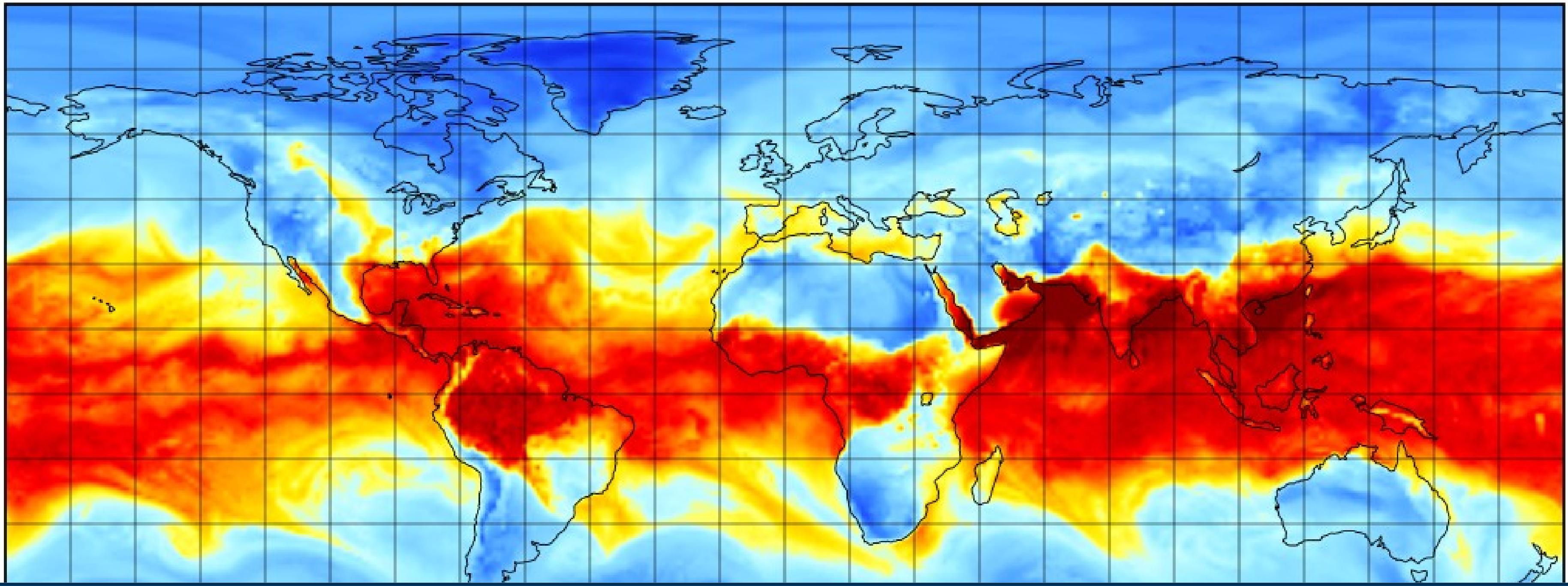

WATER IN THE ATMOSPHERE AND THE ROLE FOR CLIMATE

Part 2: Water vapor distribution in the atmosphere

WS 22/23 I CHRISTIAN ROLF

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TOPICS

1. Introduction into units and definitions
2. Water vapor distribution in the atmosphere
3. Cloud formation (water and ice clouds)
4. Water cycle
5. Water and climate feedback
6. Measurement of water in the atmosphere

SUBTOPICS

2. Water vapor distribution in the atmosphere

- **Horizontal Distribution of Water vapor**
- Lifting Condensation level
- Dry/Moist Adiabatic lapse rate
- Equivalent Potential Temperature
- Temperature and humidity dependence of rel. humidity
- Vertical Distribution of Water vapor
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- Lower stratosphere horizontal tape recorder
- Methane oxidation in the upper stratosphere

DISTRIBUTION OF WATER VAPOR

- Large range of water vapor mixing ratios in the atmosphere (4 orders of magnitude)

- **Temperature driven** differences of water vapor

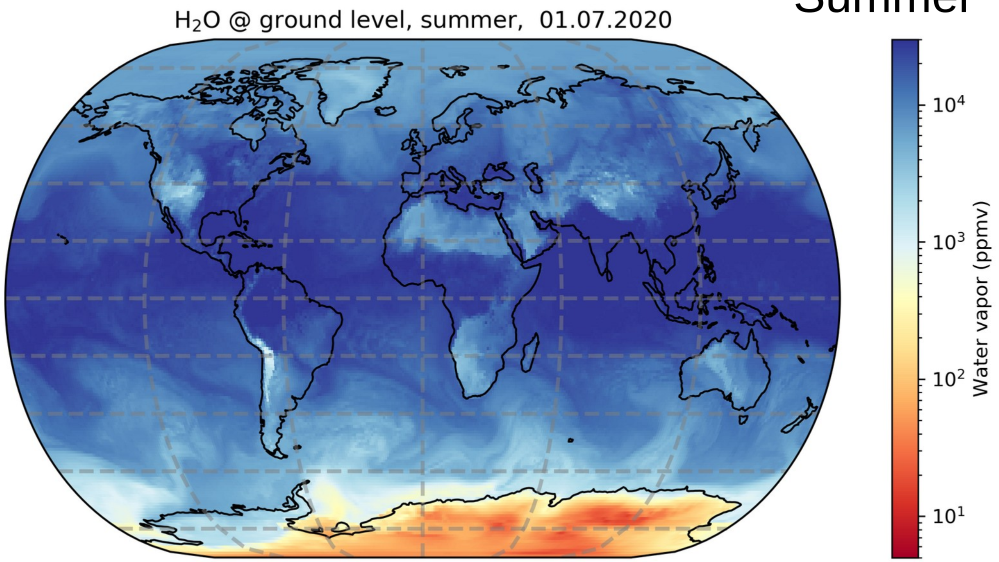
  at ground

  - ➔ tropics ↔ poles
  - ➔ Summer / winter season

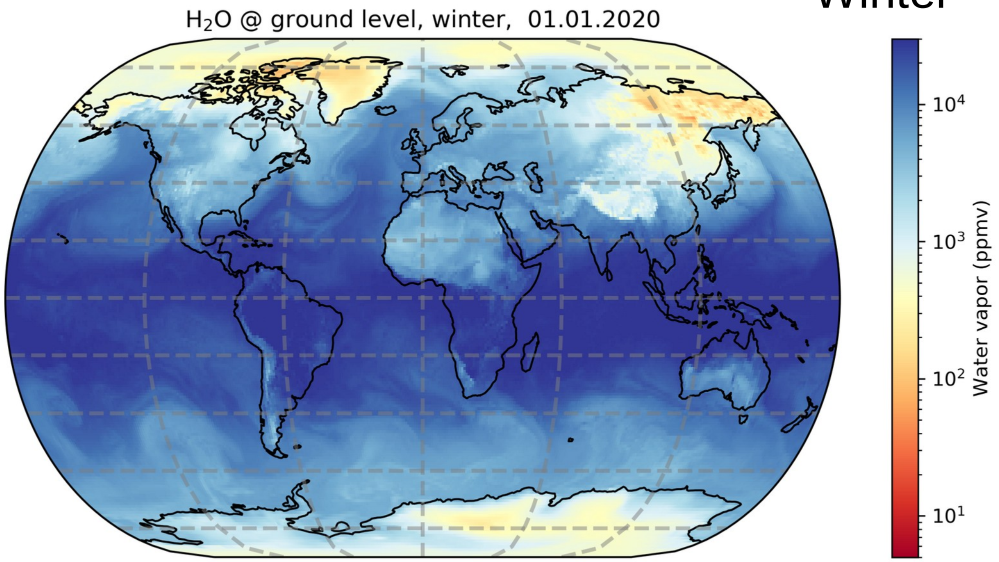
- **Water vapor driven** differences (sources)

  - ➔ Deserts

Ground level
Summer



Winter



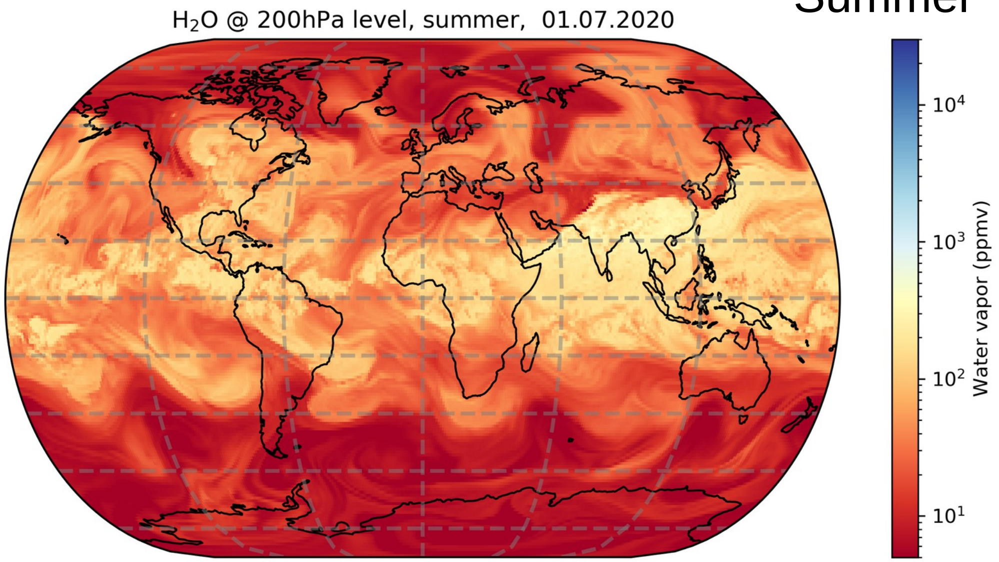
DISTRIBUTION OF WATER VAPOR

- Range of water vapor mixing ratios @ 200hPa smaller compared to ground

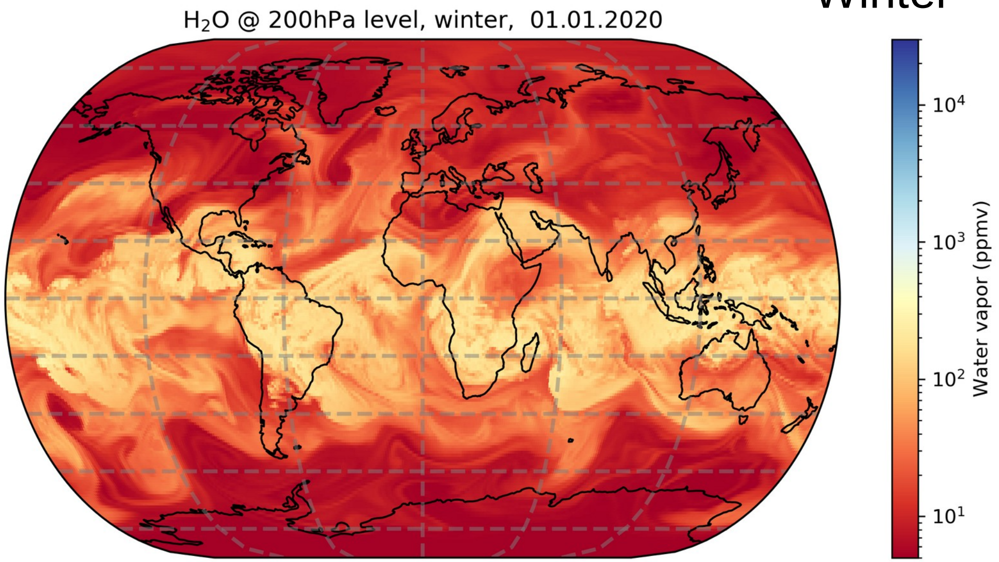
- Still large difference between Tropics and Pole regions

