Water vapor spectroscopy in the far-IR from analysis of measurements from the RHUBC field campaigns

Eli Mlawer
Atmospheric and Environmental Research (AER)

Dave Turner (NOAA), Scott Paine (SAO), Luca Palchetti (CNR), Giovanni Bianchini (CNR), Jen Delamere (Alpenglow), Vivienne Payne (JPL)
AER contributors: Karen Cady-Pereira, Matt Alvarado, Rick Pernak, Dan Gombos

Topics

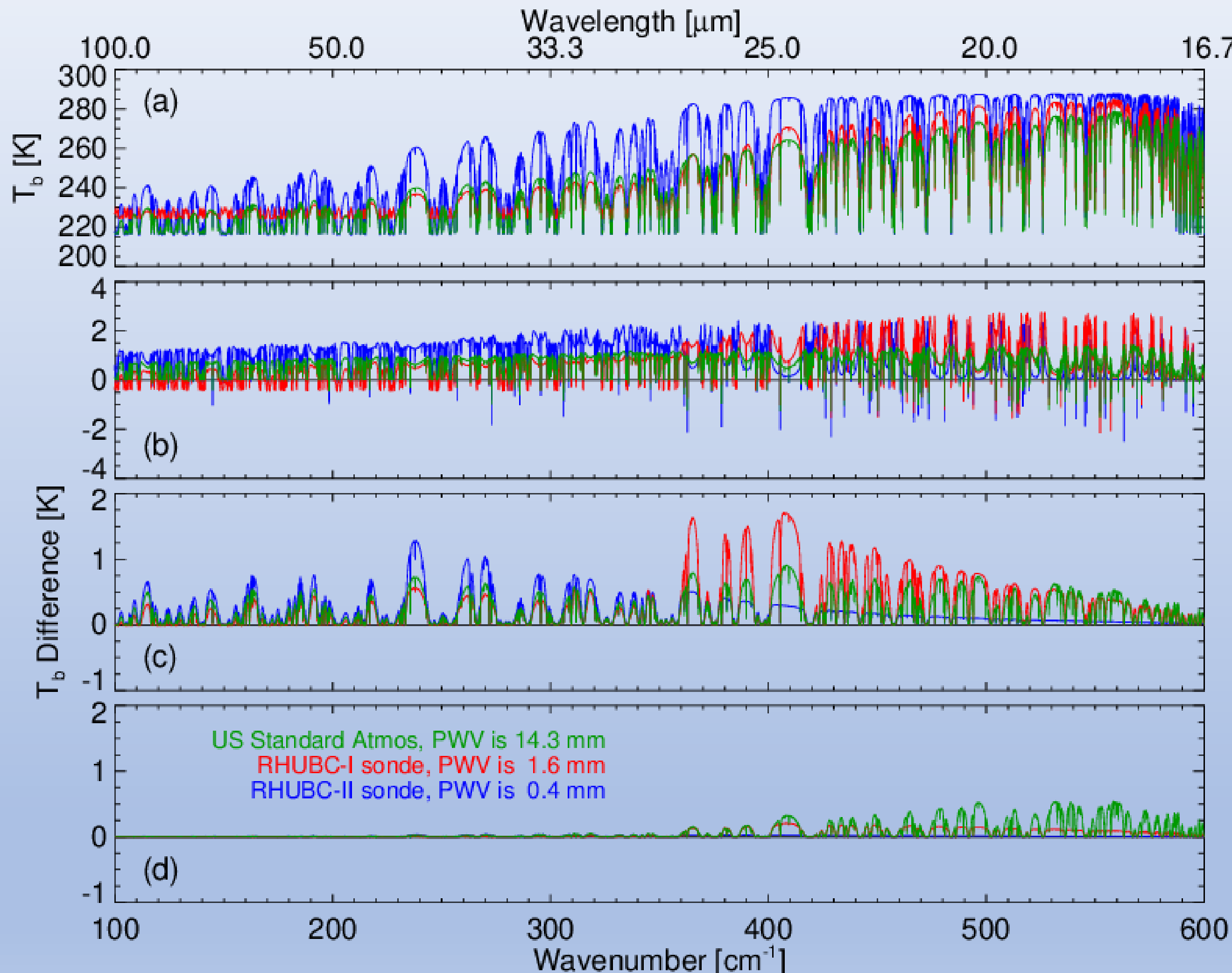
Far-infrared radiative closure studies – RHUBC-I and RHUBC-II

- retrieval of water vapor continuum and air-broadened line widths

Other far-IR analyses of the water vapor continuum

Related IR H_2O spectroscopy studies outside the far-IR

Will spectroscopic accuracy be important for FORUM?



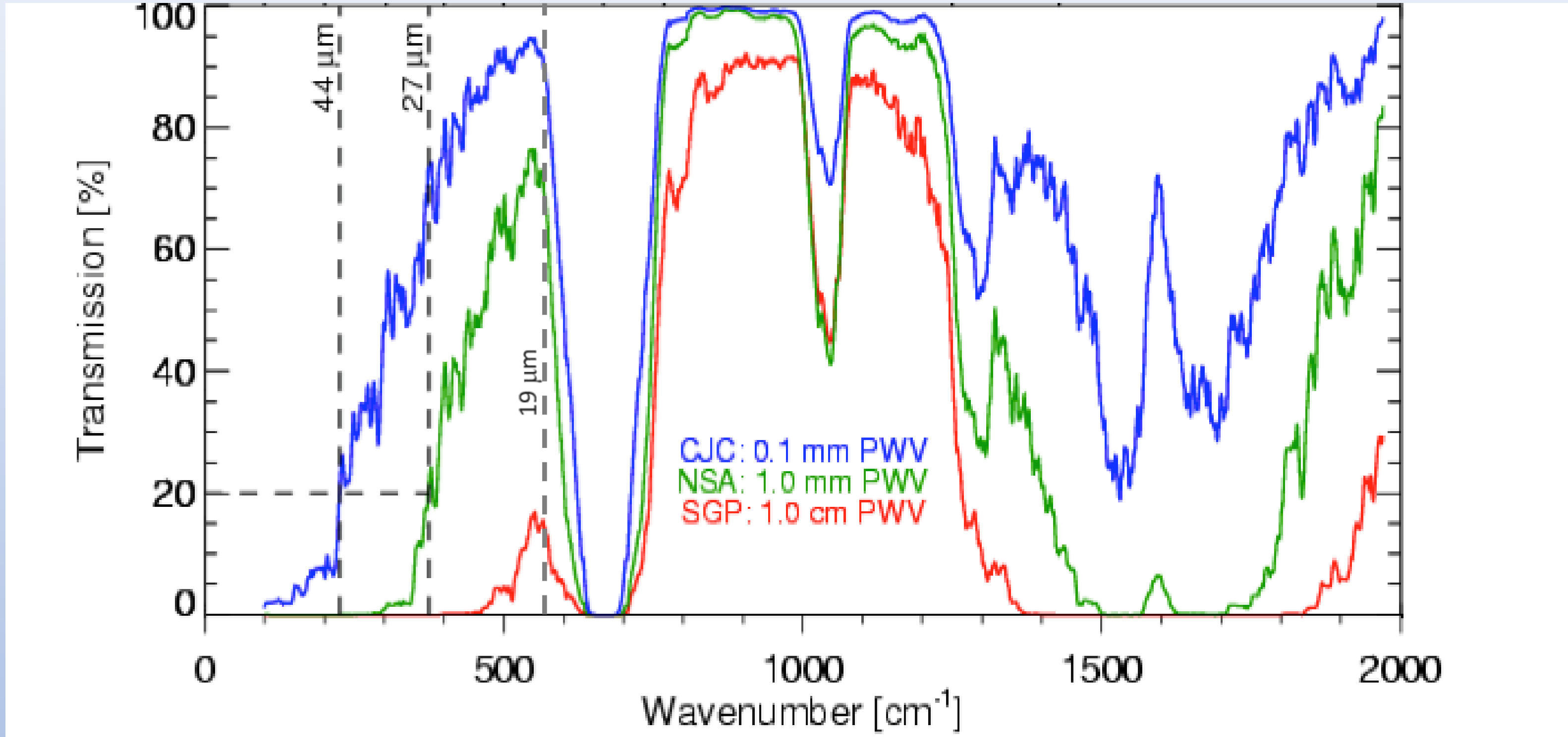
20% change in line widths

20% change in foreign continuum

20% change in self continuum

Plot: Dave Turner

Dry locations needed to evaluate far-IR spectroscopy from ground



Motivation for the Radiative Heating in Underexplored Bands Campaigns (RHUBC)

Far-IR campaigns relevant to RHUBC

Campaign	Location	Key spectral region	Spectroscopic improvements	Publications
SHEBA	Arctic Ocean	380-600 cm^{-1} (ER-AERI)	• H_2O foreign continuum 380-600 cm^{-1}	Tobin et al. (1999)
RHUBC-I	ARM NSA site Utqiagvik, AK (Barrow)	400-600 cm^{-1} (ER-AERI)	• H_2O foreign continuum 0-600 cm^{-1} • H_2O self continuum 0-400 cm^{-1} • Air-broadened widths of 42 H_2O lines	Delamere et al. (2010) Turner et al. (2012a) Mlawer et al. (2019)
RHUBC-II	Cerro Toco (5380 m) Atacama Desert, Chile	30-70 cm^{-1} (SAO FTS) 230-500 cm^{-1} (REFIR-PAD)	• H_2O foreign continuum 0-600 cm^{-1} • H_2O self continuum 0-100 cm^{-1} • Air-broadened widths of 58 H_2O lines in far-IR (240-510 cm^{-1}) • Air-broadened widths of 16 H_2O lines in sub-mm (18-70 cm^{-1})	Turner et al. (2012b) Mast et al. (2017) Mlawer et al. (2019)

Overview: Turner et al. (2010)

Key challenge for all H_2O radiative closure studies

Specifying an accurate H_2O field above the radiometer

Step 1) Start with something reasonable, but possibly biased

- typically, radiosonde

Step 2) **Either**

i. Retrieve more information about H_2O profile using a radiation measurement in a different spectral region where the spectroscopy is well known (e.g. 22 or 183 GHz H_2O lines)

ii. Do closure study in targeted spectral region

Or

Simultaneously retrieve H2O profile information and targeted spectroscopy using single measurement

