Atmospheric Cooling in the Far-Infrared

Daniel Feldman[1]

Kuo-Nan Liou[2], Yuk Yung[3], Xianglei Huang[4],

2011 Workshop on Far-Infrared Remote Sensing

November 8, 2011

[1] Lawrence Berkeley National Laboratory, Earth Sciences Division
[2] UCLA, Department of Atmospheric and Oceanic Sciences
[3] Caltech, Department of Geological and Planetary Science
[4] University of Michigan, Department of Atmospheric, Oceanic, and Space Sciences

Outline

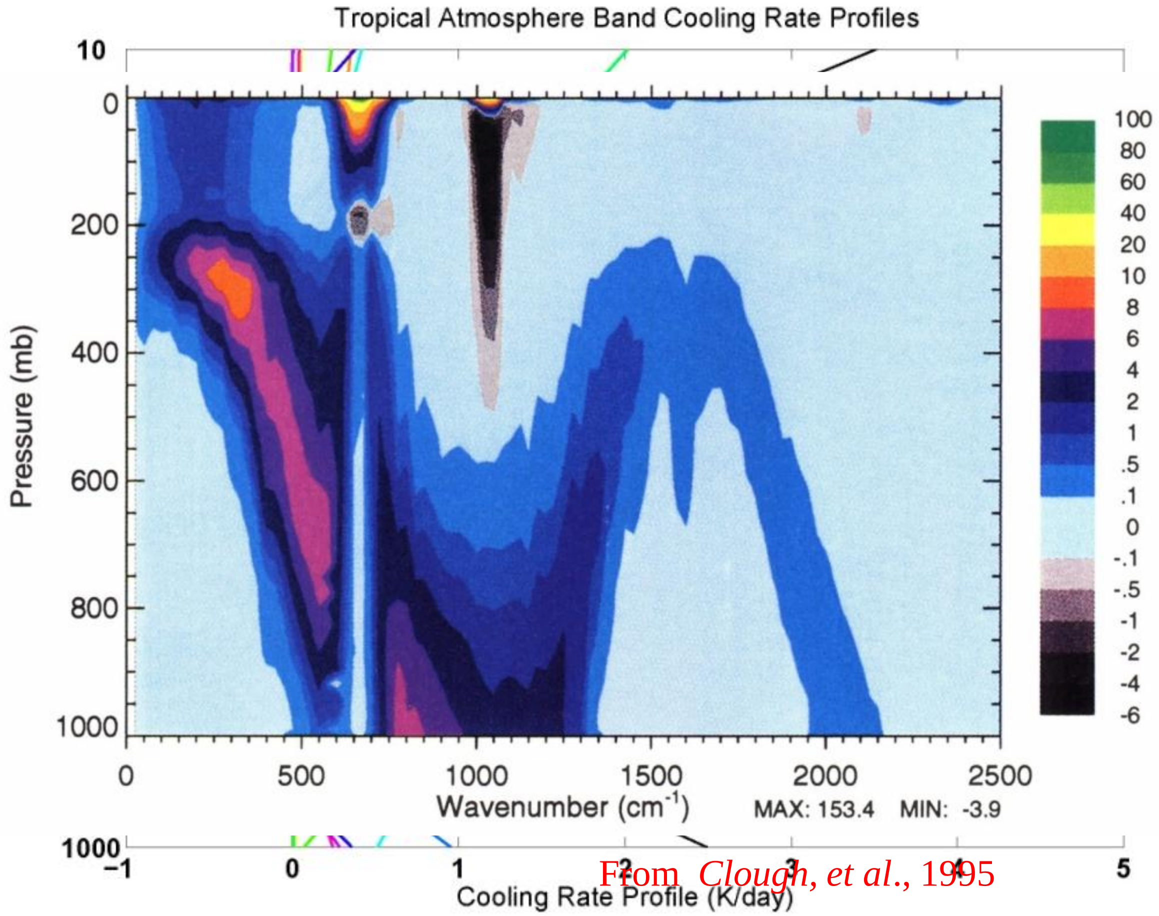
- Importance of atmospheric cooling and the role of the far-infrared.
- How measurements impart information on cooling rates (either directly or indirectly).
  - Comparison of distinct methods for determining cooling rates from measurements.
- How the current measurements from AIRS and CERES may be used to gauge processes that affect far-IR cooling.

Cooling Rate Profiles

- Cooling arises from net radiative flux divergence from absorption by gases including H_2O, CO_2, and O_3 and condensed species.

$$\dot{\theta}_{\bar{v}}(z) = \frac{1}{C_p \rho(z)} \frac{dF_{\bar{v}}^{NET}(z)}{dz}$$