  → **Difference Troposphere / Stratosphere**

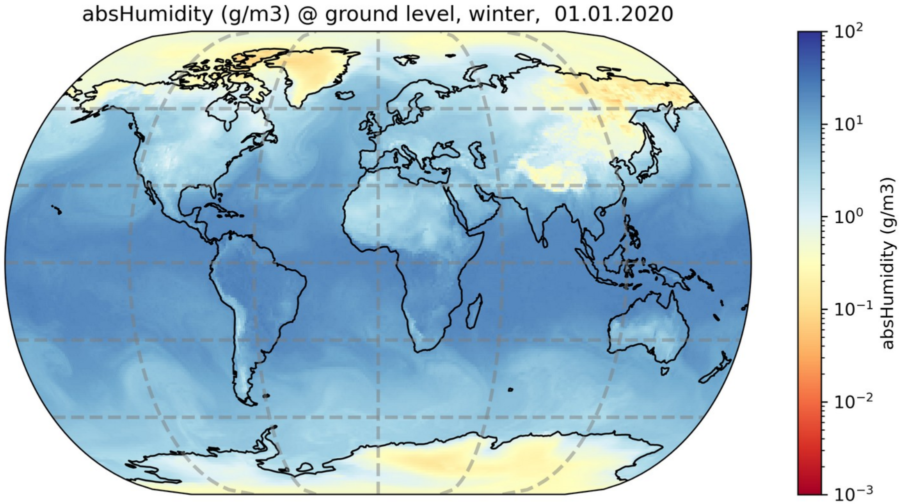
200 hPa level
Summer

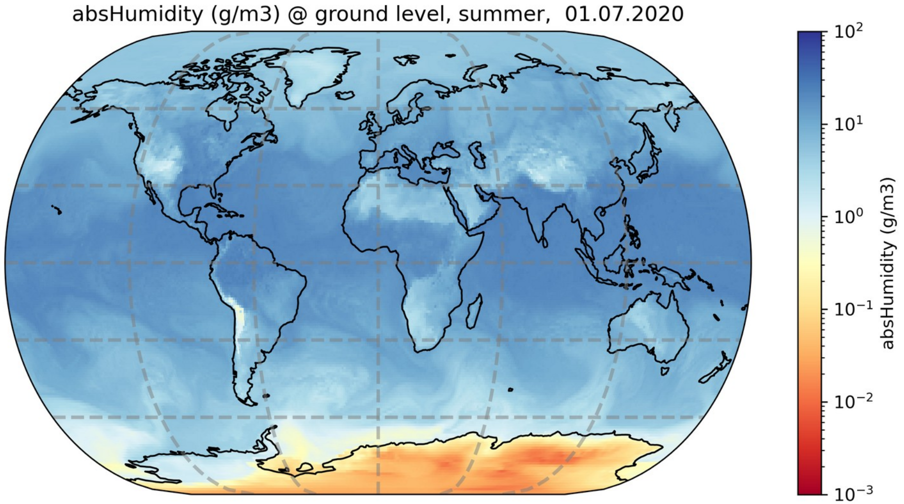


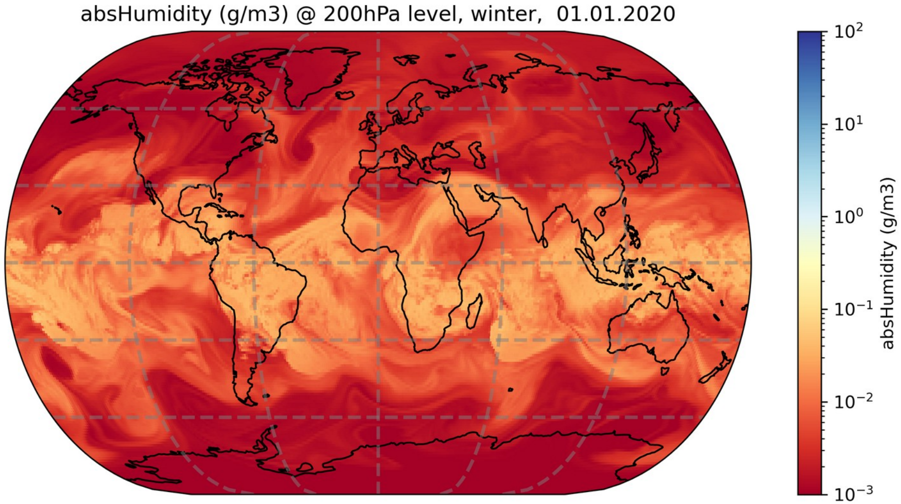
Winter

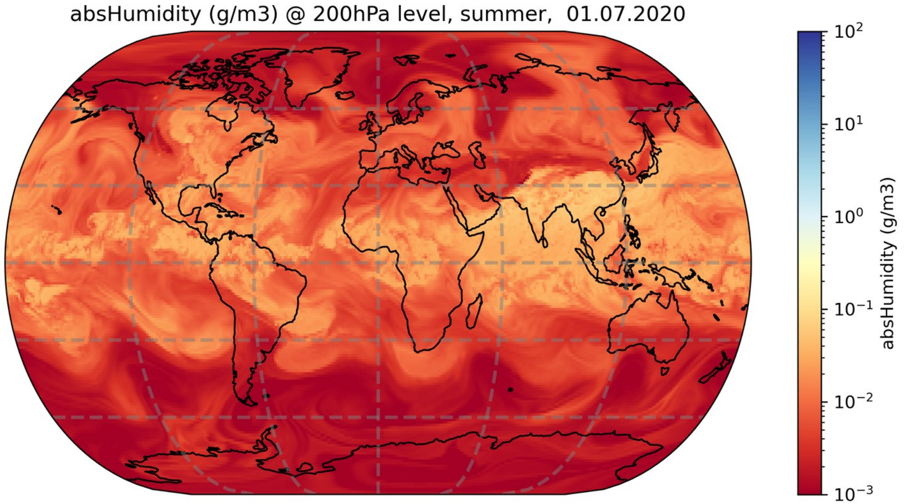


ABSOLUT HUMIDITY

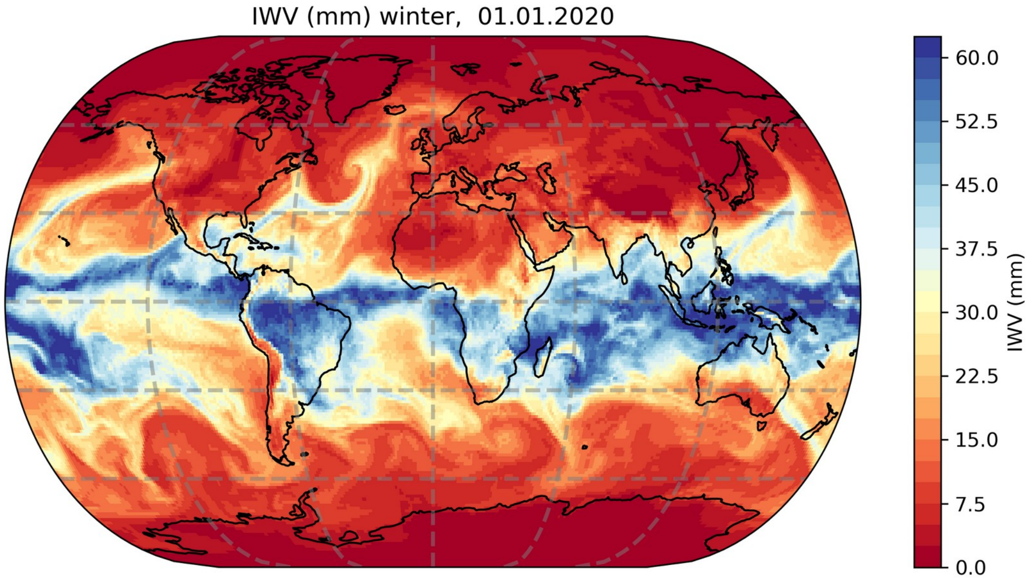


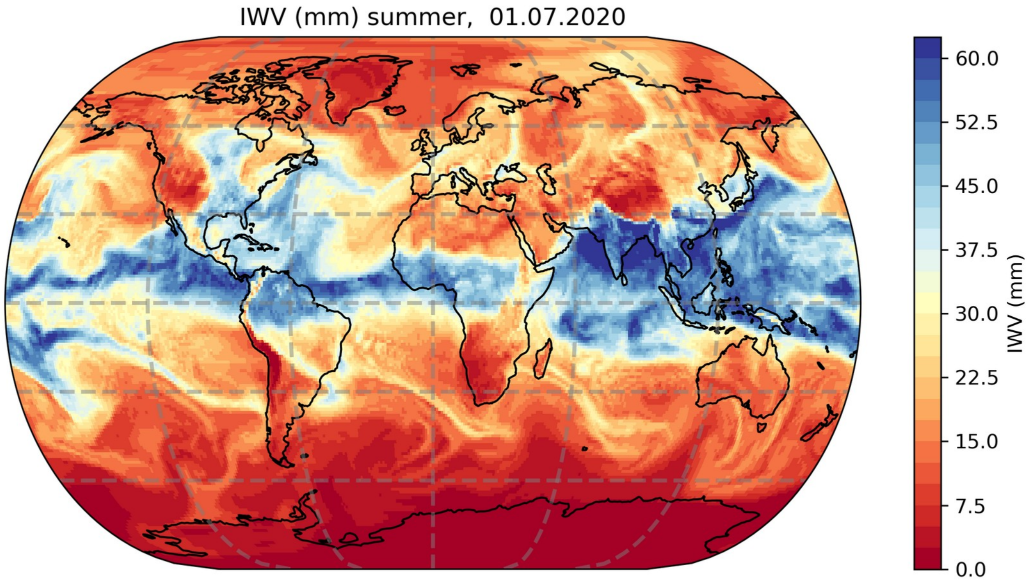






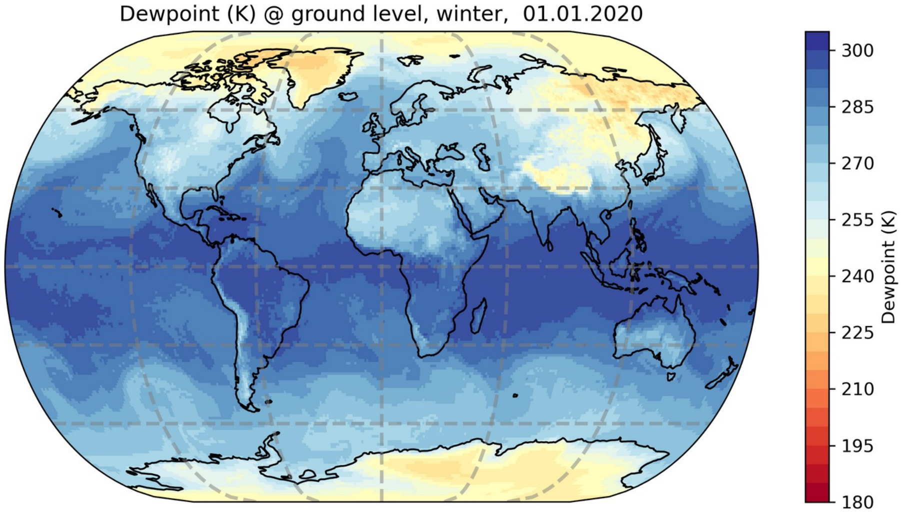
INTEGRATED WATER VAPOR

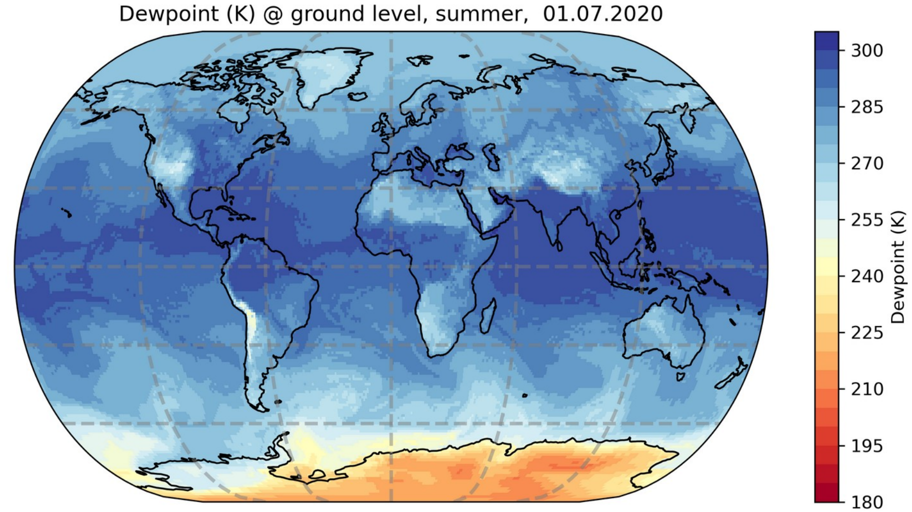


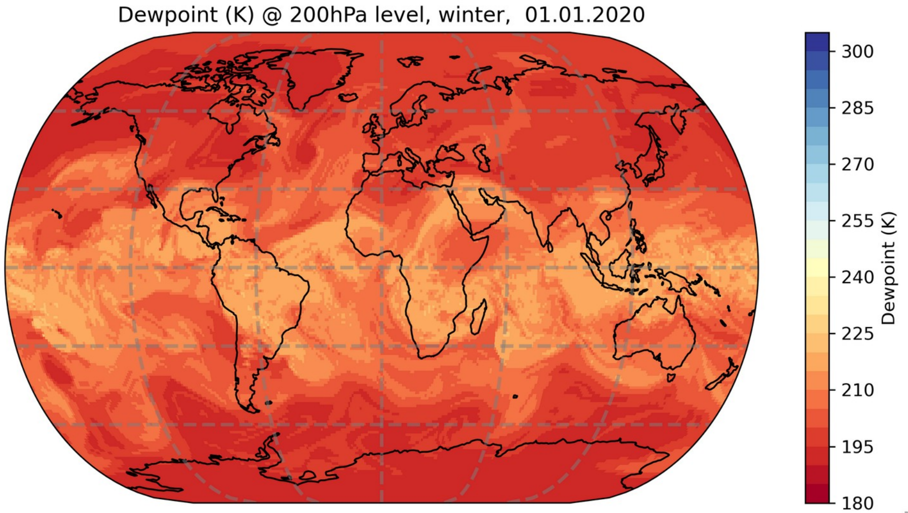


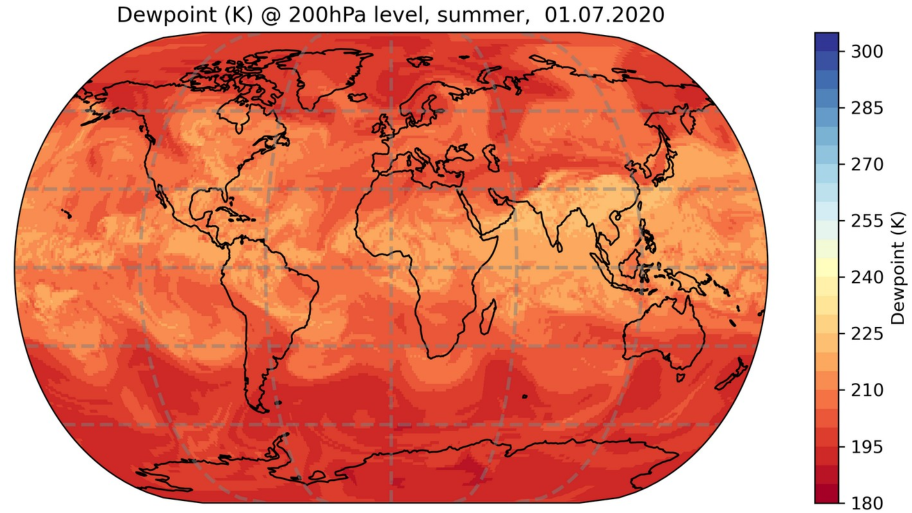
- Important quantity for the water cycle and total moisture transport
- Similar structures as mixing ratios at low levels
- Higher levels do not play large role

