Atmospheric and
Environmental Research, Inc.

Radiative Transfer Modeling Support for the CRTM

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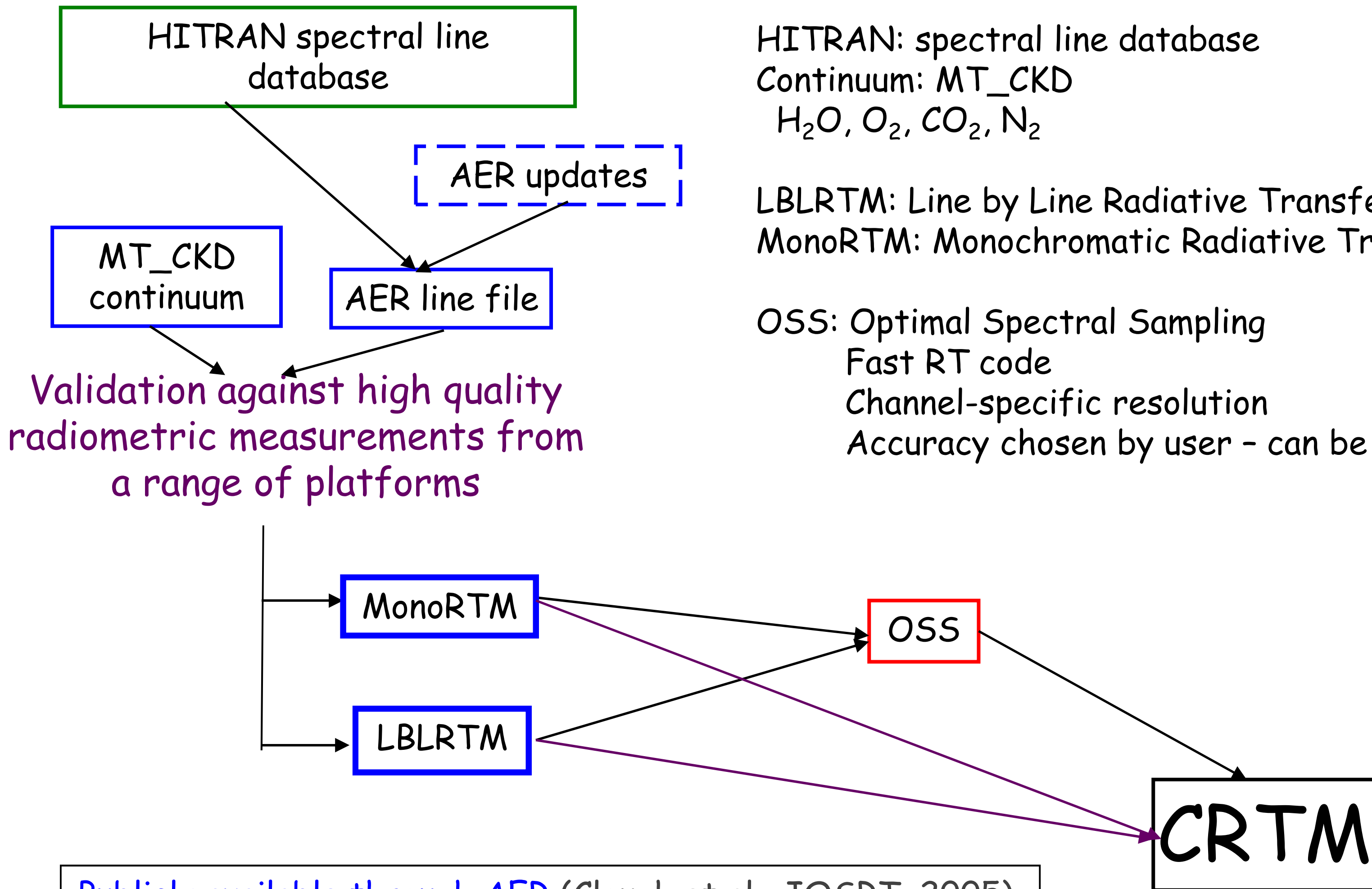
Motivation

- **Goals of this work**
  - **Improve the accuracy of fast radiative transfer models used in satellite radiance assimilation**
  - **Enable greater use of the information available in satellite radiances**
  - **Increase positive impact of satellite data on the forecast**

- **Line-by-line RT models**
  - Accuracy of calculations of molecular absorption limited mainly by uncertainties in spectroscopy
    - Line parameters, lineshape, continua
- **Fast RT models**
  - Differences from line-by-line models can be made negligible
- **Assimilation/inversion of radiances**
  - Speed limited by both forward model calculation and inversion algebra
  - Desirable to reduce dimension of the observation vector
    - Channel sub-setting
    - Principal-component-based compression
    - Node-based compression

AER radiative transfer codes and databases: Relationship with the CRTM



HITRAN: spectral line database
Continuum: MT_CKD
H_2O, O_2, CO_2, N_2

LBLRTM: Line by Line Radiative Transfer Model
MonoRTM: Monochromatic Radiative Transfer Model

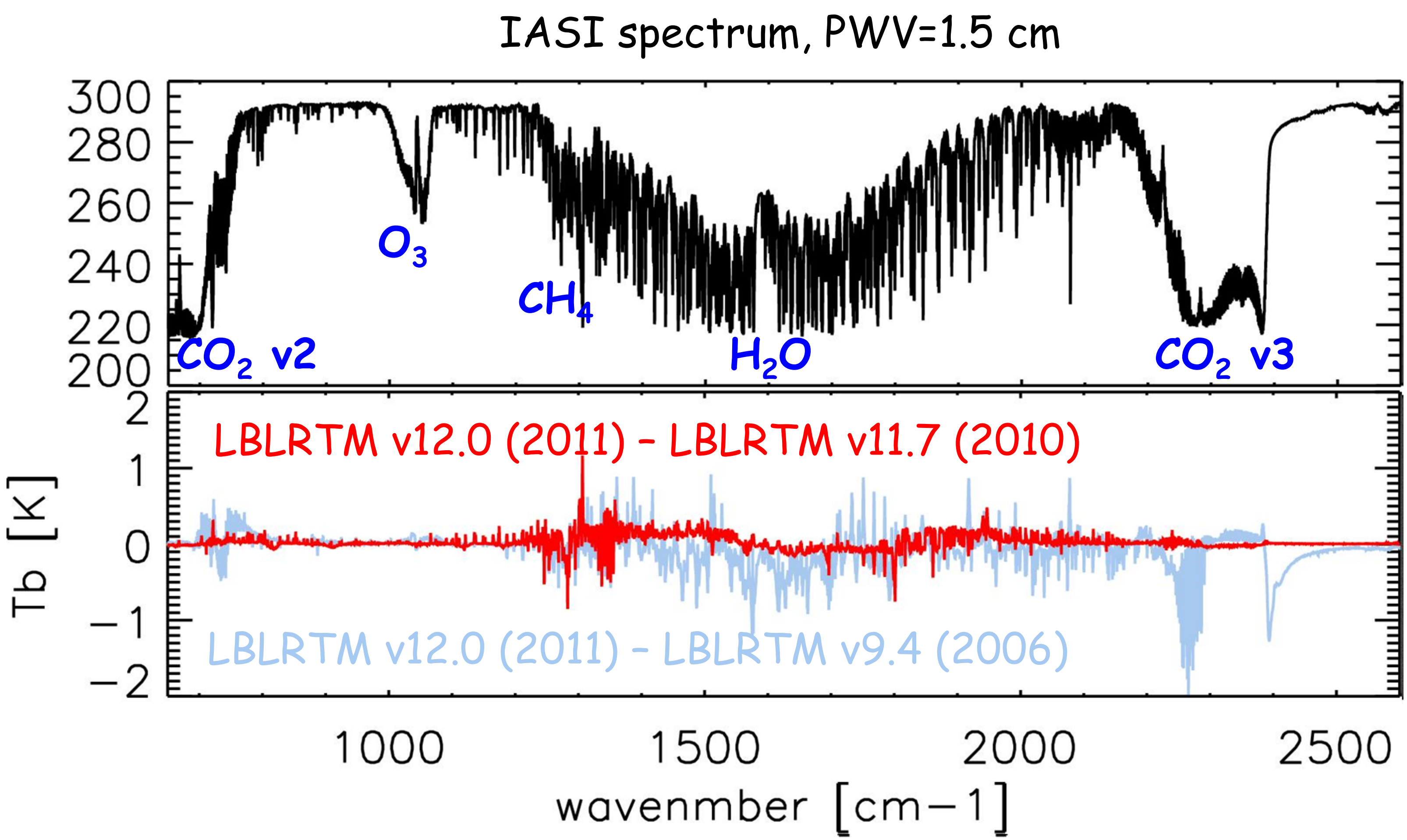
OSS: Optimal Spectral Sampling
- Fast RT code
- Channel-specific resolution
- Accuracy chosen by user – can be arbitrarily small