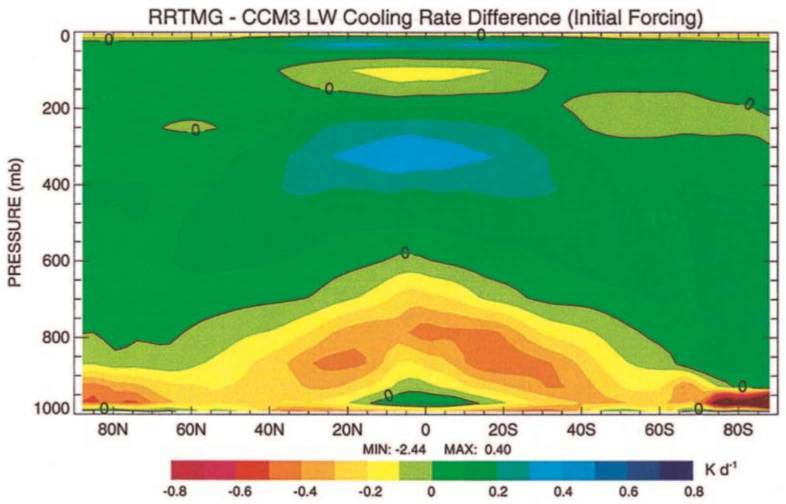
- Models perform band radiation calculations to calculate heating/cooling rates to integrate the primitive equations.
  - Radiation can account for 30% of computational expense.
  - Radiation impacts circulation, especially vertical velocity, controls TTL and convection

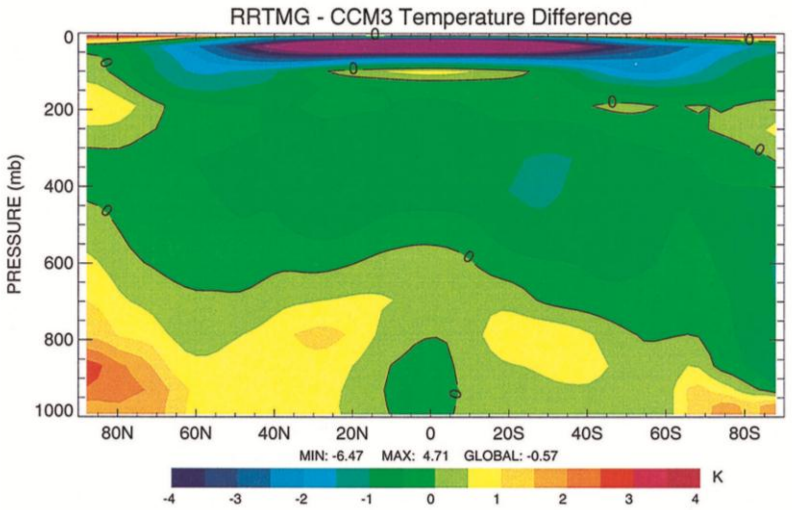


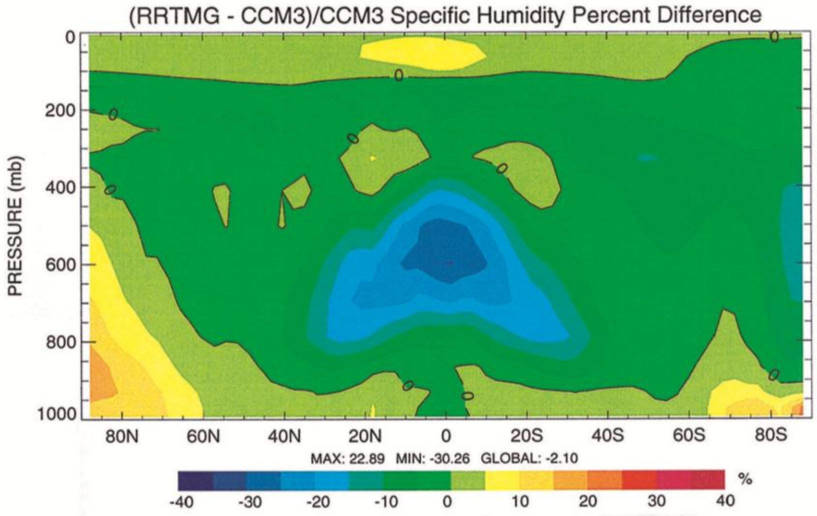
From *Clough, et al.*, 1995

Heating/Cooling Rates Matter

- *Iacono, et al.*, [2000] investigated the results of an RTM change in CCM3.
  - Significant cooling rate changes from revised H_2O continuum model.
- A comparison of model integrations shows changes in T, H_2O profiles due to altered latent, radiative energy distribution.

