Computational 3D Diffusion Targeting Local Heating/Cooling Rates

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Related Website: `http://www.lanl.gov/Caesar/`

Abstract

Accurate modeling of radiative energy transport through cloudy atmospheres is necessary for both climate modeling with GCMs (Global Climate Models) and remote sensing. The aspect ratio (horizontal/vertical) of the mesh cells used for radiation modeling in GCMs is so large that the cells are effectively shaped like square "pancakes", with rough dimensions of 100s of km horizontally and 1 km vertically. In this situation, a reasonable and commonly-used approximation known as the Independent Column Approximation (ICA) neglects transport through the sides of the pancake-shaped cells and treats each column of cells (or "stack of pancakes") as an independent one-dimensional (1D) problem. More recently, the pancakes have been divided into a number of optically distinct sub-cells (e.g., cloudy vs. clear regions) where the ICA is applied; then averaging is performed over the sub-cells. However, in order to resolve the detailed dynamics of convection and cloud processes, several ARM science teams have invested heavily into cloud[-system] resolving models (C[S]RMs) and large-eddy simulations (LESs) where the elementary cells now have aspect ratios close to unity. The multi-layer ICA is still used in such models to compute the radiative transfer but it is no longer a reasonable approximation for a refined, aspect ratio=1 mesh due to important horizontal fluxes that cannot be modeled via a cyclic boundary condition. True three-dimensional (3D) radiation transport modeling is required to derive the proper spatial distribution of radiant energy deposition.

In this poster we describe the development of a 3D radiative transfer modeling capability for transport through given 3D media, eventually in the course of a dynamical cloud modeling run, based on photon diffusion theory. At least inside cloudy regions, this modeling framework is accurate yet efficient for solar heating and thermal cooling rates. This capability is being developed in the Caesar Code Package (`http://www.lanl.gov/Caesar`), which is a parallel, object-based computational physics development environment. The package uses levelized design, Design by Contract™, extensive unit testing, and the ideas of literate programming to generate rich documentation from the source. Results from preliminary calculations are shown, drawn in particular from the Intercomparison of 3D Radiation Codes (I3RC) protocol.