Publicly available through AER (Clough et al., JQSRT, 2005)
Available through AER by arrangement
Publicly available through other sources

LBLRTM: Latest release

- LBLRTM v12.0
  - Publicly available at http://rtweb.aer.com
    - Released March 2011
    - Supplied with:
      - MT_CKD 2.5.2 continuum
      - **aer_v_3.0 line parameter database**
        - **Based on HITRAN 2008**
        - **Substitutions made where validation against high quality, spectrally-resolved measurements indicate that better parameters are available**
          - H_2O and O_2 in the MW, H_2O and CO_2 in the IR
        - **Contains line coupling coefficients for CO_2, O_2 and CH_4 (new!)**
    - Updated non-LTE capabilities

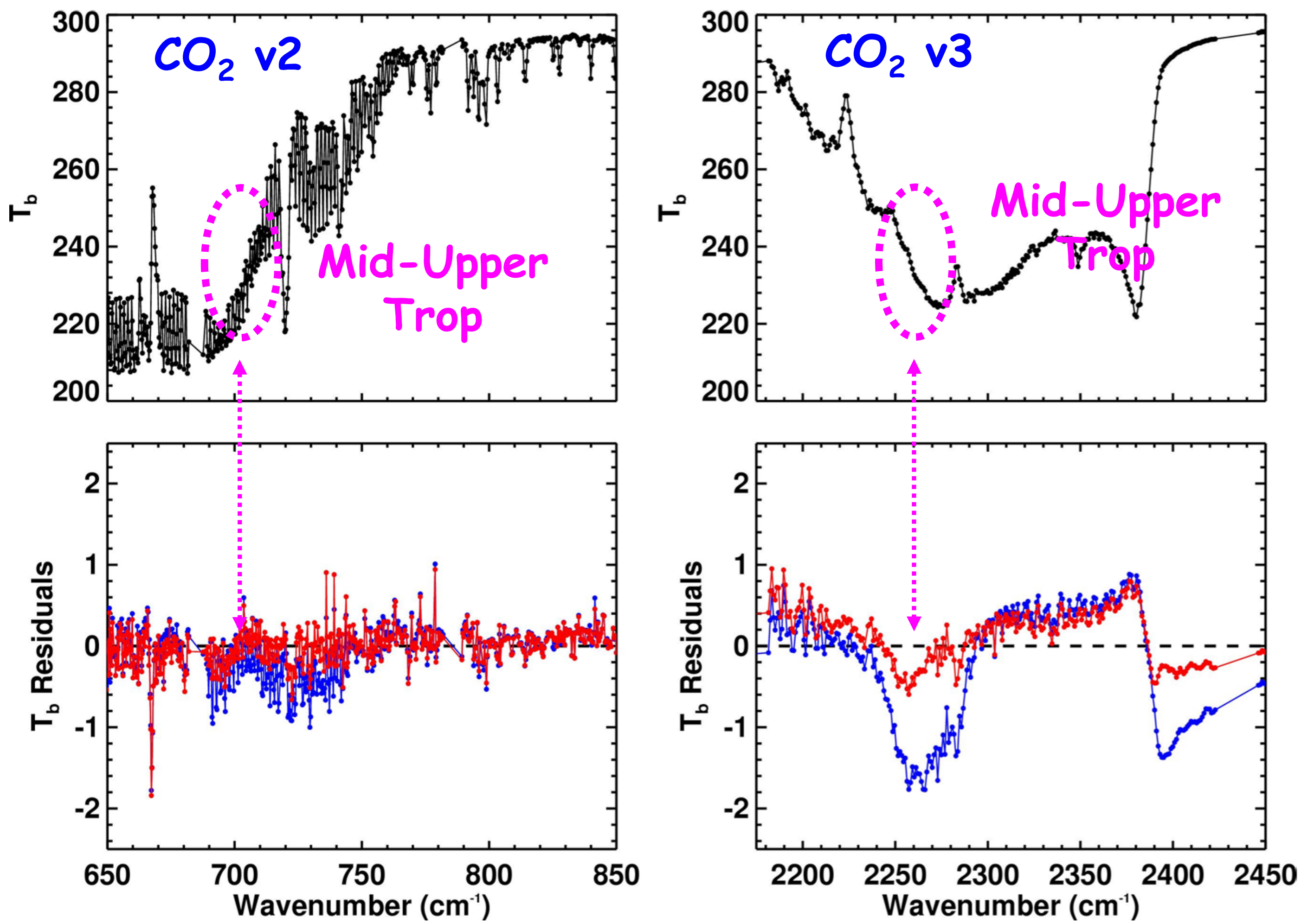
Incremental updates to spectroscopy



CO_2: Temperature information affects the modeling of all other trace gases

CO_2: Consistency between spectral regions

Mean residuals from 36 AIRS ARM TWP cases using Tobin et al. best estimate sonde profiles



Previous version (2006)

- No P/R line cpl
- HITRAN 2000 CO2 parameters

Latest version (2011)

- P, Q and R line coupling
- Lamouroux et al. widths and line coupling
- Tashkun positions, intensities
- Updated CO2 and H2O continua

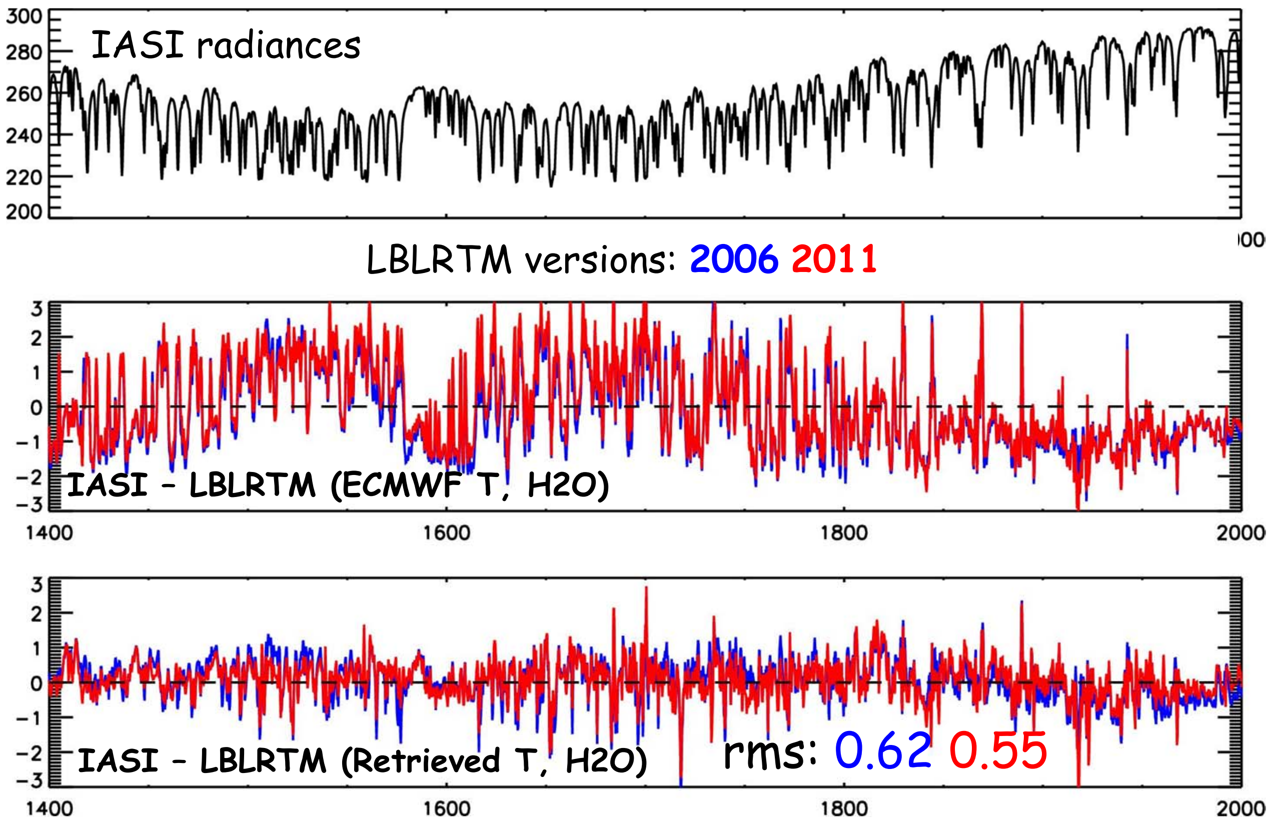
Improved agreement (Obs - Calc) and consistency across spectral bands!

