Forward Modeling for IASI: Spectroscopic Issues and LBL_CRA

Tony Clough

***C**lough **R**adiation **A**ssociates, LLC*

.

IASI, Sevrier, FR

26 Jan 2010

Collaborators and IASI Cases

- **Collaborators:**
  - M. Shephard, V. Payne, K. Cady-Pereira and J. Delamere AER, Inc.
  - W. Smith and S. Kireev Hampton U.
  - **Extension of**

    Performance of the line-by-line radiative transfer model (LBLRTM) for temperature and species retrievals: IASI case studies from JAIVEx: M. W. Shephard, S. A. Clough, V. H. Payne, W. L. Smith, S. Kireev, and K. E. Cady-Pereira, Atmos. Chem. Phys., 9, 7397-7417, 2009

- **IASI Cases from JAIVEx**
  - **2007_04_19** **Case Study**
    - » **Over SGP site (surface emissivity retrieved)**
    - » **Atmosphere**
      - **Clear and Homogeneous (h2o)**
      - **'Well Characterized'**
  - **2007_04_20** **'Control'**
    - » **Over Gulf of Mexico "**
    - » **Atmosphere**
      - **Broken Clouds and Highly Inhomogeneous (h2o)**
      - **Not So Well Characterized**

Topics / Issues

e.g. Matricardi ACP, 2009

- **Temperature**
  - **Carbon Dioxide**
    - » Line Parameters: CDDB (2008), Tashkun et al. JQSRT, 2009
    - » Line Coupling: Niro et al., JQSRT, 2005 J.M.Hartmann
    - ✓ Agreement between CO_2 ν_2 and CO_2 ν_3
    - ✓ Q-Branch 667 cm-1
    - ✓ Band Head 2385 cm-1
  - **Nitrous Oxide**
    - ? Agreement between CO_2 ν_2 and N_2O ν_3
    - » N_2O profile scaling required: 19 April case: 1.04
      20 April case: 1.02
- **Methane**
  - ✓ Line Coupling: Tran et al., JQSRT, 2006 J.M.Hartmann

Water Vapor

- **A slide of its own**
- **Significant improvements but …**

Introduction

IASI

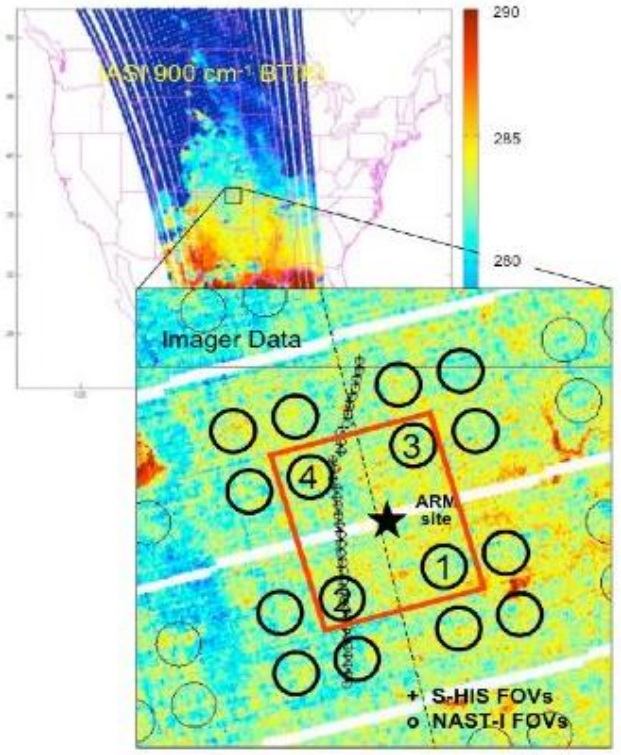
- Scan Rate 8 secs
- Scan Type Step and dwell
- Pixel IFOV 0.8225°
- **IFOV size at Nadir 12 km**
- Sampling at Nadir 18 km
- Earth View Pixels / Scan 2 rows of 60 pixels each
- Swath ± 48.98°
- Swath ± 1066 km
- Spectral Range 645 to 2760 cm-1
- **Resolution (hw/hh) 0.25 cm-1**
- Lifetime 5 years
- Power 210 W
- Size 1.2 m x 1.1 m x 1.3 m
- Mass 236 kg
- Data rate 1.5 Mbps
- **Radiometric Calibration < 0.1 K**

- **The IASI programme is led by**
- **Centre National d'Études Spatiales (CNES) in association with EUMETSAT.**
- **Alcatel Alenia Space is the instrument Prime Contractor.**

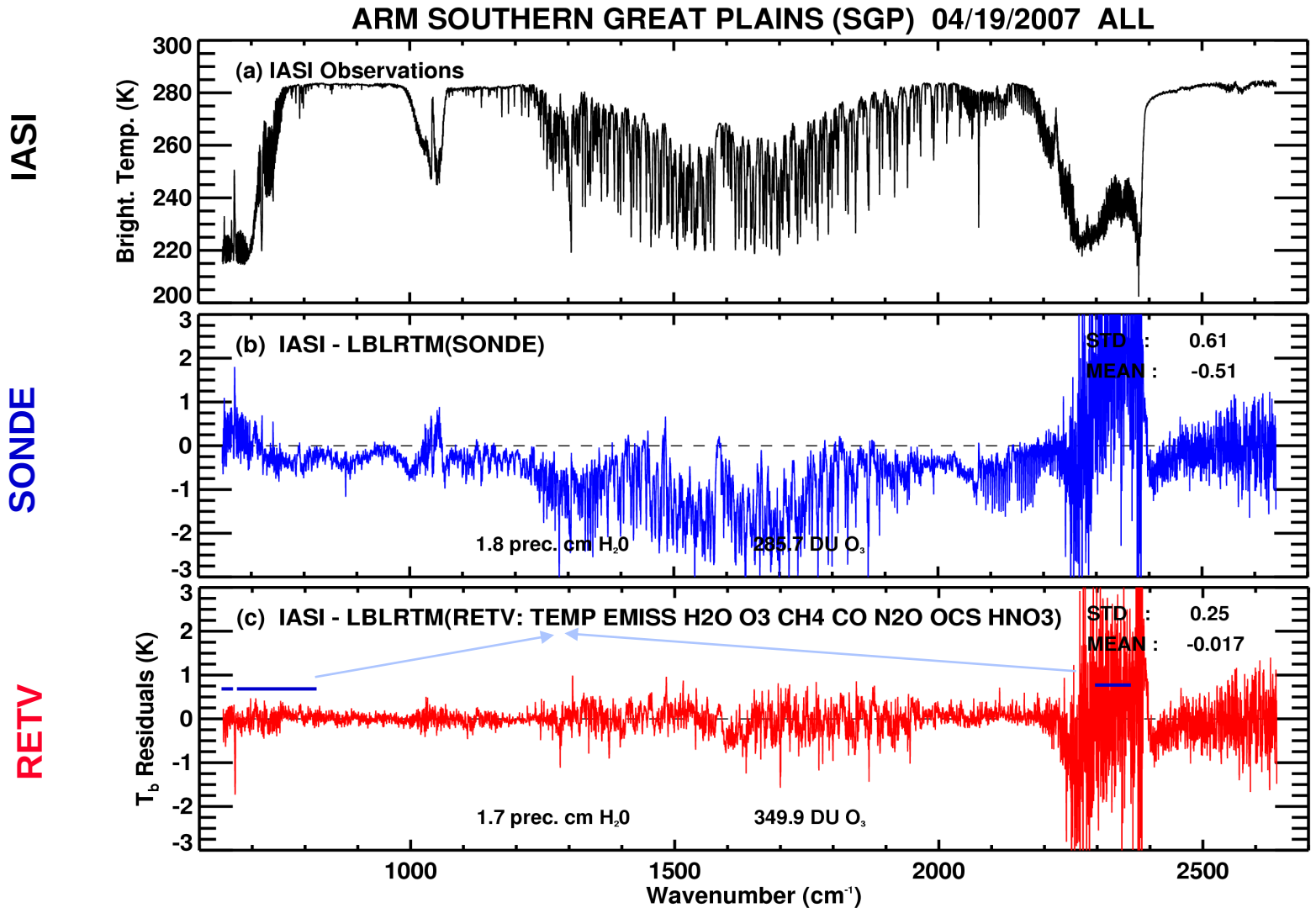
Joint Airborne IASI Validation Experiment

JAIVEx 19 Apr 2007

CART-site (03:35 UTC)