Radiative Heating in Underexplored Bands Campaigns

Goal: Improve far-IR spectroscopy

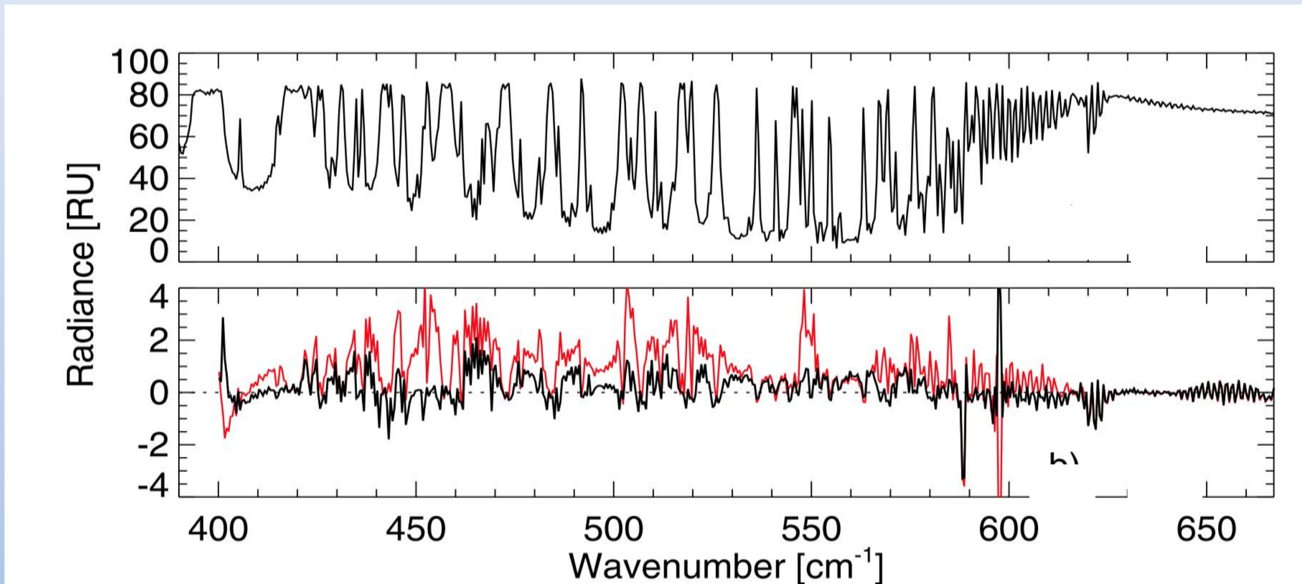
RHUBC-I

- ARM North Slope of Alaska Site, Barrow, AK
- February - March 2007, 70 radiosondes launched
- **Minimum PWV: 0.95 mm**
- 2 far-IR / IR interferometers
  - **- extended range AERI: > 400 cm^{-1}**
- 3 sub-millimeter radiometers → determine PWV

RHUBC- I: Results

Spectroscopic modifications from RHUBC-I (Delamere et al., 2010)

- adjustments to water vapor foreign continuum
- air-broadened line widths for 42 H_2O lines were adjusted

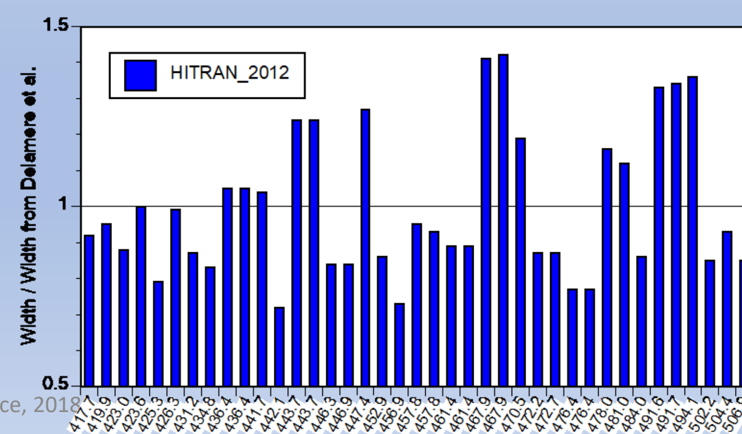


AERI_ER Measurements

AERI_ER – LBLRTM residuals before RHUBC-I

Residuals after RHUBC-I

Width ratios: HITRAN2012 / Delamere



Radiative Heating in Underexplored Bands Campaigns

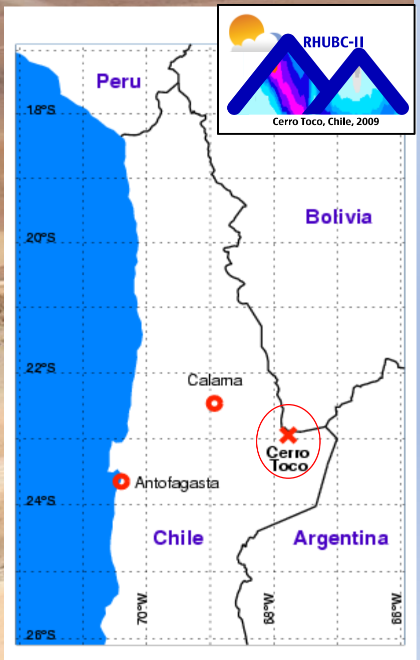
Goal: Improve far-IR spectroscopy

RHUBC-I

- ARM North Slope of Alaska Site, Barrow, AK
- February - March 2007, 70 radiosondes launched
- **Minimum PWV: 0.95 mm**
- 2 far-IR / IR interferometers
  - **- extended range AERI: > 400 cm^{-1}**
- 3 sub-millimeter radiometers → determine PWV

RHUBC-II

- Cerro Toco, Chile (23ºS, 68ºE, altitude - **5380 m**)
- August - October 2009, 144 radiosondes were launched
- **Minimum PWV: ~0.2 mm (5x drier than RHUBC-I)**
- 3 far-IR / IR interferometers
  - **REFIR-PAD (FTS) – 100-1400 cm^{-1}**
- Sub-mm radiometer: **SAO-FTS - 20-120 cm^{-1}**
- 183 GHz radiometer for determining H_2O



RHUBC-II H_2O Profiles

Step 1) "Start with something reasonable … radiosonde"

RHUBC-II: Radiosondes not too reasonable

Step 2) **Either** Retrieve H_2O using well known spectroscopy

Or Simultaneously retrieve H2O and targeted spectroscopy"

RHUBC-II REFIR-PAD:

a) Retrieve H_2O profile using GVRP (183 GHz) measurement (prior: sonde)

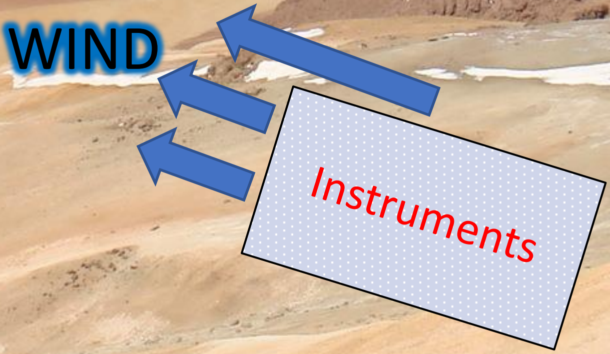
b) Scale H_2O profiles using 400-550 cm^{-1} measurements (spectroscopy reasonable from Delamere et al.)

7% scaling

RHUBC-II SAO FTS:

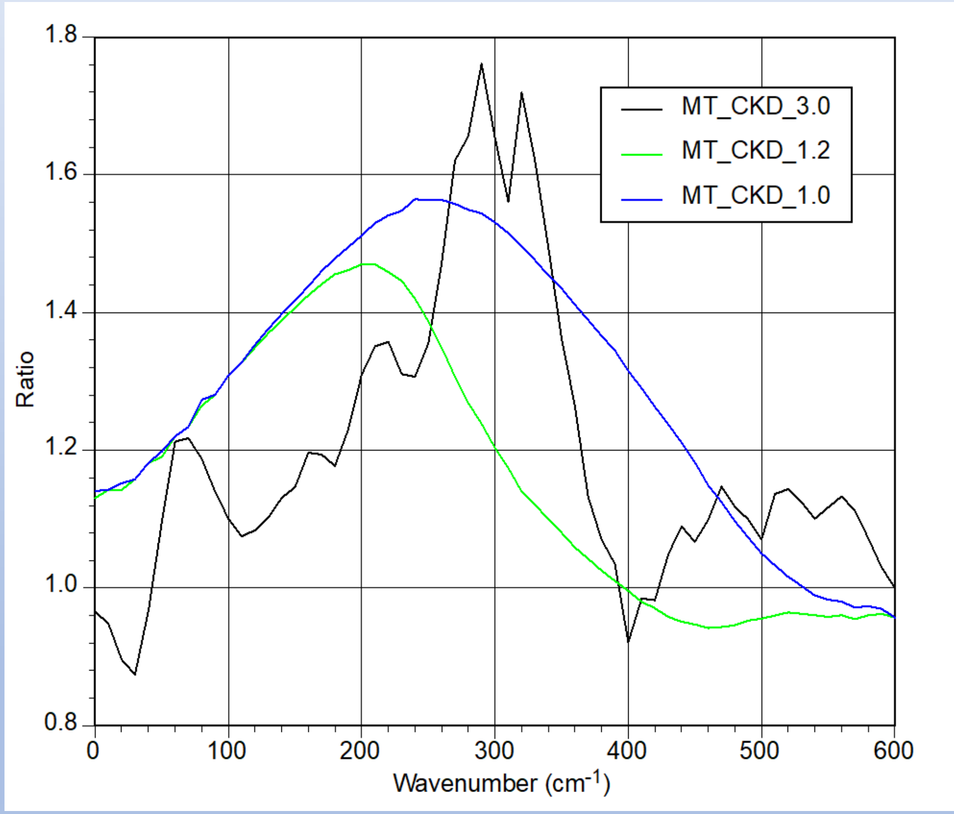
a) Retrieve H_2O scale factor using each SAO FTS measurement

