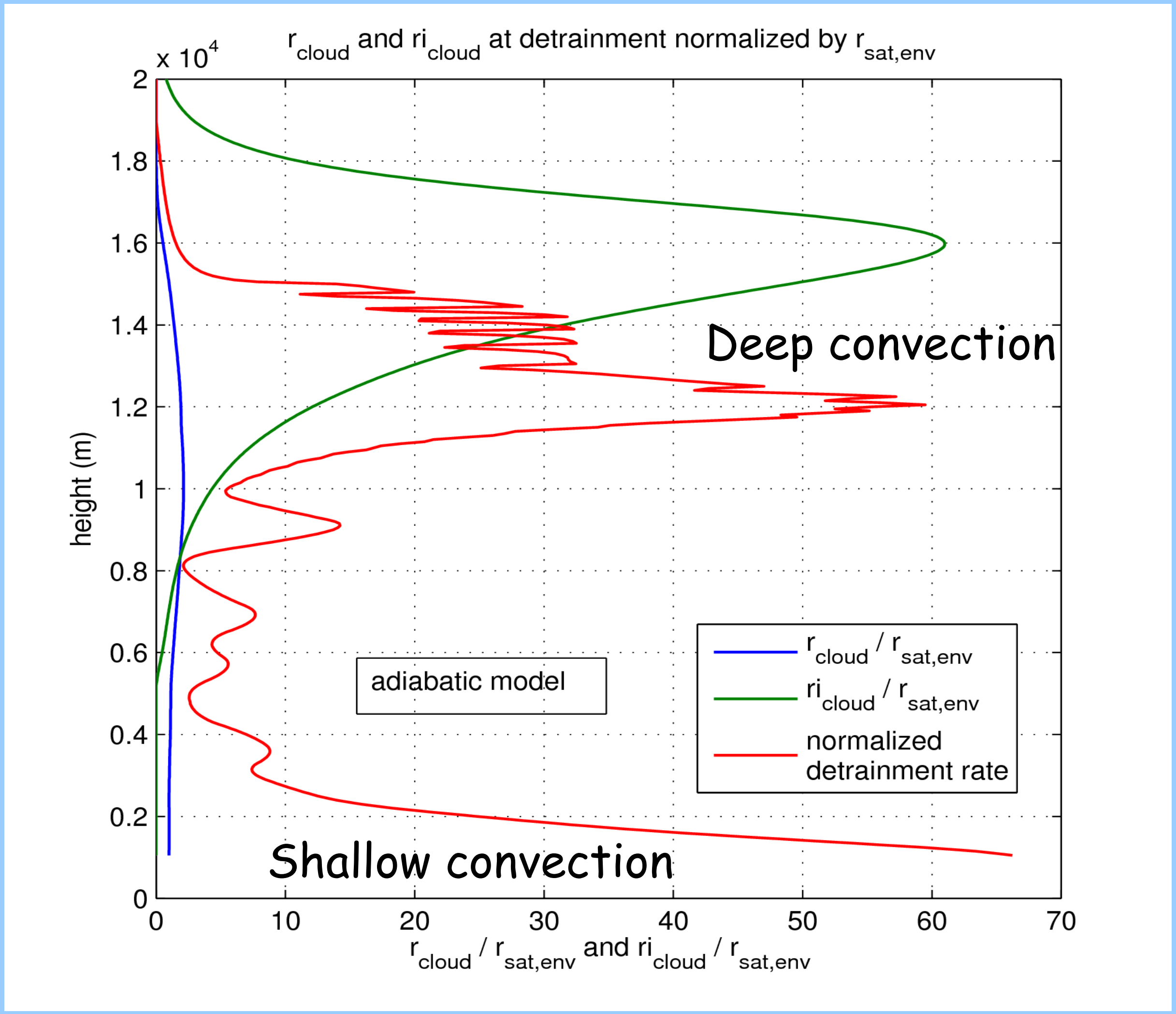
Deep convection in the tropics



Folkins and Martins, 2005

Injection of water in the upper troposphere is due to convection.
Mid -troposphere is moistened by evaporation of precipitations, descent of detrained air and exchanges with extra-tropics.

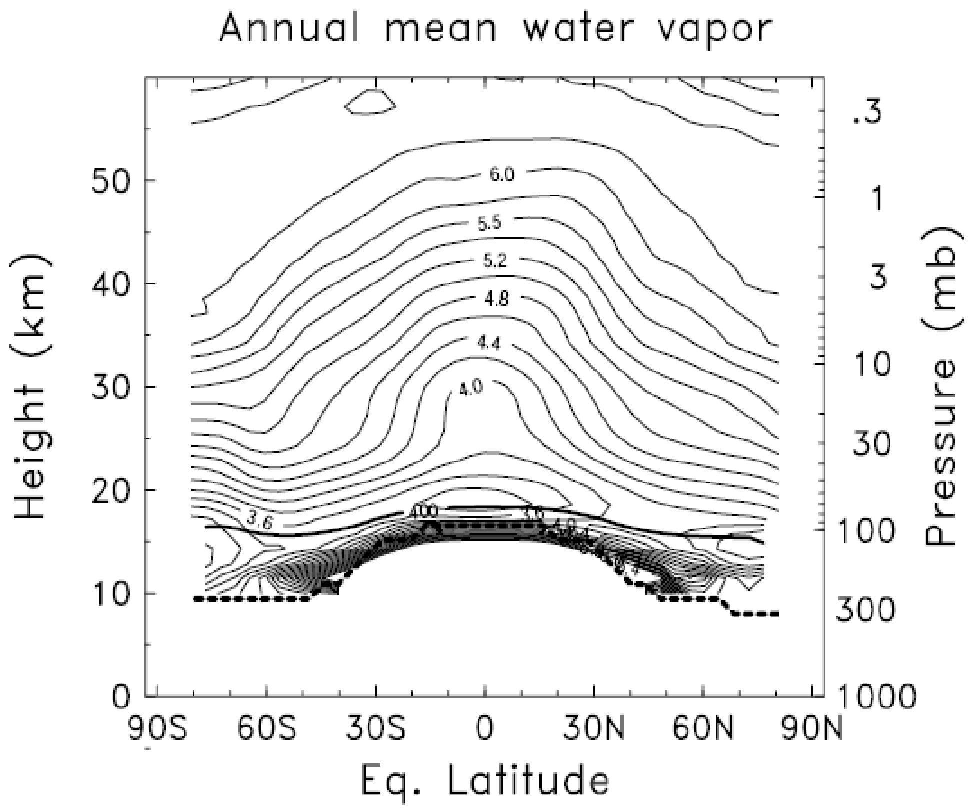
Mass detrainment and
water content of the detrained air
(vapour + ice)



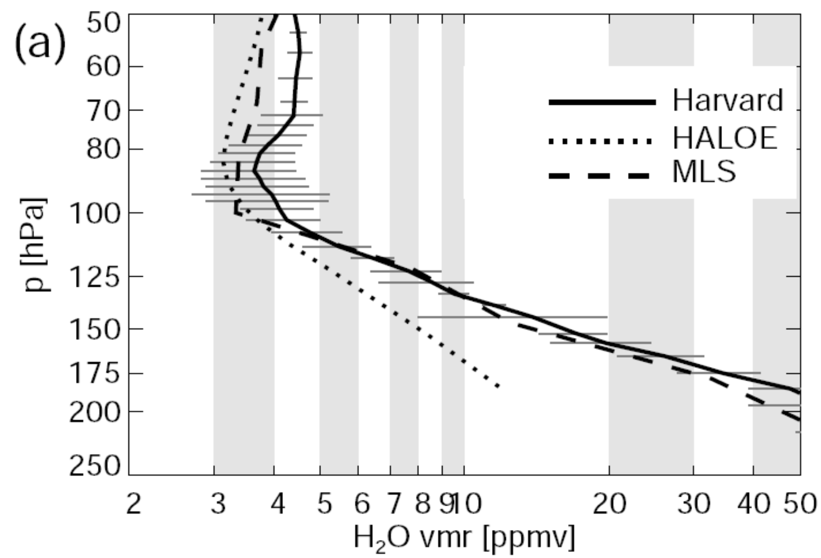
Bolot, 2009

The maximum of cloud "efficiency" occurs well above the maximum of detrainment. Whether detrained condensate evaporate, form anvils or precipitate depends on environment and microphysics.

Stratospheric water vapour



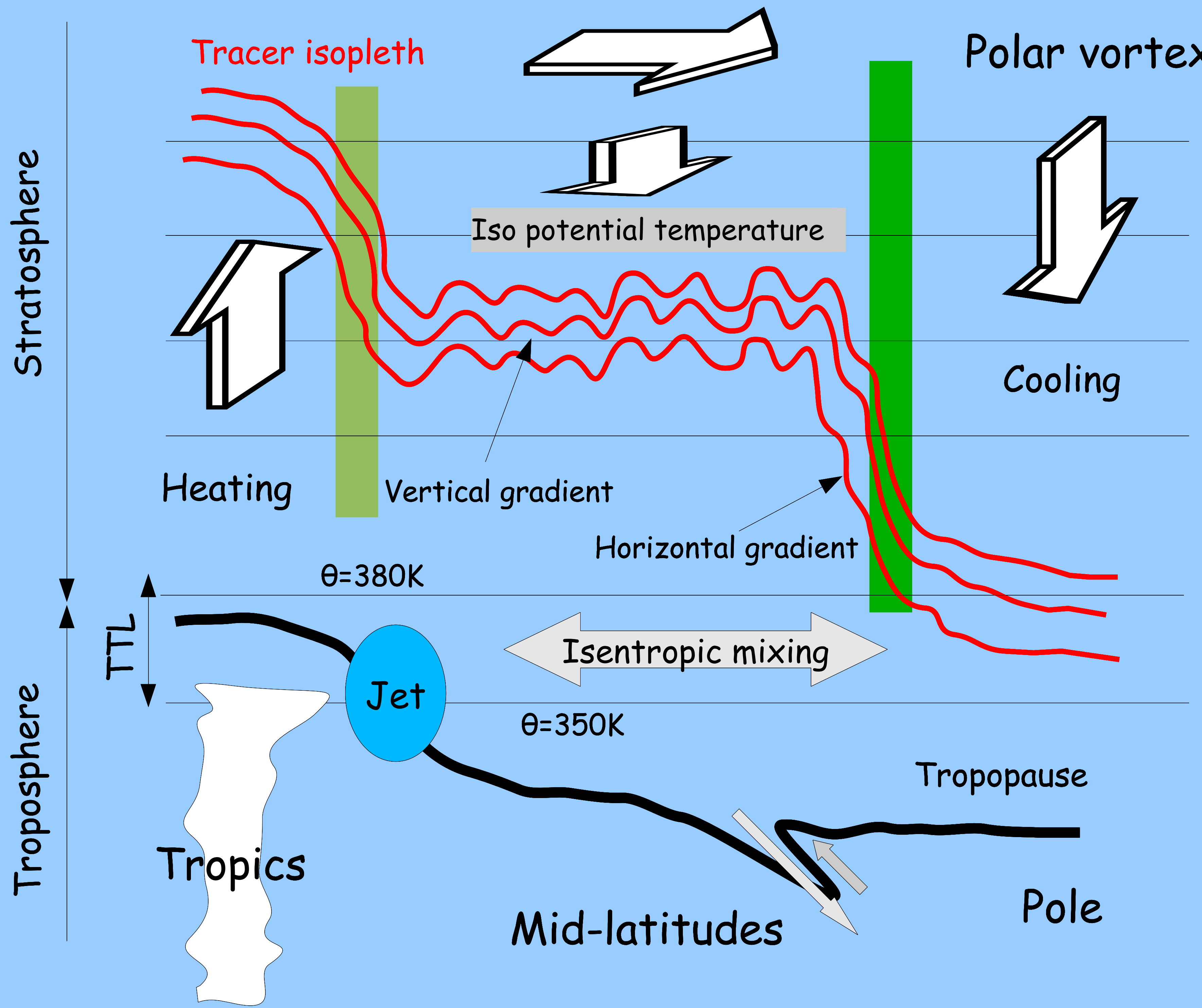
Annual zonal mean water vapour from HALOE and MLS data by height and equivalent latitude. Contour interval of 0.2 ppmv. The thick dashed line is the tropopause, and the thick solid line is the 400K potential temperature surface.



