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Direct Retrieval of Radiative Flux-Divergence and Radiative Forcing from Satellite Spectral Measurements

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Abstract

We explore the concept of a retrieval of the thermal infrared cooling rate profile using top-of-atmosphere spectral radiance measurements and demonstrate that the retrieval of this quantity can be performed directly [1, 2]. Our approach has specific advantageous in terms of accuracy and computational speed, as compared to the conventional indirect approach using the retrieved atmospheric state vector coupled with a band-model calculation of the cooling rate profile. As a test case, we carried out a retrieval in the strong cooling band associated with the 15 µm band of CO_2 employing the Top-of-Atmosphere (TOA) spectra of the Atmospheric Infrared Sounder (AIRS, 2002-present) [3] on board the Aqua satellite, along with validation campaign data and under-flight Scanning High-Resolution Interferometer (S-HIS) zenith and nadir spectra taken aboard a high-altitude aircraft [4]. Also, retrieval sensitivity analyses have been performed for the AIRS instrument. Preliminary study of the Infrared Interferometer Sounder (IRIS-D) [5] data is also discussed. It is anticipated that the large changes in cooling rate profile of the 15 µm between the two missions would lead to detectable changes in the CO_2 radiative forcing at the tropopause so long as the IRIS-D instrument can be appropriately characterized.

Introduction:

The infrared cooling rate profile is dependent upon individual layer atmospheric state vector values and their relationship to the broad structure of the atmospheric state, we seek to understand whether high-resolution infrared spectra can offer a better description of the infrared cooling rate profile beyond the atmospheric state standard products, especially in polar regions. Therefore, the retrieval must analyze absorption band channels in the context of a channel's description of the radiative cooling of that band at a certain level as opposed to a channel's description of an atmospheric state quantity at that level.

The cooling rate profile is proportional to the net radiative flux divergence in a spectral interval. The total clear-sky IR cooling rate profile is determined by strong radiators including H_2O, CO_2, O_3, and CH_4.

Spectral Cooling Rate Profile Definition:

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

Spectral Cumulative Cooling Rate Contribution Function

$$\dot{\Theta}(\nu,z)=\frac{\int_0^{\nu}\dot{\theta}(\nu,z)\,d\nu}{\int_0^{\nu_{\max}}\dot{\theta}(\nu,z)\,d\nu}$$

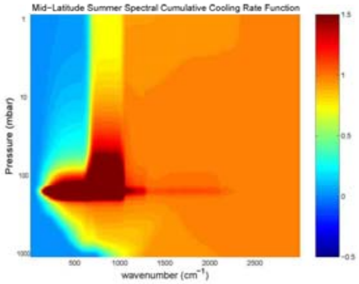


Figure 1: Spectral cumulative cooling rate contribution function for mid-latitude summer conditions [6]. Values in excess of unity are allowed for levels where spectral heating occurs.

15 µm Cooling Rate Profile Variability:

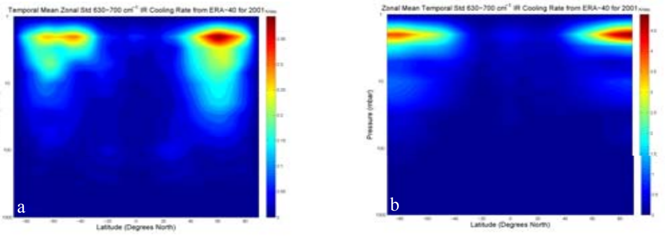


Figure 2: Meridional profile of (a) mean zonal and (b) mean monthly temporal variability of cooling rate from 630-700 cm^{-1} calculated with RRTM [7] using ERA-40 T, H_2O, and O_3 fields for 2001 [8].

Retrieval Setup:

$$\int_0^{\infty}\rho(z)*C_pT(\nu,z,\mu)\dot{\theta}_{band}(z)dz=\alpha(\nu,\mu)*I_{band}(\overline{\mu})+\beta(\nu,\mu)*I(\nu,\mu)=y$$

According to [2], the measurements from which the cooling rate profile is inverted are a function of channel radiance measurements taken at viewing angle μ and the mean band radiance taken at a viewing angle $\overline{\mu}$ (around 45° from nadir). The weighting function is defined by the first 3 terms (density profile, heat capacity, and channel transmittance, respectively) of the integrand of the left-hand side of the above equation. The weighting terms $\alpha(\nu,\mu)$ and $\beta(\nu,\mu)$ are determined empirically. The first term on the right-hand side is proportional to the TOA band flux while the second term indicates the particular channel's spectral cooling rate contribution to the total band cooling. The inversion of the measurement **y** is performed through a linear Bayesian update [9] to the *a priori* cooling rate profile. We adhere the notation in [9] to describe retrieval quantities:

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

The *a priori* covariance matrix $\mathbf{S}_a$ is created according to a differential analysis of the temperature dependence of the cooling rate profile. The measurement covariance matrix $\mathbf{S}_\varepsilon$ is created by multiplying channel noise-effective radiance by the weighting terms $\alpha(\nu,\mu)$ and $\beta(\nu,\mu)$.