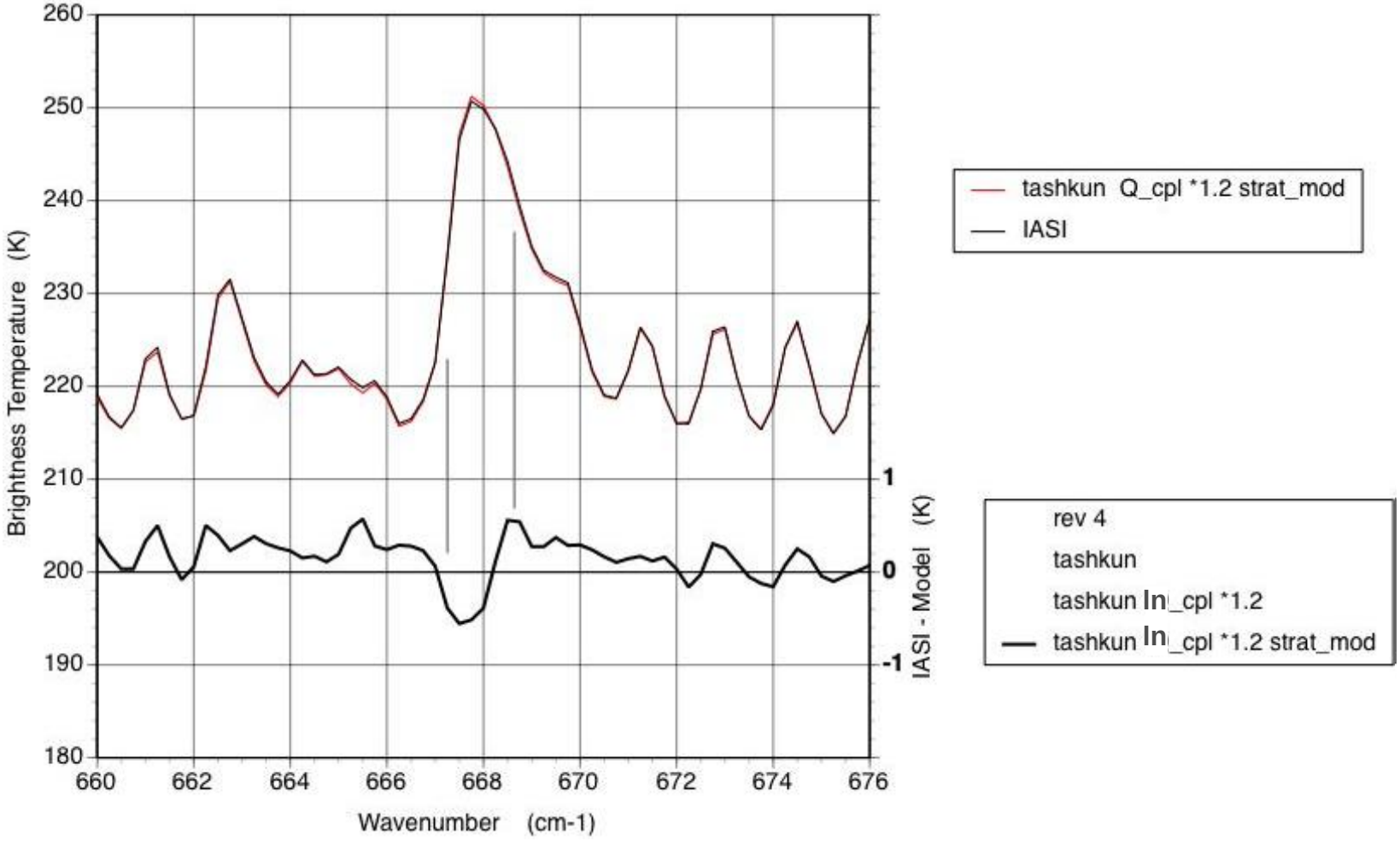
IASI/LBLRTM Validation



Strategy: to analyze the spectroscopy in the context of these red residuals

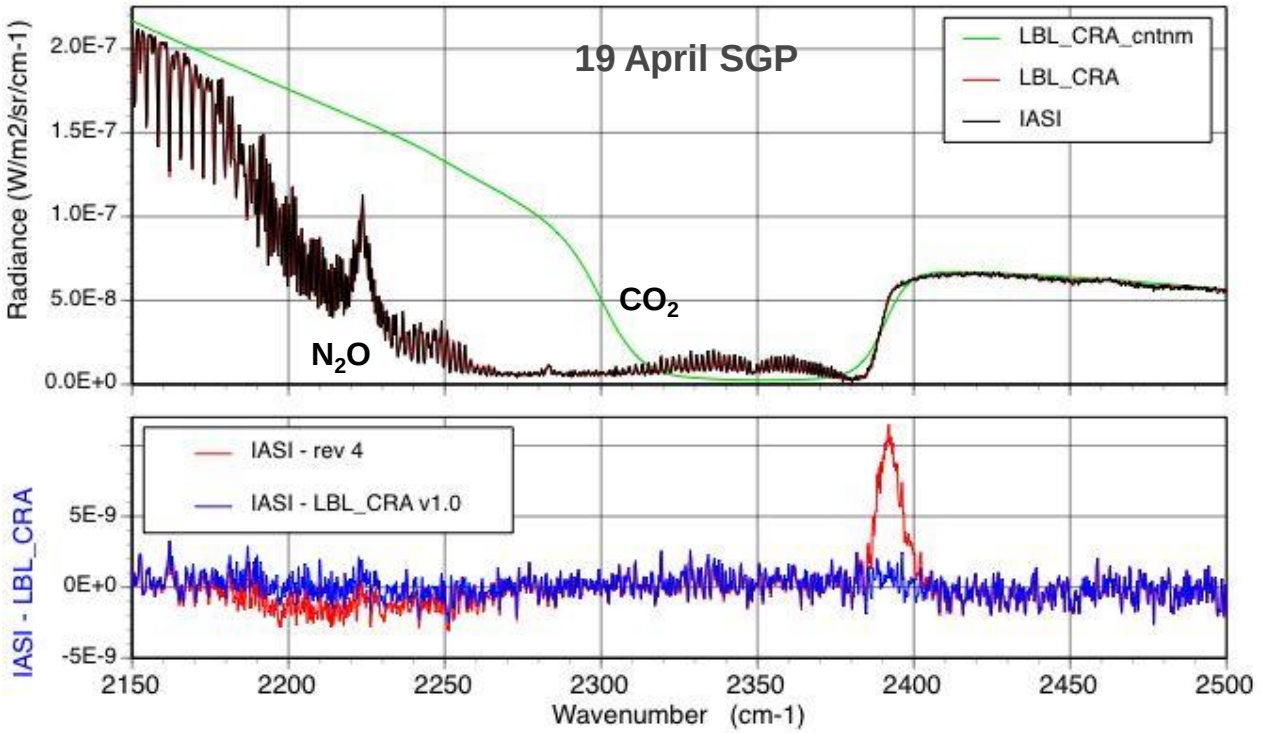
IASI 19 Apr 2007 CO_2 Q-Branch

Sensitivity to Upper Stratosphere



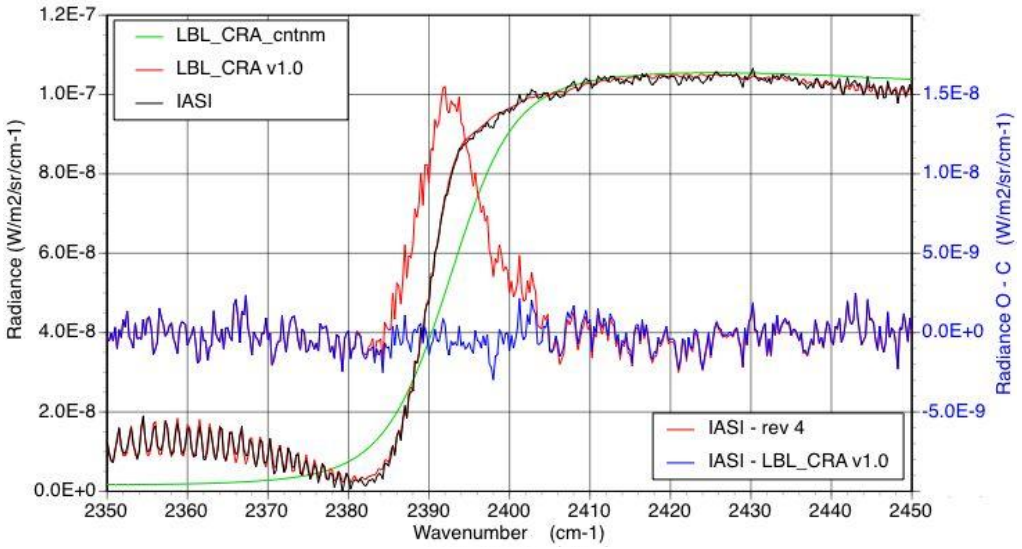
ν_3 Bands of N_2O and CO_2

2150 - 2500 cm-1



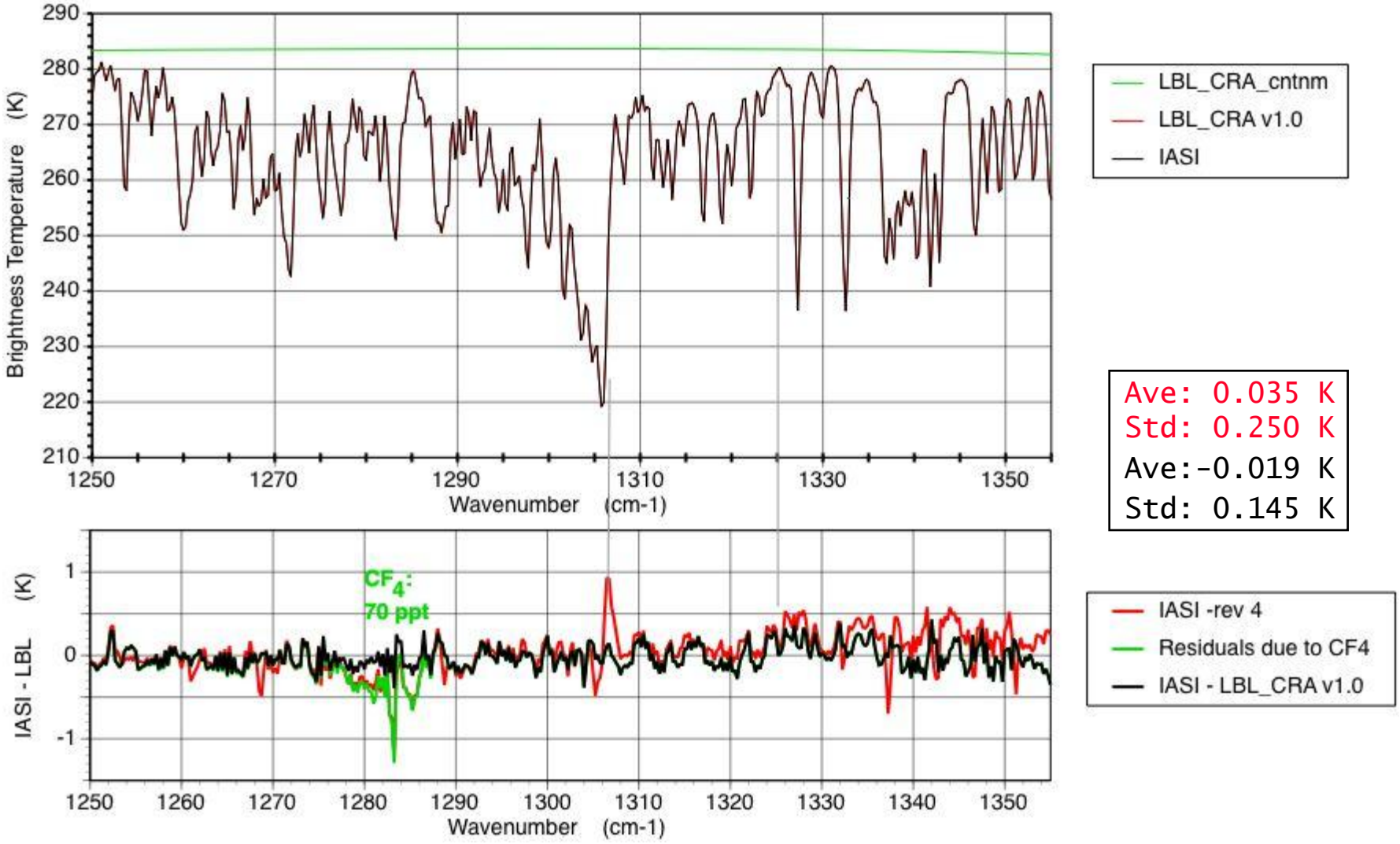
LBL_CRA: N_2O increased by 1.04

20 April GoM



Line Coupling in Methane

Tran et al., JQSRT, 2006

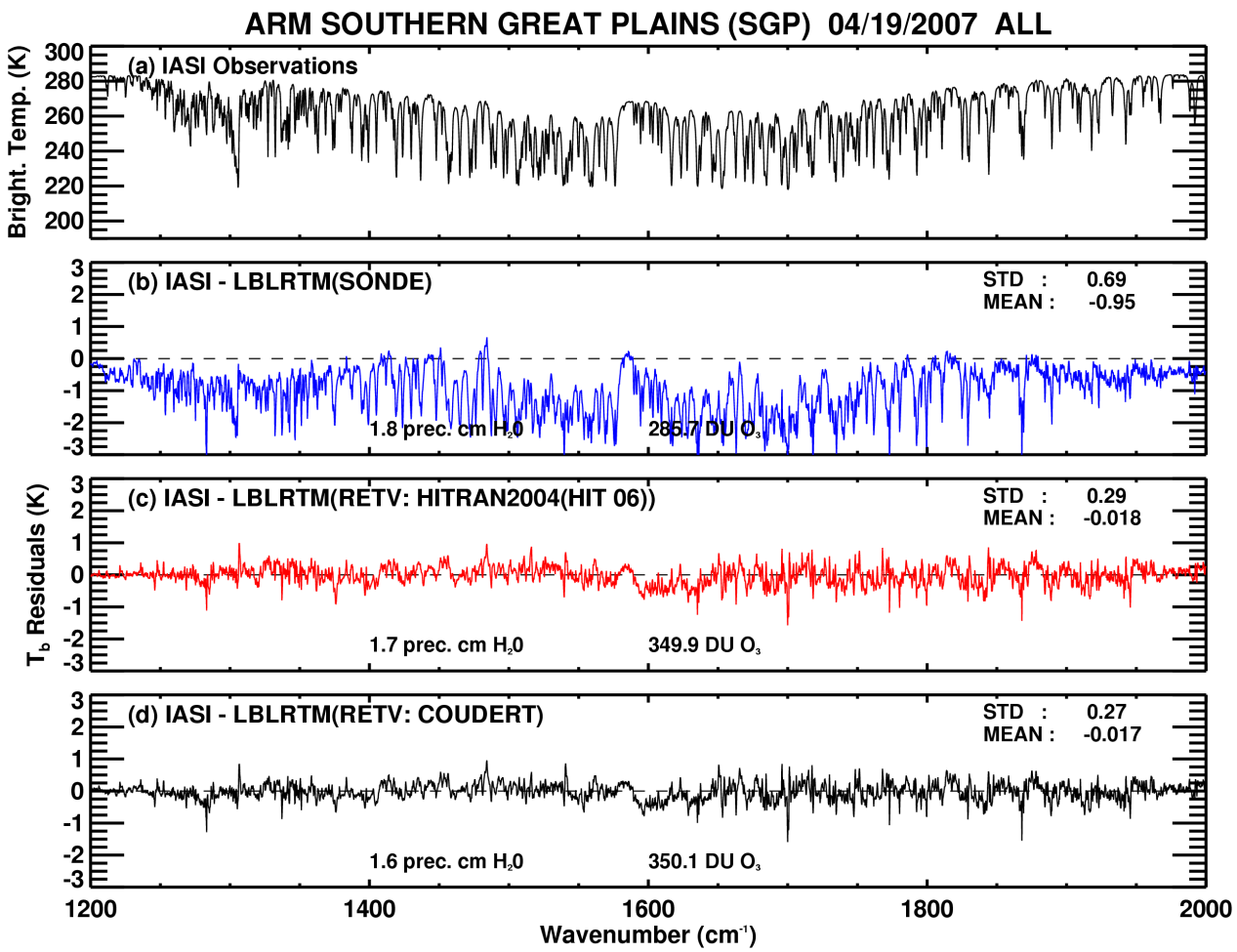


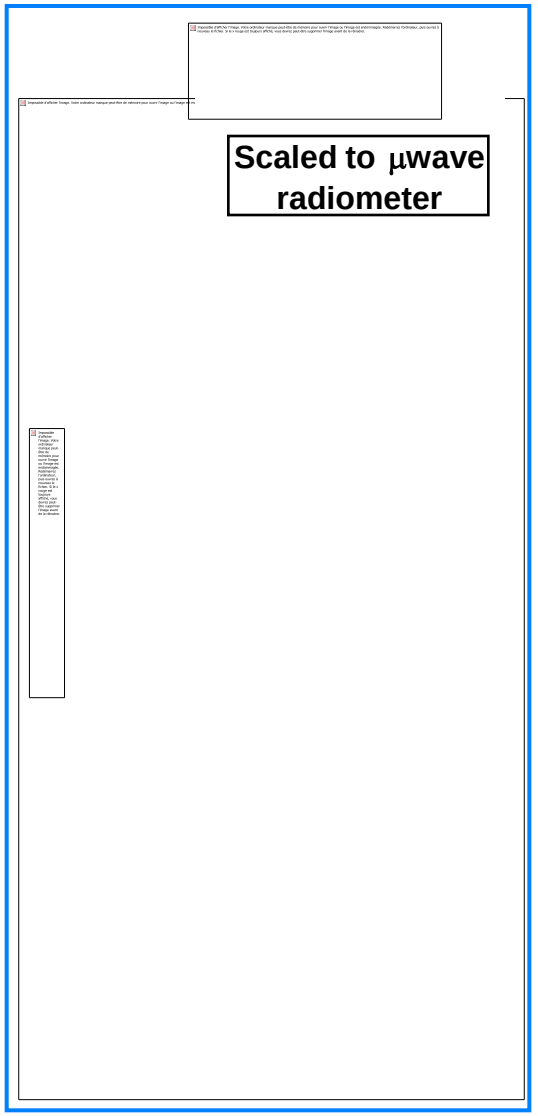
Water Vapor: 'The Most Important Greenhouse Gas'

Critical for NWP and Climate

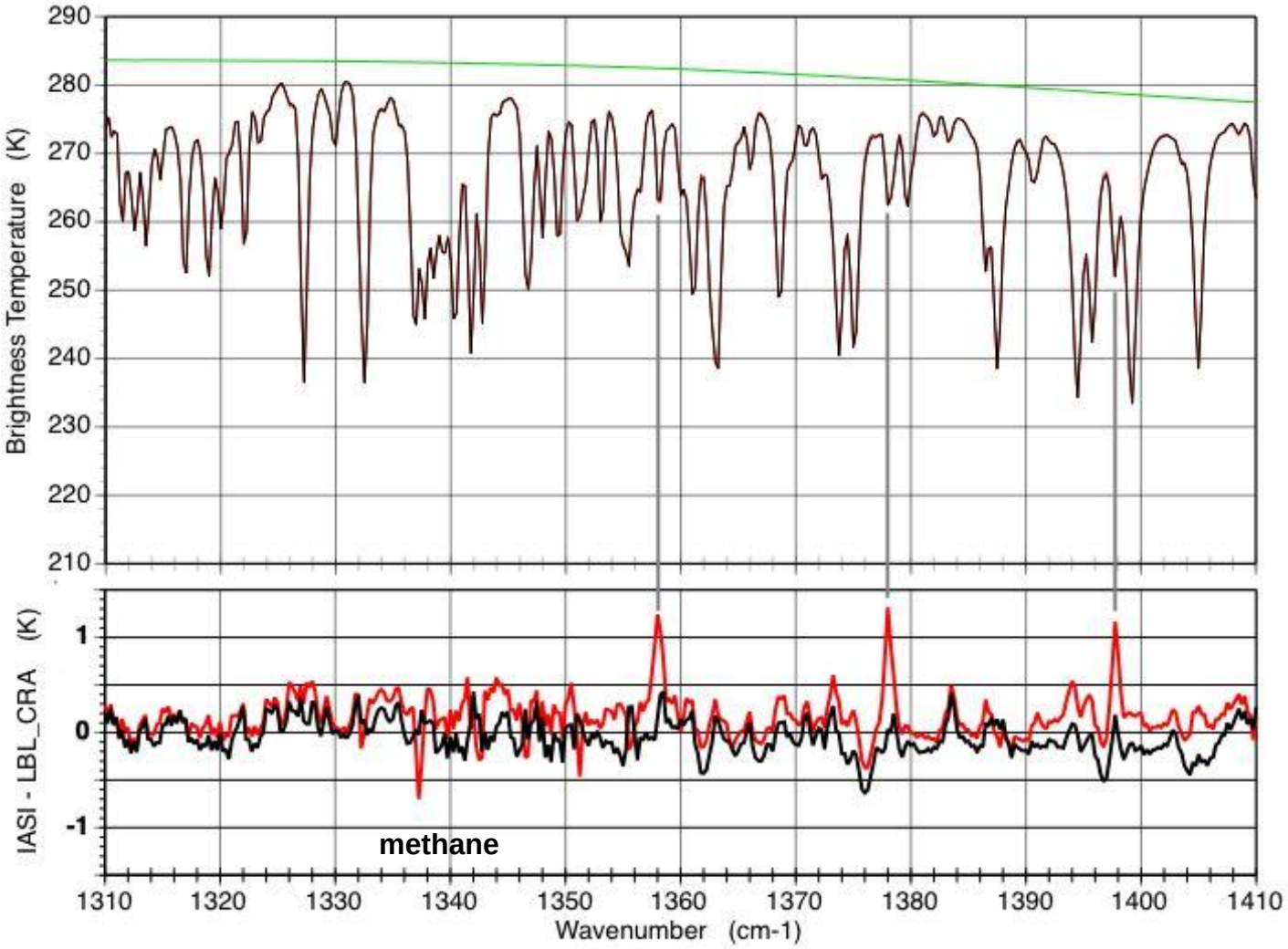
- **Line Parameters**
  - Laurent Coudert
    - » Strong Lines: Intensities increased by ~ 5 %
- **Line Widths and Shifts / Temperature Dependence**
  - Bob Gamache &
  - this paper
- **Line Coupling**
  - Linda Brown (accidental two line resonances)
  - Revised relaxation rates
  - First Order
- **Continuum**
  - Inextricably linked to the width
  - mt_ckd_2.4
  - Scaled in selected regions of the water band by ~5%

