The Zugspitze water vapor radiative closure experiment.

Part 1: basic idea and implementation

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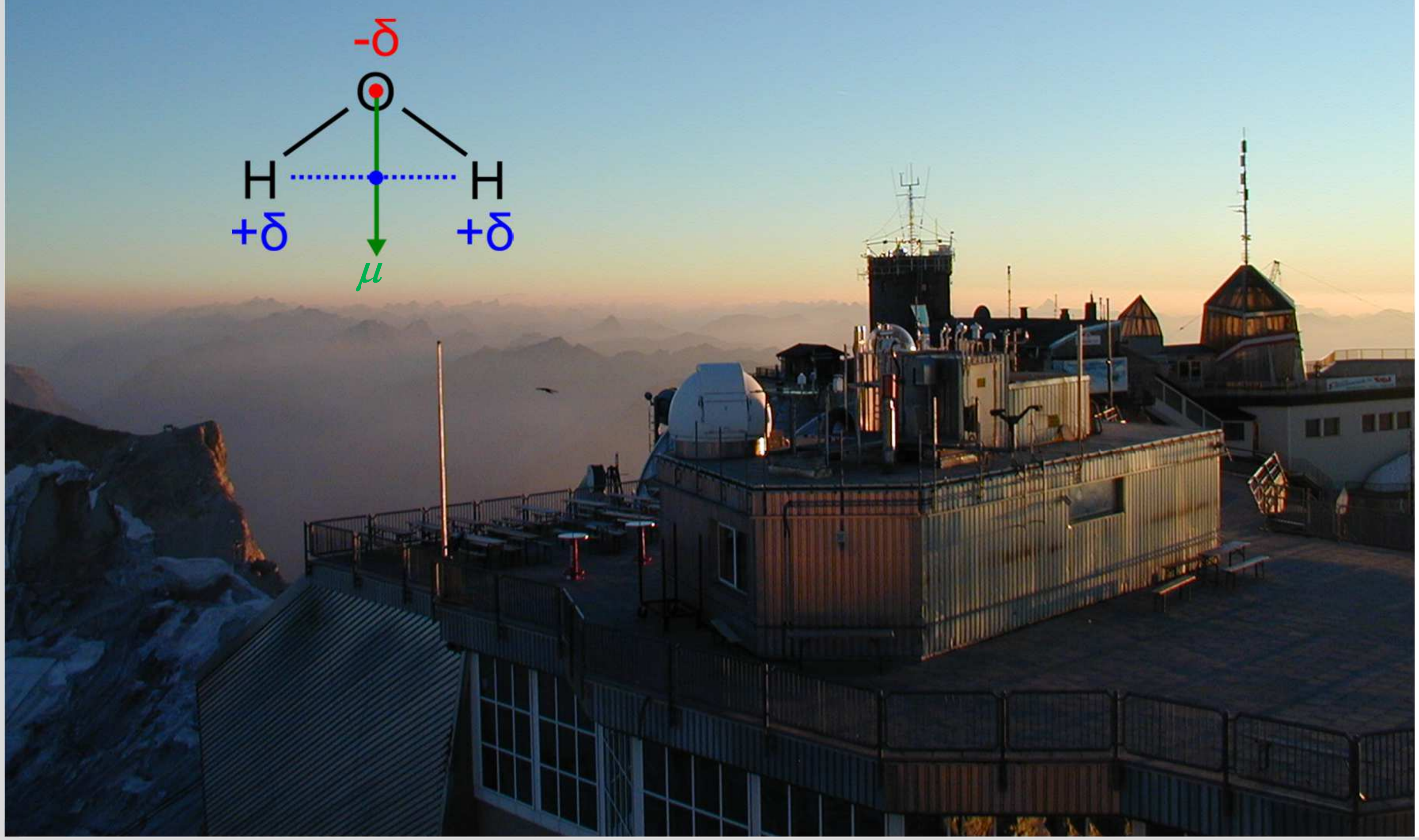


Outline

(I) Importance of water vapor absorption in climate simulations

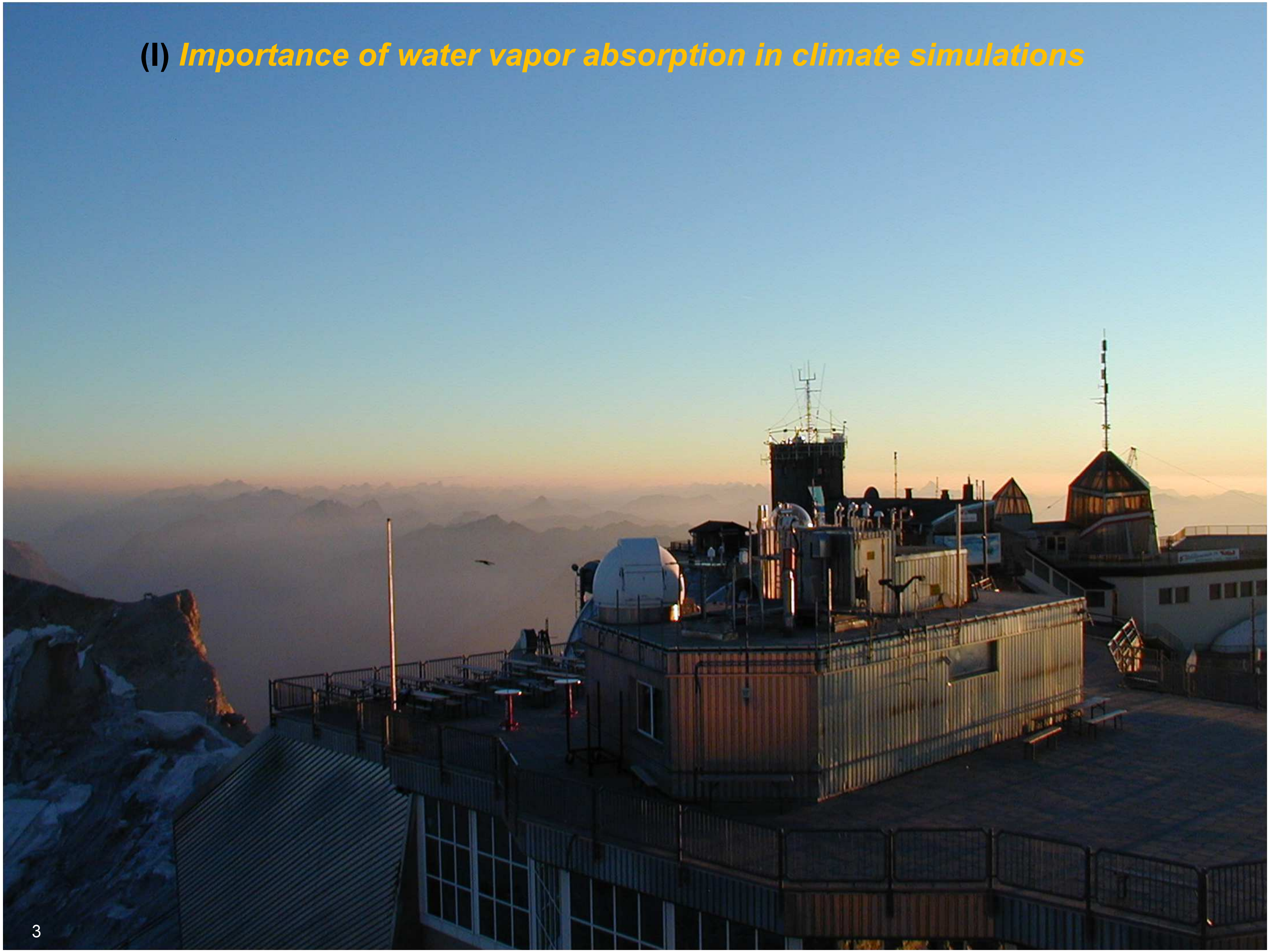
(II) Difficulties in quantifying water vapor absorption

(III) How to quantify water vapor absorption under atmospheric conditions: radiative closure principle

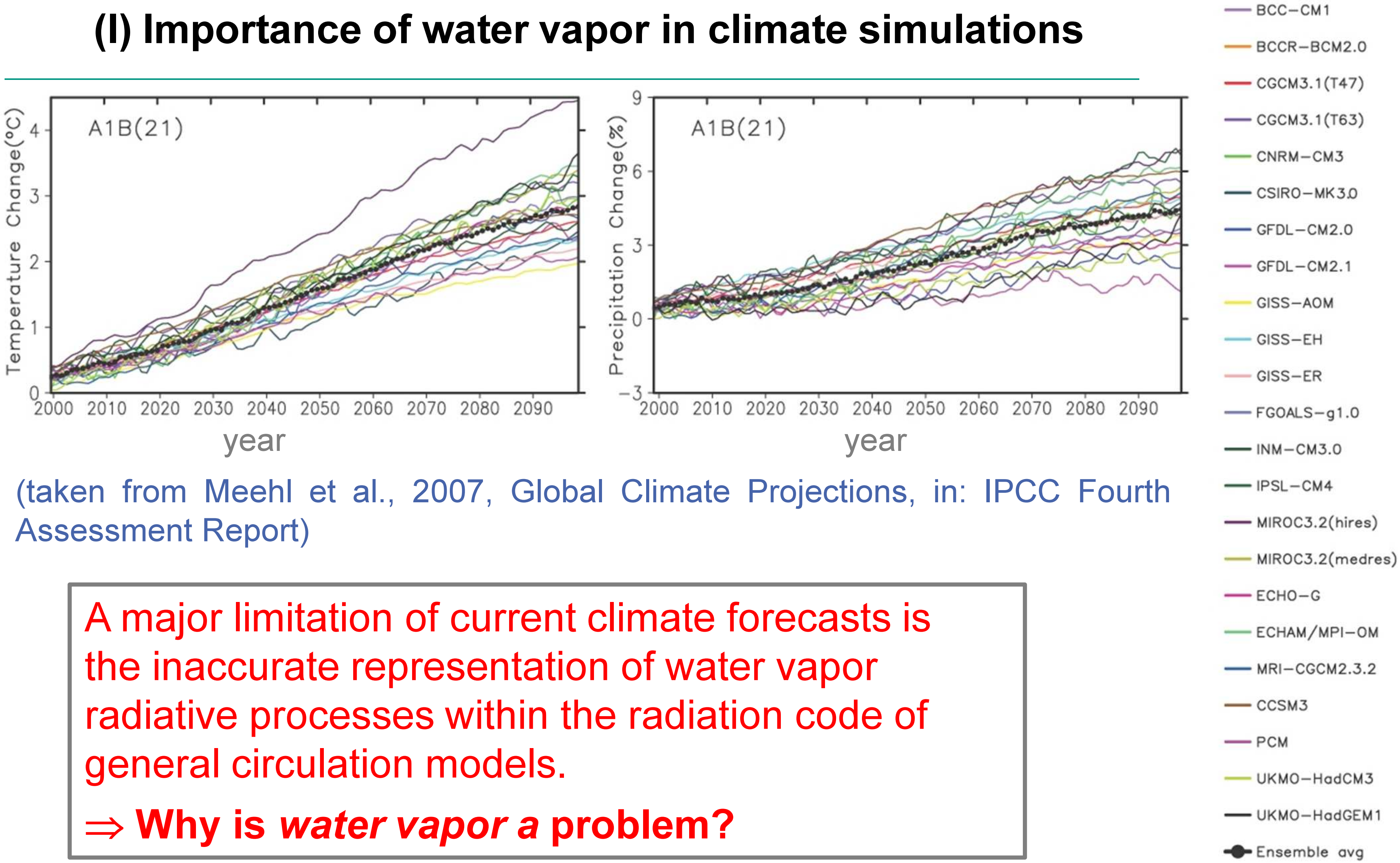
(IV) Setup of the Zugspitze radiative closure experiment