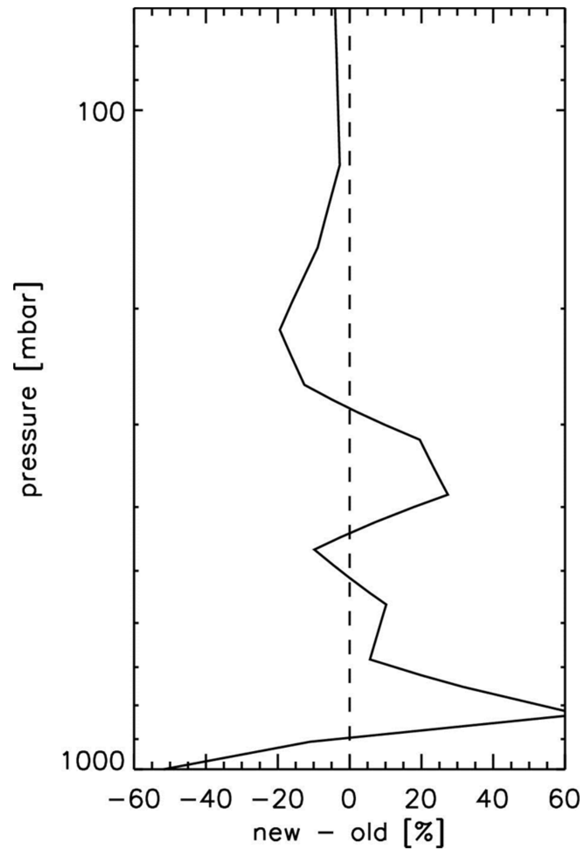
(Input profiles supplied by L. Strow and S. Hannon).

H_2O region: Example IASI case

ECMWF profiles and "clear-sky" IASI radiances supplied by Marco Matricardi

H_2O: Specification of "true" atmospheric state is particularly difficult
Perform retrieval, then assess consistency in the spectral residuals





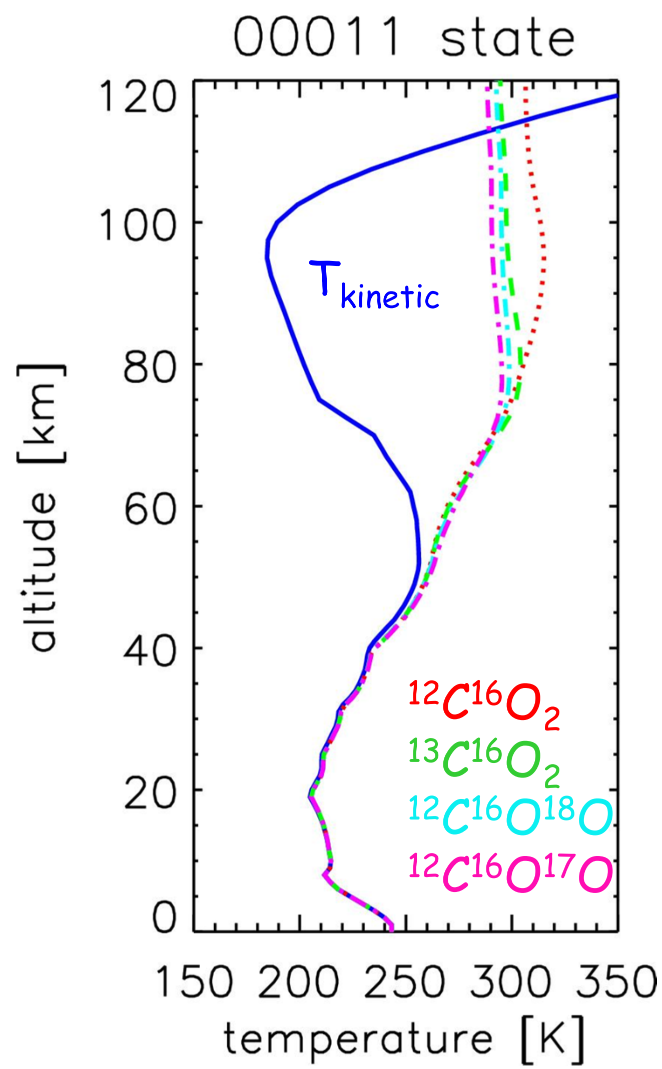
Future work: Assess impact of spectroscopy updates for a range of conditions (~100 cases)

Non-LTE

- **Local Thermodynamic Equilibrium (LTE)**:
  - Behavior dictated by kinetic temperature
  - Population of energy levels follows Boltzmann distribution
- **Non-LTE:**
  - "Solar pumping" populates energy levels more quickly than collisions can thermally redistribute the energy
  - Different vibrational temperature profiles for different vibrational states
  - Affects **daytime** radiances, **high altitude** (>45 km) channels
  - Strong effect for **CO_2 channels in 2200-2400 cm^{-1} region**
    - Can lead to errors of up to ~15 K (AIRS resolution) if not accounted for

Non-LTE

- Initial non-LTE package delivered to JCSDA in April 2010
  - Vib. Temp. profiles supplied by M. Lopez-Puertas (Granada)
  - Yong Han's presentation
- Updated capability in LBLRTM v12.0:
  - Allows different vibrational temperature profiles for different isotopes
  - Impact: ~0.2 K differences for strongest band

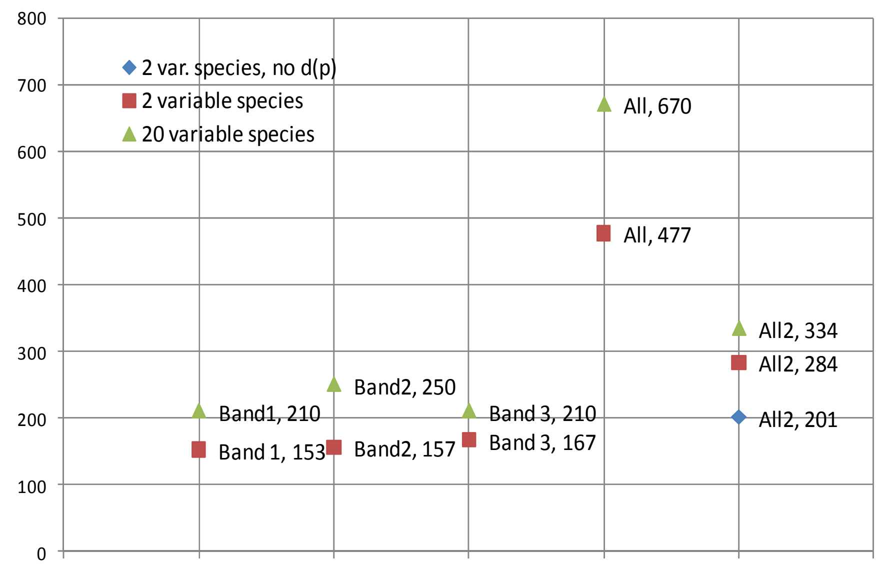


Optimal Spectral Sampling (OSS) development status

- CRTM-OSS
  - **Implementation of infrared forward model complete**
    - Same speed performance as AER standalone OSS model
  - **Tangent linear and adjoint coding complete**
    - In testing phase
  - **Next step:** include microwave and multiple sensor modeling capability
- Generalized training
  - **Finalizing training method**
  - **Integrate Principal Components (PC) modeling capability**
  - **Assimilation/retrieval execution time limited by inversion algebra**
    - focusing on reducing dimension of observation vector
  - **PC offers best radiance compression performance but suffers from well-known limitations which limit its application to assimilation/retrieval**
  - **Alternative node-based representation provides factor 10-20 speed up in retrieval applications and avoids mixing of spectral information**
    - **Keeps same attributes as channel-space wrt**
      - dynamic channel selection (for e.g. clear-sky retrieval down to cloud top)
      - bias removal
      - preserving information relative to minor absorbers.

