An Unconventional 1D Model for Bulk Time-Dependent Radiation Transport in Complex Cloud Scenes,

With a Validation Test Using Ground-Based Observations of Solar Photon Path Length Statistics

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Summary

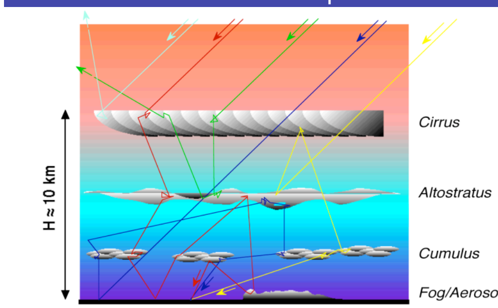
State-of-the-art O_2 A-band data favors the new 1D anomalous *transport* model over its anomalous *diffusion* predecessor.

Can this validation procedure be applied to operational GCM shortwave parameterizations?

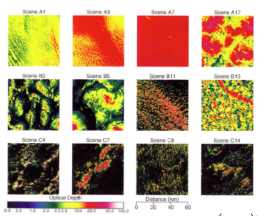
With high-resolution O_2 A-band spectroscopy, the atmospheric radiation community is opening an important new window into the solar heating of cloudy atmospheric columns. As an ARM-relevant application, we foresee new observational tests for the performance of GCM shortwave parameterizations in complex cloudy cases. More precisely, in combination with ARM's futuristic 3D take on clouds using multiple scanning radars (AVA, the ARM Volume-imaging Array), path length observations from the O_2 A-band will strongly constrain the challenging spatial part of the RT problem: cloud fractions, aspect ratios, correlations, overlap, etc. The spectral integration part of the shortwave parameterization problem (i.e., band models) has received so far more scrutiny and, at any rate, is best tested independently in order to disentangle the sources of modeling error and allocate effort at improvement.

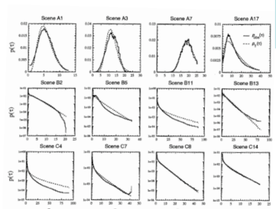
To illustrate the proposed testing procedure, we show numerical results from a new 1D radiative transfer (RT) model with an unconventional propagation kernel, i.e., the term in the integral RT equation determines the precise distribution of step sizes s between scatterings (as illustrated schematically in opposite figure). This kernel is controlled by a single new parameter a that, at least in principle, can be constrained by independent observations. In general, the kernel has a power-law tail in $s^{-(1+a)}$ but in the limit $a \to \infty$, it reverts to the standard exponential case. For transmitted light, we obtain a spectacular agreement with the most recent analyses of hi-resolution A-band data collected by the Heidelberg group that yield accurate 1st- and 2nd-order moments of solar photon path length.

The new 1D RT model leads, in the asymptotic limit of very large optical depth, to the preliminary model we have referred to in the past as "anomalous" or "Lévy" photon diffusion. But the new data shows that the conditions in the real cloudy atmosphere are not consistent with this asymptotic regime. The new transport model therefore supercedes the older diffusion model. By comparing the 1st- and 2nd-order moments, both empirical and theoretical estimates, we conclude furthermore that there is in fact not much new information about the structure of cloudiness in higher-order statistics, beyond the mean. Numerical simulations show that this sobering assessment does not carry over to reflected sunlight, so we can look forward to high-resolution A-band spectra from space when NASA's Orbiting Carbon Observatory (OCO) is launched into the "A train" constellation in 2008.



This cartoon illustrates how a 1D RT model with a propagation kernel (i.e., step distribution law) that is power-law rather than exponential can account for the strong-but-correlated spatial variability of cloudiness in the Earth's atmosphere. The power-law tail will indeed generate a mix of small, large and huge steps between scatterings or reflections.





LandSat cloud scenes analyzed by Barker et al. (1996) into p.d.f.'s for optical thickness τ, which turn out to be well modeled with Gamma laws.