Water Vapor ν_2 Region : Impact of Coudert Intensities





Water Vapor P-Branch: 1310 -1410 cm-1



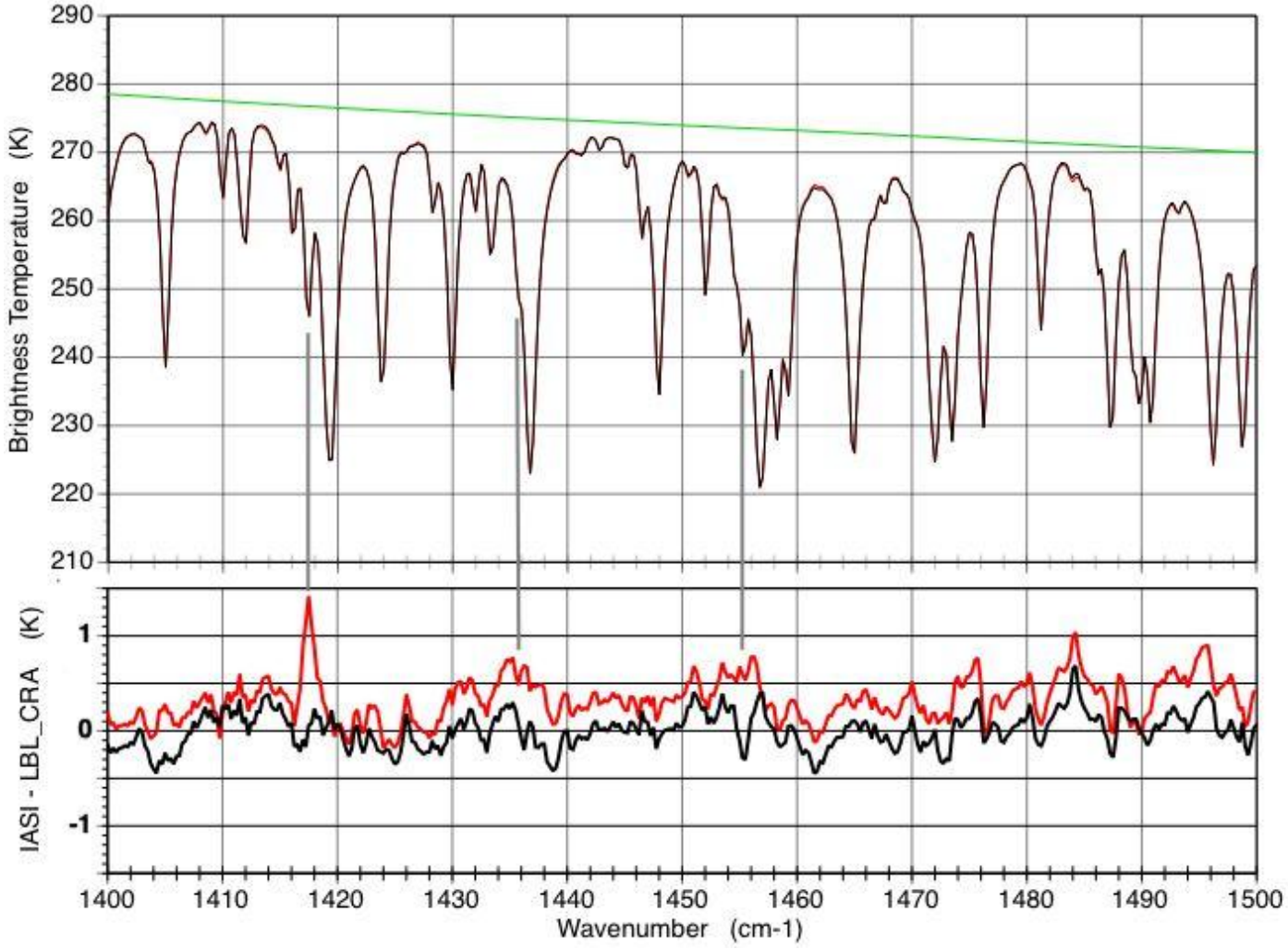
LBL_CRA_cntnm
LBL_CRA_v1.0
IASI

Widths modified

Ave: 0.173 K
Std: 0.225 K
Ave: 0.044 K
Std: 0.183 K

IASI - rev4
IASI - LBL_CRA_v1.0

Water Vapor P-Branch: 1400 -1500 cm-1



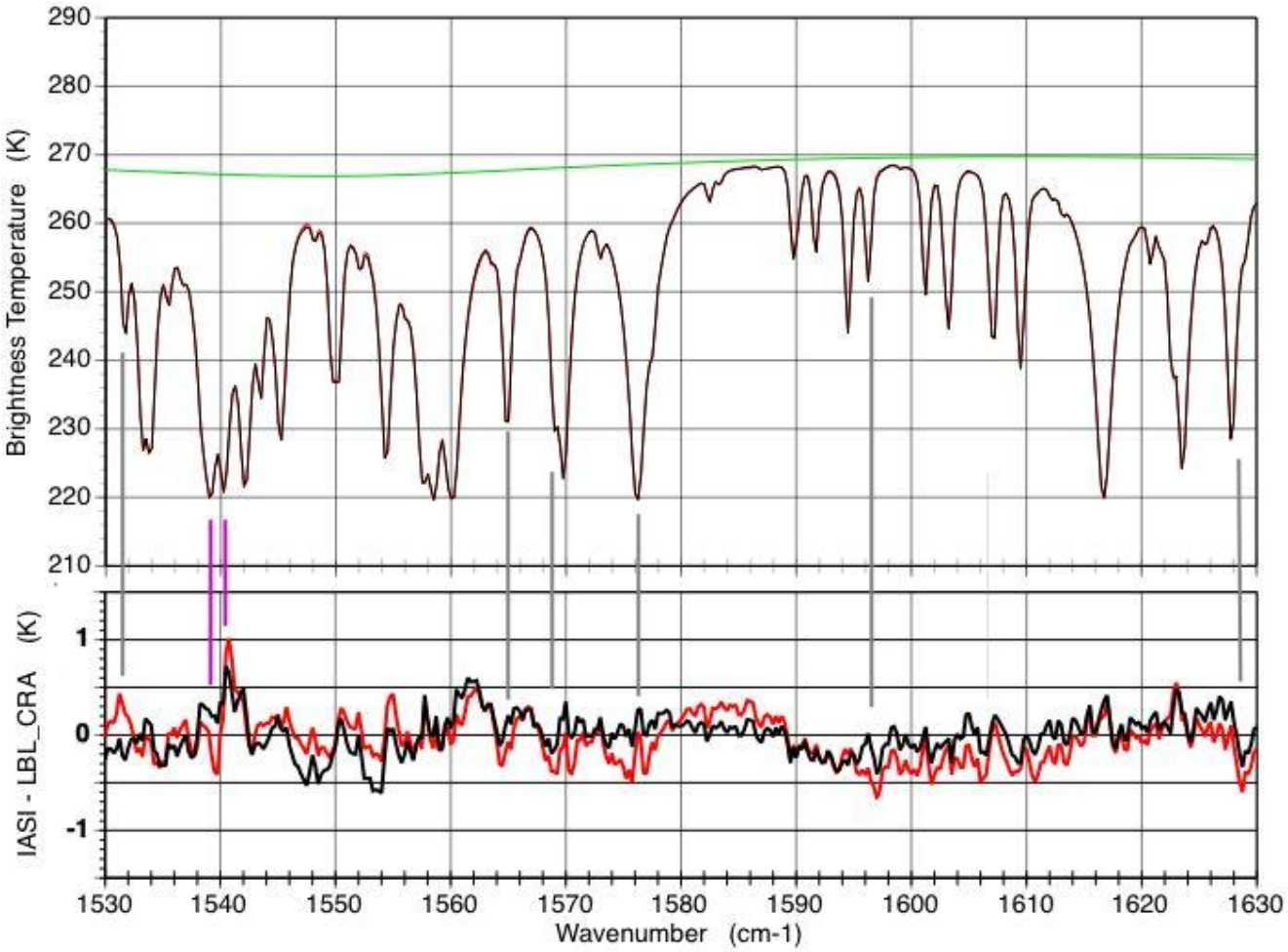
LBL_CRA_cntnm
LBL_CRA_v1.0
IASI

Widths and Continuum modified

Ave: 0.372 K
Std: 0.242 K
Ave: 0.008 K
Std: 0.190 K

IASI - rev4
IASI - LBL_CRA_v1.0

Water Vapor Band Center: 1530 -1630 cm-1



LBL_CRA_cntnm
LBL_CRA_v1.0
IASI

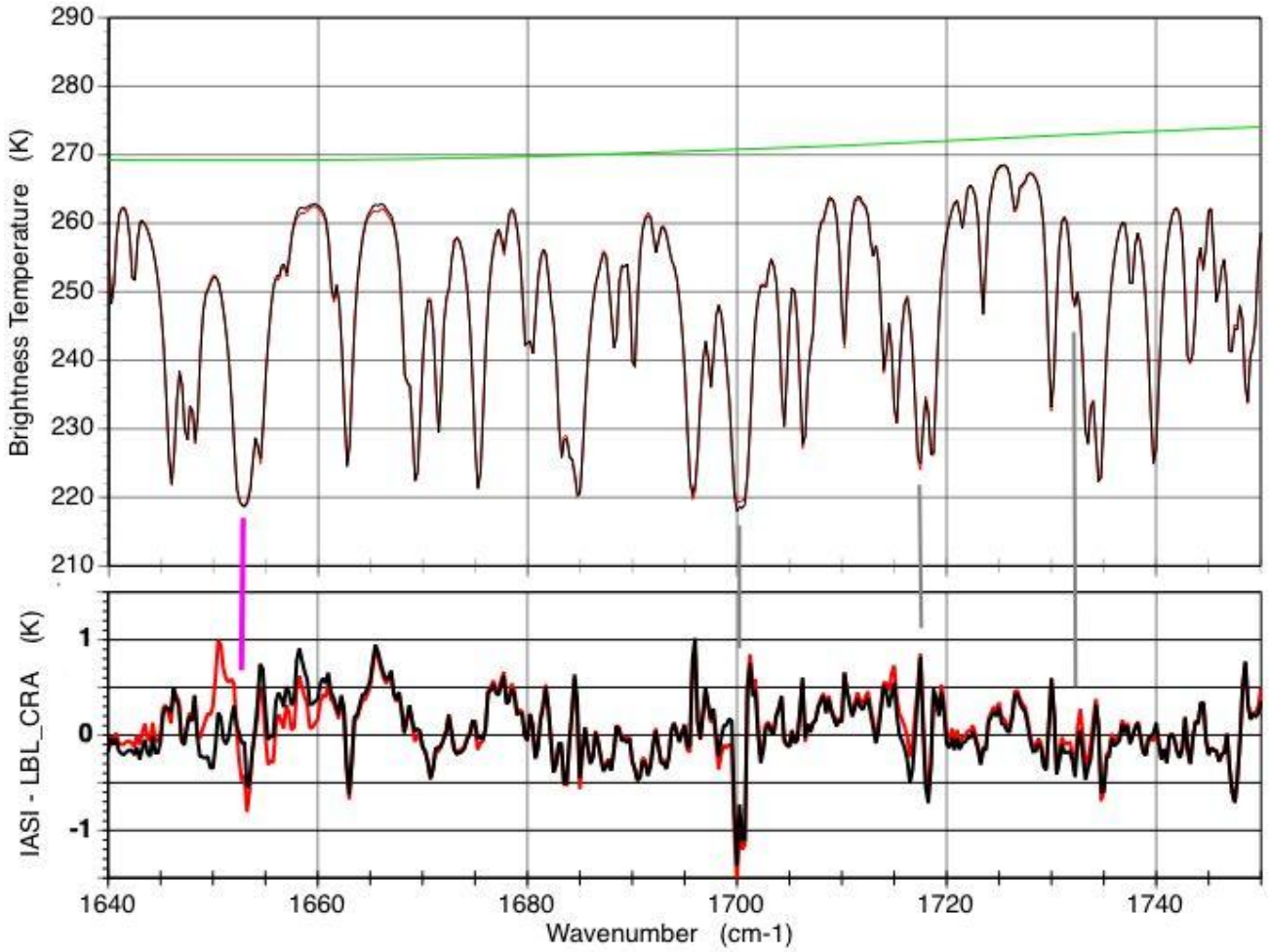
Widths and Continuum modified

Ave:-0.047 K
Std: 0.267 K
Ave: 0.007 K
Std: 0.219 K

IASI - rev4
IASI - LBL_CRA_v1.0

Line Coupling 1540 cm-1

Water Vapor R-Branch: 1640 -1750 cm-1



LBL_CRA_cntnm
LBL_CRA_v1.0
IASI

Widths modified

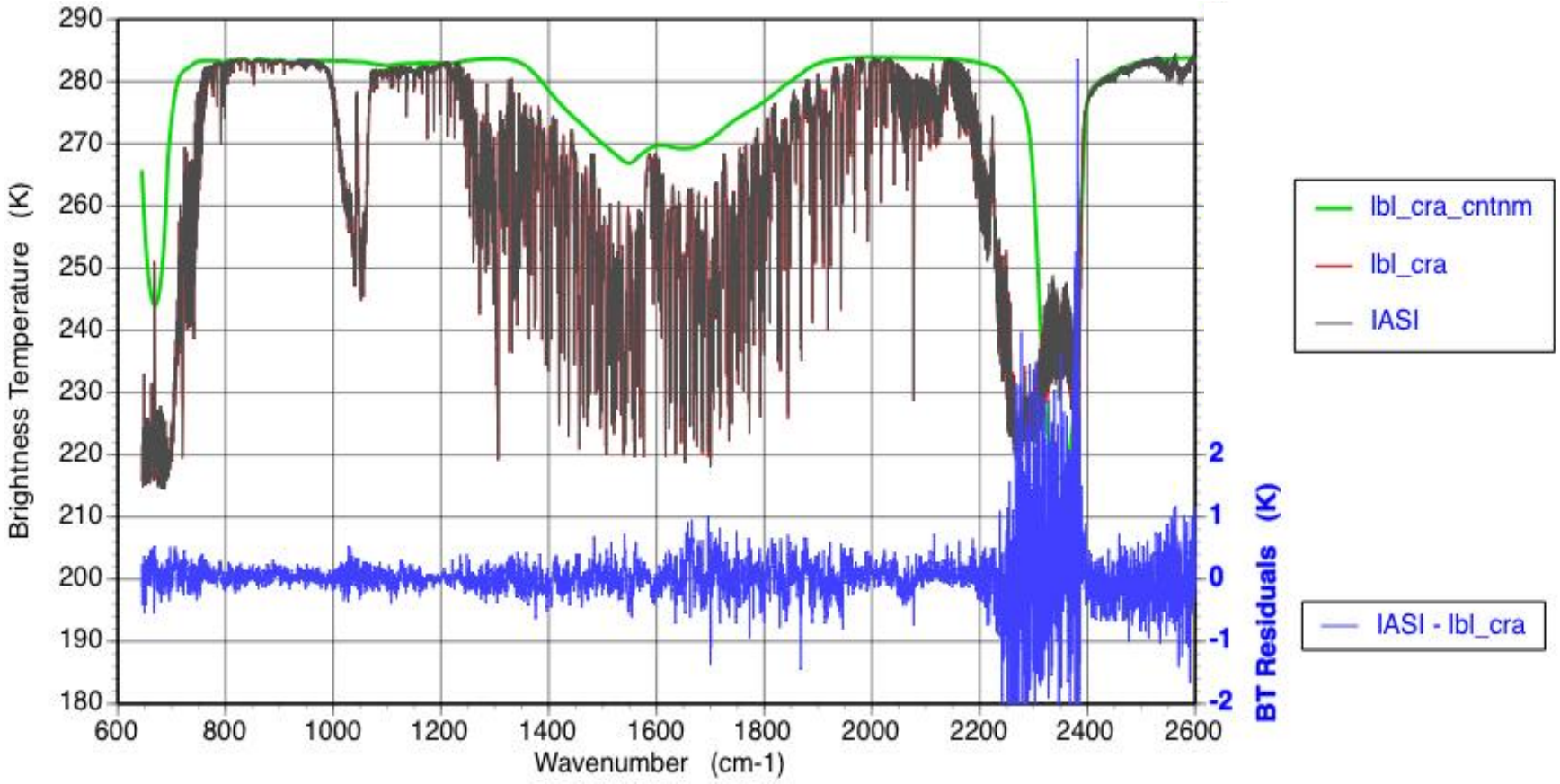
Ave: 0.060 K
Std: 0.321 K
Ave: 0.056 K
Std: 0.329 K

IASI - rev4
IASI - LBL_CRA_v1.0

Line Coupling 1653 cm-1

Overall Comparison of LBL_CRA with IASI

19 Apr 2007 SGP case



Summary

- **Temperature**
  - **Carbon Dioxide**
    - » **Line Parameters: CDDB (2008), Tashkun et al. JQSRT, 2009**
    - » **Line Coupling: Niro et al., JQSRT, 2005 J.M.Hartmann**
    - ✓ **Agreement between CO_2 ν_2 and CO_2 ν_3**
    - ✓ **Q-Branch 667 cm-1 line couping resolve: * 1.2**
    - ✓ **Band Head 2385 cm-1 robust for both cases**
  - **Nitrous Oxide**
    - ? **Agreement between CO_2 ν_2 and N_2O ν_3**
    - » **N_2O profile scaling required: 19 April case: 1.04**
      20 April case: 1.02
- **Methane**
  - ✓ **Line Coupling: Tran et al., JQSRT, 2006 J.M.Hartmann**
  - ✓ *** 1.5**

Summary

- Water Vapor
  - Coudert strengths
    - Is it possible that there are errors in R lines?
  - Widths are the current major issue
  - Widths and continuum are inextricably linked
  - Line shape may be an issue as refinements proceed
  - P-Branch has much lower residuals in LBL_CRA than R-Branch
  - Sondes provide an excellent first guess / structure
  - 19 April 2007 case is superb for FM improvement
  - Due to the resolution of IASI there is a limit to the extent spectroscopic improvements can be made

Summary

- Next Steps
  - Resolve R-Branch Issues
  - More Cases
    - Night time IASI preferred (we have some AIRS cases)
    - High Water

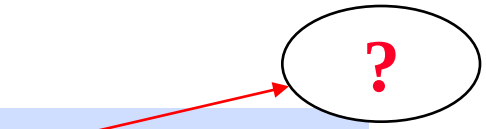
Model Availability:

- unfortunate situation
- Mark Shephard > Environment Canada
- contact me for the package- return 20 February
- clough.associates@gmail.com

```
c            if (vj.ge.1300. .and. vj.lt.1590.) fact = 0.9
c            if (vj.gt.1590. .and. vj.lt.1900.) fact = 1.1
c            fh2o(j) =  fact*fh2o(j)

           fscal_sav = fscal

           i_fac  = (vj-v1_h2o)/dv_h2o + 1.0001

c            if (i_fac.eq.29) fscal = 0.95*fscal !   1530
c            if (i_fac.eq.30) fscal = 0.95 *fscal !   1540
c            if (i_fac.eq.31) fscal = 0.95 *fscal !   1550
c            if (i_fac.eq.32) fscal = 0.95 *fscal !   1560
           if (i_fac.eq.33) fscal = 0.90 *fscal !   1570
           if (i_fac.eq.34) fscal = 0.90 *fscal !   1580
           if (i_fac.eq.35) fscal = 0.98 *fscal !   1590
           if (i_fac.eq.36) fscal = 1.07 *fscal !   1600
           if (i_fac.eq.37) fscal = 1.10 *fscal !   1610
           if (i_fac.eq.38) fscal = 1.08 *fscal !   1620
c           if (i_fac.eq.39) fscal = 1.092*fscal !   1630
           if (i_fac.eq.39) fscal = 1.06 *fscal !   1630
c            if (i_fac.eq.40) fscal = 1.084*fscal !   1640
           if (i_fac.eq.40) fscal = 1.04 *fscal !   1640
c            if (i_fac.eq.41) fscal = 1.076*fscal !   1650
           if (i_fac.eq.41) fscal = 1.02 *fscal !   1650
c            if (i_fac.eq.42) fscal = 1.068*fscal !   1660
           if (i_fac.eq.42) fscal = 0.98 *fscal !   1660
c            if (i_fac.eq.43) fscal = 1.060*fscal !   1670
           if (i_fac.eq.43) fscal = 0.98*fscal !   1670
c            if (i_fac.eq.44) fscal = 1.052*fscal !   1680
           if (i_fac.eq.44) fscal = 0.98*fscal !   1680
c            if (i_fac.eq.45) fscal = 1.044*fscal !   1690
           if (i_fac.eq.45) fscal = 0.98*fscal !   1690
c            if (i_fac.eq.46) fscal = 1.036*fscal !   1700
           if (i_fac.eq.46) fscal = 0.98*fscal !   1700
c            if (i_fac.eq.47) fscal = 1.028*fscal !   1710
           if (i_fac.eq.47) fscal = 0.99*fscal !   1710
c            if (i_fac.eq.48) fscal = 1.020*fscal !   1720
```

What is 'Truth'?