Justification

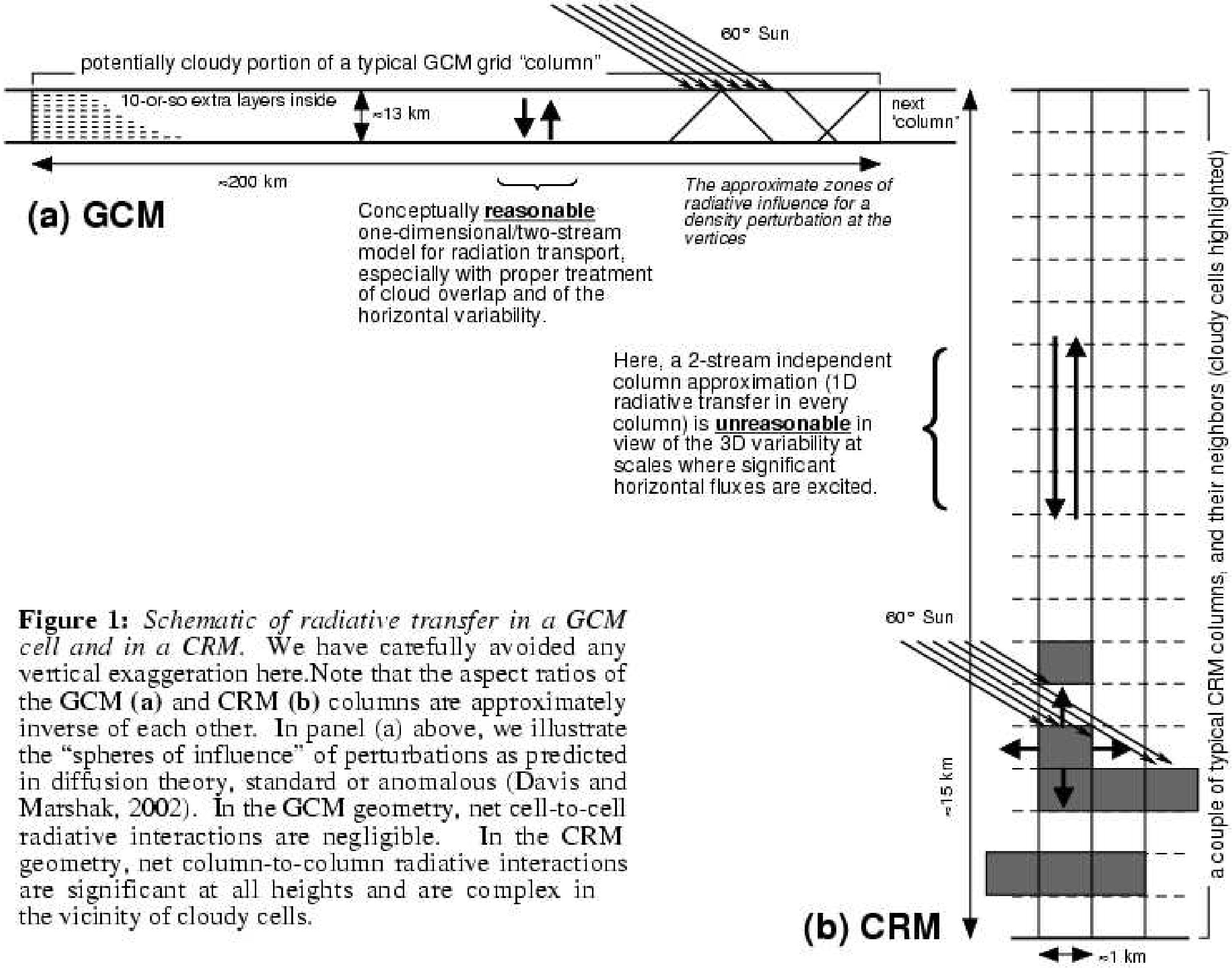
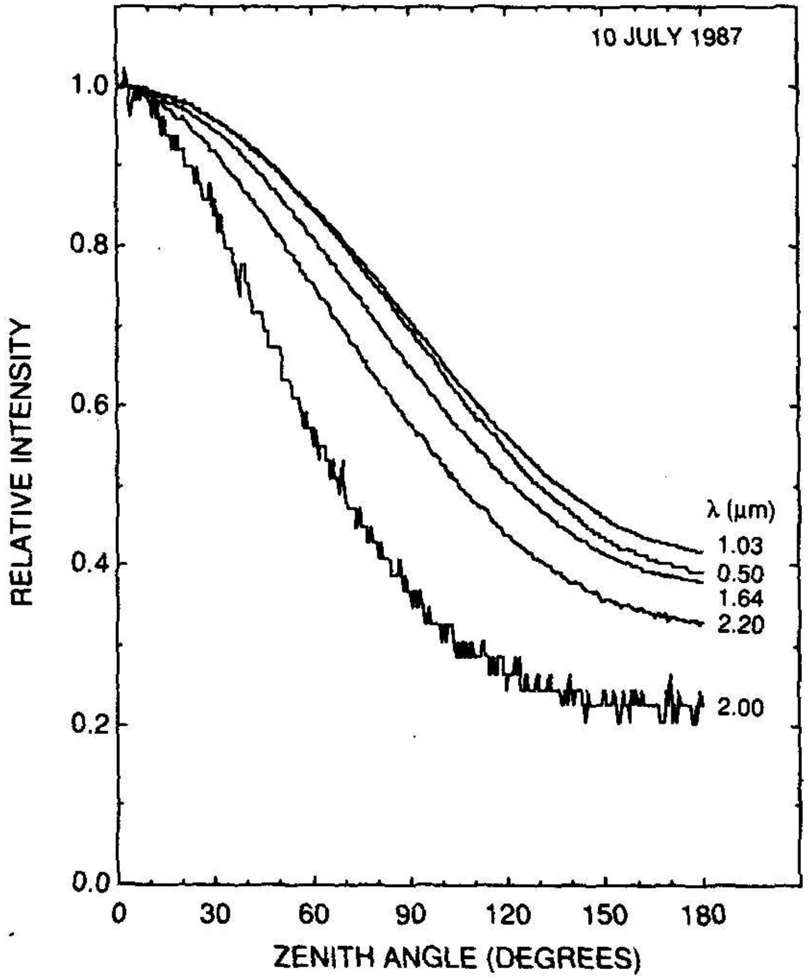