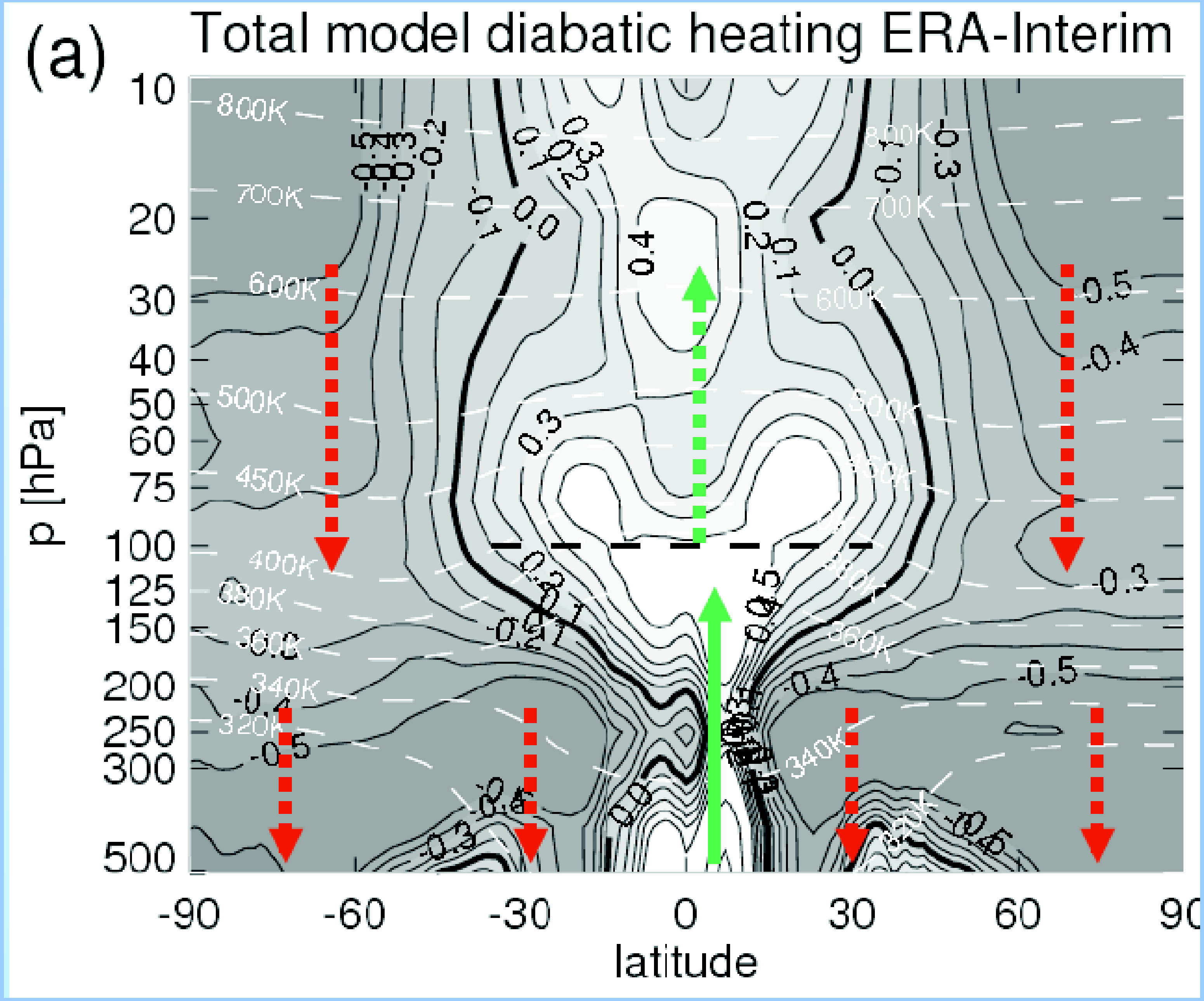
Minimum of water vapour just above the tropical tropopause.

Source of water vapour in the stratosphere from the oxidation of methane

The Brewer Dobson meridional circulation

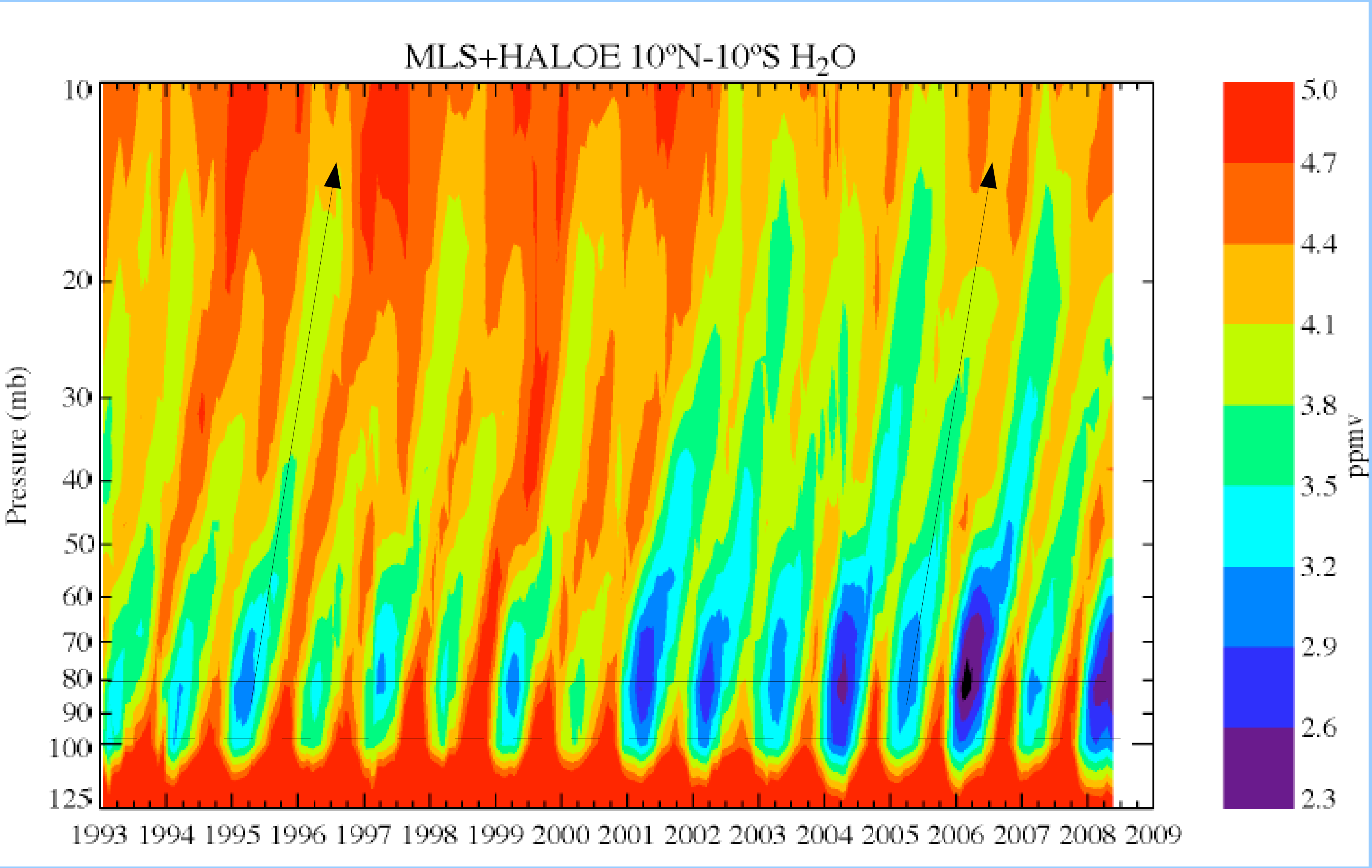


The Brewer-Dobson circulation from the point of view of heating rates



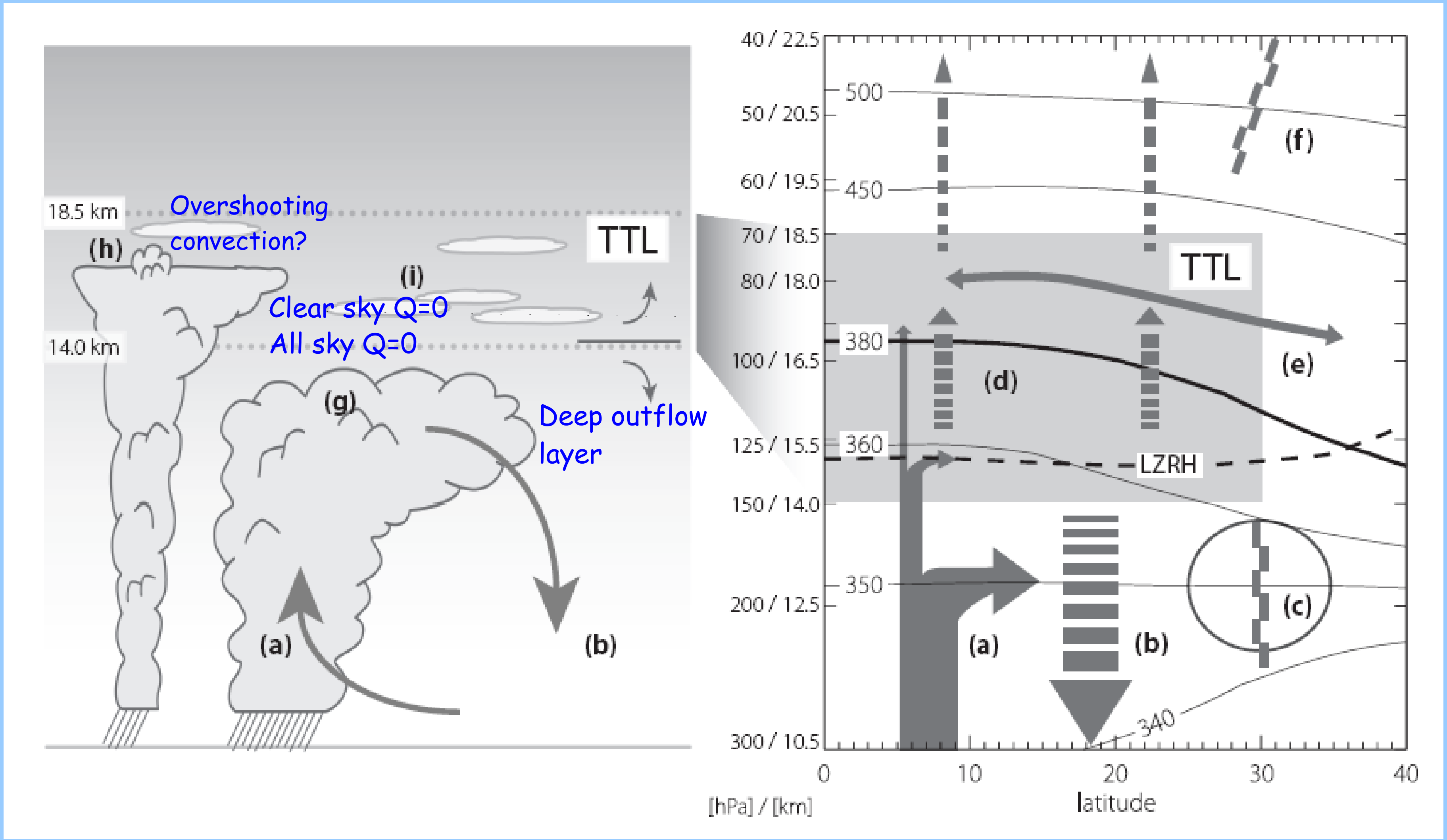
Fueglistaler, Legras et al., QJRMS (subjudice), 2008

Tape recorder of H2O in the tropical stratosphere



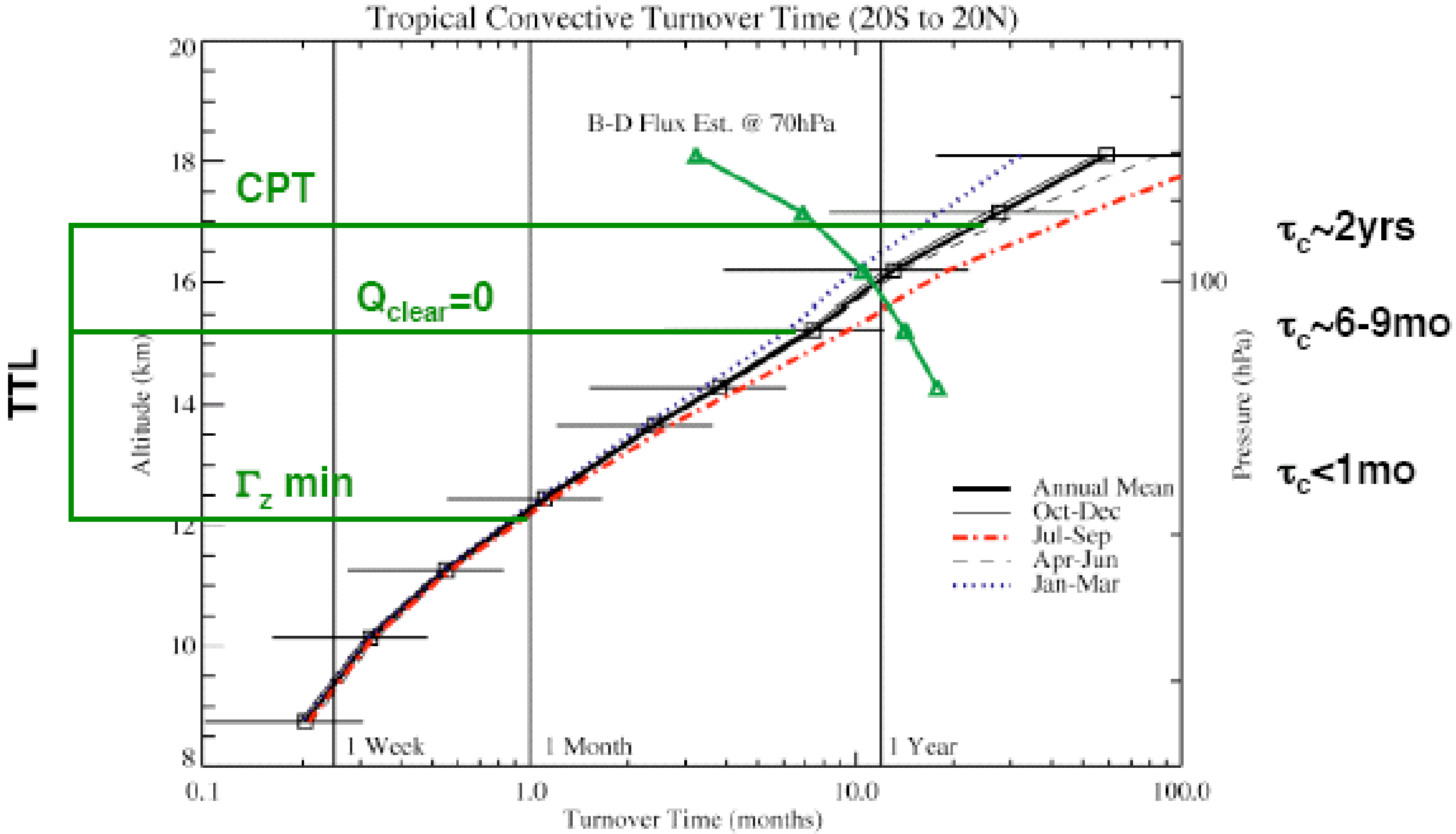
Courtesy of Rosenlof and Reid, 2008

Tropical tropopause layer as a an intermediate region between troposphere governed by convection and stratosphere governed by the Brewer -Dobson circulation (Highwood & Hoskins, 1998)