Example of OSS performance (IASI)

- IASI: ~8000 channels
- Model accuracy (0.05K)
- Number of variable species (from 2 to 20 in current RT model)
- Training set:
  - random perturbations d(p) added to profiles to remove vertical correlation
  - secular trends for e.g. CO_2 added
- Nadir viewing geometry (currently applies from 0 to ~70° to include geostationary sensors – scan angle binning could further reduce # nodes)

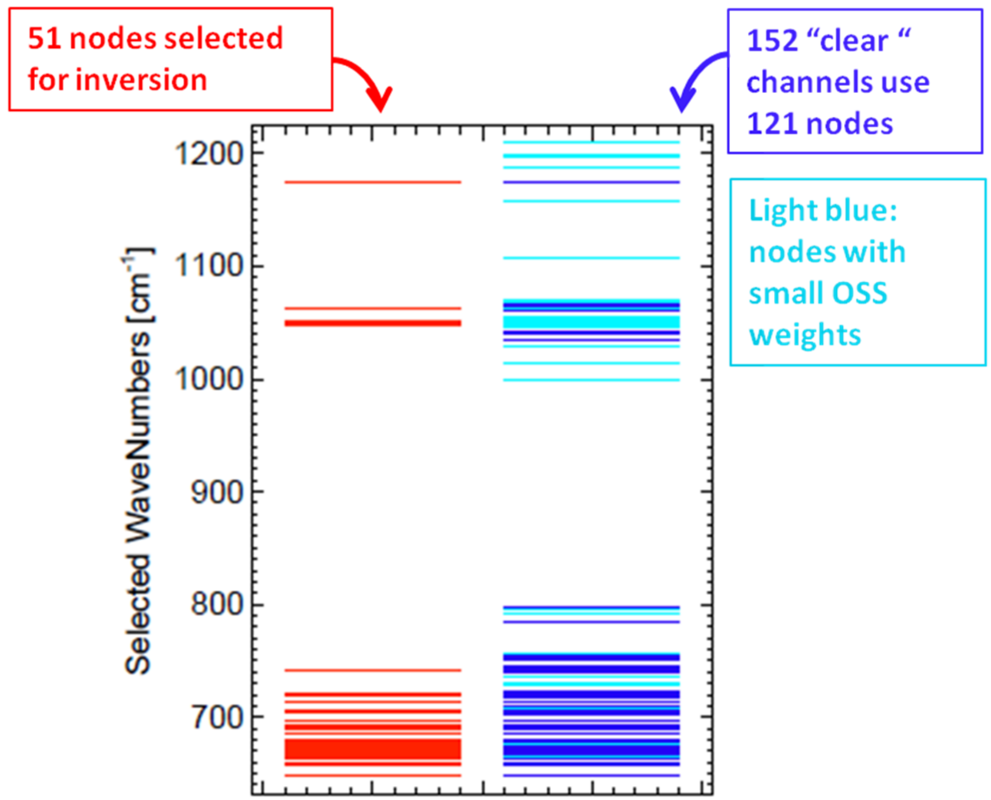


Node-based representation:
Application to clear retrieval down to cloud top

Approach:

- Project full cloudy radiance spectrum onto nodes
- Perform dynamic node selection
  - Using e.g. Jacobians and 1DVAR cloud top retrieval (Pavelin et al., 2008) or other technique
  - In this experiment, perfect knowledge of cloud top is used
  - Nodes have sharper weighting functions than channels – practical benefits not assessed
- Trim obs error covariance matrix (node space) and perform retrieval with reduced set of nodes

IASI Band 1 - black cloud at 500 mb



Example of 1D-VAR retrieval results

Red: Node space

Clear (dashed)/cloudy (solid) temperature retrieval errors with cloudy node selection

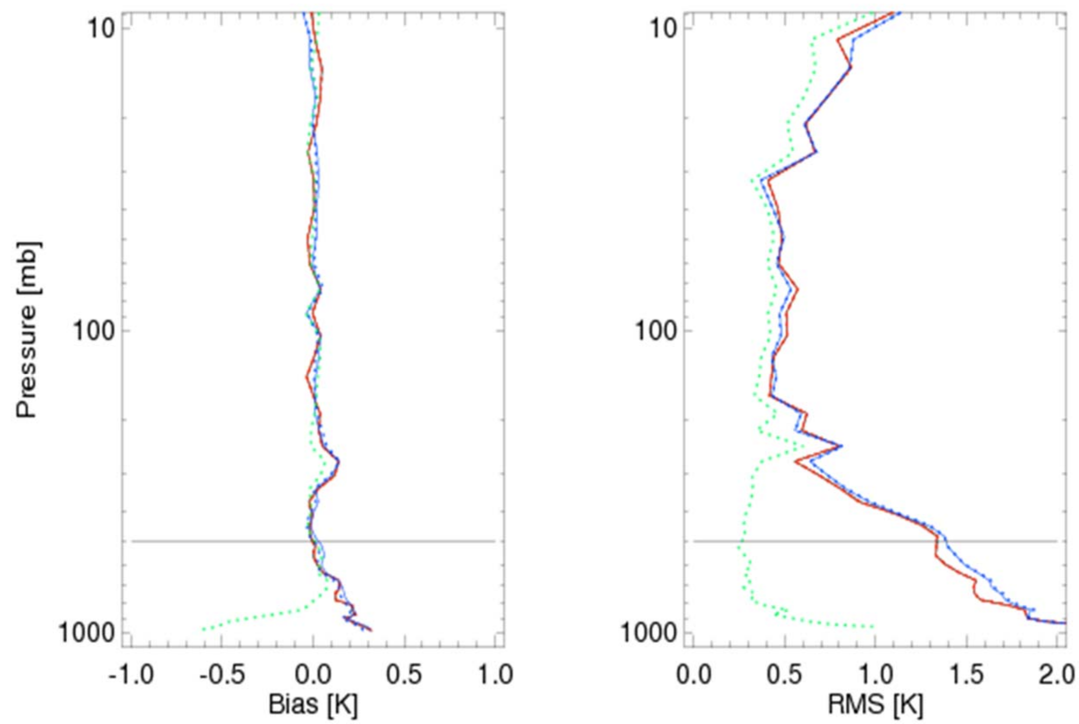
Blue: Channel space

Retrieval with 500mb clear channel selection

Green: Channel space

Full Band 1 channel set clear-sky retrieval (for reference only)

Retrieved temperature profile rms and bias
(climatology background)



OSS on the GPU

- OSS is ideally suited for the GPU because of the many **independent** calculations that can be done in Parallel.

```
Loop over Profiles
{
Loop over Nodes
{
Loop over Layers
{
ComputeOpticalDepth();
}
}
}
```

```
queue.enqueueNDRangeKernel
(
kernel,
cl::NullRange,
clNDRange(numProfs,
numNodes,
numLayers)
cl::NullRange,
NULL
);
```

Radiance Accuracy Results So Far

average difference	5.42092E-09
min difference	0
max difference	7.63E-06
average percent difference	4.5E-08%
min percent difference	0%
max percent difference	1.8E-05%

Speedup Results So Far (100 profiles)

	CPU	GPU NVidia 480GTX	Speedup
Optical Depths	30.6s	0.31s	98.71X
Radiances	20.4s	0.20s	102.00X