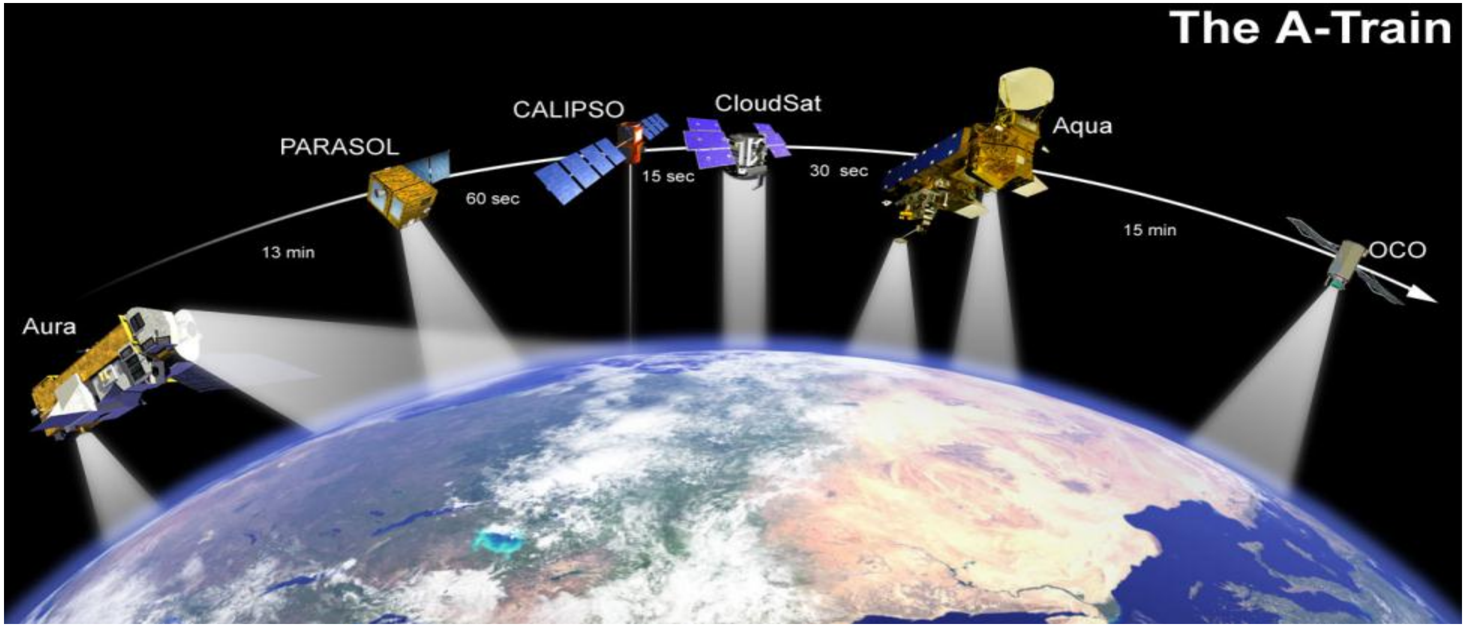

RRTMG - CCM3 LW Cooling Rate Difference (Initial Forcing)