(V) Summary & Outlook

(I) *Importance of water vapor absorption in climate simulations*



(I) Importance of water vapor in climate simulations



(taken from Meehl et al., 2007, Global Climate Projections, in: IPCC Fourth Assessment Report)

A major limitation of current climate forecasts is the inaccurate representation of water vapor radiative processes within the radiation code of general circulation models.

⇒ **Why is *water vapor a* problem?**

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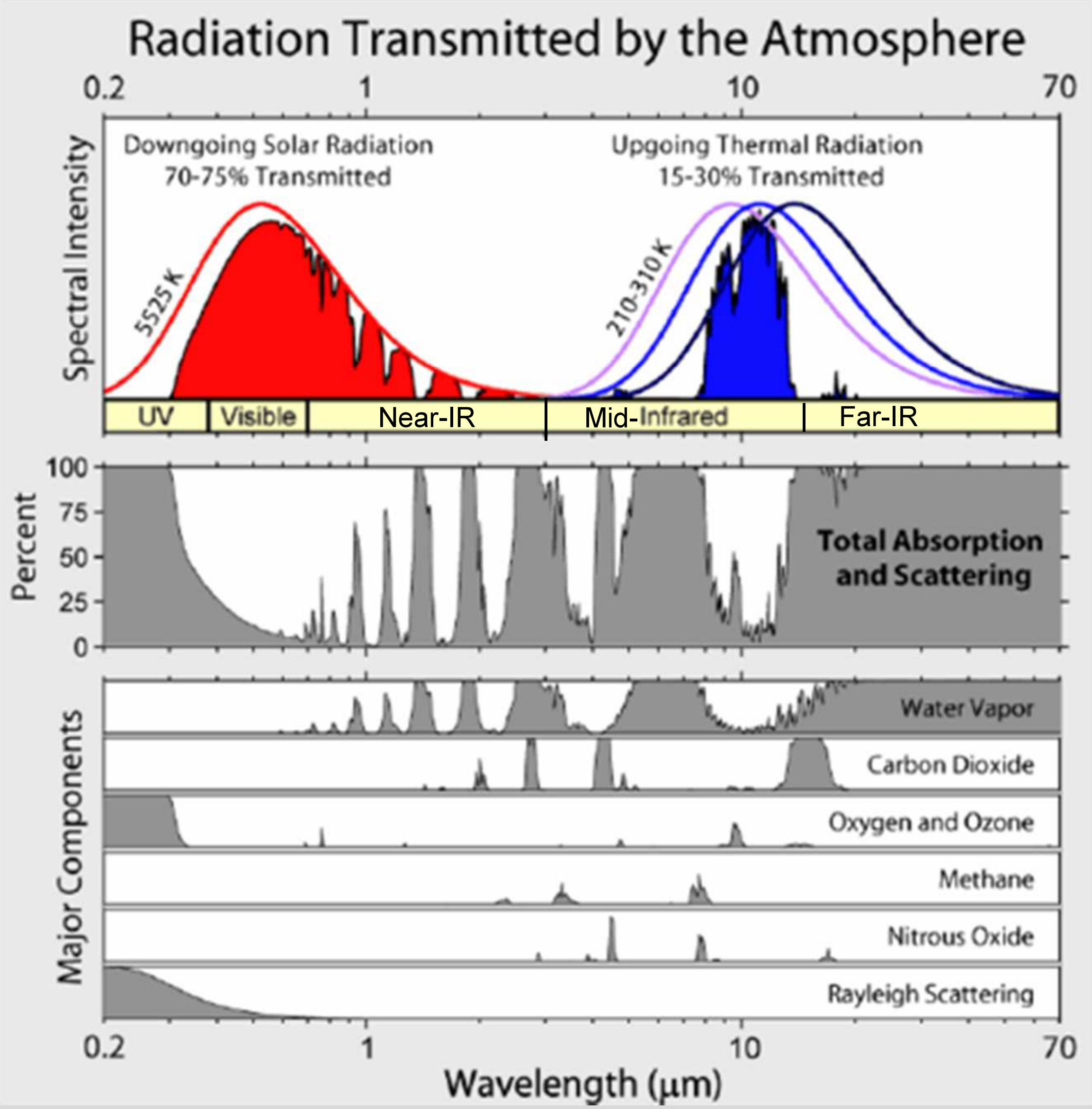
(I) Importance of water vapor in climate simulations



from website of:
Oregon Institute Of Science & Medicine

(I) Importance of water vapor in climate simulations

H_2O is the atmospheric species which causes the strongest absorption/ emission of radiation:

- ~ 60% of the atmospheric absorption of incoming solar radiation
- ~ 60% of the clear-sky greenhouse effect

Kiehl and Trenberth, 1997

Shine et al., 2012

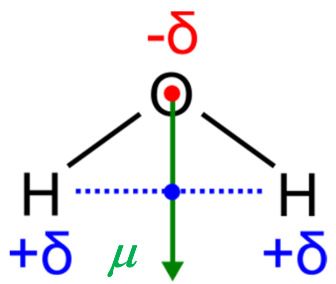
H_2O feedback approximately doubles the response of surface temperature to the imposition of an external forcing (e.g., CO_2)

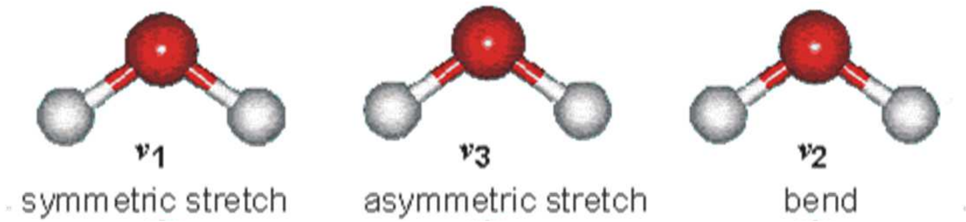
⇒ Water vapor radiative processes have to be simulated accurately within climate models

(I) Importance of water vapor in climate simulations:
why is water vapor the strongest absorber?

1. Because there are much more water molecules in the atmosphere compared to all other greenhouse gases

2. Because ALL 3 H_2O vibrations go along with a change of dipole moment, i.e. ALL 3 are infrared active (for CO_2 only 2 from 3, for CH_4 only 2 from 4):

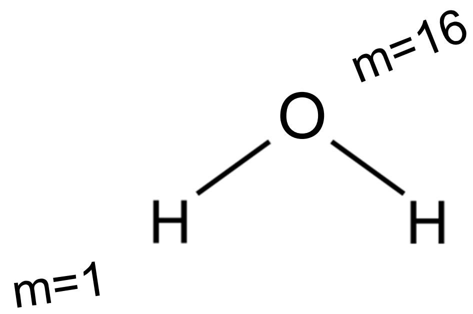




4049 cm^{-1} (λ=2.5 μm)	4084 cm^{-1} (λ=2.4 μm)	1960 cm^{-1} (λ=5.1 μm)

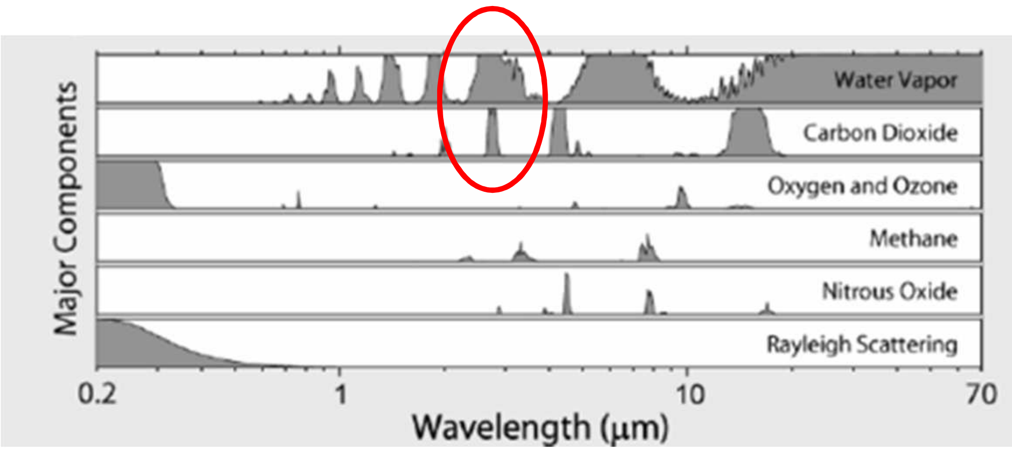
(I) Importance of water vapor in climate simulations:
why is water vapor the strongest absorber?