Figure 1: *Schematic of radiative transfer in a GCM cell and in a CRM.* We have carefully avoided any vertical exaggeration here.Note that the aspect ratios of the GCM **(a)** and CRM **(b)** columns are approximately inverse of each other. In panel (a) above, we illustrate the "spheres of influence" of perturbations as predicted in diffusion theory, standard or anomalous (Davis and Marshak, 2002). In the GCM geometry, net cell-to-cell radiative interactions are negligible. In the CRM geometry, net column-to-column radiative interactions are significant at all heights and are complex in the vicinity of cloudy cells.

Justification (cont.)

Spectral radiance ratio $I_\lambda(\theta)/I_\lambda(0)$ for the indicated values of λ observed at the position of the U. of Washington's Convair C-131A at 09:37 PDT along its flight inside a marine stratocumulus layer on July 10, 1987 (during FIRE) in the Cloud Absorption Radiometer's scan plane, perpendicular to the line-of-flight. For all but $\lambda = 2$ μm we have a clear diffusion-domain dependence in $\cos\theta$. For $\lambda = 2$ μm a CO_2 absorption feature leads to less light (increased noise) and the requirement of higher-order spherical harmonics to model the radiance. This plot is reproduced from Fig. 6 by King, Radke and Hobbs (*J. Atmos. Sci.*, **47**, 894-907, 1990). For more on the CAR instrument, see the URL http://car.gsfc.nasa.gov/.



Atmospheric Radiation Model Equation Set

$$-\overrightarrow{\nabla} \cdot D \overrightarrow{\nabla} J + (1 - \varpi_0)\, \sigma J = \varpi_0 \sigma e^{-\tau_0}$$

Which can be written

$$\overrightarrow{\nabla} \cdot \overrightarrow{F} + (1 - \varpi_0)\, \sigma J = \varpi_0 \sigma e^{-\tau_0}$$

$$\overrightarrow{F} = -D \overrightarrow{\nabla} J$$

Where

$$J = \text{Intensity} = \int_\Omega I\,(x, z, \Omega)\; d\Omega\ .$$

$$\overrightarrow{F} = \text{Flux} = \int_\Omega \Omega I\,(x, z, \Omega)\; d\Omega\ .$$