DEWPOINT TEMPERATURE

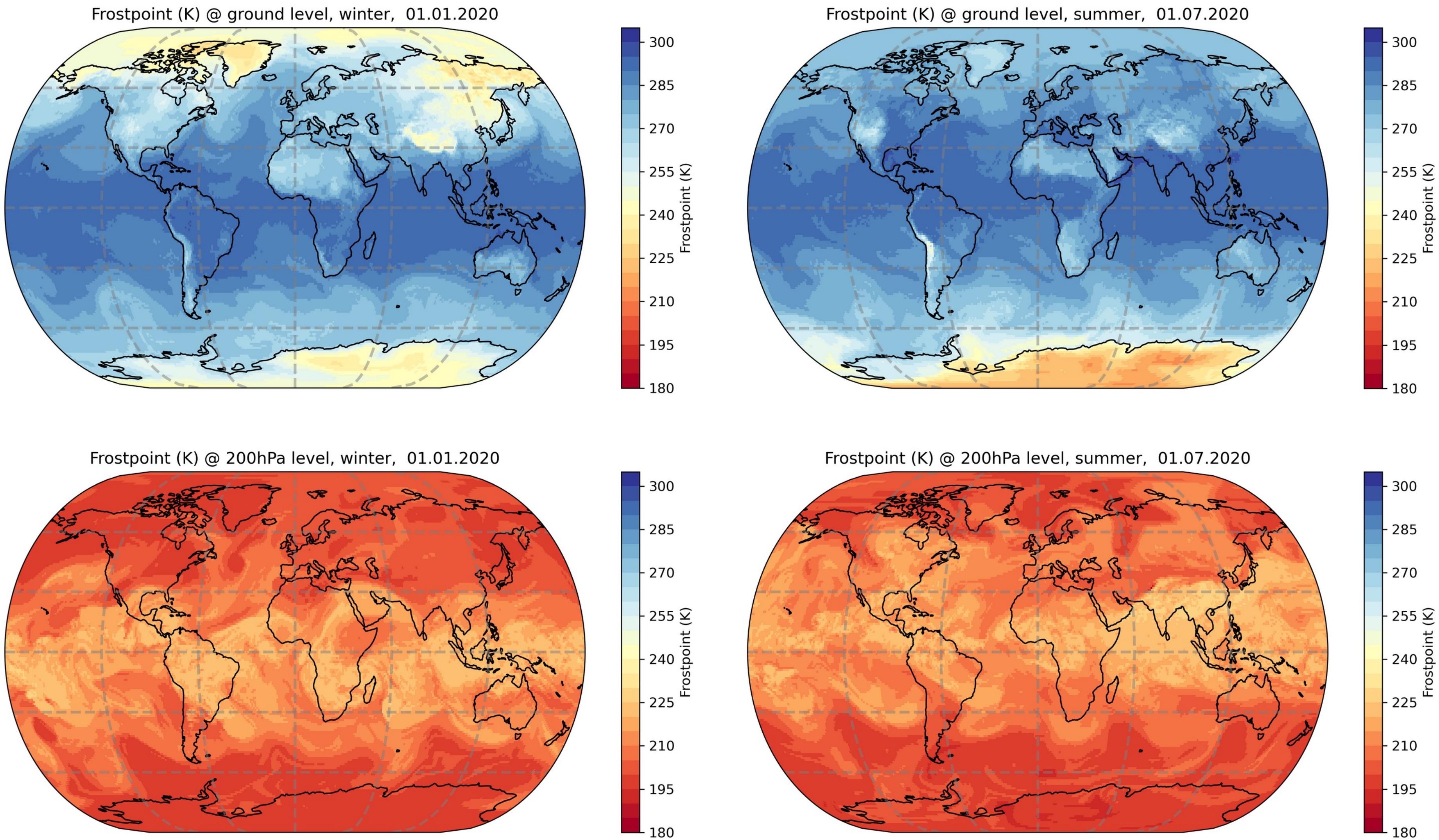




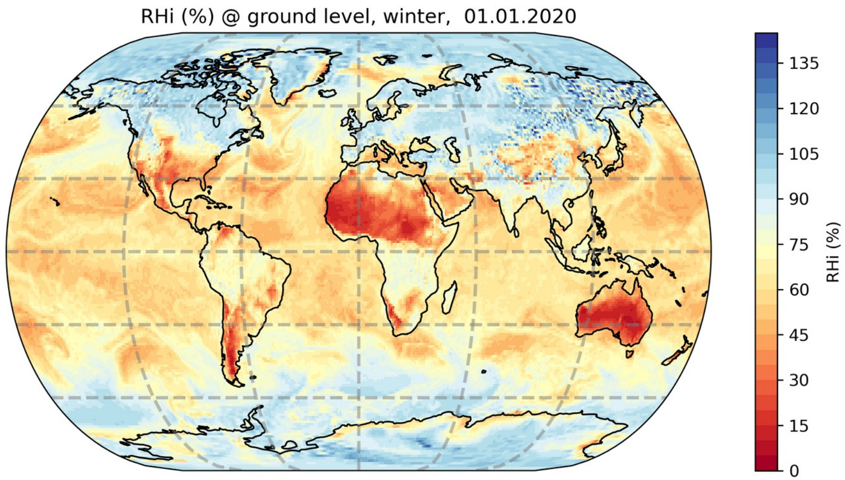


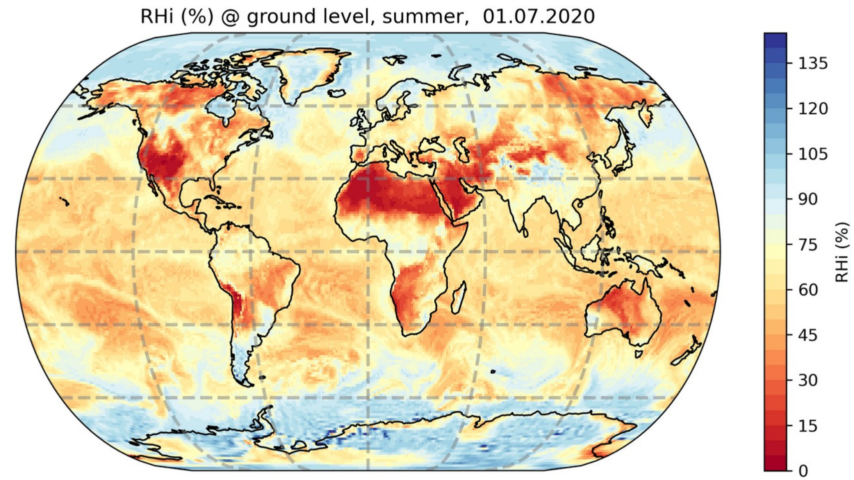


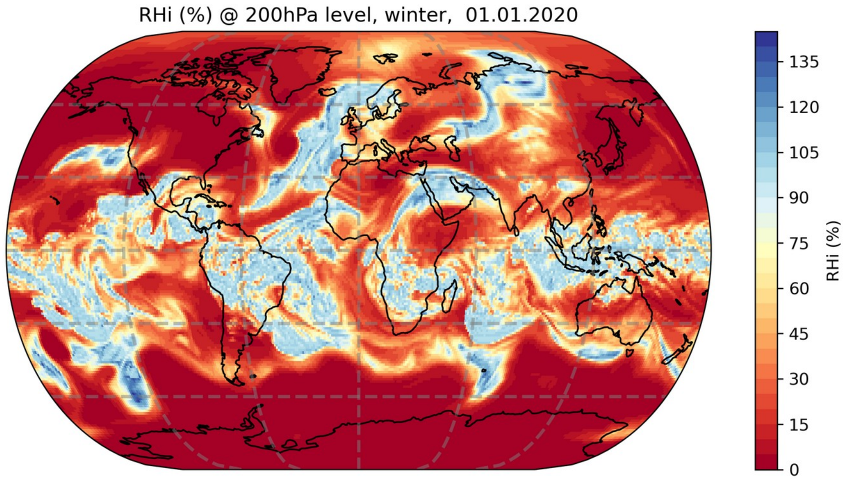
FROSTPOINT TEMPERATURE

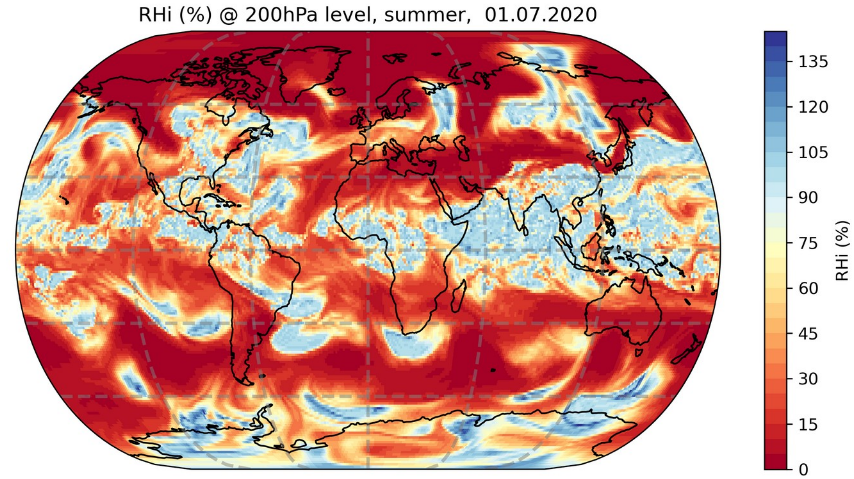


RELATIVE HUMIDITY WRT. ICE

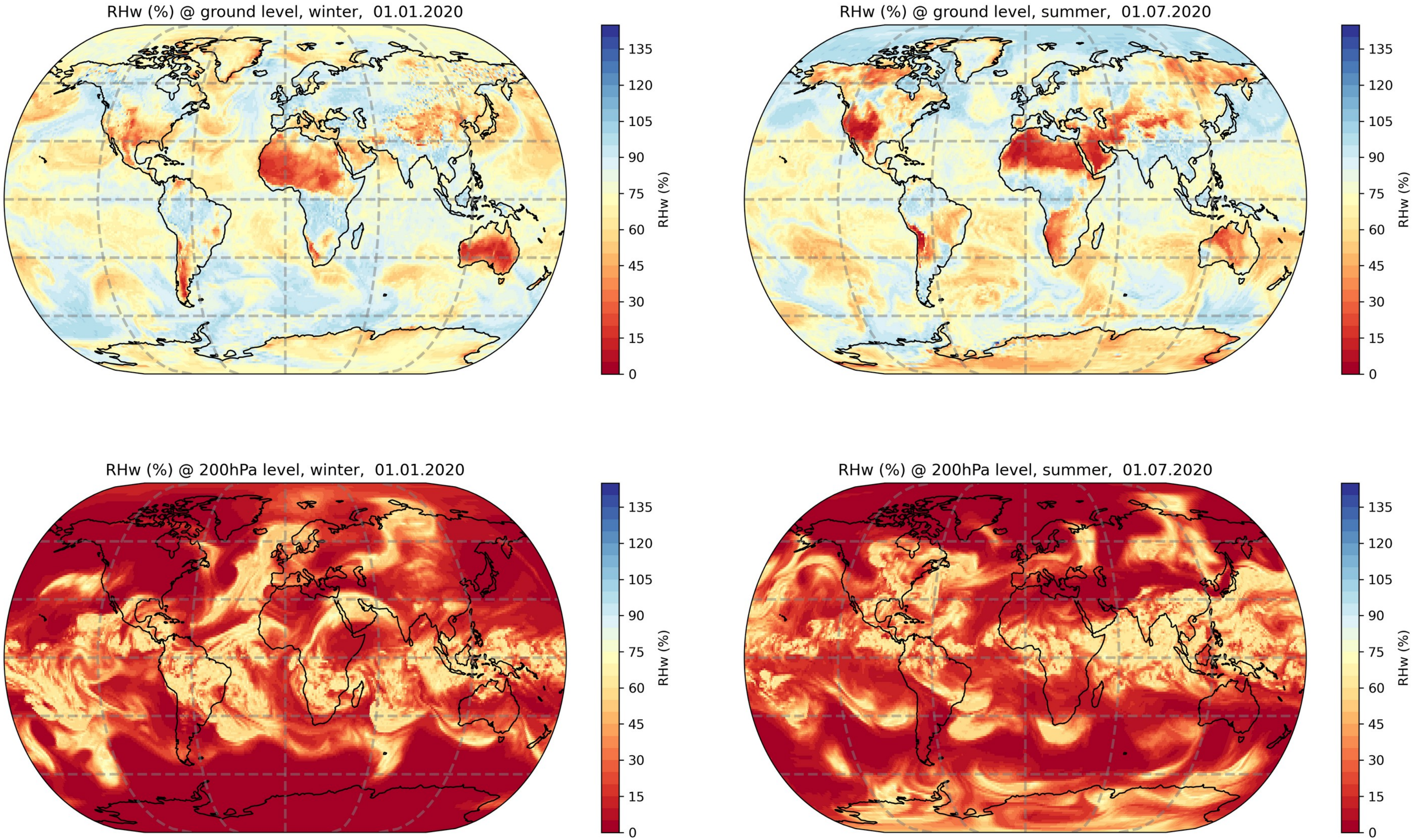








RELATIVE HUMIDITY WRT. WATER



SUBTOPICS

2. Water vapor distribution in the atmosphere

- Horizontal Distribution of Water vapor
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LIFTING CONDENSATION LEVEL

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

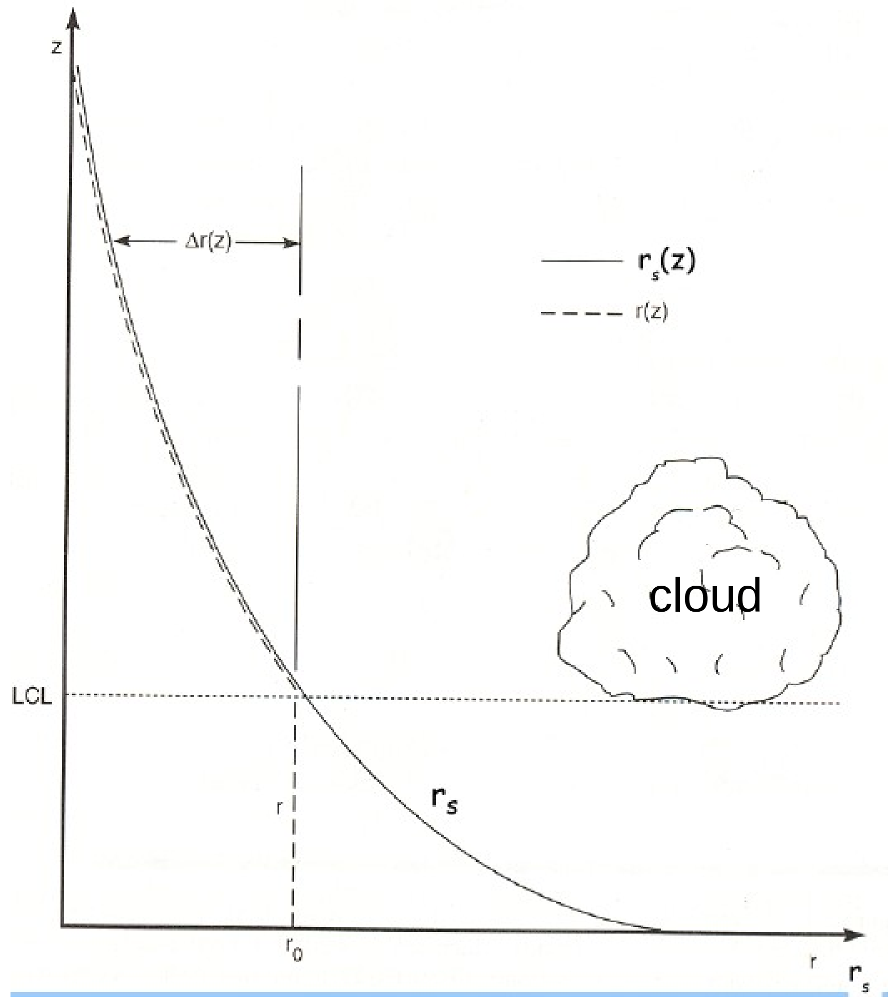
$$r=\frac{m_v}{m_d}=\frac{\rho_v}{\rho_d}=\epsilon\frac{e}{p-e}\approx\epsilon\frac{e}{p}$$

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

$$e_{sw}\approx 611.\,\mathrm{e}^{\frac{L_v}{R_v}\cdot\left(\frac{1}{T_0}-\frac{1}{T}\right)}$$