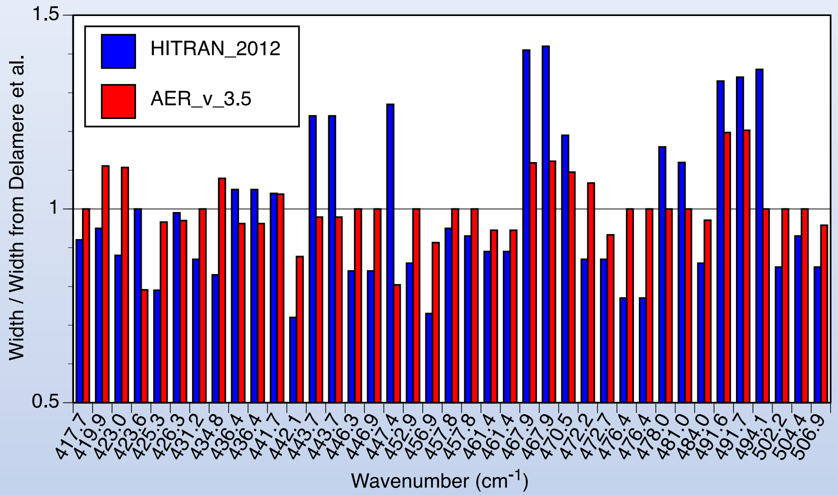
average – 5.5% scaling



RHUBC-II spectroscopic improvements

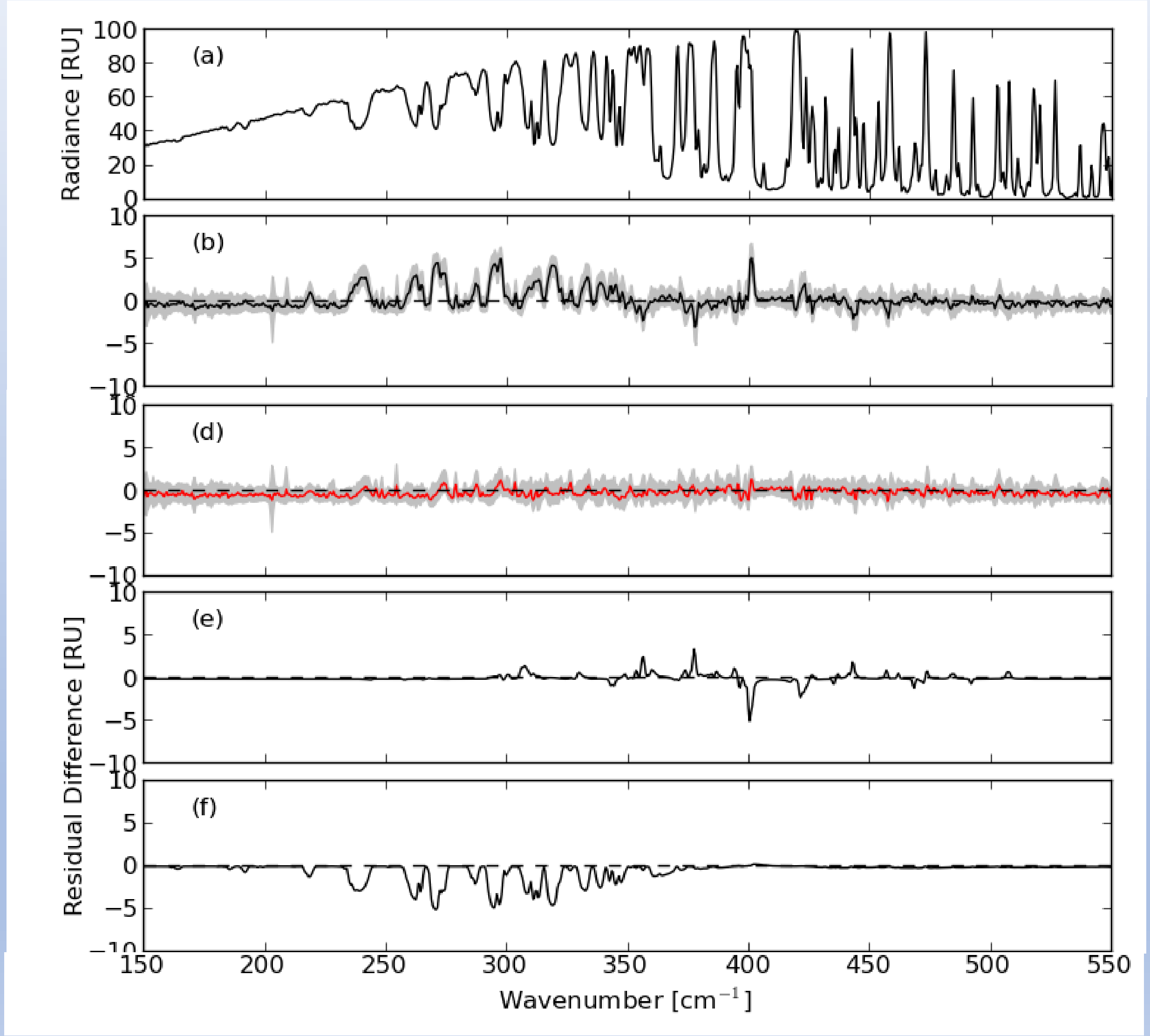
Foreign continuum changes from RHUBC-II analysis (with respect to Delamere et al.)





Line width changes from RHUBC-II analysis (with respect to Delamere et al.)

Far-IR results for cases with 0.3 mm < PWV < 0.5 mm



Median REFIR-PAD observations

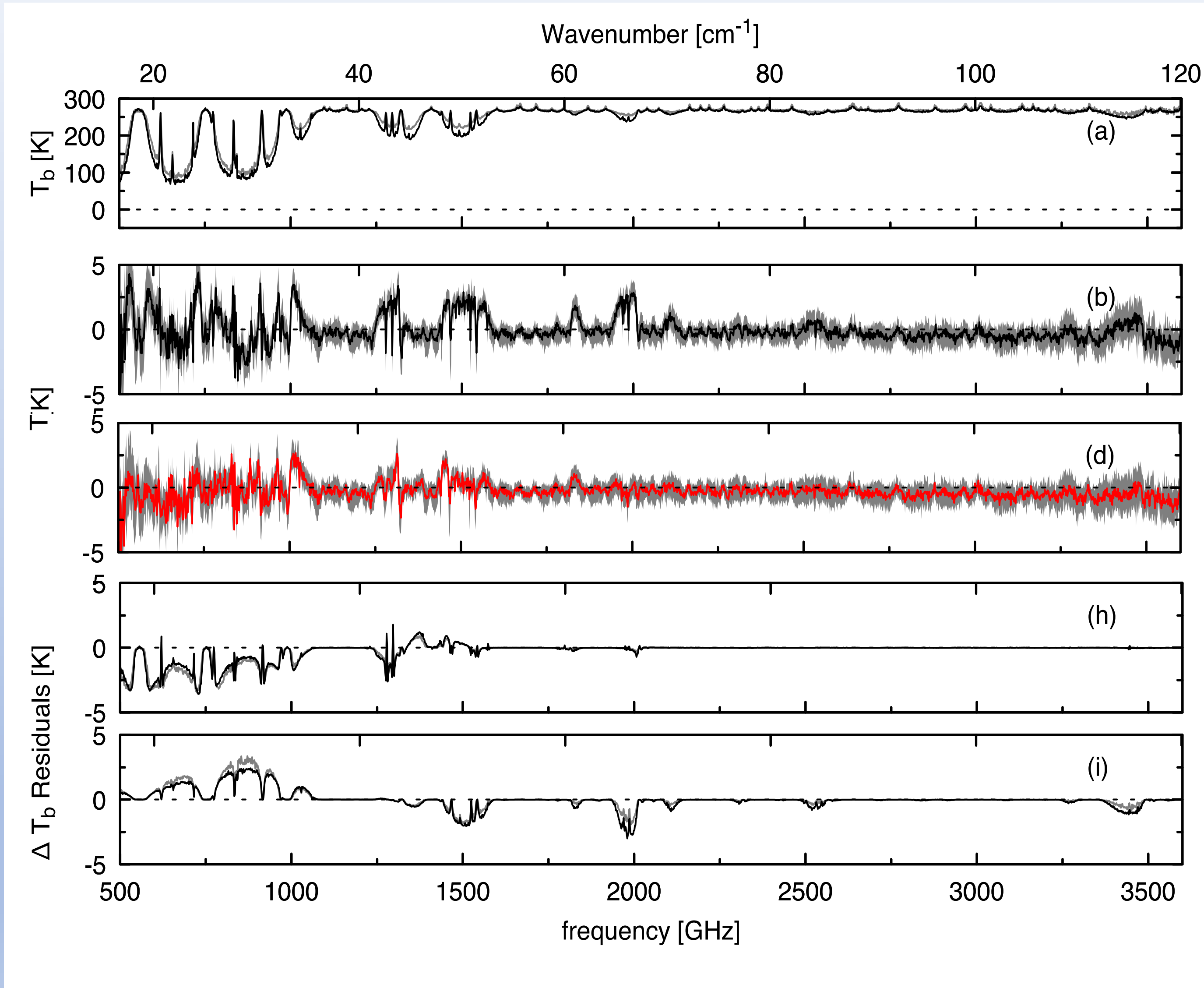
Median REFIR-PAD – LBLRTM residuals with previous spectroscopy