$$D = \text{Diffusion Coefficient} = \frac{1}{3\sigma(1-\varpi_0 g)}\ .$$

$$\sigma = \text{Extinction or Total Cross-Section.}$$

$$Q = \text{Intensity Source Term} = \varpi_0 \sigma e^{-\tau_0}.$$

$$\varpi_0 = \text{Single-Scattering Albedo.}$$

$$\tau_0 = \text{Optical Depth.}$$

$$g = \text{Mean cosine of the scattering angle.}$$

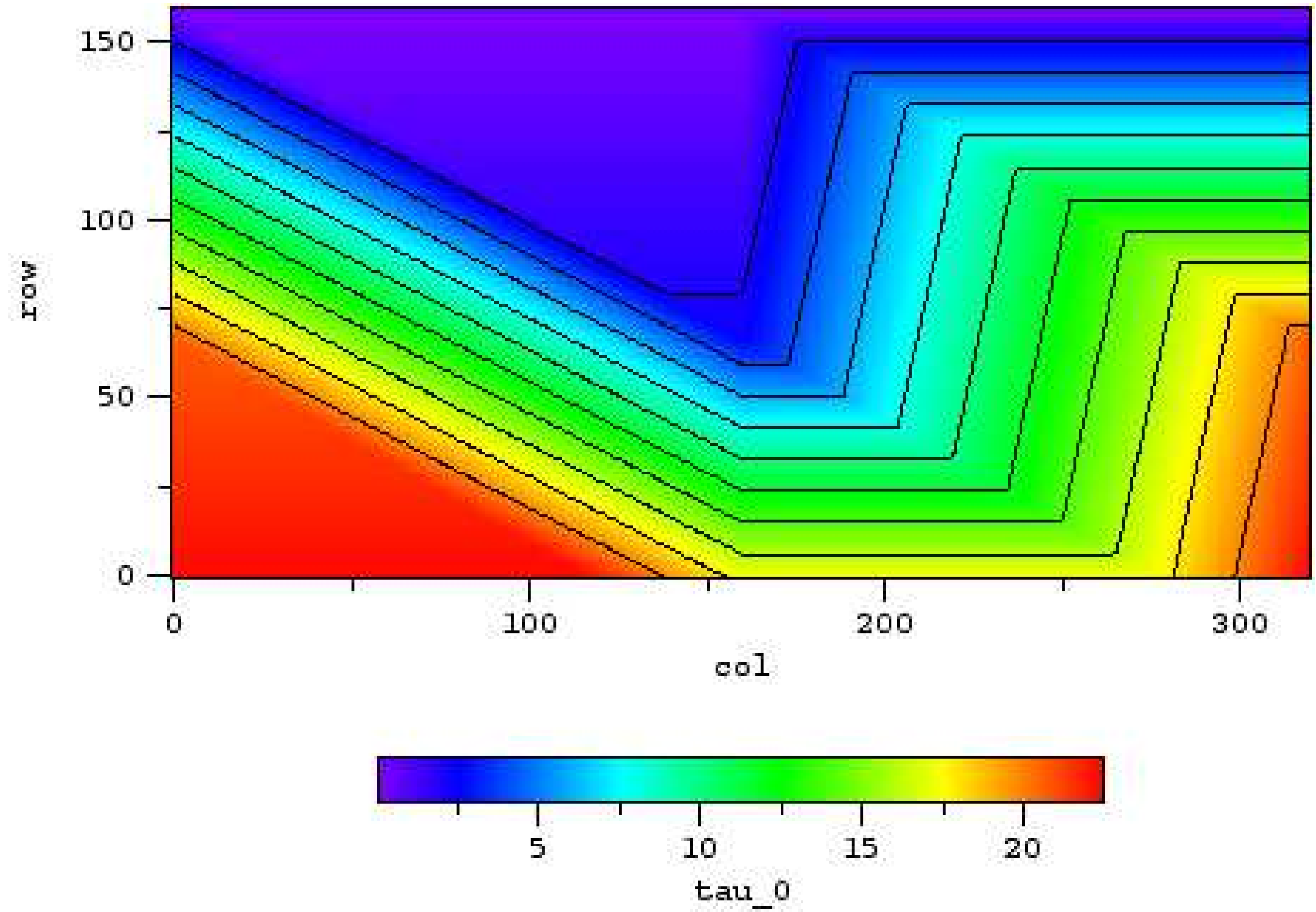
Intercomparison of 3D Radiation Codes Project (I3RC) Case 1: Square-Wave Cloud

- Aspect ratio of 2: $h = 0.25$ km, $L = 2h$.
- Boundary conditions: Periodic at $x = 0$ and $x = L$, Vacuum at $z = 0$ and $z = h$.
- Optical depth τ of 2 for $x < L/2$; τ of 18 for $x > L/2$.
- Two solar illumination angles, 0° ($\mu_0 = 1$) and 60° ($\mu_0 = 1/2$).
- Two single-scattering albedos, $\varpi_0 = 1$ and $\varpi_0 = 0.99$.
- Volume source term, $Q(x, z)$, is the scattering from an uncollided flux calculation, $\varpi_0 \sigma e^{-\tau_0}$.