- **Spectral Residuals are Key!**



- **Consistency within a band system**
  - **ν_2 band to investigate consistency for H_2O**
- **Consistency between bands**
  - **IASI ν_2 and ν_3 bands to investigate consistency for CO_2**
- **Consistency between species**
  - **TES: temperature from O_3 and H_2O consistent with CO_2 ; N_2O**
- **Consistency between instruments**
  - **IASI**
  - **AIRS**
  - **ACE**
  - **TES**
  - **MIPAS**
  - **SHIS**
  - **NAST-I**
  - **AERI**

Temperature Retrievals

- **Carbon Dioxide**
  - **Niro et al. Line Coupling- implications for co2 continuum**
    - **Accuracy of collision rates**
    - **Limitations of impact approximation**
    - **Significant impact on our understanding of absorption far from band center**
  - **Duration of collision effects- chi factor**
  - **Line intensities- MIPAS line strengths**
    - **Tashkun, Teffo, Flaud et al.**
  - **H_2O broadening of CO_2**

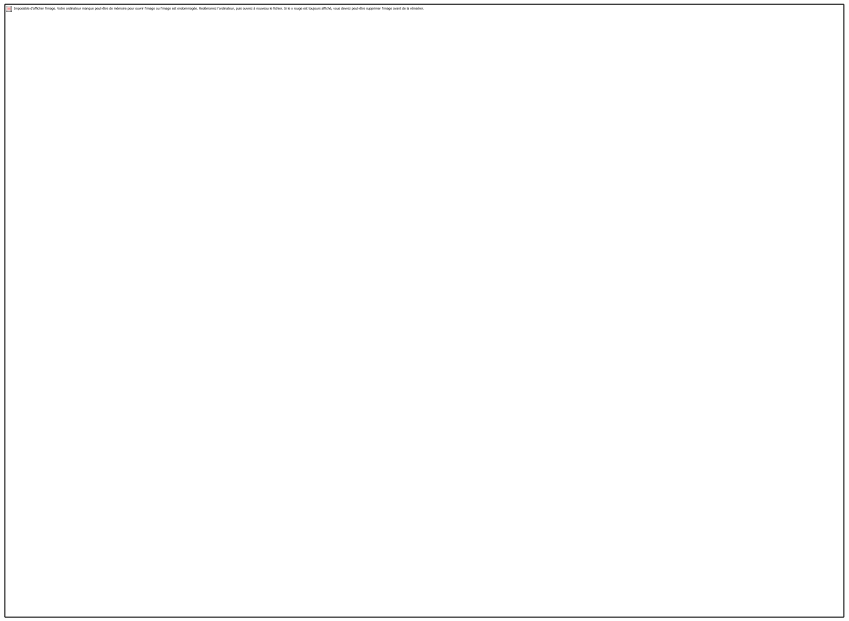
CO_2 Line Coupling : Effect on Spectra

- **Line Parameters:**
  - Niro, F., K. Jucks, J.-M. Hartmann, Spectra calculations in central and wing regions of CO2 IR bands. IV : Software and database for the computation of atmospheric spectra: J Quant Spectrosc Radiat Transfer., 95, 469-481.
  - P, Q, & R line coupling for bands of importance
  - Niro et al. code modified to generate first order line coupling coefficients, y_i.
  - Works in regular line by line mode with LBLRTM
  - Temperatures: 4

Chi Factor

- **Line Shape:**
  - Impact Approximation
  - Duration of collision effects under study

- **Continuum:**
  - X Factor
  - Sampled 2 cm^{-1}
  - New definition required
  - Temperature dependence ??



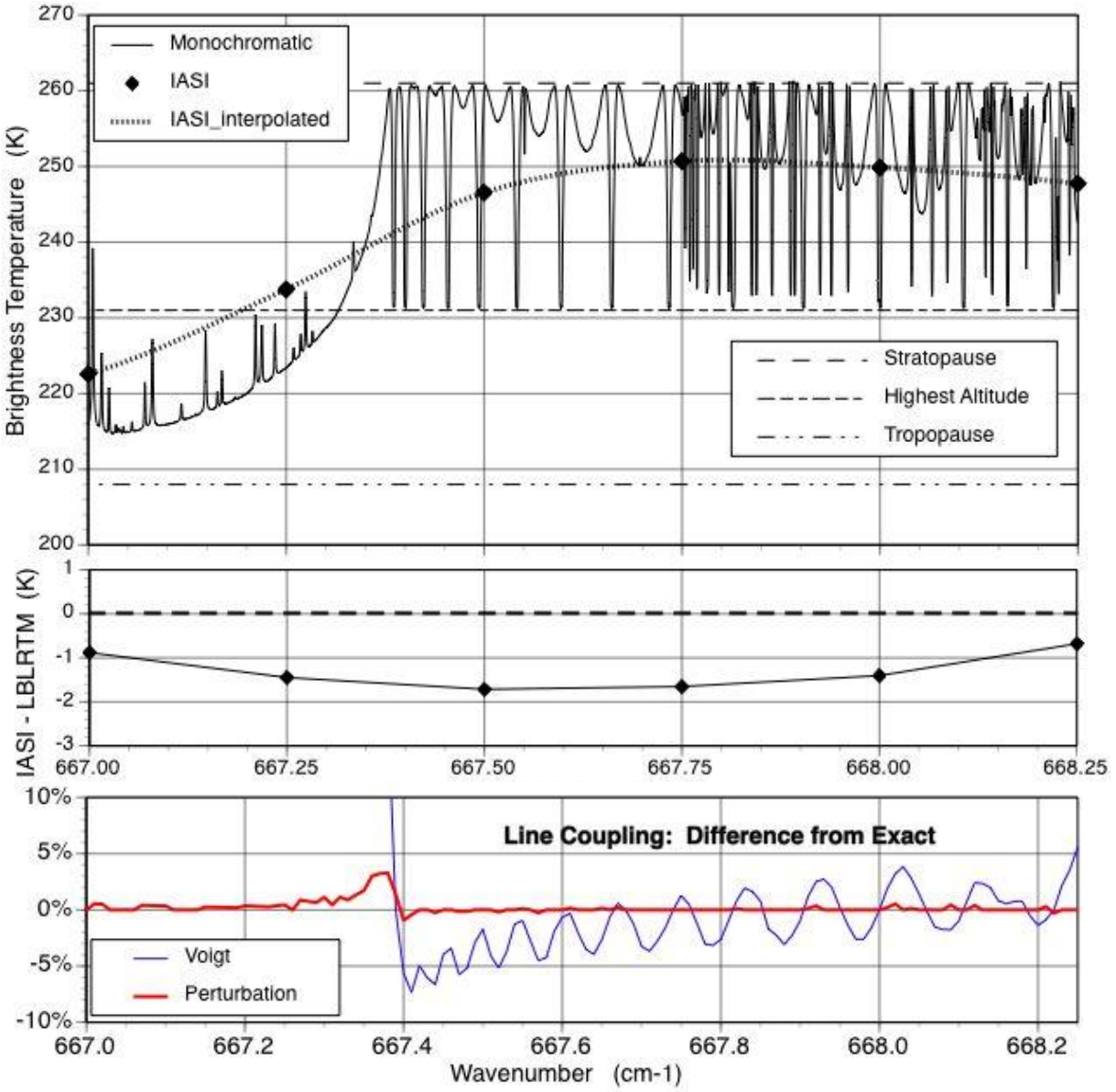
CO2 Q-Branch: 667 cm-1

IASI

Monochromatic Radiance

Residuals

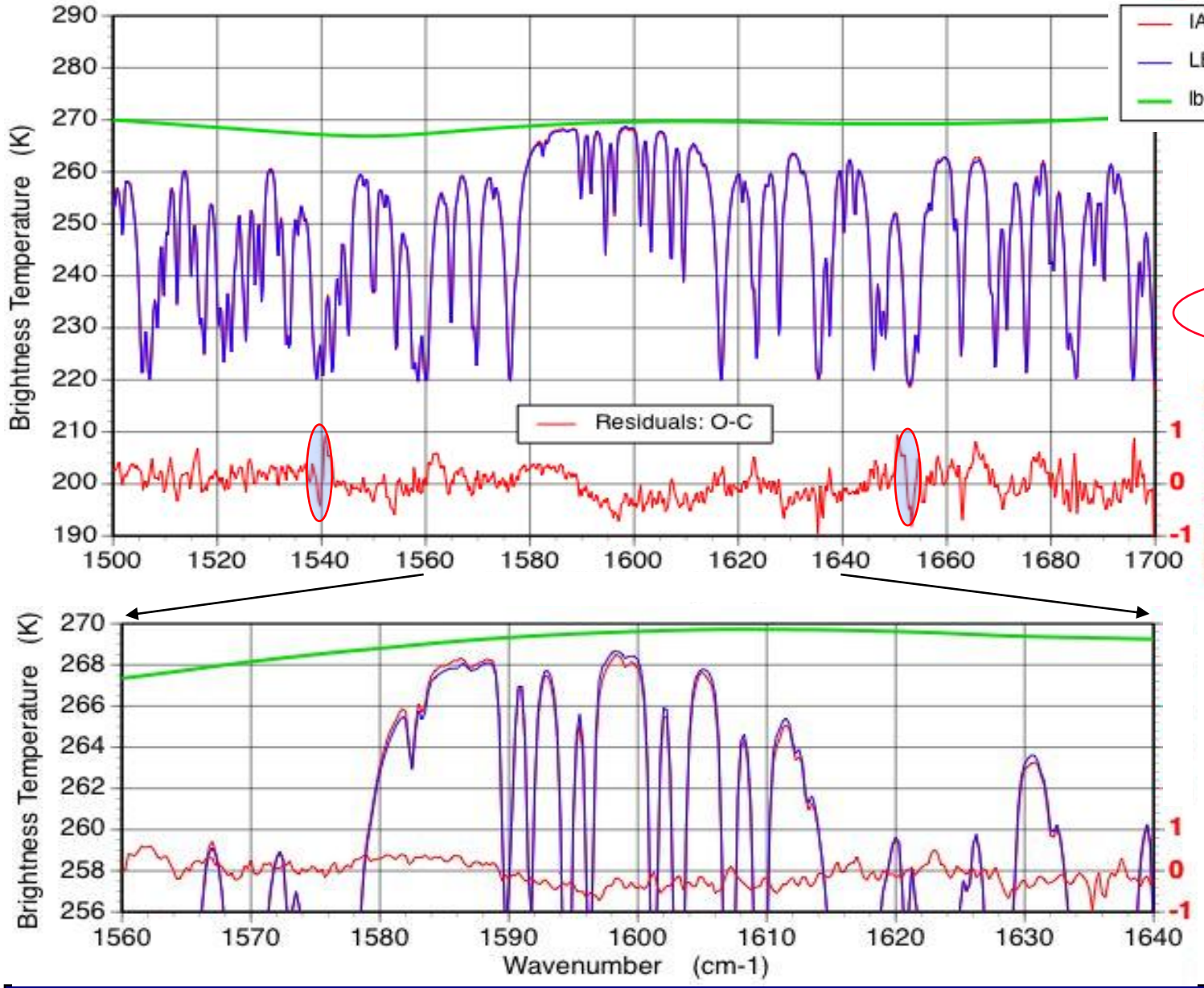
Line Coupling:
% difference from exact



Water Vapor Retrievals

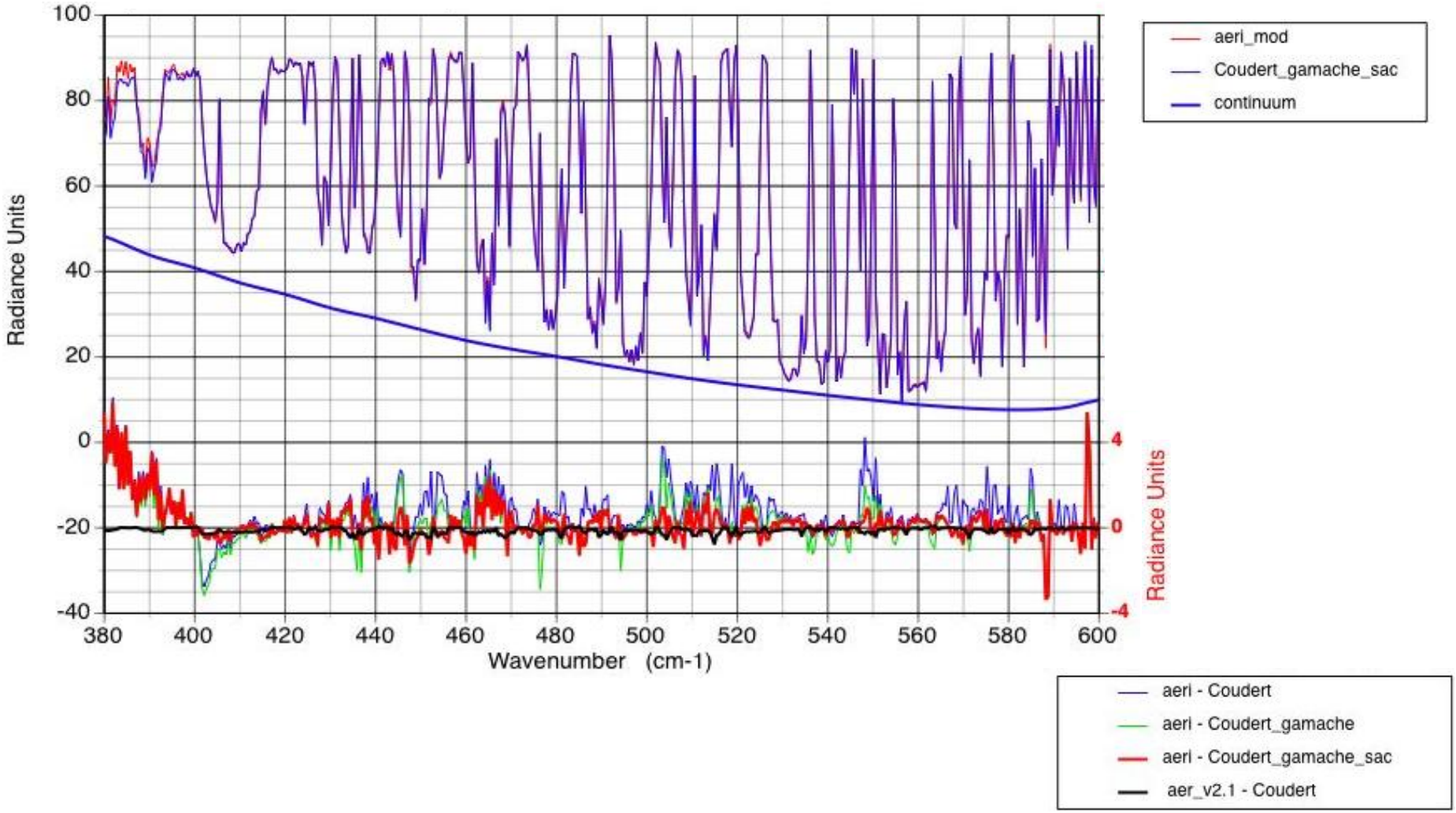
- **Water Vapor**
  - **Variability: Horizontal / Vertical / Time**
  - **Residuals are consistently greater than IASI noise**
  - **Coudert et al. Line Strengths**
  - **Line Widths**
  - **Continuum**
    - **Provides the extra absorption previously provided by the 'super Lorentzian' chi factor**
    - **Based on dipole allowed transitions with widths ~ 50 cm-1**
    - **Same line shape is used for every line from the Microwave to UV**
  - **Implications from downwelling spectra at the ARM NSA site.**

