The spectroscopic foundation of radiative forcing of climate by carbon dioxide

Marty Mlynczak
NASA Langley Research Center
&
Co-Authors

Co-Authors

- NASA Langley
  - Taumi Daniels
  - David Kratz
  - Jeffrey Mast
  - Linda Hunt
- AER
  - Eli Mlawer
  - Matthew Alvarado
- Lawrence Berkeley Lab
  - William Collins
  - Daniel Feldman
- NOAA ESRL
  - David Fahey
- University of Wisconsin
  - Wilmer Anderson
  - James Lawler

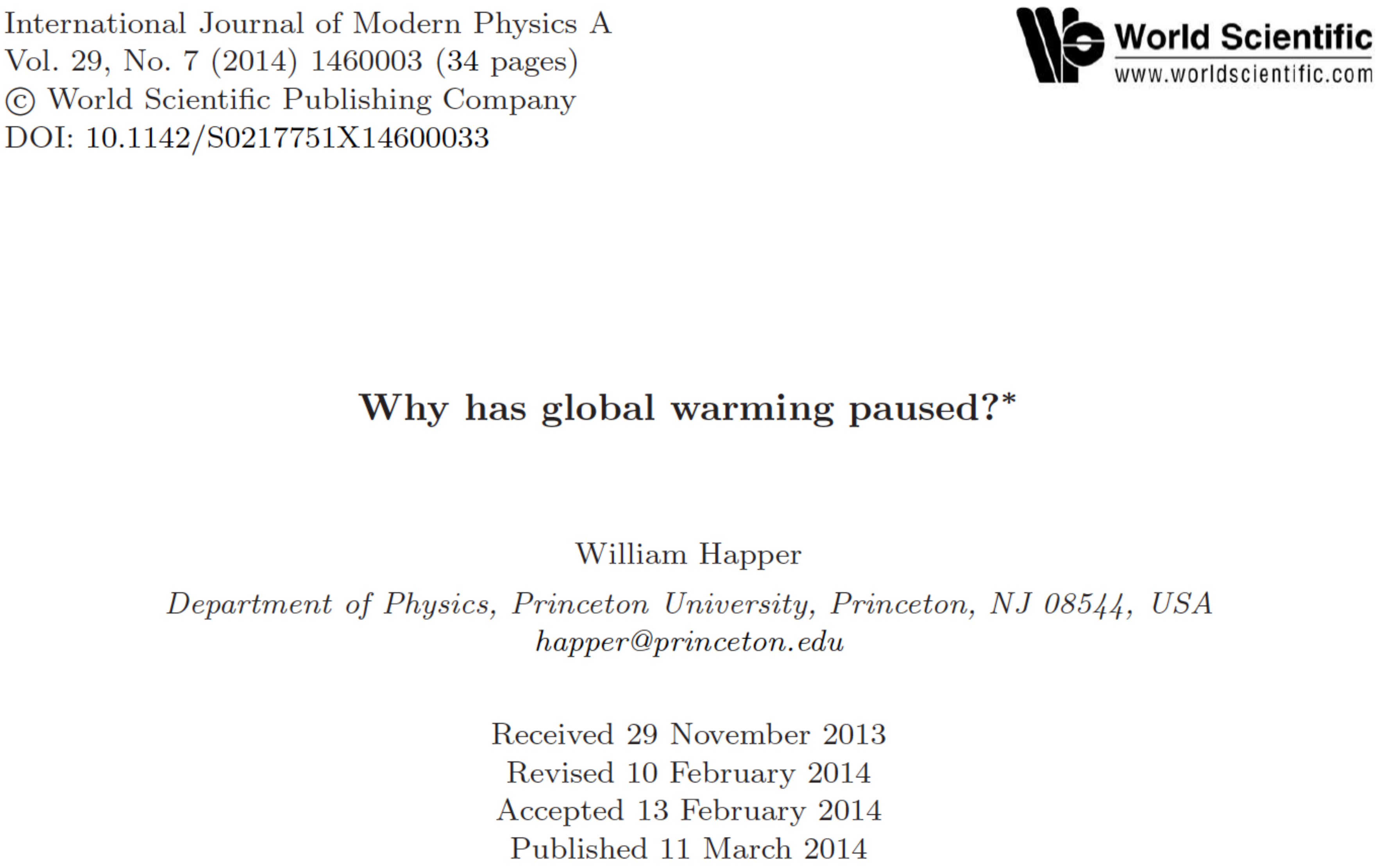
Outline

- Motivation
- Definition and Examples of Radiative Forcing
- Uncertainty in RF due to Spectroscopic Parameters
  - Line shape and line mixing
  - Line Strengths
  - Air-broadened halfwidths
- Results
- Utility of the Voigt lineshape
- Summary and Conclusions

Motivation

- **Radiative forcing (RF) by CO_2 is the leading contribution to anthropogenic climate change**
- **Uncertainties in CO_2 RF impact scientific and policy assessments**
- **Goals of this work:**
  - **Assess uncertainty in RF associated with infrared spectroscopy of CO_2**
  - **Of particular interest is line mixing and line shape function**
  - **Refute recent assertions that RF is greatly overestimated due to inappropriate use of Voigt lineshape (Happer, 2014)**

- ***Result*: RF spectroscopic uncertainty is < 1% and the foundation of climate change modeling is sound**



International Journal of Modern Physics A
Vol. 29, No. 7 (2014) 1460003 (34 pages)
© World Scientific Publishing Company
DOI: 10.1142/S0217751X14600033

World Scientific
www.worldscientific.com

Why has global warming paused?*

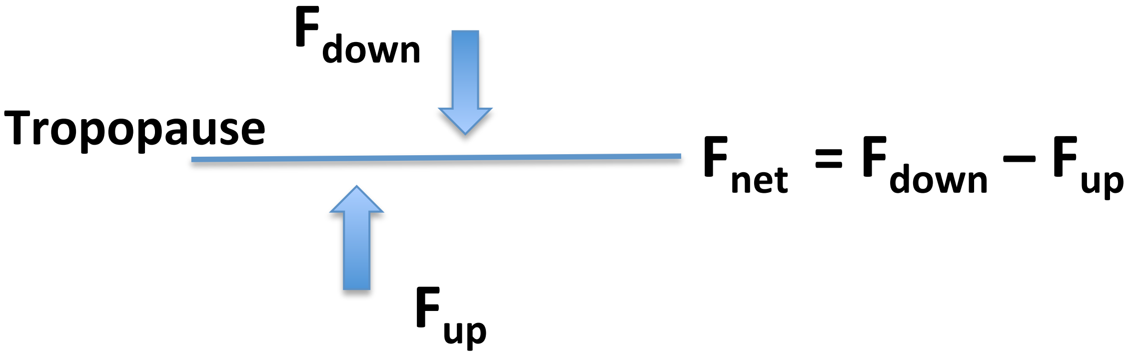
William Happer

Department of Physics, Princeton University, Princeton, NJ 08544, USA
happer@princeton.edu

Received 29 November 2013
Revised 10 February 2014
Accepted 13 February 2014
Published 11 March 2014

Definition of Radiative Forcing (RF) - 1

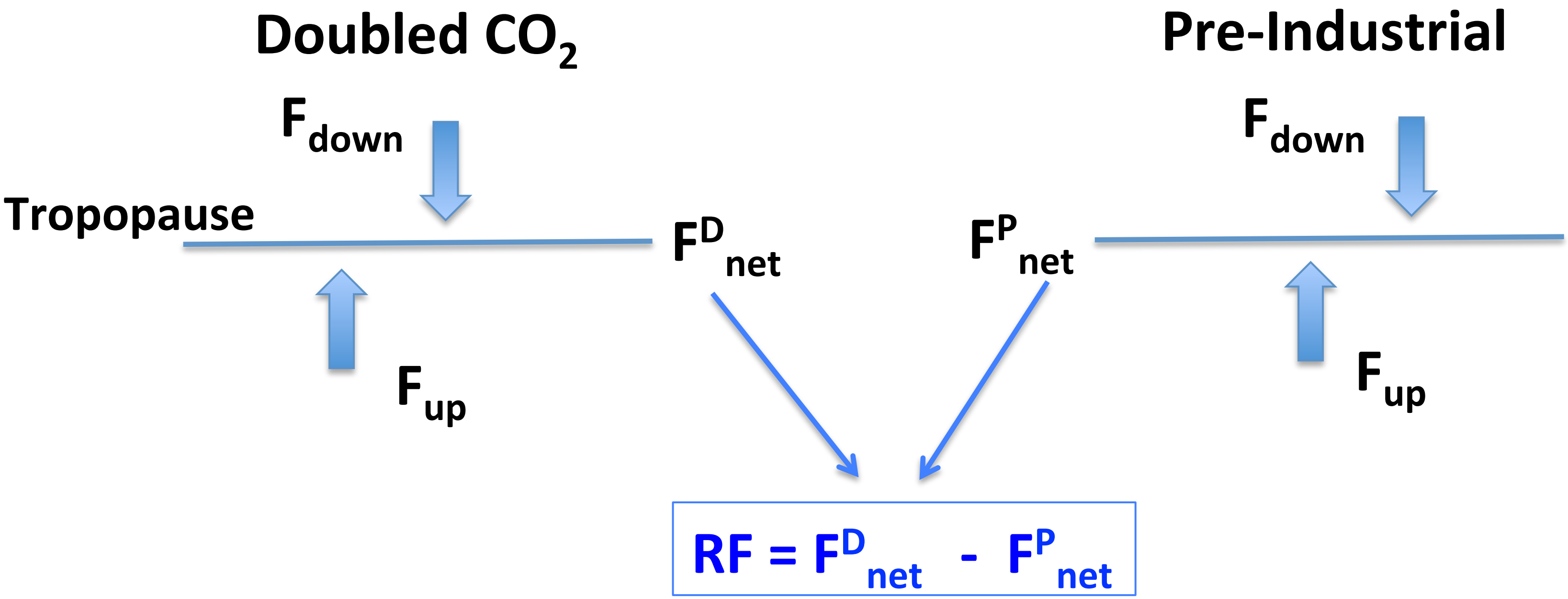
- RF is the ***change*** in the ***net*** radiative flux at the ***tropopause***
- ***Net flux*** is defined as F(down) minus F(up)



