Determination of the infrared radiative forcing at the tropical tropopause with AIRS

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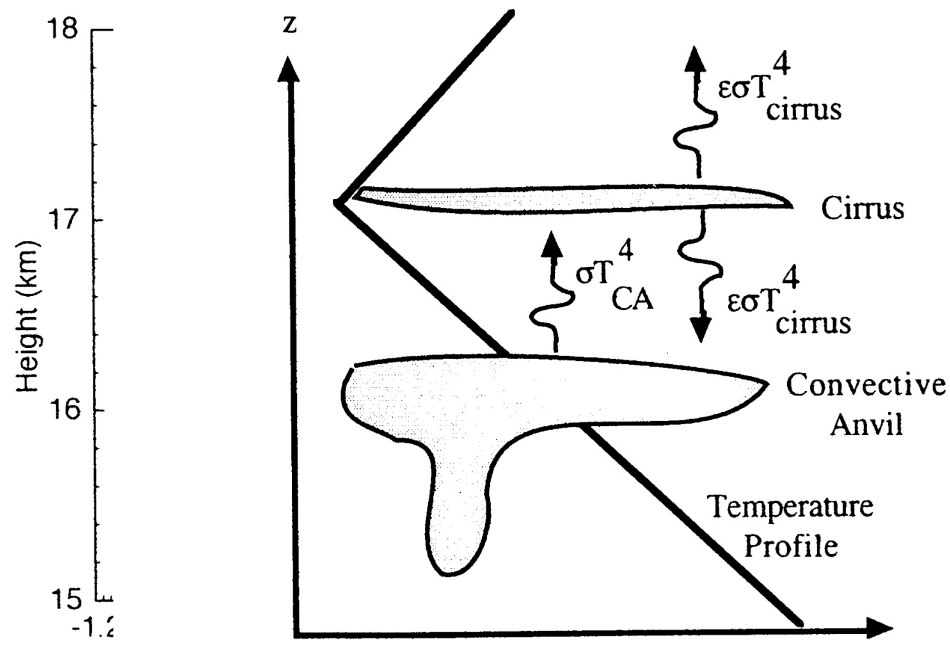
Daniel Feldman, Caltech
Brian Kahn, JPL
Kuo-Nan Liou, UCLA
Yuk Yung, Caltech

Outline

- Motivation
- Background and Theory
- Test case: the tropical model atmosphere
- TWP ARM site study
- Cooling rate profile retrieval
- Conclusion

Heat Balance Considerations at the Tropical Tropopause Layer (TTL)

- TTL is a region that influences stratosphere-troposphere exchange
- Overly-dehydrated lower stratosphere
- TTL evolution not fully understood, but radiative effects may be important
- Upper Troposphere (UT) H_2O, O_3 and different cloud types affect radiative balance.



Hartmann et al., GRL 2001

➢ Motivation

Infrared Cooling Rate Profile Calculation

- Conventionally use T, H_2O, O_3, CH_4, and N_2O profiles
- Cooling rate profile proportional to net flux divergence in a layer
  - Exchange with surface, exchange with space, layer interaction
- Conventional radiative transfer codes can calculate cooling rates
  - Correlated-K calculation in RRTM currently radiometrically accurate to 0.07 K/day in troposphere & 0.3 K/day in stratosphere

$$F^{\pm}(z) = \int_{\nu_1}^{\nu_2} \int_0^1 I_\nu(\pm\mu, z)\mu \, d\mu \, d\nu$$

$$\dot{\theta} = \frac{1}{C_p \rho(z)} \frac{dF^{NET}(z)}{dz}$$

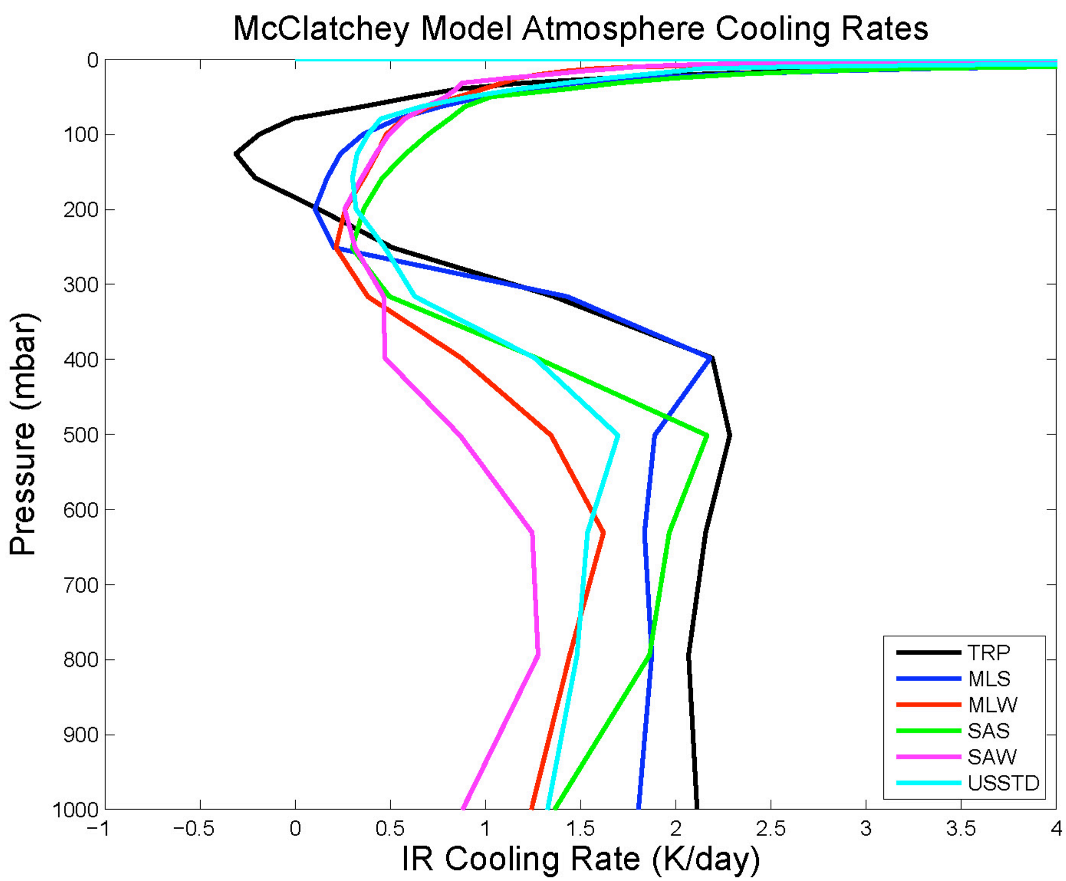
$$F^{+}(\tau) = 2\pi B(\theta_{surf}) E_3(\tau_{surf} - \tau) + \int_0^{\tau} B(\theta(t)) E_2(t - \tau) dt$$

