ARM Radiative Heating Rate Workshop,
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Time-Domain Radiative Transfer in the O_2 A-Band:

A New Observational Constraint on the Solar Heating Rate Prediction Problem in the Presence of Clouds?

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… with ideas, papers, discussions, critiques from/by many colleagues, primarily:

Sasha Marshak

Warren Wiscombe

Howard Barker

Klaus Pfeilsticker

Qi-Long Min

Lee Harrison

Greame Stephens

Dennis O’Brien

David Crisp

Alex Kostinski

Mike Larsen

Eugene Clothiaux

Palvos Kollias

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James Kamm

ARM STM member/affiliate

Validation and Verification (V&V) ideas based on:

D. Sornette, A. B. Davis, K. Ide, K. R. Vixie, V. Pisarenko, and J. R. Kamm:

"Algorithm for Validation:

Theory and Application,"

Proc. Nat. Acad. Sci. (2007, in press).

Final version available in preprint form at

http://arxiv.org/abs/physics/0511219

(or email me)

Definitions used in aerospace and (now) in nuclear engineering:

- **Verification**
  - *Are we solving the equations right?*
- **Validation**
  - *Are we solving the right equations?*
  - The **process** of determining the degree to which a model is an accurate representation of the **real world** <u>from the perspective of its intended uses</u>
- (Model) **calibration**
  - Use of observations to determine model parameters, including initial conditions, numerical controls, etc.
  - Contrast with "prediction," which happens next.

Mine: (Performance) **test**

- inter-model comparison when one approximates the other

P.J. Roache, *Verification and Validation in Computational Science and Engineering*, Hermosa Publishers, Albuquerque, NM (1998).

Problem:

- Nature uses the steady-state 3D RTE to "compute" solar heating line-by-line at all scales, given the 3D distribution of optical properties at the micro-scale (where we need to use EM wave theory, QM, and Co).
- We can only afford to use in a GCM to compute HR profiles using band-models at the grid-scale ($100 \times 2^{\pm 1}$ km) is the 1D RTE, or some variation thereof that remains cost-effective.

Problem:

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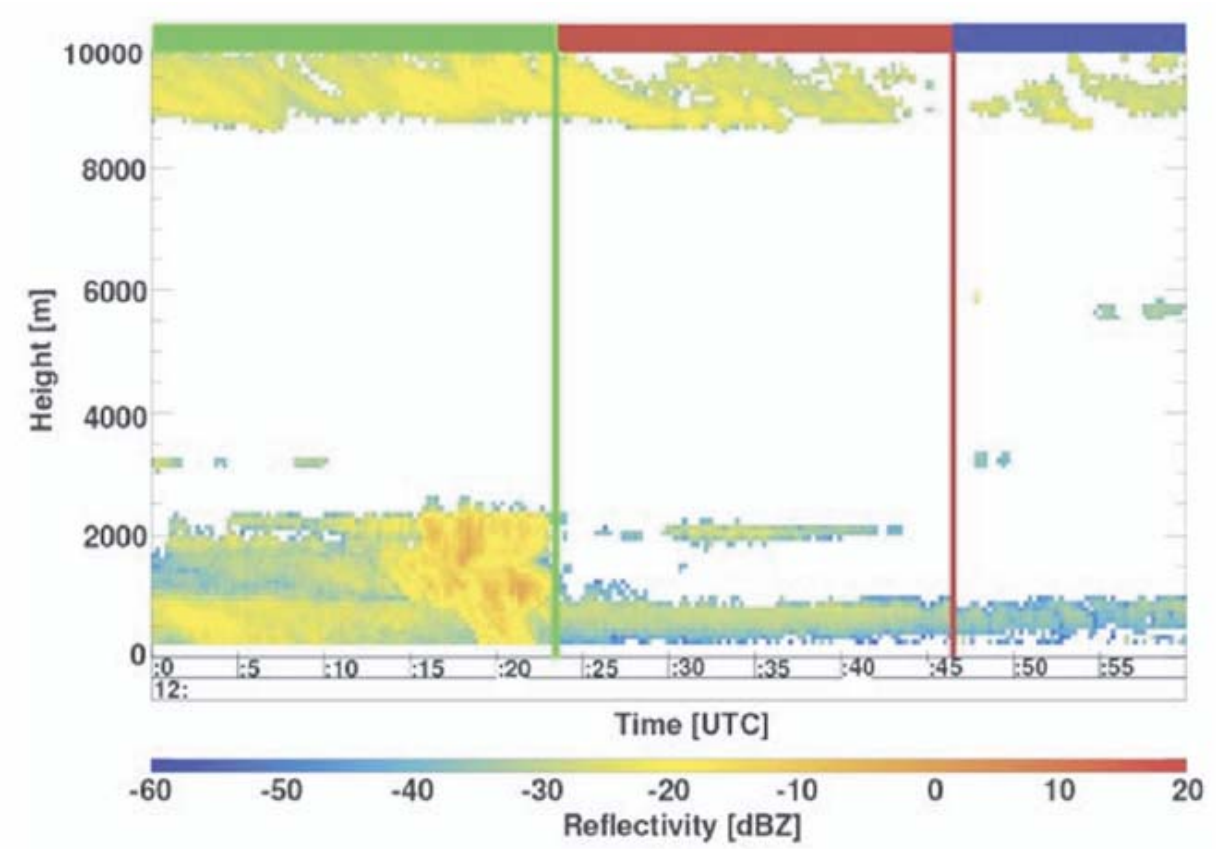
$$-\frac{\mathrm{d}F_\lambda}{\mathrm{dz}} = (1-\varpi_{0\lambda})\sigma_\lambda\left[J_\lambda - 4\pi B_\lambda\right]$$