$F_{net} = F_{down} – F_{up}$

Definition of Radiative Forcing (RF) - 2

- ***Change*** **in net flux is difference for two different CO_2 burdens, typically doubled (D) from pre-industrial (P) minus P**



Doubled CO_2

Pre-Industrial

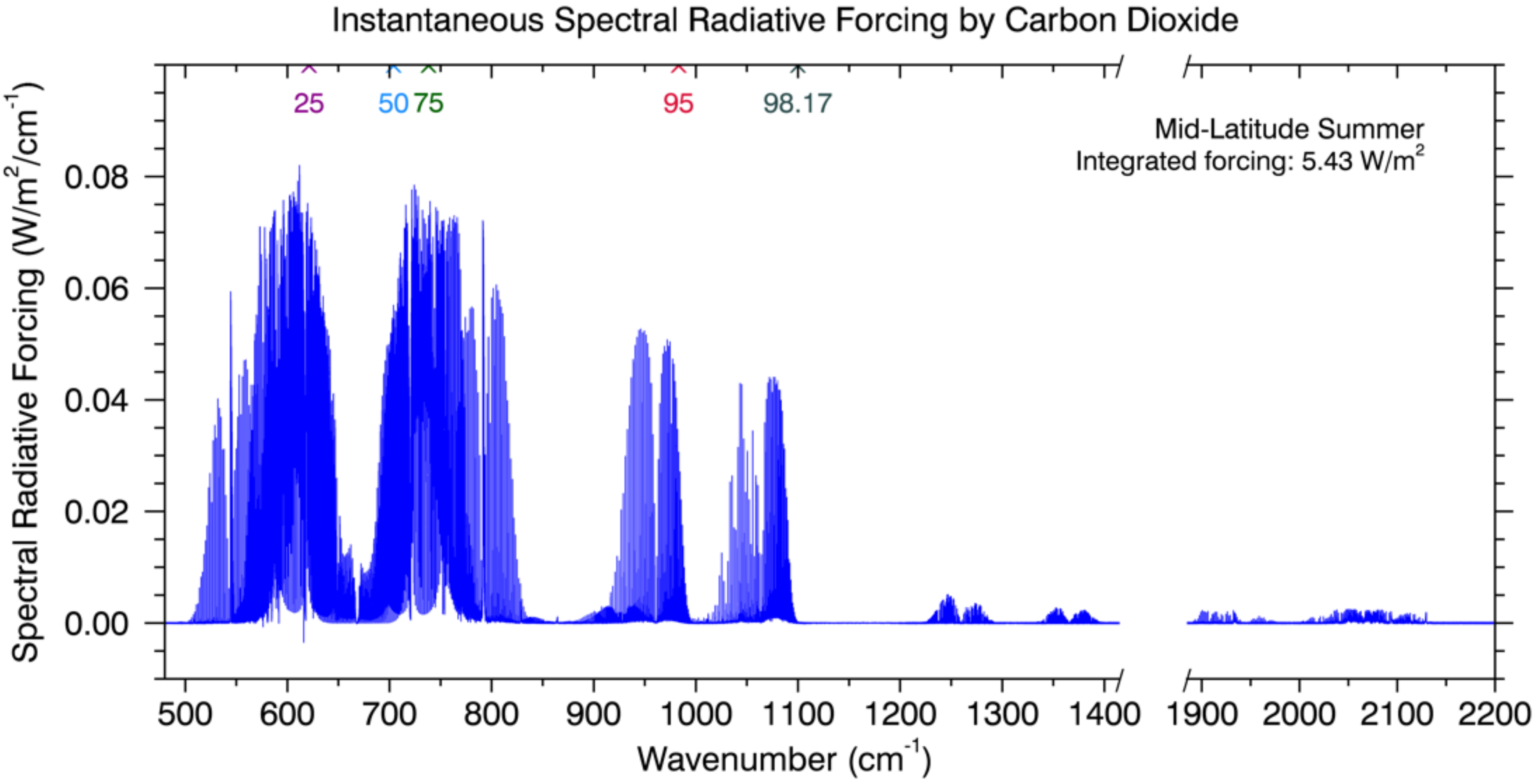
Tropopause

F_{down} F_{up} F^D_{net} F^P_{net} F_{down} F_{up}

$$RF = F^D_{net} - F^P_{net}$$

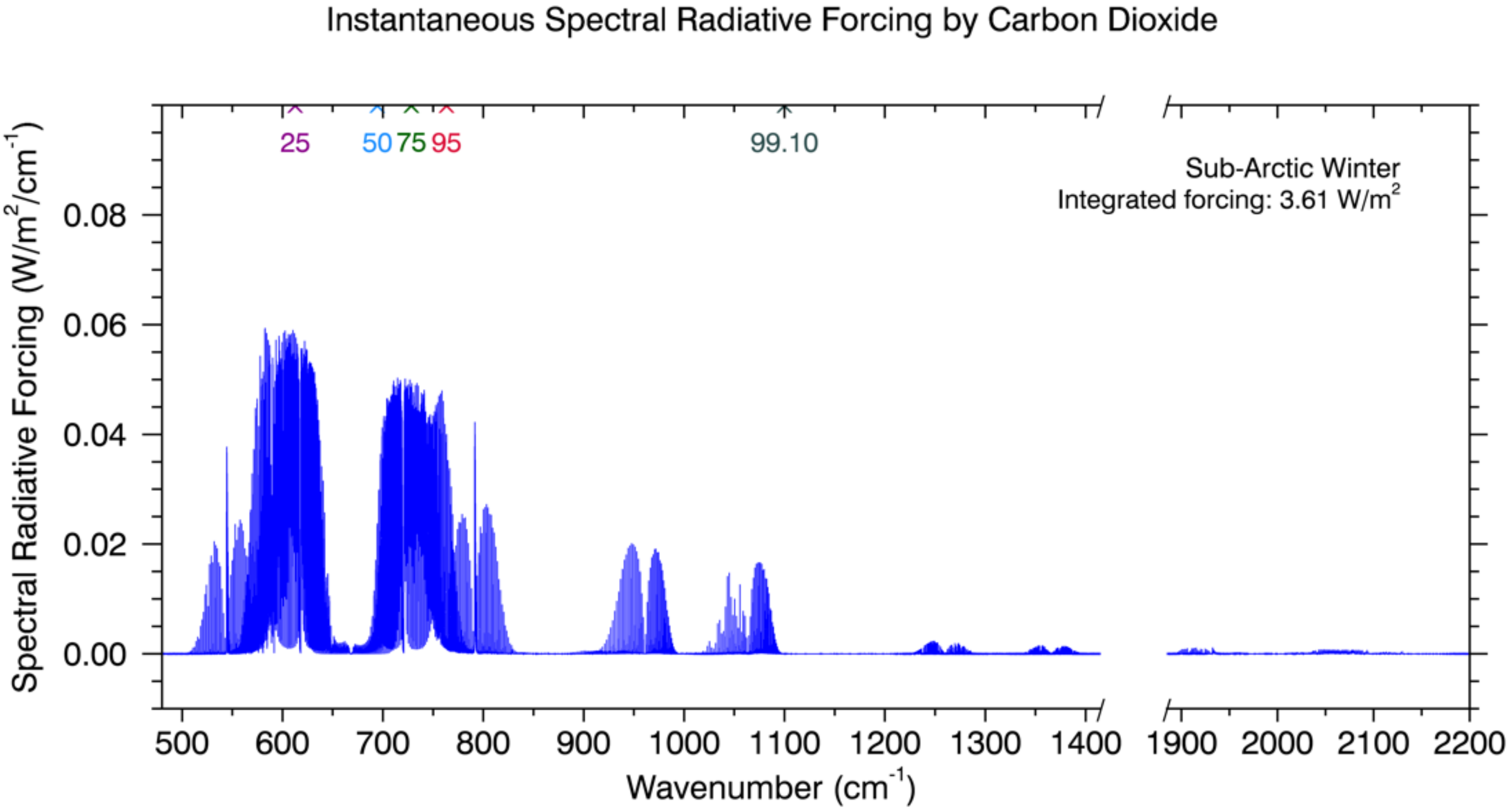
Use LBLRTM v12.2 to model radiances and fluxes in computation of RF

The Spectrum of Radiative Forcing for 2 x CO_2



Baseline Case, Mid-Latitude Summer

The Spectrum of Radiative Forcing for 2 x CO_2



Baseline Case, Sub-Arctic Winter

Spectroscopic Uncertainty - Methodology

- Use LBLRTM v12.2 to evaluate up and down radiances/fluxes
- Compute ***instantaneous*** radiative forcing
- Only uncertainty in the transmittance function is considered:

$$T_\nu(z,z') = \exp\left(-\sum_i S_i(\Theta) g_i(\nu - \nu_0) \frac{u(z,z')}{\mu} \right)$$

  - Line shape function $g(\nu - \nu_o)$
  - Line strength $S_i(\Theta)$
  - Air-broadened halfwidth (in lineshape function)

- Perturb these parameters to assess uncertainty in spectroscopy; compute difference with “baseline” case

Uncertainties in Spectroscopy – Line Shape/Mixing

- **Classically, the Voigt lineshape is used to represent the effects of collision/Lorentz and Doppler broadening**
- **Wings of many IR-active species are sub- or super-Lorentzian**
- **The 15-μm bands of CO_2, lines are densely packed and cannot be considered isolated during collisions**
- **Line mixing occurs, resulting in additional absorption near line centers and sub-Lorentzian behavior in the line wings**
  - **There is a 50-year history of modeling sub-Lorentzian wings in CO_2**

- **LBLRTM adopts line mixing from Niro et al. (2005)**
  - **Replaces classic line shape function in transmittance calculation**