Median REFIR-PAD – LBLRTM residuals with **improved** spectroscopy

Radiance change due to width improvements

Radiance change due to foreign continuum improvements

Sub-mm results for cases with 0.3 mm < PWV < 0.5 mm



Median SAO FTS observations

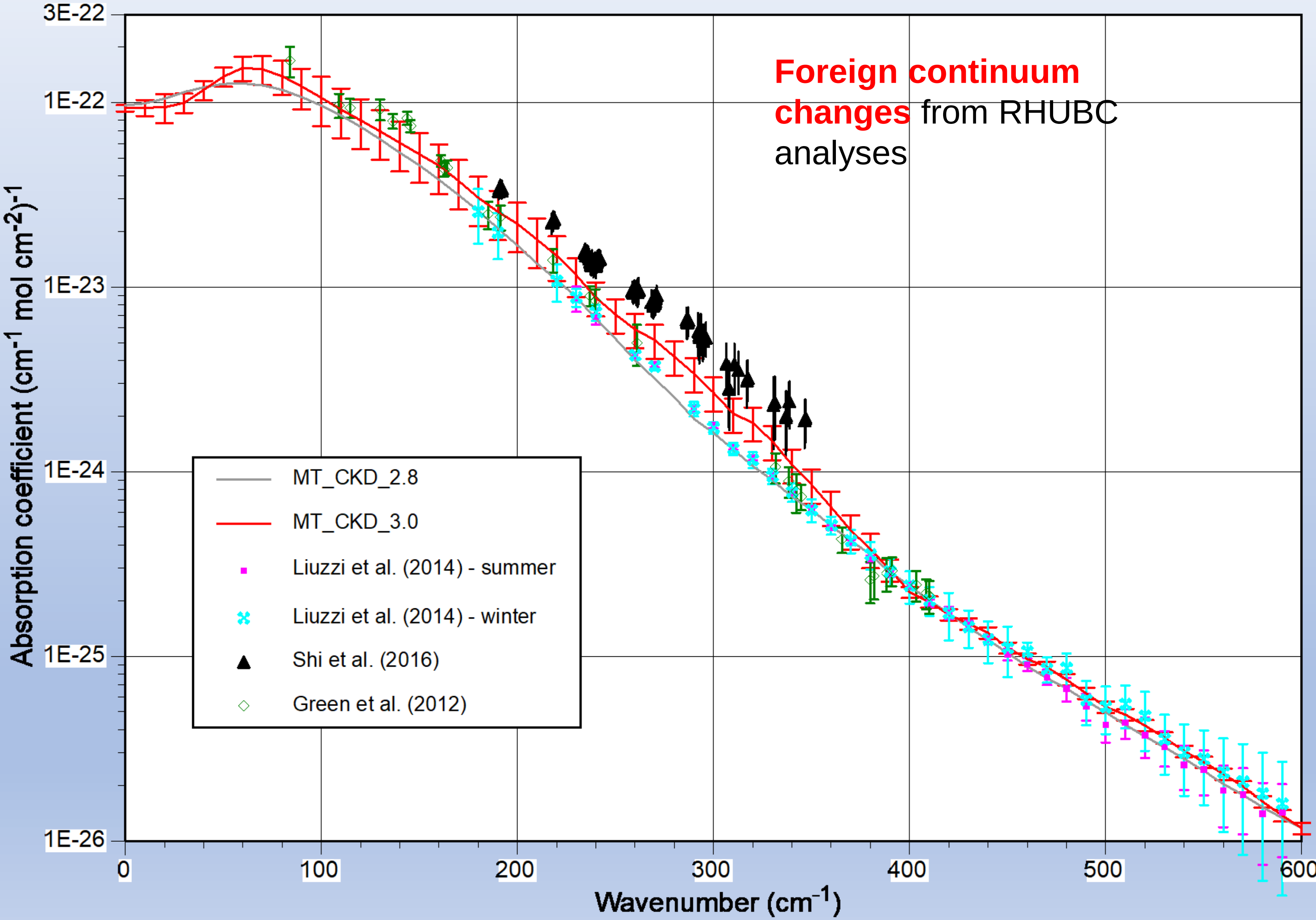
Median SAO FTS – LBLRTM residuals with previous spectroscopy

Median SAO FTS – LBLRTM residuals with **improved** spectroscopy

Radiance change due to width improvements

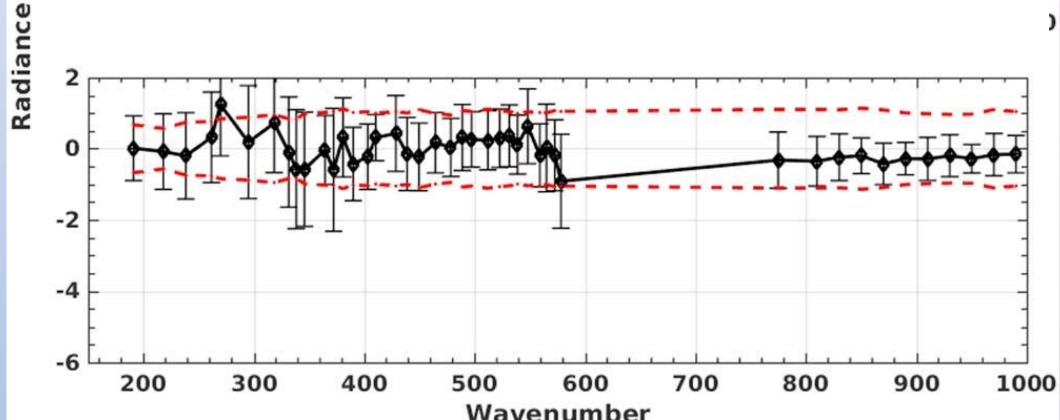
Radiance change due to foreign continuum improvements

RHUBC-II spectroscopic improvements



Independent evaluation

Rizzi et al. (2018) used REFIR-PAD measurements from Antarctica to evaluate the improved LBLRTM (v12.7 with MT_CKD_v3.0).



Winter cases from Rizzi et al. (2018)

“The new simulations show that residuals between 200 and 400 cm^{-1} are much reduced with respect to (previous results) and are now within the combined error estimates ... average residuals for austral winter days are remarkably close to zero”

Effect of line widths on the observed CIA

From K. Sung - Preliminary

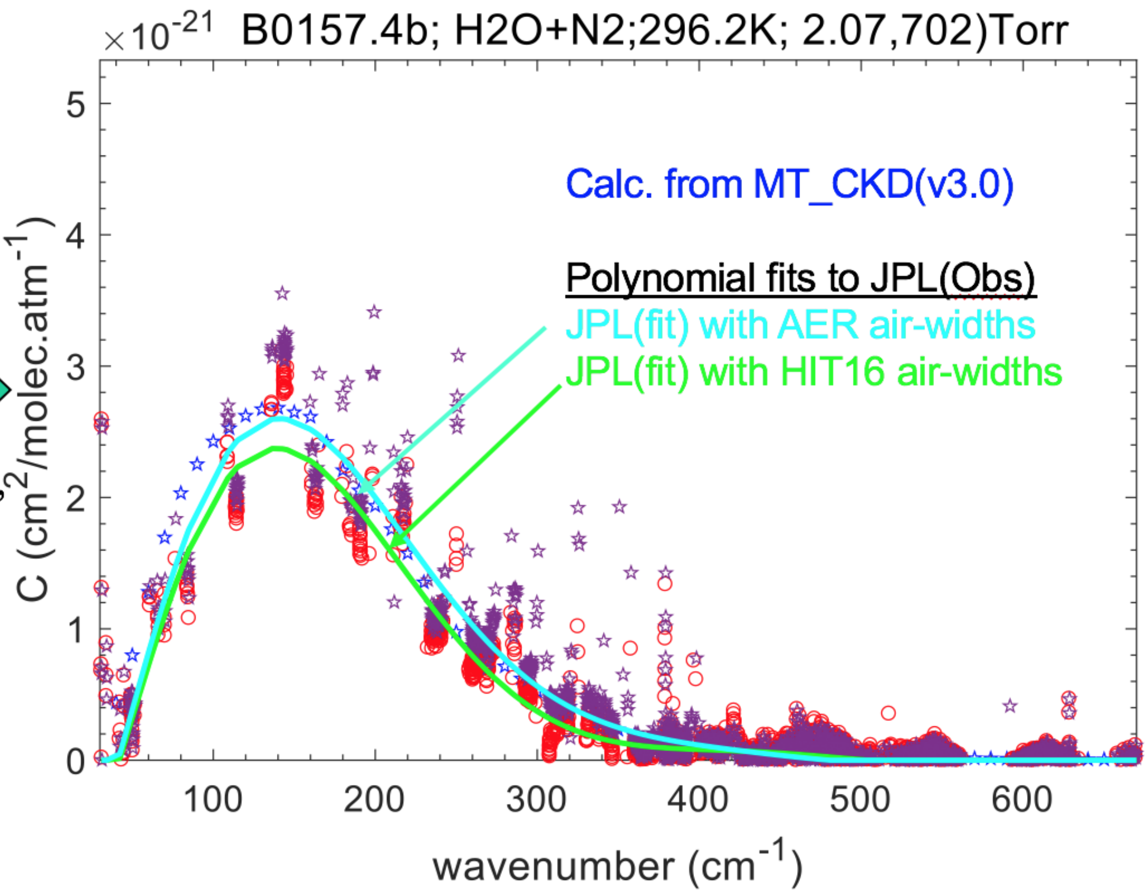
- **B1057.4b spectrum**

H_2O broadened by N_2 at 289 K
296.2 K , P=(2.7, 701.7) Torr

- **CIA comparison**

MT_CKD(v3.0) [water+air]
JPL(Obs) [water+N_2]
(1) used AER air-widths
(2) used HIT16 air-widths

For the resonance absorption simulation, the air-broadened widths were adjusted to be $\gamma_{N2} = \gamma_{air} \times 1.12$ and $\gamma_{O2} = \gamma_{N2} \times 0.50$.



- **New results at 296 K**

(1) A better agreement bet. MT_CKD and JPL(Obs.)
(2) Still, JPL(obs) is lower in the region > ~120 cm^{-1}