3. Because H-Atoms are light:



⇒ H_2O molecule has extremely small moments of inertia I

- ⇒ large line spacing (rotational contant $B_{H2O} = 1 / I = 27.4$ cm^{-1}) compared to line width (≈0.1 cm^{-1} @ 1 bar)
- ⇒ **less overlap of H_2O lines compared to CO_2 (B_{CO2} = 0.39 cm^{-1})**
- ⇒ **less saturation for H_2O compared to CO_2 (in spite of $c_{H2O} >> c_{CO2}$)**

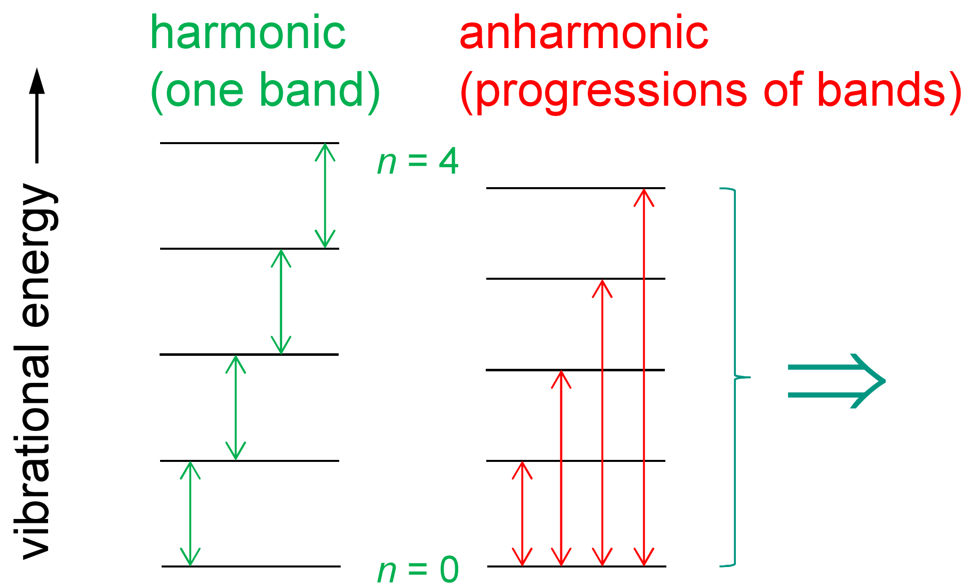


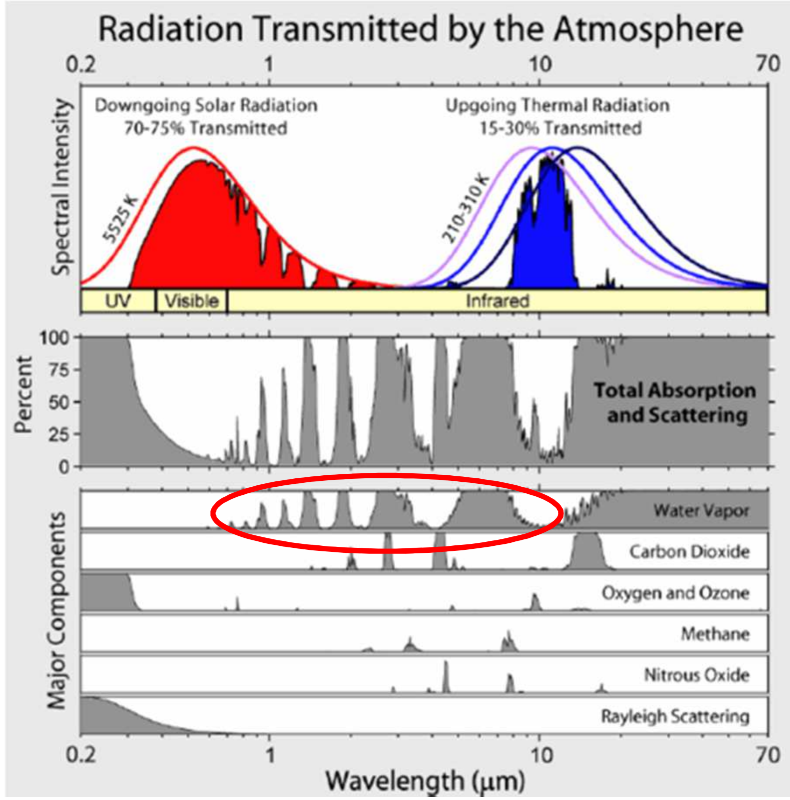
(I) Importance of water vapor in climate simulations:
why is water vapor the strongest absorber?

4. Because H-Atoms are light:

⇒ vibrational motions of H_2O have <u>large amplitudes</u>

⇒ harmonic oscillator selection rule ($\Delta n = \pm 1$) breaks down and transitions up to $\Delta n = \pm 8$ become allowed (“progressions“ of “overtone bands“)

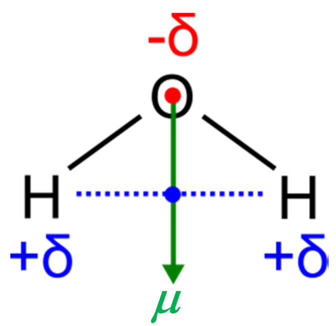


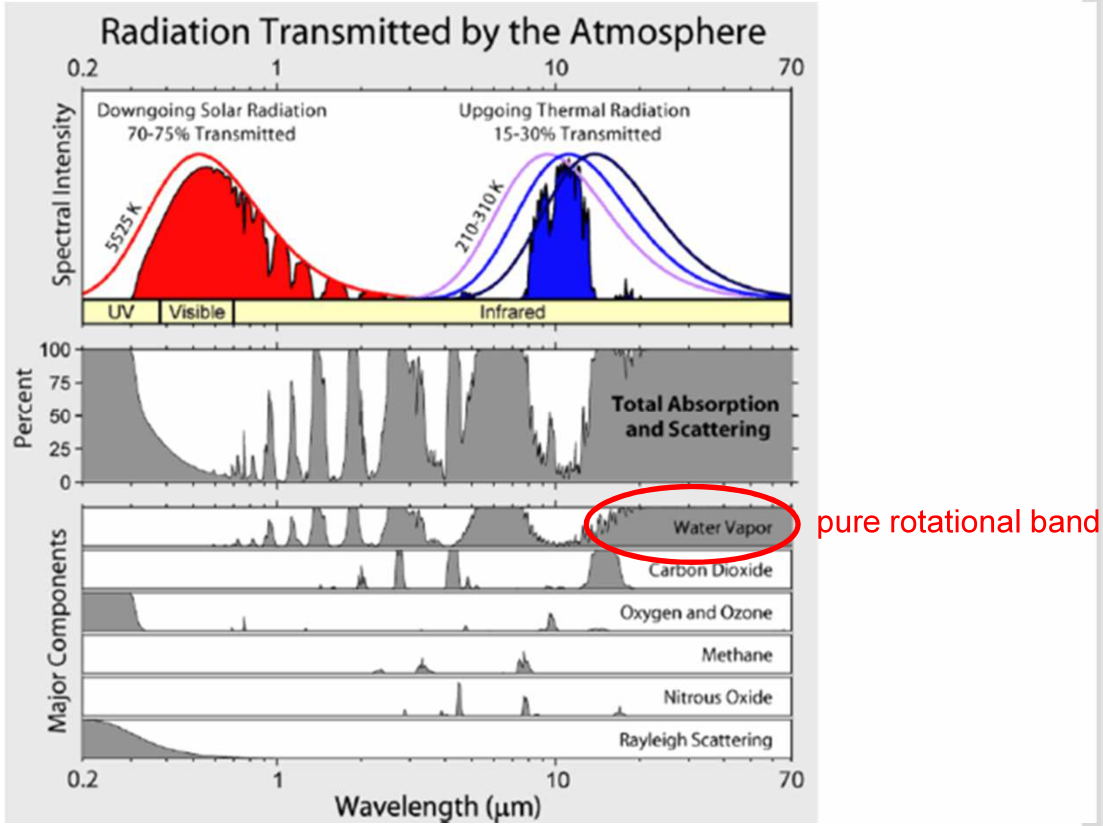


(I) Importance of water vapor in climate simulations:
why is water vapor the strongest absorber?