➢ Background and Theory

Goody and Yung, 1989

Model Atmospheres

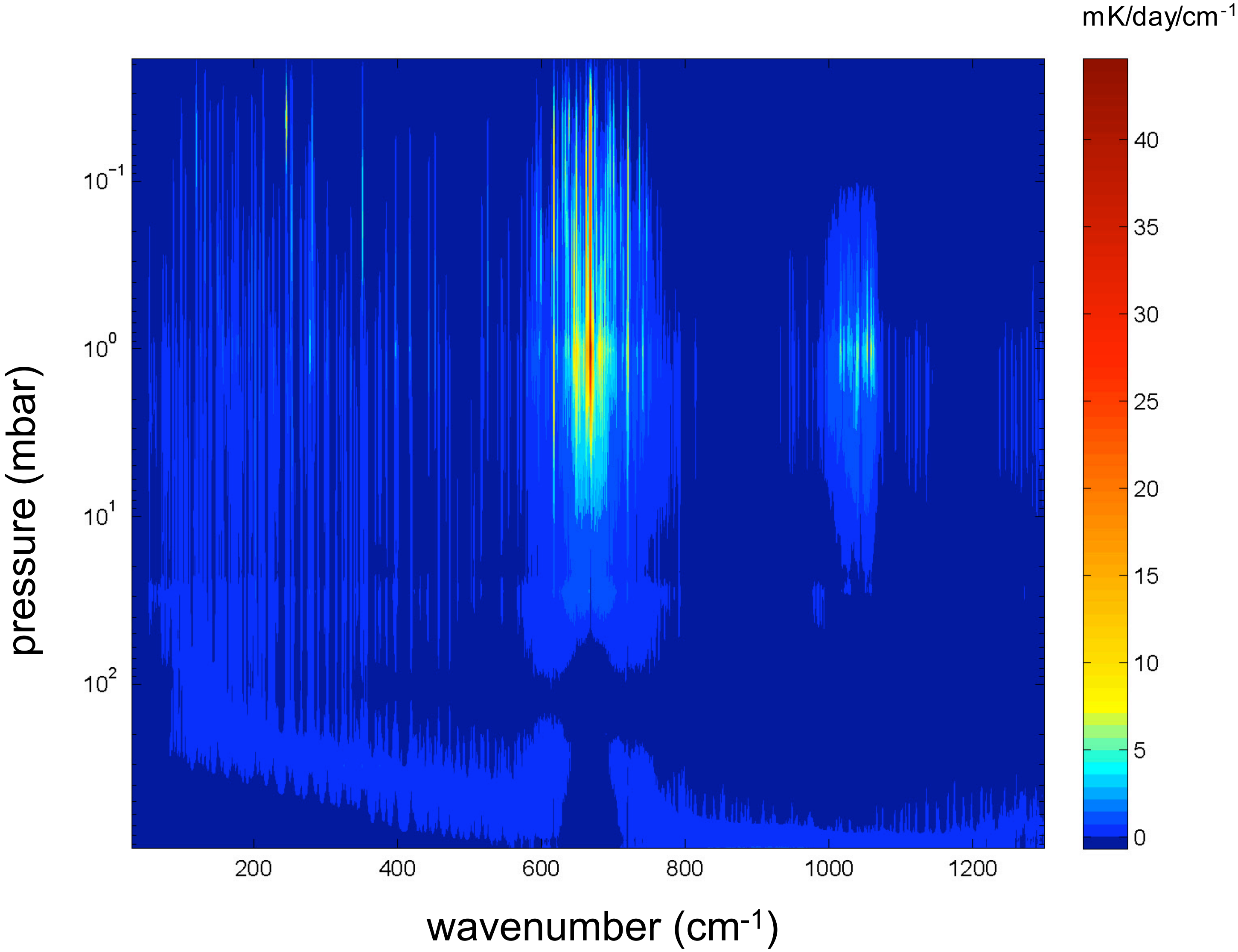
- Well-characterized and standard atmospheric profiles facilitate sensitivity studies.