$$r_s=\epsilon\frac{e_{sw}}{p-e_{sw}}\approx\epsilon\frac{e_{sw}}{p}$$

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



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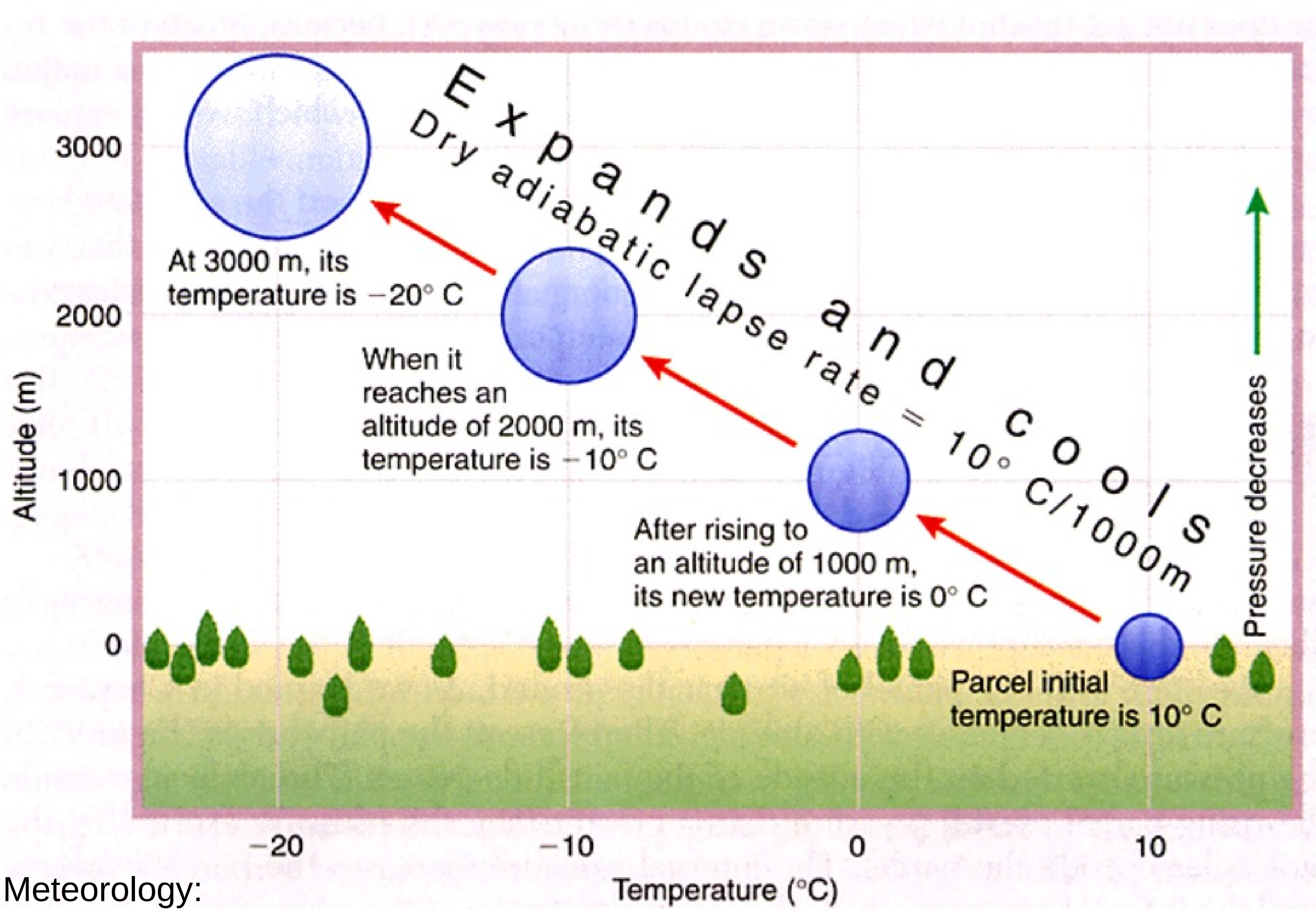
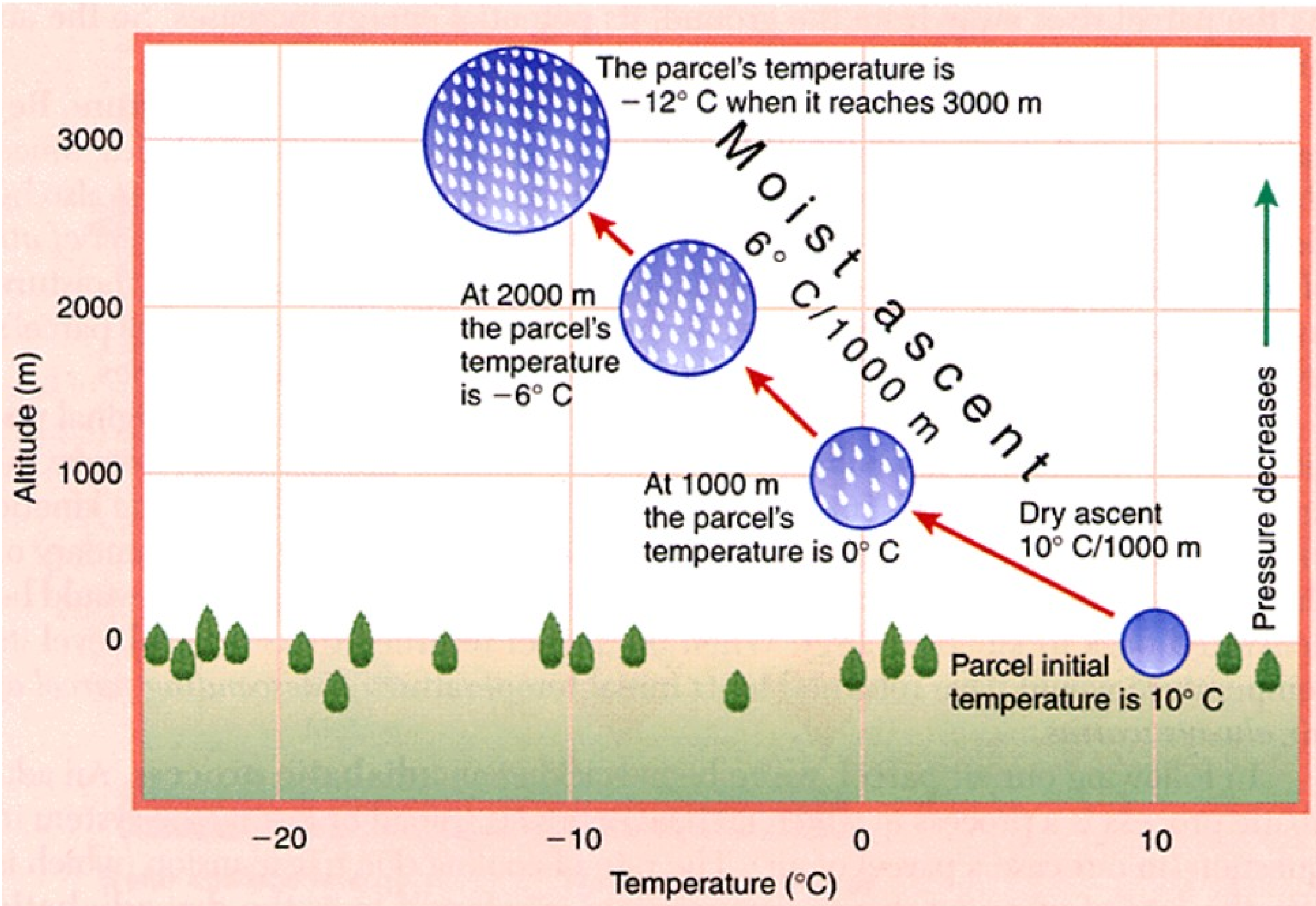
DRY ADIABATIC LAPSE RATE



(from Meteorology:
Understanding the Atmosphere)

MOIST ADIABATIC LAPSE RATE



(from Meteorology: Understanding the Atmosphere)

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EQUIVALENT POTENTIAL TEMPERATURE

- Potential temperature: $\theta = T\left(\frac{p_0}{p}\right)^{R_d/c_p}$

c_p : *Specific heat capacity at constant pressure* $\left(c_p \simeq 1004\ J\ K^{-1}\ kg^{-1},\ dry\ air\right)$
R_d : *Gas konstant* $\left(R \simeq 287\ J\ K^{-1}\ kg^{-1}\right)$

- Equivalent potential temperature:

$$c_p \approx c_p + r_t c_{pw}$$

$$\theta_e = T\left(\frac{p_0}{p}\right)^{R_d/(c_p + r_t c_{pw})} RH_w^{-r_v R_v/(c_p + r_t c_{pw})} \exp\left[\frac{l_v r_v}{(c_p + r_t c_{pw})\,T}\right] \approx \theta \cdot \exp\left(\frac{l_v r_v}{c_p T}\right)$$

c_{pw} : *Specific heat capacity at constant pressure* $\left(c_{pw} \simeq 4184\ J\ K^{-1}\ kg^{-1},\ water\right)$
R_v : *Gas konstant of water vapor* $\left(R_v \simeq 462\ J\ K^{-1}\ kg^{-1}\right)$
$r_{v,t}$: *Mixing ratio of total* $(t) \wedge$ *vapor* (v) *of water*
RH_w : *relative humidity with respect* ¿ *water*
l_v : *Latent heat of vaporization*

EQUIVALENT POTENTIAL TEMPERATURE

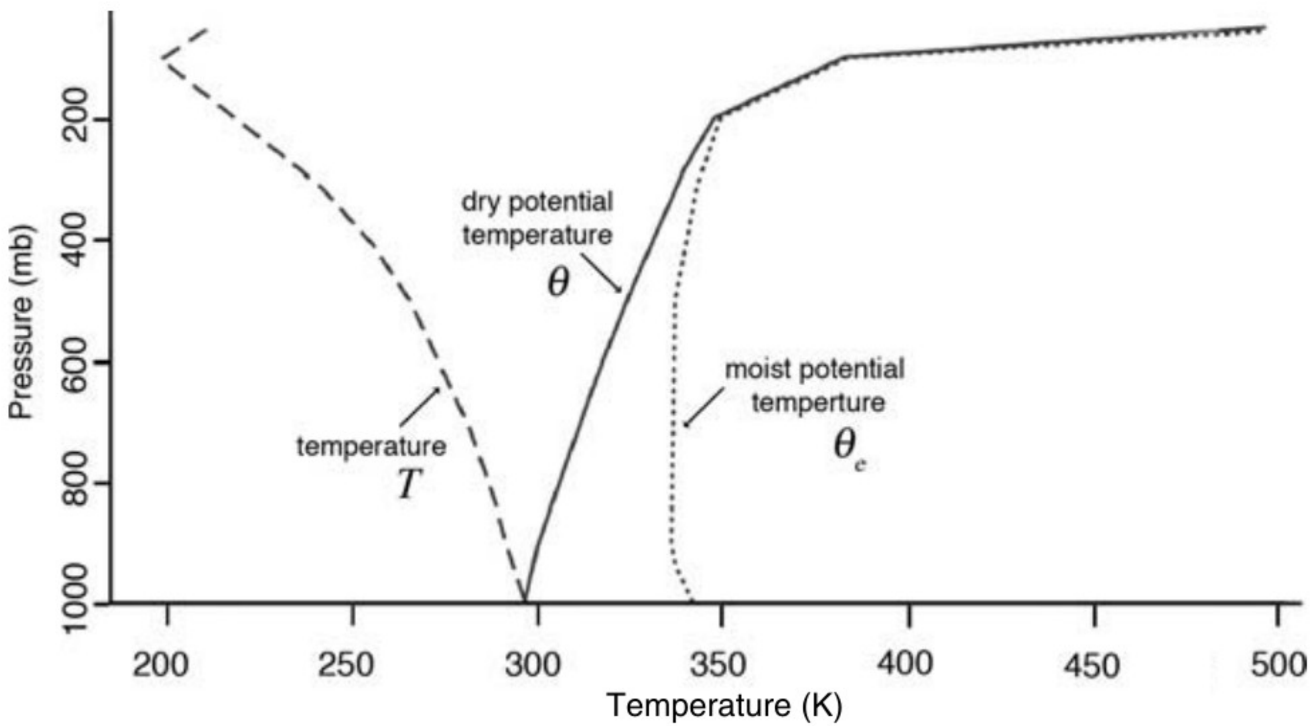

FIGURE 4.9. Climatological atmospheric temperature T (dashed), potential temperature θ (solid), and moist potential temperature θ_e (dotted) as a function of pressure, averaged over the tropical belt ±30°

Marshall & Plumb: Atmosphere, Ocean and Climate Dynamics

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EQ. POT. TEMP. (NORMAND'S RULE)

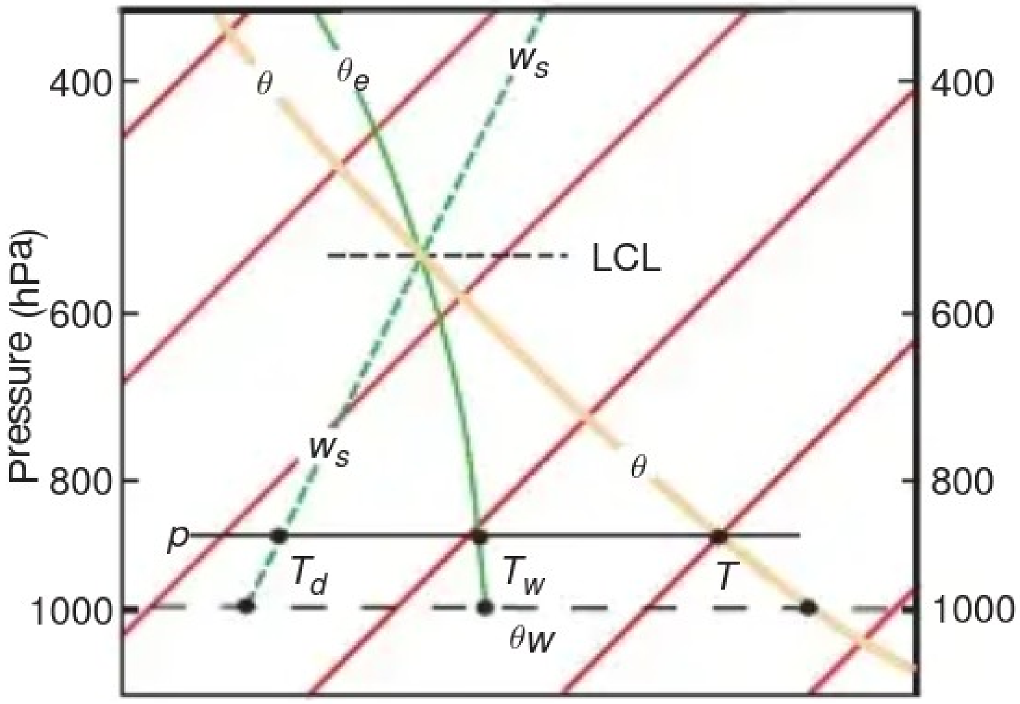

Fig. 3.11 Illustration of Normand's rule on the skew $T - \ln p$ chart. The orange lines are isotherms. The method for determining the wet-bulb temperature (T_w) and the wet-bulb potential temperature (θ_w) of an air parcel with temperature T and dew point T_d at pressure p is illustrated. LCL denotes the lifting condensation level of this air parcel.

θ Conserved for dry adiabatic motions

θ_e Conserved for saturated adiabatic motions

w_s saturation mixing ratio crossing T_d at surface pressure

from Wallace and Hobbs

LAPSE RATE DEPENDENCE ON TEMP.

- Dry adiabatic lapse rate is constant 10˚C/km.
- Moist adiabatic lapse rate is NOT a constant. It depends on the temperature of saturated air parcel.
- The higher the air temperature, the smaller the moist adiabatic lapse rate.

→ When warm, saturated air cools, it causes more condensation (and more latent heat release) than for cold, saturated air.

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TEMPERATURE AND HUMIDITY DEPENDENCE OF RH

Definition of relative humdity:

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

with definition of specific humidity

$$q \approx \epsilon \frac{e}{p}$$

Relative variation of rh:

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

Relative variation of q_s:

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

Assume !isobar!

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

Clausius-Claperon-Eq.:

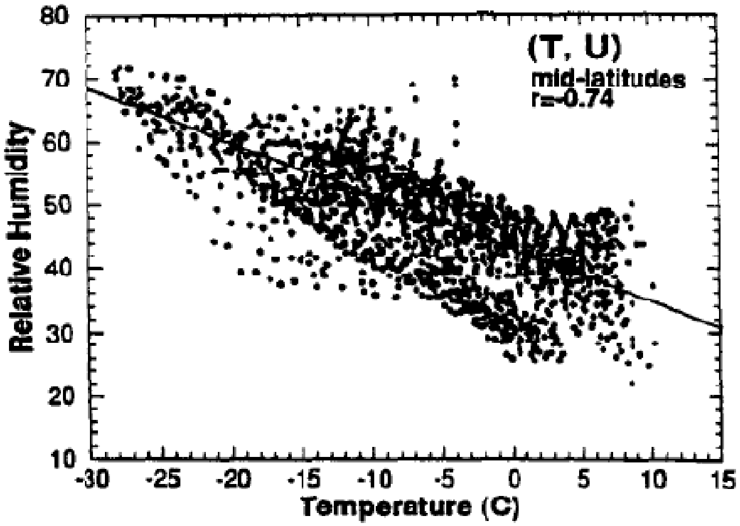
$$\frac{de_s}{e_s} = \left(\frac{L}{R_v T}\right) \frac{dT}{T}$$

For tempature range T = 260-285K, using L_v=2500 J/g and R_v=466.5J/kg/K

$L/R_v T = 18.9$

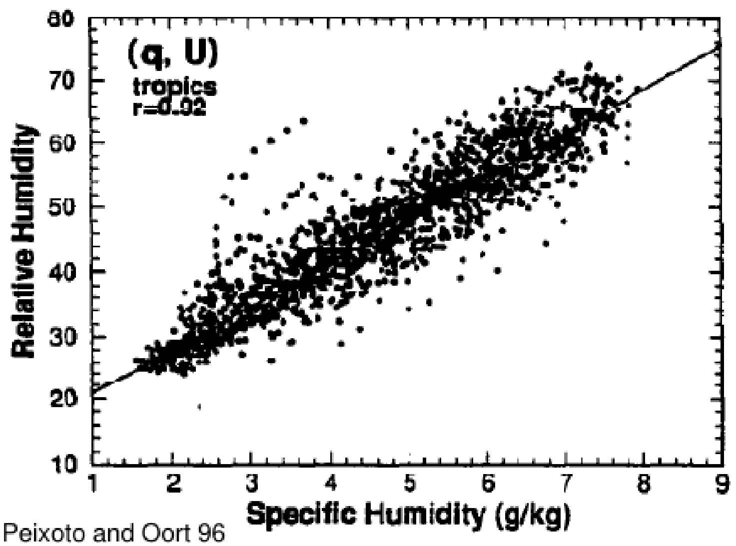
$$\frac{\Delta rh}{rh} = \frac{\Delta q}{q} - 19 \frac{\Delta T}{T}$$