Effect of line widths on the observed CIA

From K. Sung - Preliminary

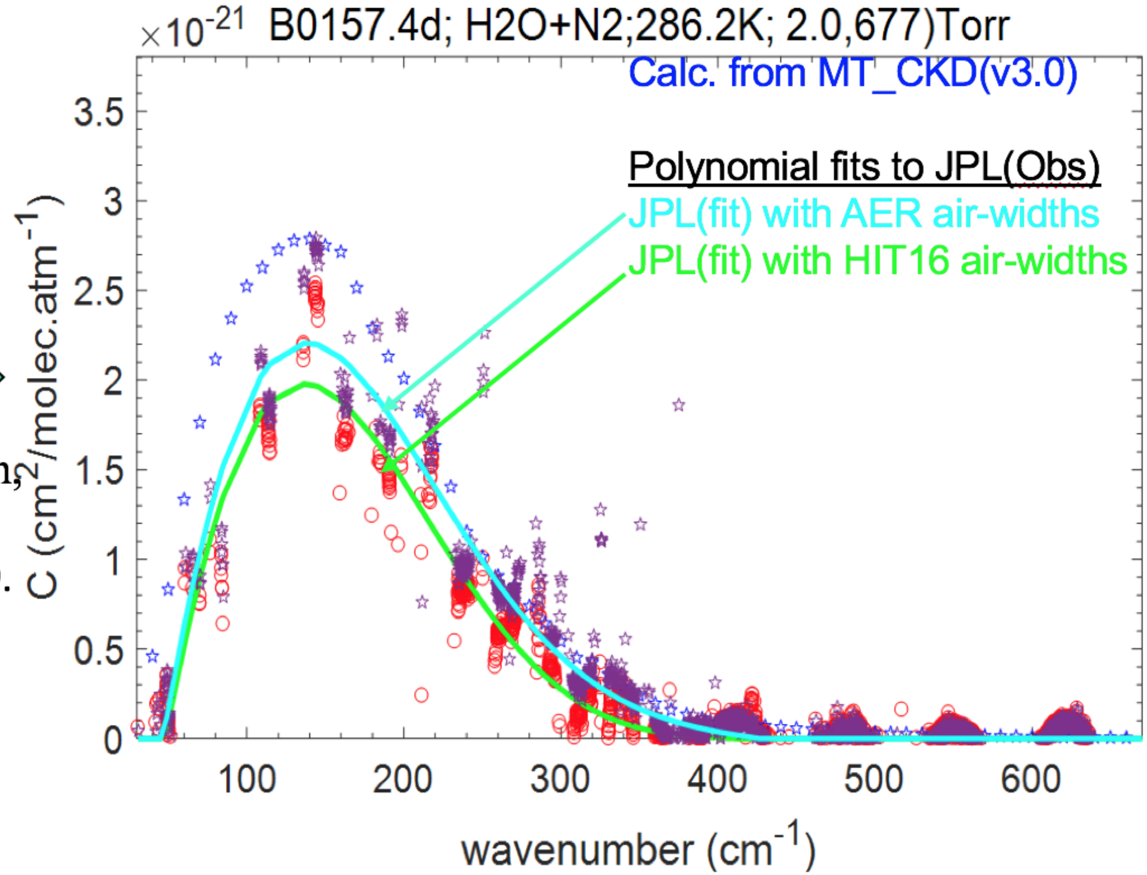
- **B1057.4d spectrum**

H_2O broadened by N_2 at 286 K
286 K , P=(2.0, 677) Torr

- **CIA comparison**

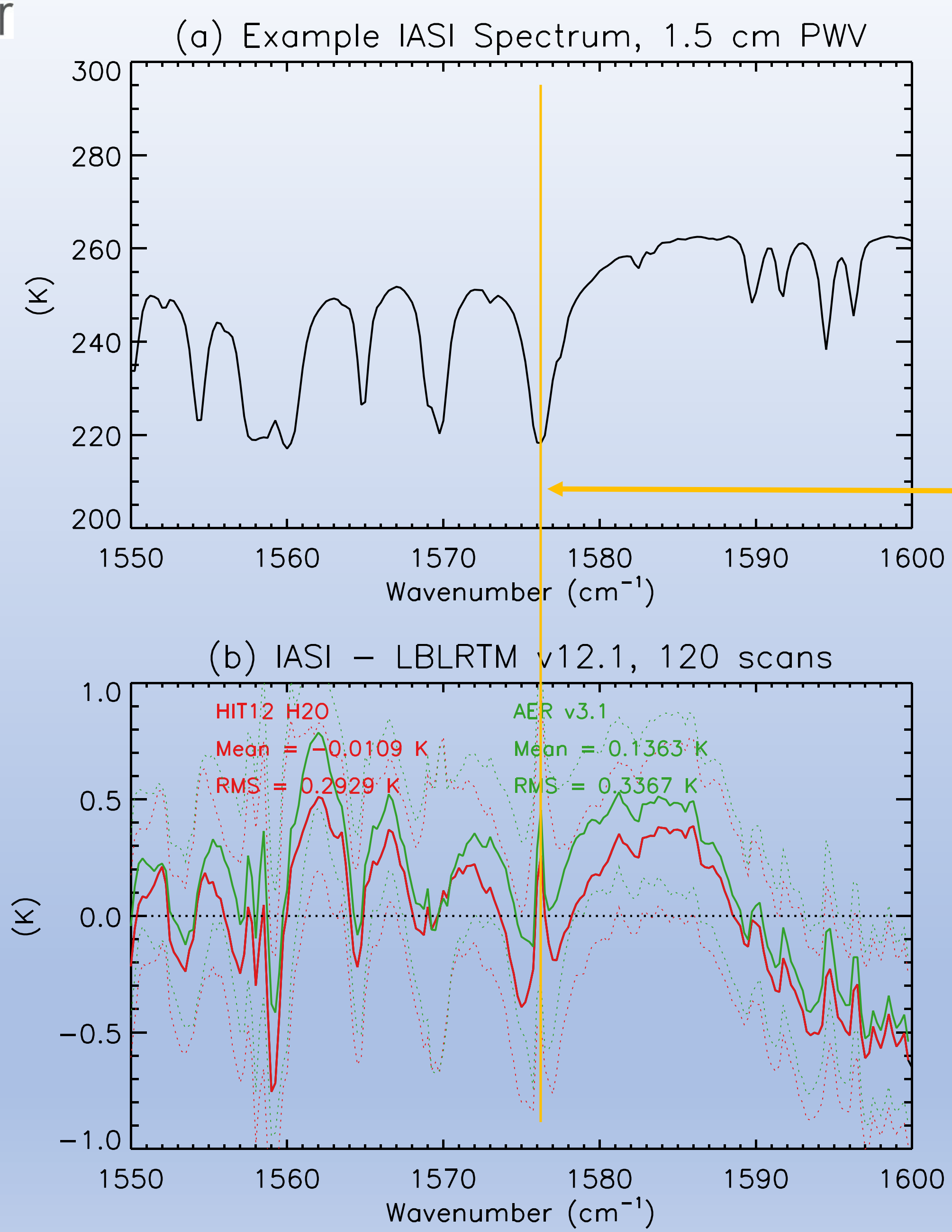
MT_CKD(v3.0) [water+air]
JPL(Obs) [water+N_2]
(1) used AER air-widths
(2) used HIT16 air-widths

For the resonance absorption simulation, the air-broadened widths were adjusted to be $\gamma_{N2} = \gamma_{air} \times 1.12$ and $\gamma_{O2} = \gamma_{N2} \times 0.50$.



- **New results at 286 K**

(1) Better agreement than JPL(obs) from HITRAN widths
(2) However, still JPL(obs) is lower.
(3) Perhaps, T-dep. of the widths needs further inspection.



Numerous lines in the H_2O ν_2 band with air-broadened width issues in HITRAN 2012

Related project

- Funded by DOE Atmospheric Systems Research Program
- Collaboration between AER, Dave Turner, Vivienne Payne, Dan Feldman
- Objectives include:
    - Use AERI measurements from dry locations (e.g. AWARE campaign in Antarctica, NSA) as well as IASI measurements to evaluate and improve the H_2O air-broadened line widths and foreign continuum in the ν_2 band (1200-2000 cm^{-1})
    - Use AERI measurements from multiple locations, including those with high values of PWV (e.g. Darwin) to improve water vapor self continuum, self continuum temperature dependence, and water vapor foreign continuum in atmospheric window (800-1200 cm^{-1})
        - Improve upon analysis in Turner et al. (2004), the foundation for the window self continuum in all GCMs
        - Very important for water vapor feedback due to climate change

Main points

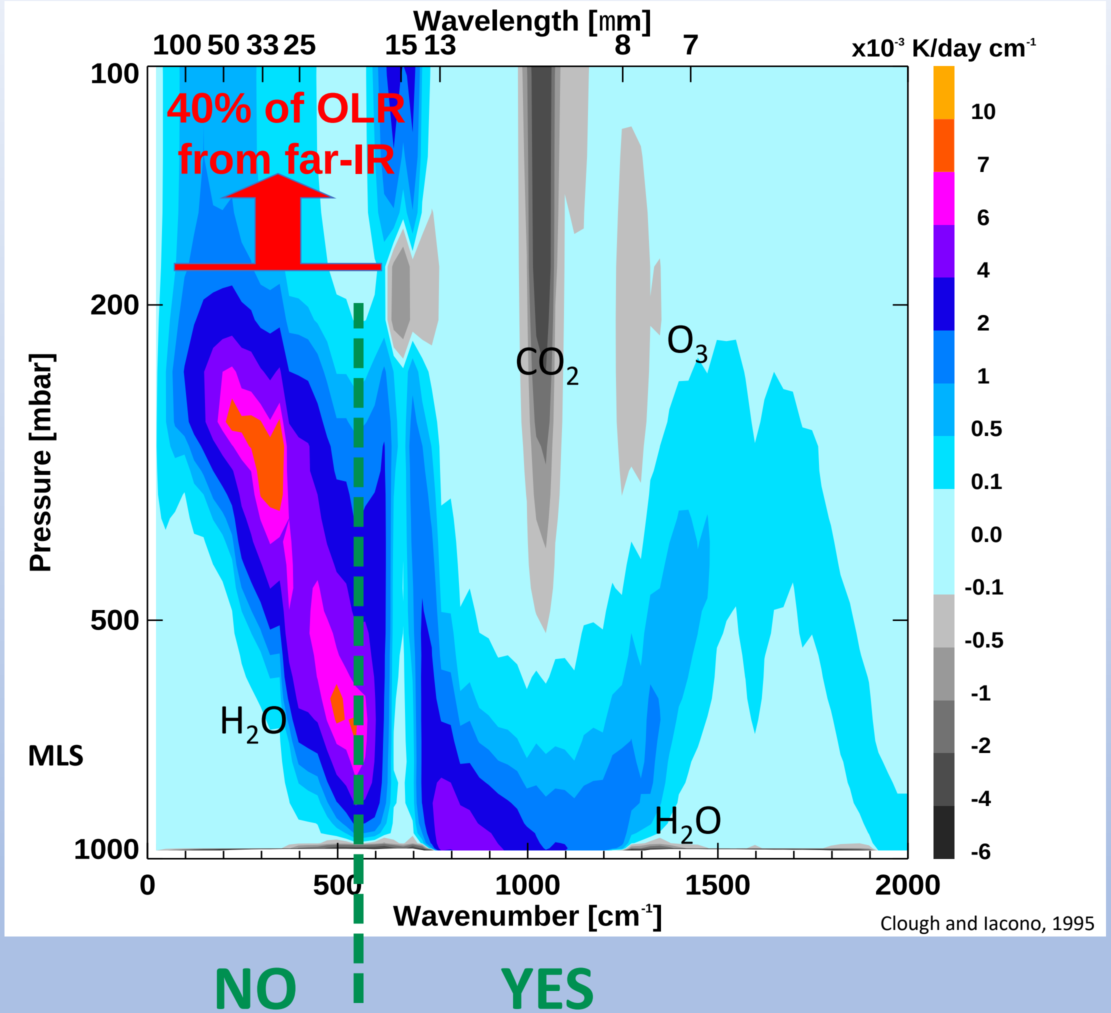
- Radiative closure experiments continue to play an important role in improving and validating spectroscopic input to radiative transfer calculations
  - e.g. RHUBC-I and –II, far-IR H_2O line widths and continuum
- Significant uncertainty remains in the far-IR continuum, impacting broadband flux and upper troposphere heating rate calculations, as well as H_2O retrievals from FORUM.
  - The analysis of accurate FORUM measurements can help lead to improvements to these issues
- Water vapor continuum gets attention, but the important role of accurate line widths get less