➢ Test case

McClatchey et al, AFRL 1972; Mlawer et al., JGR 1997

Clear-Sky Spectral Cooling Rate Profile

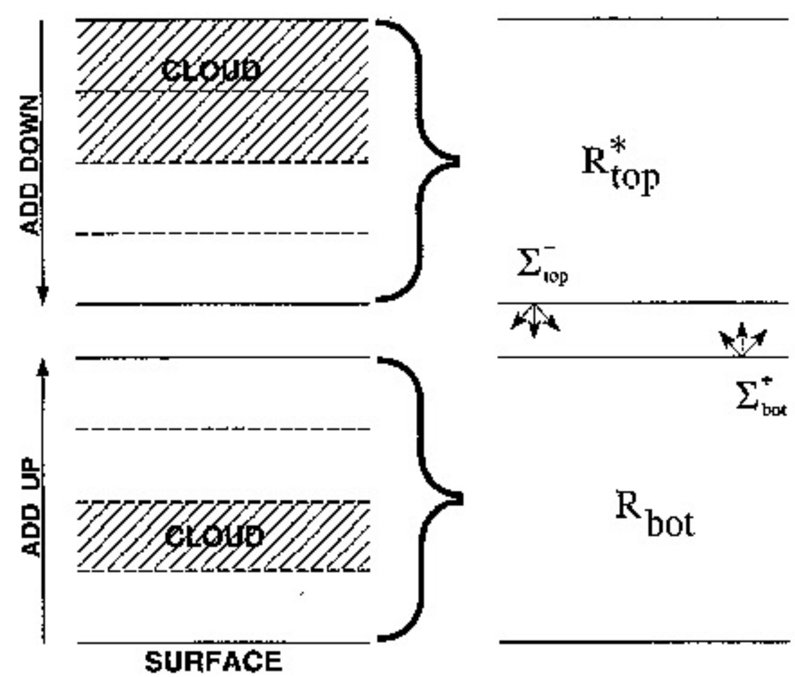


- Test case

After Mertens et al., JGR 1999; Clough et al., JGR 1995

f-CHARTS: flux Code for High-Resolution Accelerated RT with Scattering

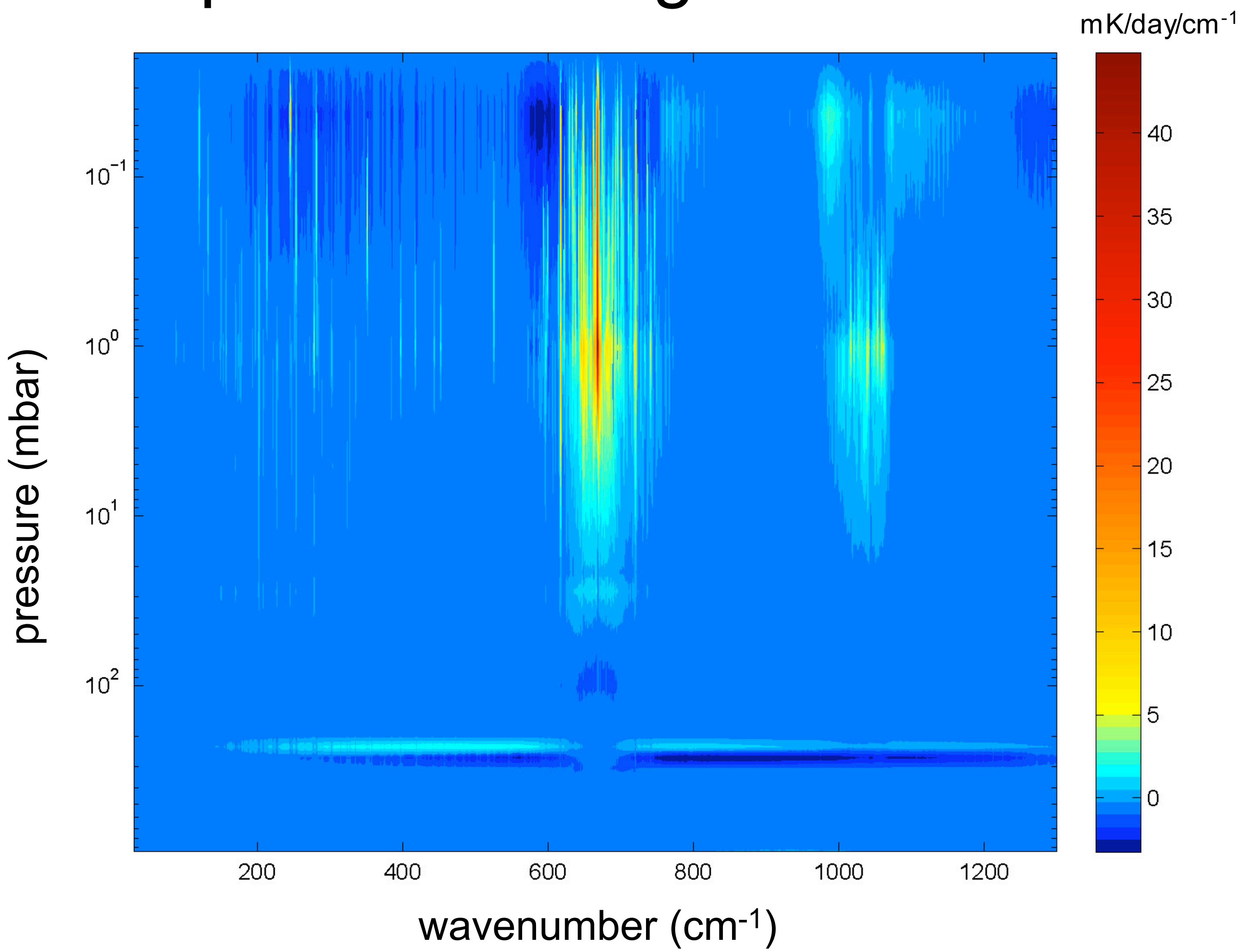
- Gaseous optical depth from monochromatic LBLRTM calculations
- Multiple scattering capability (DA method)
- Radiance to flux conversion
- Cooling rates produced by finite difference of fluxes