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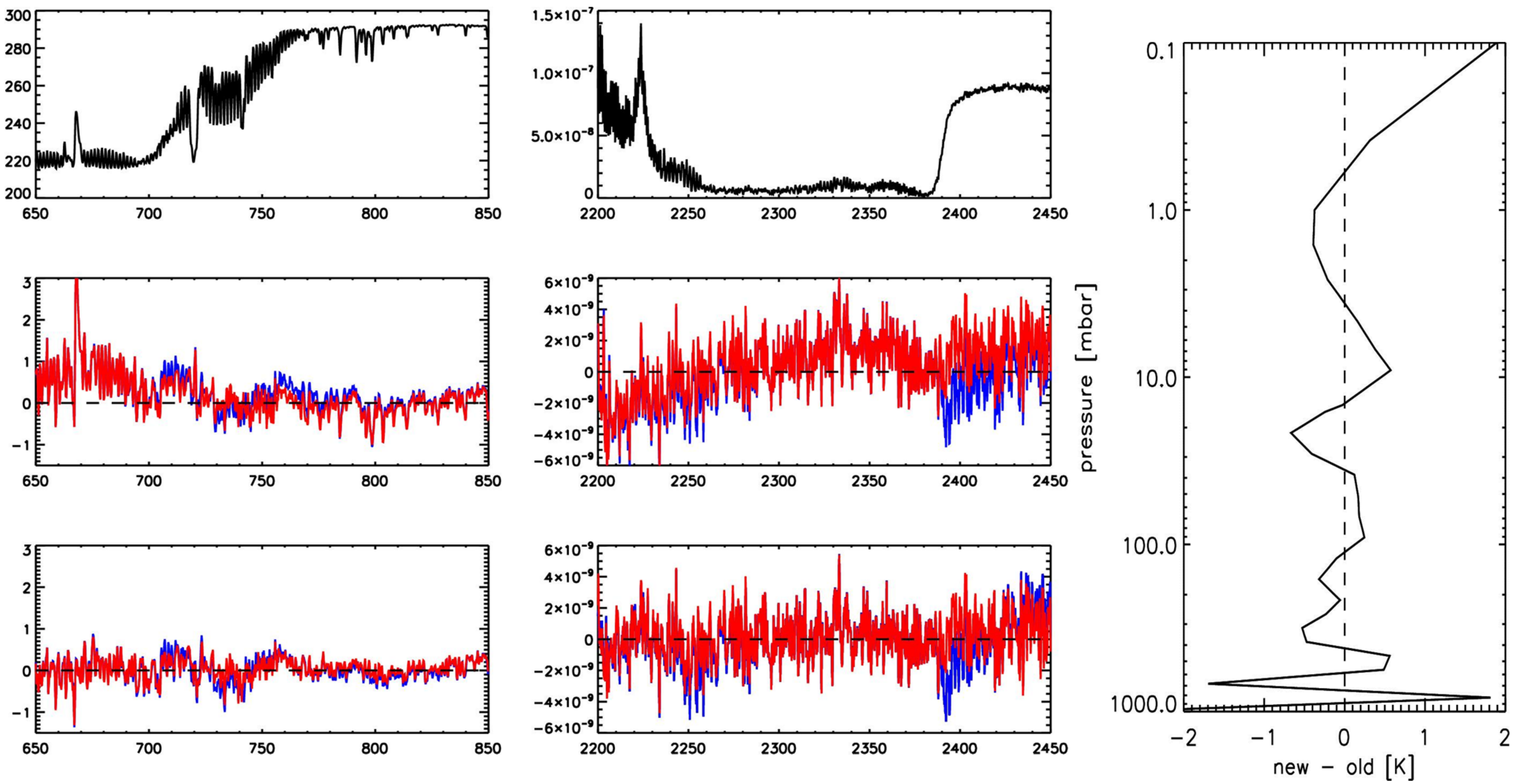
Summary

- Improvements to spectroscopy continue to improve consistency in spectral residuals
- LBLRTM v12.0 now available at http://rtweb.aer.com
- Continued progress in CRTM-OSS development
  - Finalization of training method is underway
- Contact:
  - vpayne@aer.com
  - jmoncet@aer.com