H_2O: Detail of Band Center

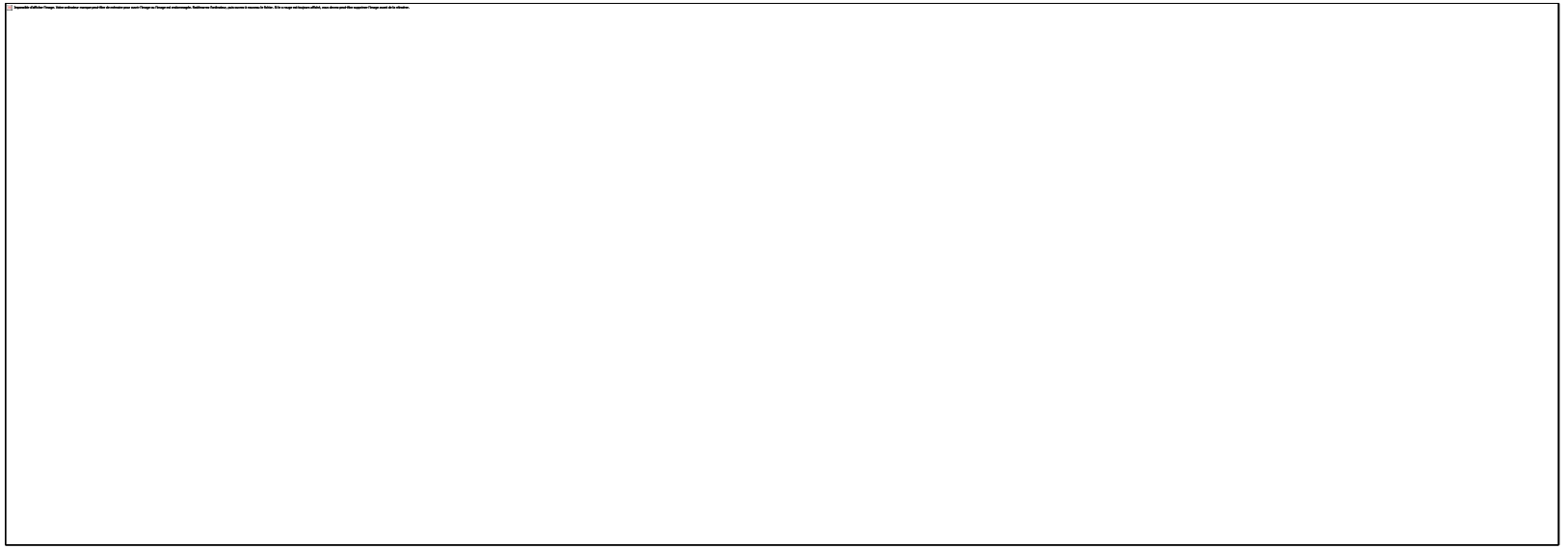


h2o line coupling

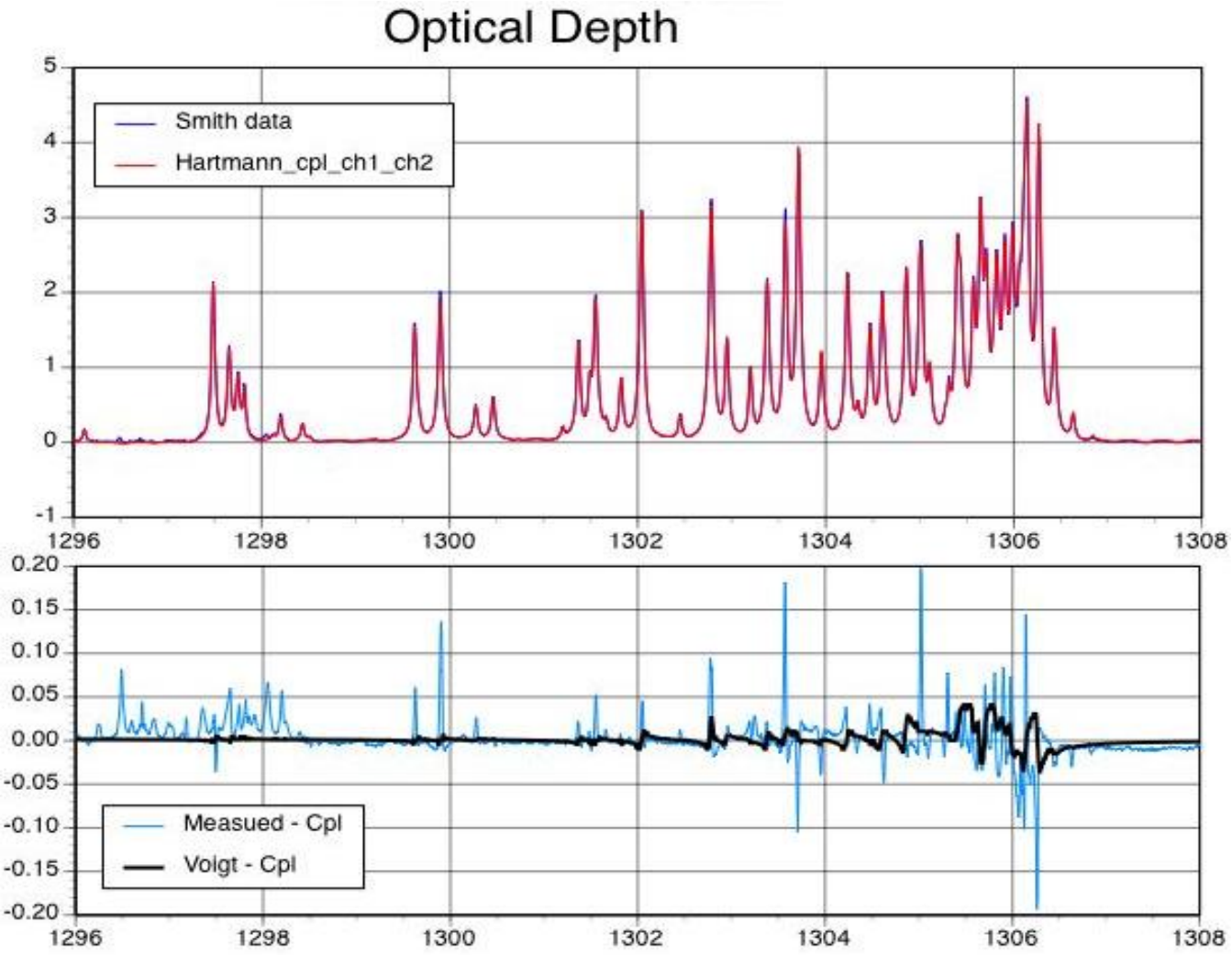
AERI Downwelling Radiances
ARM NSA Site



AERI Downwelling Radiances: 408 cm-1
ARM NSA Site



						Transition Frequency		Strength	E"	Gamache Width	% Change	"Clough Width"
10	4	6	9	3	7	400.221819	0.259221	1.053E-20	1216.2313	0.0791	-25.0	0.0593
10	6	4	9	5	5	400.481040		1.051E-20	1474.9810	0.0510	-25.0	0.0383


Optical Depth
Smith data
Hartmann_cpl_ch1_ch2
5
4
3
2
1
0
-1
1296
1298
1300
1302
1304
1306
1308
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
Measued - Cpl
Voigt - Cpl

Summary

- **Carbon Dioxide:**
  - Line Coupling is critical!
  - Relaxation Matrix needs adjustment

    and/or
  - Duration of Collision Effects need to be included
  - ν_2 and ν_3 approaching consistency ν_2 and ν_3 approaching consistency
  - ν_2 Q-Branch not yet understood
- **Water Vapor:**
  - Line Intensity Issue

    Coudert Line Parameters have been adopted

    Internal consistency is not necessarily conclusive
  - Residuals are too large (much larger than IASI noise)
  - Line Coupling, Widths, Shifts, Speed Dependent Voigt ?
- **Retrievals for other species are generally very good**
- **Updated Code and Line Parameters are available**
  - Separate Line Coupling file (Hartmann) available: aer_v2.1
- **Spectral Residuals are a CRITICAL validation criterion**

IASI

C'est Incroyable !

Summary

- **Carbon Dioxide:**
  - **Line Coupling is critical!**
  - **Relaxation Matrix needs adjustment**

    and/or
  - **Duration of Collision Effects need to be included**
  - **CO_2 Continuum requires modification**
  - **ν_2 and ν_3 approaching consistency**

    Tashkun ν_3 line parameters to be evaluated
  - **ν_2 Q-Branch not yet understood**

Summary

- Water Vapor:
  - Line Intensity Issue
    - Coudert Line Parameters have been adopted
    - Internal consistency is not necessarily conclusive
  - Residuals are too large (much larger than IASI noise)
  - Line Coupling, Widths and Shifts ?
- xx Simultaneous retrieval of Temperature and Water Vapor xx
- Retrievals for other species are generally excellent
- Updated Code and Line Parameters are available
  - Separate Line Coupling file (Hartmann) available: aer_v2.1
- Spectral Residuals are a CRITICAL validation criterion

More Spectroscopy Than You Ever Hoped to Hear About

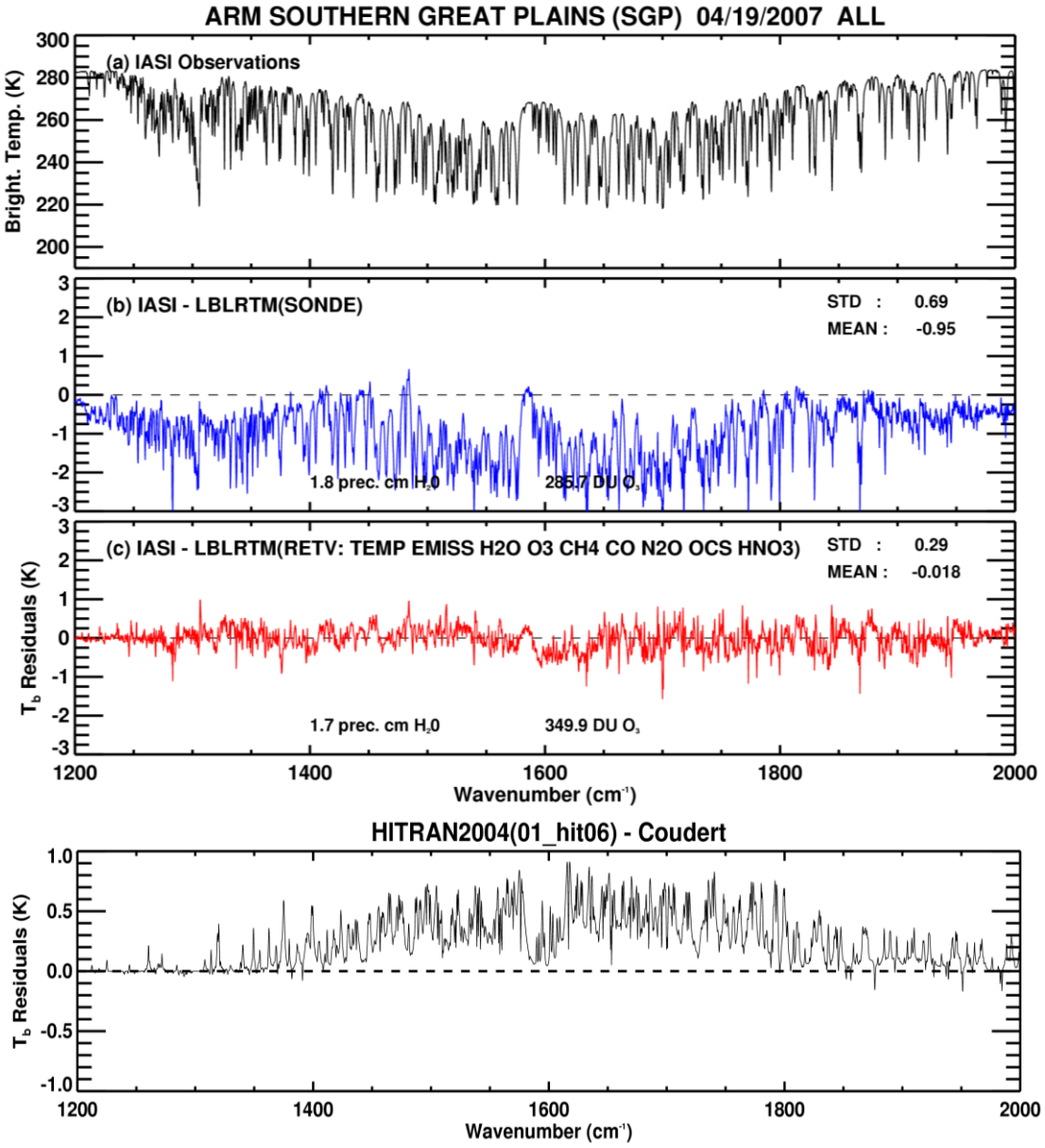
Tony Clough

Advanced High Spectral Resolution Infrared Observations
EUMETSAT
16 September 2008

LBLRTM Considerations

- **LBLRTM Issues**
  - **Changing water in a layer > changes layer boundary altitudes > changes level temperatures**
    - **Simultaneous temperature and water vapor retrievals are effected**
    - **Fix boundary altitudes on input (hydrostatic equation not satisfied)**
  - **AJ: self broadening of water vapor lines is not treated**
  - **Upwelling Radiance Calculations: Currently NO capability to include downwelling radiance at upper boundary**
    - **Not a problem for TOA**
    - **Problem for HIS, e.g. ozone**
    - **Problem for AJ**

Water Vapor ν_2 Region



Larger residuals remain:

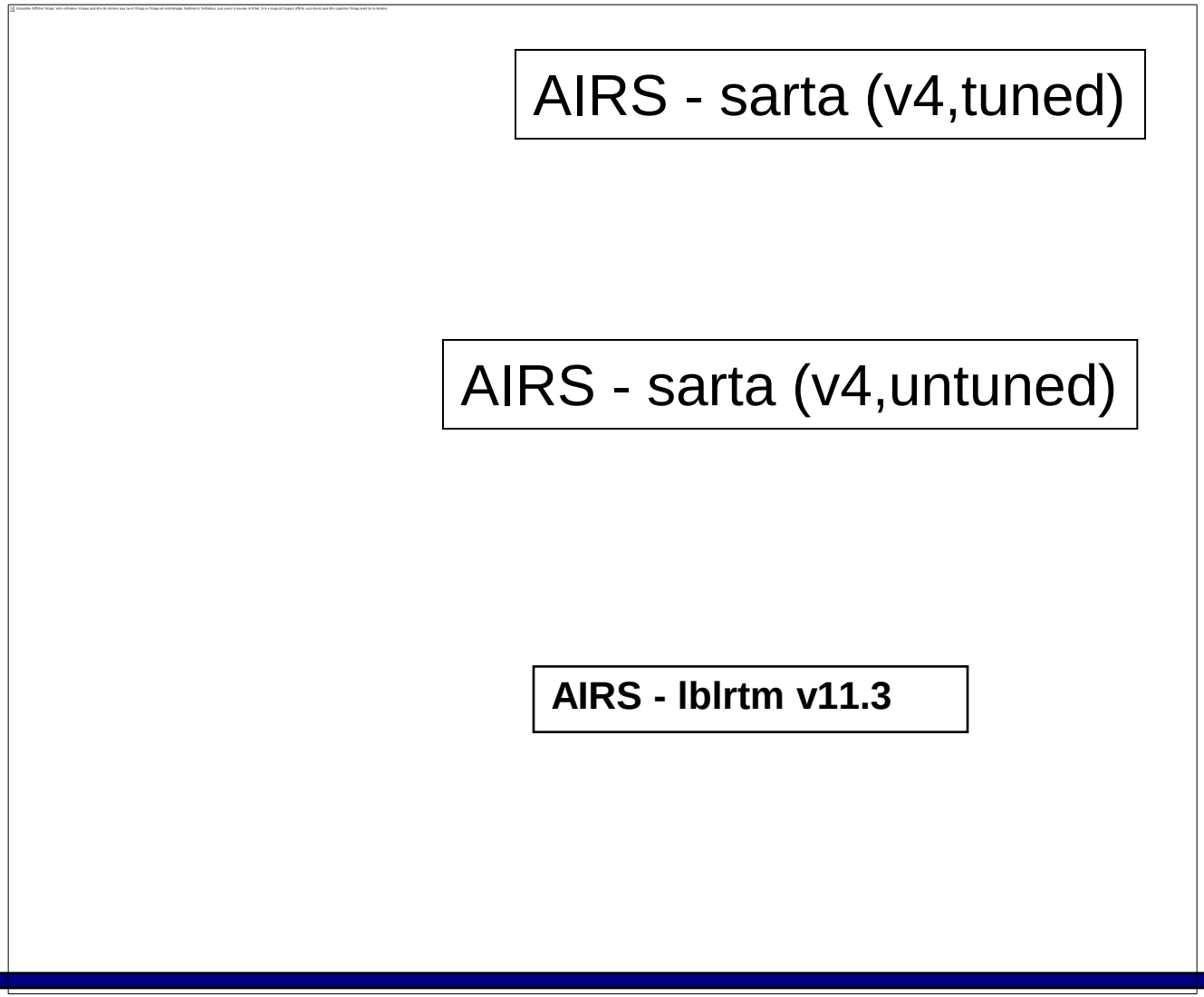
- **IASI Noise: ~0.15K**
- **Atmospheric state: retrieved**
- **Likely Spectroscopy**

Coudert water vapor intensities?