Weighting Functions:

$$K_{CLR}(\nu,z)=C_p\,\rho(z)T(\nu,z)$$

$$K_T(\nu,z)=dy(\nu,x+\Delta x(z))/\Delta x(z)$$

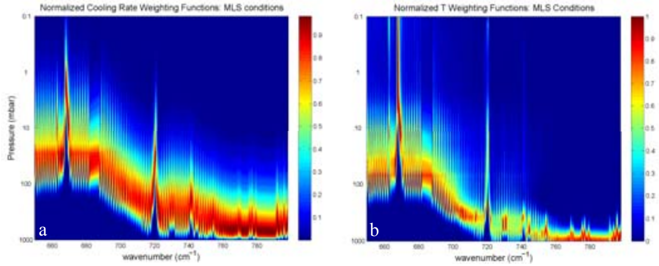
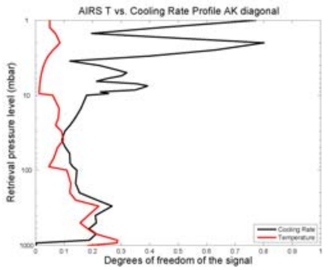


Figure 3: Normalized weighting functions for (a) cooling rate profile retrieval and (b) temperature profile retrieval for mid-latitude summer conditions with the AIRS instrument.

Averaging Kernels:



Averaging Kernel Matrix

$$\mathbf{A}=\begin{cases}d\hat{\mathbf{x}}/d\mathbf{x}\\ \left(\mathbf{K}^T\mathbf{S}_\varepsilon^{-1}\mathbf{K}+\mathbf{S}_a^{-1}\right)^{-1}\left(\mathbf{K}^T\mathbf{S}_\varepsilon^{-1}\mathbf{K}\right)\end{cases}$$

Figure 4: Temperature vs. 649-800 cm^{-1} cooling rate profile averaging kernel matrix diagonals for mid-latitude summer conditions [6].

Computational Expense:

Computational Comparison

Conventional Approach	Cooling Rate Retrieval
N * ΔT + CLR	(M+1) * ΔT

ΔT: time for radiative transfer calculation
CLR: time for cooling rate calculation
N: # model layers
M: # cross-track scan angles used

Results from AVE and MPACE

Direct validation of cooling rate profile retrievals requires data from *in situ* vertically ascending or descending hemispheric radiometers that have the same overpass time as the remote sounder. In lieu of this, we perform a cross-comparison by analyzing other sets for atmospheric state information, and then comparing the calculated cooling rate to our retrieval.

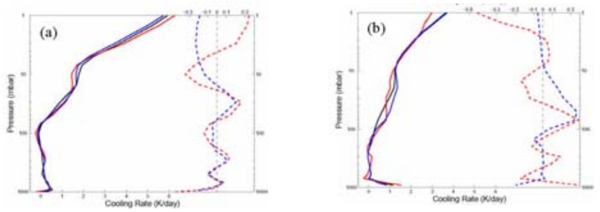


Figure 5: Deviation from *a priori* cooling rate profile (black) for spectral interval 649-800 cm-1 for AIRS retrieved (red) and S-HIS calculated (blue) cooling rate profiles. (a): AVE [10] Flight: 10/31/2004, 24.8 N, 271.8 E. (b): MPACE [11] flight: 10/10/2004, 62.7 N, 214.4 E.

Comparison with IRIS-D:

The stratosphere has changed substantially between the time of the operation of IRIS-D and AIRS. CO_2 has increased by over 50 ppmv, O_3 has decreased by 6% or more, and T has decreased by 3 K or more [12]. All of these factors affect the cooling rate profile in the 15 µm band. With the cooling rate profile, the net flux at the tropopause and hence the radiative forcing can be determined.

We have done preliminary analysis using the Integrated Global Radiosonde Archive (IGRA) [13] and found that night-time radiosonde observations (RAOBs) in conjunction with IRIS-D spectra will allow the characterization of stratospheric temperatures above 30 mbar with ~ 1 degree of freedom.

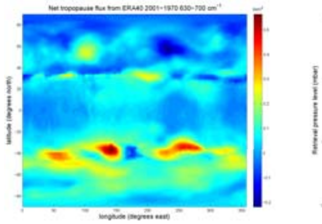


Figure 6: Expected change in net tropopause flux over 630-700 cm^{-1} band (2001-1970) using ERA-40 T, H_2O, and O_3 fields [8] and 323 and 379 ppmv for CO_2 for 1970 and 2001 respectively.

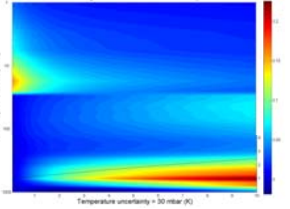


Figure 7: Temperature averaging kernel diagonals for IRIS-D + RAOB data on retrieved pressure level vs. RAOB accuracy for USSTD [6]. Right axis indicates total degrees of freedom of the signal.

Conclusions:

1) Cooling rate retrievals represent a novel utilization of cross-track-scanning radiance data to offer the prospect of retrieving cooling rate profiles by bypassing standard atmospheric state retrievals and subsequent cooling rate calculations. There is a computational advantage and weighting functions for the same channel peak higher in the atmosphere.
2) Cross-comparison of calculated cooling rate profiles from AVE and MPACE with AIRS retrieved cooling rate profiles in the 15 µm band lend confidence to our methods.
3) Changes in the 15 µm band cooling rate profile in between 1970 and present may be detectable using IRIS-D spectra in conjunction with IGRA RAOBs and current satellite IR spectrometers.

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