Back-up slides

The importance of the far-IR

Spectral Cooling Rates (troposphere)

"Clough Plot"

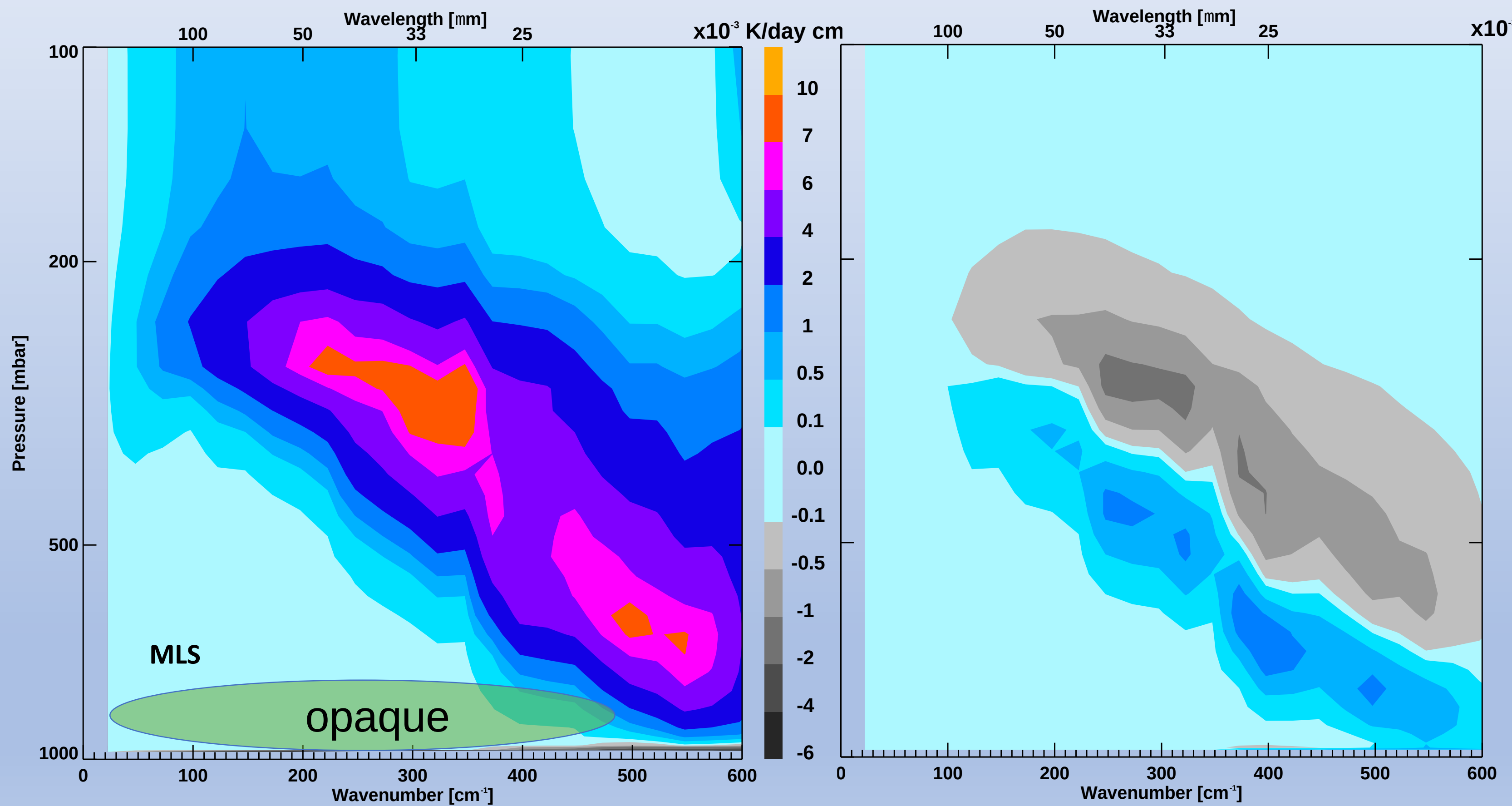


As of ~10 years ago, had spectroscopic parameters been evaluated by field observations?

Far-Infrared Radiative Processes

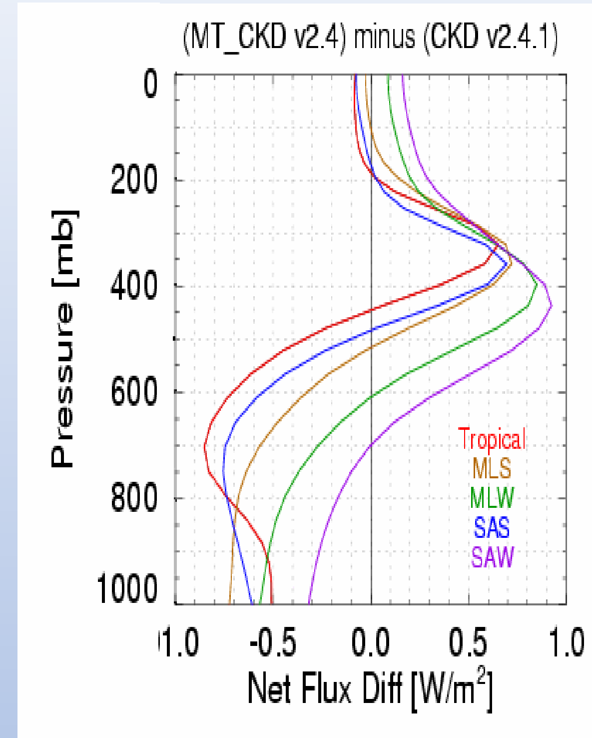
Cooling rates due to H_2O lines and H_2O continuum

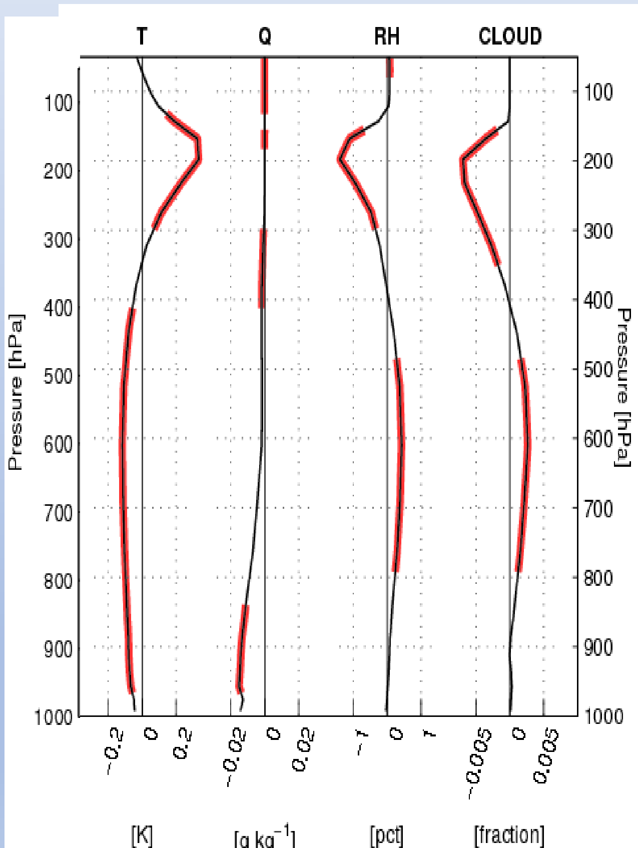
Impact on cooling rates of turning off H_2O continuum



RHUBC- I: Results

Revised continuum and widths lead to significant changes in net flux





- RRTMG updated with revised continuum (MT_CKD_2.4)
- 20-yr simulation performed with CESM v1 (Turner et al., 2012)
  - statistically significant changes in temperature, humidity, and cloud fraction

Radiative Heating in Underexplored Bands Campaign - II

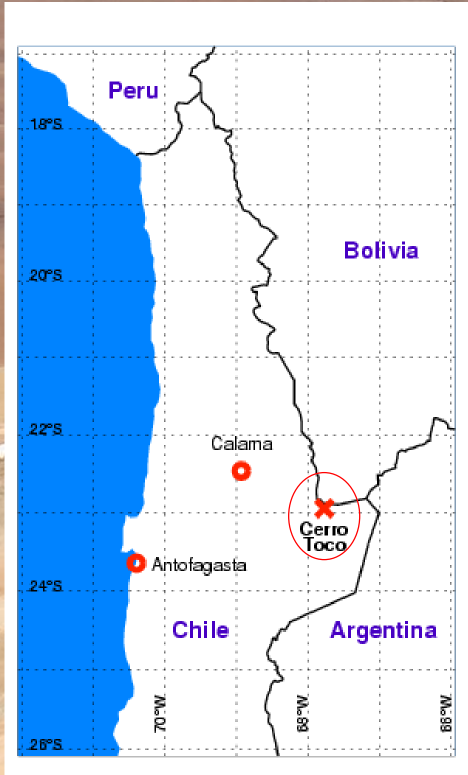
RHUBC-II

- Cerro Toco, Chile (23ºS, 68ºE, altitude - 5380 m)
- August - October 2009, 144 radiosondes were launched
- Minimum PWV: ~0.2 mm (5x drier than RHUBC-I)
- 3 far-IR / IR interferometers (**REFIR**, FIRST, AERI)
    - REFIR (FTS) – 100-1400 cm^{-1}
- 183 GHz radiometer for determining H_2O (GVRP)

Major issues in RHUBC-II analysis:

Specifying accurate atmospheric profiles (temperature and H_2O) above the radiometers given that RHUBC-II radiosondes were blown east off cliff by consistent 30 m/s winds

- also, sonde H_2O measurements have known inaccuracies (as much as 60%) in dry conditions