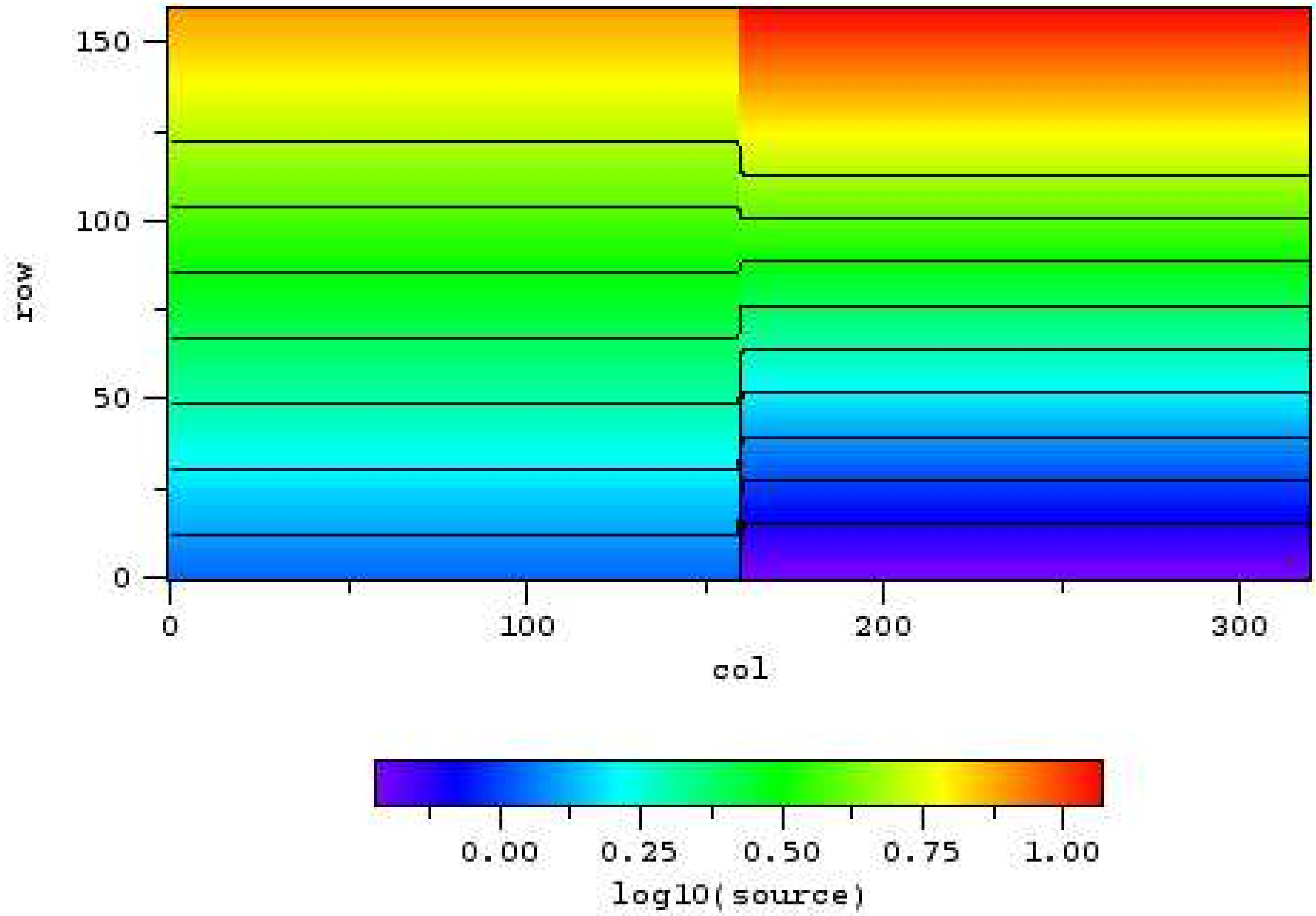
Output of Interest

$$\begin{aligned}
\tau_0(x,z) &= \text{Optical Depth for the Incident Solar Radiation, used in the uncollided flux calculation.} \\
Q(x,z) &= \varpi_0 \sigma e^{-\tau_0} = \text{Intensity Source Term from the isotropic scattering of the uncollided flux.} \\
J(x,z) &= \text{Intensity.} \\
q_{rad}(x,z) &= (1-\varpi_0)\,\sigma J(x,z) = \text{Heating Rate.} \\
R(x) &= \overrightarrow{F} \cdot \hat{n}|_{\text{top}} = \text{Normal Flux directed outwards at the top of the problem.} \\
T(x) &= \overrightarrow{F} \cdot \hat{n}|_{\text{bottom}} = \text{Normal Flux directed outwards at the bottom of the problem.} \\
A(x) &= \int_z (1-\varpi_0)\,\sigma J(x,z)\,dz = \text{Column Absorption.} \\
H(x) &= 1 - R(x) - T(x) - A(x) = \text{Horizontal Flux Divergence.}
\end{aligned}$$