TEMPERATURE AND HUMIDITY DEPENDENCE OF RH



Midlatitudes
ΔRH due to ΔT

Temperature dependence



Peixoto and Oort 96

Tropics
ΔRH due to Δq

Tranport dependence

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

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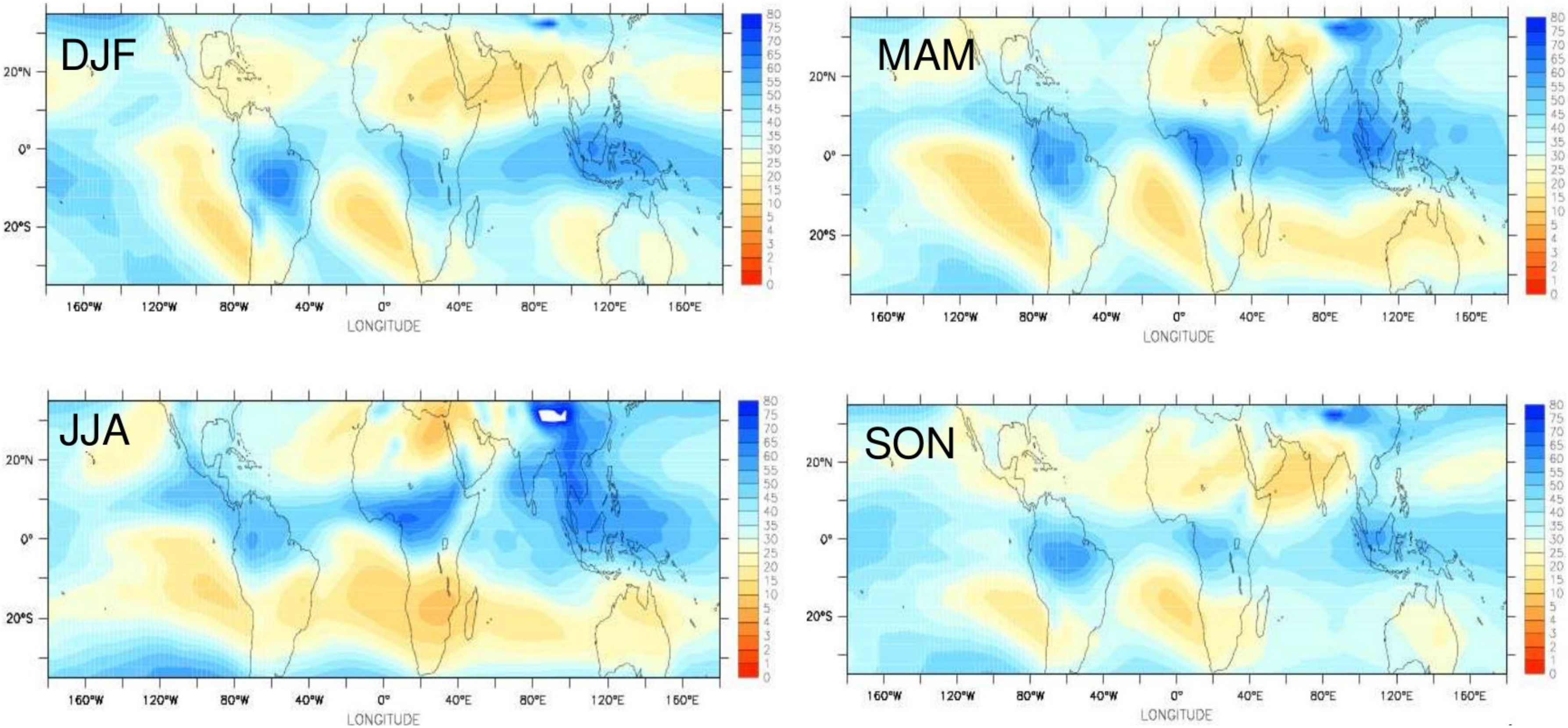
HUMIDITY IN THE FREE TROPOSPHERE

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 ?

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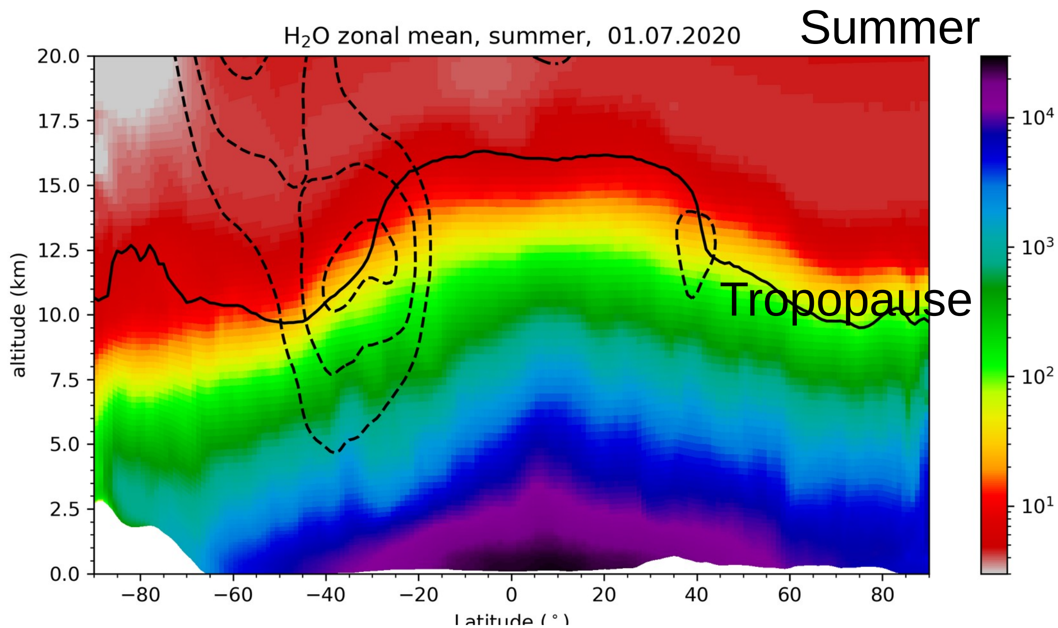
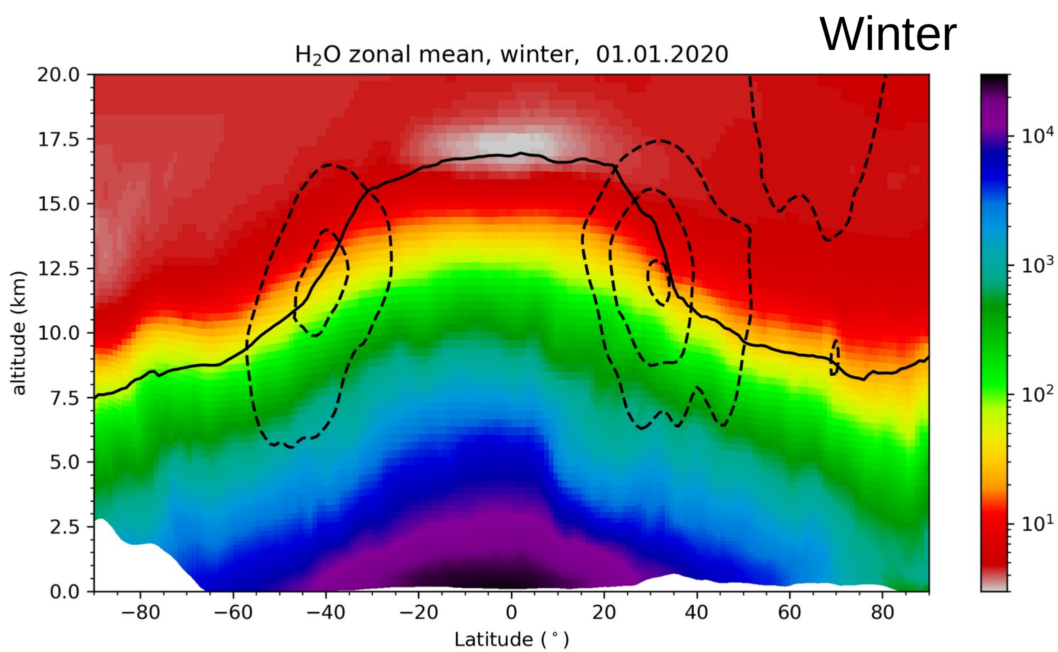
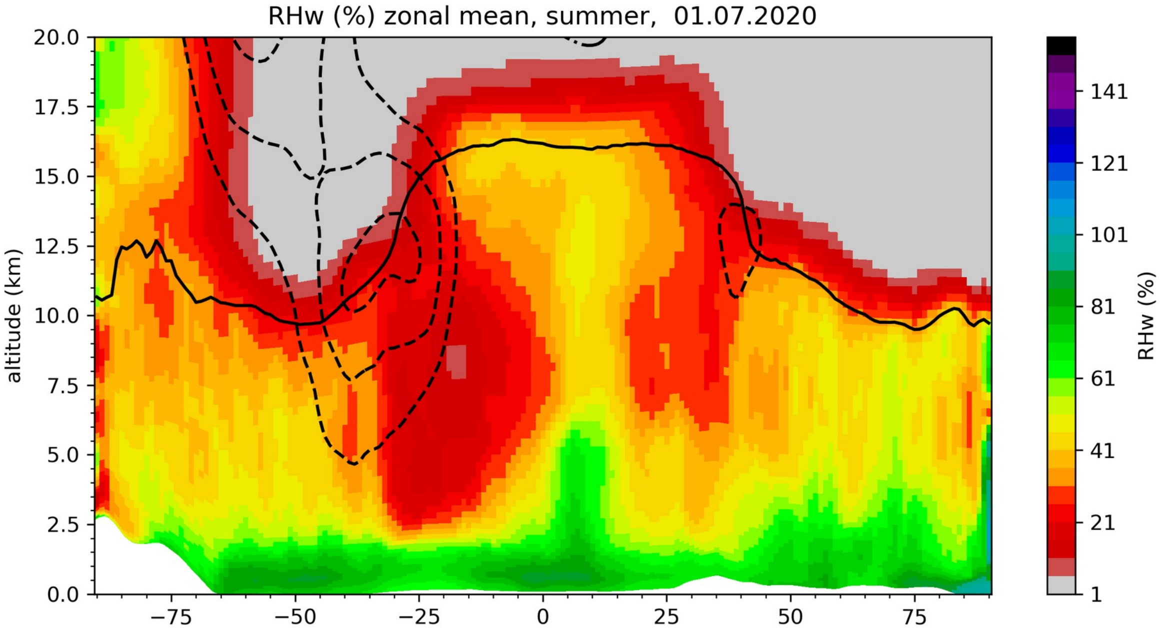
VERTICAL DISTRIBUTION OF WATER VAPOR

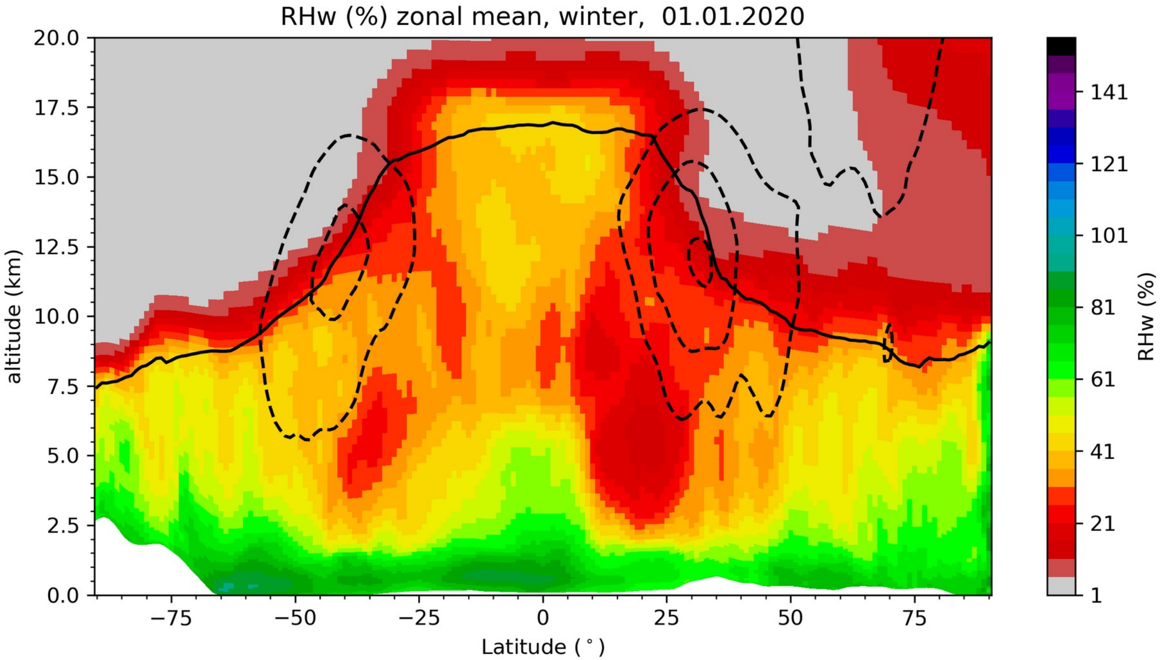
- Vertical distribution of water vapor in the atmosphere strongly (exponentially) dependent on temperature.
- **Large difference between Troposphere (moist) and Stratosphere (dry); four order of magnitude between the surface and the tropical tropopause.**
- Dry conditions in the winter pole stratosphere (dehydration due to low temperatures in the polar vortex)
- Dry conditions in the tropical lower stratosphere (dehydration due to cooling by convection)





RELATIVE HUMIDITY WRT. WATER





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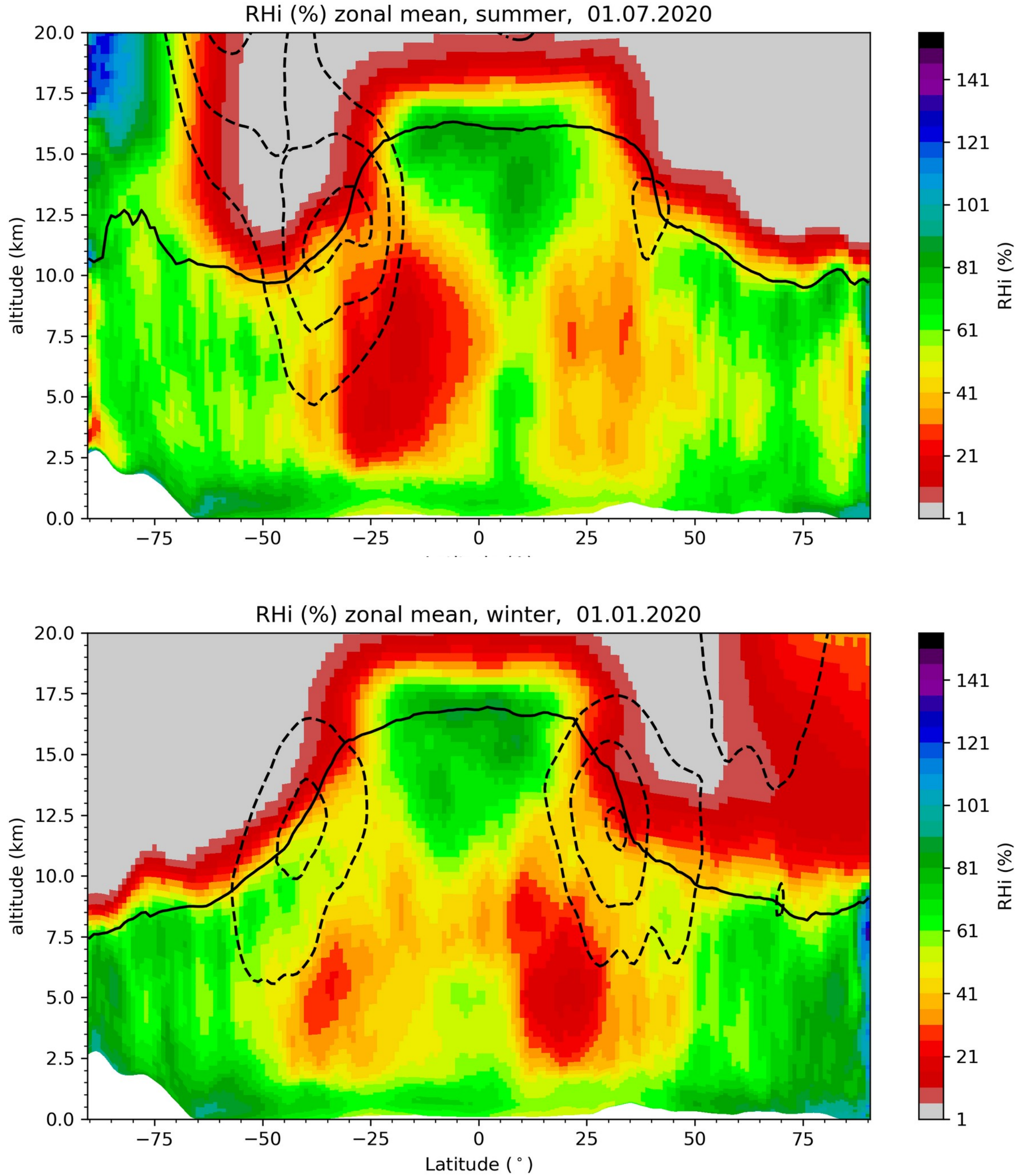