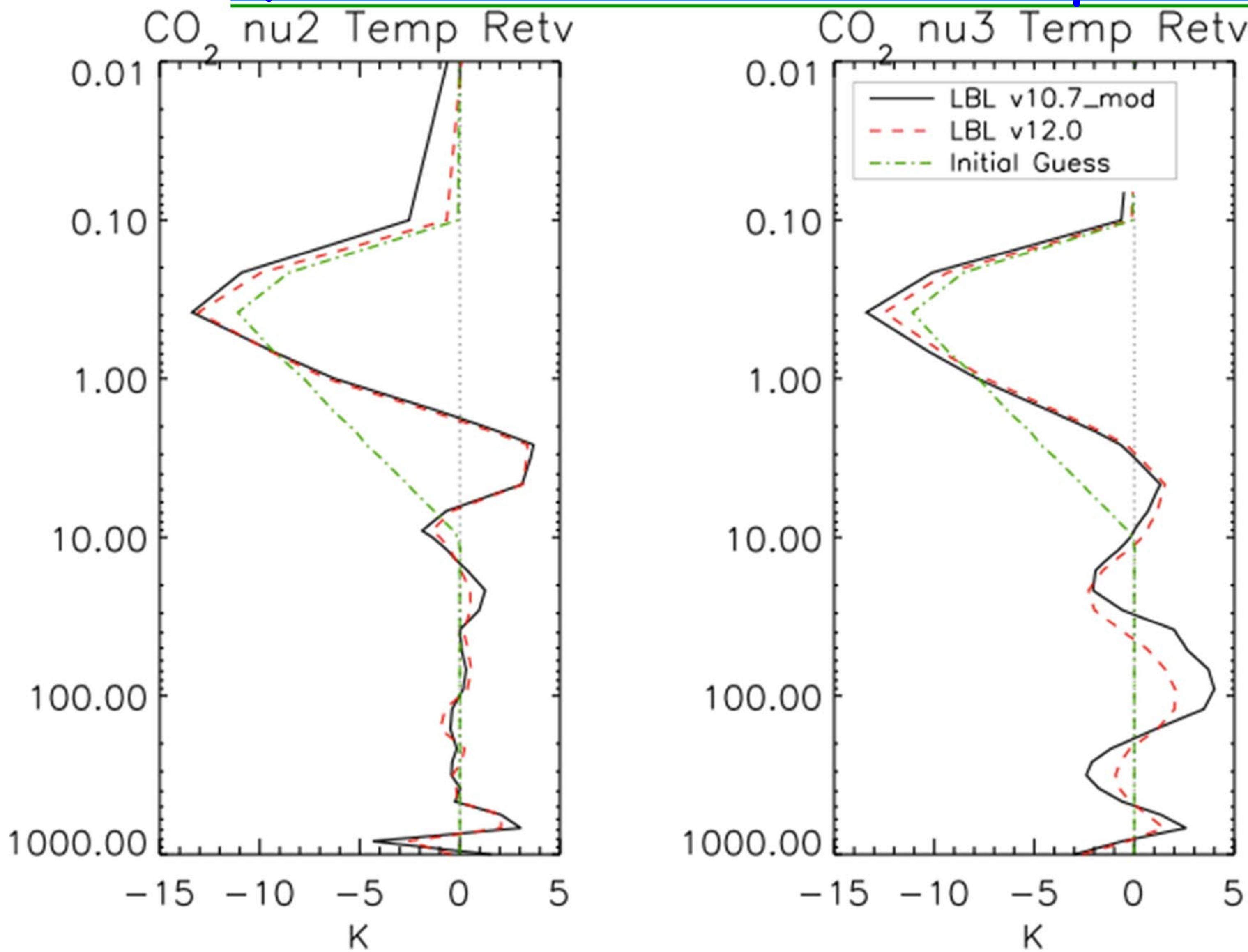
Back up

Impact on temperature profile

- Perspective 2: retrieval to achieve consistency



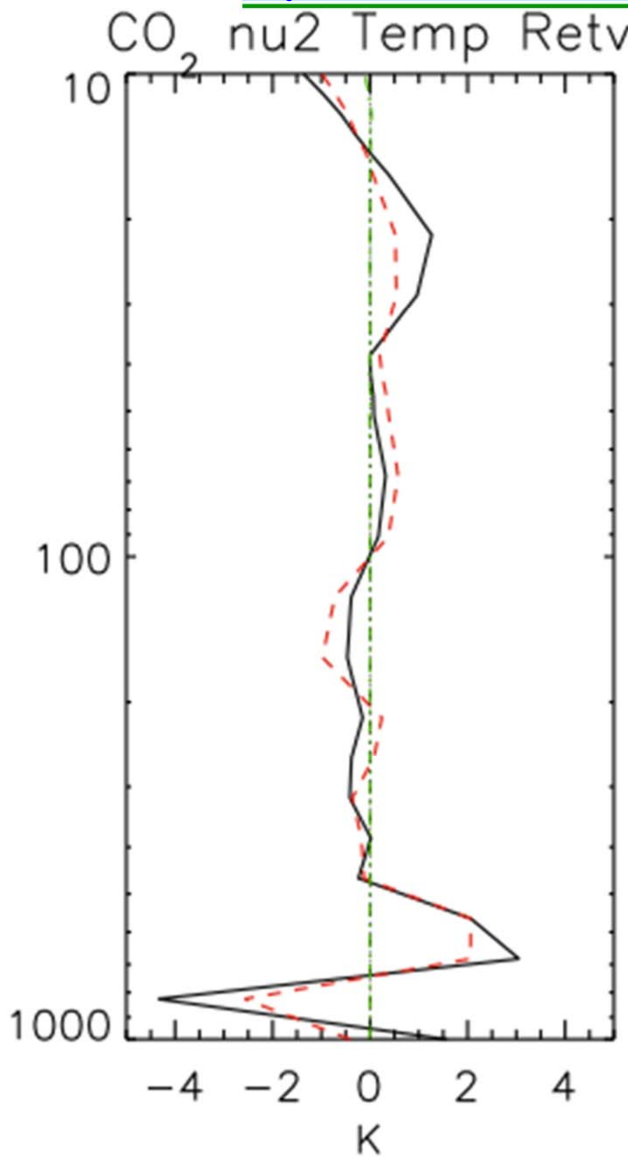
Temperature profiles (retrieval minus ECMWF profile)

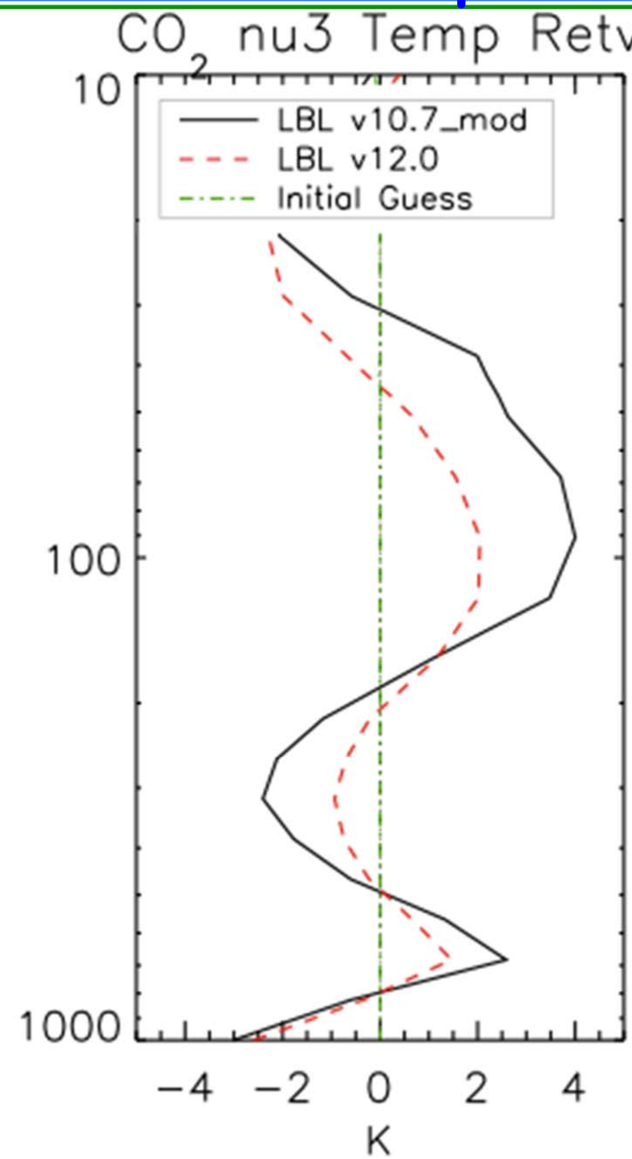


<u>Temperature Constraint</u>

- Surface
  - σ = 1 K
- Below 200 hPa
  - σ = 2 K
- 50 - 200 hPa
  - σ = 4 K
- 10 - 50 hPa
  - σ = 7 K
- Above 10 hPa
  - σ = 10 K
- Corr. Len. = 1.0

Temperature profiles below 10 hPa (retrieval minus ECMWF profile)





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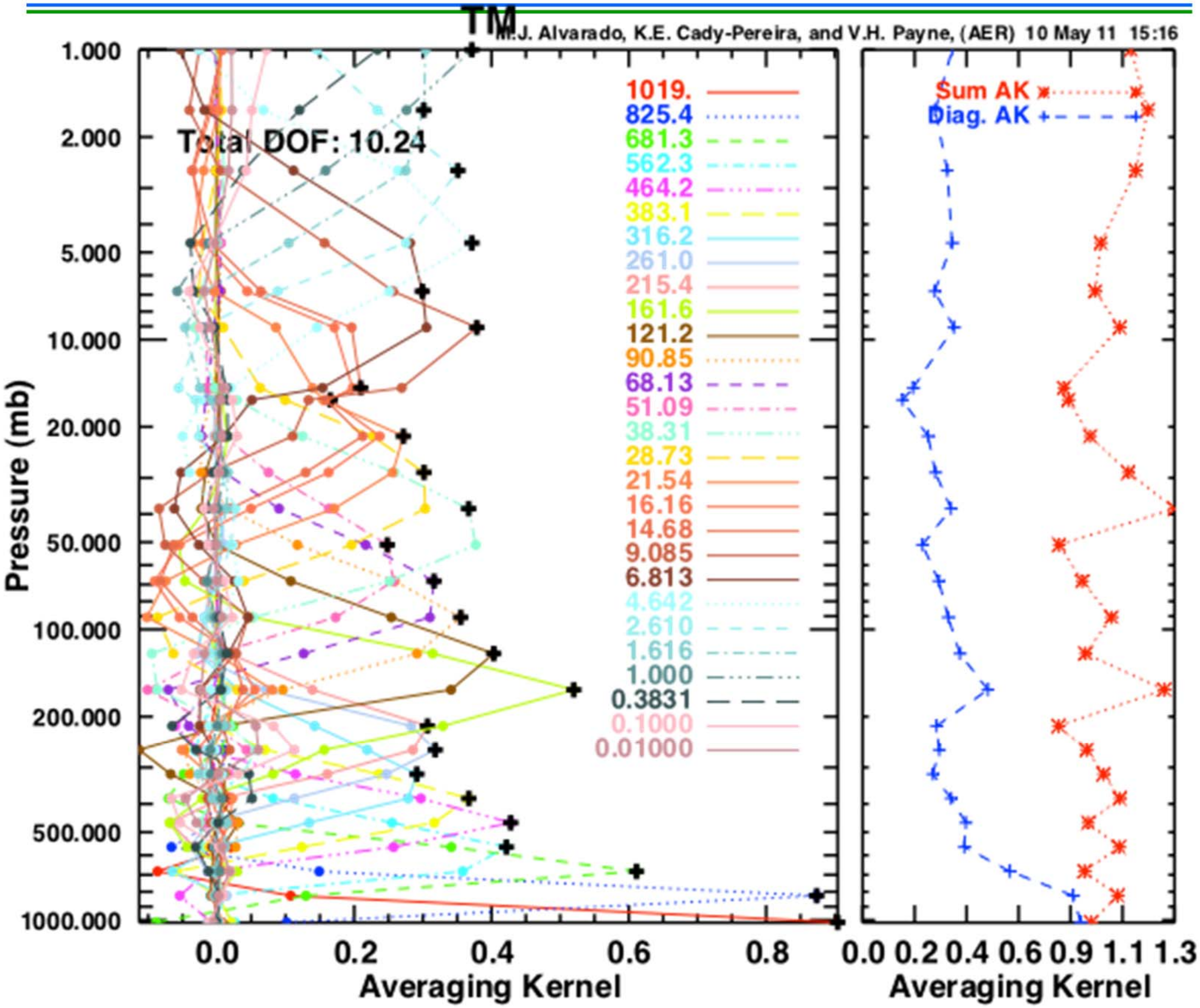
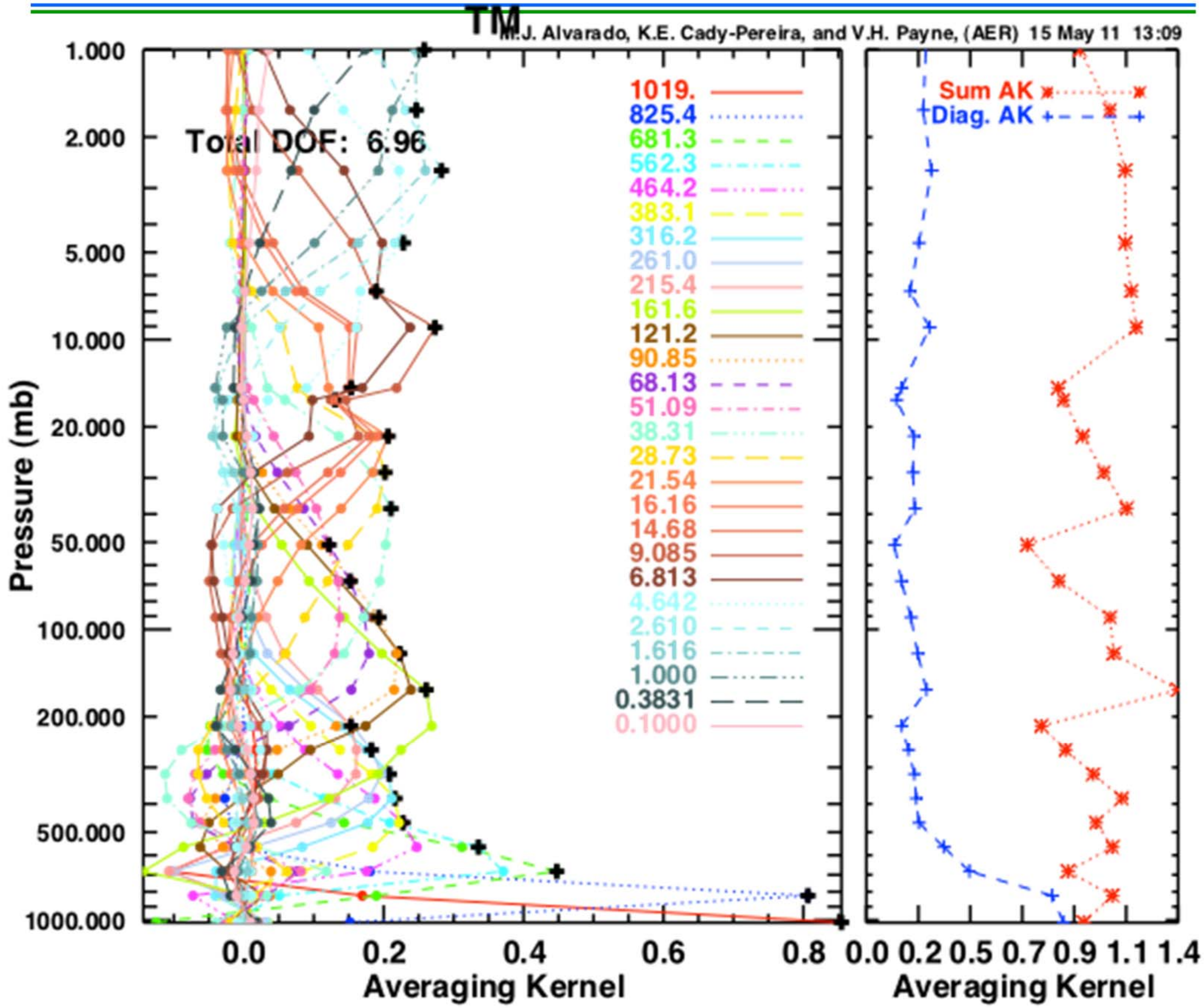
CO_2 nu2 Temperature Averaging Kernel