AERI Downwelling Radiances
ARM NSA Site

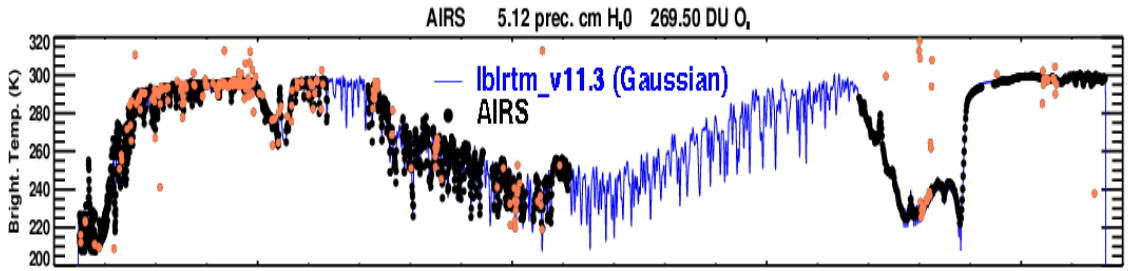
Transition Frequency							Strength	Gamache Width	% Change	"Clough Width"	Self Width
396.432560	8	2	6	7	1	7	2.396E-20	0.0807	-7.5	0.0746	0.384
397.318923	9	3	6	8	2	7	5.811E-20	0.0804	-7.5	0.0743	0.328
397.675624	10	6	5	9	5	4	3.104E-20	0.0565	-7.5	0.0522	0.301
398.941390	9	7	3	8	6	2	1.825E-20	0.0415	-20.5	0.0330	0.328
398.976486	9	7	2	8	6	3	5.476E-20	0.0414	-20.5	0.0329	0.328
400.221819	10	4	6	9	3	7	1.053E-20	0.0791	-25.0	0.0593	0.301
400.481040	10	6	4	9	5	5	1.051E-20	0.0510	-25.0	0.0383	0.301

SRF file: srftables_031115v3.hdf

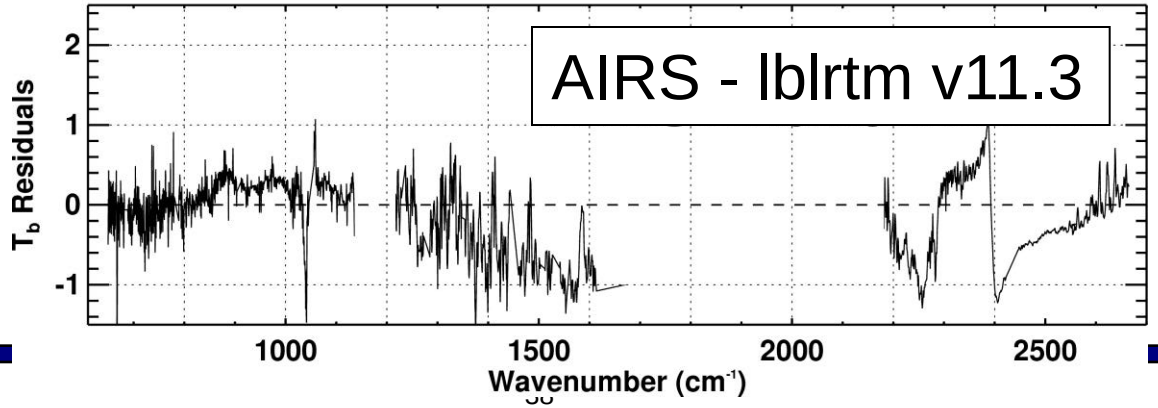


AIRS/model comparisons

- **Mean residuals for 36 “clear-sky” cases**
  - **ARM TWP Phase 1 AIRS validation**
  - **Layer profiles, AIRS and SARTA radiances supplied by L. Strow and S. Hannon**

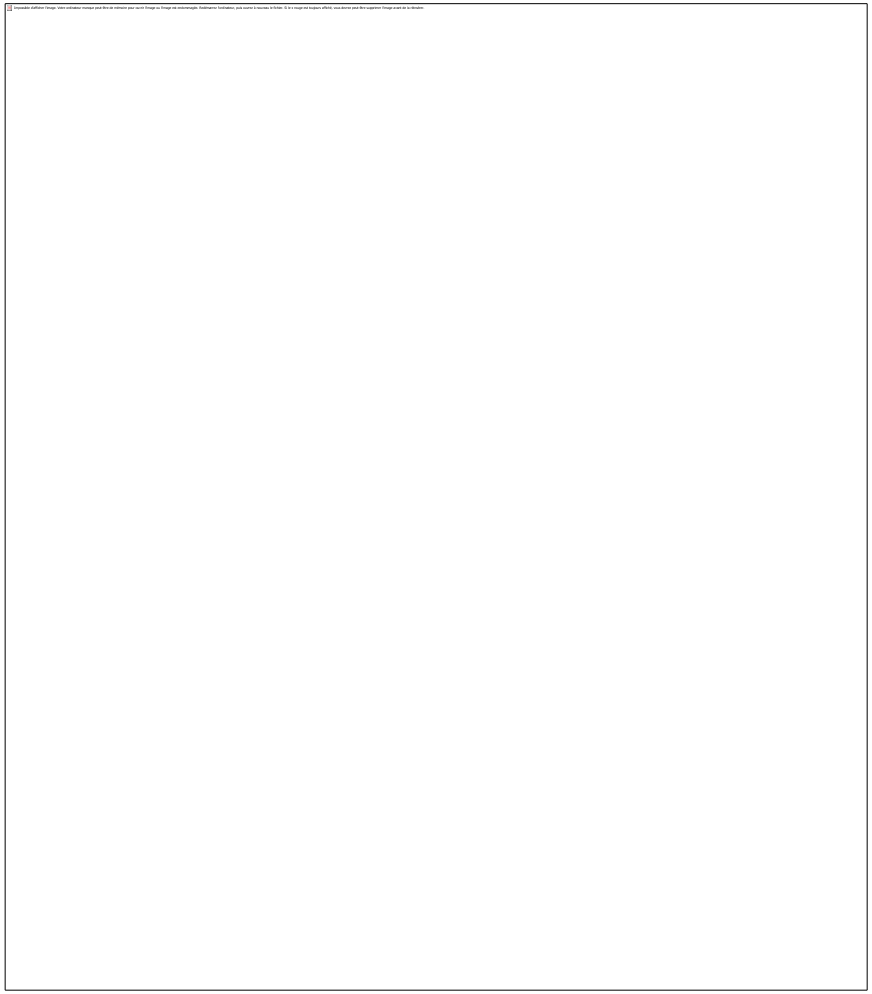


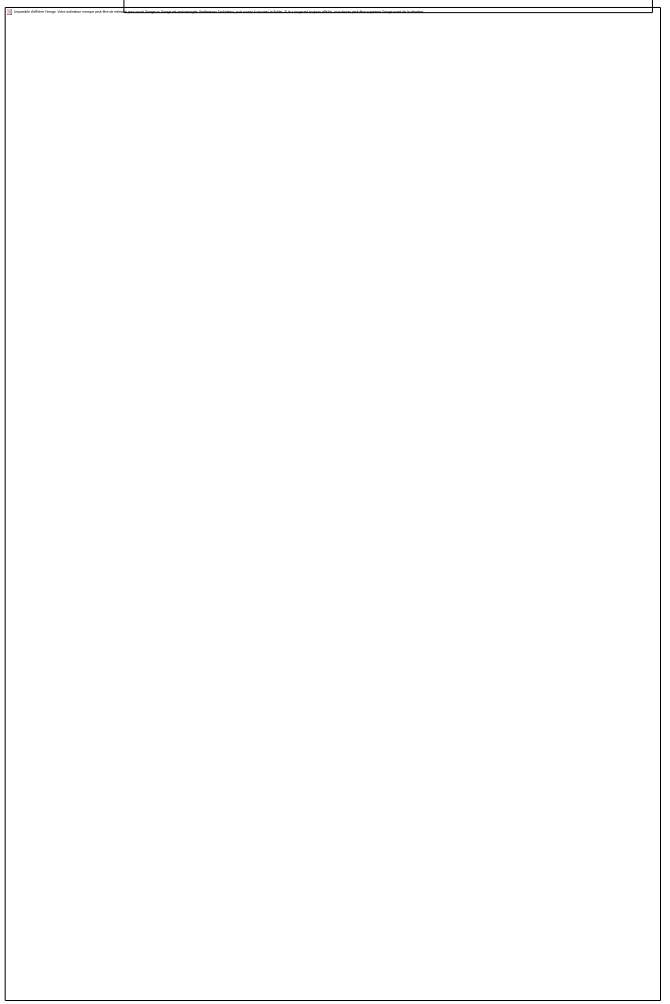
Example case



Mean residuals for all “clear-sky” cases

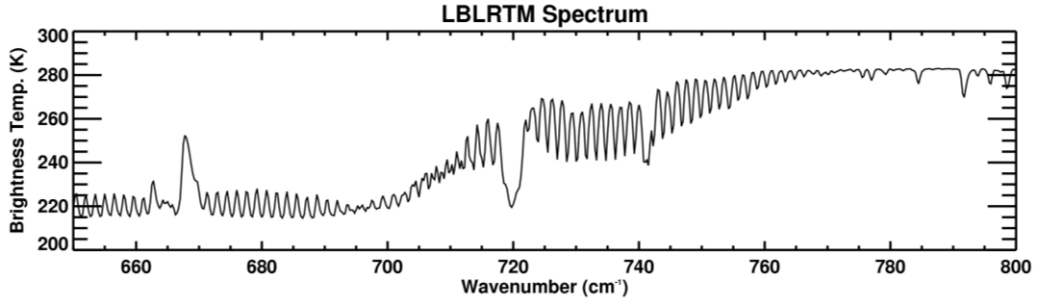
Temperature

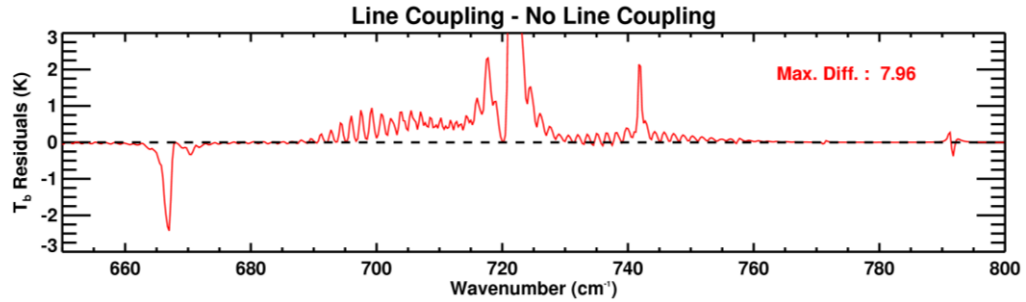




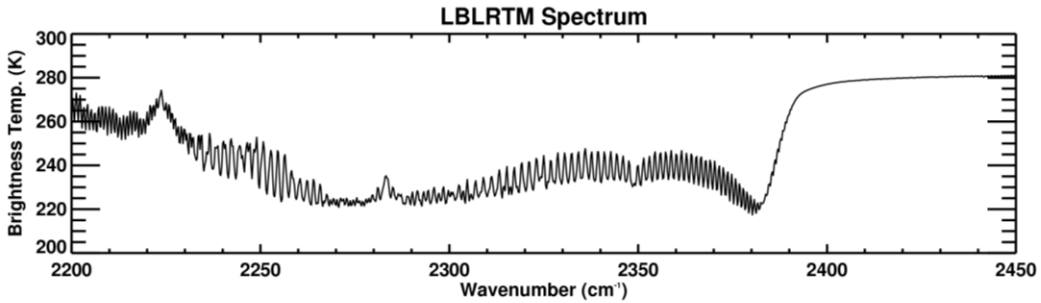
Impact of CO_2 Line Coupling in the Infrared