Fueglistaler et al., Rev. Geophys., 2008

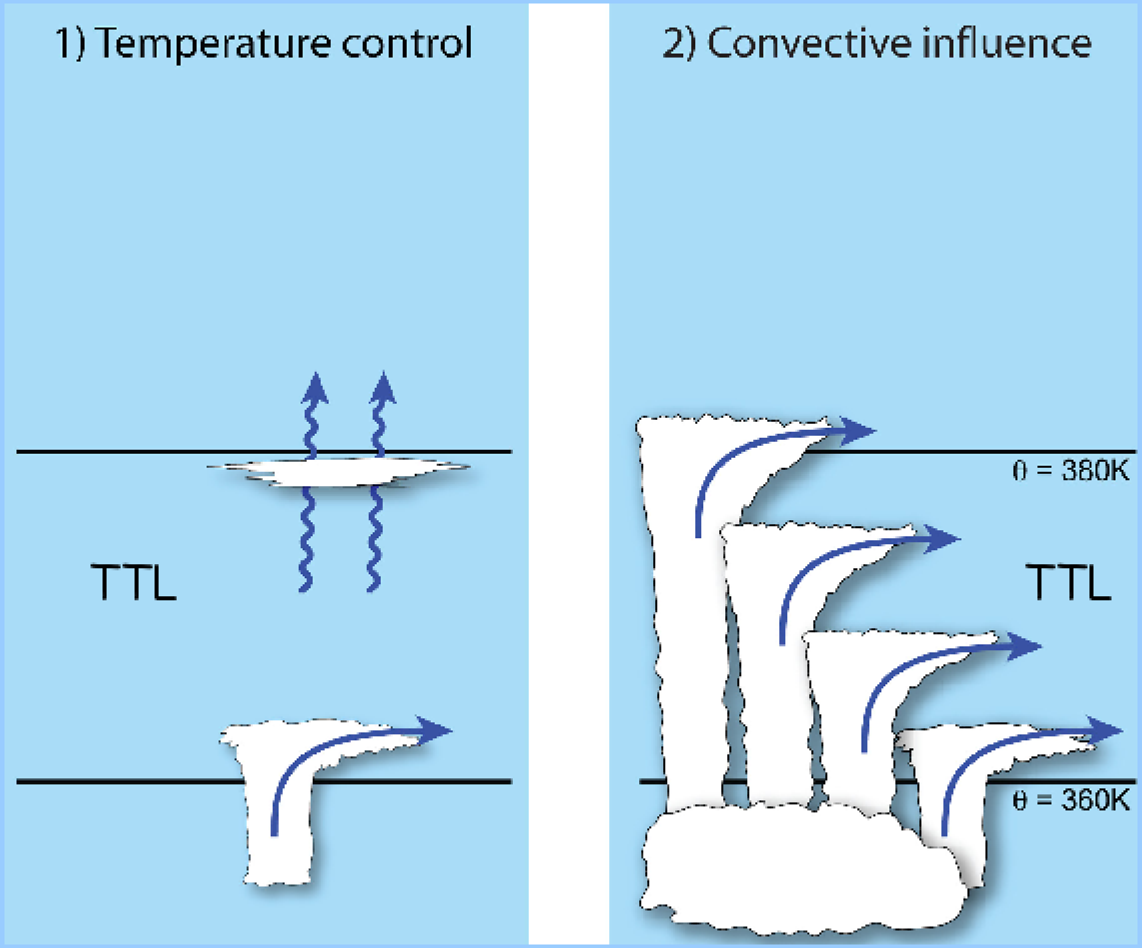
Convective Turnover Time



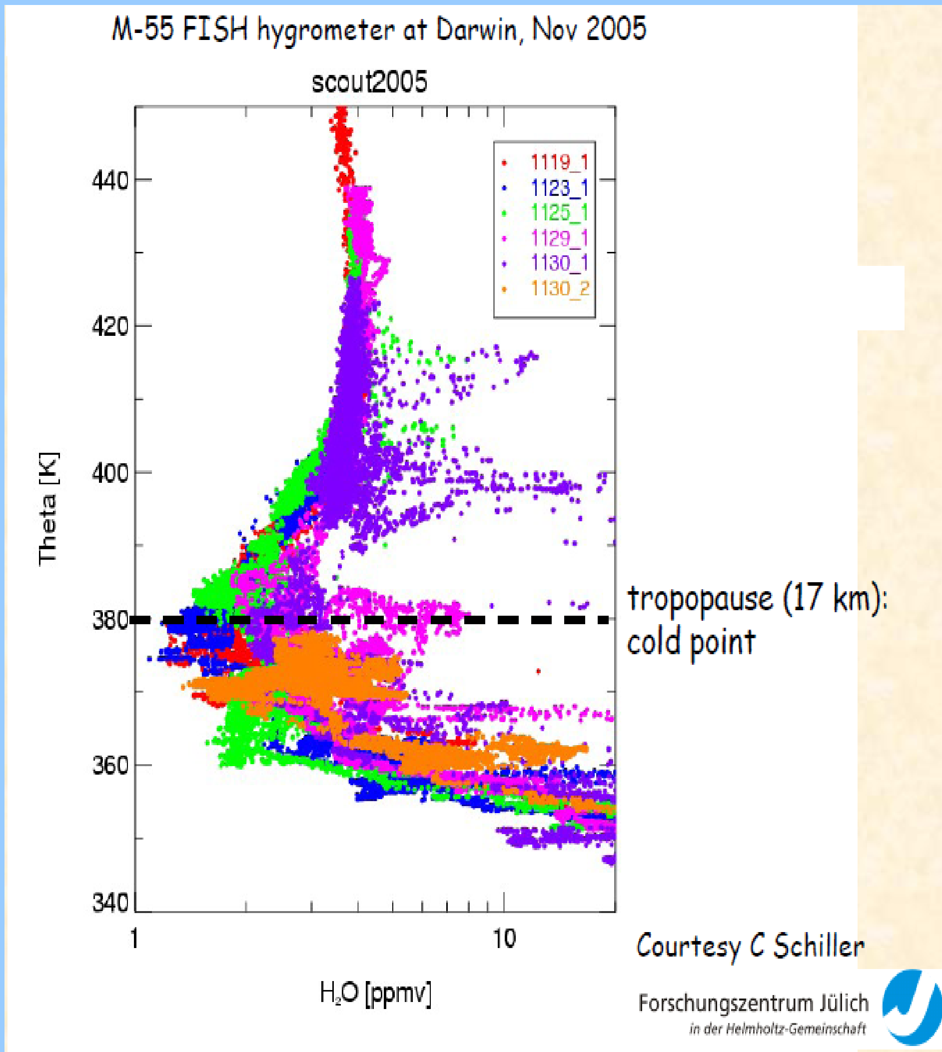
Gettelman et al 2002, JGR, Fig 9

The TTL has long turnover time (> 1 month). Hence, local processes are important.

The slow ascent hypothesis versus the overshoot hypothesis

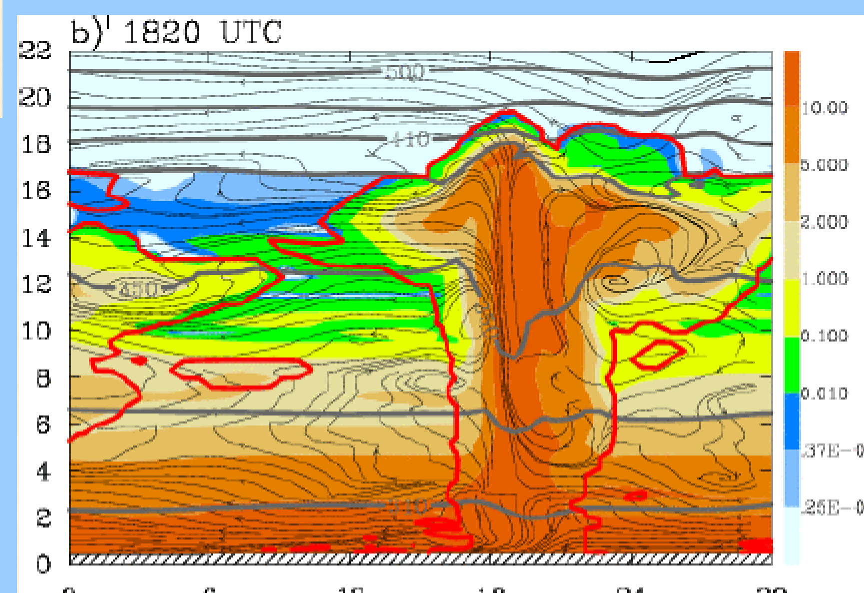


Although a very small number of clouds reach the tropopause (<0,5%), the impact on water vapour might be noticeable.



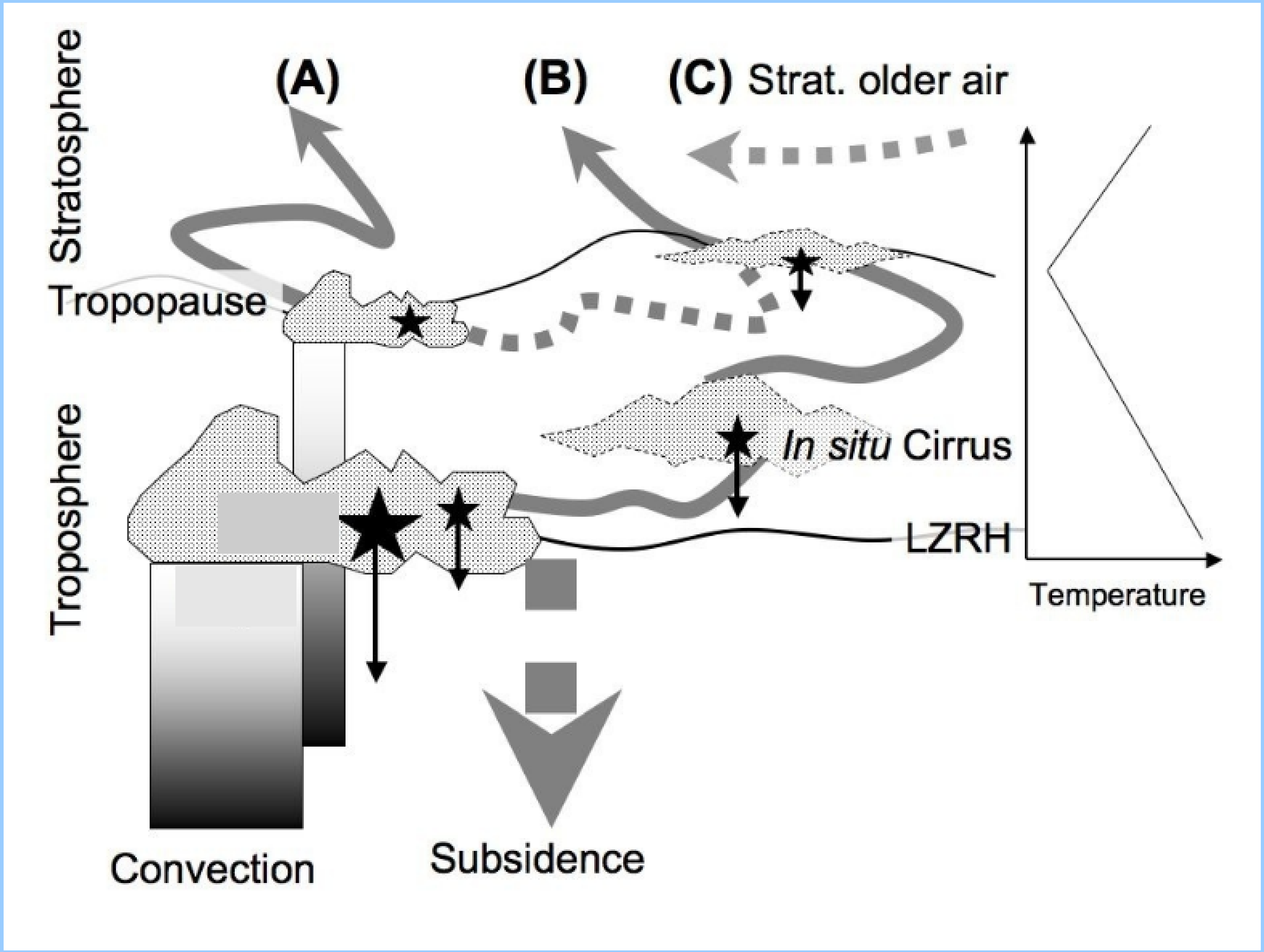
Overshoots in cloud resolving models:

- 5-10 km
- duration 10-20'
- max speed 80 m/s
- inject 6t/s of water up to 410K



Chaboureau, 2007

However, overshoots do not seem to contribute above the tropopause
See longer story later this week.