Approach to Computing Spectroscopic Uncertainty

- Uncertainty determined by perturbation analysis

- Compute RF for “Baseline” case

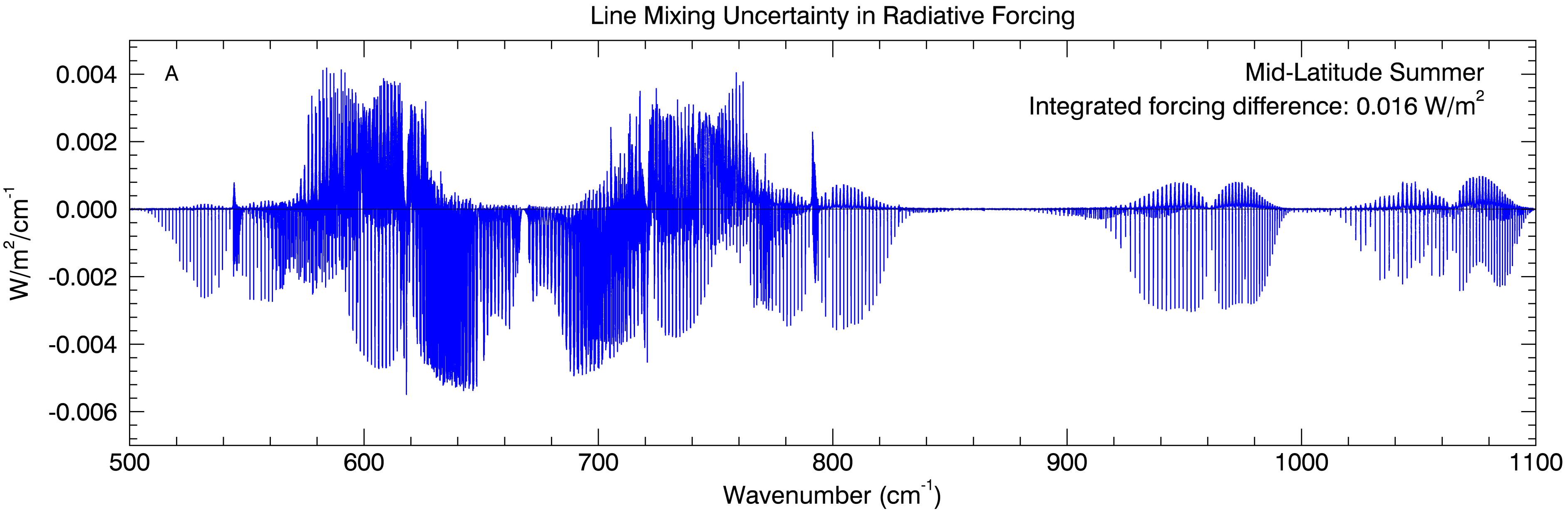
- Compute RF for “Perturbed” case
  - Increase line mixing by 20%
  - Perturb line strengths by assigned uncertainty on AER v3.2 database
  - Perturb line halfwidths by assigned uncertainty on AER v3.2 database

- Compute Uncertainty = Perturbed minus Baseline
  - Spectra, and spectrally integrated differences
  - RSS all uncertainties to get total uncertainty

Uncertainty in Radiative Forcing due to Line Mixing

RF (increased line mixing) – RF (baseline)

Mid-Latitude Summer Atmosphere



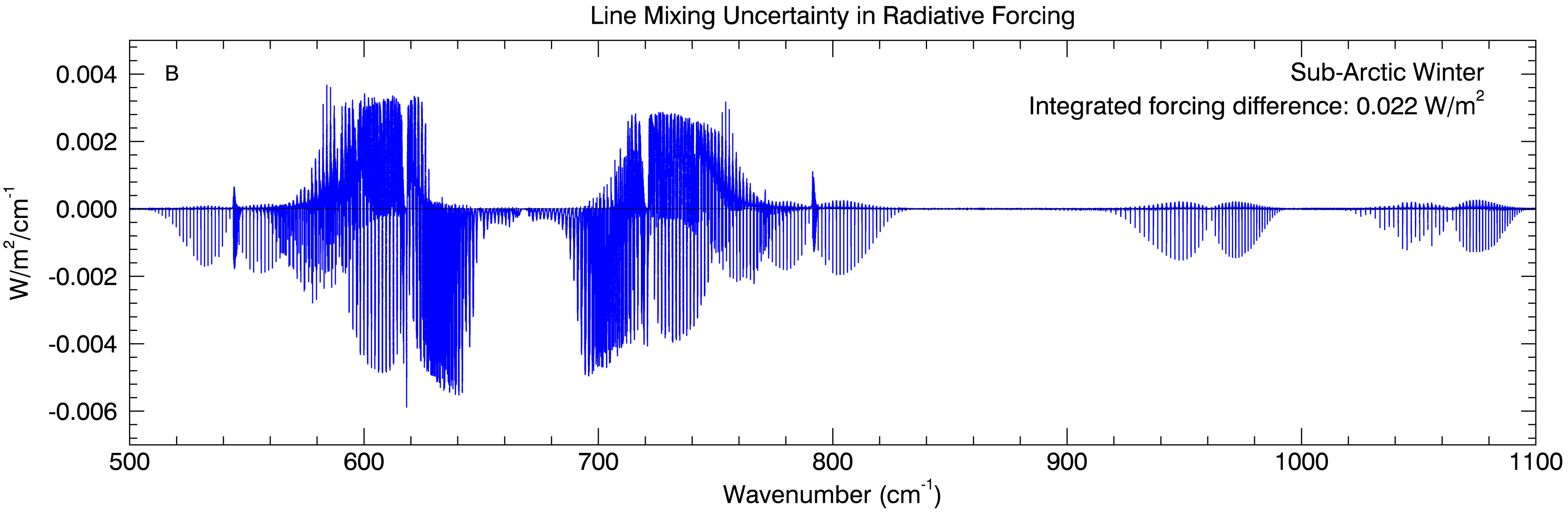
Significant but compensating spectral structure

RF difference is 0.016 W/m^2 or 0.3% of RF baseline

Uncertainty in Radiative Forcing due to Line Mixing

RF (increased line mixing) – RF (baseline)