RELATIVE HUMIDITY WRT. ICE

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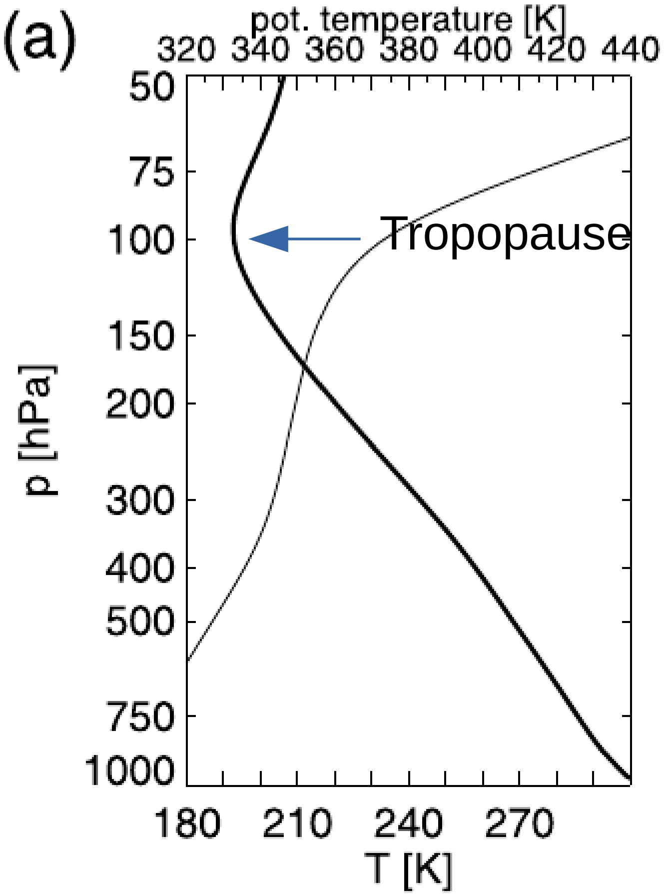
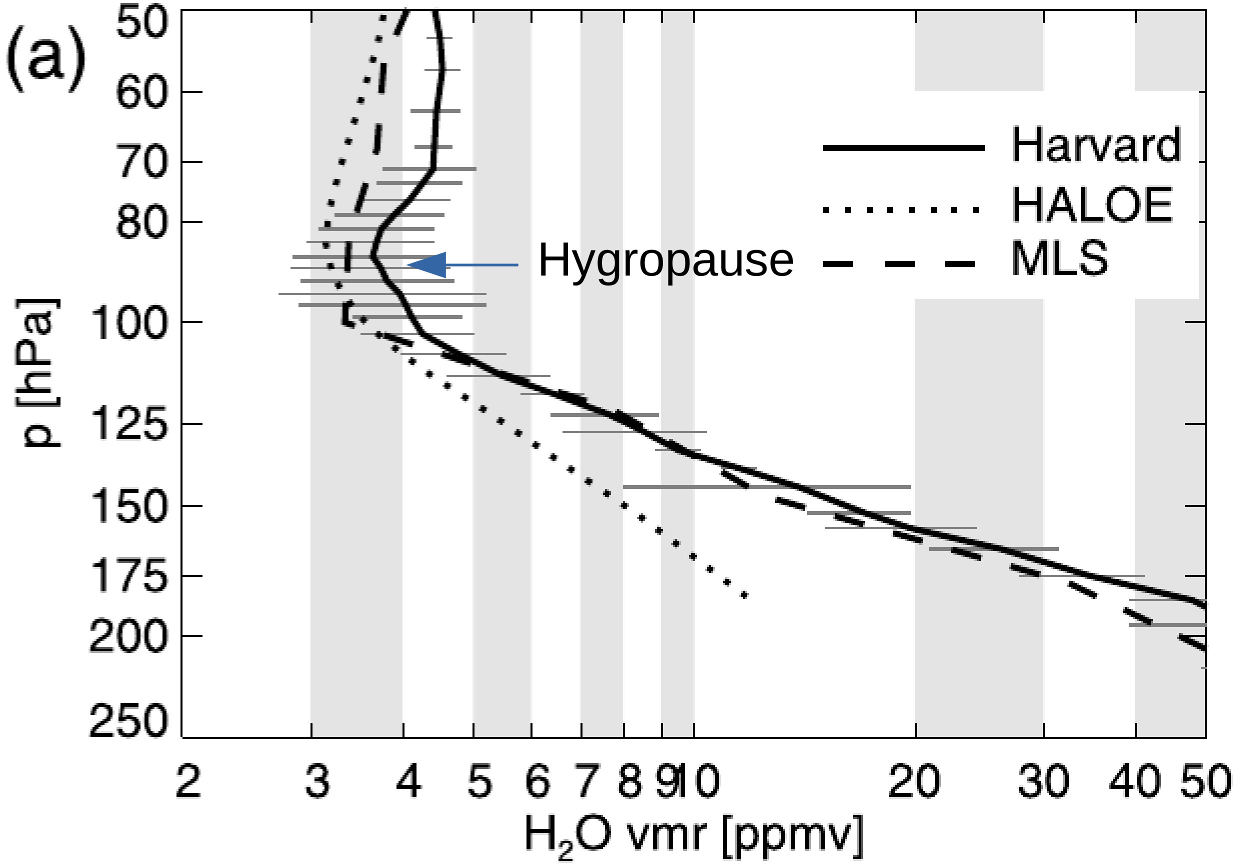
VERTICAL WATER VAPOR DISTRIBUTION

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

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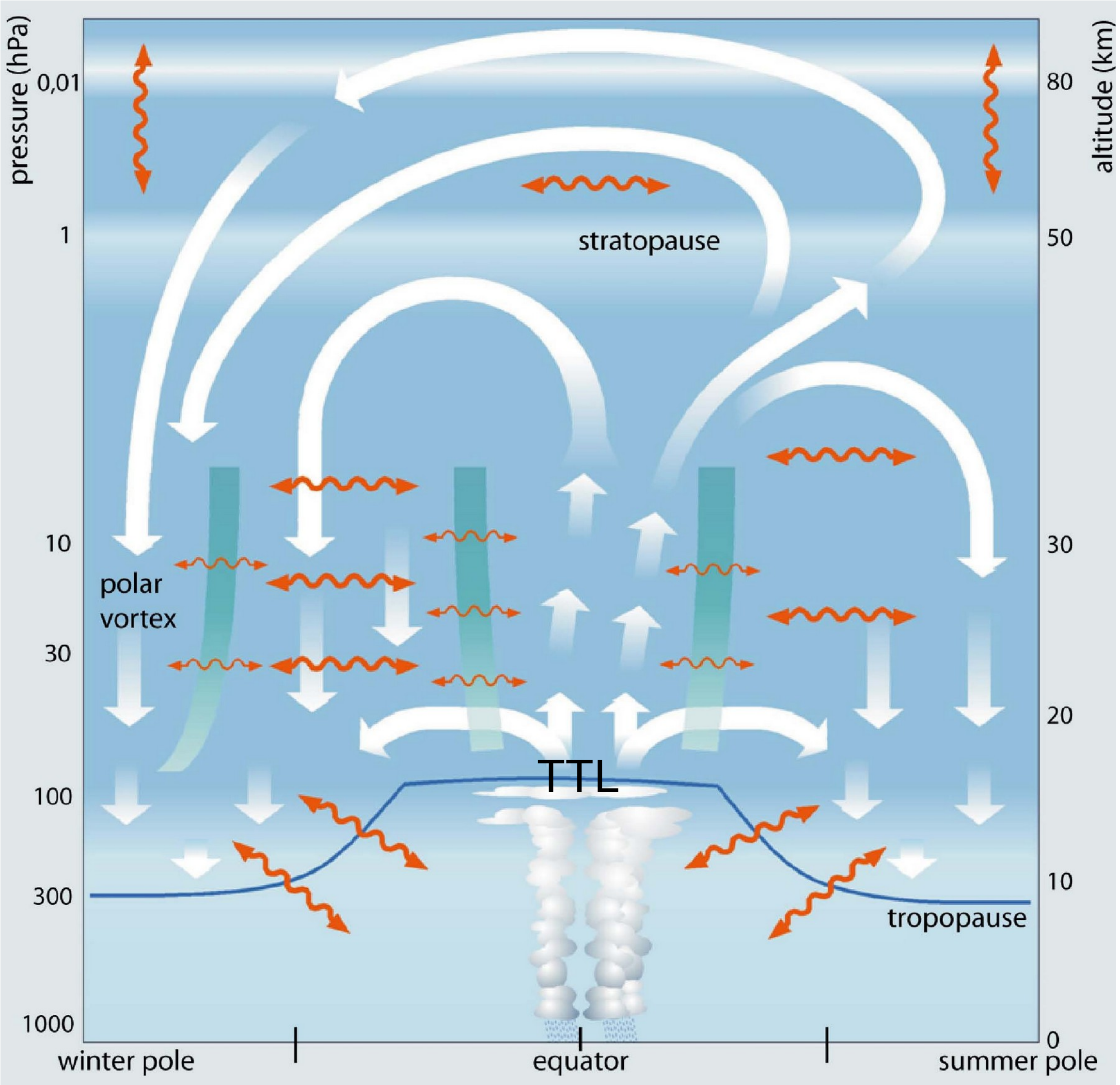
BREWER-DOBSON CIRCULATION



The B-D circulation represents Lagrangian-mean motion in the stratosphere and mesosphere from the tropics into polar regions.

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

Boenisch et al., ACP, 2011

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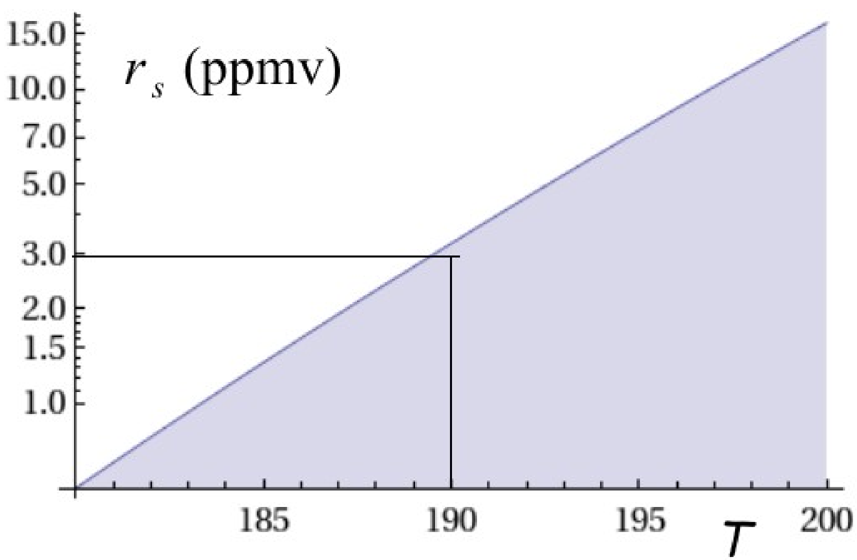
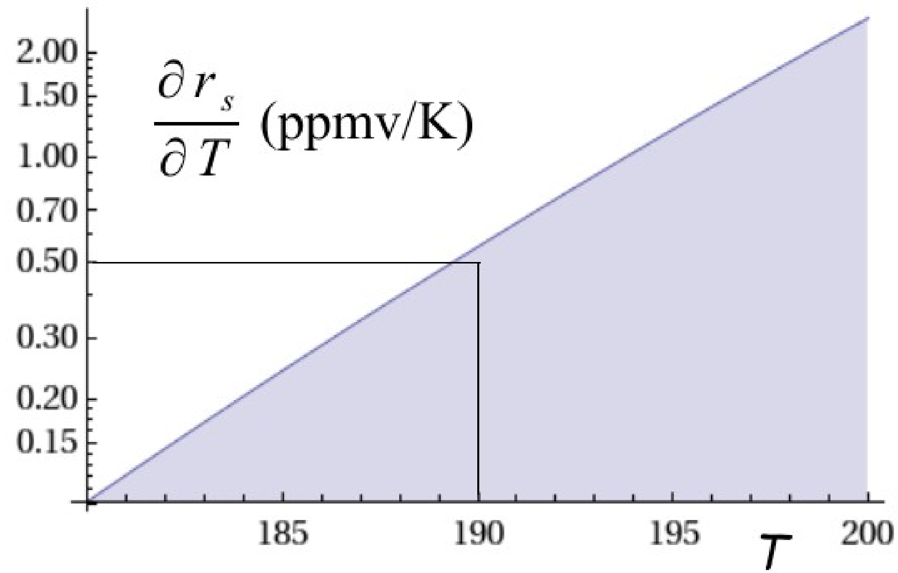
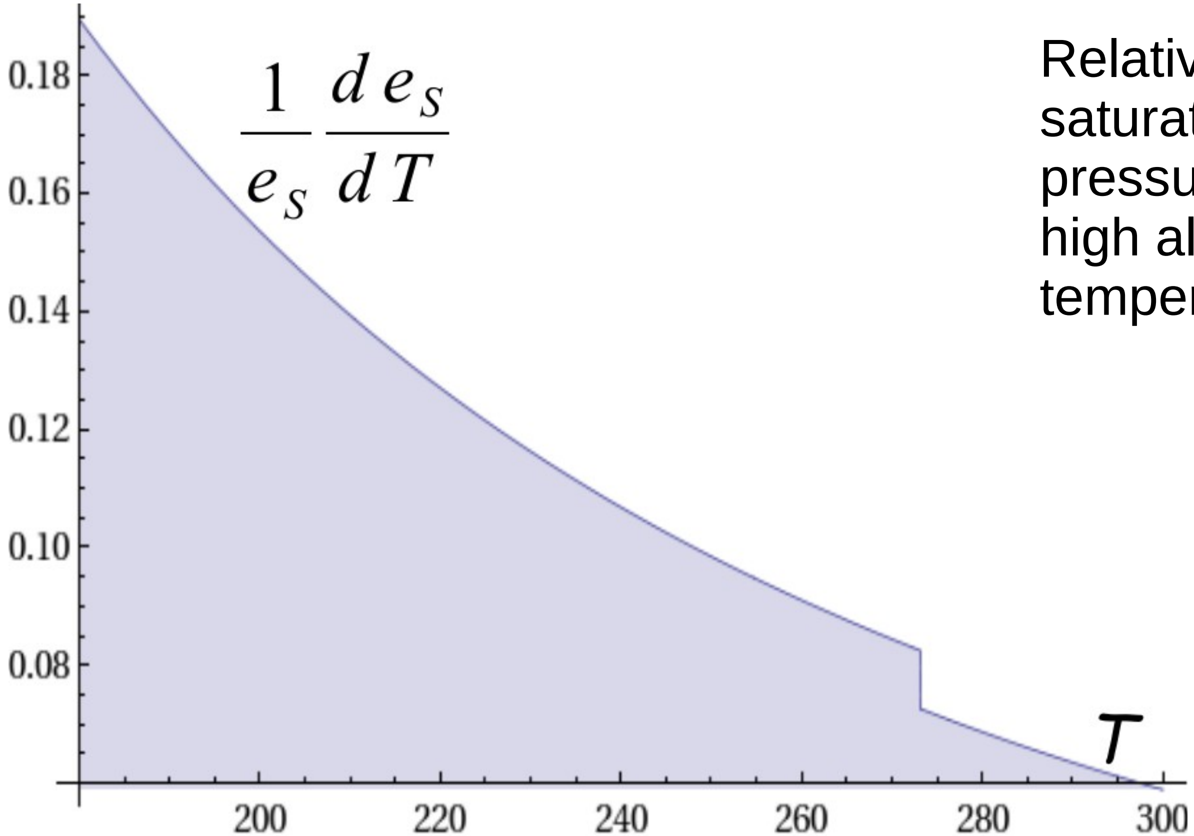
SATURATION MIXING RATIO AT THE TROPICAL TROPOPAUSE