Courtesy of T. Roeckmann

The last saturation paradigm

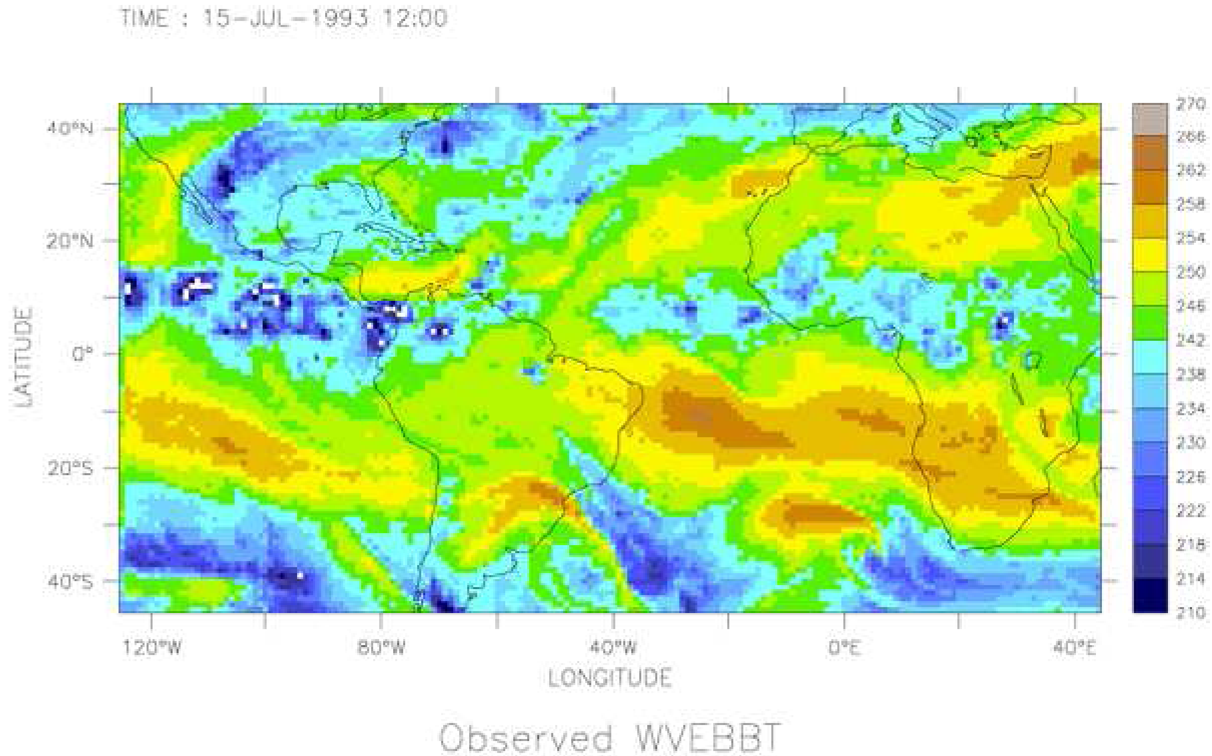
The last saturation paradigm has been used in a number of studies.

The hypothesis is that relative humidity could be entirely explained by the temperature and pressure history of the parcel. Namely, the humidity content is determined by the lowest saturation ratio during the past history of the parcel.

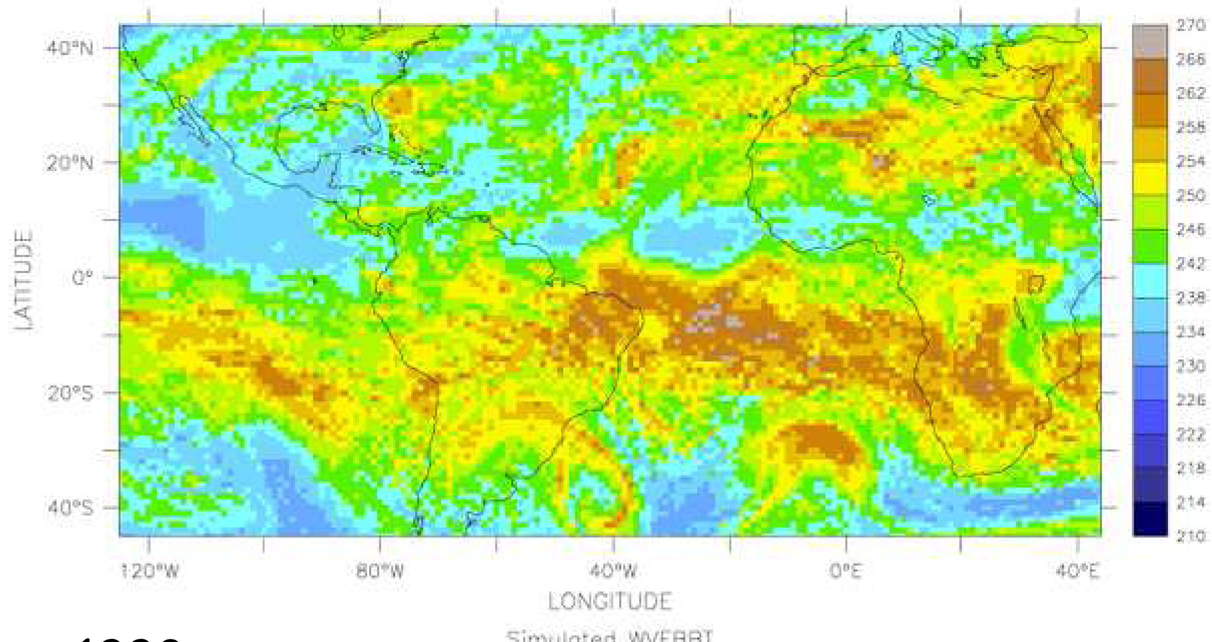
This principle has been applied to the entry of water into the stratosphere and to the distribution of water in the troposphre.

It works strikingly well in the first approximation.

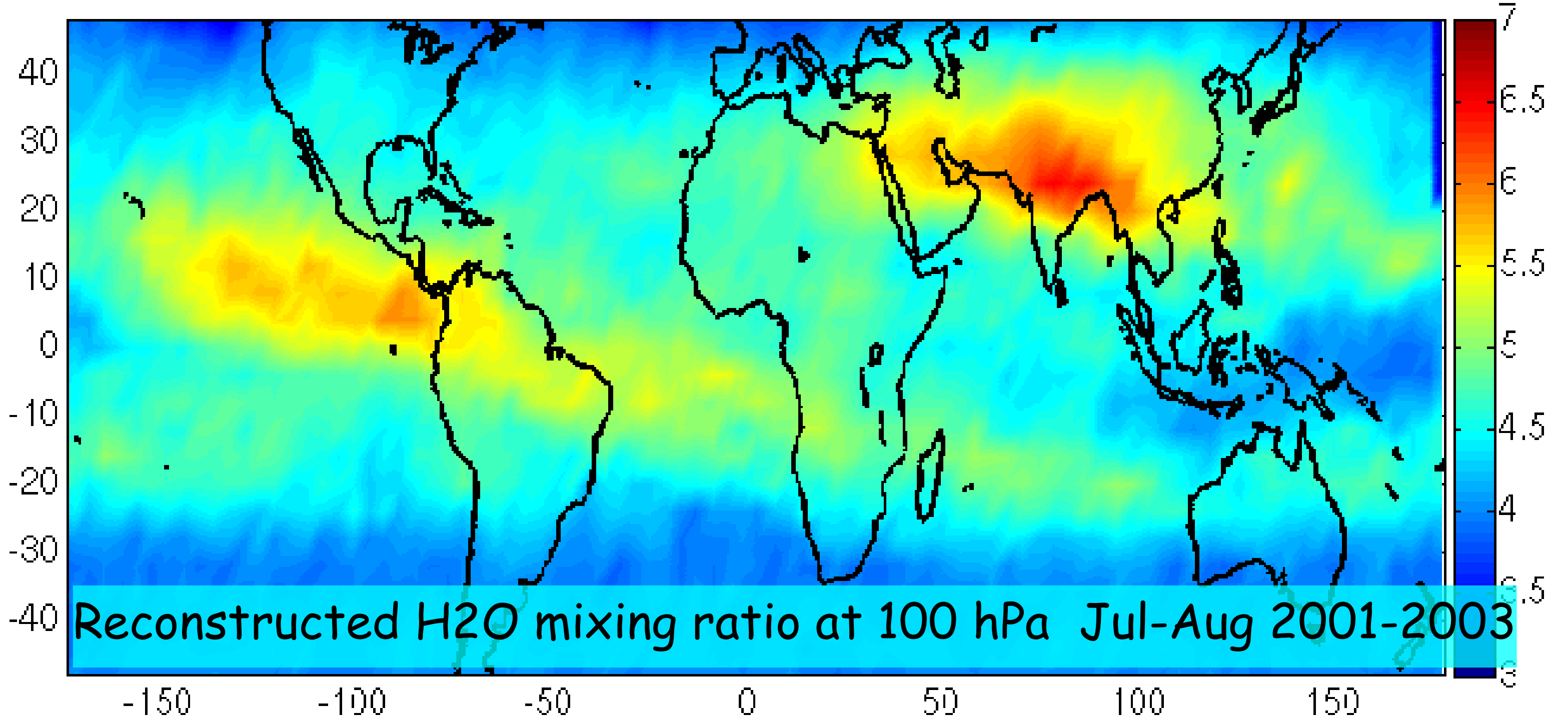
Observed brightness at 6.3µm



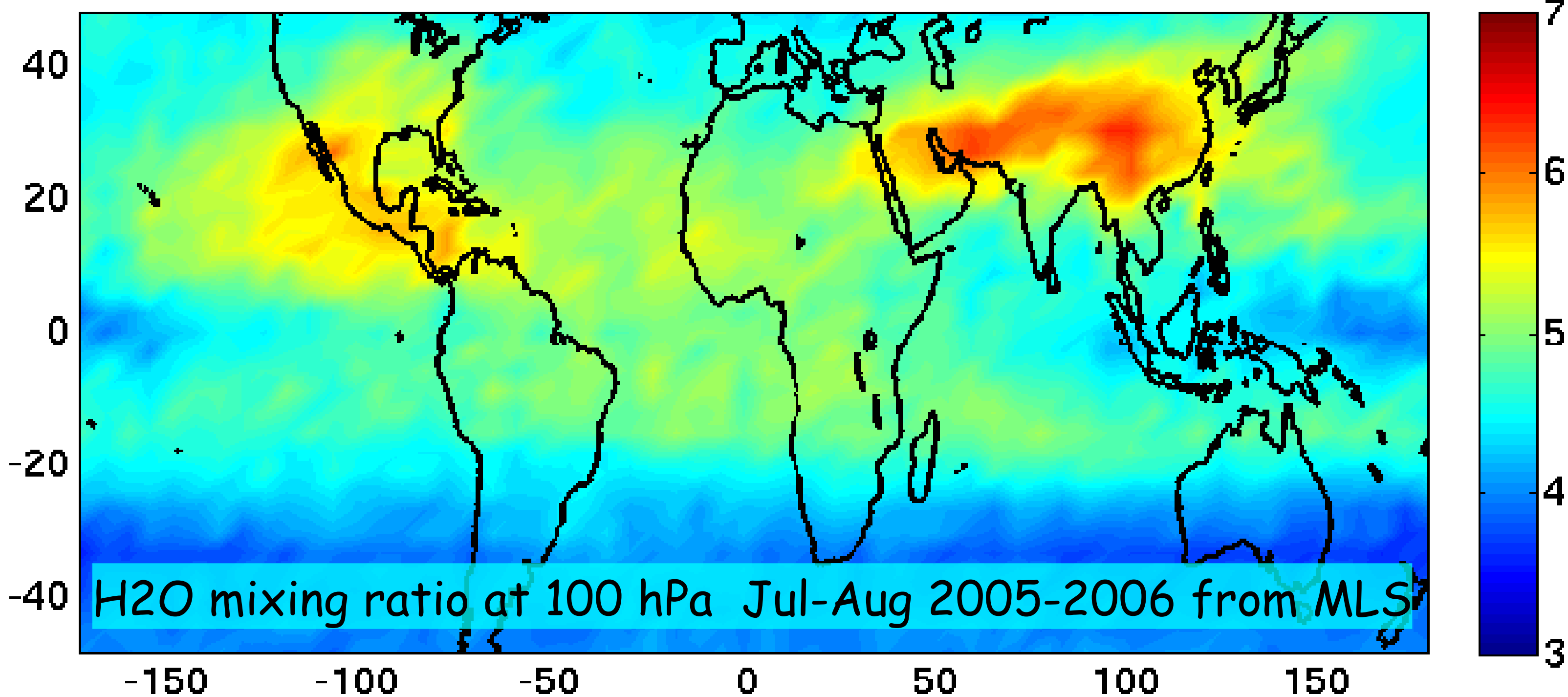
Calculated brightness



Pierremhumbert & Roca, 1998

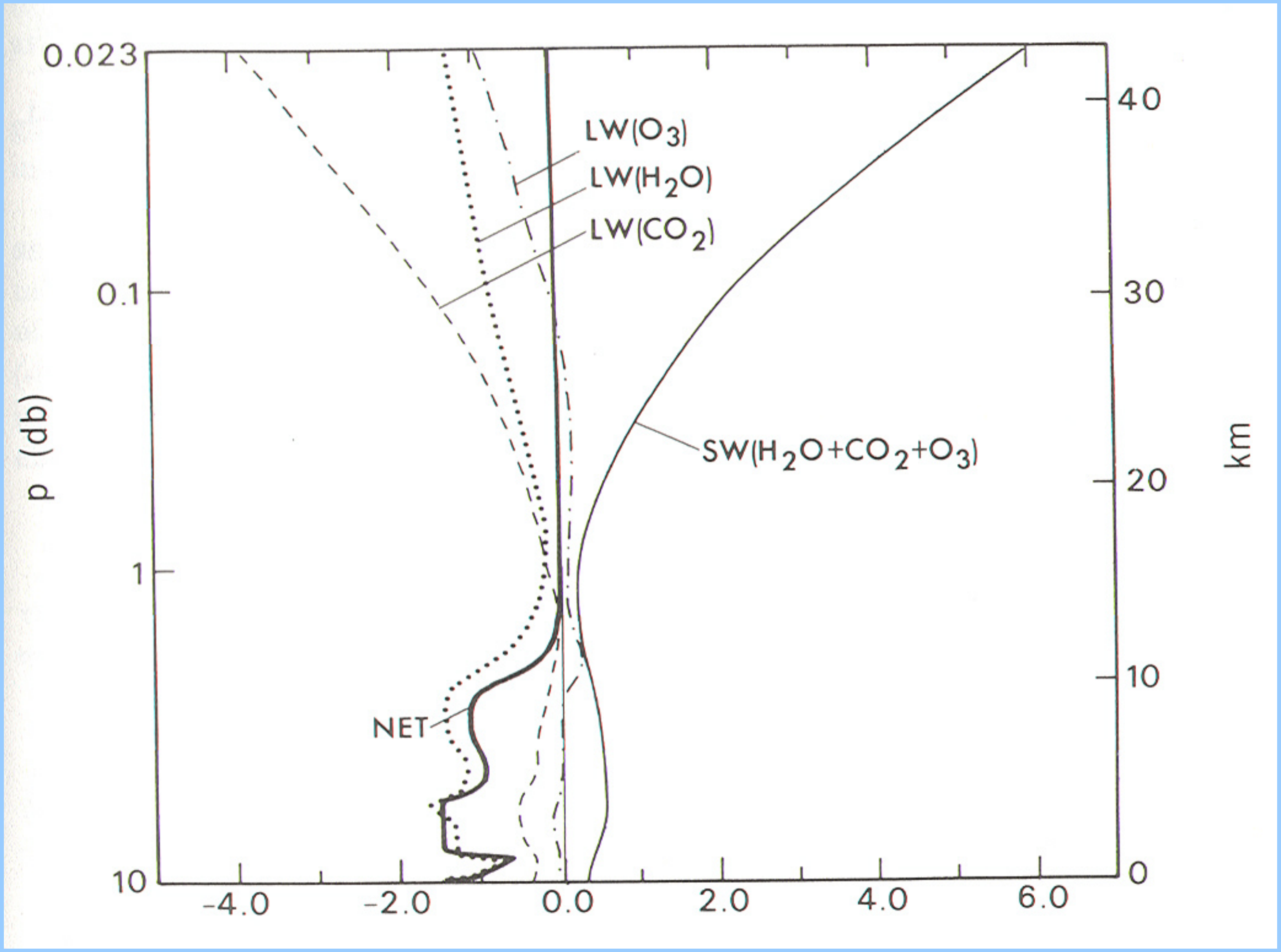


James et al., GRL, 2008



The radiative effect of water vapour and climate change

Profile of radiative budget



Water vapour is the most powerful greenhouse gas in the atmosphere.