RRTMG - CCM3 Temperature Difference


(RRTMG - CCM3)/CCM3 Specific Humidity Percent Difference

All figs. from *Iacono, et al.*, 2000

Remote Sensing Measurements

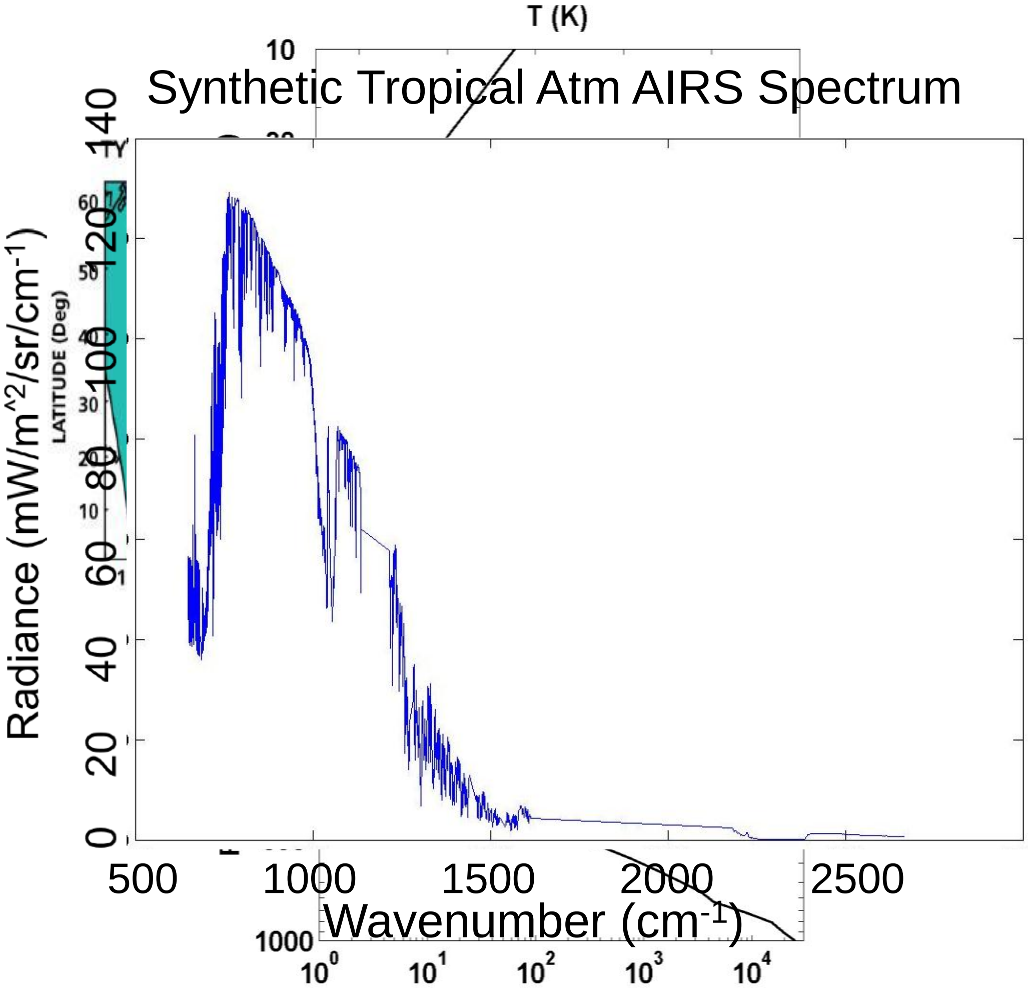


Artist's rendition of the A-Train courtesy of NASA

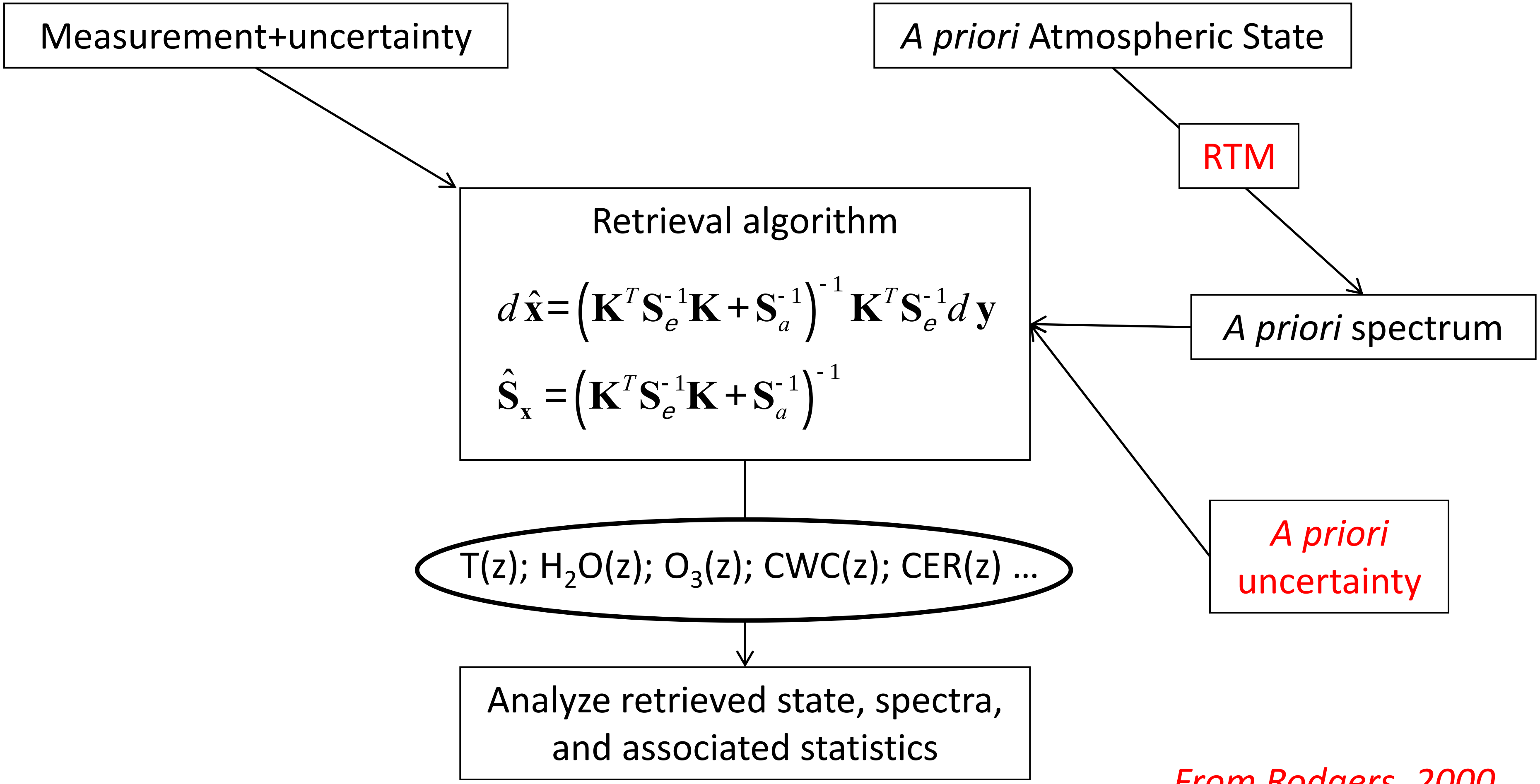
- There is a critical need for having accurate, computationally-inexpensive cooling rate data and remote sensing systems may be able to provide this.
- The polar-orbiting EOS A-Train flotilla presents a voluminous dataset describing the earth's lower atmosphere including T, H_2O, O_3, and clouds
  - AIRS has been operational for 9+ years.
  - CloudSat and CALIPSO platforms operational for 5+ years.

Information in AIRS measurements

- Passive IR spectra provide information on the T, H_2O, and O_3 profiles through differential absorption.
  - 2378 channels
  - 3.7 to 15.4 μm (650-2700 cm^{-1})
  - No far-IR coverage mostly due to detector limitations.



Deriving Information from Retrieval Flow Chart



Measurement+uncertainty

A priori Atmospheric State

RTM

A priori spectrum

A priori uncertainty

Retrieval algorithm

$$d\hat{\mathbf{x}} = \left(\mathbf{K}^T \mathbf{S}_e^{-1} \mathbf{K} + \mathbf{S}_a^{-1}\right)^{-1} \mathbf{K}^T \mathbf{S}_e^{-1} d\,\mathbf{y}$$

$$\hat{\mathbf{S}}_{\mathbf{x}} = \left(\mathbf{K}^T \mathbf{S}_e^{-1} \mathbf{K} + \mathbf{S}_a^{-1}\right)^{-1}$$