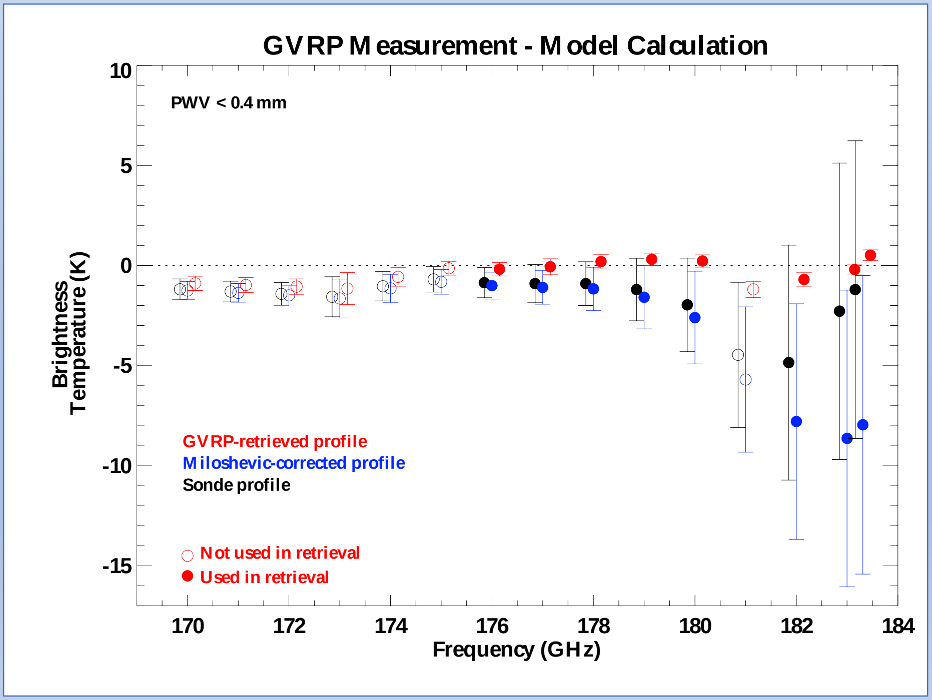


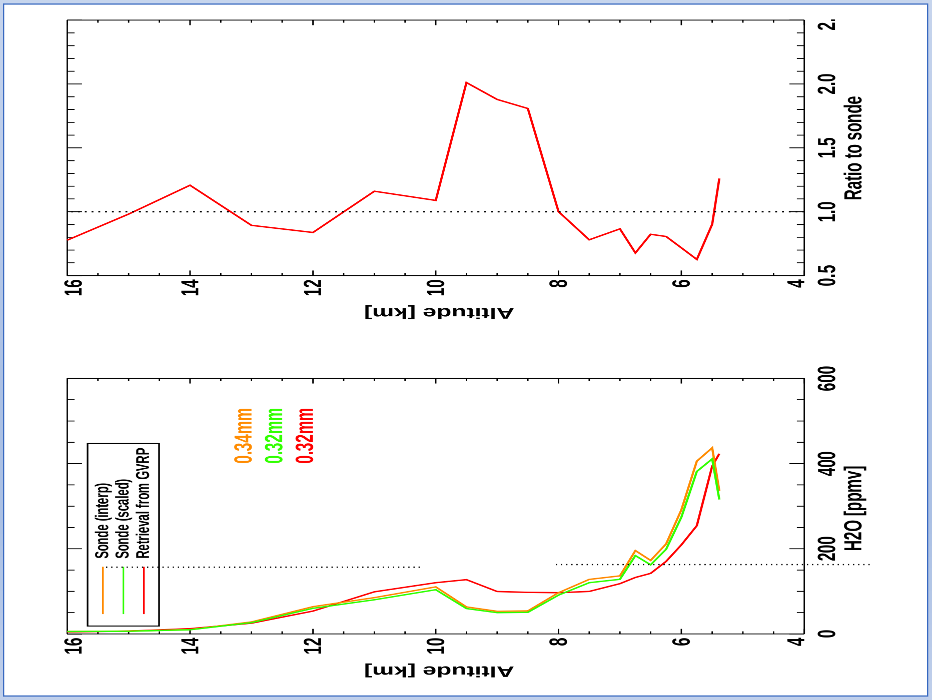
RHUBC – II: Analysis

Determining 'best guess' temperature and H_2O profiles

- **Temperature** – (at each AERI measurement time) blend together:
  - surface - met tower measurement
  - below 3.0 km – combine AERI T retrievals from two strong CO_2 bands
  - above 3.0 km – radiosonde observation (interpolated to time)
- **H_2O** – retrieve H_2O profile using GVRP (183 GHz) and sonde measurements

Example of GVRP Retrieval of H2O Profile

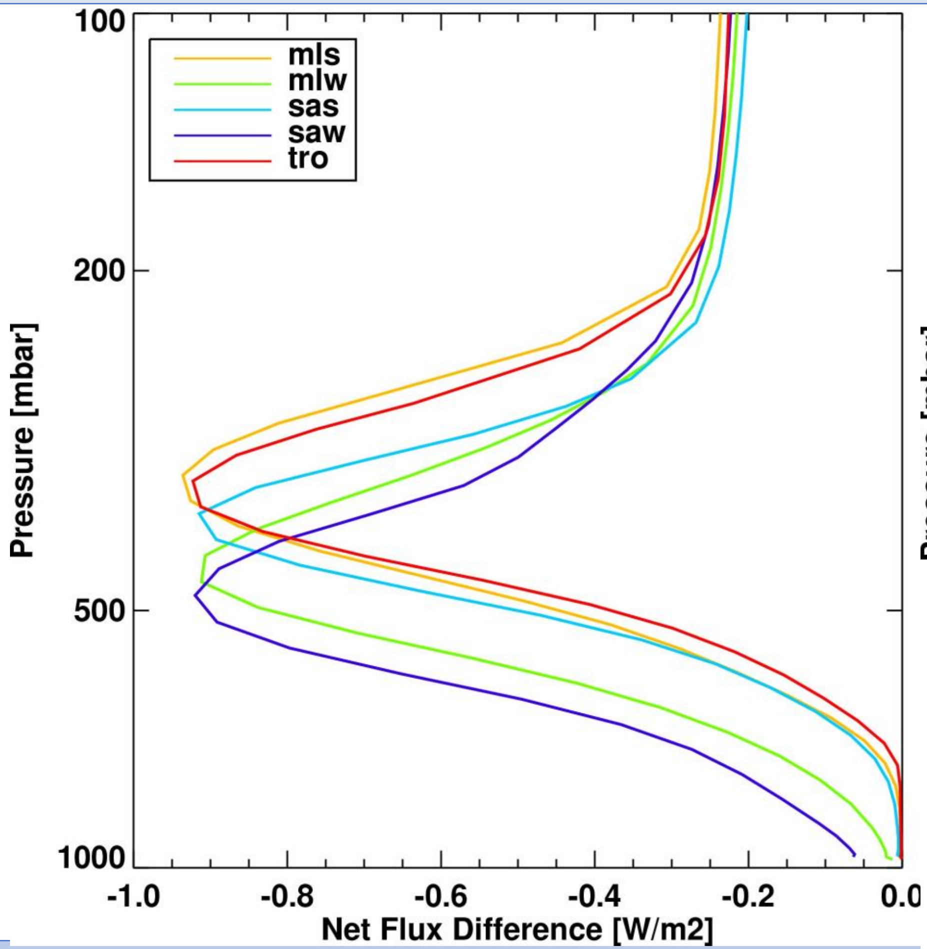




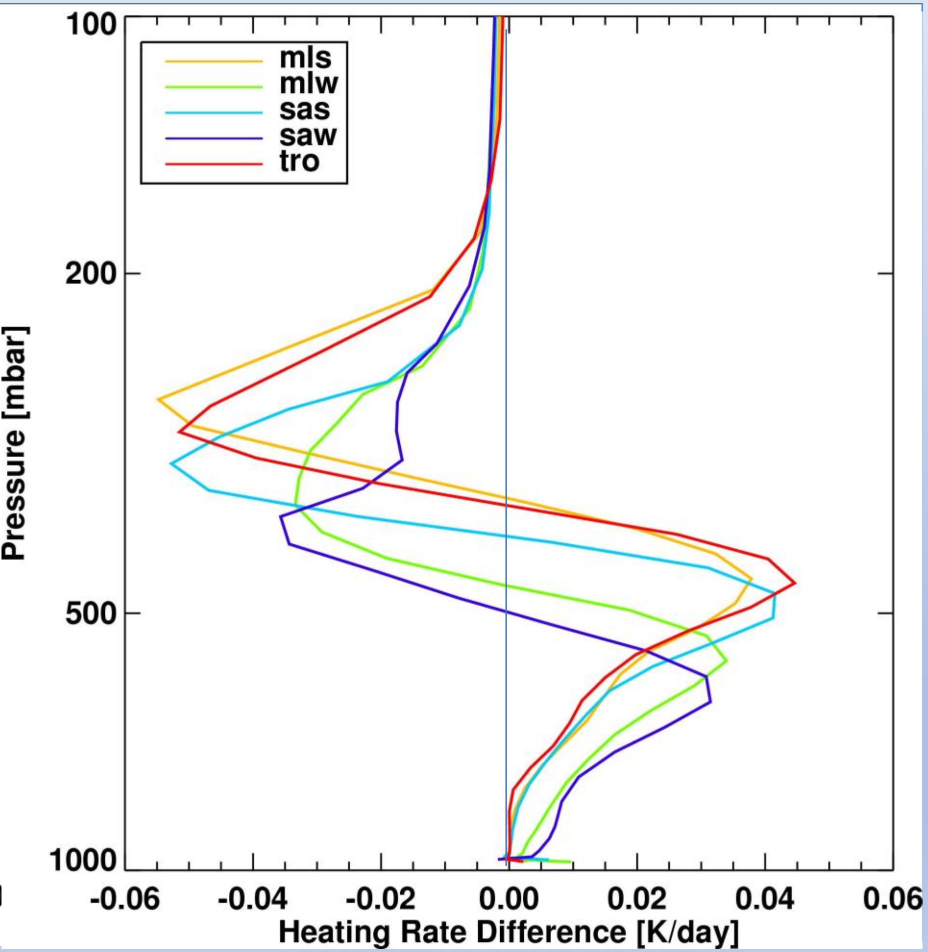
RHUBC – II: Analysis

Effect of foreign continuum derived from RHUBC-II observations
(compared to previous version)