Solution:

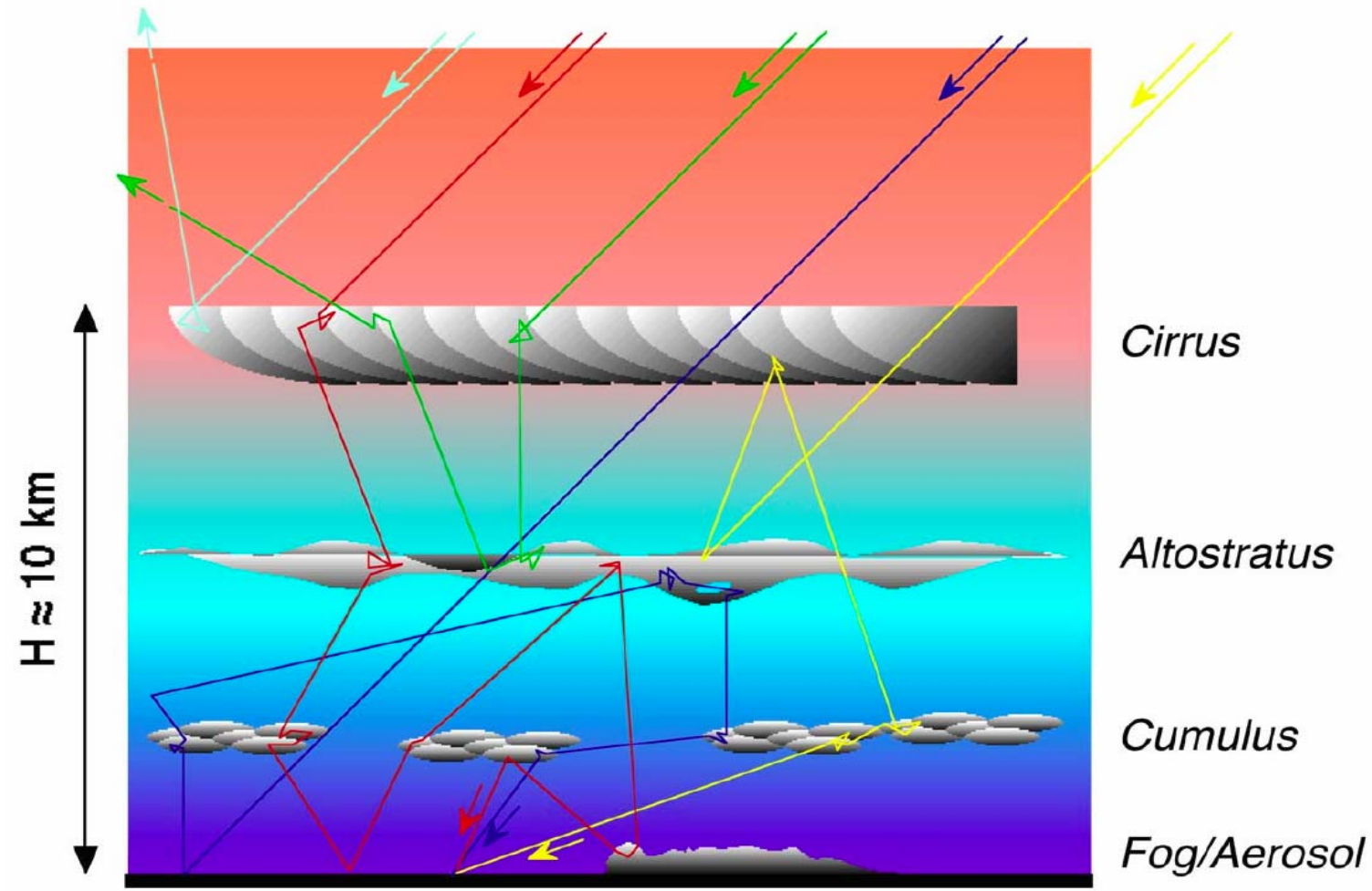
- **Separate spectral and spatial aspects**
  1. Build/refine spectral band models for BB integration
  2. Test them against line-by-line in plane-parallel geometry
  3. Validate with observations under clear-skies and single/unbroken cloud layers (à la ARESE)
- **Core problem of RT with *unresolved* spatial variability of clouds at one/few relevant λ's**
  1. Build/refine 1D-type RT models for domain-averages
  2. Test them against detailed 3D RT models
  3. Validate with observations under skies with multiple and/or broken cloud layers