$T(z)$; $H_2O(z)$; $O_3(z)$; CWC(z); CER(z) …

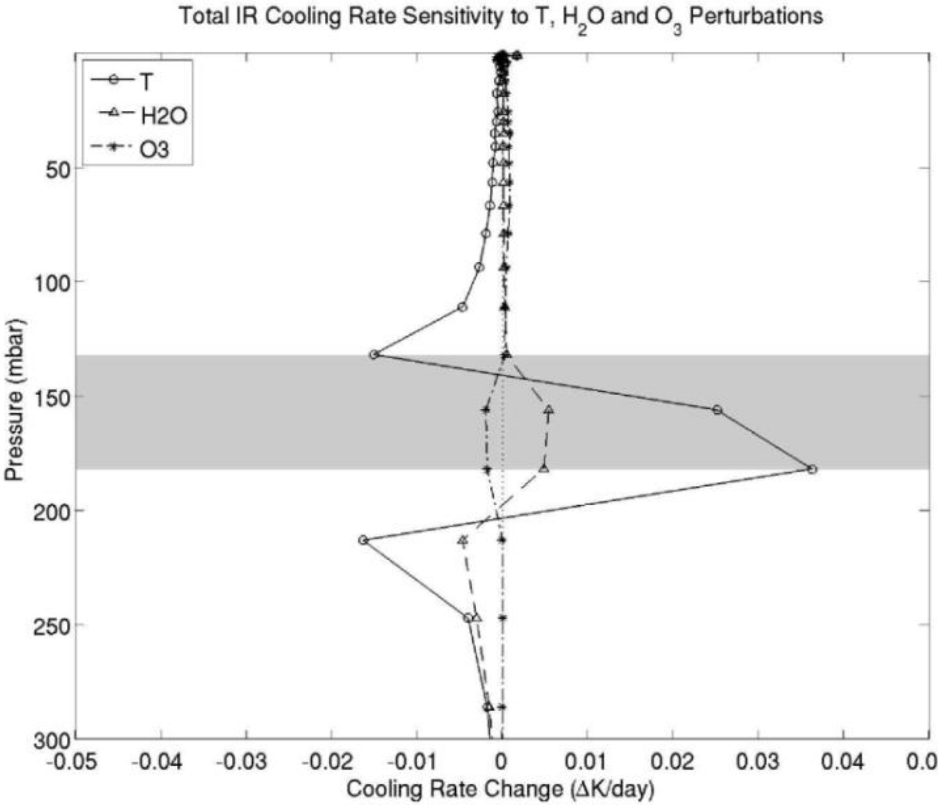
Analyze retrieved state, spectra, and associated statistics

From Rodgers, 2000

Cooling Rate Profile Uncertainty

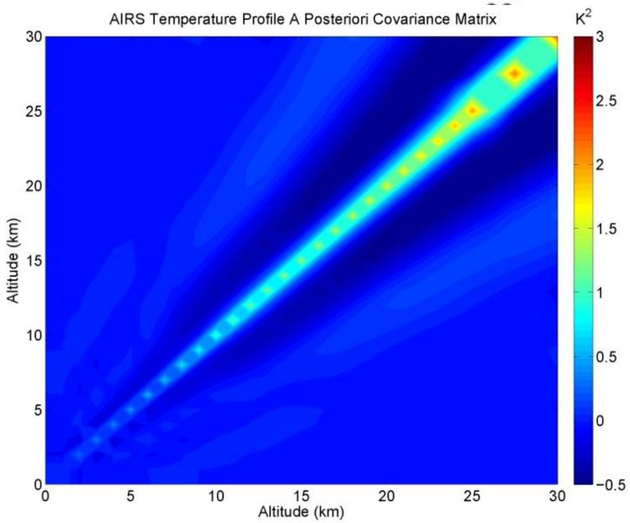
- Perturbations in T, H_2O, O_3 profiles lead to θ’ changes that propagate across layers.
- Calculation of θ’ uncertainty requires formal error propagation analysis.
  - Covariance counts!

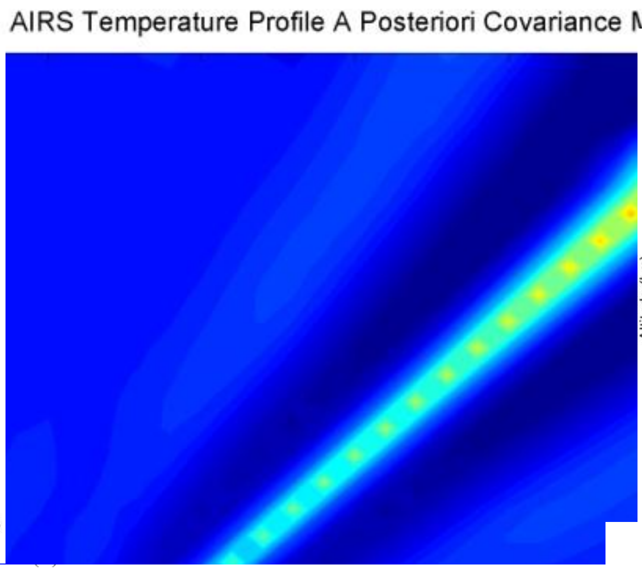
$$\left[\Delta\dot{q}(z)\right]^2 = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\partial\dot{q}(z)}{\partial x_i}\frac{\partial\dot{q}(z)}{\partial x_j}\operatorname{cov}\left(x_i, x_j\right)$$