5. H_2O is the only GHG that can also absorb in the far-infrared spectral region via pure rotational excitation -

because it has a **permanent dipole** moment:






(II) *Difficulties in quantifying water vapor absorption*

(II) Difficulties in quantifying water vapor absorption:
example erroneous MIR linewidth & lineshape

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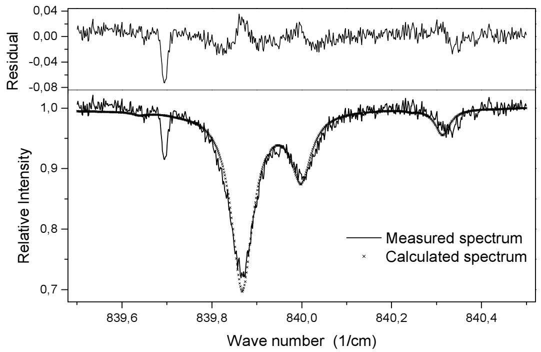
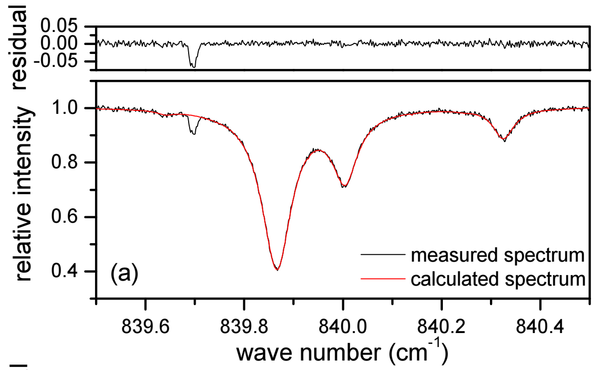
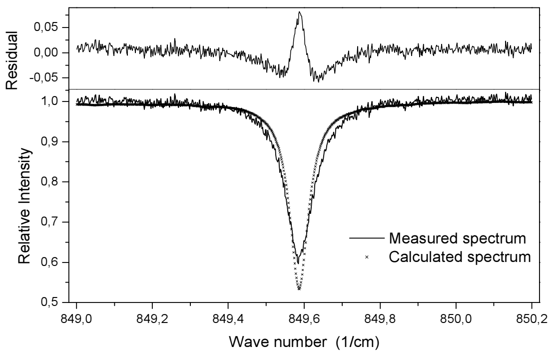
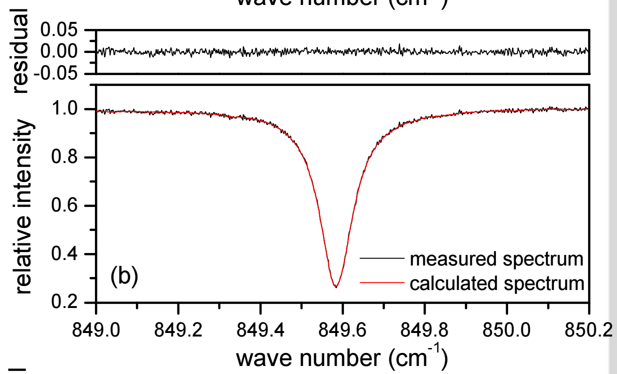
HITRAN1996 HITRAN2000



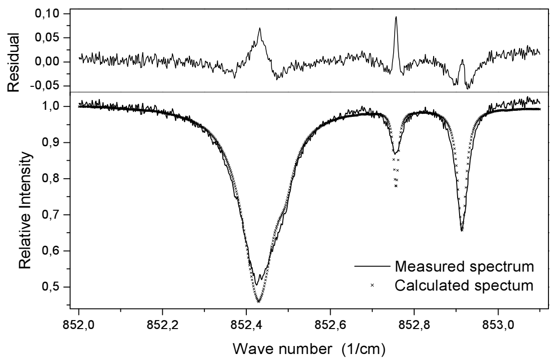


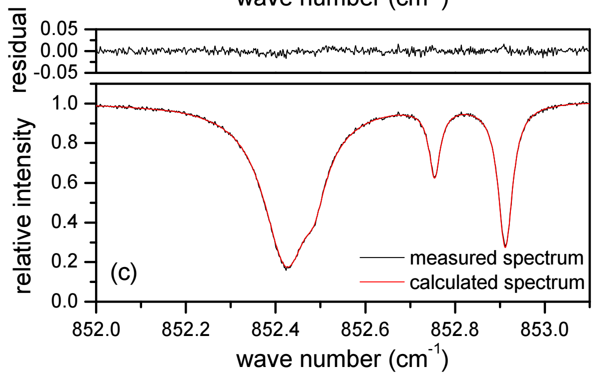
010-010
R10, R14
water vapor lines,
1 solar OH line





010-010
R11
water vapor line





010-010
R10, R13, R16
water vapor lines

Sussmann, R., Borsdorff, T., Rettinger, M., Camy-Peyret, C., Demoulin, P., Duchatelet, P., Mahieu, E., and Servais, C.: Harmonized retrieval of column-integrated atmospheric water vapor from the FTIR network – first examples for long-term records and station trends, Atmos. Chem. Phys., 9, 8987-8999, 2009.

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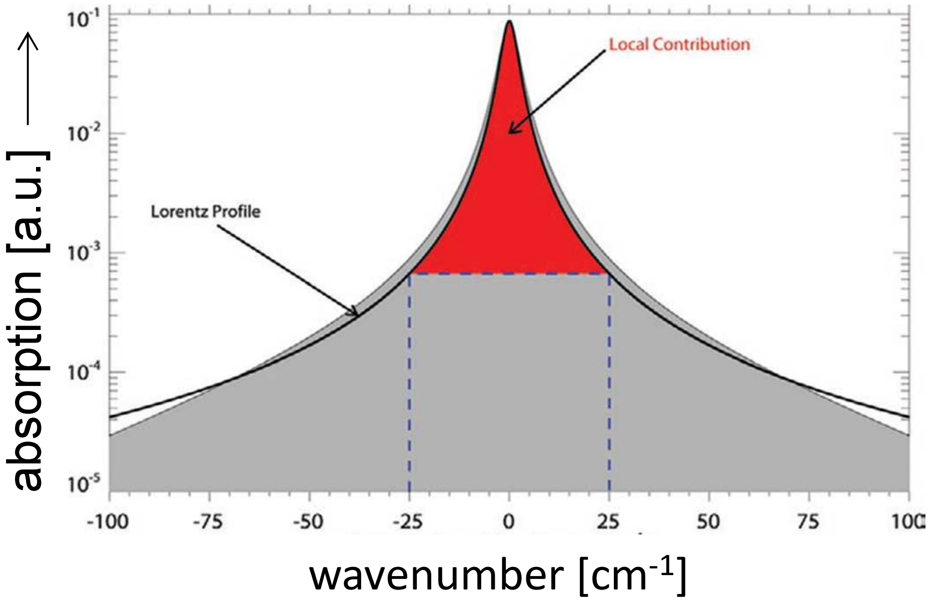
(II) Difficulties in quantifying water vapor absorption:
Continuum: no clear theory

Far-wing theory:

- non-zero duration of collisions (H-bond)

$\Rightarrow$ super-Lorentzian near-wings &
sub-Lorentzian far-wing line shapes

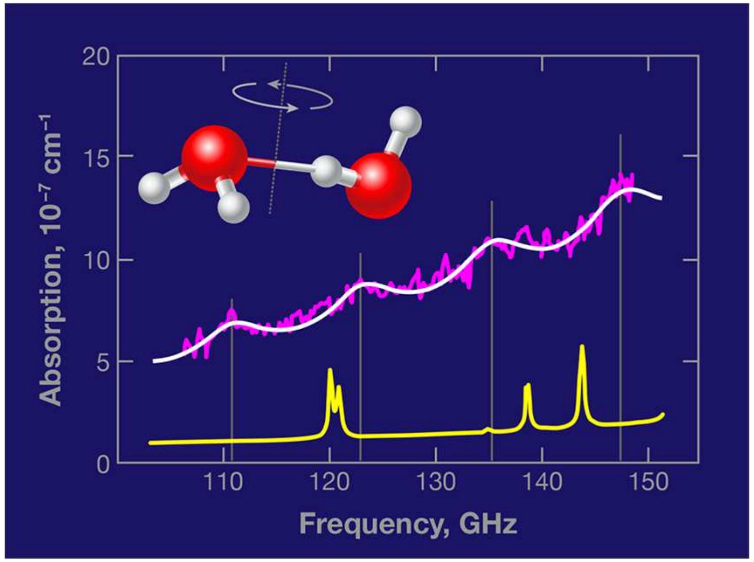
- doesn´t comply with strong negative temperature dependence



Turner, Mlawer, BAMS, 2012

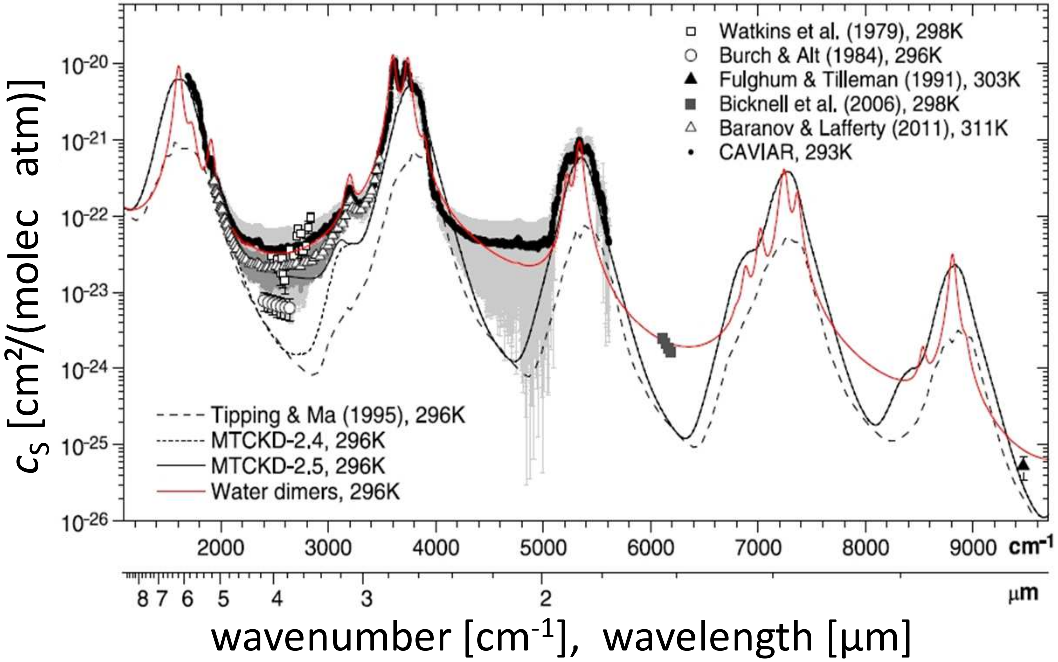
Dimer theory:

- dimer-formation via H-bond
- complies with neg. T-dependence
- lines broader due to shorter lifetime
- small frequency shift
- additional lines



Tretyakov et al., Phys. Rev. Lett., 2013:
first evidence for dimer existence at room temperature ?