Sensibility of radiative flux to the variations of water vapour

Fasullo & Sun, 2000

Figure 5: Downwelling longwave flux sensitivity to a 10% reduction in water for all-sky conditions.

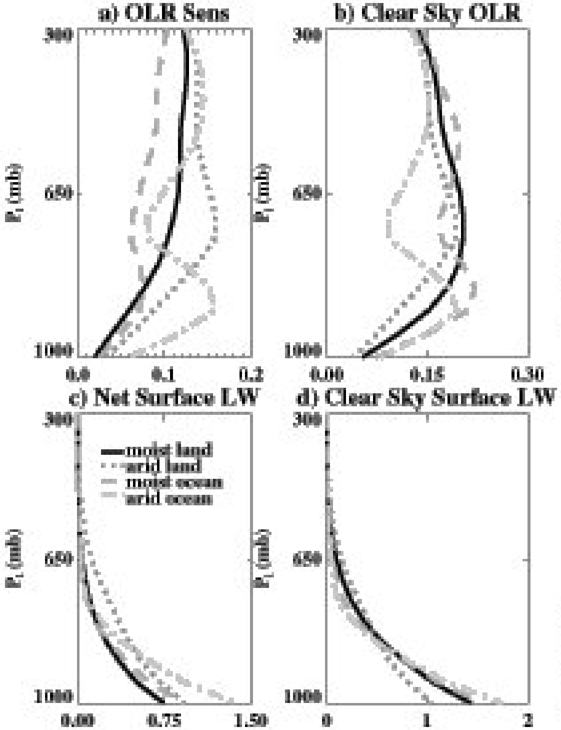


Figure 6: Mean magnitude of variations in water vapor amounts by level as a percentage of the long-term mean from the NCEP/NCAR reanalysis for a) unfiltered, b) intraseasonal, c) seasonal, and d) interannual variations.

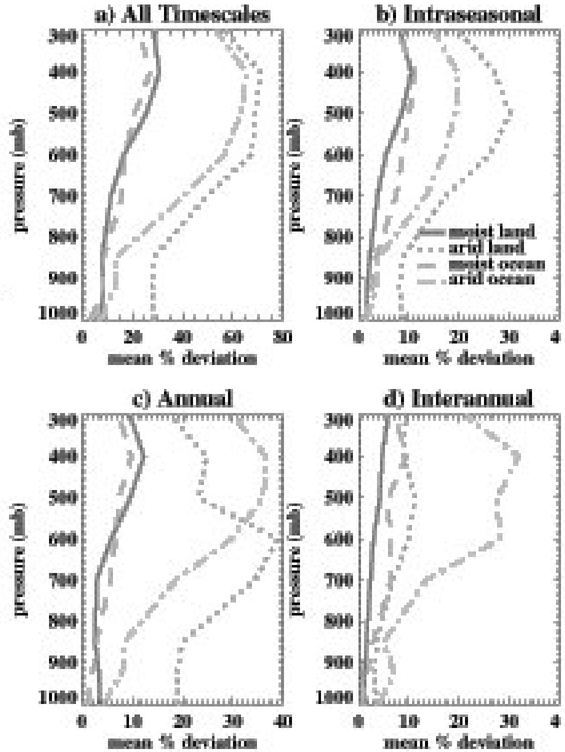
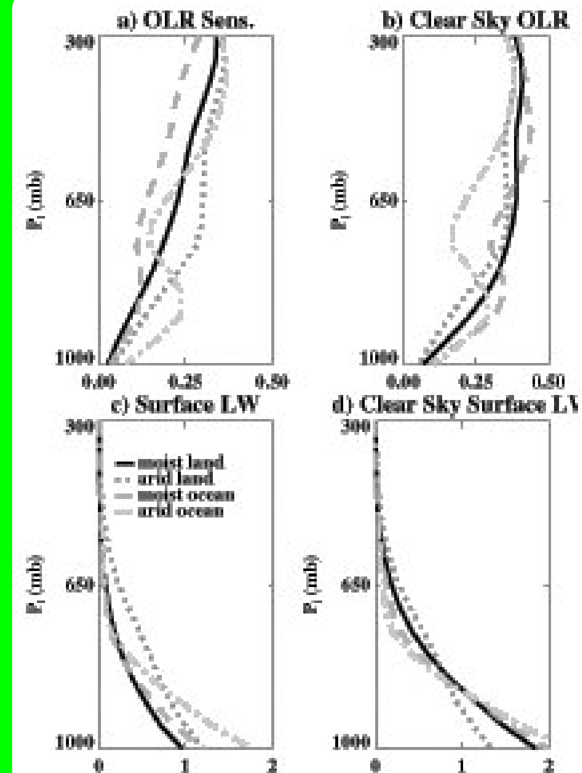
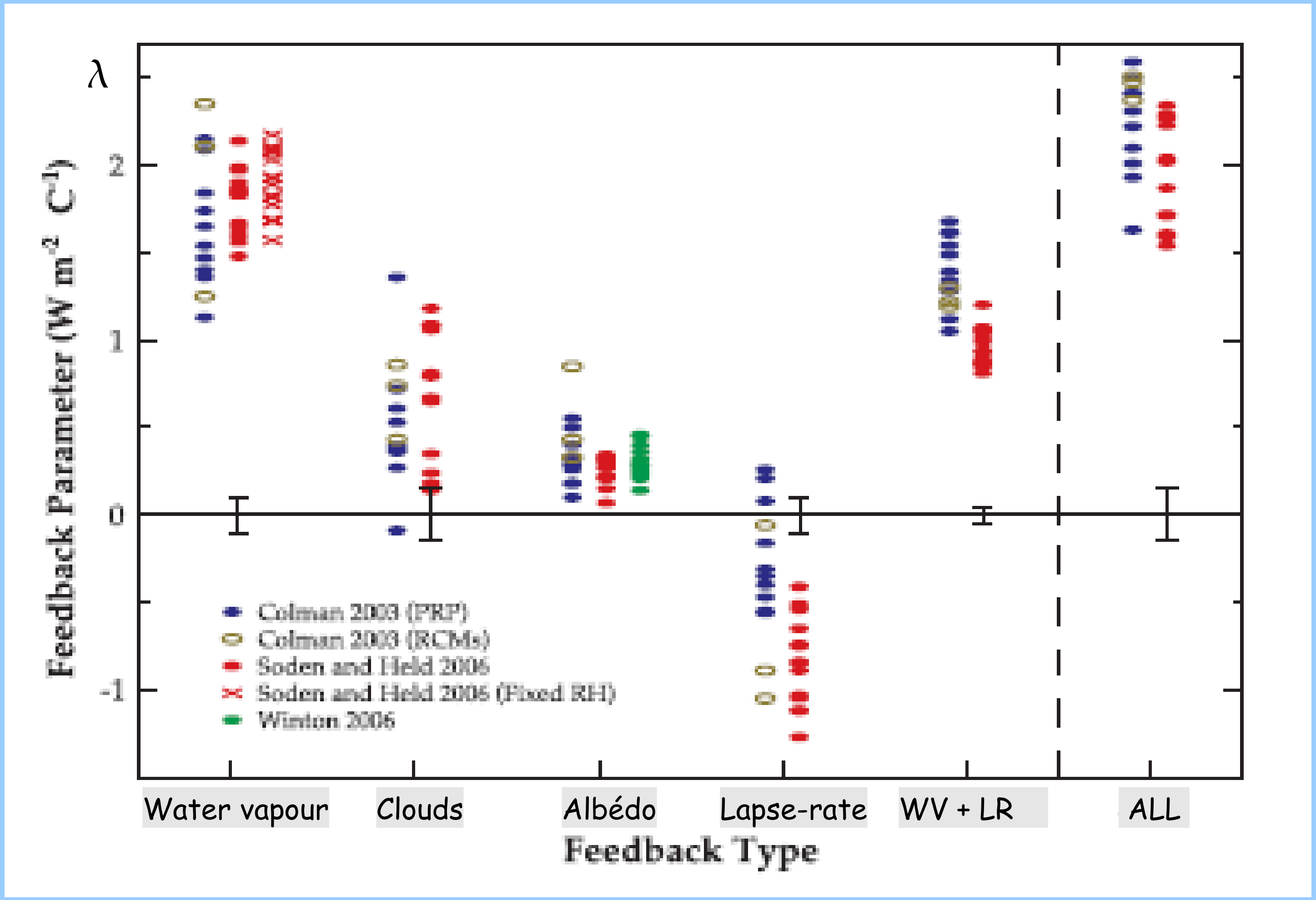


Figure 7: Sensitivity of longwave fluxes to perturbations scaled linearly from 10% near the surface to 50% at 300 mb at the TOA and surface for clear-sky and all-sky conditions.



Sensibility is largest at 300 hPa, the reason being that lower layers of the troposphere are opaque for water vapour absorption.



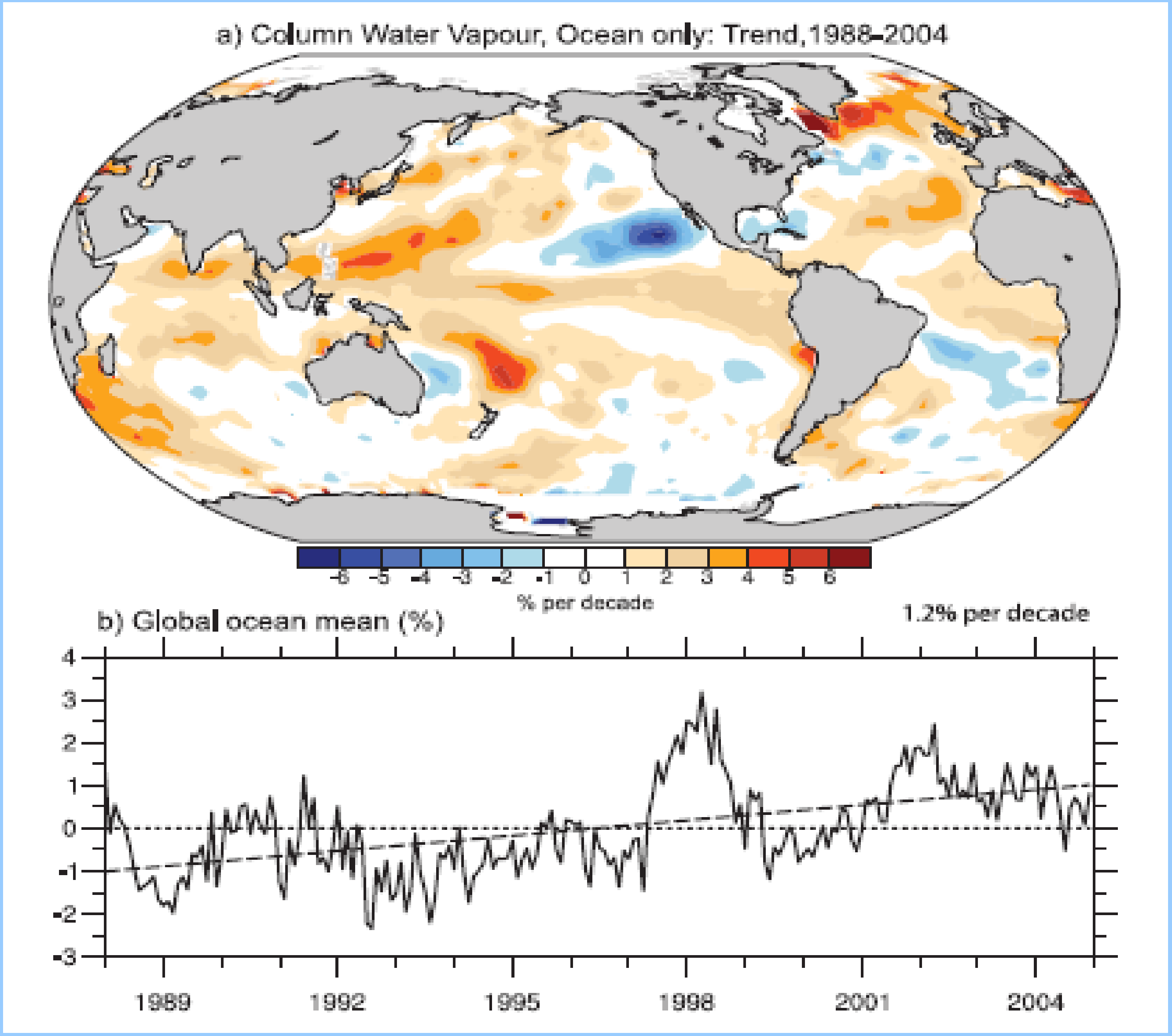
Models predict that water vapour increases while maintaining relative humidity essentially constant. Water vapour has the largest feedback in climate model.