If we take $p(\bar\sigma;\langle\bar\sigma\rangle,a) \approx \dfrac{1}{\Gamma(\nu)}\left(\dfrac{a}{\langle\bar\sigma\rangle}\right)^a \bar\sigma^{a-1}\exp[-a\dfrac{\bar\sigma}{\langle\bar\sigma\rangle}]$, where $a = \dfrac{1}{\langle\bar\sigma^2\rangle/\langle\bar\sigma\rangle^2-1}$, then mfp $\ell = \left\langle\dfrac{1}{\bar\sigma}\right\rangle = \dfrac{a}{a-1}\dfrac{1}{\langle\bar\sigma\rangle}$

and $\langle T_0(s)\rangle = \langle\exp[-\bar\sigma s]\rangle = \left(1+\dfrac{\langle\bar\sigma\rangle s}{a}\right)^{-a} = \left(1+\dfrac{s/\ell}{(a-1)}\right)^{-a}$.

New family of 1D integral RTEs parameterized by $1 < a < \infty$ (Davis, 2006):

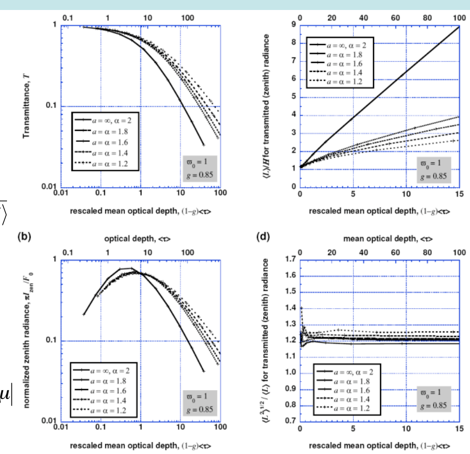
$$\begin{cases} I(z,\mu>0) = \varpi_0\int_0^z \left|\dfrac{\mathrm{d}}{\mathrm{d}s}\langle T_0(s)\rangle\right|_{s=(z-z')/\mu} \int_{4\pi} p(\Omega'\to\Omega)\, I(z',\Omega')\,\mathrm{d}\Omega' \dfrac{\mathrm{d}z'}{\mu} + Q(z,\mu) \\ I(z,\mu<0) = \varpi_0\int_z^H \left|\dfrac{\mathrm{d}}{\mathrm{d}s}\langle T_0(s)\rangle\right|_{s=(z'-z)/|\mu|} \int_{4\pi} p(\Omega'\to\Omega)\, I(z',\Omega')\,\mathrm{d}\Omega' \dfrac{\mathrm{d}z'}{|\mu|} \end{cases}$$

$$\begin{cases} T = \dfrac{2\pi}{F_0}\int_0^1 \mu I(z=h,\mu)\,\mathrm{d}\mu \\ R = \dfrac{2\pi}{F_0}\int_0^1 |\mu| I(z=0,-|\mu|)\,\mathrm{d}|\mu| \end{cases}$$

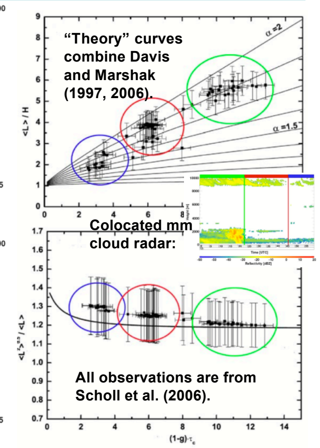
where $Q(z,\mu) = (\mu F_0/\pi) \times \langle T_0(s=z/\mu)\rangle$ for $\mu > 0$, and 0 otherwise.

$I_{zen} = \pi I(z=h,\mu=+1)/F_0$ ✔
$I_{nad} = \pi I(z=0,\mu=-1)/F_0$?

Asymptotic trends (a.k.a. anomalous diffusion model): $T \sim \tau_{tr}^{-\alpha/2}$ and $\langle L\rangle \sim h\times\tau_{tr}^{\alpha-1}$ as $\tau_{tr} \to \infty$ (Davis and Marshak, 1997)



Numerical solution of new 1D RTE, using a Monte Carlo scheme



Path length stats from A-band data

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