➢ Test case

Moncet et al., JGR 1997

Scattering Atmosphere
Spectral Cooling Rate Profile

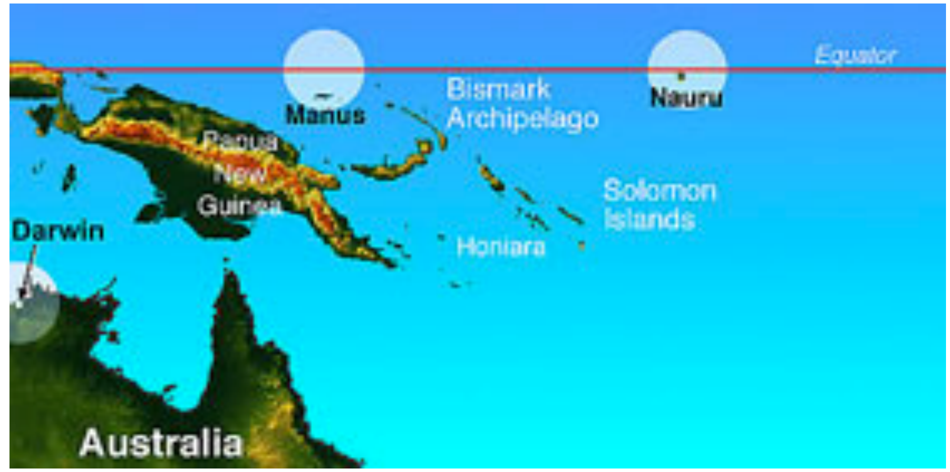


- Test case

Cirrus properties from Baran et al., JQSRT 2001

Atmospheric Radiation Measurement Tropical Western Pacific Site

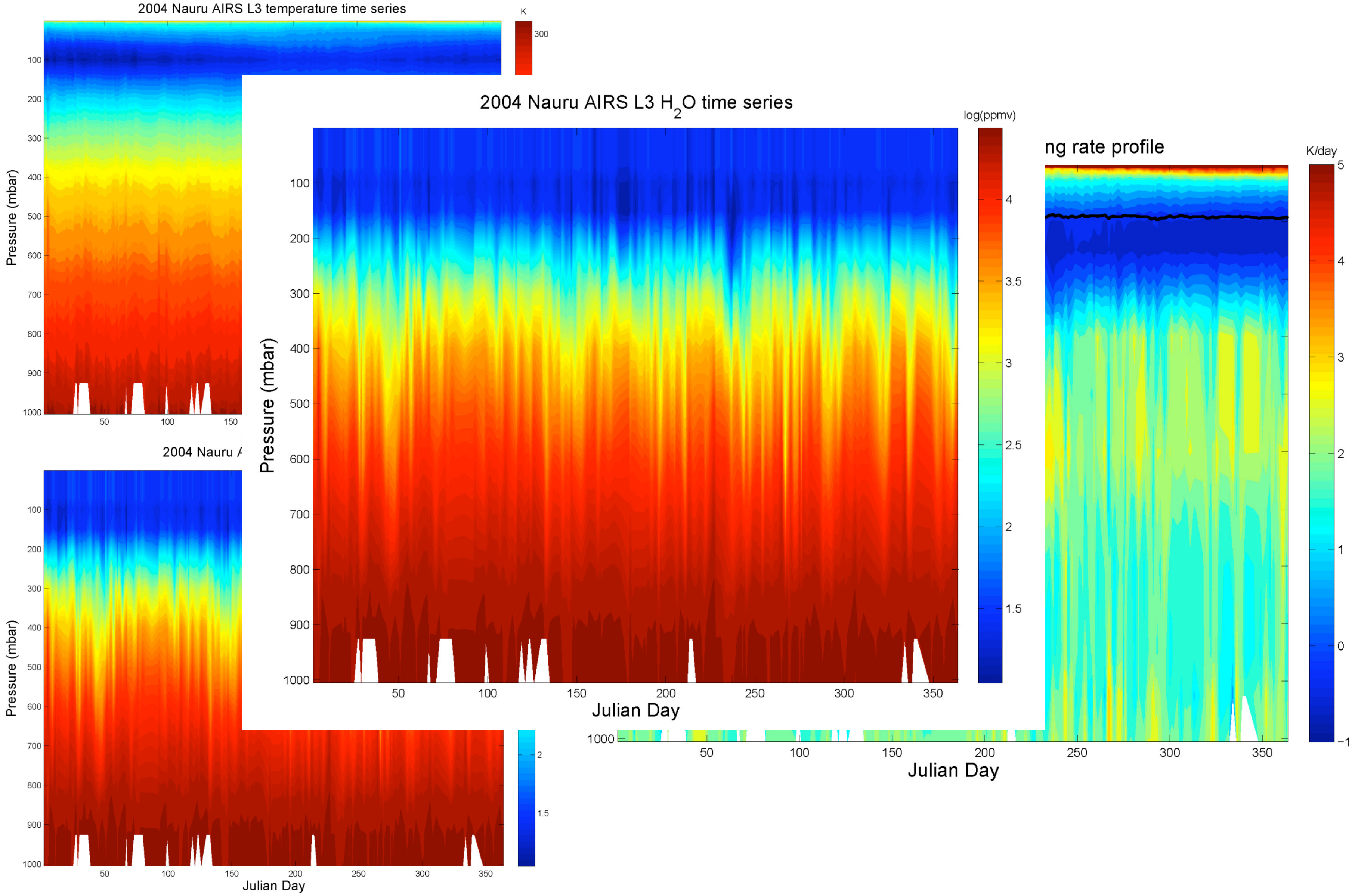
- Three highly-instrumented stations at Manus Island, Nauru, and Darwin
- Twice daily radiosonde launches
- Cloud products from active sensing
  - MMCR
  - MPL
  - MWR