If $\lambda_p = 4\sigma T_{\text{Earth}}^3 \approx 3{,}5\, W\, m^{-2}\, K^{-1}$ is the uniform radiative cooling response to temperature change, the climate amplification factor in temperature is

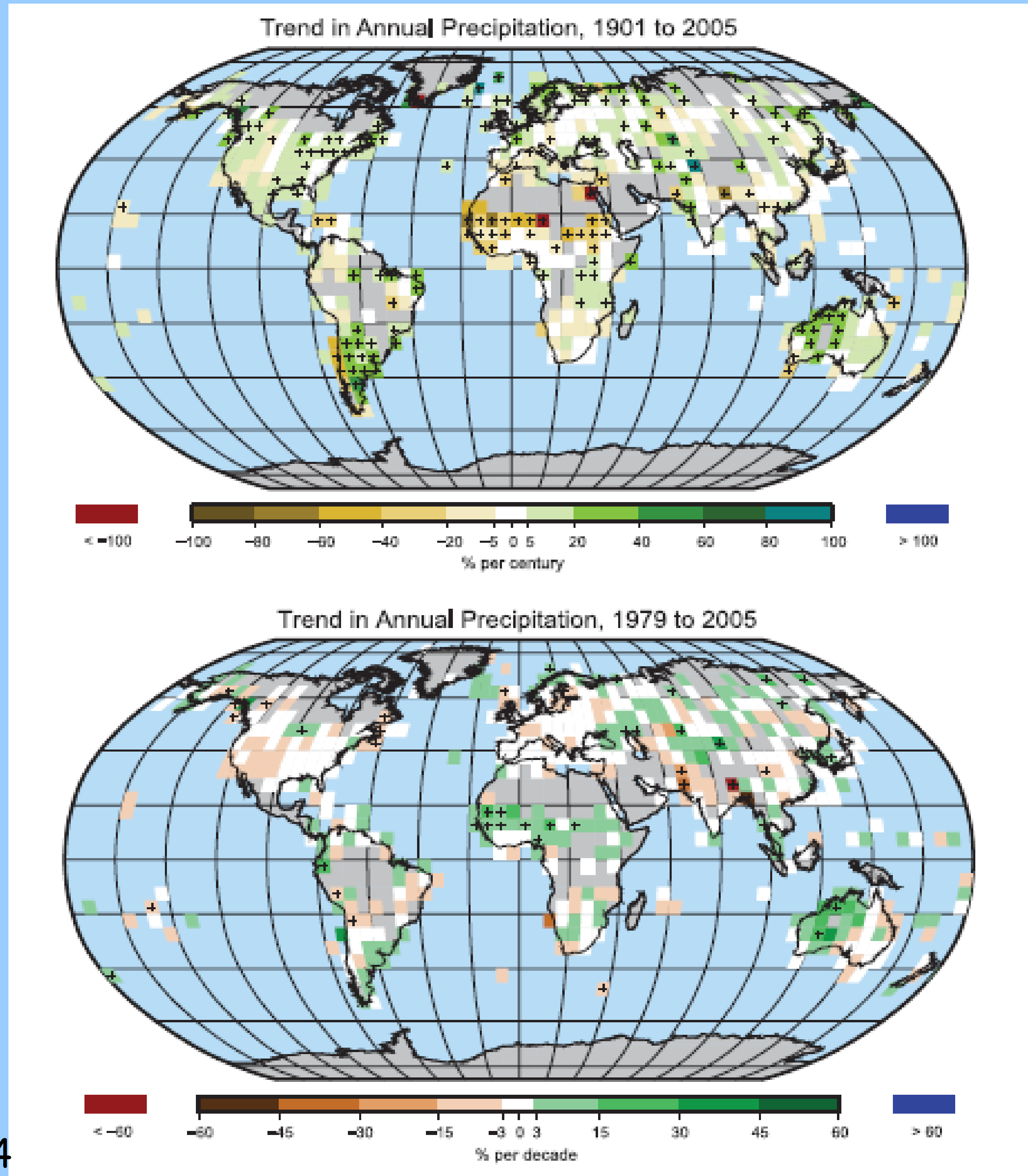
$$\frac{\lambda_p}{-\lambda + \lambda_p} \approx 2$$

Trend in column water vapour

IPCC, AR4

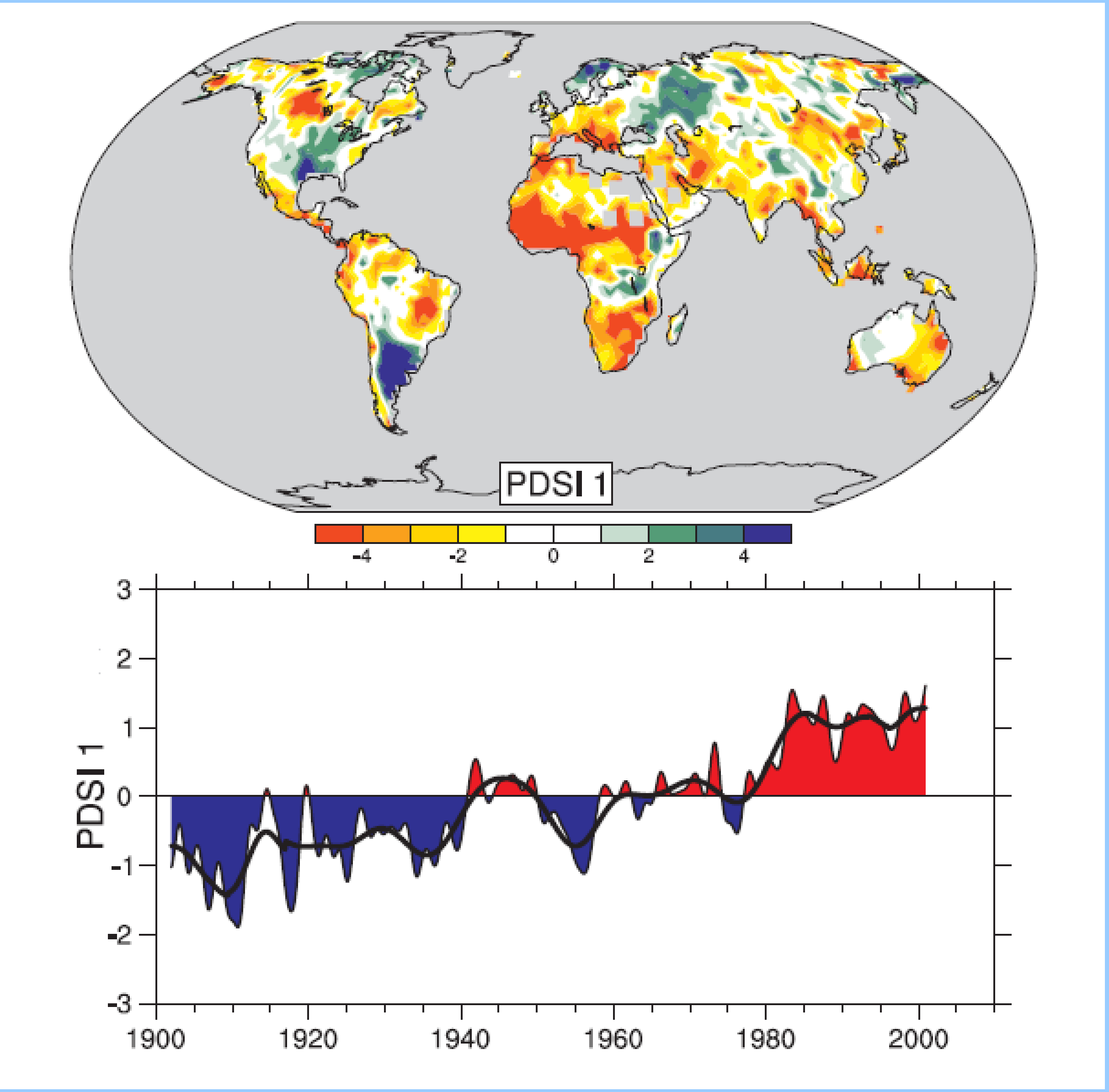


More water means more intense precipitations but not necessarily more precipitation.