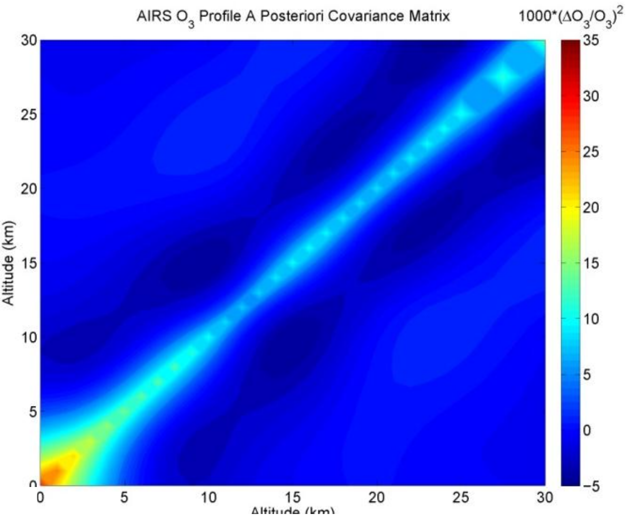


From *Feldman, et al., 2008.*

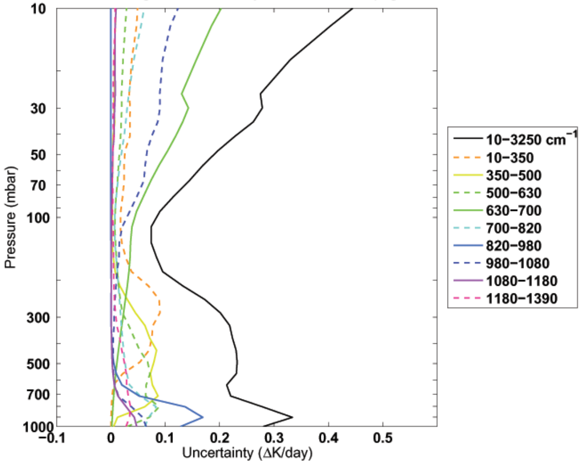
Cooling Rate Error Propagation

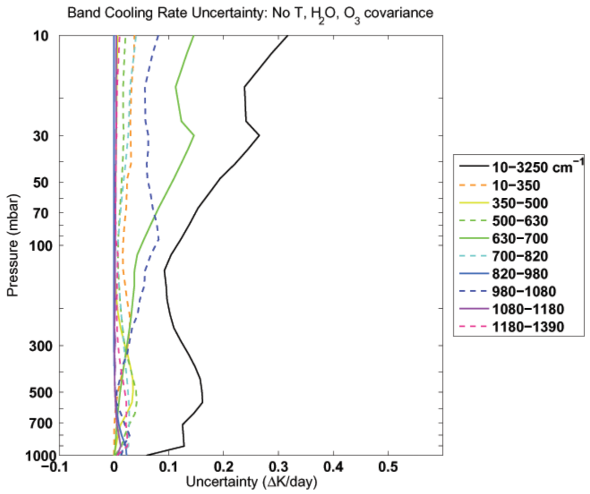






- T, H_2O, O_3 profile covariance matrix derived from kernel spread.
- Exclusion of off-diagonal elements leads to underestimation of uncertainty.