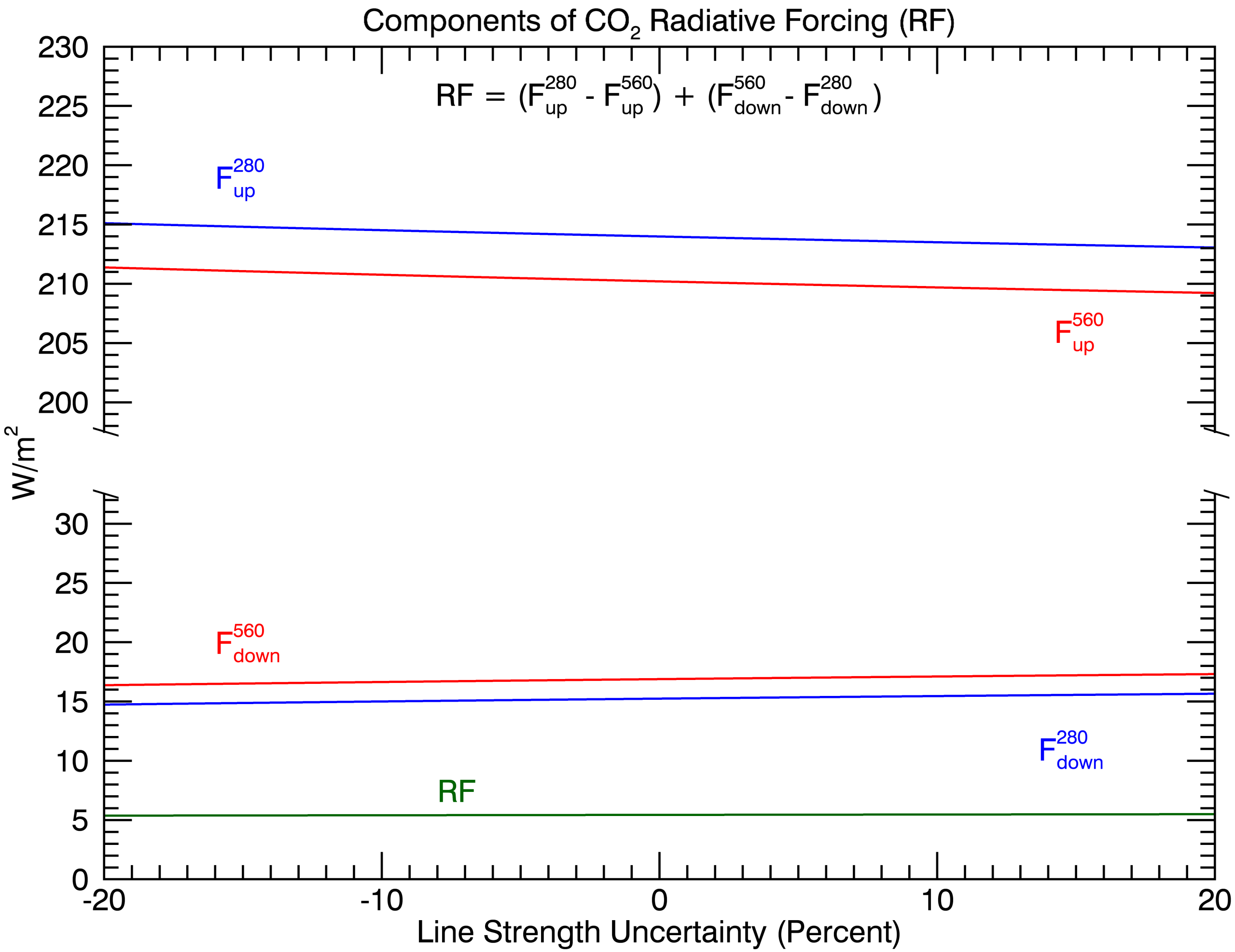
Sub-Arctic Winter Atmosphere



Significant but compensating spectral structure

RF difference is 0.022 W/m^2 or 0.6% of RF baseline

Radiative Forcing Uncertainty due to Line Strength



Virtually no change in RF with up to 20% increase/decrease in S

Summary of Spectroscopic Uncertainty in RF

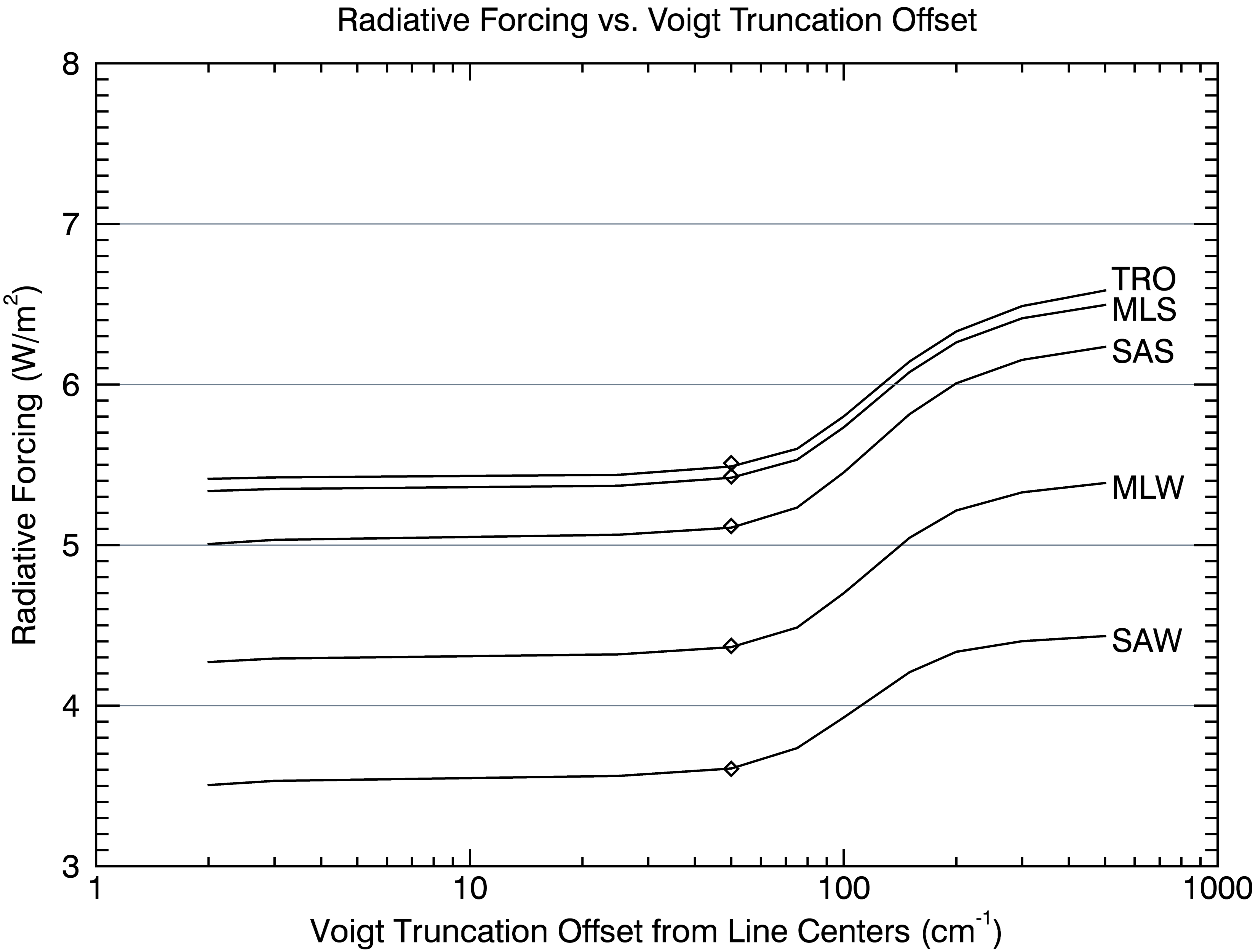
Atmosphere	Line Shape Uncertainty W/m^2	Line Strength Uncertainty W/m^2	Halfwidth Uncertainty W/m^2	RSS W/m^2	Error as % of Baseline RF
Mid-Latitude Summer	0.016	0.015	0.005	0.022	0.41
Mid-Latitude Winter	0.016	0.010	0.004	0.019	0.44
Sub-Arctic Summer	0.023	0.009	0.007	0.028	0.55
Sub-Arctic Winter	0.022	0.015	0.006	0.025	0.68
Tropical	0.010	0.014	0.002	0.017	0.51

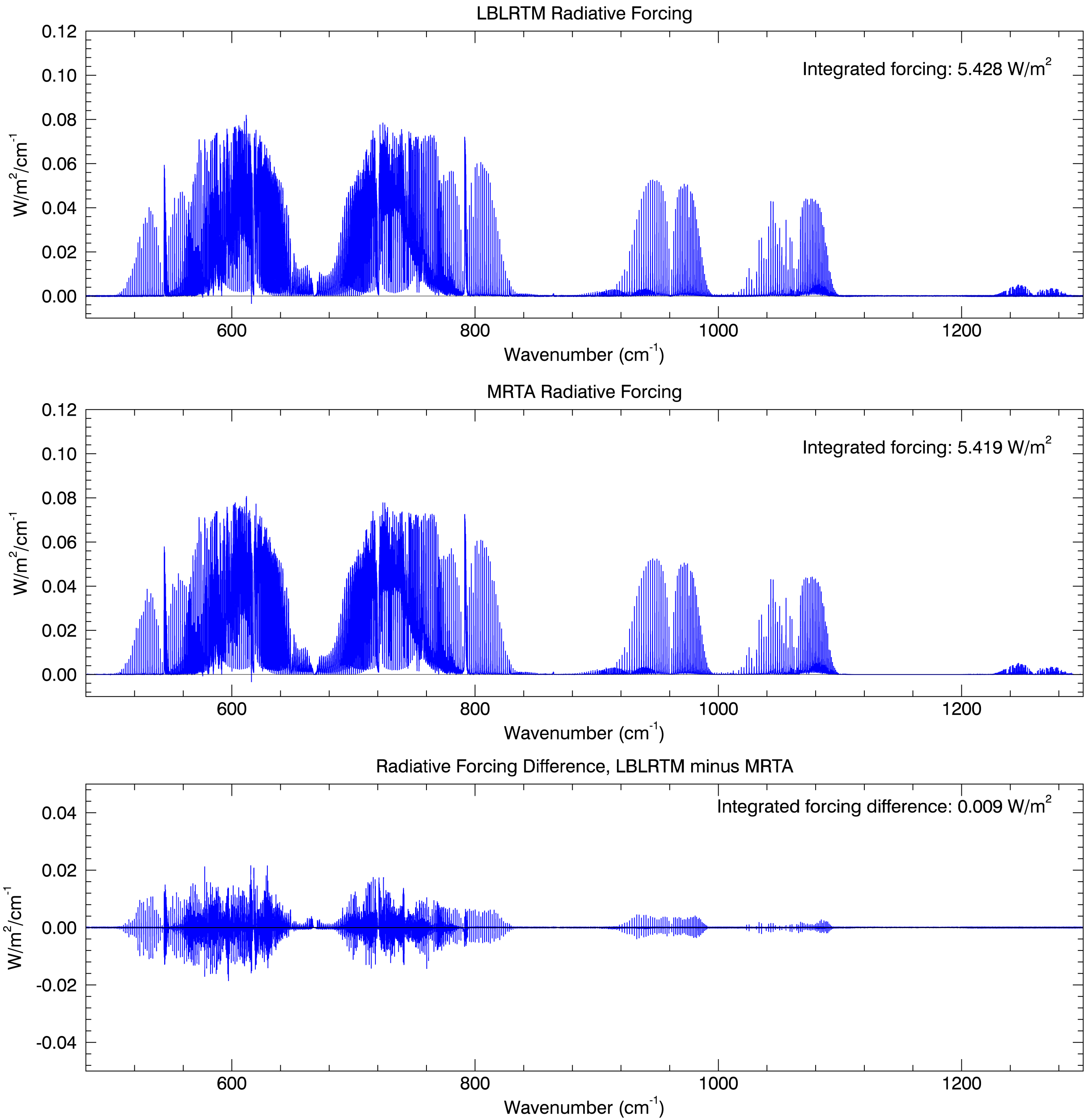
Spectroscopic Uncertainty in RF is < 0.7% of Forcing in a Variety of Atmospheres

Summary

- **We have examined uncertainty in radiative forcing by CO_2 associated with spectroscopic parameters**
- **Combined uncertainty of line shape, line strength, and halfwidth is < 0.7% for a variety of standard atmospheres**
- **Line mixing is rigorously included in state of the art line-by-line models and in rapid codes used in climate models**
- **Voigt shape provides good agreement at 50 cm^{-1} wing truncation, but does overestimate at larger truncations**
- **Foundation of climate modeling is robust with regards to uncertainties in spectroscopy**

Backup Slides


Radiative Forcing vs. Voigt Truncation Offset
Radiative Forcing (W/m^2)
Voigt Truncation Offset from Line Centers (cm^{-1})
8
7
6
5
4
3
1
10
100
1000
TRO
MLS
SAS
MLW
SAW



LBLRTM Radiative Forcing

Integrated forcing: 5.428 W/m^2

MRTA Radiative Forcing

Integrated forcing: 5.419 W/m^2

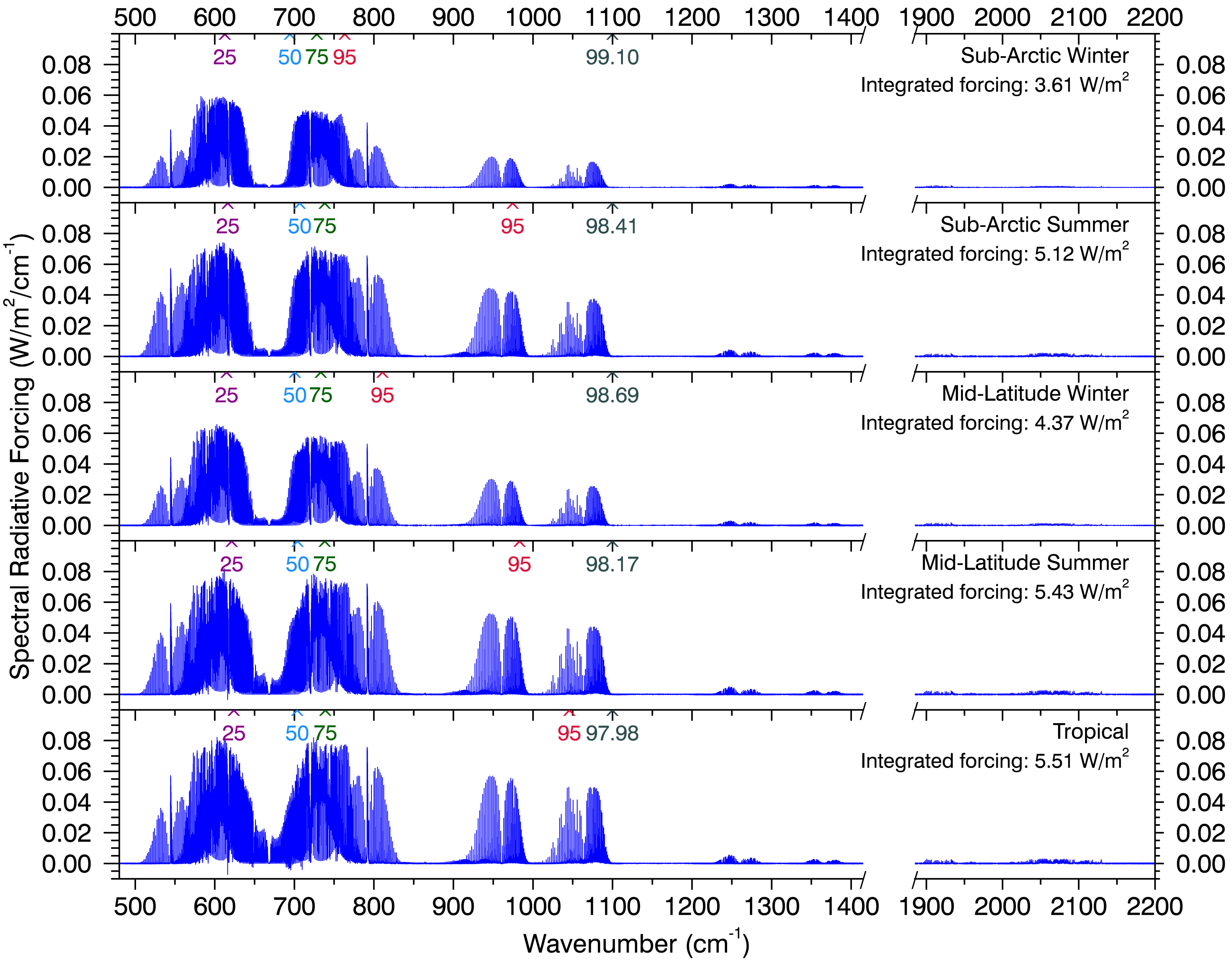
Radiative Forcing Difference, LBLRTM minus MRTA