(II) Difficulties in quantifying water vapor absorption:
Continuum: theories disagree, lab measurements disagree



Comparison of laboratory measurements and MT_CKD prediction for the water vapor self-continuum *(from: Ptashnik et al., 2011)*

- dimer theory doesn´t agree with far-wing theory
- both theories don´t agree to measurements (Ptashnik et al., 2013)
- different measurements disagree by up an order or magnitude
- no measurements at atmospheric temperatures
- high-temperature laboratory measurements cannot be extrapolated to low atmospheric temperatures because of unknown temperature dependency

(III) *Approach to quantify water vapor absorption under atmospheric conditions: radiative closure principle*

(III) Radiative closure principle:
schematical setup

Atmospheric state measurements

- H_2O column, profile
- pT profile
- further trace gas columns (CO_2,CH_4,O_3)

Spectral radiance measurements

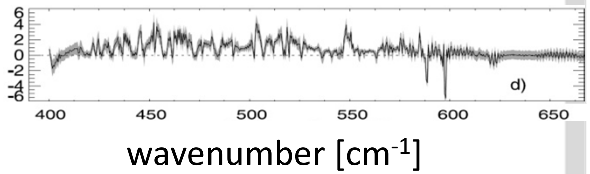
- far-/mid-infrared thermal emission spectra
- near-infrared solar absorption spectra

Radiative transfer model (LBLRTM)

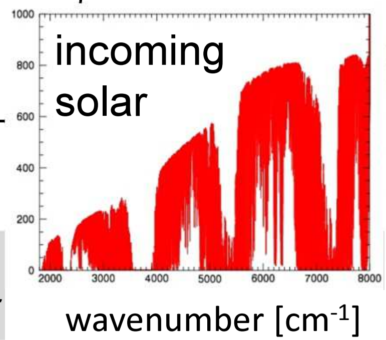
Modeled radiance spectrum

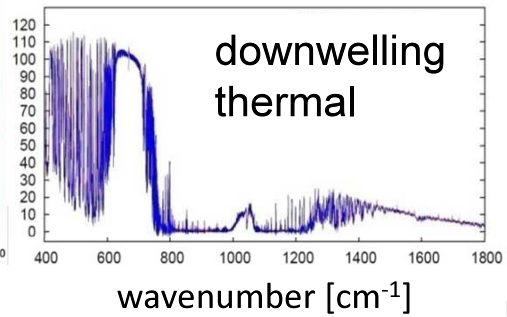
Measured radiance spectrum

Difference spectrum ("residuals")



iterative adjustment of water vapor absorption parameters
⇒ minimization of spectral residuals



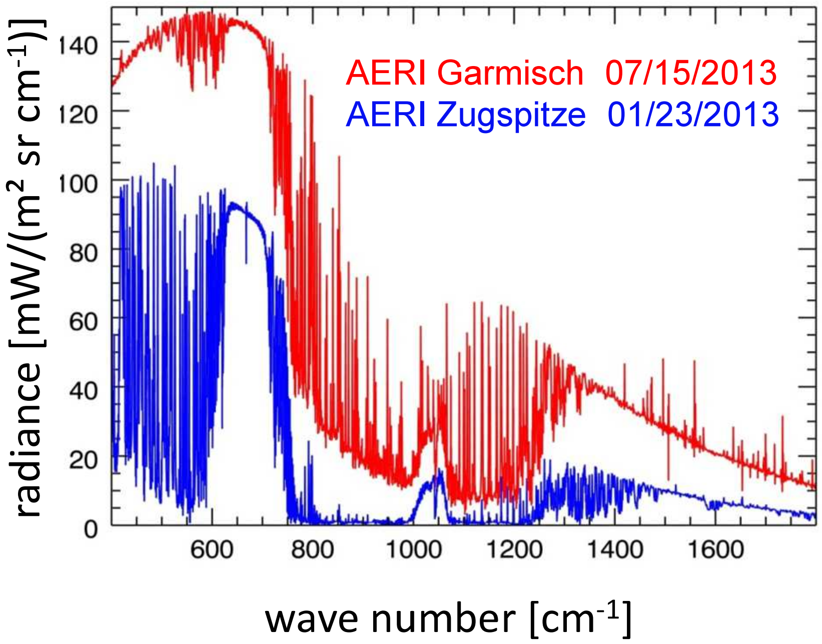


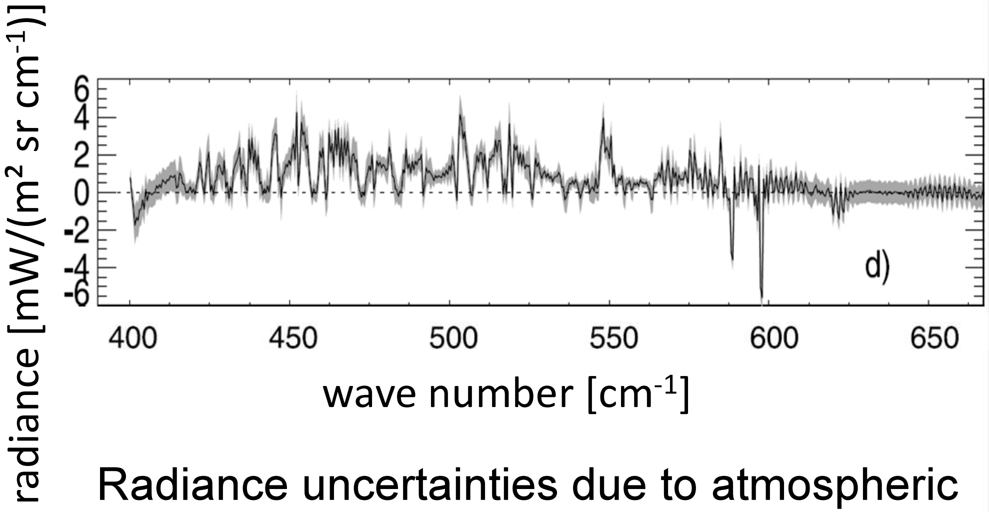
⇐ outgoing thermal

(IV) *Setup of the Zugspitze radiative closure experiment*

(IV) Setup of the Zugspitze radiative closure experiment: requirements

downwelling clear sky spectra



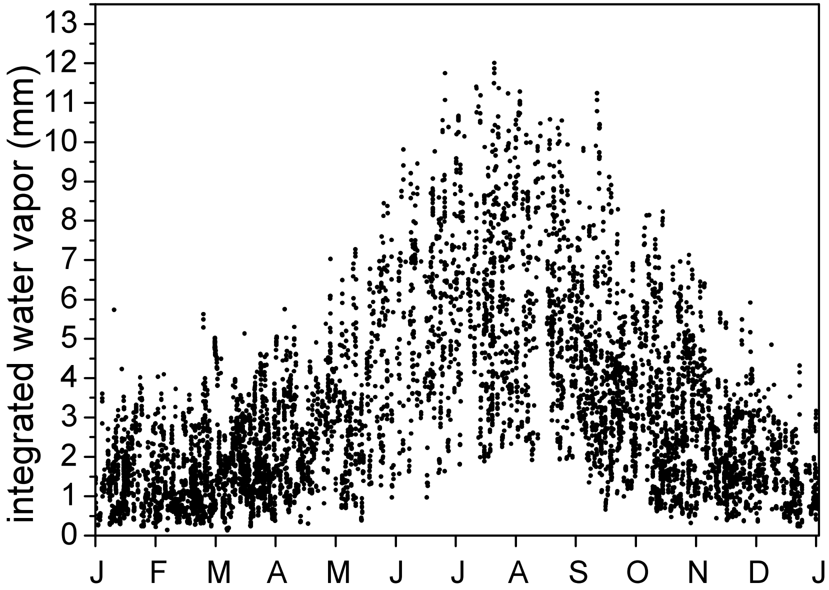


Radiance uncertainties due to atmospheric state errors (from: Delamere et al., 2010)

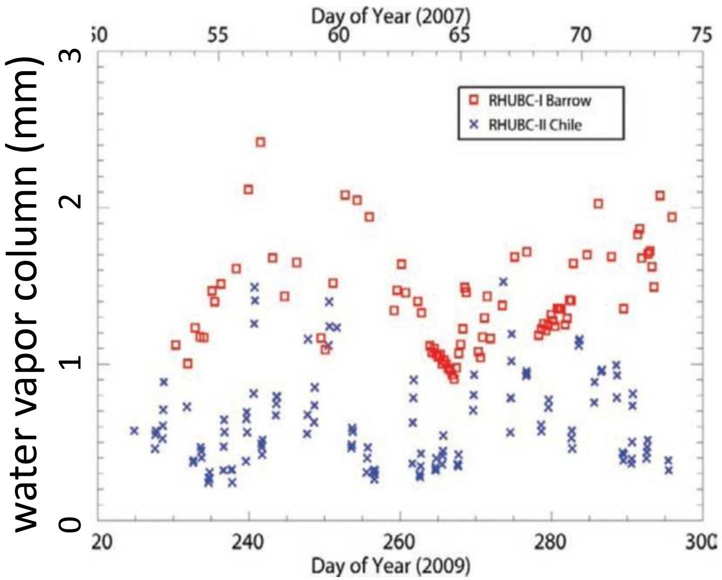
- require low water vapor column

- require high-precision atmospheric state measurements (key parameter: water vapor column)

(IV) Setup of the Zugspitze radiative closure experiment:
Zugspitze benefits to fulfill requirements



Zugspitze water vapor column multi-annual data (from FTIR)



Water vapor columns during the RHUBC measurement campaigns
(from: Turner and Mlawer, 2010)

- high-altitude location: very low atmospheric water vapor column
- long-term measurements: reduce statistical errors compared to short measurement campaigns

(IV) Setup of the Zugspitze radiative closure experiment: need for (solar) spectral radiance measurements in the NIR

Paynter & Ramaswamy, 2011: *"…the continuum contributes notably to our lack of complete understanding of shortwave absorption. There is a need for improved measurements of the continuum in the shortwave (infrared) to help constrain these values better. Until this is done, there is a caution in performing shortwave radiative transfer calculations."*

(IV) Setup of the Zugspitze radiative closure experiment: concepts & projects

Suggested to funding agencies

• add key instrumentation to the existing Zugspitze remote sounding setup

• combine NIR investigatins (new) with FIR & MIR investigations (done in the US)