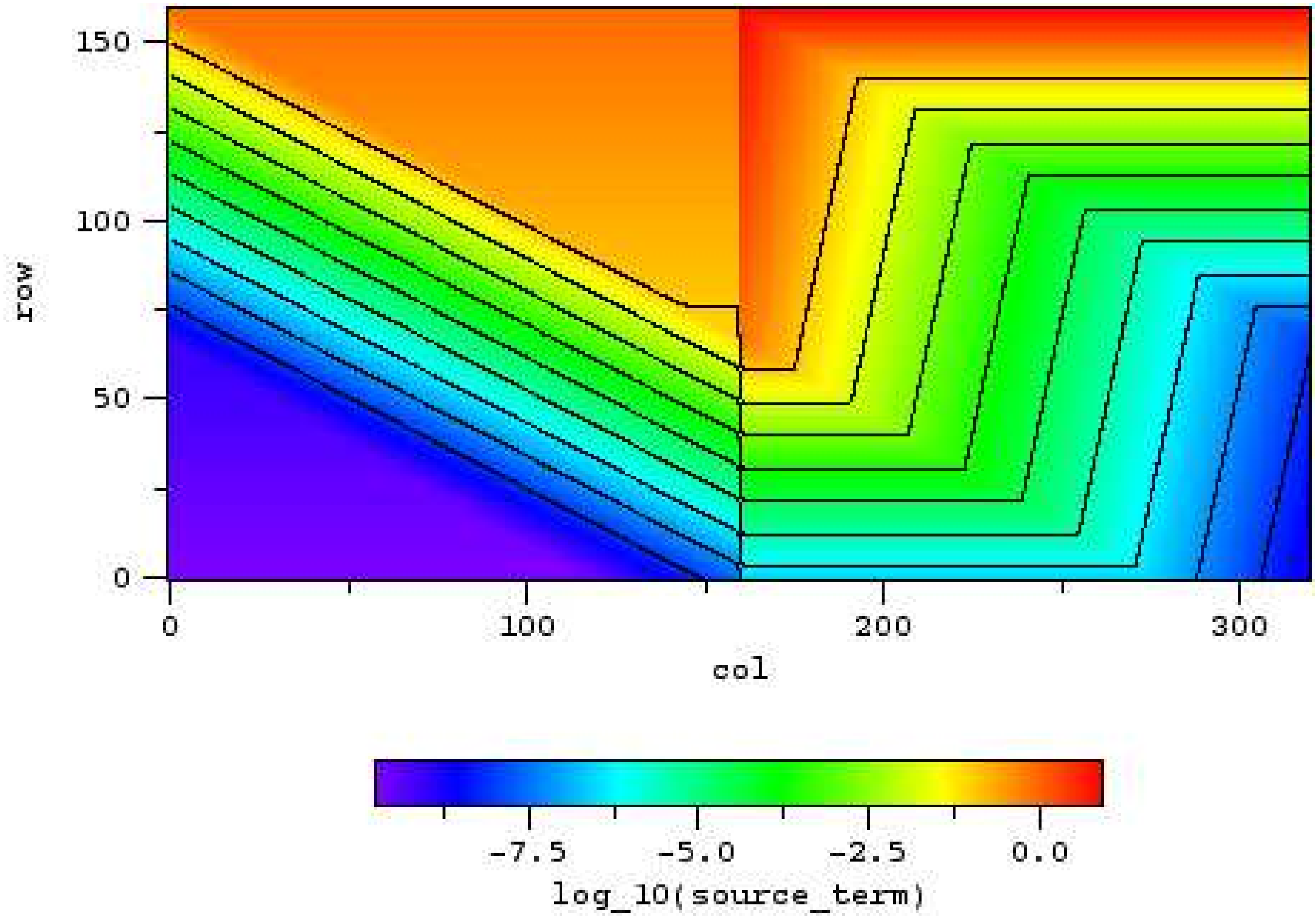
Optical Depth, $\tau_0\,(x,z)$, $\theta = 60^\circ$