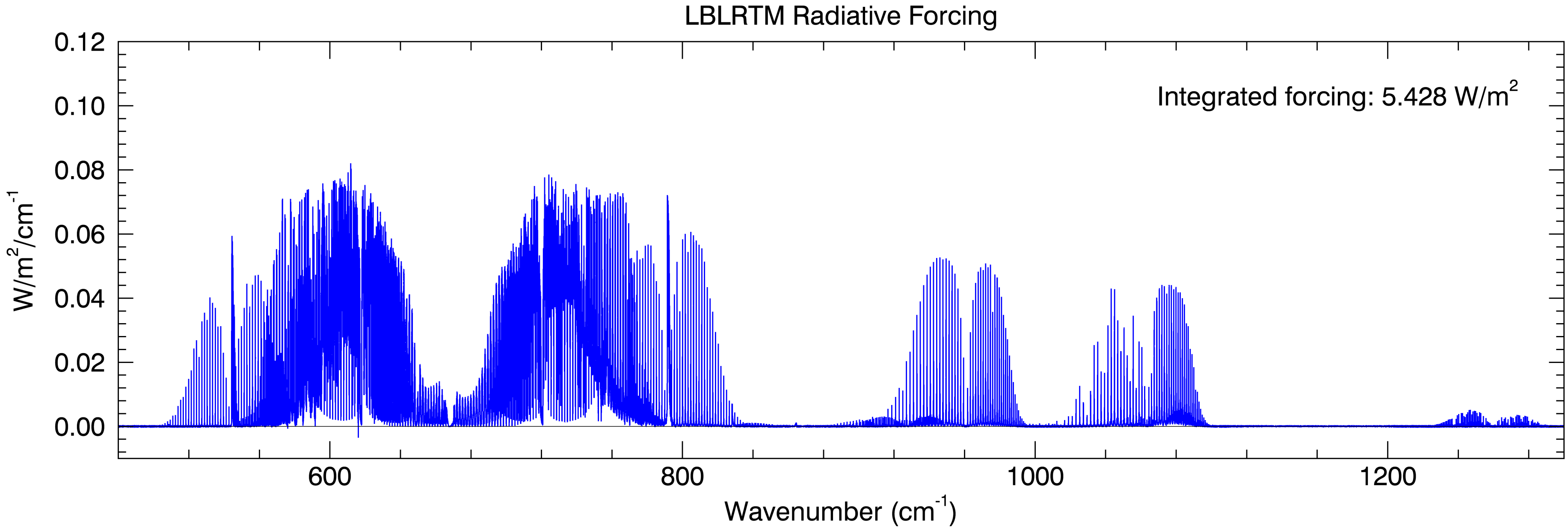
Integrated forcing difference: 0.009 W/m^2

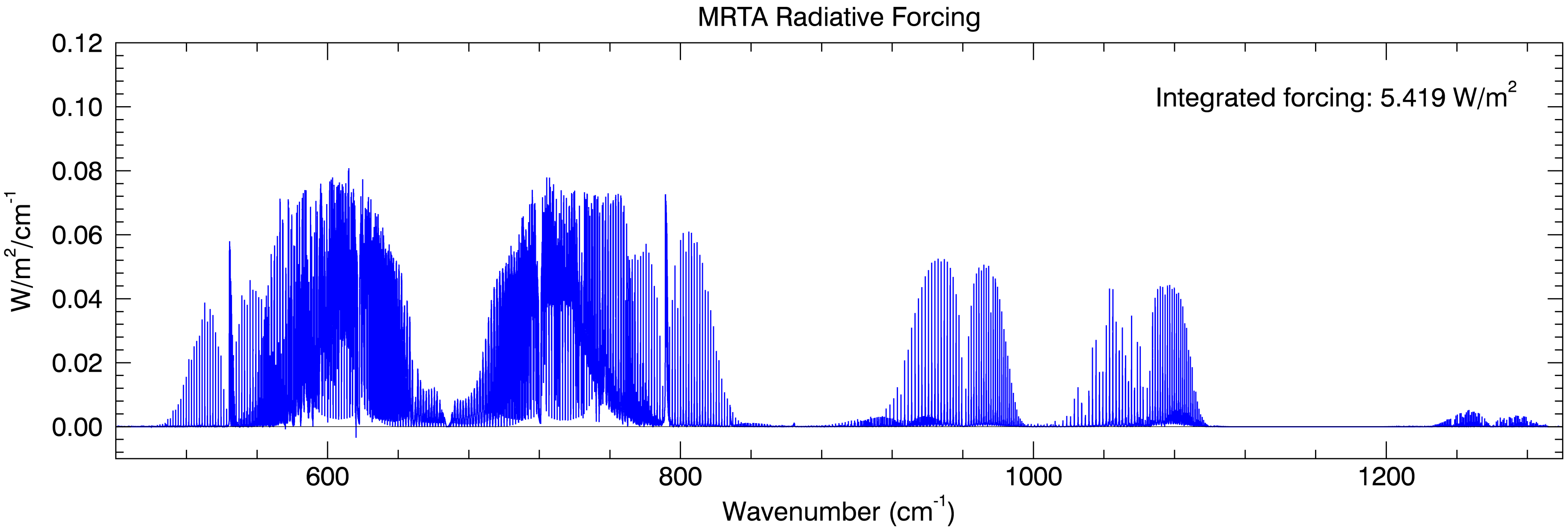
Summary of Spectroscopic Uncertainty in RF

Atmosphere	RF LBLRTM Baseline W/m^2	RF LBLRTM 20% Pert. W/m^2	Uncertainty Line Shape/Line Mixing W/m^2	Uncertainty Line Strength W/m^2	Uncertainty Half Width W/m^2	RSS W/m^2	RSS as Percent of baseline LBLRTM Forcing
MLS	5.428	5.444	0.016	0.015	0.005	0.022	0.41
MLW	4.372	4.388	0.016	0.010	0.004	0.019	0.44
SAS	5.118	5.141	0.023	0.015	0.007	0.028	0.55
SAW	3.606	3.628	0.022	0.009	0.006	0.025	0.68
TRO	5.509	5.519	0.010	0.014	0.002	0.017	0.31

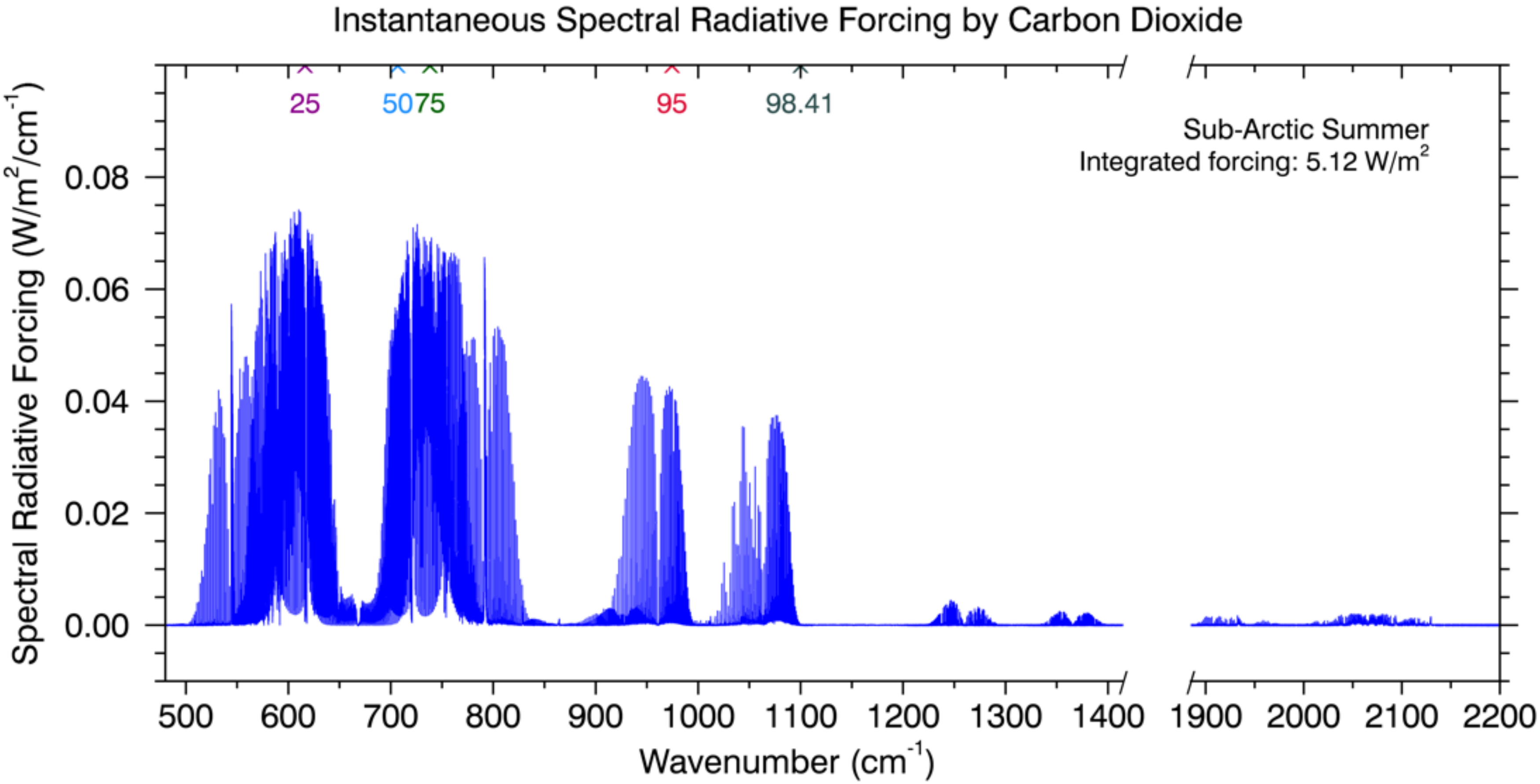
Instantaneous Spectral Radiative Forcing by Carbon Dioxide