Net Flux

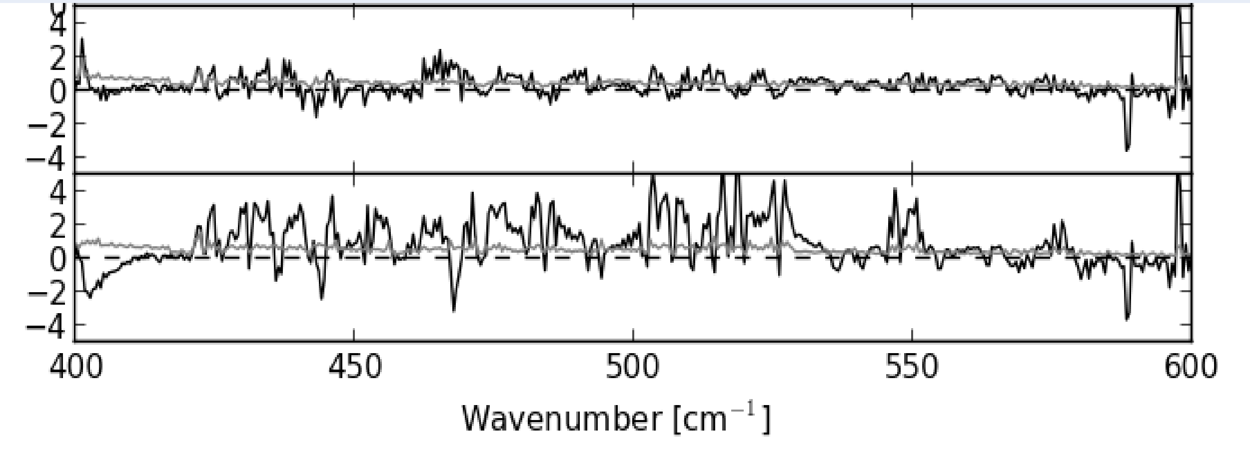


Heating Rates



Impact of HITRAN widths on residuals

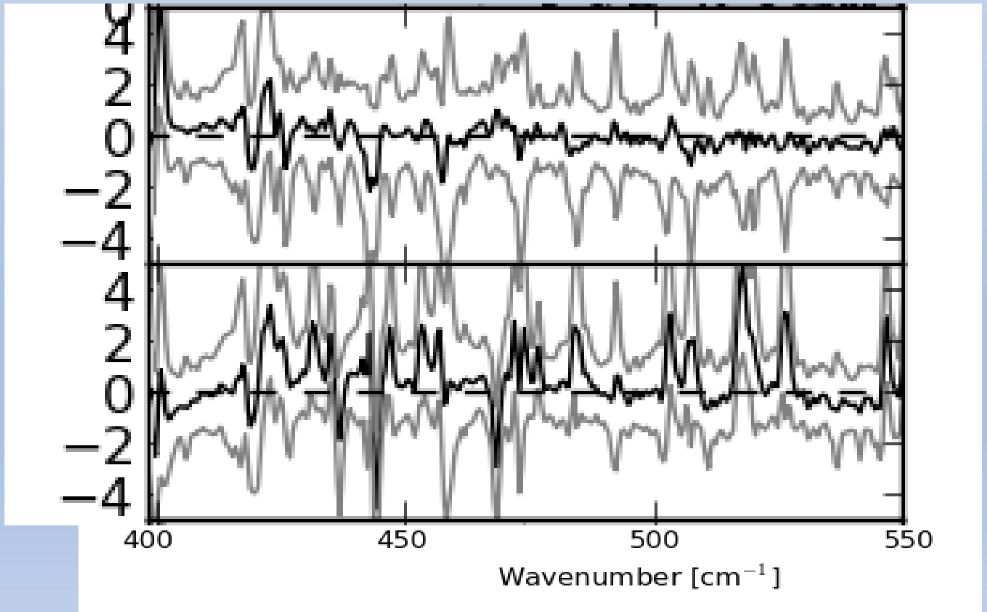
RHUBC-I



AERI – LBLRTM residuals with Delamere et al. widths

Residuals with HITRAN_2012 widths

RHUBC-II



REFIR-PAD – LBLRTM residuals with Delamere et al. widths

Residuals with HITRAN_2012 widths

RHUBC – II: Analysis

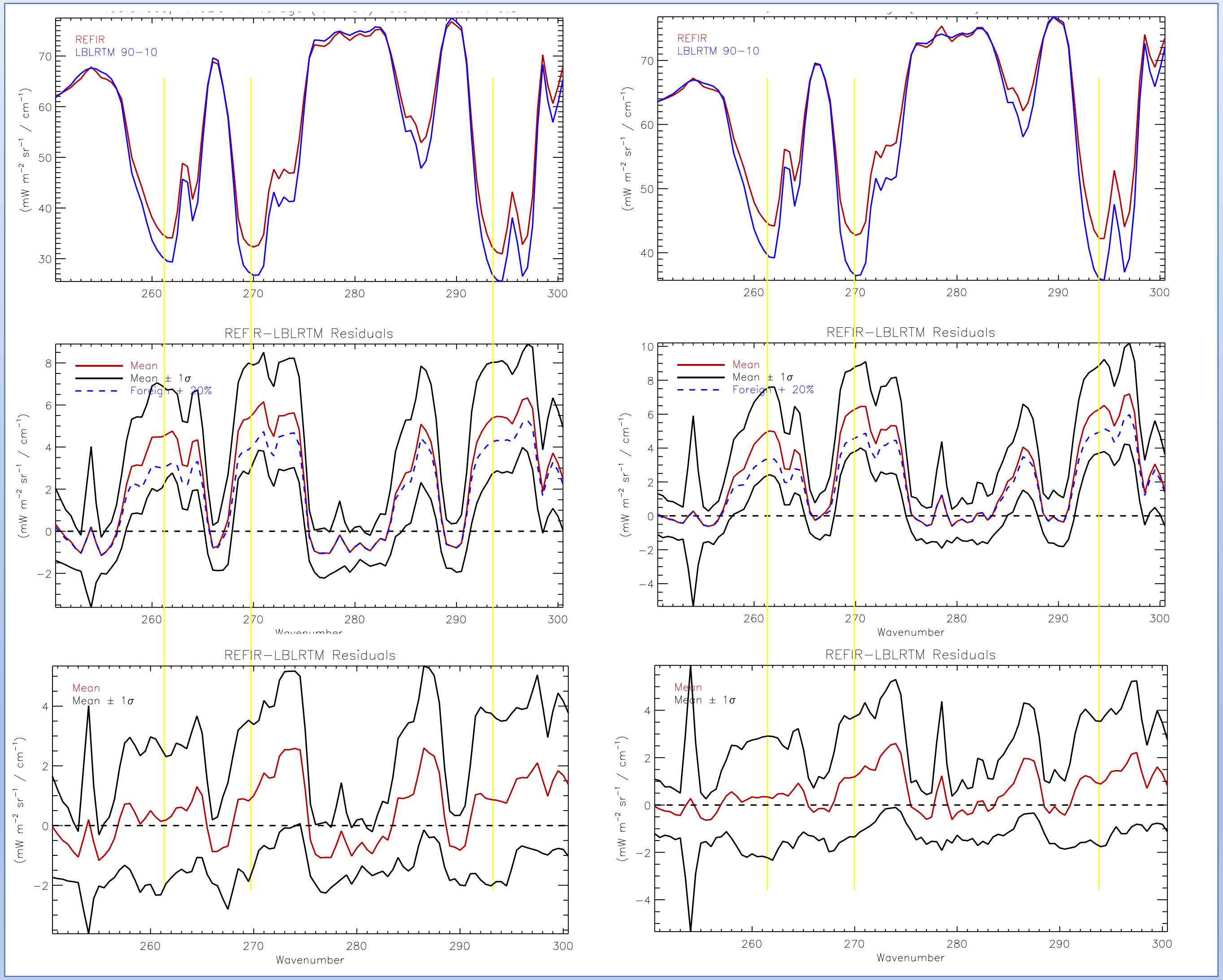
0.0 mm < PWV < 0.3 mm
(34 cases)

0.3 mm < PWV < 0.5 mm
(122 cases)

Observed radiances (REFIR)
LBLRTM calculation (MT_CKD_2.4)

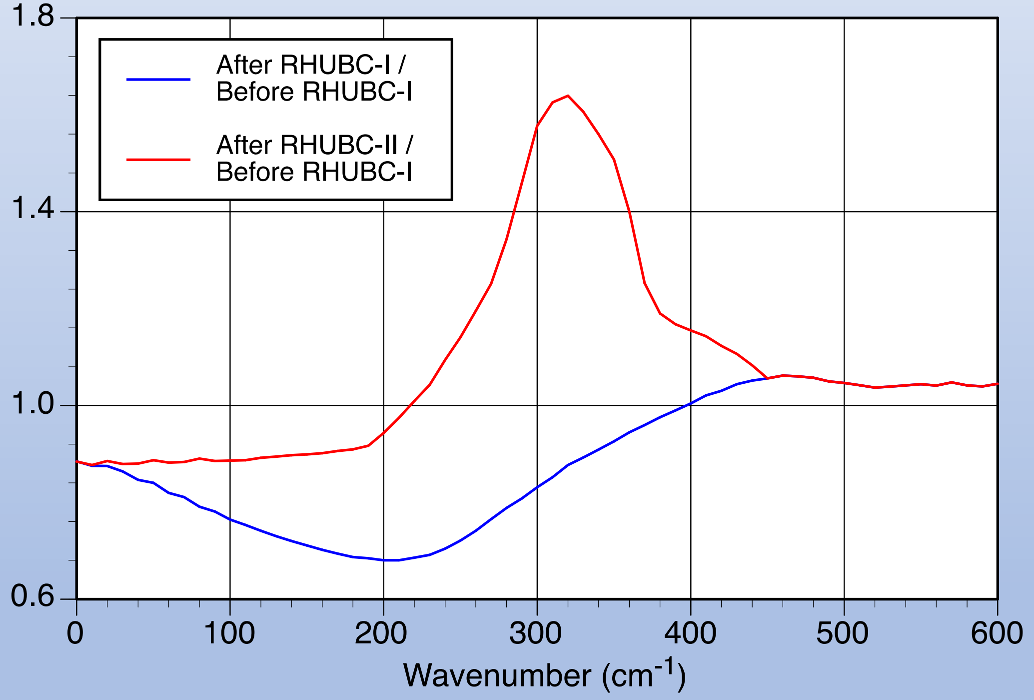
Residuals (REFIR-LBLRTM)
+- 1 stdev
+20% foreign continuum

Residuals (REFIR-LBLRTM) with modified foreign continuum
+- 1 stdev



RHUBC – II: Analysis

RHUBC-II: the H_2O foreign continuum between 200-400 cm^{-1} is much larger than in recent versions of MT_CKD



Aside: What error in calculated absorbed flux matters?

- Having a rule of thumb would be nice, but depends on application

  (ignoring that, let's look at another application)

- Figure 3 from D'Angelis et al. (2015)
  - Clear difference between "observed" sensitivity of absorbed SW (SWA) to precipitable H_2O (PW)
  - dSWA/dPW in models related to dSWA/dT and d(precip)/dT
- Estimate missing absorbed flux that matters:
  - For a value of dSWA/dPW not in agreement with "observations", plot SWA(PW)
  - For a typical PW, find difference in SWA between this curve and one in agreement with observations