➢ TWP ARM site study

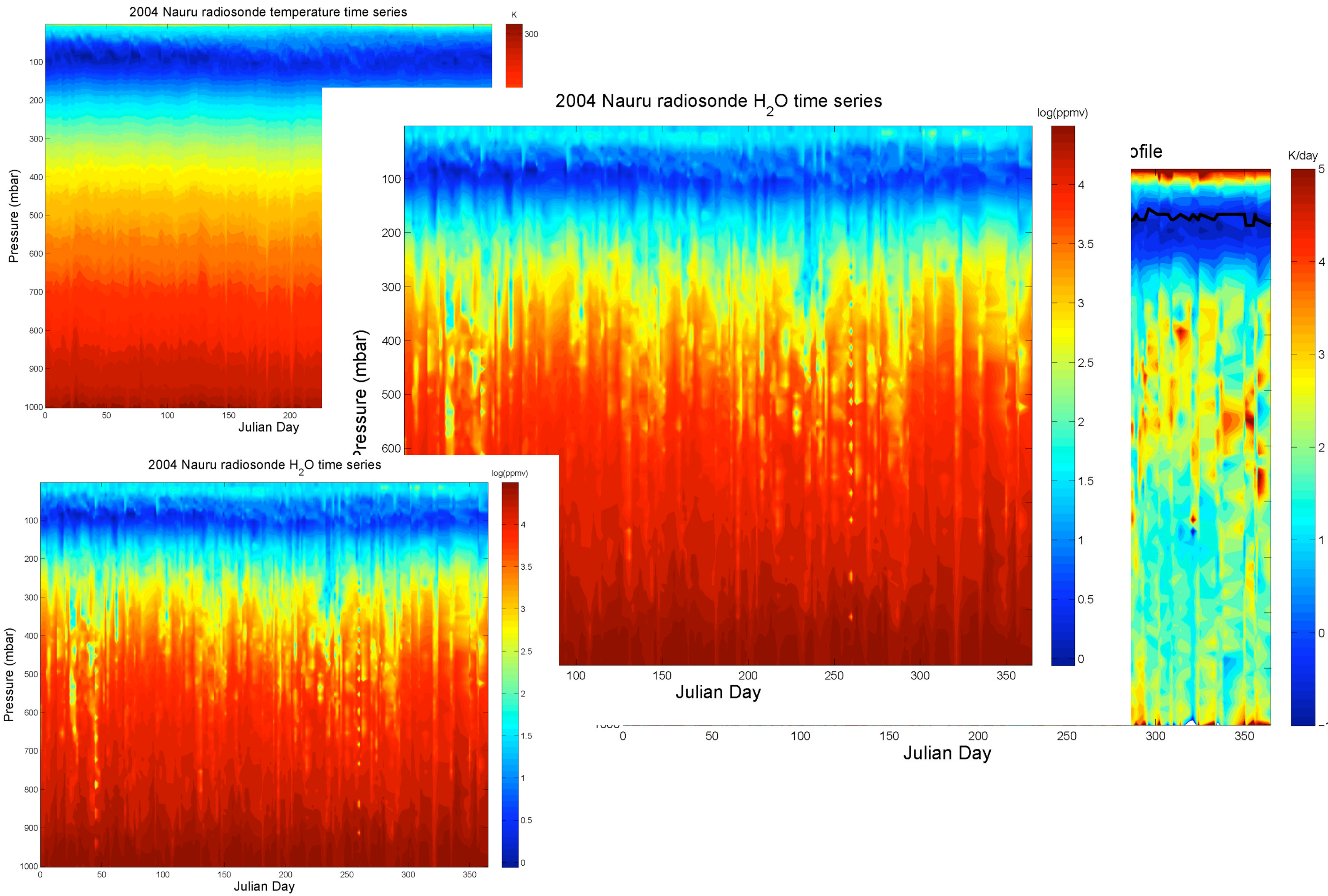
from www.arm.gov

Manus Island Intercomparison: AIRS



- TWP ARM site study

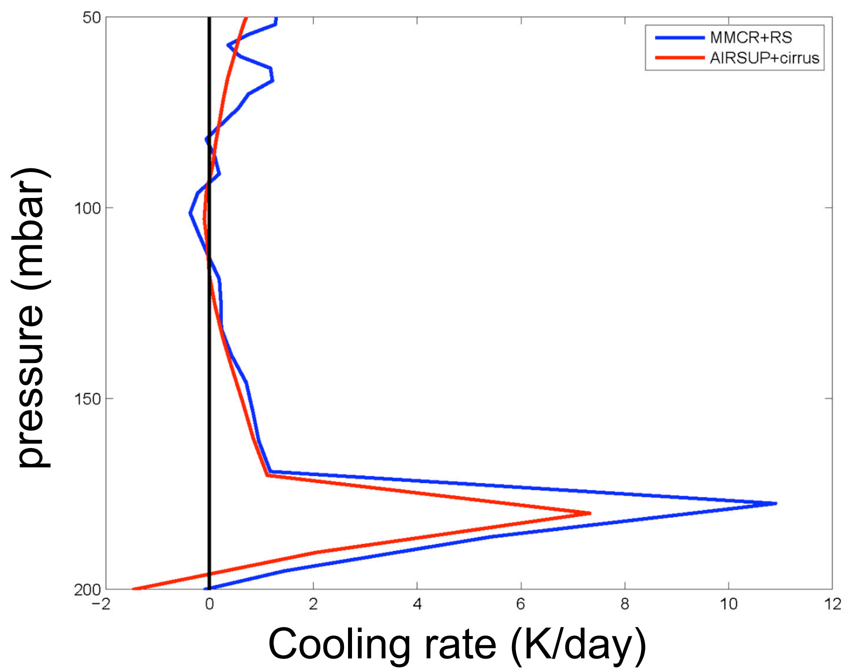
Manus Island Intercomparison: Radiosonde