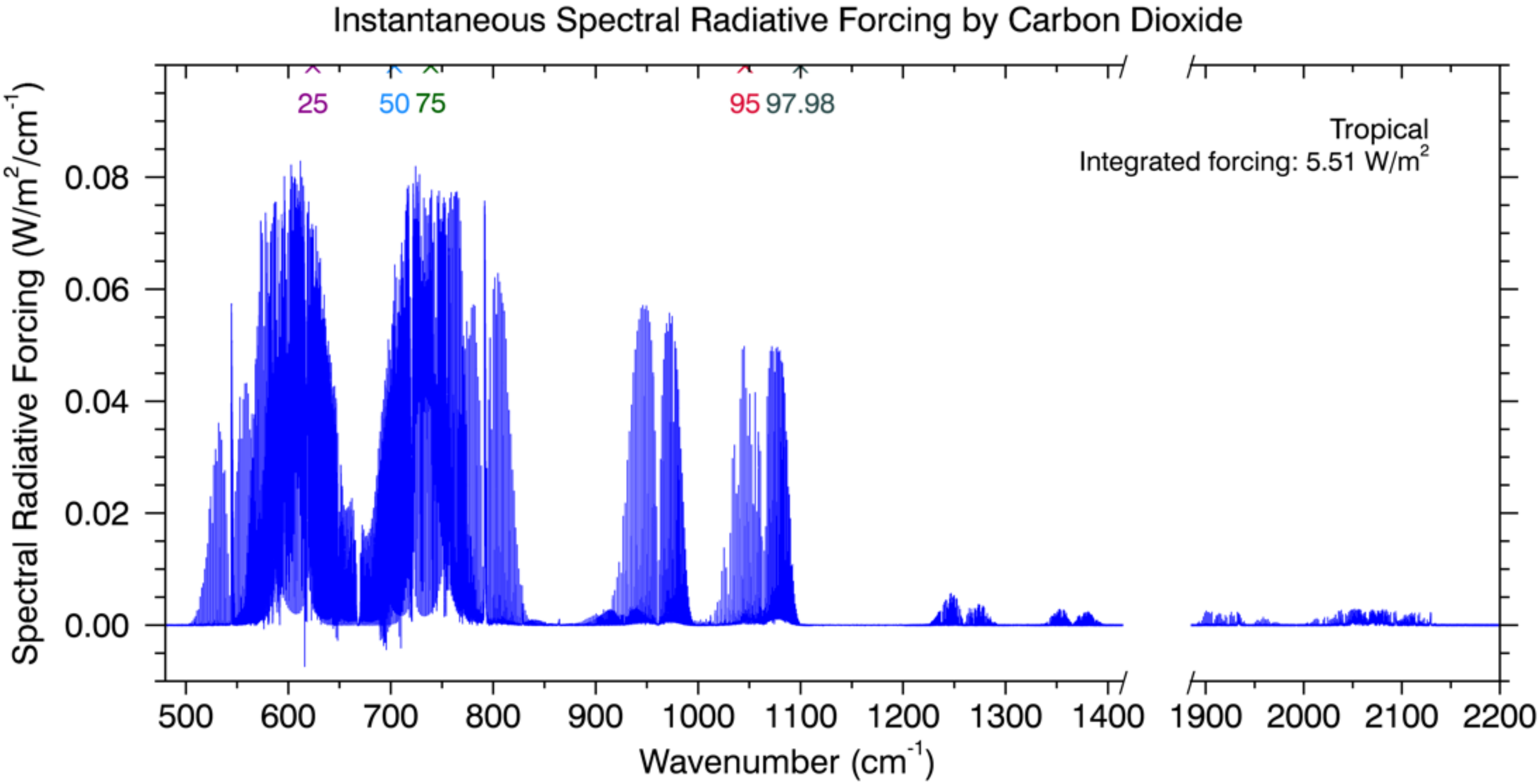

LBLRTM Radiative Forcing
Integrated forcing: 5.428 W/m^2
W/m^2/cm^{-1}
0.12
0.10
0.08
0.06
0.04
0.02
0.00
600
800
1000
1200
Wavenumber (cm^{-1})


MRTA Radiative Forcing
Integrated forcing: 5.419 W/m^2
W/m^2/cm^{-1}
0.12
0.10
0.08
0.06
0.04
0.02
0.00
600
800
1000
1200
Wavenumber (cm^{-1})