From *Feldman, et al., 2008*

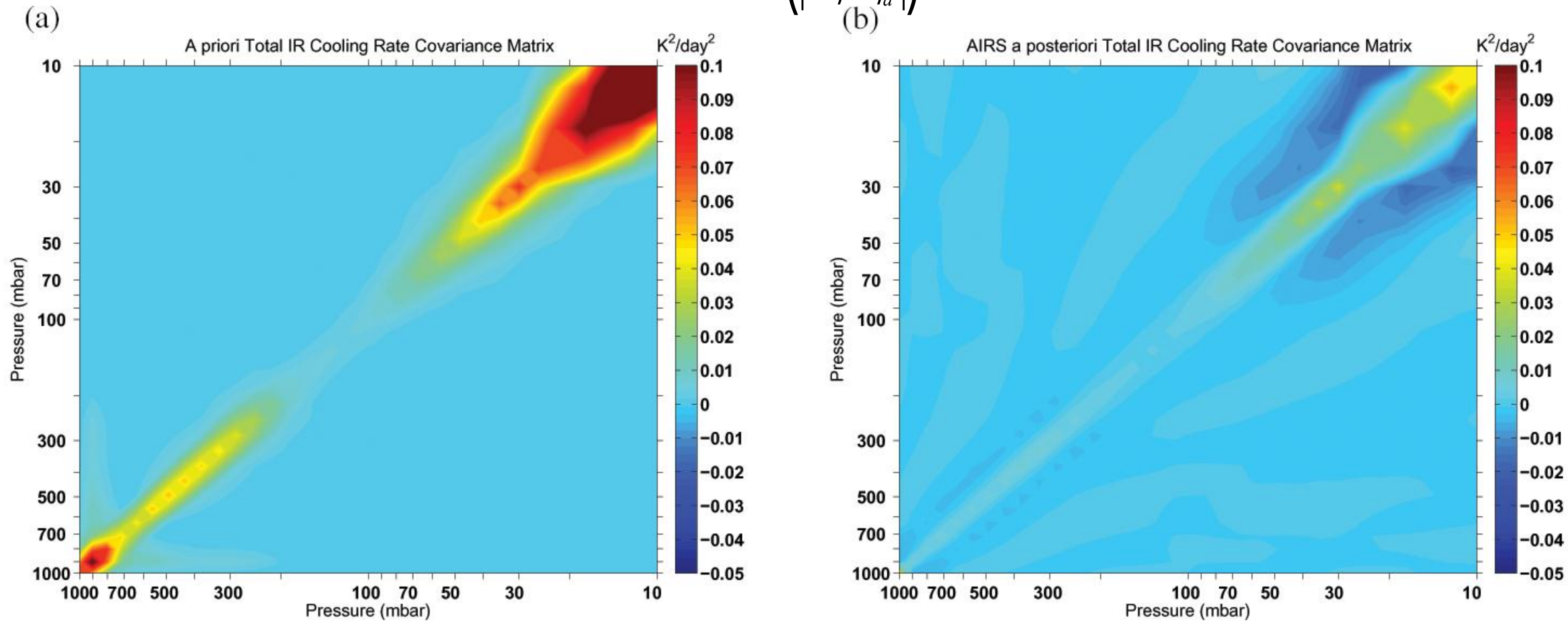
Cooling Rate Covariance Matrix

- Covariance matrices assess how prior and posterior errors are correlated

$$\hat{\Sigma}_{\dot q} = \frac{\partial \dot q}{\partial \mathbf{x}} \hat{\Sigma}_{\mathbf{x}} \left(\frac{\partial \dot q}{\partial \mathbf{x}} \right)^T$$

- Information content of a measurement vis-avis the cooling rate profile can be assessed.

$$h \propto -\log\left(\left| \hat{\Sigma}_{\dot q} \Sigma_{\dot q_a}^{-1} \right| \right)$$



From *Feldman, et al., 2008*

Cooling Rate Information Content

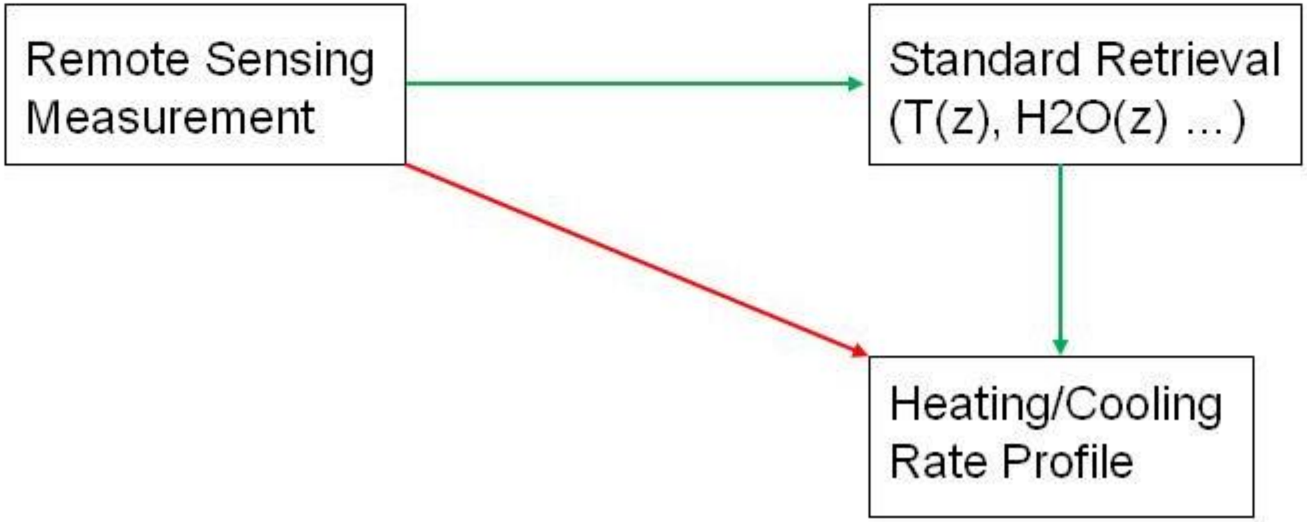
- Information content is related to the change in understanding of a set of correlated variables as a result of the measurement.

From *Feldman, et al.* 2008

Instrument	Time period	Spectral range (cm^{-1})	NeDT (K)	Spectral resolution (cm^{-1})	h_{TRP} (bits)	h_{MLS} (bits)	h_{SAW} (bits)
IRIS-D	1970-71	400-1600	2-4	2.8	9.8	8.4	6.4
AIRS	2002-Present	650-1400, 2100-2700	0.1-0.6	1-2	17.1	11.5	12.6
TES	2004-Present	650-1325, 1900-2250	1-4	0.12	13.2	10.5	8.0
IASI	2006-Present	650-2700	0.3-0.5	0.5	21.8	19.9	18.3
Far-IR	Proposed	200-2000	1.1	0.6	17.5	18.3	11.4

Retrieval of Cooling Rates

- Many products derived from the satellite instrument measurements through retrievals.
- Many different approaches to retrieving quantities from measurements.
  - Cooling rates retrieval proposed by Liou and Xue [1988] and Feldman et al [2006]



Remote Sensing Measurement

Standard Retrieval (T(z), H2O(z) ...)