IPCC, AR4

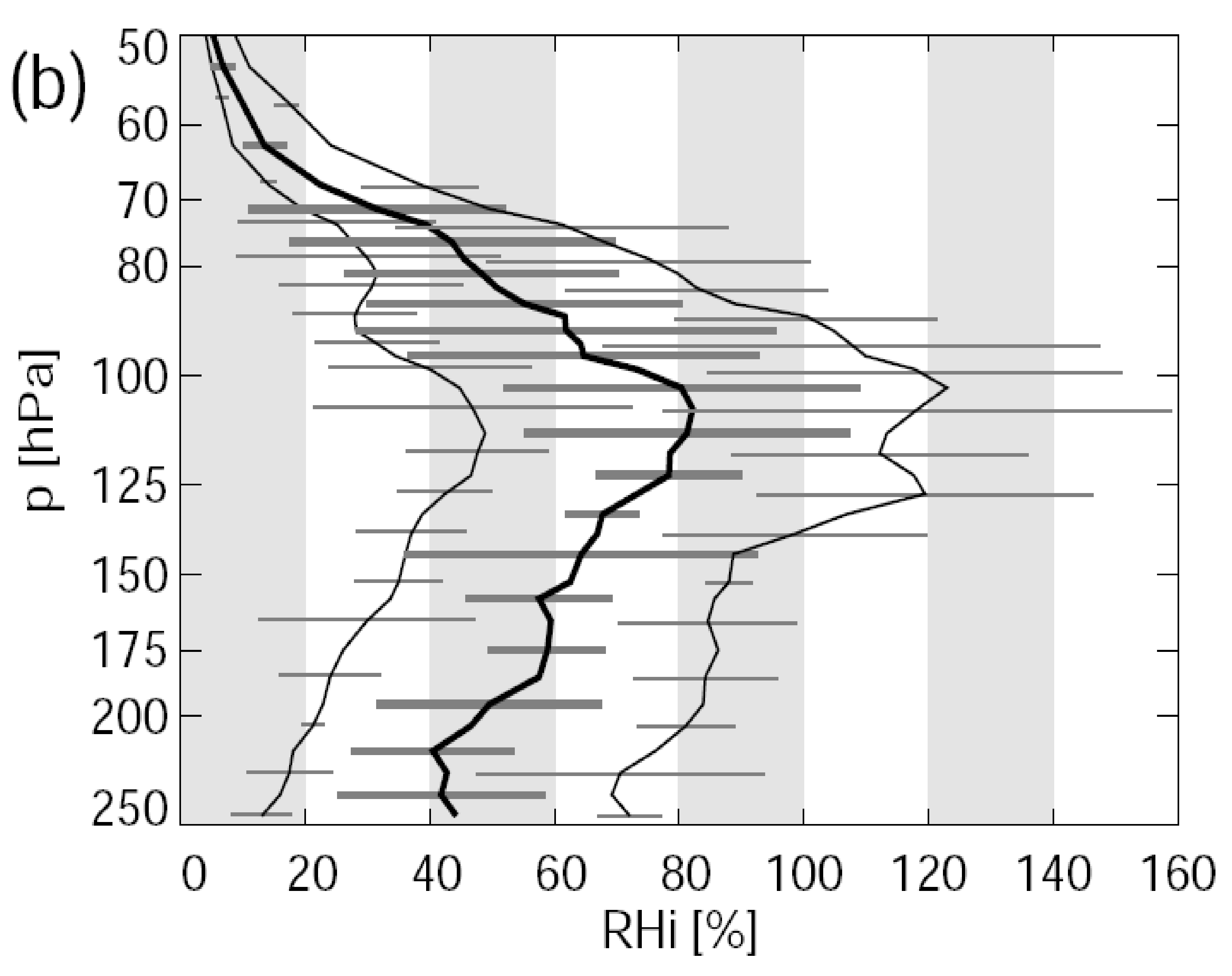
Trend in drought index



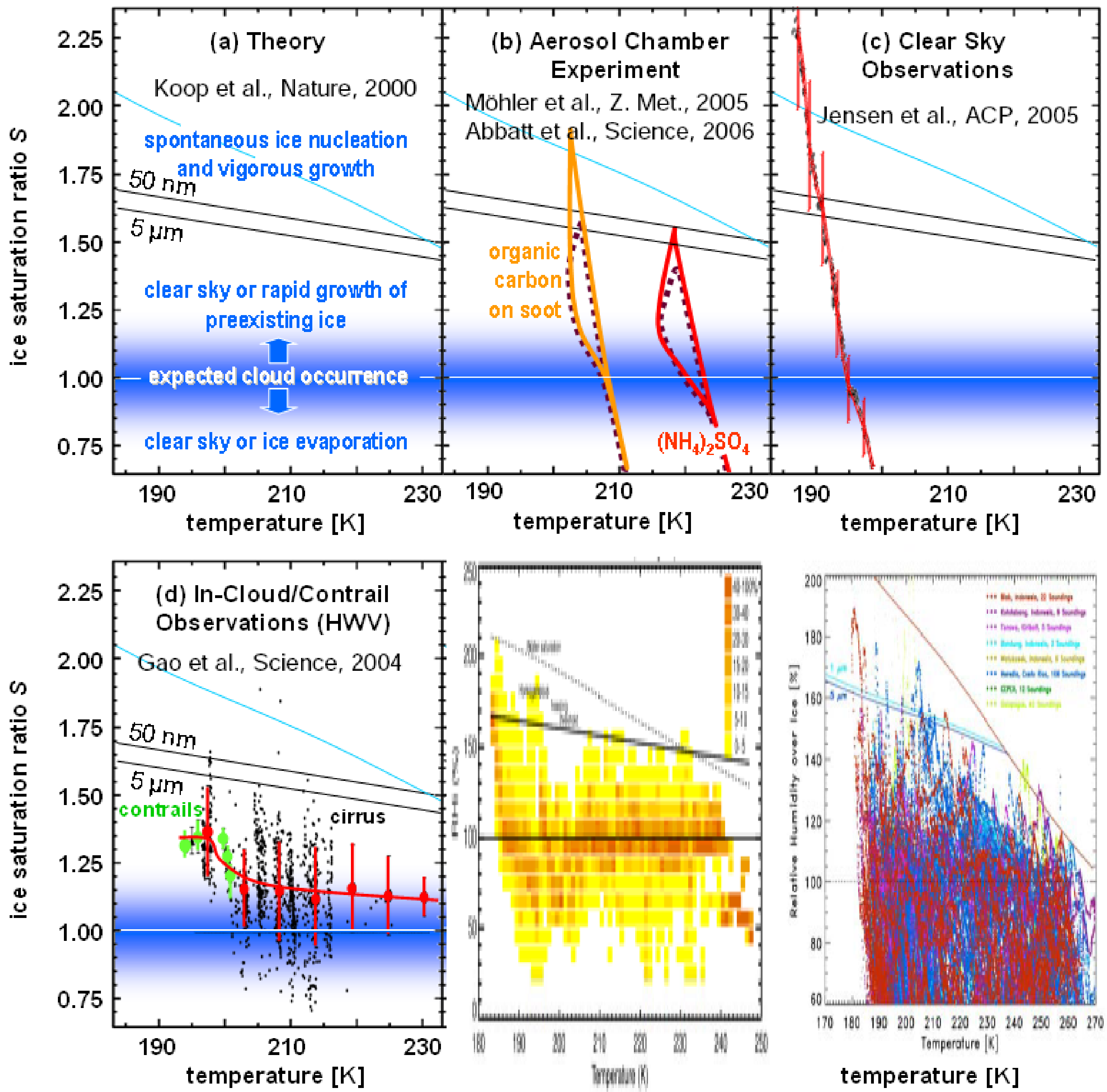
IPCC
AR4

Supersaturation and cirrus clouds

Relative humidity rises to 80% with frequent supersaturation near the tropopause



Fueglistaler et al, Rev Geophys, 2009



Peter et al., Science 2006

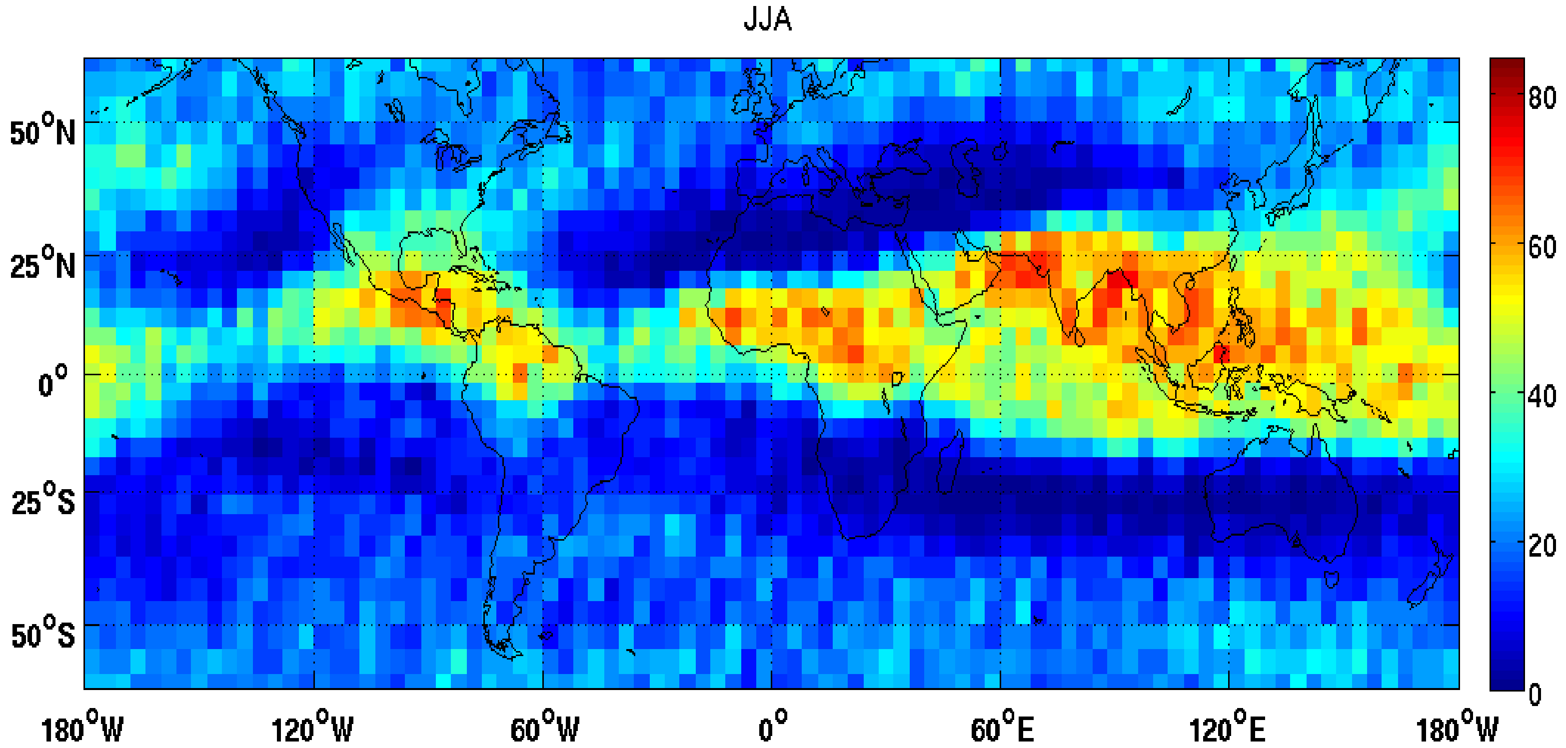
RHi workshop Karlsruhe 2007

Courtesy of C. Schiller

WAVACS Introduction

B. Legras WAVACS Cargèse 16/09/2009

Thin cirrus (T<-40°C, optical depth < 0.3)
Average from CALIPSO
June-July-August 2006-2008



E. Martins, 2009

Thin cirrus extend over a large range in the tropics

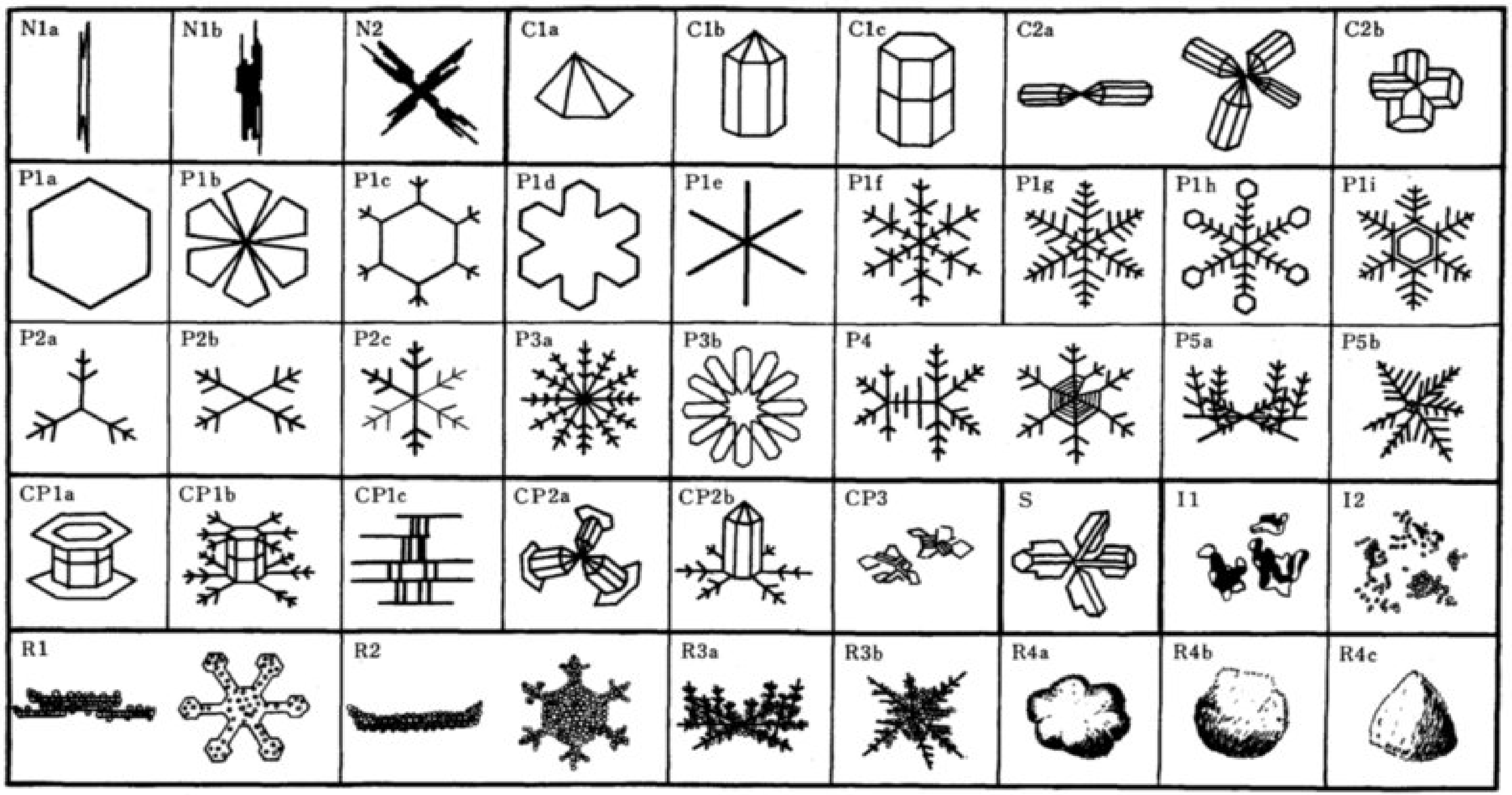


Fig. 197. General classification of snow crystals, sketches.

There is a large amount of crystal shapes according to the generation mechanism and temperature history. Properties (radiative, growth, sedimentation, evaporation) vary accordingly. Climate and weather models do not take this into account.

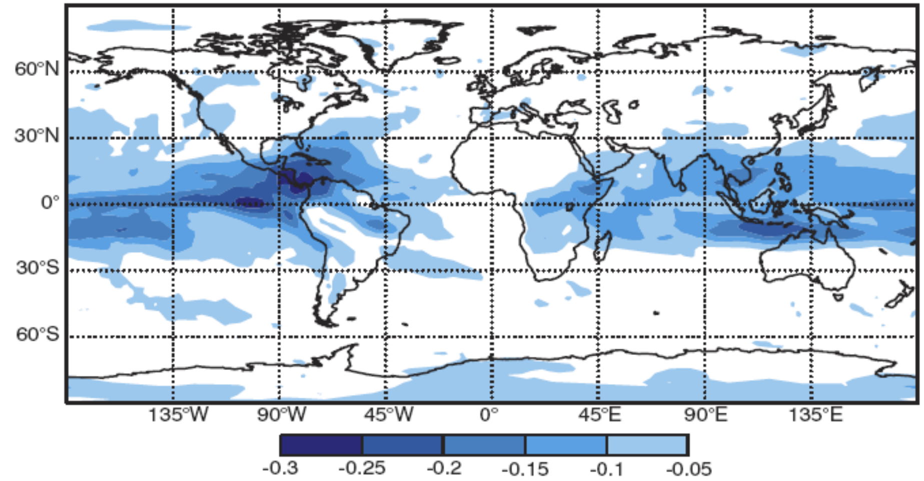


Figure 1 Difference in high cloud cover (pressure < 450 hPa approximately) between experiments using the new supersaturation scheme and the control, respectively, based on7-member ensemble mean 12-month averages.

Introducing supersaturation parameterization in a GCM or weather forecast has significant impact on humidity and cloud cover (here ECMWF IFS).