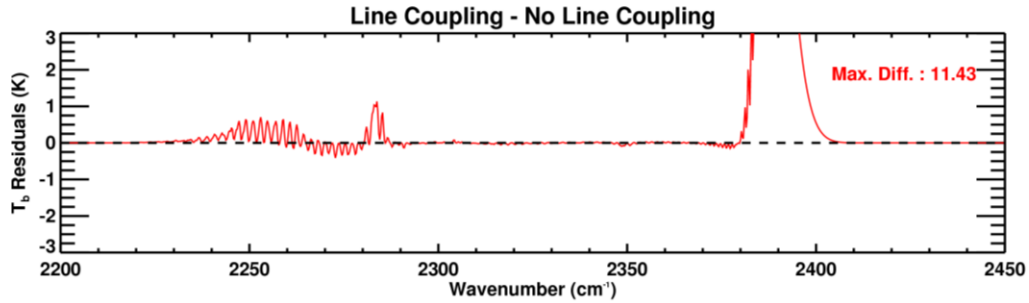
CO_2 v_2





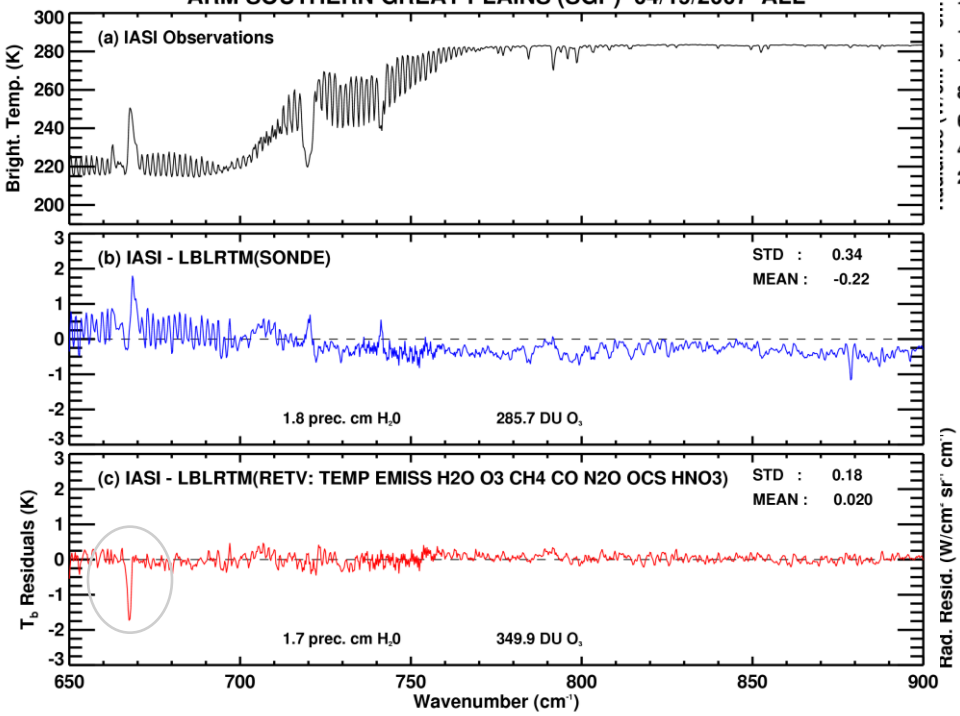
CO_2 v_3



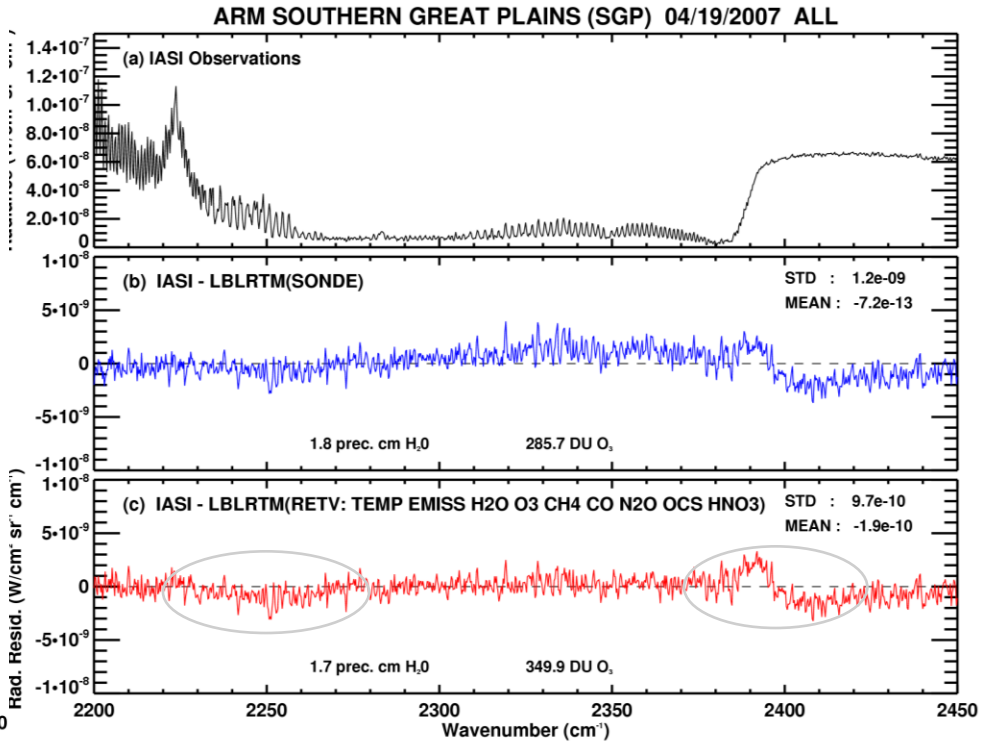


Temperature: CO_2 Spectral Regions

CO_2 v_2

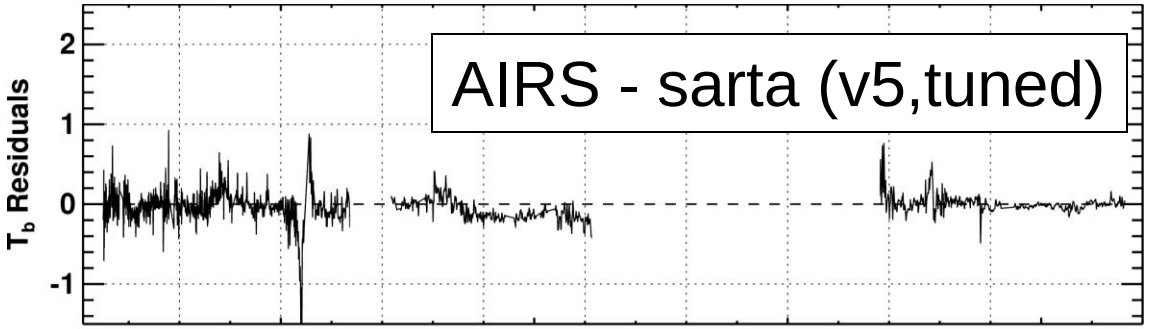


CO_2 v_3

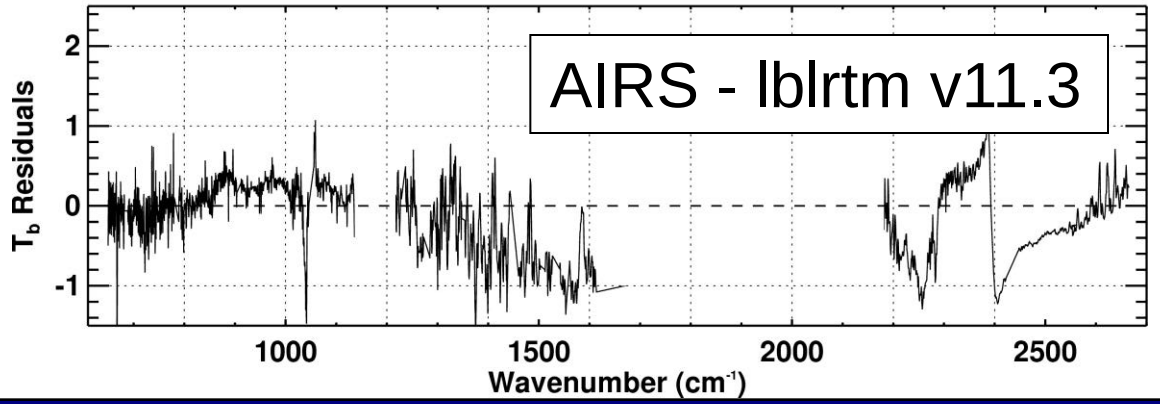


SRF file: srftables_051118v4.hdf

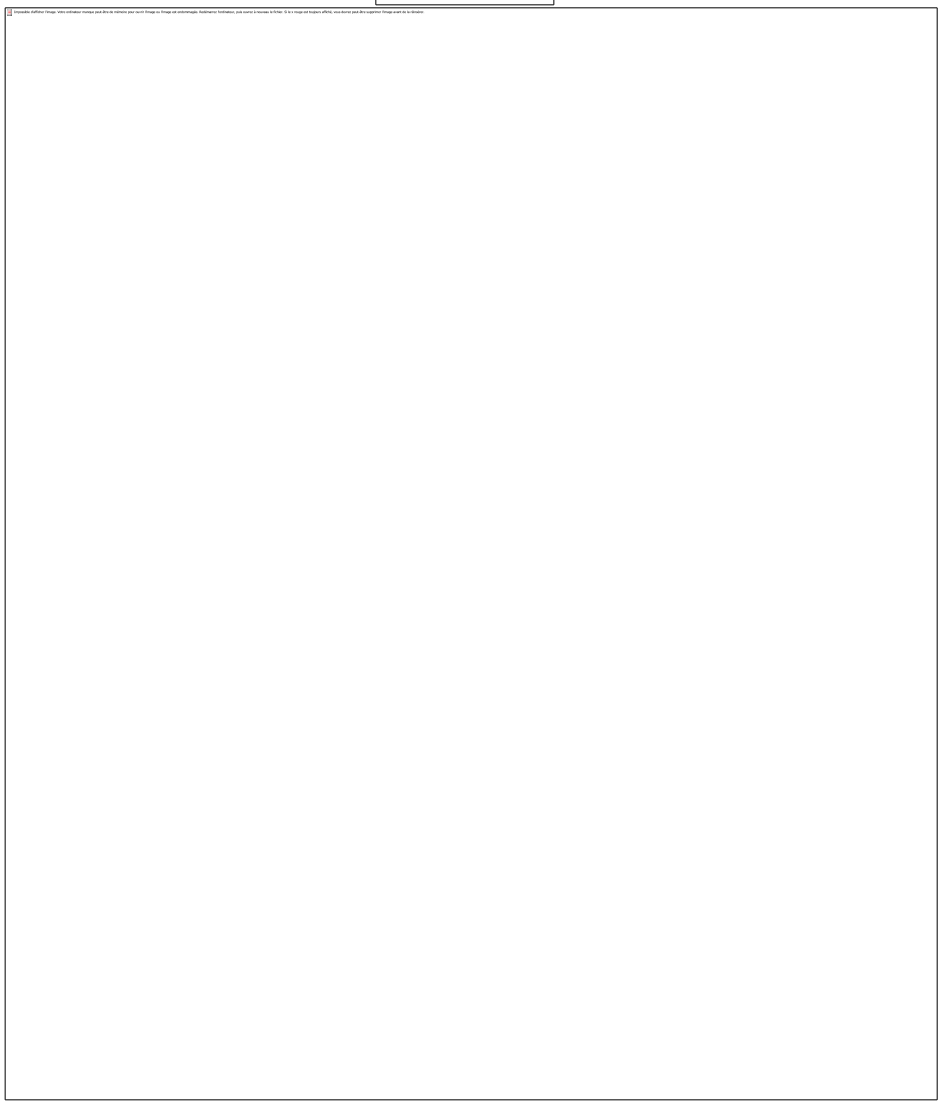
(d)

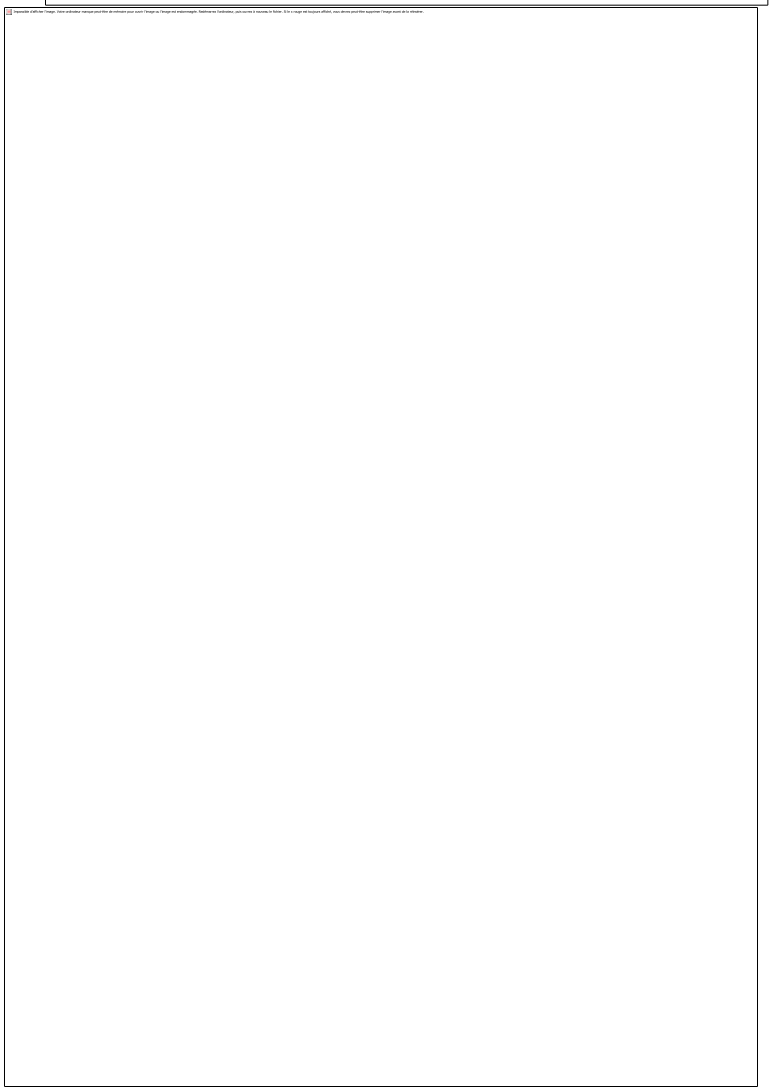


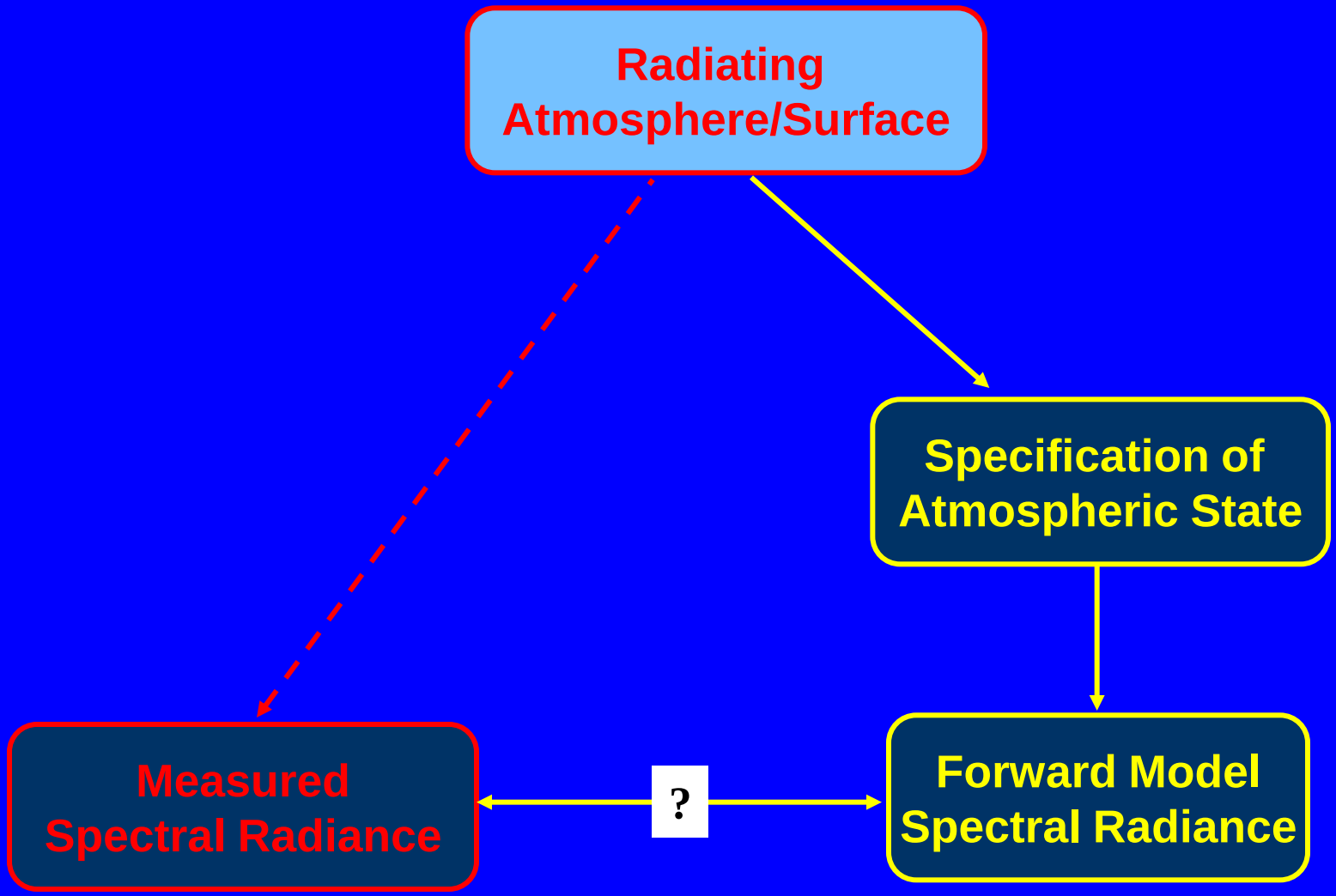
(e)



Water Vapor

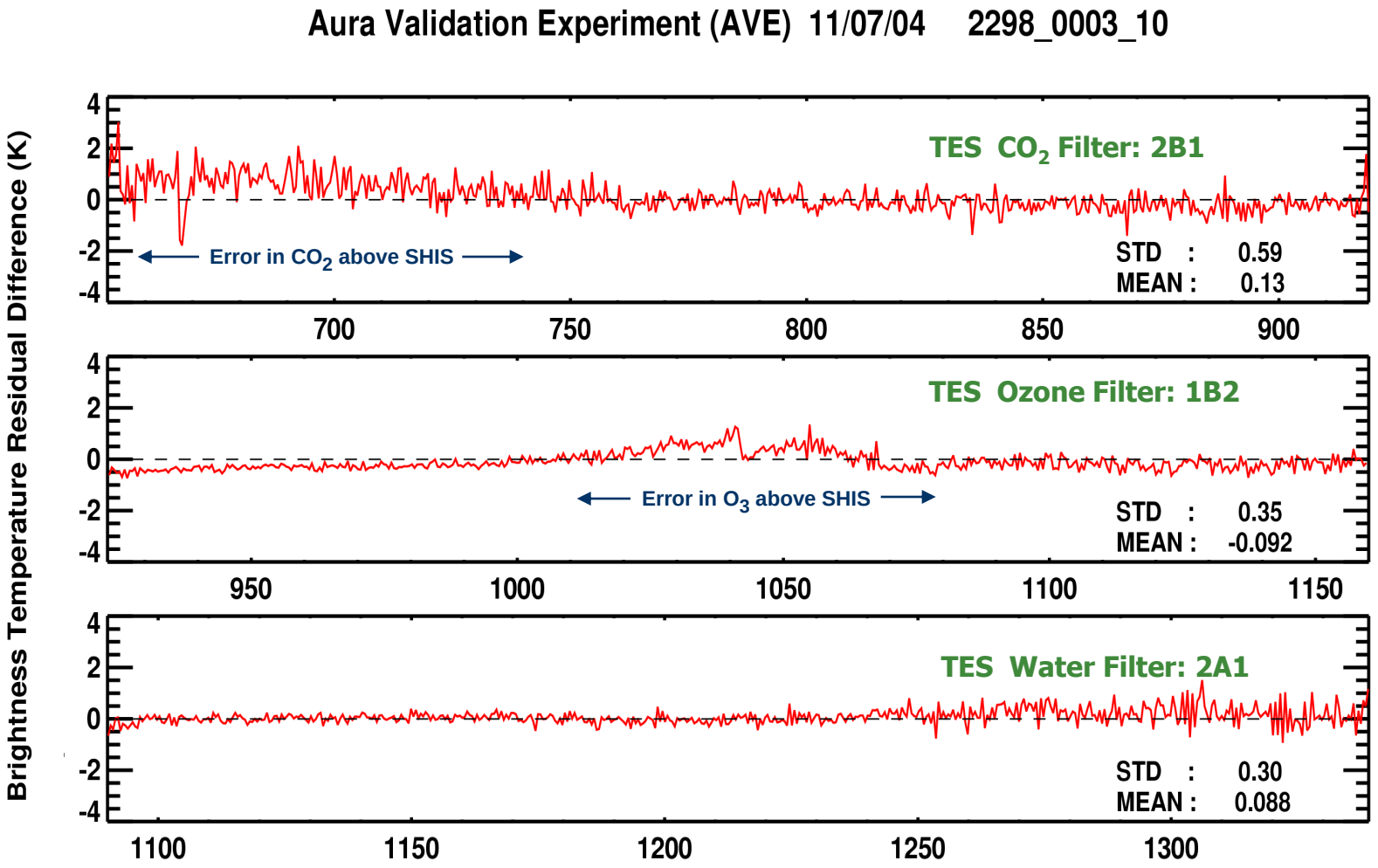





Radiating
Atmosphere/Surface
Specification of
Atmospheric State
Measured
Spectral Radiance
?
Forward Model
Spectral Radiance

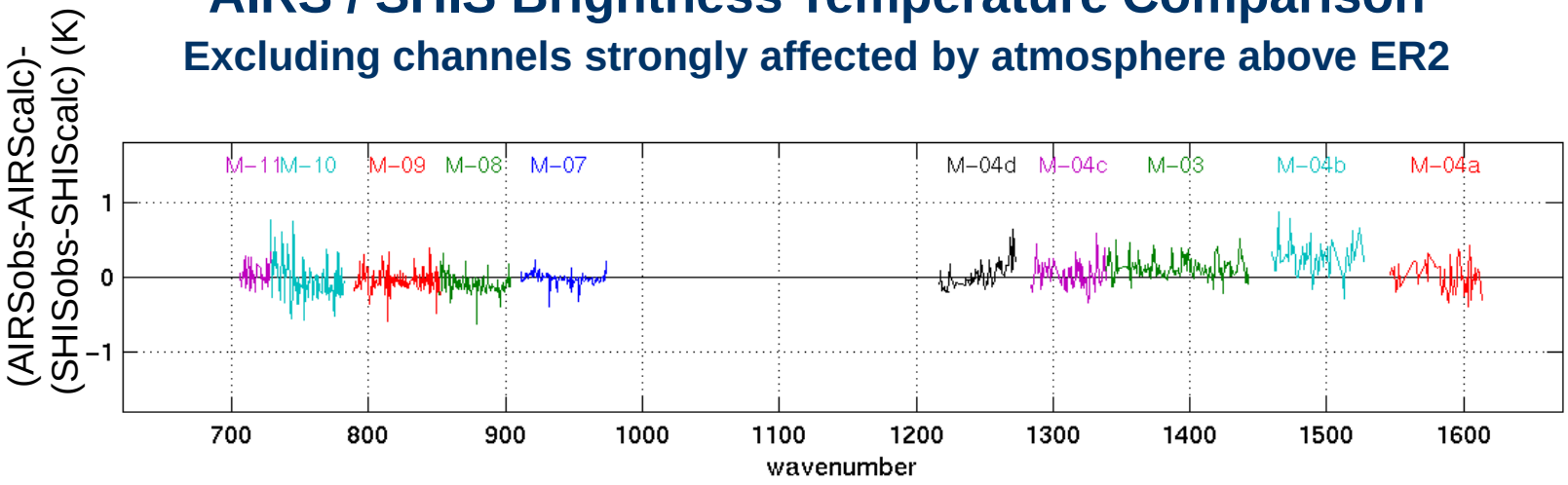
TES - SHIS Radiance Comparison

- **TES Convolved to SHIS ILS**
- **{TES - LBLRTM(TES Geometry)} - {SHIS - LBLRTM(SHIS Geometry)}**