Reality

More reality



Cartoon



1. <u>Build</u> GCM SW transport schemes (1D-type RT models for averages over large domains)

- **Conceptualize <u>unresolved</u> variability**
  - Cloud fraction, cloud aspect ratio
  - Internal variability?
  - Spatial correlations, including layer-to-layer overlap
  - Need other parameters?
- **Make reasonable statistical assumptions**
  - Fractals and power-laws
  - Exponentials, lognormals, Gamma, etc.
- **Use judicious approximations in the RT**
- **Write code … and *verify* it!**

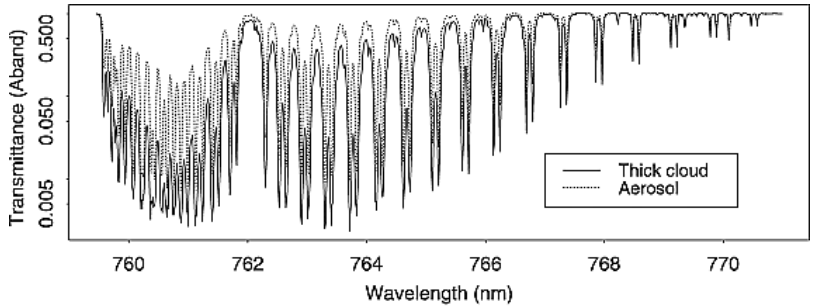
2. Test GCM SW transport schemes with detailed 3D RT

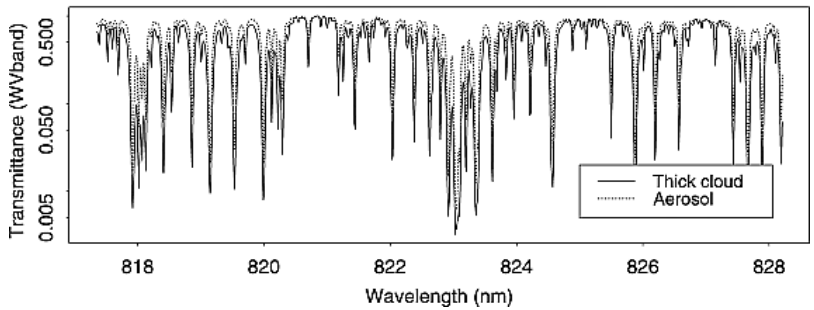
- **Need 3D clouds from observations**
  - Could use CSRM output [OK for starts]
  - Better to use imagers and profilers
    - Ground-based: ARM sites
    - Space-based: A-train, especially CloudSat/Calipso
  - Best to use ARM Volume-imaging Array (AVA)
    - Need confidence in extracting optical properties
- **Need *verified* 3D RT codes**
  - full cloudy column capability
  - use to “assimilate” available data
- **Compare 3D (spatially averaged) and 1D-type RT model outputs for given inputs**