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

SATURATION MIXING RATIO AT THE TROPICAL TROPOPAUSE



Temperature (K)

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

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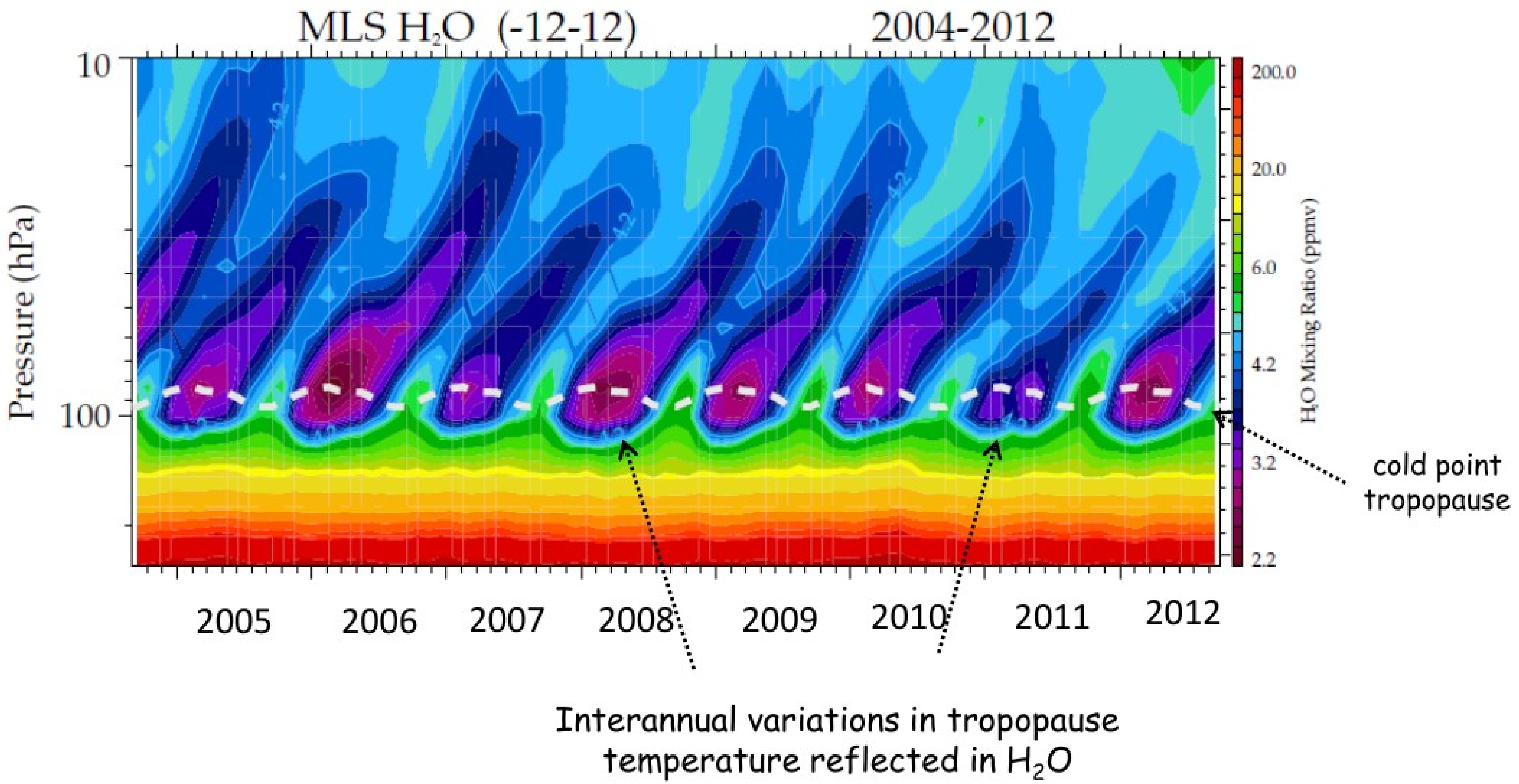
VERITCAL TROPICAL TAPE RECORDER



Nominal stratospheric values of water vapor set by the tropical cold point temperature!

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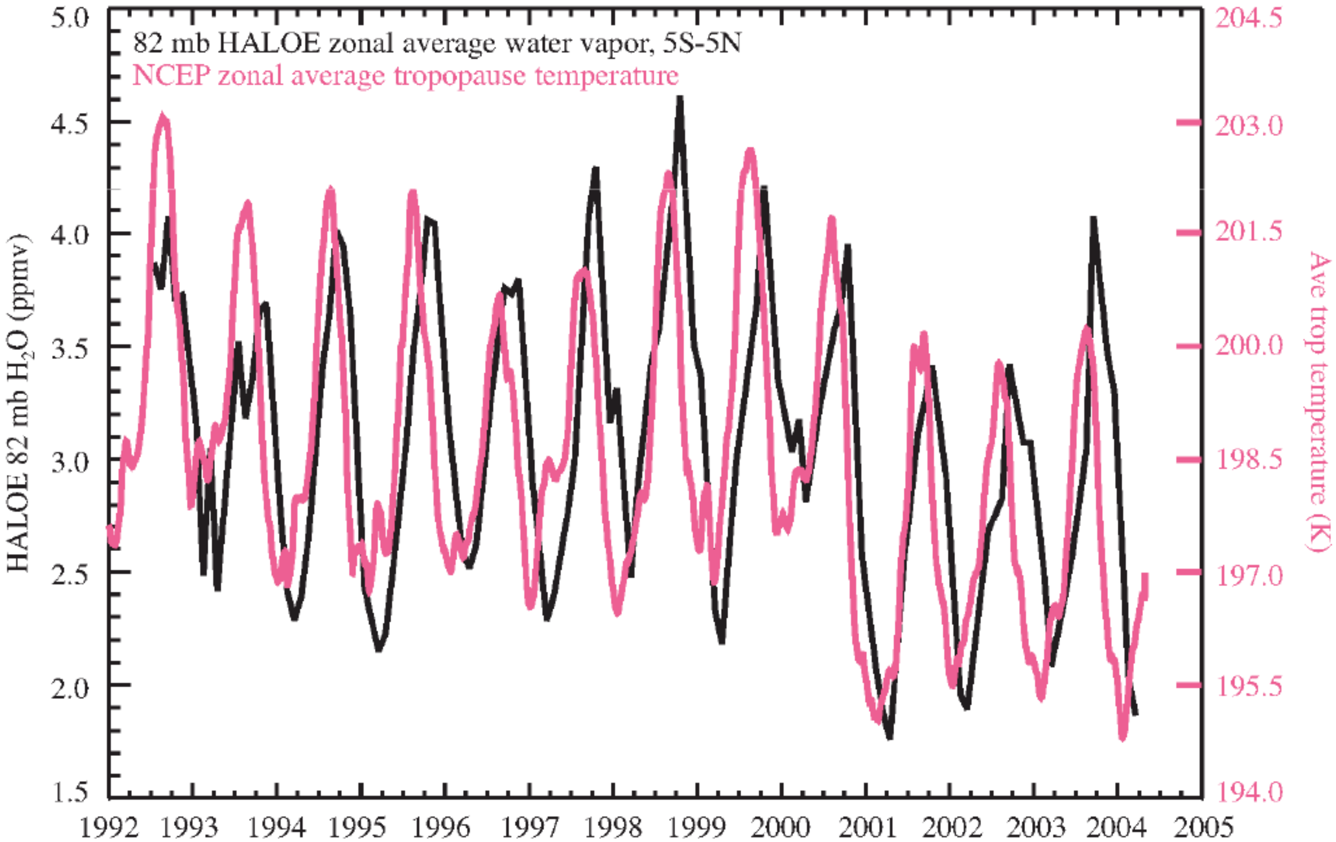
TROPICAL WATER VAPOR VS. TEMPERATURE

Annual cycle in the entry value of water vapor due to an annual cycle in tropical cold point (or near tropopause temperatures).



Randel et al., 2008

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- Methane oxidation in the upper stratosphere

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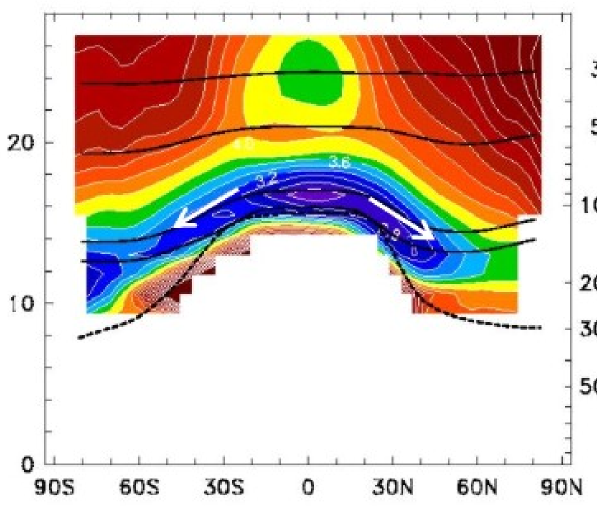
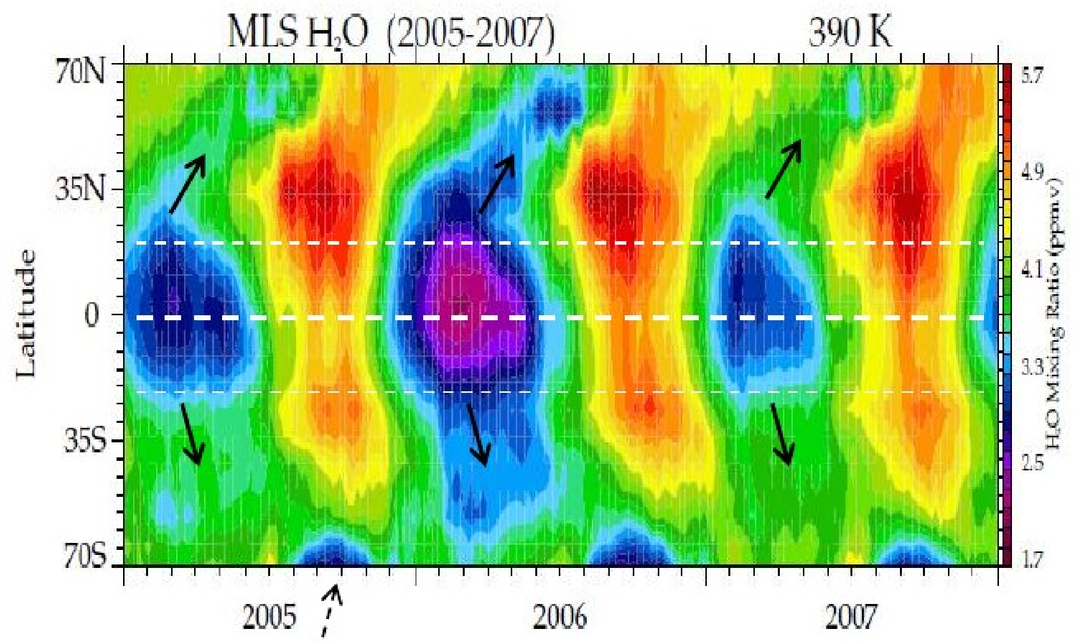
LOWER STRATOSPHERE HORIZONTAL TAPE RECORDER



quasi-horizontal transport
in lower stratosphere, approximately
following 400 K isentrope

3 years from MLS observations



dehydration in
Antarctic polar vortex

Tropical dehydration zone is ~20 N-S

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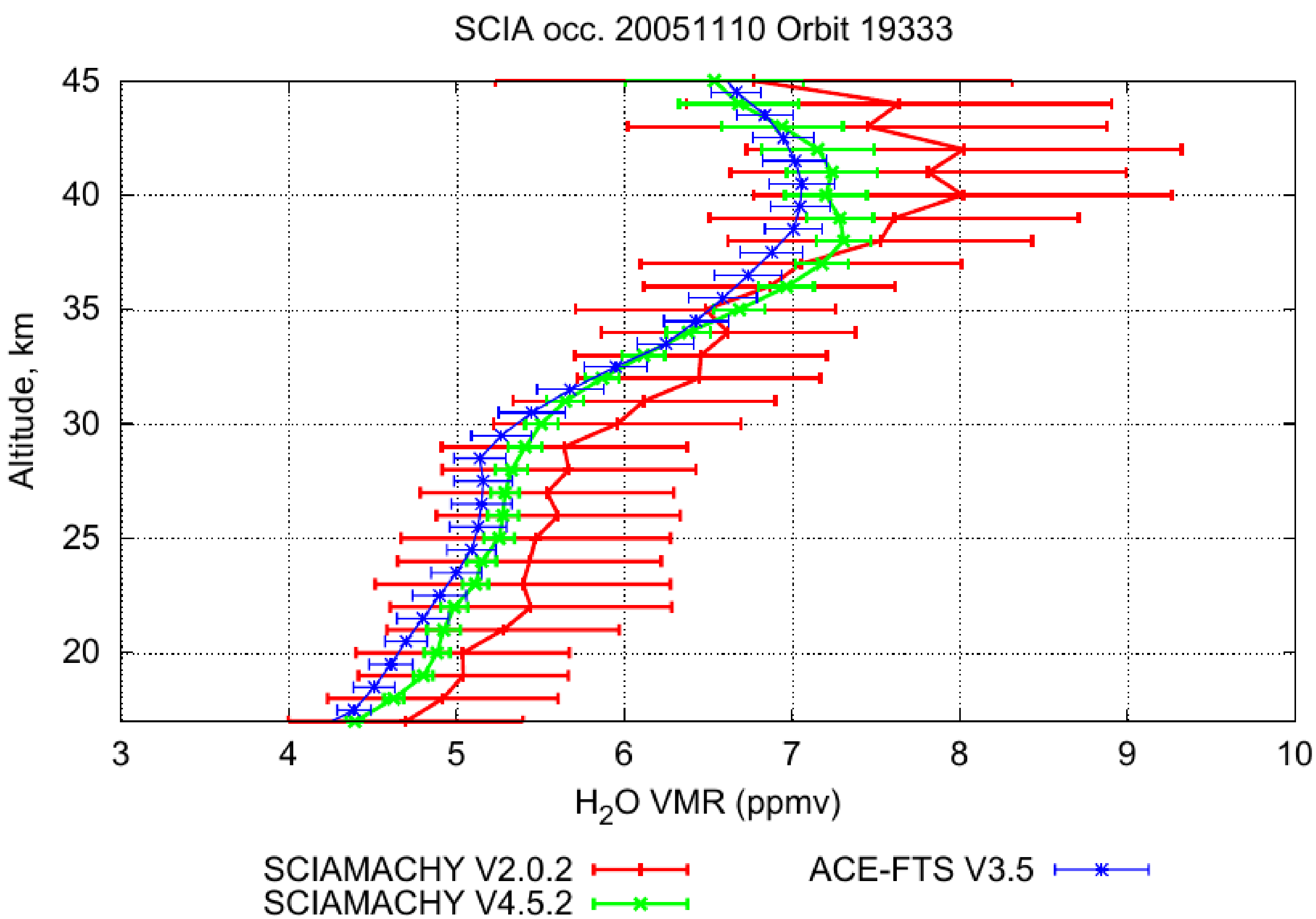
SUBTOPICS

2. Water vapor distribution in the atmosphere

- Horizontal Distribution of Water vapor
- Lifting Condensation level
- Dry/Moist Adiabatic lapse rate
- Equivalent Potential Temperature
- Temperature and humidity dependence of rel. humidity
- Vertical Distribution of Water vapor
- Saturation mixing ratio at the tropical tropopause
- Vertical Tropical tape recorder
- Lower stratosphere horizontal tape recorder
- **Methane oxidation in the upper stratosphere**

WATER VAPOR IN THE UPPER STRATOSPHERE



- Satellite observations show increase of water vapor mixing ratio with altitude.
- In the mesophere, there is photolysis of water vapor, so the vertical gradient reverses.