• perform first *long-term* closure experiment (improve relative to US *campaigns*)

⇒ 4/5 success quote: Acknowledgments:

Helmholtz Invest. Proposal for FIR/MIR and microw. radiometers (420 kEuro, 2011)

PhD thesis proposal to DBU (personell costs 3 years: 2012-14)

Proposal for Helmholtz Virtual Institute (preproposal failed)

Proposal to BStMUV for technical setup project (175 kEuro, 2012-14)

Proposal to BStMUV for science project (270 kEuro, 2014-17)

First activity of this kind in Germany

(IV) Setup of the Zugspitze radiative closure experiment:
instruments overview

spectral radiance measurements

measurements of atmospheric state parameters

radiance FIR & MIR,
T-profile (+ NCEP)

AERI

radiance NIR

solar FTIR

H_2O column & profile

microwave radiometer LHATPRO

Sussmann, Reichert, to be published

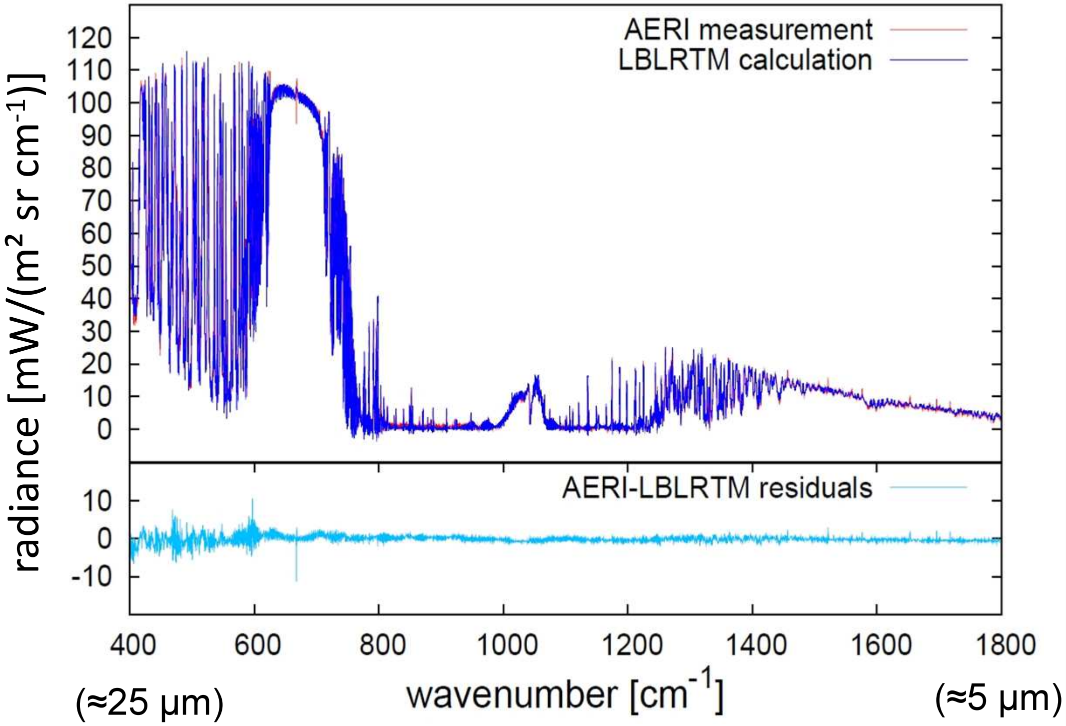
(IV) Setup of the Zugspitze radiative closure experiment:
Line-By-Line Radiative Transfer Model (LBLRTM)

• LBLRTM is a line-by-line spectral high resolution radiative transfer code (AER, Inc., Massachusetts)

• LBLRTM is used as foundation for the faster Rapid Radiative Transfer Model (RRTM, AER., Inc.) which is used to compute radiative fluxes and heating rates in GCM´s (e.g., ECHAM)

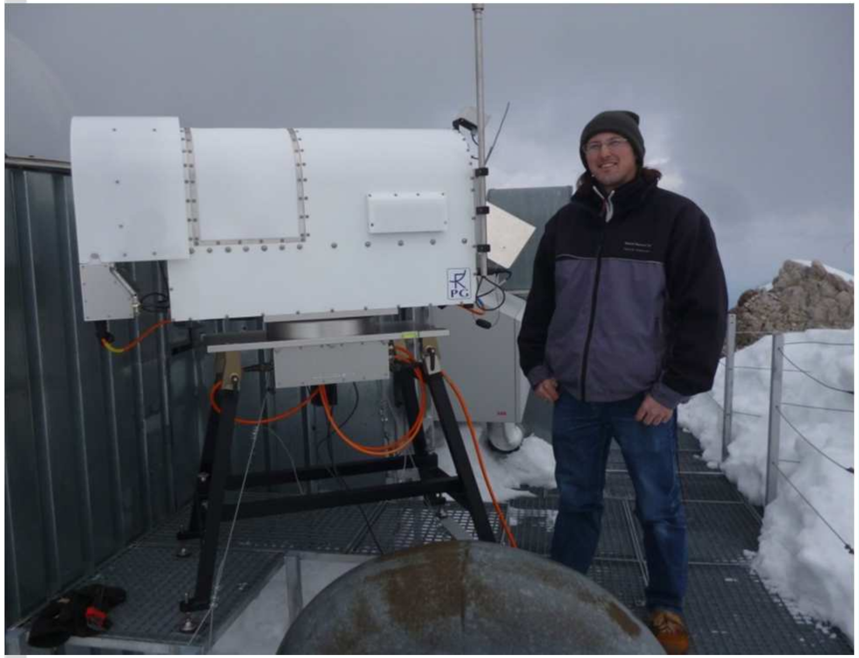
⇒ improvements of line parametes or continuum coefficients found from the use of LBLRTM can be directly transferred to RRTM/ECHAM

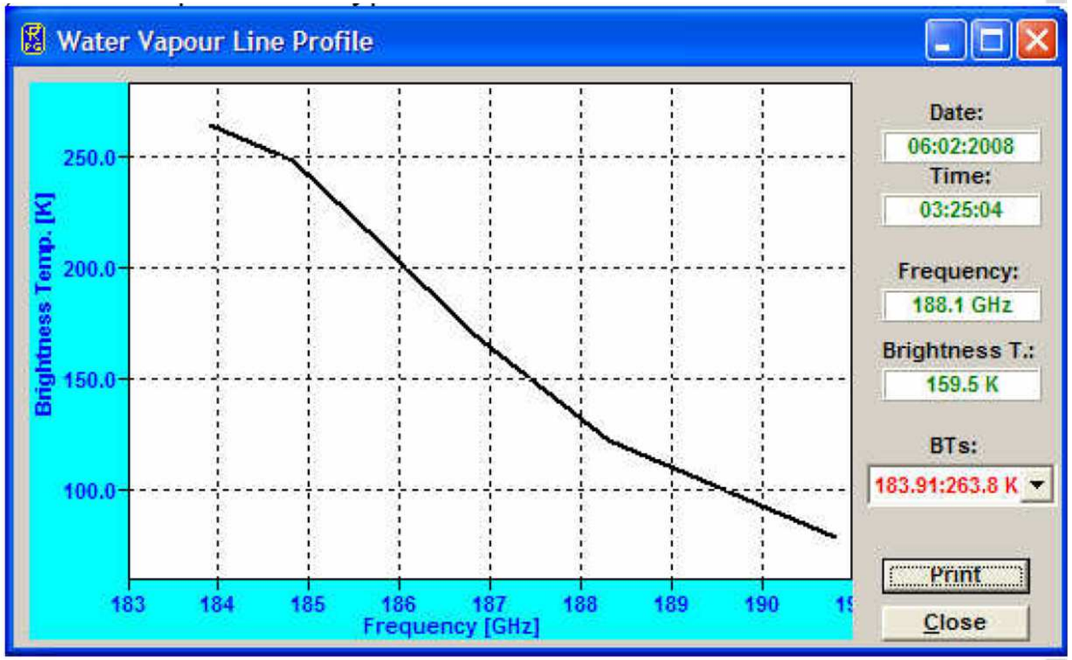
(IV) Setup of the Zugspitze radiative closure experiment:
spectral radiance measurements in the FIR and MIR



- AERI: FIR & MIR downwelling thermal emission with ~1 cm^{-1} resolution
- calibration: hot (~ 60 °C) and ambient blackbodies

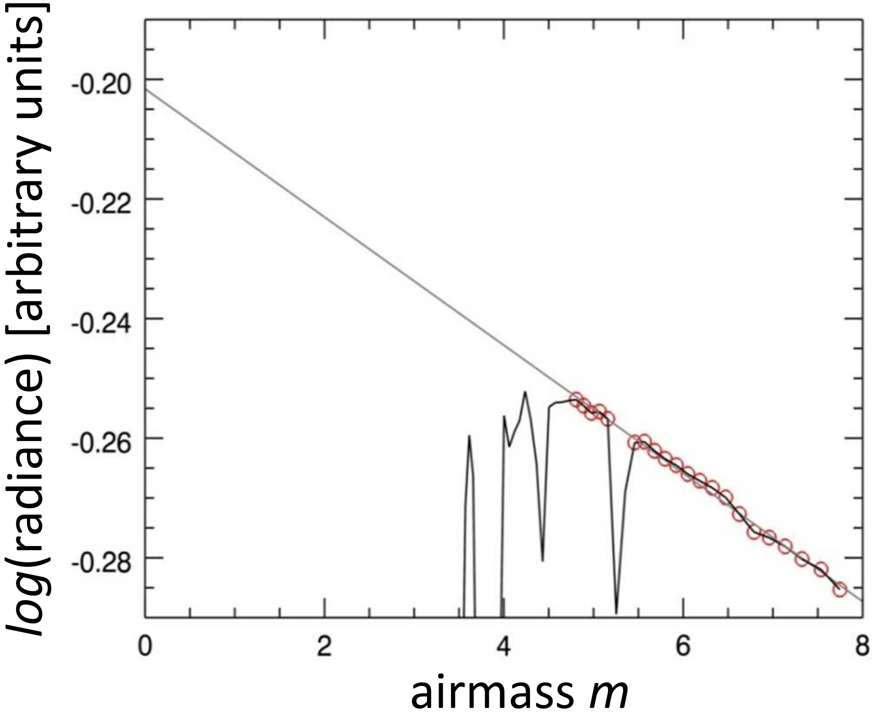
(IV) Setup of the Zugspitze radiative closure experiment:
H_2O column & profile: LHATPRO microwave radiometer