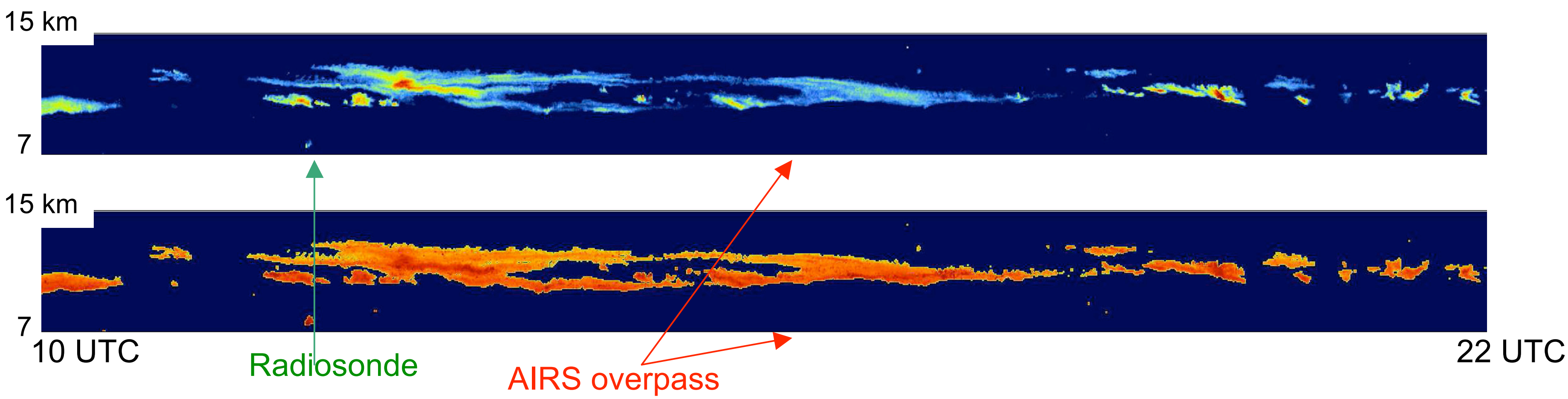


- TWP ARM site study

TTL Cooling Rate Comparison for 06/20/03

- AIRS data:
  - Supplemental T, H_2O, O_3 (v4)
  - Retrieved τ, D_e
- Comparison data:
  - Radiosonde profile
  - MMCR τ, D_e retrieval





➢ TWP ARM site study

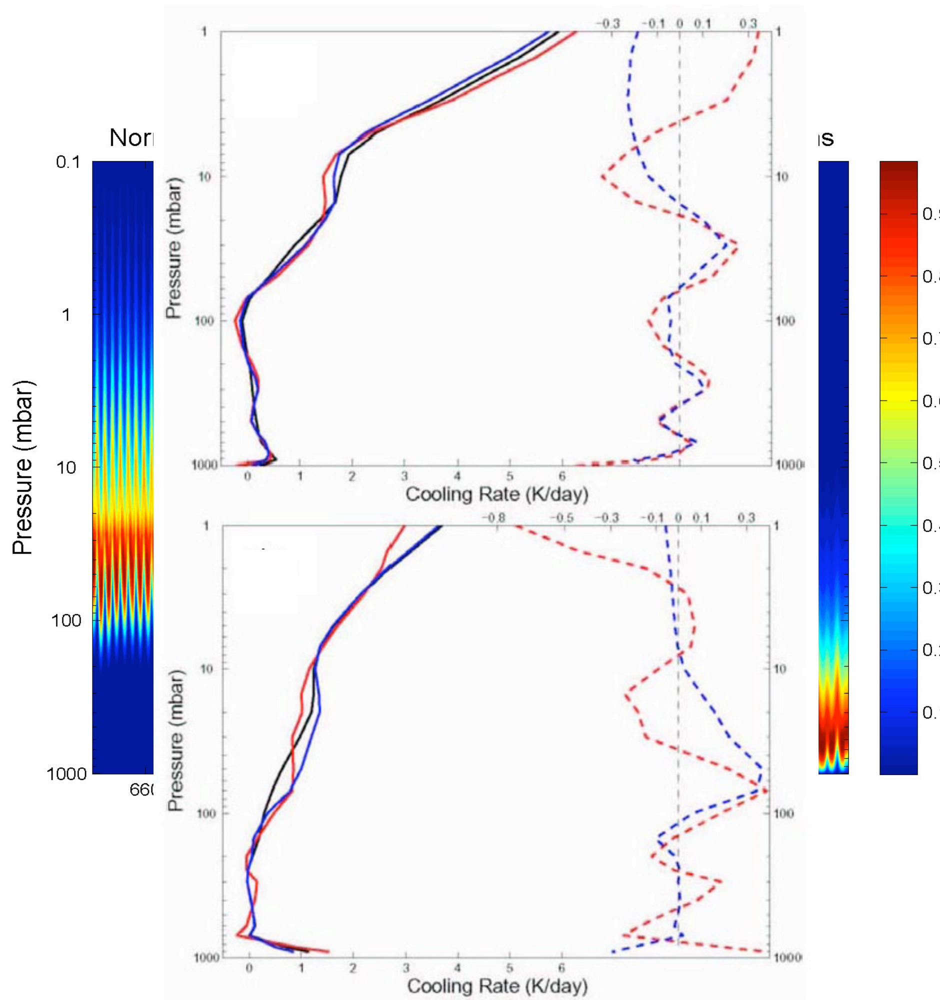
Mace et al, JGR 2002; Yue et al., JAS submitted

Cooling Rate Profile Retrieval Considerations

- Radiance measurement can describe cooling rate profiles
  - Retrieval (OET) + RTM run
  - Direct retrieval (OET)
    - Use $T_{\upsilon}(z)$ as kernel, angular radiance information
    - Retrieve with estimates of spectral flux (through Angular Distribution Models)

$$F_{TOA}^{NET} = F_{SURF}^{NET} + \int_0^\infty \frac{dF^{NET}(z')}{dz'} dz'$$

  - Prior constraint derived analytically from atmospheric state variability
- Far-IR (>15.4 μm) contributes significantly to the cooling rate profile, yet few measurements