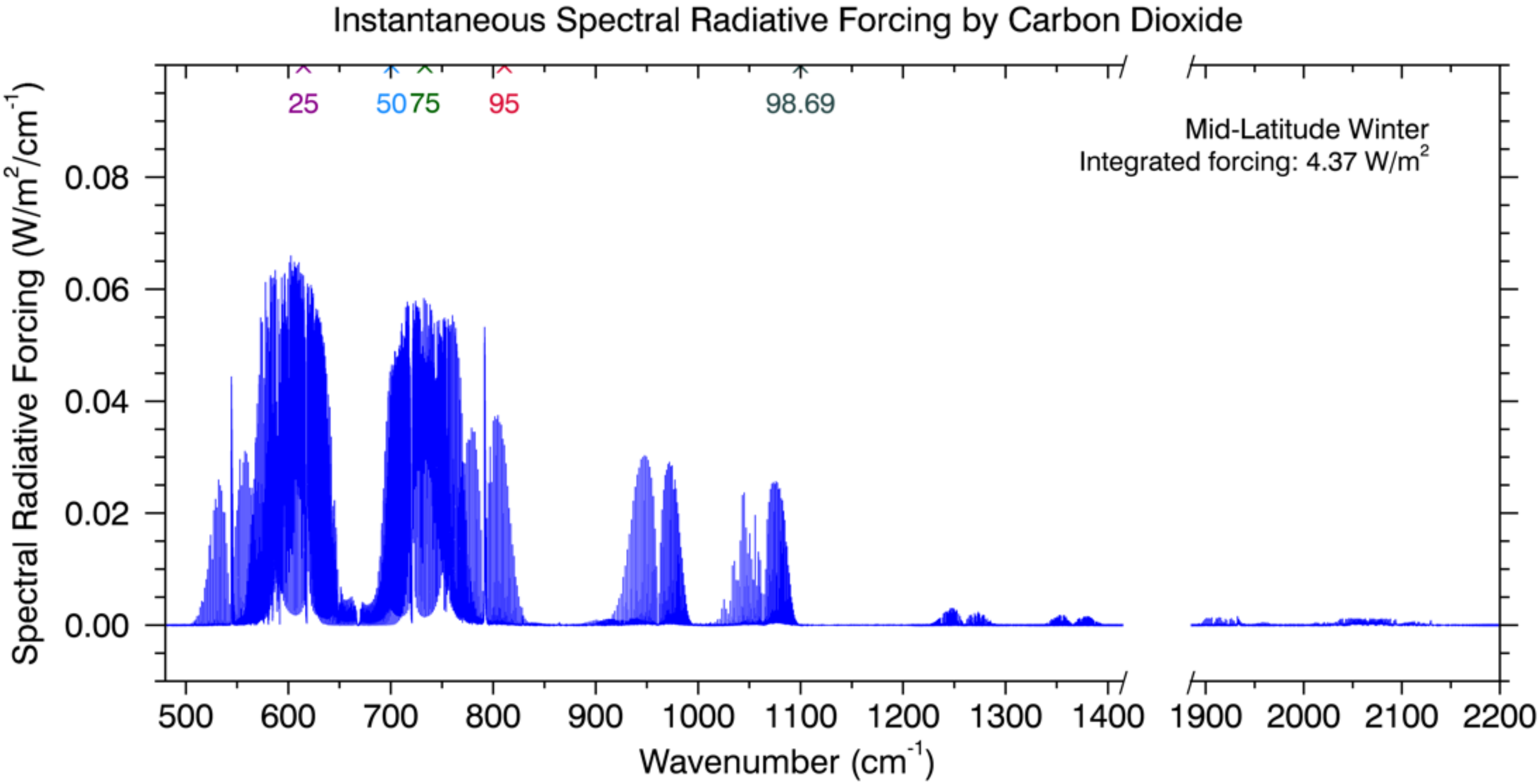
The Spectrum of Radiative Forcing

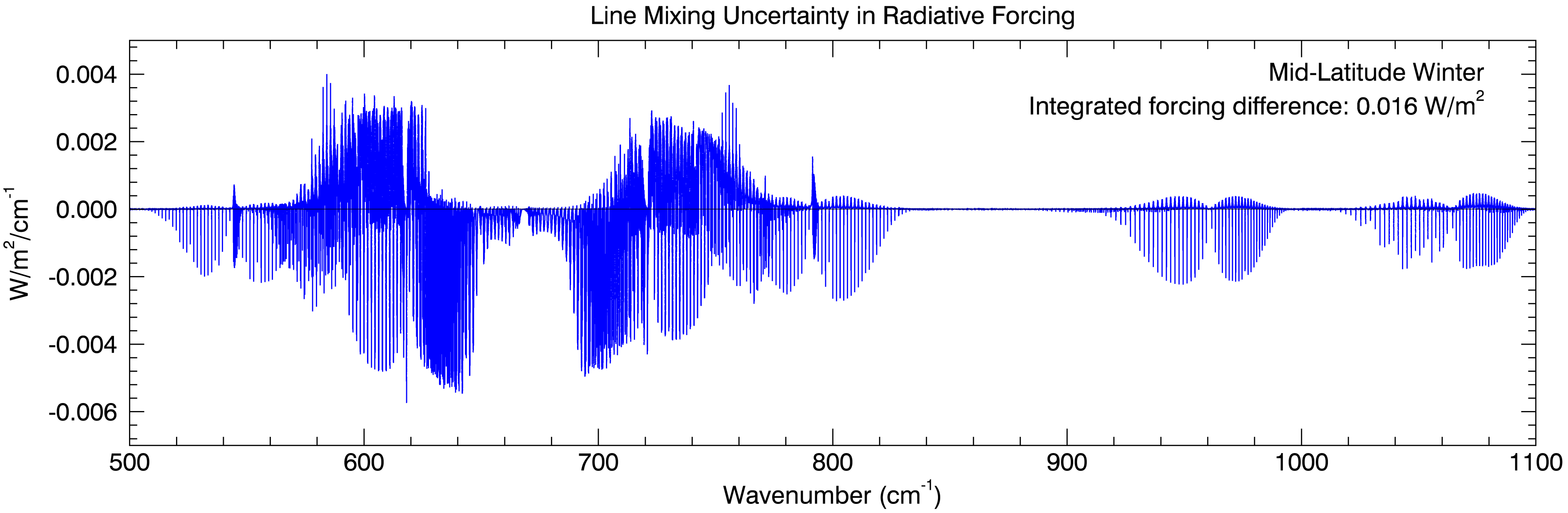


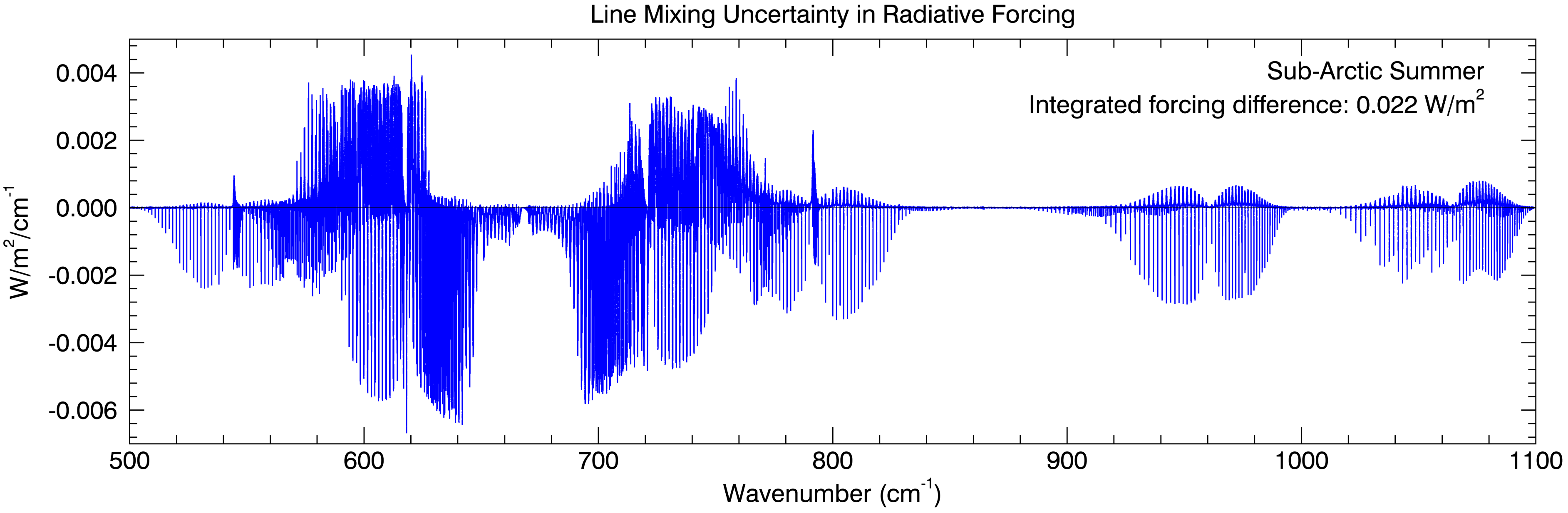
The Spectrum of Radiative Forcing

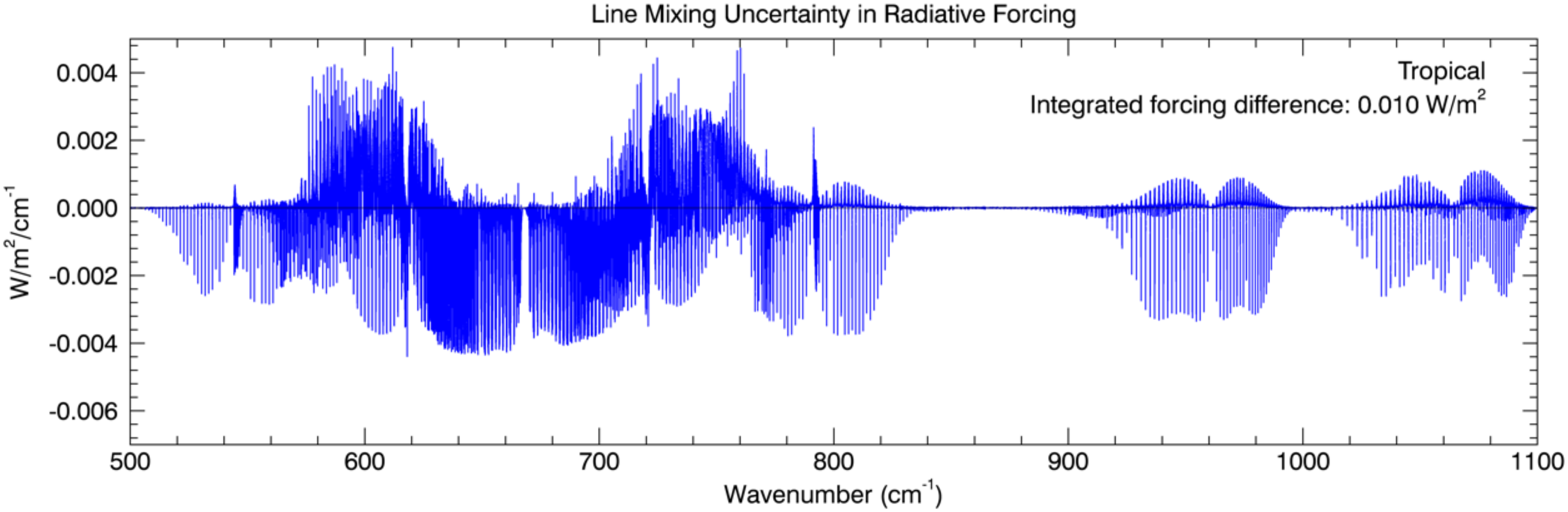


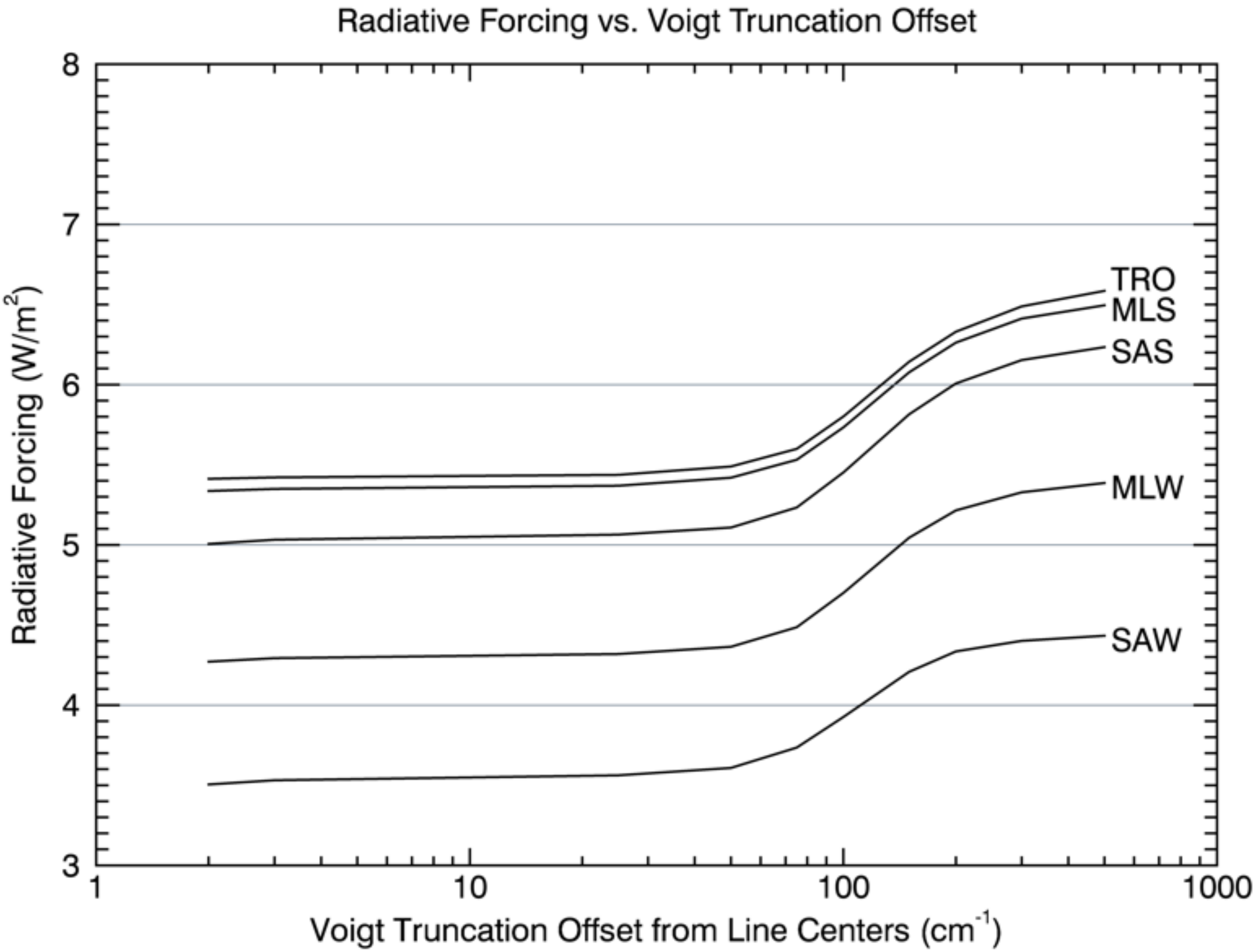
The Spectrum of Radiative Forcing




Line Mixing Uncertainty in Radiative Forcing
Mid-Latitude Winter
Integrated forcing difference: 0.016 W/m^2
$W/m^2/cm^{-1}$
0.004
0.002
0.000
-0.002
-0.004
-0.006
500
600
700
800
900
1000
1100
Wavenumber (cm^{-1})