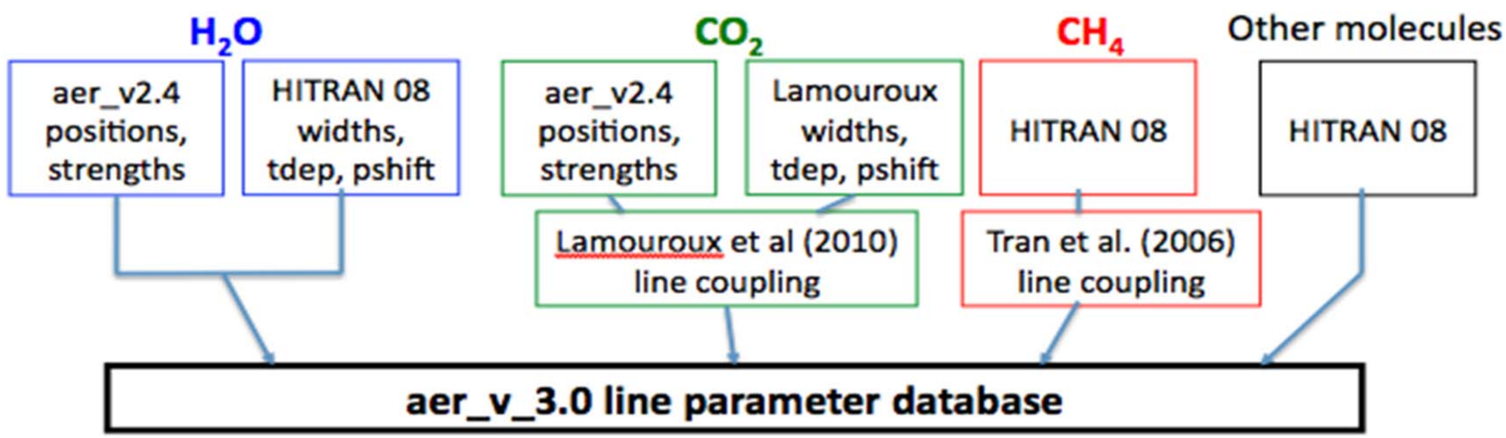
LBL v12.0, v10.7_mod similar



CO_2 nu3 Temperature Averaging Kernel
LBL v12.0, v10.7_mod similar

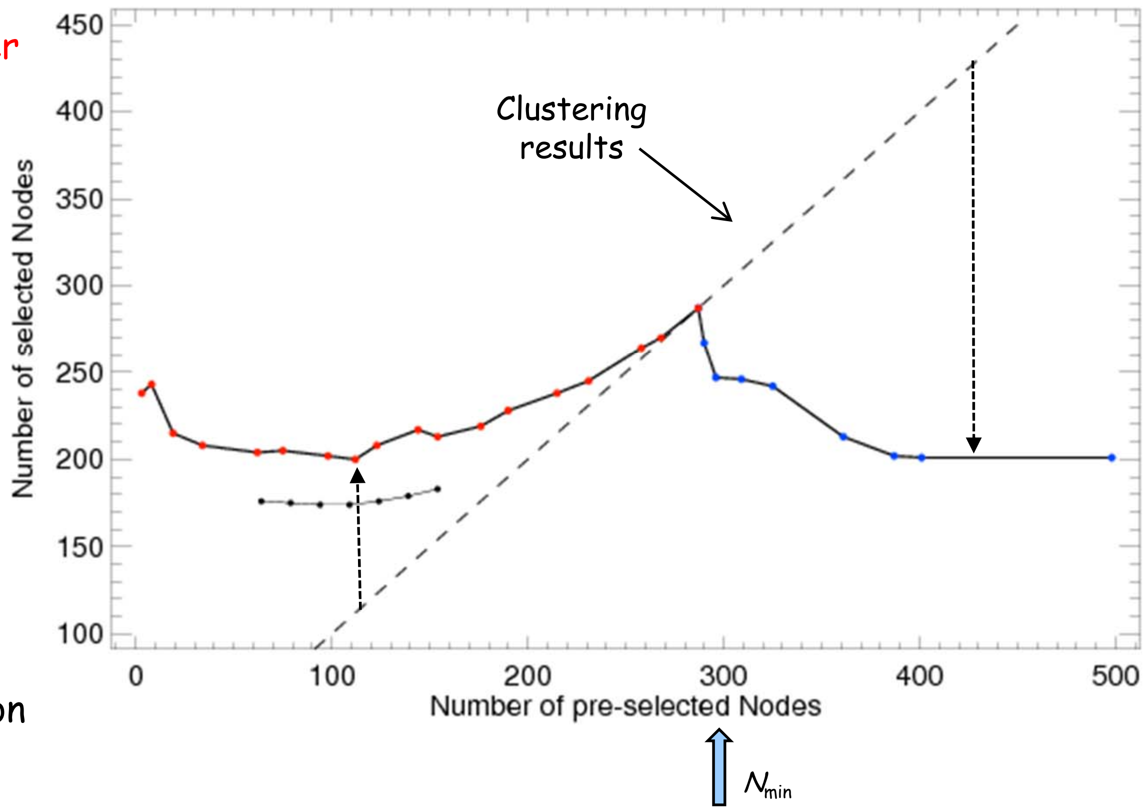


aer_v_3.0 line parameters in the mid-IR:



Generalized training: Methodology trade

- Two approaches considered:
- Method 1: Reduce initial number of nodes by clustering below minimum required to model the spectral domain and add back nodes on a channel per channel basis until all channels meet accuracy threshold.
- Method 2: Apply clustering to reduce initial number of nodes to N > Nmin. Apply extended (vector) search for final selection.
- Look for fastest implementation and capability of providing continuous trade off between minimizing Nav (local training) and Ntot (global training).