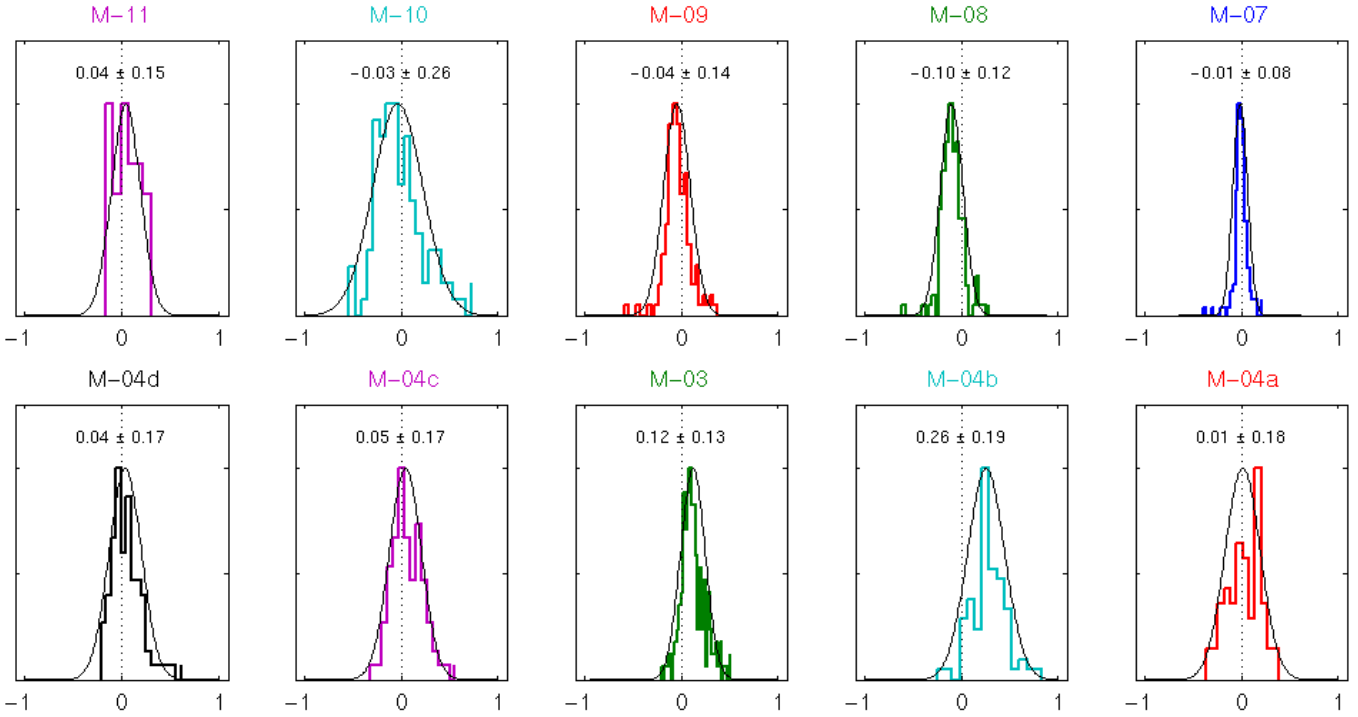


AIRS / SHIS Brightness Temperature Comparison

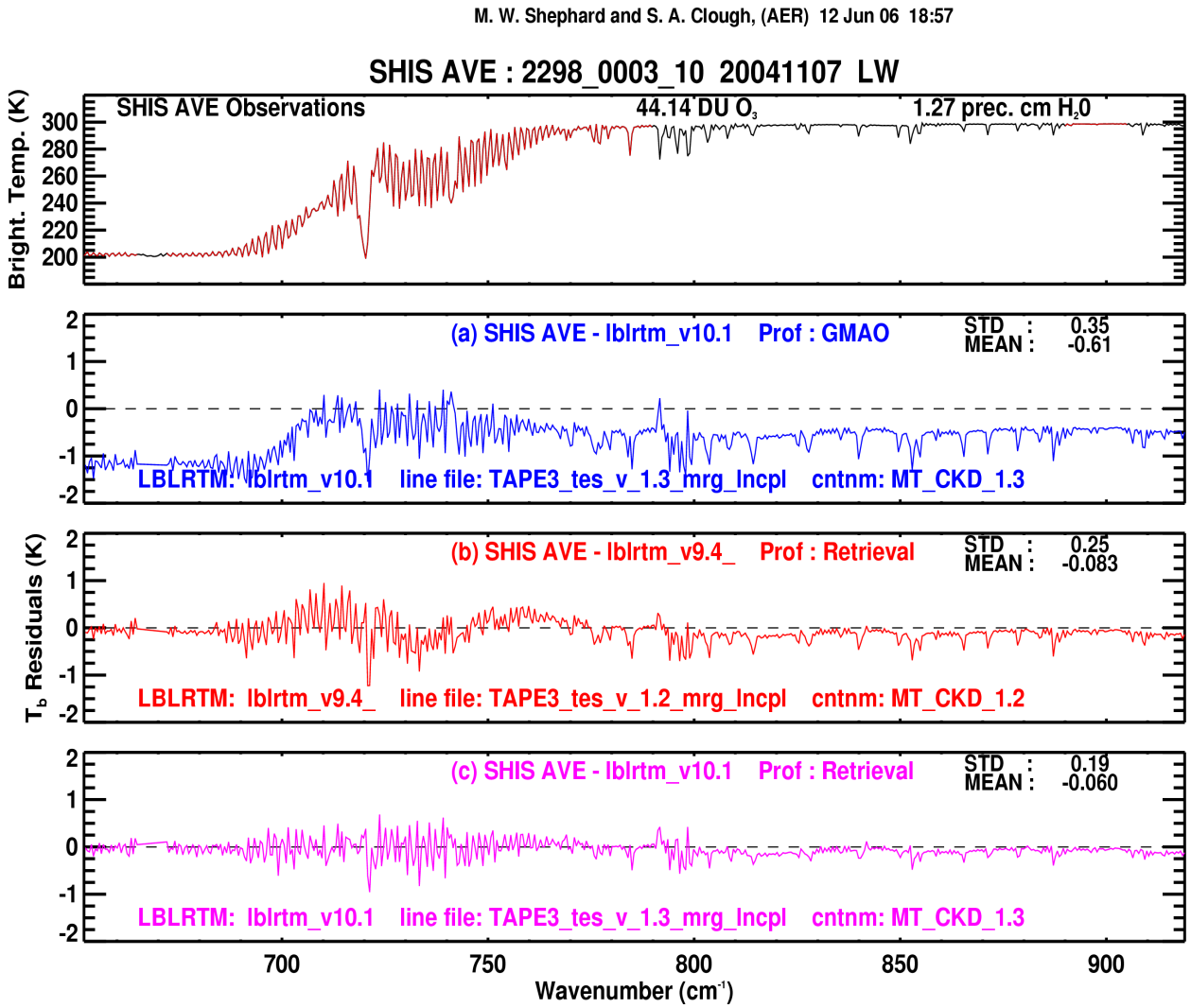
Excluding channels strongly affected by atmosphere above ER2



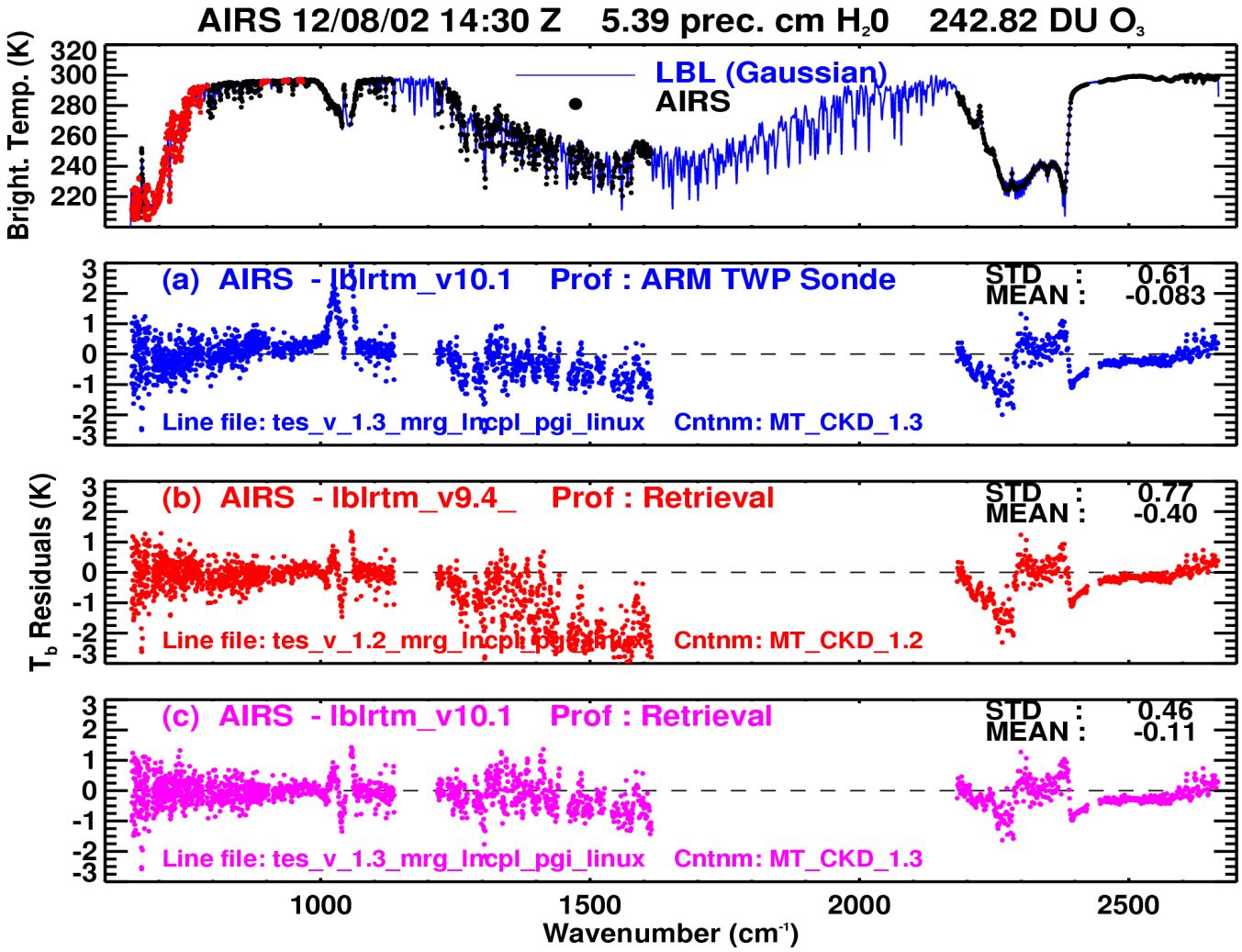
Histograms



SHIS Analysis from AURA Validation Experiment
Gulf of Mexico - no sonde



AIRS Analysis
ARM Tropical Western Pacific site - sonde



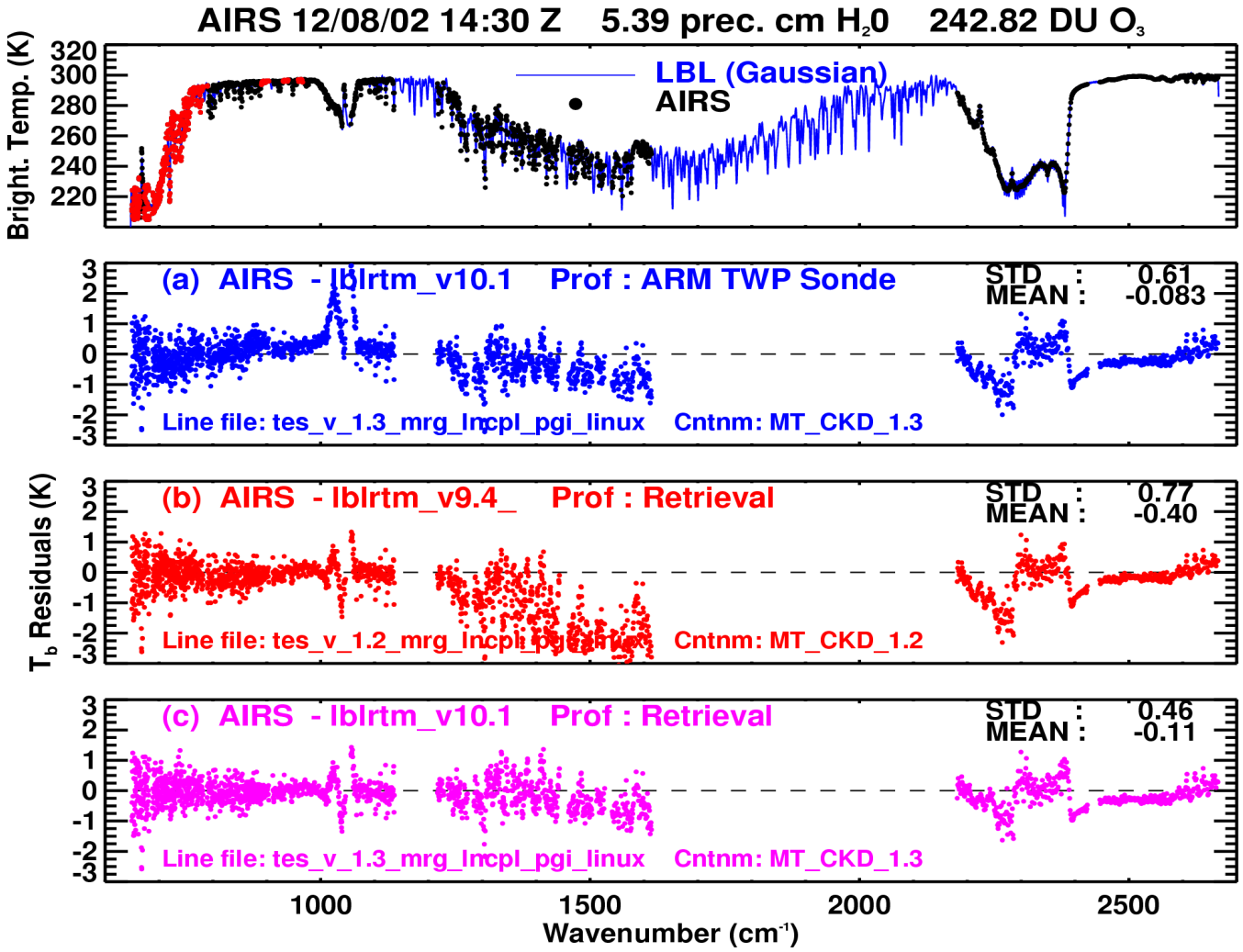
Summary 1

- Forward Model for Temperature Retrievals significantly improved
  - P-R line coupling is a key element
- Carbon Dioxide:
  - χ factor and continuum strongly influenced by line coupling
  - need to introduce small χ factor for duration of collision effects
  - CO_2 Continuum has been reduced by 25% for best fit at bandhead
- ν_2 and ν_3 are apparently not yet fully consistent
- Line Coupling for N_2O
- Updated Code and Line Parameters to be made public
  - separate Line Coupling file (Hartmann) available: TAPE2
- Spectral Residuals will likely become the validation criterion

MT_CKD Water Vapor Continuum Model

- **Definition: Continuum is that absorption with slow spectral dependence which, when added to the line by line absorption, provides agreement with measurement.**
- **Scaling: Dependence on pressure, temperature and mixing ratio must be correct**
- **The model is based on contributions from two sources:**
  1. **Allowed line contribution**
     - **Line wing formalism constrained by the known physics with relevant parameters (~2) determined from laboratory and atmospheric Measurements**
     - **Same line shape is used for every line from the Microwave to 20,000 cm-1**
  2. **Collision-Induced contribution**
     - **Provides the extra absorption previously provided by the 'super Lorentzian' chi factor**
     - **Based on dipole allowed transitions with widths ~ 50 cm-1**
     - **Same line shape is used for every line from the Microwave to UV**
- **The model includes both self and foreign continuum**
- **Spectral region: 0 - 20,000 cm^{-1}**

AIRS Analysis
ARM Tropical Western Pacific site - sonde



Summary 2

- Issues with water vapor continuum have become remarkably muted
- Collision induced component addresses measurement issues
  - No direct validation of mechanism is apparent
- Self and Foreign each use a single separate line shape for all lines to construct the respective continua over full frequency domain
- Self Continuum (line wing component) dominant between bands
- Foreign Continuum (collision induced) dominant within bands
- Well Validated in 0-10 cm-1 (microwave); 400-500 cm-1; 800 -1300 cm-1; and 2500-2700 cm-1 (SST)
- Validations needed 10-400 cm-1 and Shortwave
- Temperature Dependence! Laboratory Measurements (Lafferty)
- MT_CKD Water Vapor Continuum is publicly available
  - http://rtweb.aer.com