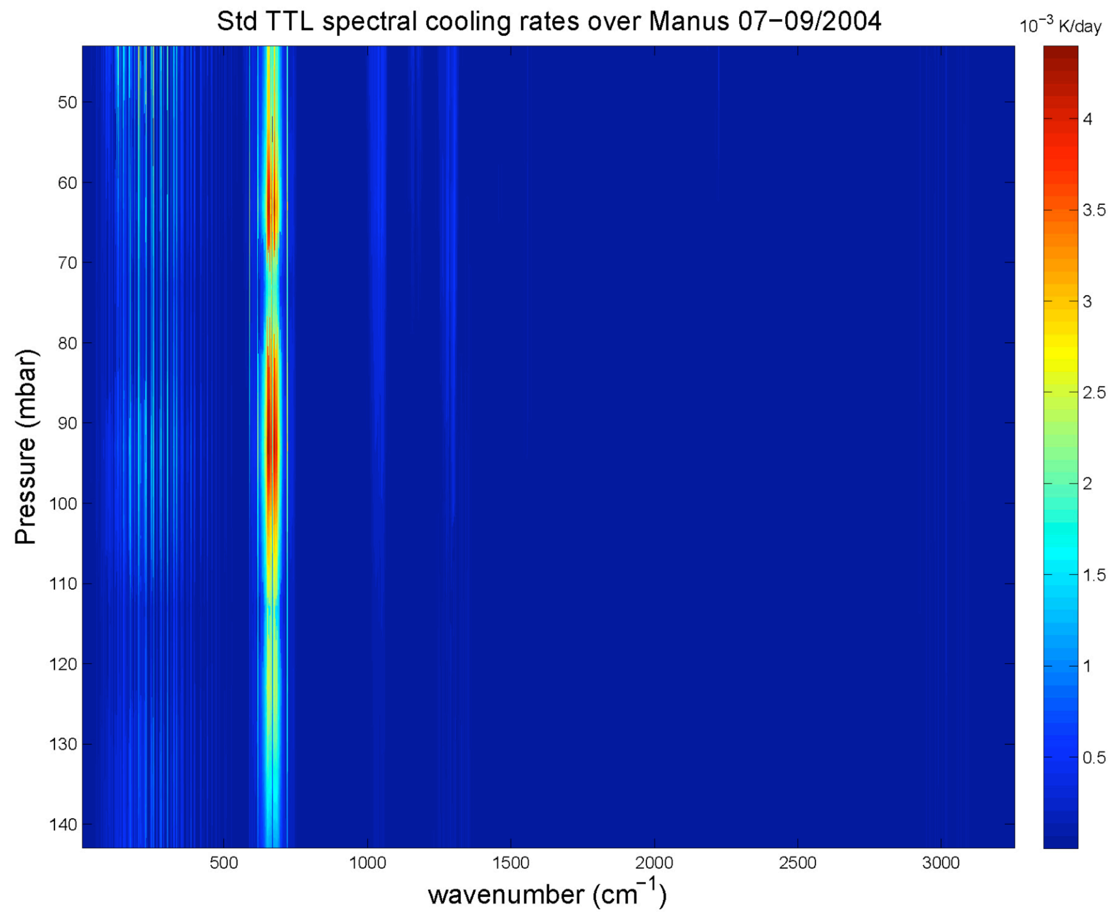


➢ Cooling rate profile retrieval

Feldman et al, GRL accepted; Liou et al., MAP 1988

Spectral Cooling Rate Profile Variability

- Tropical tropopause temperature structure (CO_2 15 μm band), TTL H_2O and O_3 all impact cooling rate profile variability seen in this region.



➢ Cooling rate profile retrieval

Conclusions

- Spectral cooling rate information shows the relative roles of various constituents for the total IR radiative forcing.
- Introduction of cirrus layer
  - Overwhelms most H_2O rotational band cooling.
  - Eliminates O_3 v_3 heating at TTL.
  - Marginally influences CO_2 v_2 band heating/cooling.
- Lower cirrus boundary heating and upper cirrus boundary cooling show slow spectral variation.
- AIRS has moderate descriptive power for the temperature structure of the TTL.
- UT H_2O discrepancy with RS and AIRS broad averaging kernels fail to capture much of the TTL cooling rate variability.
- Novel retrieval techniques with respect to cooling rates retain retrieval error information unlike standard cooling rate calculation approach.

Conclusions Continued …

- Future work includes:
  - Intercomparison of datasets with tropopause-resolving data such as from AVE Houston 2004.
    - JPL Laser Hygrometer
    - Cloud Pulse Lidar
  - Formal error estimates for spectral radiance to flux conversion.
  - Further exploration of the spectral cooling rate information provided by different cloud layering.
  - Study of AIRS CTP and CTT in terms of multiple cloud layering influence on TTL cooling.

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- ARM program
- NASA ESSF program

➢ Conclusion

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Extra slides: flux divergence retrieval

- Formulation of the retrieval problem in terms of spectral flux measurements
- Weighting functions determined in 2 dimensions:
  - Vertically by non-peaked (unitary) kernel
  - Spectrally by relative contribution to band-averaged cooling.

$$F^{NET}(\nu,\infty) = F^{NET}(\nu,0) + \int_0^\infty \frac{dF^{NET}(\nu,z)}{d\tau(\nu,z)} \frac{d\tau(\nu,z)}{dz} dz$$

$$F(\nu,z) = \int_0^1 \mu \, I(\nu,\mu,z) d\mu = ADM(\hat{\mathbf{i}}, \mathbf{I}(\nu,\mu,z))$$

$$ADM_\nu(\hat{\mathbf{i}}, \mathbf{I}(\nu,\mu,z)) = y_\nu = \mathbf{G}\left(\frac{dF_{\bar{\nu}}^{NET}}{dz}\right)$$

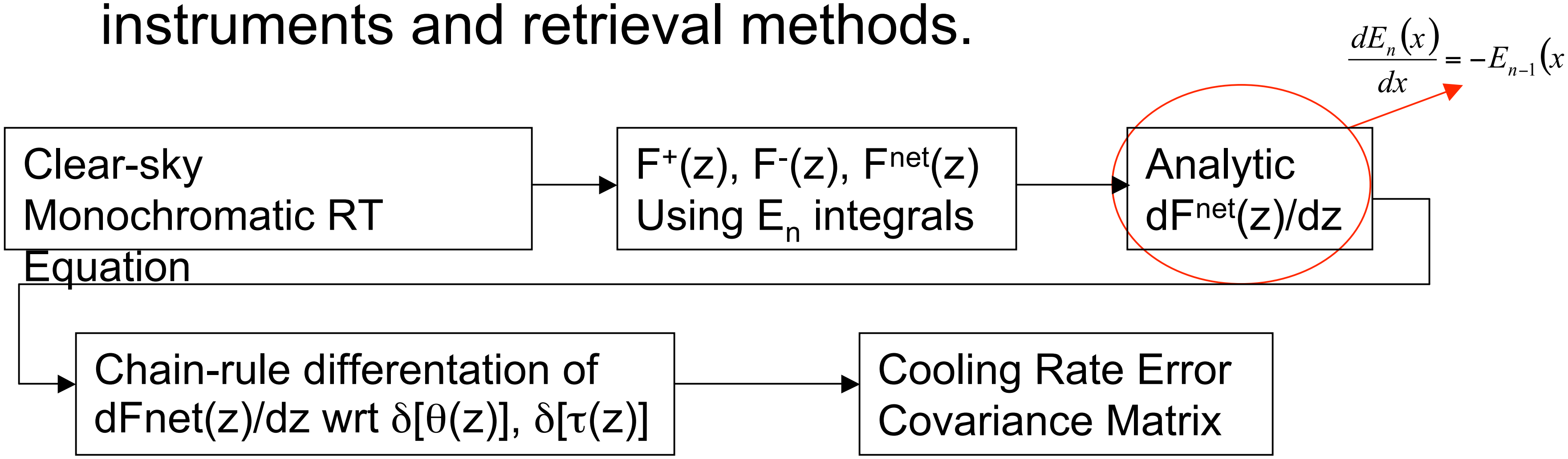
$$\mathbf{y} = \begin{bmatrix} y_1 & \cdots & y_n \end{bmatrix}$$