Tompkins et al. QJRMS, 2007

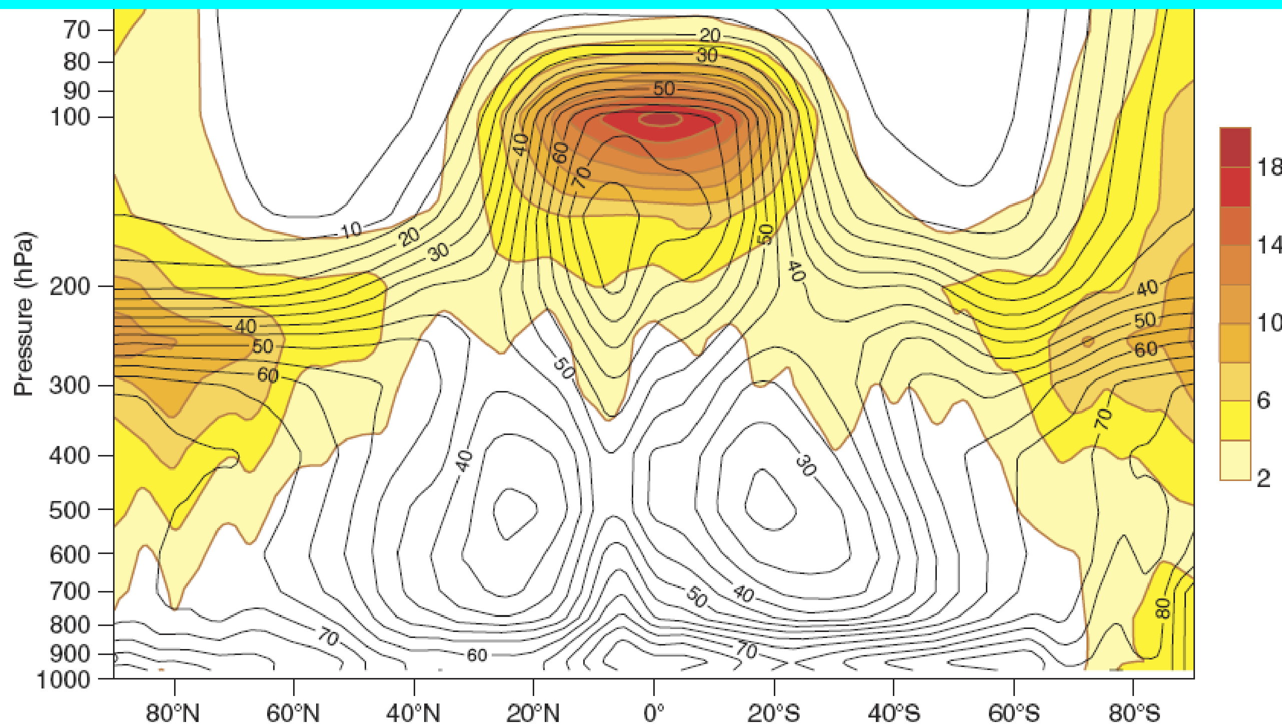
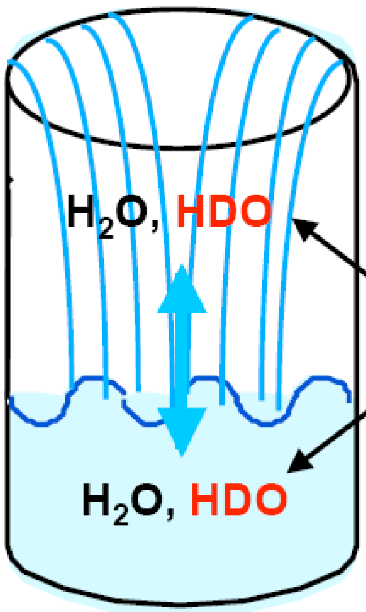


Figure 2 Difference in zonal mean relative humidity between experiments using the new supersaturation scheme and the control (shaded contours) and the zonal mean relative humidity in the control forecast (line contours with 5% intervals) based on the 7-member 12-month averages.

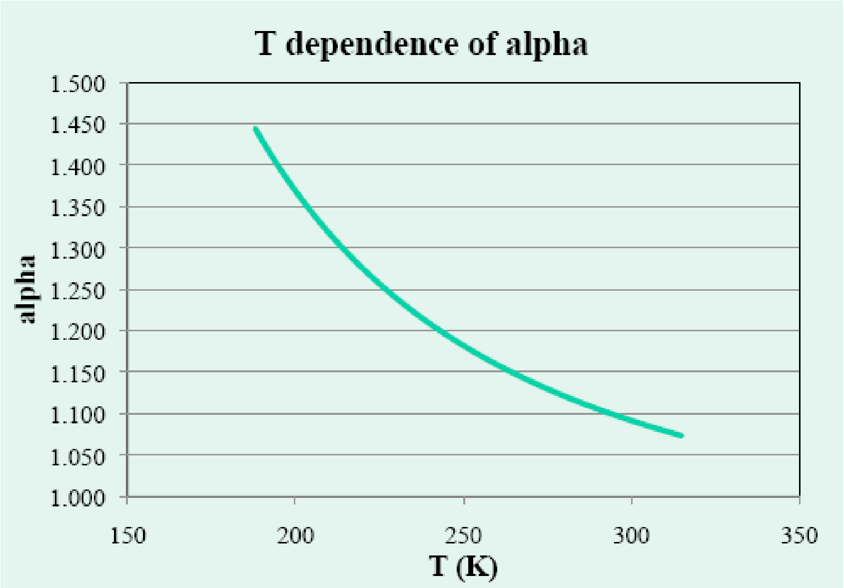
Water isotopologues

Vapour pressure isotope effect in water



Evaporation of water

$$\alpha = \frac{\left[\frac{HDO}{H_2O}\right]_{gas}}{\left[\frac{HDO}{H_2O}\right]_{liq}}$$



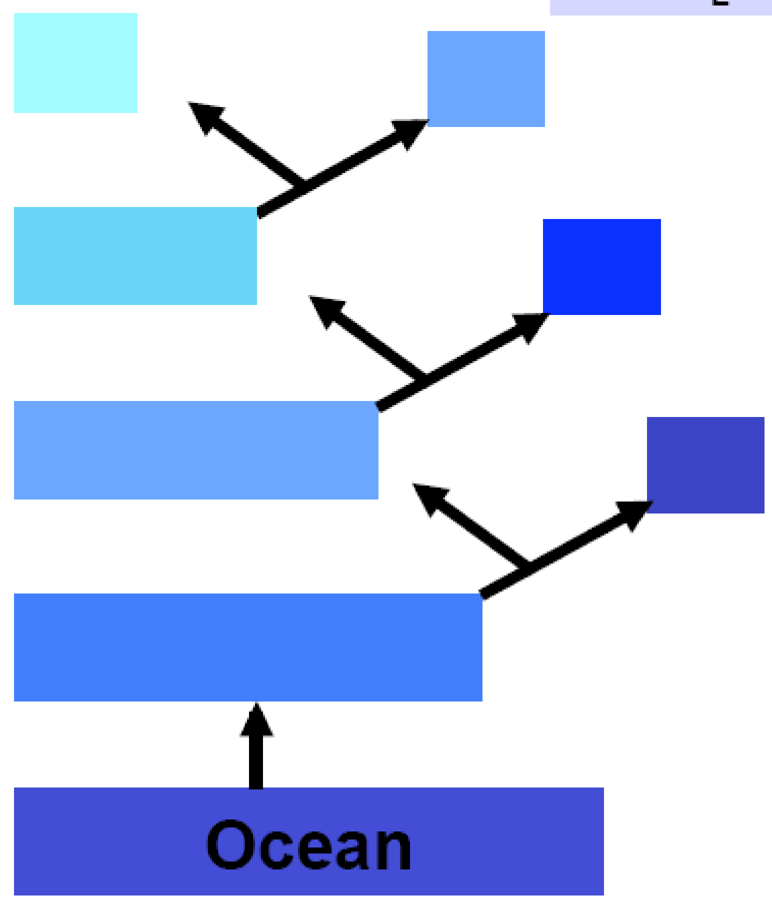
Adapted from Roeckmann, 2009

Isotopic ratio is the main paleo-thermometer used to retrieve temperature from ice records.

$$\delta D = \left[\frac{\left(D/H \right)_{SA}}{\left(D/H \right)_{ST}} - 1 \right] * 1000 \text{ ‰}$$

Continuous depletion of gas phase reservoir

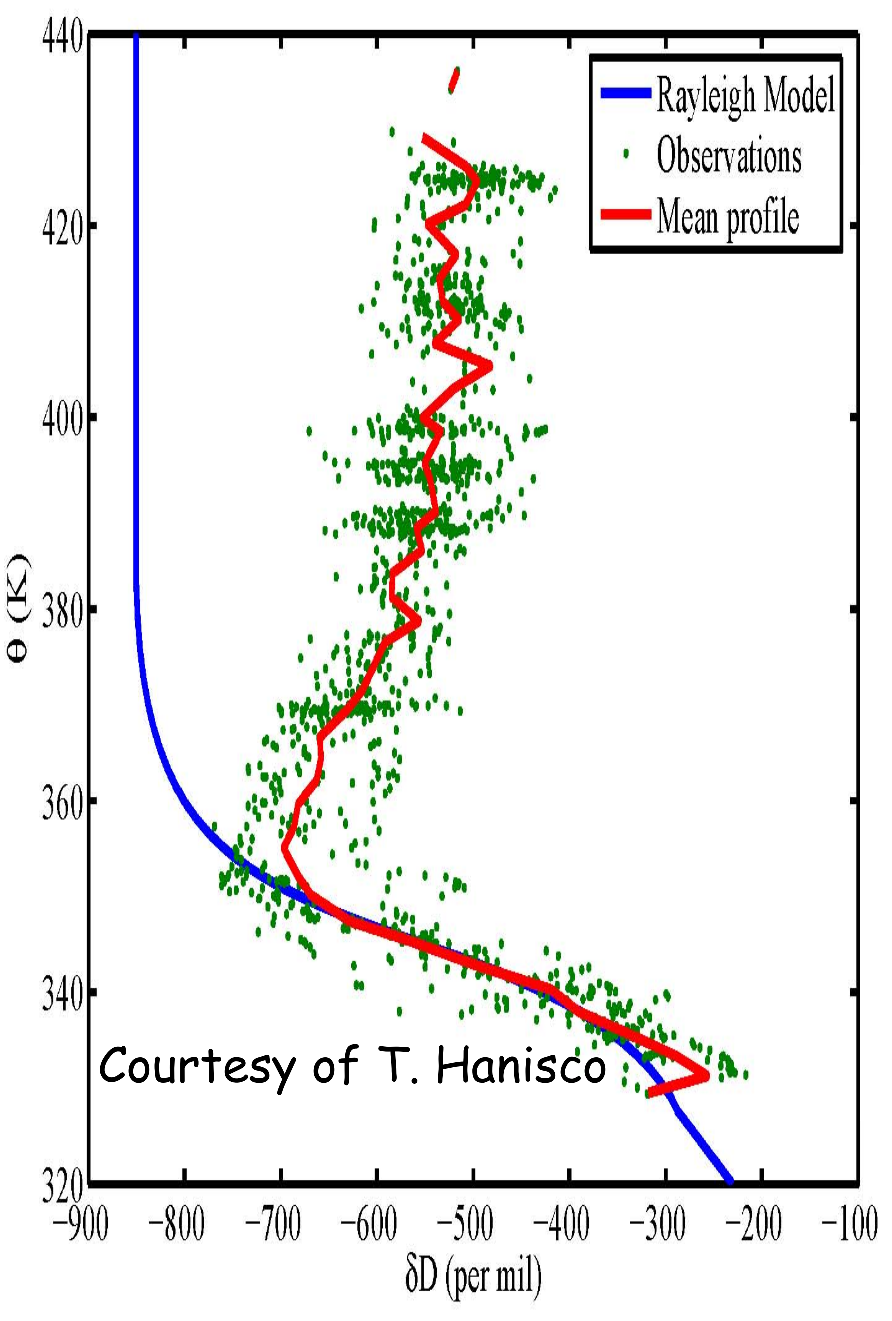
Removal of heavy condensate

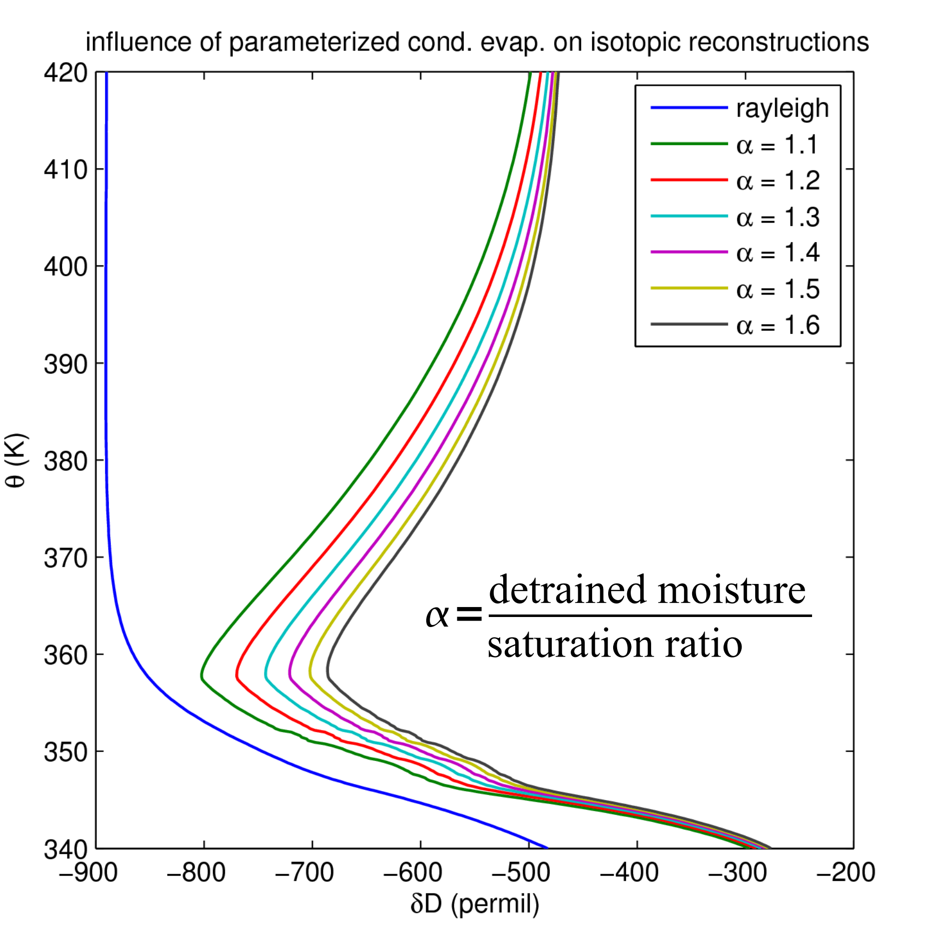


Depletion during evaporation from ocean

Water isotopologues concentrate within condensates. If condensates are removed by precipitaion, the humid air parcel is depleted. If condensates are lifted within the air parcel and subsequently evaporate, there is no depletion. Hence, depletion provides information on processes occuring within clouds and helps to improve parameterizations.

HDO profile in the TTL





Modelized HDO

M. Bolot, LMD, 2009

Water vapour database

Our Water Vapour Literature Database:
http://www.watervapor.org

UNIVERSITÄT BERN
OESCHGER CENTRE
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Theses

Hocke, 2009

Water, water, every where,
And all the boards did shrink ;
Water, water, every where,
Nor any drop to drink.

The Rime of the Ancient Mariner,
S.T. Coleridge


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