Heating/Cooling Rate Profile

Inversion for Infrared Cooling Rate Profile

- Conventionally use T, H_2O, O_3, CH_4, and N_2O profiles
- Remote sensing measurements can be inverted for atmospheric state ➔ calculate cooling rates.
- TOA radiance closely related to TOA flux which is a function of net flux divergence
  - Monotonic kernel but *a priori* constraint guarantees measurement information imparted uniformly across profile

Measurement

$$I_\nu(+\mu, z) = B_\nu(\theta_{surf})\, T_\nu(z,0) + \int_0^z B_\nu(\theta(z'))\frac{\partial T_\nu(z,z')}{\partial z'}\, dz'$$

TOA Flux

$$F^{TOA} = F^{SURF} + \int_0^\infty \frac{\theta'(z)}{\rho(z)C_p}\, dz$$

Kernel

Flux interpretation

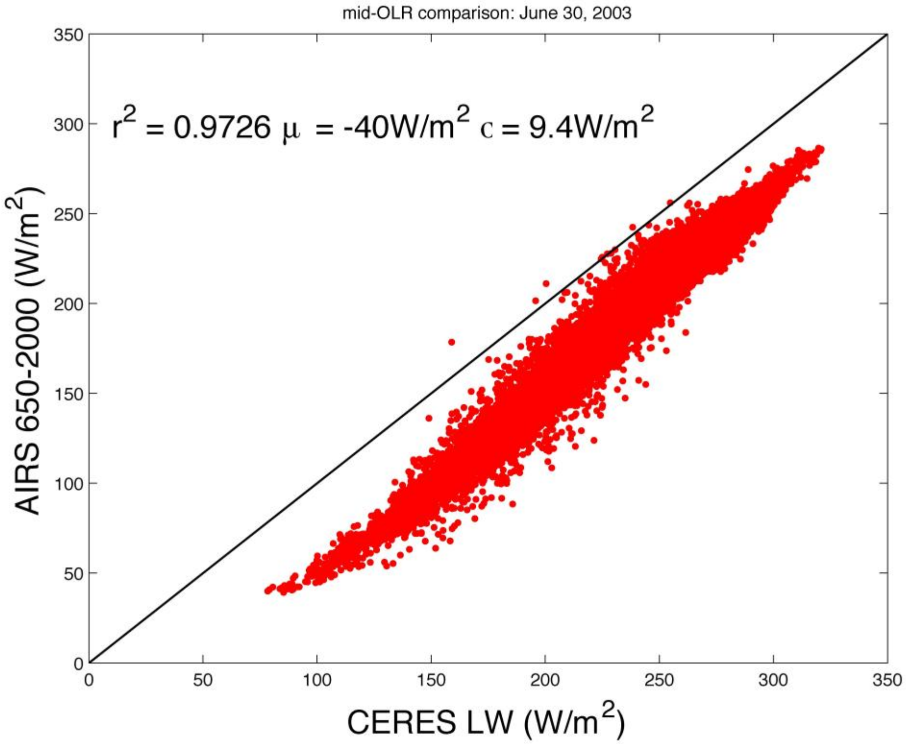
$$dF^{TOA} = \sum_{i=1}^{n}\frac{\partial F^{SURF}}{\partial x_i}\, dx_i + \int_0^\infty \frac{1}{\rho(z)C_p}\sum_{i=1}^{n}\frac{\partial \theta'(z)}{\partial x_i}\, dx_i\, dz$$

In the absence of TOA far-IR measurements

- Extensive datasets of mid-IR measurements and also information from CloudSat and CALIPSO.
    - Standard retrieval products can (and should) be used to gauge estimate far-IR cooling
    - These require covariance matrix estimates!
- In the absence of far-IR measurements, measurements from other sources must be extrapolated
    - Critical requirement for accurate spectroscopy, cloud optical properties, and an appropriate mapping from mid-IR clouds to far-IR clouds.
- The data is out there!
    - Routine calculations are performed by weather models, in climate models and for satellite products. Comparison required.

Using AIRS + CERES to understand far-IR

- AIRS radiance spectra has been converted to spectrally-resolved fluxes collocated with Aqua CERES LW fluxes [Huang et al, 2010].
- A comparison of the principal components AIRS mid-IR flux (650-2000 cm^{-1}) to CERES broadband flux (200-2000 cm^{-1}) will indicate the extra information in the far-IR.
- Process studies are likely required to understand how the discrepancies between mid-IR and broadband flux map onto far-IR cooling.



Data courtesy of Xianglei Huang

Discussion

- Radiative cooling rates are important to atmospheric circulation and far-IR cooling from water vapor and clouds represent a significant component of this cooling.
- Remote sensing measurements provide information, either directly or indirectly, about spectral and broadband cooling rates
  - The incorporation of this information requires careful attention to retrieval theory.
- Ongoing efforts to compare mid- and broadband IR measurements from AIRS and CERES respectively may yield extra information about far-IR flux and ultimately far-IR cooling.

Acknowledgements

- Collaborators Marty Mlynczak and Dave Johnson of LaRC.
- NASA Earth Systems Science Fellowship, grant number NNG05GP90H.
- NASA Grant NNX08AT80G, NAS2-03144, NNX10AK27G and NNX11AE65G.
- Yuk Yung Radiation Group: Jack Margolis, Vijay Natraj, King-Fai Li, & Kuai Le
- AER, Inc. including Eli Mlawer, Mark Shepard, and Tony Clough for tech support
- Xianglei Huang from University of Michigan
- Yi Huang from (recently) McGill University