$$\frac{d\hat{F}_{\bar{\nu}}^{NET}}{dz} = \mathbf{G}^{-1}\left(\mathbf{y}, \mathbf{S}_{dF_{\bar{\nu}}^{NET}/dz}, \mathbf{S}_{\mathbf{y}}\right)$$

$$H = -k \log\left(\left|\hat{\mathbf{S}}_{dF_{\bar{\nu}}^{NET}/dz} * \mathbf{S}^{-1}_{dF_{\bar{\nu}}^{NET}/dz}\right|\right)$$

Extra slides: flux divergence error budget

- Motivation: to understand discrepancies between *in situ* and remote sensing-derived cooling rate profiles.
- Difficult to measure *in situ* net flux and flux divergence.
- Atmospheric state vector covariance terms impact cooling rate uncertainty budget.
- Information theoretic approach allows for comparison of instruments and retrieval methods.



- Cooling rate profile retrieval

Extra slides: flux divergence error budget continued …

$$F_\nu^{\uparrow}(\tau_\nu) = 2\pi B_\nu(\theta_{surf})E_3(\tau_{surf,\nu} - \tau_\nu) + 2\pi\int_{\tau_\nu}^{\tau_{surf,\nu}} B_\nu(\theta(\tau_\nu'))E_2(\tau_\nu' - \tau_\nu)d\tau_\nu'$$

$$F_\nu^{\downarrow}(\tau_\nu) = 2\pi\int_0^{\tau_\nu} B_\nu(\theta(\tau_\nu'))E_2(\tau_\nu - \tau_\nu')d\tau_\nu'$$

$$\frac{dF_\nu^{NET}}{dz} = \begin{cases} 2\pi B_\nu(\theta_{surf})E_2(\tau_\nu(z_{surf}) - \tau_\nu(z))\frac{d\tau_\nu(z)}{dz} - 2\pi B_\nu(\theta(z))\frac{d\tau_\nu(z)}{dz} + \\ 2\pi\frac{d\tau_\nu(z)}{dz}\int_1^{E_2(\tau_\nu(z_{surf})-\tau_\nu(z))} B_\nu(\theta(z'))dE_2(\tau_\nu(z') - \tau_\nu(z))dz + \\ -2\pi B_\nu(\theta(z))\frac{d\tau_\nu(z)}{dz} - 2\pi\frac{d\tau_\nu(z)}{dz}\int_{E_2(\tau_\nu(z))}^{1} B_\nu(\theta(z'))dE_2(\tau_\nu(z) - \tau_\nu(z')) \end{cases}$$

$$\delta\left(\frac{dF_\nu^{NET}}{dz}\right) = \begin{cases} 2\pi\frac{dB_\nu(\theta_{surf})}{d\theta}E_2(\tau_\nu(z_{surf}) - \tau_\nu(z))\frac{d\tau_\nu(z)}{dz}\delta(\theta_{surf}) + 4\pi\frac{dB_\nu(\theta(z))}{d\theta}\frac{d\tau_\nu(z)}{dz}\delta(\theta(z)) + \\ 2\pi\frac{d\tau_\nu(z)}{dz}\int_1^{E_2(\tau_\nu(z_{surf})-\tau_\nu(z))}\frac{dB_\nu(\theta(z'))}{d\theta}\delta(\theta(z,z'))dE_2(\tau_\nu(z') - \tau_\nu(z)) + \\ 2\pi\frac{d\tau_\nu(z)}{dz}\int_{E_2(\tau_\nu(z))}^{1}\frac{dB_\nu(\theta(z'))}{d\theta}\delta(\theta(z,z'))dE_2(\tau_\nu(z) - \tau_\nu(z')) \\ 2\pi B_\nu(\theta_{surf})E_1(\tau_\nu(z_{surf}) - \tau_\nu(z))\left(\frac{d\tau_\nu(z)}{dz}\right)^2\delta(\tau_\nu(z)) + 4\pi B_\nu(\theta(z))\frac{d^2\tau_\nu(z)}{dz^2}\delta(\tau_\nu(z)) \\ 2\pi\frac{d\tau_\nu(z)}{dz}\int_\infty^{E_1(\tau_\nu(z_{surf})-\tau_\nu(z))} B_\nu(\theta(z'))\delta(\tau(z,z'))dE_1(\tau_\nu(z') - \tau_\nu(z)) + \\ 2\pi\frac{d\tau_\nu(z)}{dz}\int_{E_1(\tau_\nu(z))}^{\infty} B_\nu(\theta(z'))\delta(\tau(z,z'))dE_1(\tau_\nu(z) - \tau_\nu(z')) \end{cases}$$

Error inputs

$$\delta\theta(z,z') = \left(\left|S_{a_T}(z,z')\right|\right)^{1/2}$$

$$\delta\tau(z,z') = \int_\infty^{z}\left(\left|S_{a_x}(z,z')\right|\right)^{1/2} k_\nu(z)dz$$