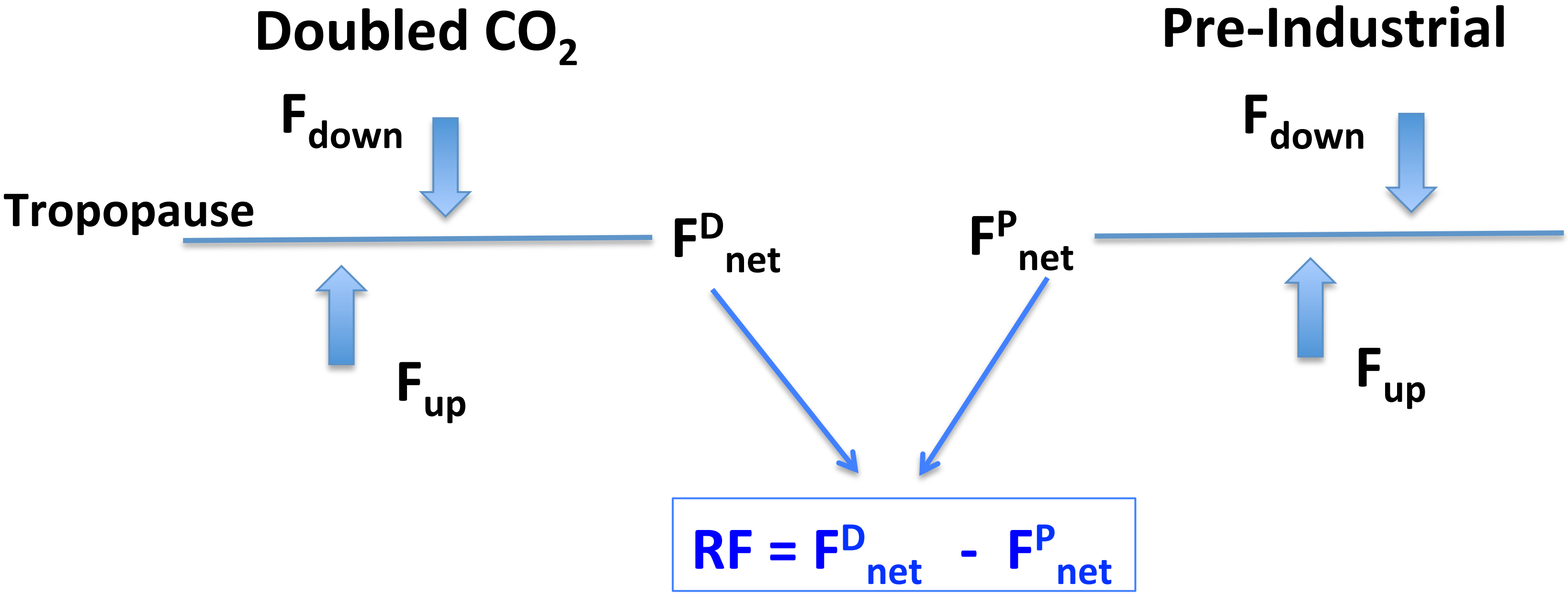

Line Mixing Uncertainty in Radiative Forcing
Sub-Arctic Summer
Integrated forcing difference: 0.022 W/m^2
0.004
0.002
0.000
-0.002
-0.004
-0.006
W/m^2/cm^{-1}
500
600
700
800
900
1000
1100
Wavenumber (cm^{-1})


Line Mixing Uncertainty in Radiative Forcing
Tropical
Integrated forcing difference: 0.010 W/m^2
W/m^2/cm^{-1}
0.004
0.002
0.000
-0.002
-0.004
-0.006
500
600
700
800
900
1000
1100
Wavenumber (cm^{-1})


Radiative Forcing vs. Voigt Truncation Offset
Radiative Forcing (W/m^2)
Voigt Truncation Offset from Line Centers (cm^{-1})
8
7
6
5
4
3
1
10
100
1000
TRO
MLS
SAS
MLW
SAW

Definition of Radiative Forcing (RF)

- RF is the ***change*** in the ***net*** radiative flux at the ***tropopause***
- ***Net flux*** is defined as F(down) minus F(up)
- ***Change*** in net flux is difference for two different CO_2 burdens, typically doubled from pre-industrial (PI) minus PI



Doubled CO_2

F_{down}

Tropopause

F_{up}

F^{D}_{net}

F^{P}_{net}

Pre-Industrial

F_{down}

F_{up}

$$RF = F^{D}_{net} - F^{P}_{net}$$

Methodology

- **Use LBLRTM v12.2 to evaluate up and down radiances/fluxes**

$$I_\nu(\mu,z) = B_\nu(\Theta_s)T_\nu(z,0) + \int_0^z B_\nu\left(\Theta(z')\right)\frac{\partial T_\nu(z,z')}{\partial z'}dz'$$

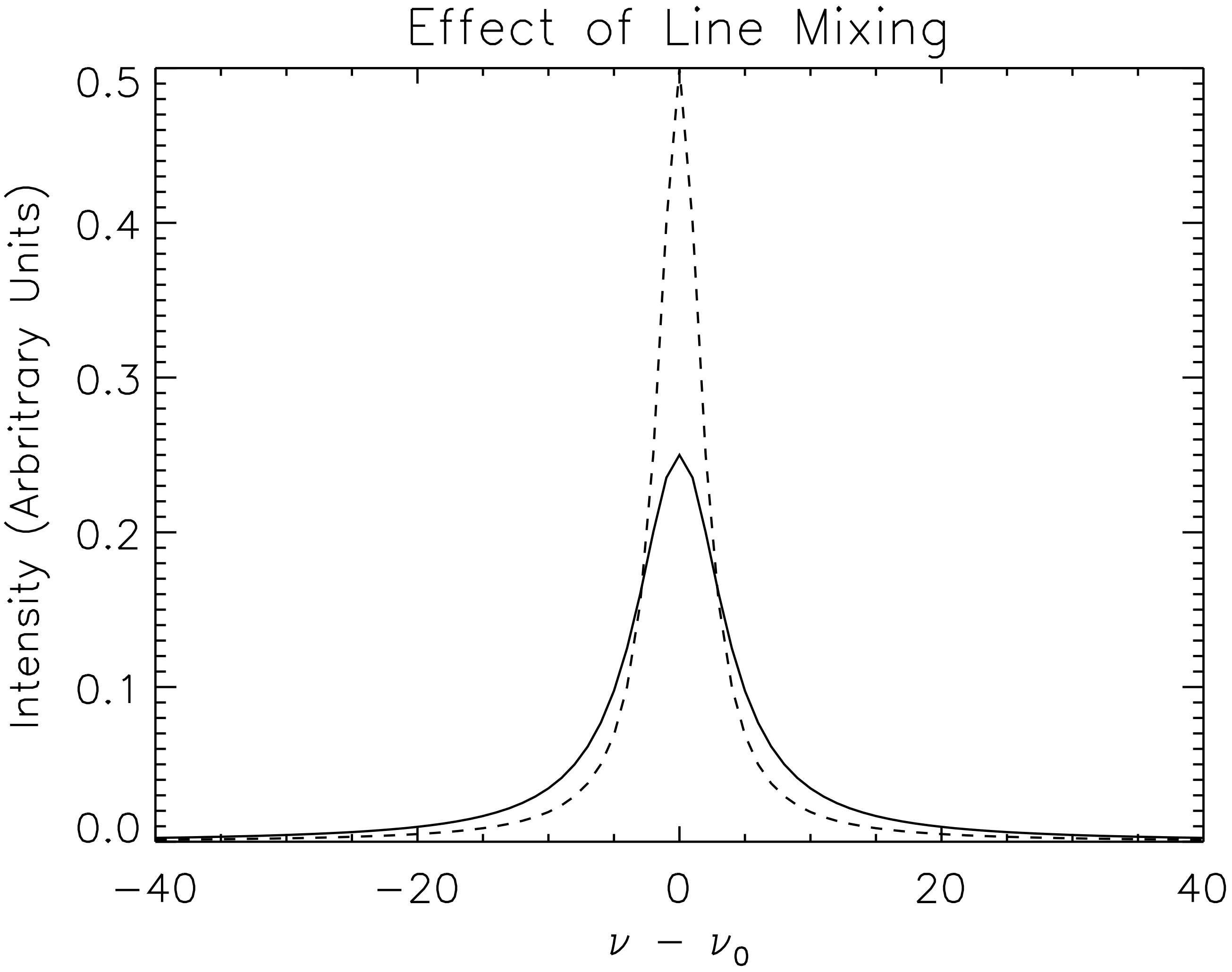
$$I_\nu(-\mu,z) = -\int_z^\infty B_\nu\left(\Theta(z')\right)\frac{\partial T_\nu(z,z')}{\partial z'}dz'$$

- **The key to our study is the transmittance function:**

$$T_\nu(z,z') = \exp\left(-\sum_i S_i(\Theta)g_i(\nu-\nu_0)\frac{u(z,z')}{\mu}\right)$$

- **Compute instantaneous forcing, no change in temperature**

- **Vary g($\nu - \nu_o$), S$_i$, and α_L to assess *spectroscopic* uncertainty in RF**


Effect of Line Mixing
Intensity (Arbitrary Units)
0.0
0.1
0.2
0.3
0.4
0.5
−40
−20
0
20
40
$\nu - \nu_0$