Noel et al., 2018

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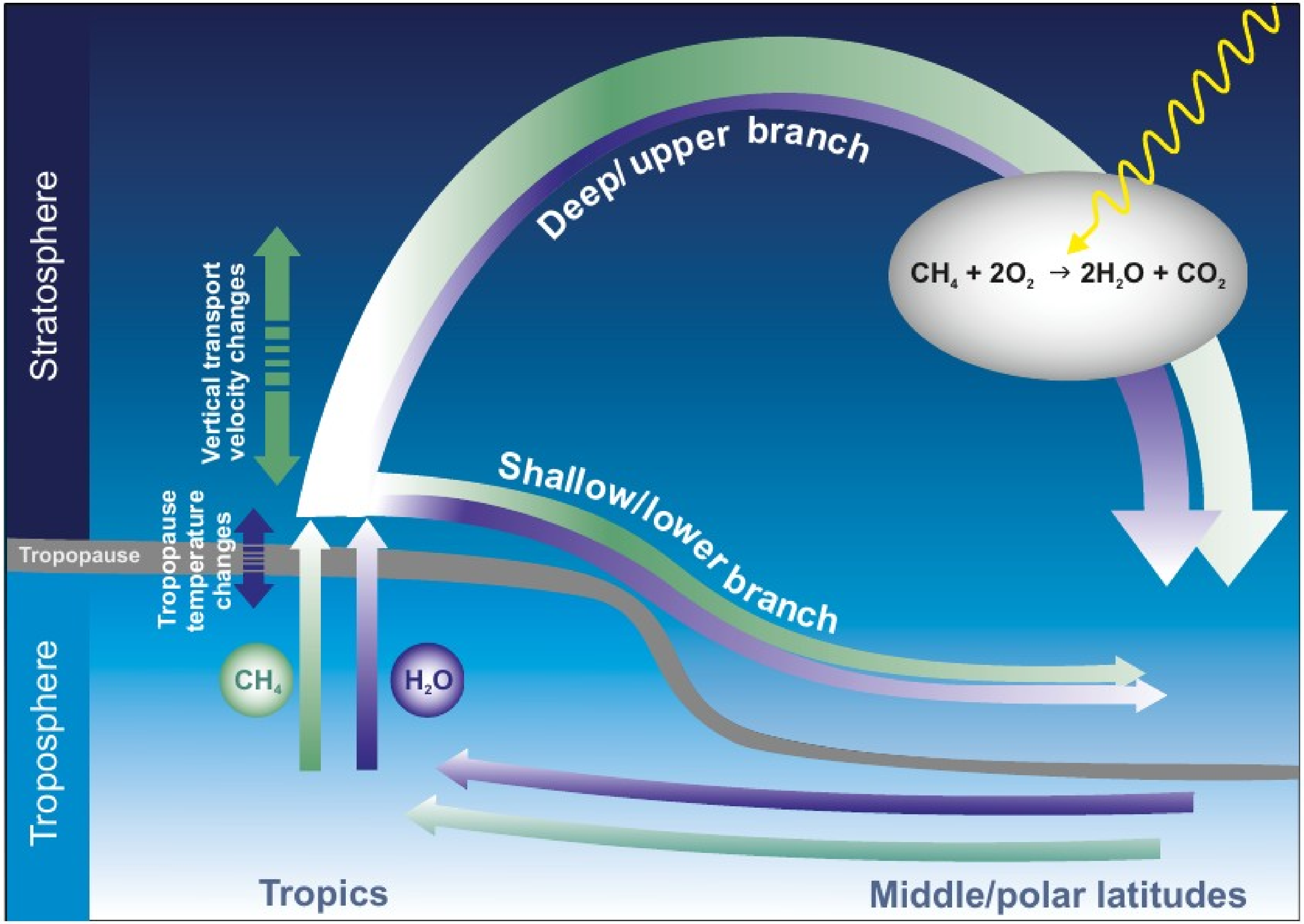
METHANE OXIDATION



Noel et al., 2018

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METHANE OXIDATION

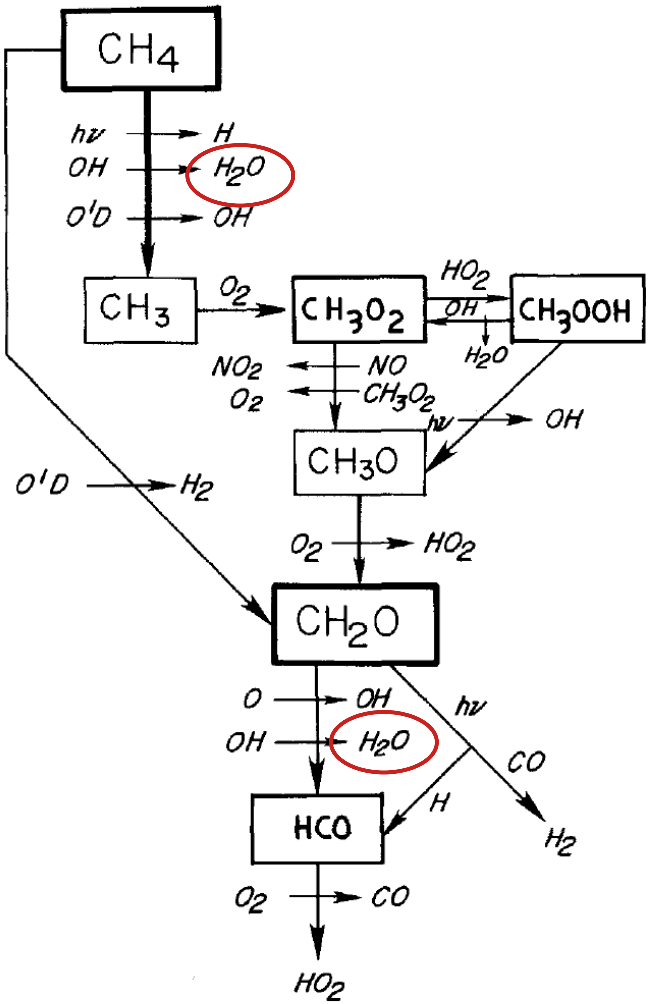

Figure 3. Diagram of the methane oxidation chain of photochemical reactions.

Methane is destroyed by two mechanisms in the stratosphere:

$CH_4 + OH \rightarrow CH_3 + H_2O$
$CH_4 + O(^1D) \rightarrow CH_3 + OH$

Net: $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$.

$[H_2O] + 2[CH_4] = \text{constant}$

Sum of volume mixing ratios $[H_2O] + 2[CH_4]$, referred to as potential water (PW), is expected to be roughly conserved following a stratospheric parcel.

LeTexier et al, 1988

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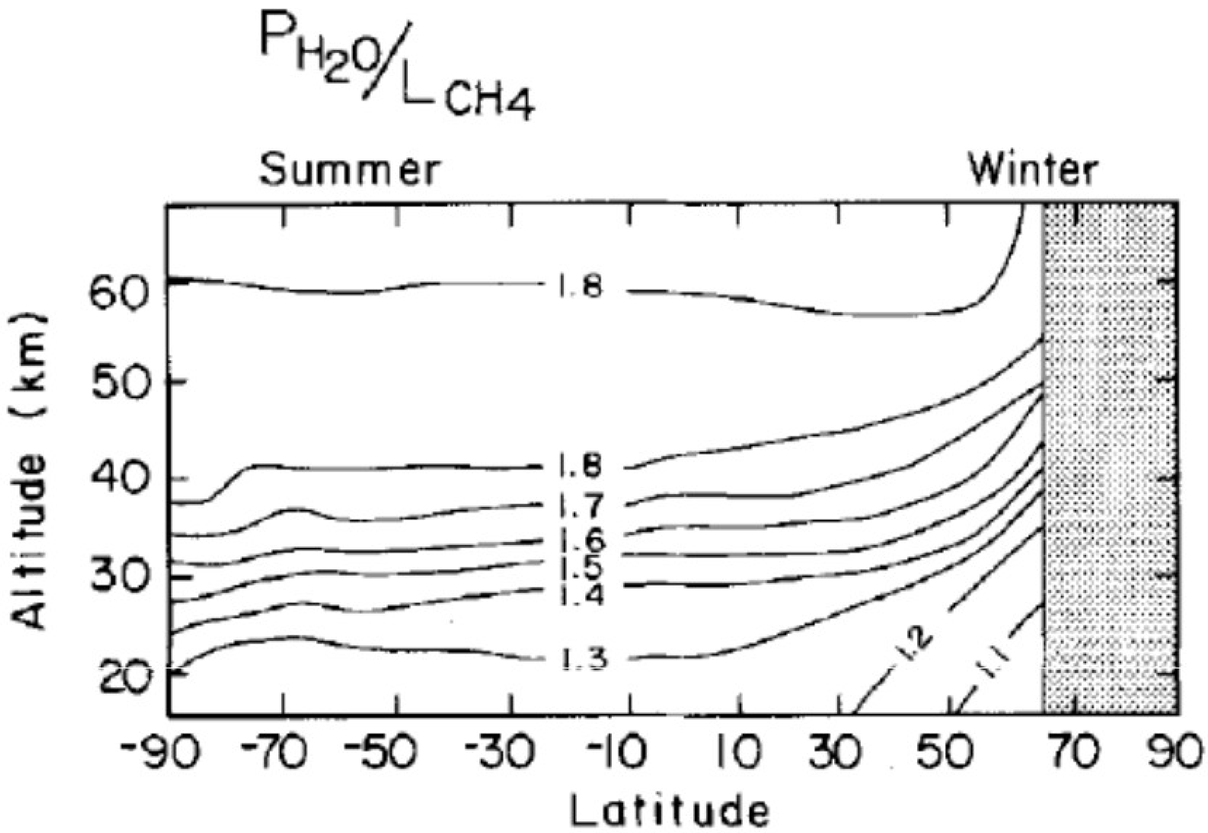
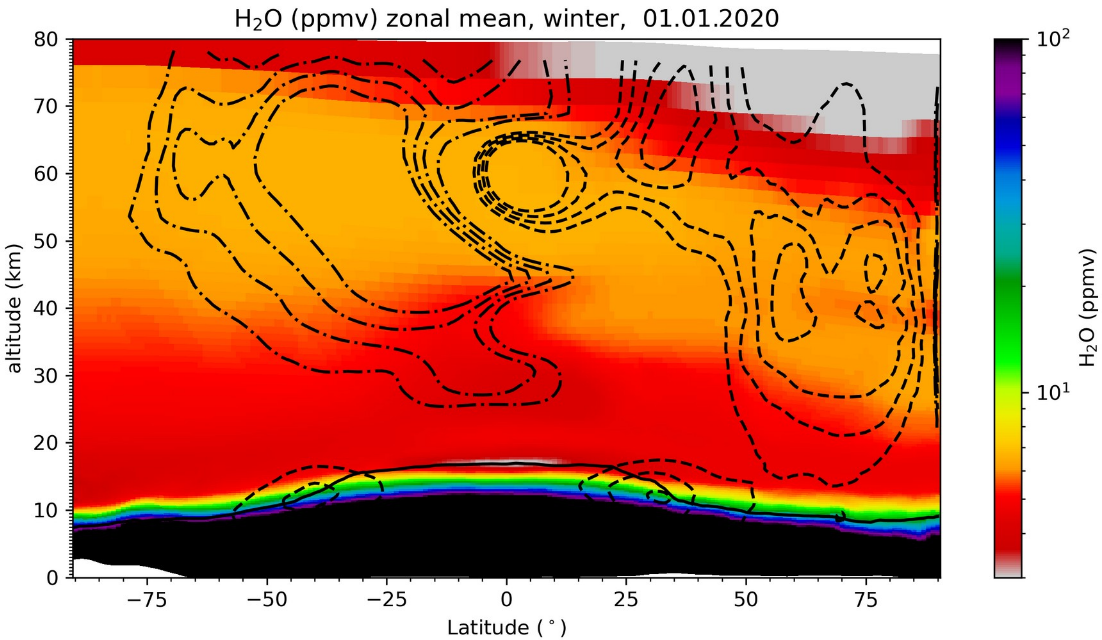
METHANE OXIDATION

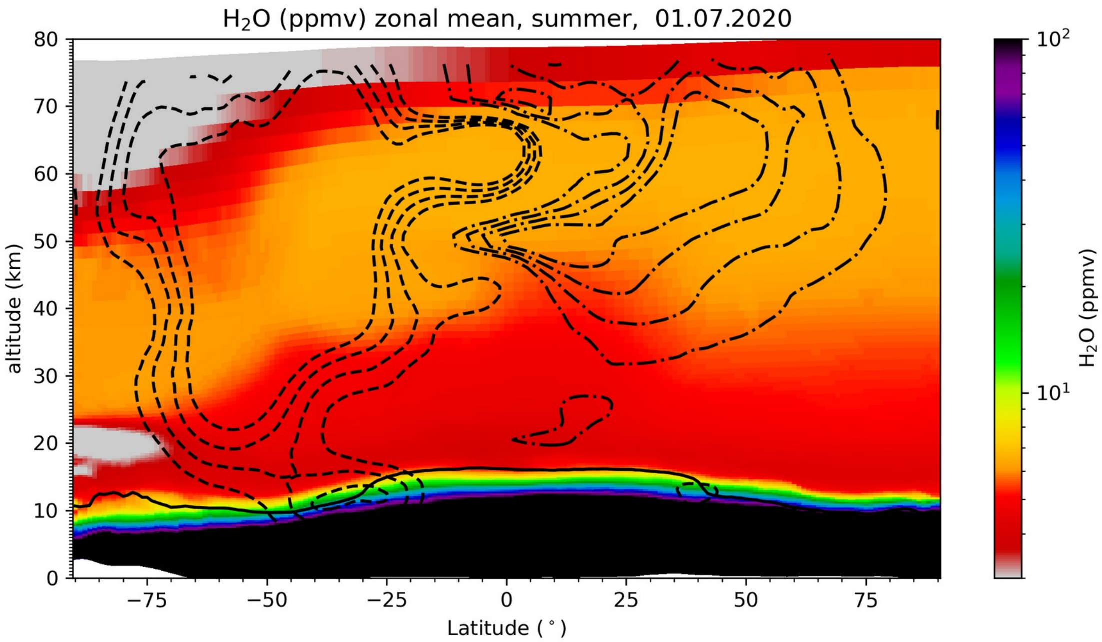


LeTexier et al, 1988

How many water molecules come from the destruction of 1 methane molecule as a function of latitude/altitude.

VERTICAL DISTRIBUTION OF WATER VAPOR IN THE STRATOSPHERE





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