3. <u>Validation</u> of GCM grid-scale SW transport schemes, a.k.a. "closure" experiments

- **Need new observations directly related to the domain-average HR profile predictions (i.e., output of new/improved SW transport codes) … at selected λ's**
- **Focus on process (physics) of absorption by interstitial gases in complex cloudy conditions**
  - **use O_2 A-band:** known amount and known cross-section, but unknown path distribution
  - from below (ARM), within (UAVs), and above (OCO) …
  - fully stress the 1D-type RT model: use scenarios with multiple and/or broken cloud layers

Differential absorption spectroscopy at high resolution





From: Min Q.-L., L. C. Harrison, P. Kiedron, J. Berndt, and E. Joseph, 2004: A high-resolution oxygen A-band and water vapor band spectrometer, *J. Geophys. Res.*, **109**, D02202, doi:10.1029/2003JD003540.

$$I(\nu)/I_0 = \exp[-\underbrace{\sigma_\nu}_{\text{x-section}} \times \underbrace{n}_{\text{density}} \times \underbrace{L}_{\text{pathlength}}]$$

$$\text{known/not}: \begin{cases} ? & \surd & \surd & \text{estimating molecular cross-sections in the laboratory} \\ \surd & ? & \surd & \text{monitoring amounts of chemical effluent in situ} \\ \surd & \surd & ? & \text{scattering/reflection diagnostics of media permeated with gas} \end{cases}$$

$$I(\nu) = I(k_\nu) = \boxed{I_0} \int_0^\infty \exp[-k_\nu L] \boxed{p(L)}\, \mathrm{d}L \text{ (equivalence "theorem")} \Rightarrow \langle L \rangle = -\left(\frac{\mathrm{d}}{\mathrm{d}k_\nu}\right) \ln I(k_\nu)$$

Temporal Green function of “3+1 D” RTE

Response of $\langle L \rangle_F$ (F=R,T) to a 3D redistribution of cloud water?

- **GSFC/LANL story:**
  - at fixed optical depth: $\langle L \rangle_T$ goes down, and T goes up.
  - Davis & Marshak (1997), anomalous/Lévy diffusion
  - Davis & Marshak (2002), Gamma-IPA argument
  - Davis (2006), anomalous transport (using a 1D Monte Carlo)
- **CSU story:**
  - at fixed optical depth: $\langle L \rangle_R$ down a little, and R down a lot.
  - Stephens & Heidinger (2000)
  - Heidinger & Stephens (2002), 3D Monte Carlo
  - Stephens, Heidinger & Gabriel (2005), 3D Monte Carlo

NB. precise references available upon request

Observational investigations of multiple scattering in clouds using A-band and path stats

- **Heidelberg group:**
  - Pfeilsticker et al. (1998), methodology
  - Pfeilsticker (1999), focus on variability with $\langle L \rangle_T$
  - Scholl et al. (2006), variability with $\langle L \rangle_T$ and $\langle L^2 \rangle_T^{1/2}$
- **SUNY-Albany group:**
  - Min & Harrison (1999), methodology
  - Min et al. (2001), focus on variability with $\langle L \rangle_T$
  - Min et al. (2004), extensions from $\langle L \rangle_T$ to $\langle L^2 \rangle_T$ & O_2 to H_2O
- **NOAA/AL group:**
  - Portman et al. (2001), focus on overcast skies
  - Daniels et al. (2006), extension to *liquid* H_2O (ie, $\langle L \rangle$ to $\langle n \rangle$)

Summary/Recommendations

- **Proposed performance test for SW schemes in GCMs**
  - Strip away spectral integration, and test it otherwise.
  - Use O2 absorption coefficients and cloud/surface properties at A-band (760-770 nm) from $P(z)$,$T(z)$.
  - Predict spectro-radiometric signal, or path stats.
  - Validation "metric:" compare with A-band observations, from ground (ARM) or space (OCO).
- **Required investments:**
  - Continuous A-band capability (2π and NFOV)
  - 3D cloud tomography: AVA, scanning μwave, etc.
  - "Operational" full-column 3D RT modeling (as part of a proposed ARM simulator)
- **Get More?**
  - From A-band: aerosol and cloud properties, new instrument synergies (especially MMCR).
  - From other investments: CSRM and sat-product validations.