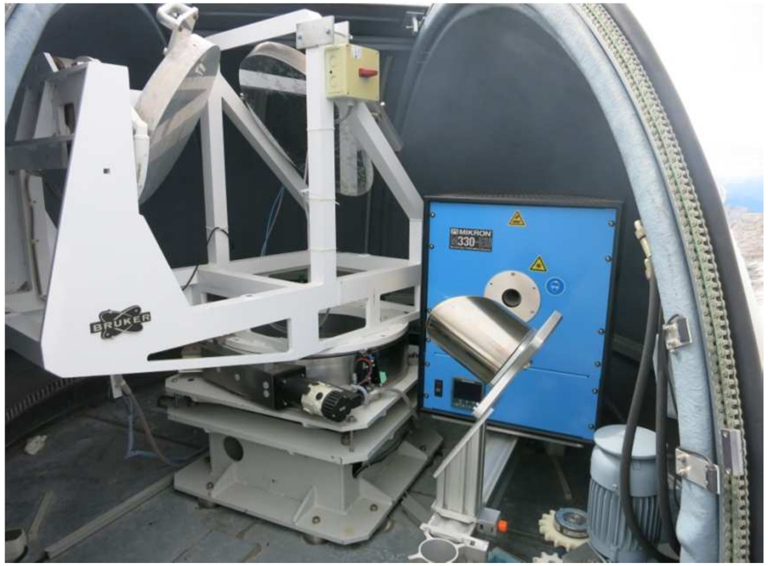




- water vapor column uncertainty: ~ 0.02 mm (for iwv < 1 mm) ; ~ 0.5 mm (for iwv > 6-8 mm)

(IV) Setup of Zugspitze closure experiment: combined Langley + blackbody calibration of solar FTIR for NIR closure





Beer-Lambert law: $F_\nu = F_{\nu 0}\, exp(-\tau_\nu m)$

Langley plot: $ln(F_\nu) = ln(F_{\nu 0}) - \tau_\nu m$

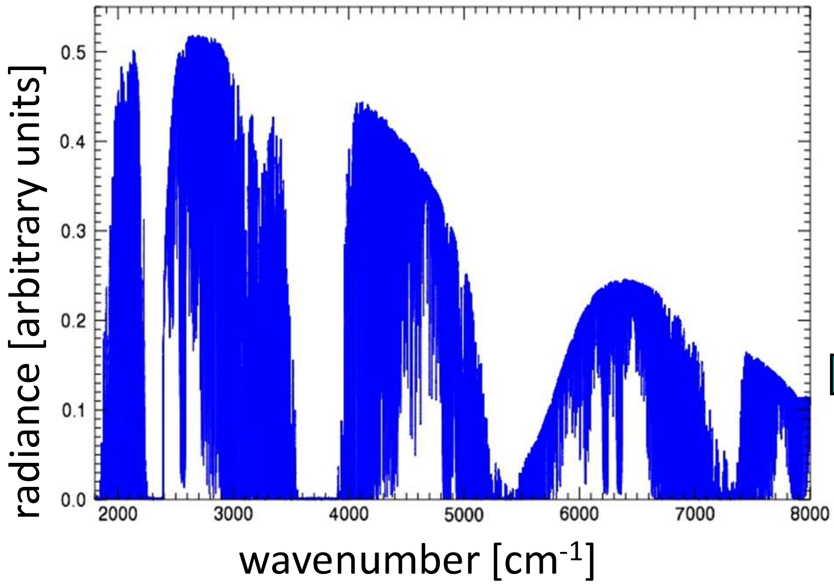
- Langley method provides precise absolute calibration at narrow spectral regions with little molecular absorption

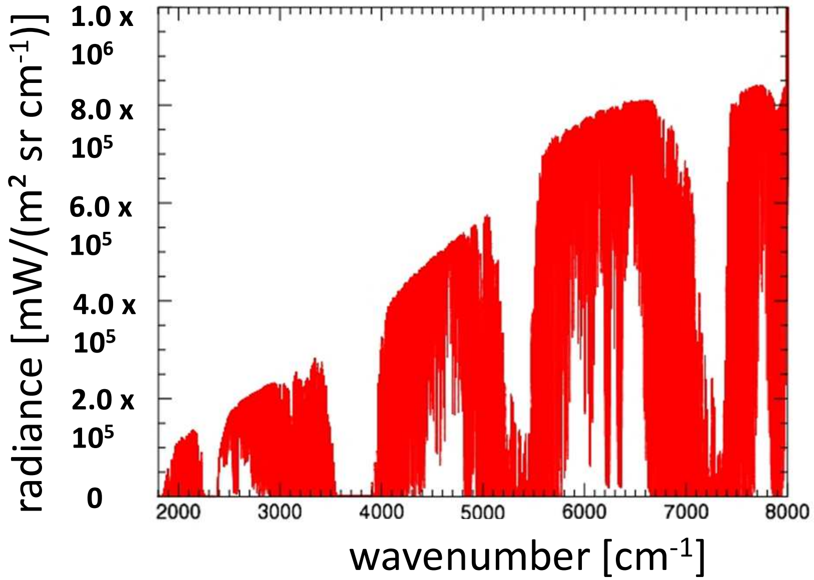
- spectral shape between Langley calibration points determined with a high-temperature blackbody (1900 °C)

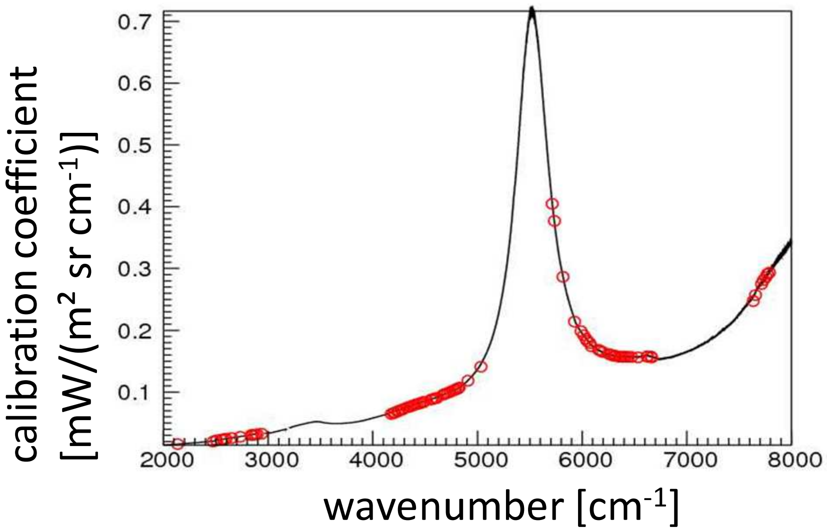
⇒ combined calibration uncertainty: ~ 2 %

Reichert, Sussmann, to be published

(IV) Setup of Zugspitze closure experiment: combined Langley + blackbody calibration of solar FTIR for NIR closure







Reichert, Sussmann, to be published

Summary

- accurate knowledge of water vapor absorption:
  - crucial in radiation codes of GCM´s
  - problem of continuum lab measurements
- setup of Zugspitze long-term radiative closure study:
  - FIR, MIR & NIR
  - long-term setup