Profile data sources

1	H_2O	ECMWF with noise added; same as standard training set
2	O_3	ECMWF with noise added; same as standard training set
3	CO_2	GMI ±10°lat, ±1 month match, plus 2002-2012 secular trend, noise added on primary and secondary levels and interpolated
4	CH_4	GMI ±10°lat, ±1 month match, plus 2002-2012 secular trend, noise added on primary and secondary levels and interpolated
5	N_2O	GMI ±10°lat, ±1 month match, noise added on primary and secondary levels and interpolated
6	CO	GMI ±10°lat, ±1 month match, noise added on primary and secondary levels and interpolated
7	F11	GMI ±10°lat, ±1 month match, noise added on primary and secondary levels and interpolated
8	F12	single profile from Matricardi w/ ±10% random scaling
9	CCl_4	single profile from Matricardi w/ ±10% random scaling
10	HNO_3	single profile from Matricardi scaled to get 0.4 DU, then randomly varied by ln(q')=ln(q)±ln(5) (varied by factor of 5)
11	SO_2	single US Standard Atmosphere profile scaled to get 0.1 DU, then randomly scaled (on a log scale) to get random range of 0.09 to 900 DU. The scale factor is a two-piece hyperbolas of log(p), with the maximum factor D (and zero vertical derivative) at 235 mb tapering to D/1000 at the top and D/100 at the bottom. The rate of tapering was arbitrary.
12	OCS	constant with height at 500 pptv from surface up to 20 km an then linearly decrease to 0 at 50 km; the suggested dynamic range (randomized) is ±10% (per S. Tjemkes)
13	CF_4	dynamic range (randomized) of 50 to 70 pptv, constant profile (per S. Tjemkes)
14	NH_3	Derived from profiles over Australian fires and sugar cane fields provided by Guergana Guerova, University of Wollongong
15	HCOOH	ATMOS profile
16	CH_3OH	GEOS-CHEM profile provided by Dylan Millet. Harvard University
17	C_2H_2	Remedios [MIPAS team]: mean profile and 1-STD variability. For the training we use N-STD
18	C_2H_4	ATMOS profile
19	HCN	Remedios [MIPAS team]: mean profile and 1-STD variability. For the training we use N-STD
20	$CHClF_2$ (F22)	Remedios [MIPAS team]: mean profile and 1-STD variability. For the training we use N-STD

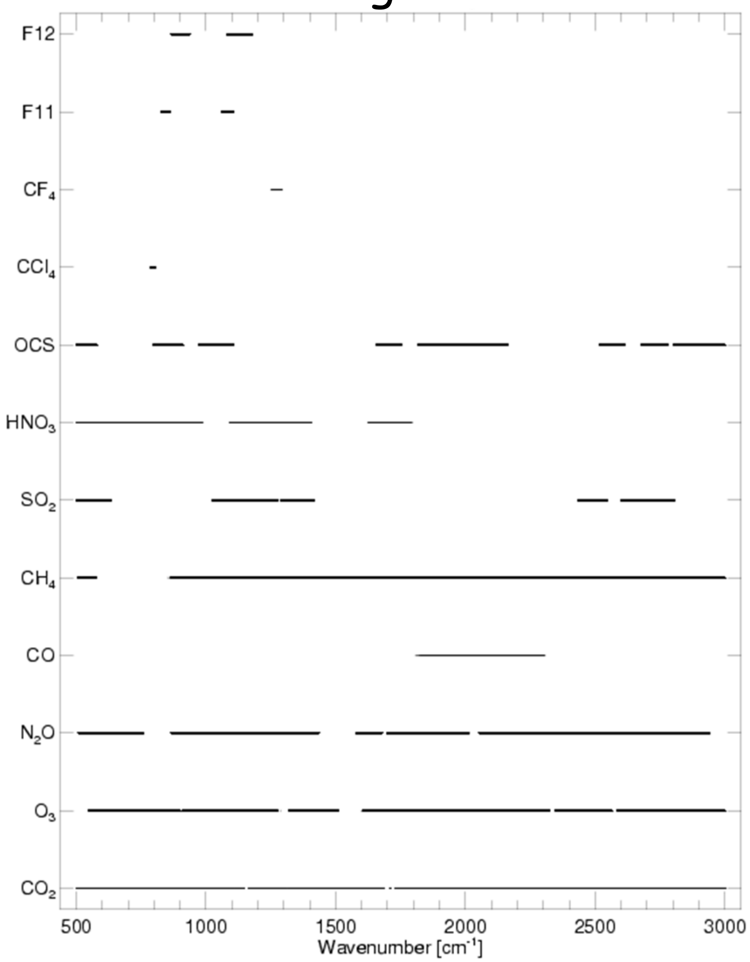
4 fixed gases (source AFGL standard atmospheres):
O_2, NO, NO_2, N_2

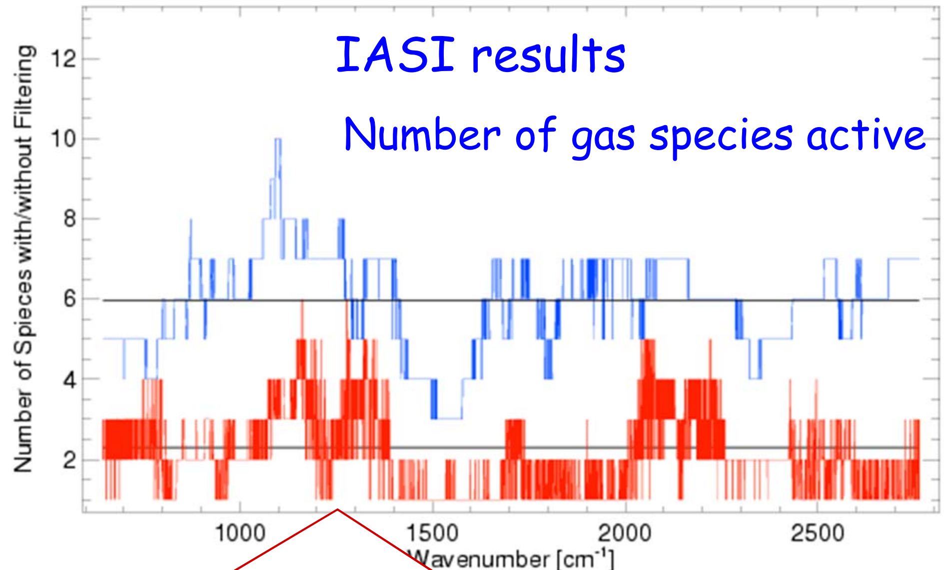
Number of variable trace species can be decided at run time. Non-selected species are assigned user-supplied profile and merged with fixed gases (no retraining required)

**Newly added variable species for Aura-TES

Trace gases

Where trace gases are active





After filtering to retain only the species that significantly affect optical depth

# of variable species	Filter	Avg. # of species /node	Timing (s)	
			Fwd only	Fwd+ Jacobians
2	No	1.89	0.20s	0.36s
	Yes	1.31	0.18s	0.28s
13	No	5.97	0.29s	0.67s
	Yes	2.30	0.22s	0.39s

Timing not much affected by adding species