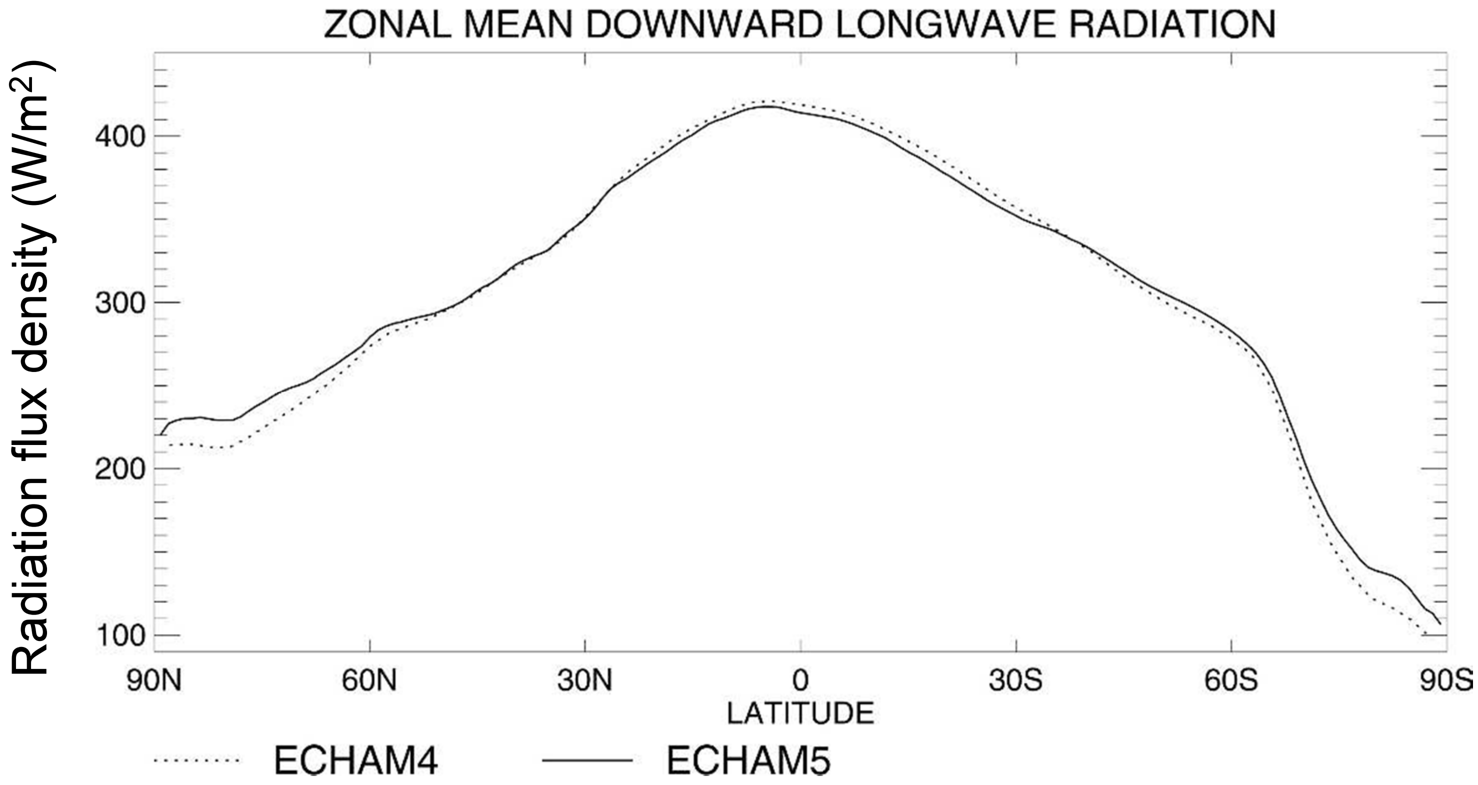
Outlook

- validate/improve NIR continuum parameters
- perform ECHAM run with improved near-infrared continuum (collab. AER Inc. & MPI-Hamburg)
- extend studies to ice clouds (collab. LMU Munich)

Supplementary viewgraphs

Changes in radiation codes: Previous example studies

Wild and Röckner, 2006



In ECHAM5 the longwave radiation code RRTM (Mlawer et al., 1997) was introduced. This code includes the CKD formulation of the water vapor continuum (Clough et al., 1989)

Changes in radiation codes: Previous example studies

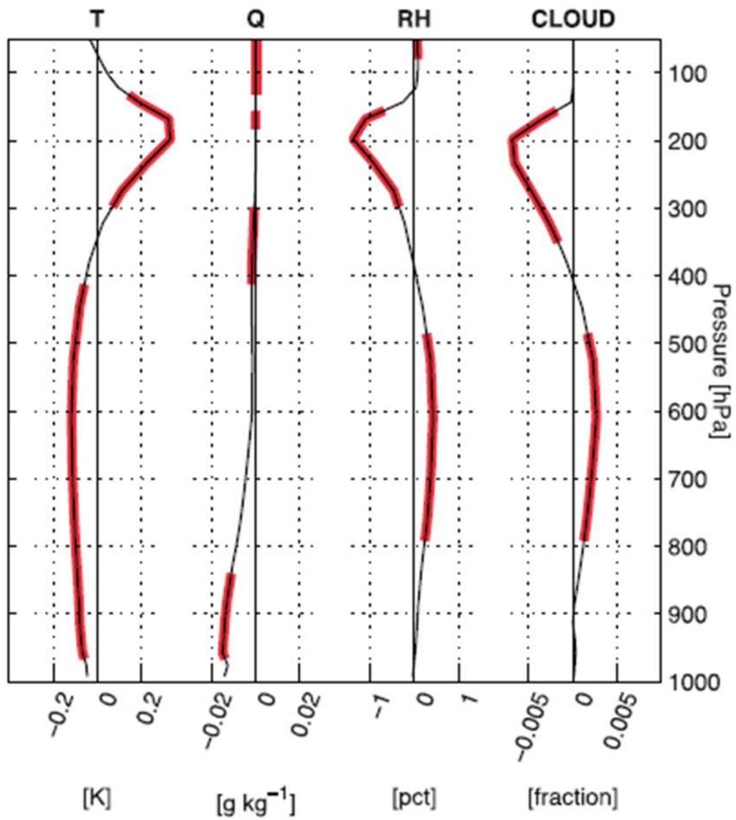
Turner, Merrelli, Vimont, Mlawer, J. Geophys. Res., 2012:

The far-infrared (wavelengths longer than 17 mm) has been shown to be extremely important for radiative processes in the earth's atmosphere. The strength of the water vapor continuum absorption in this spectral region has largely been predicted using observations at other wavelengths that have been extrapolated using semiempirical approaches such as the Clough-Kneizys-Davies (CKD) family of models.

Recent field experiments using new far-infrared instrumentation have supported a factor of 2 decrease in the modeled strength of the foreign continuum at 50 µm and a factor of 1.5 increase in the self-continuum at 24 µm in the Community Earth System Model (CESM v1.0, 20 year integrations with prescribed sea surface temperatures):

Changes in radiation codes: Previous example studies

⇒ *"The radiative impact results in a small but statistically significant change in the mean temperature and humidity fields, and also a slight decrease (order 0.5%) of high-cloud amount. <u>The change in the cloud amount</u> modified the longwave cloud radiative forcing, which <u>partially offset the radiative heating caused by the change in the water vapor continuum</u> absorption model."*



Note, there was a 300% change made to the foreign continuum absorption in the FIR from the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment in 1998 [Tobin et al., 1999], which was subsequently further refined by RHUBC-I. Thus, if this GCM sensitivity study was repeated using the pre-SHEBA version of the water vapor continuum model (CKD v2.1), the impact on the simulated atmosphere should be much larger.

Improved radiation code in ECHAM from Zugspitze closure experiment:
Plans to demonstrate the impact

Karlsruhe Institute of Technology

MPI-M will implement the improved RRTM radiation code within ECHAM6 and explore the effects of the changed spectral data base on the quality of atmospheric simulations for the recent past (~1979-2005) for observed lower boundary conditions.

This work will include the retuning of the model to obtain the best possible top-of-the-atmosphere radiation fluxes compared to CERES (satellite radiometric measurements) data.

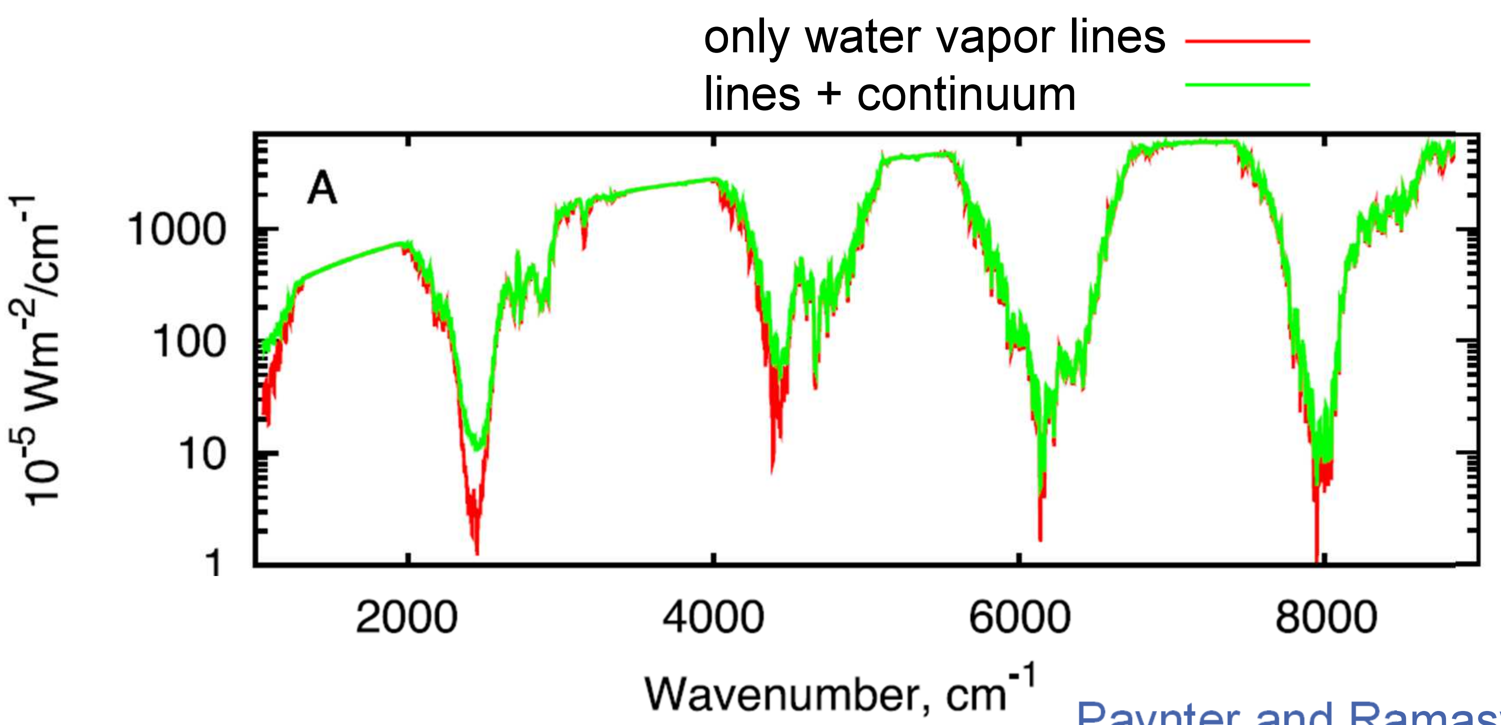
Further experiments will include a coupled 3d-ocean general circulation model to assess the effect of the modified RRTM schemes in idealized climate change experiments.

Results will be compared to simulations done with the coupled ECHAM6/MPI-OM atmosphere-ocean climate model within the (CMIP5) project preparing climate simulations and projections for the Fifth IPCC Assessment Report.

M. Giorgetta, Hamburg

(I) What we know about water vapor radiative processes:
rel. importance line absorption and continuum

clear sky **shortwave absorption** due to water wapor with and without continuum



Paynter and Ramaswamy, 2011

⇒ continum causes additional absorption up to a factor of 10