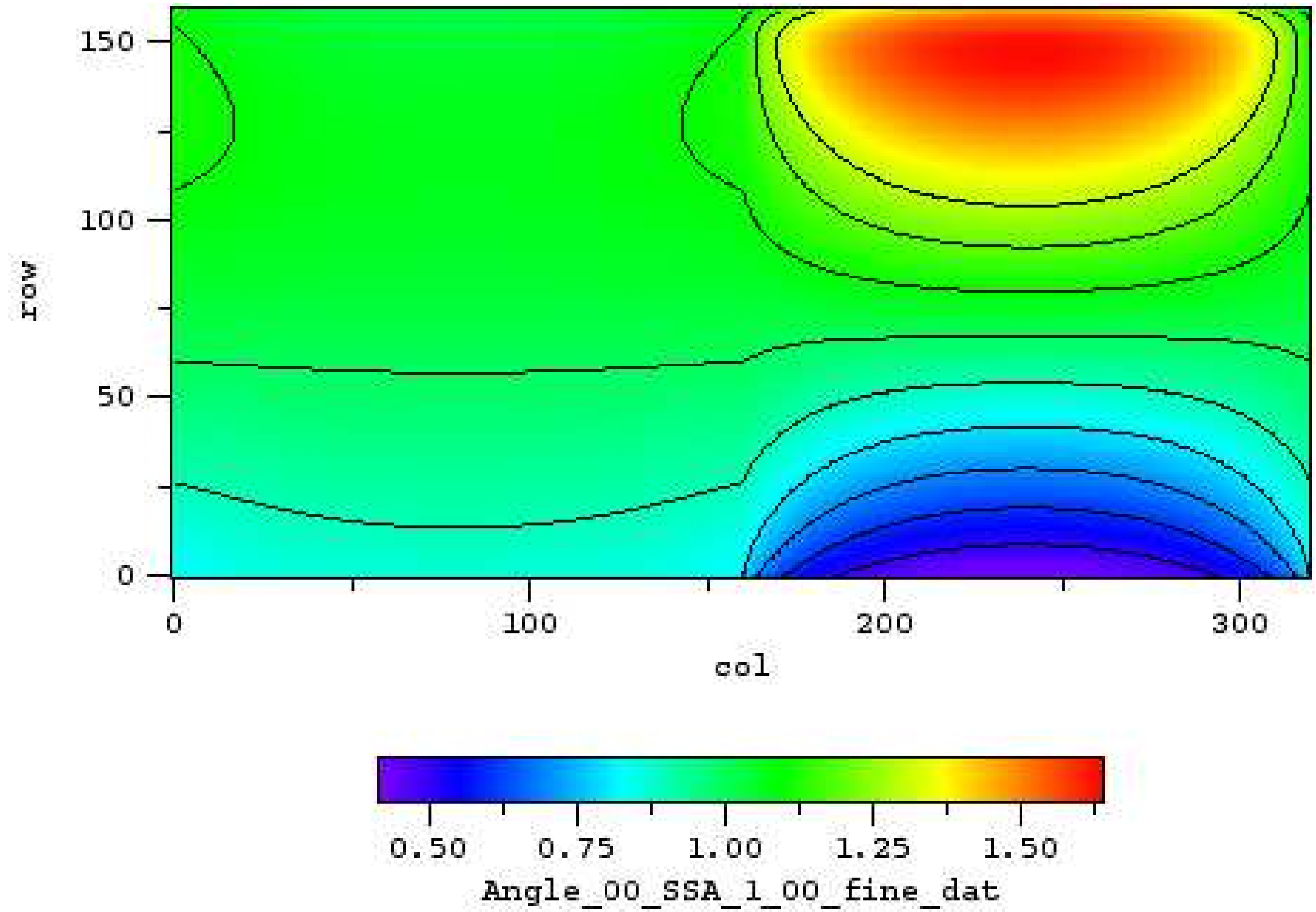
Source, $Q(x, z) = \varpi_0 \sigma e^{-\tau_0}$, $\theta = 0^\circ$



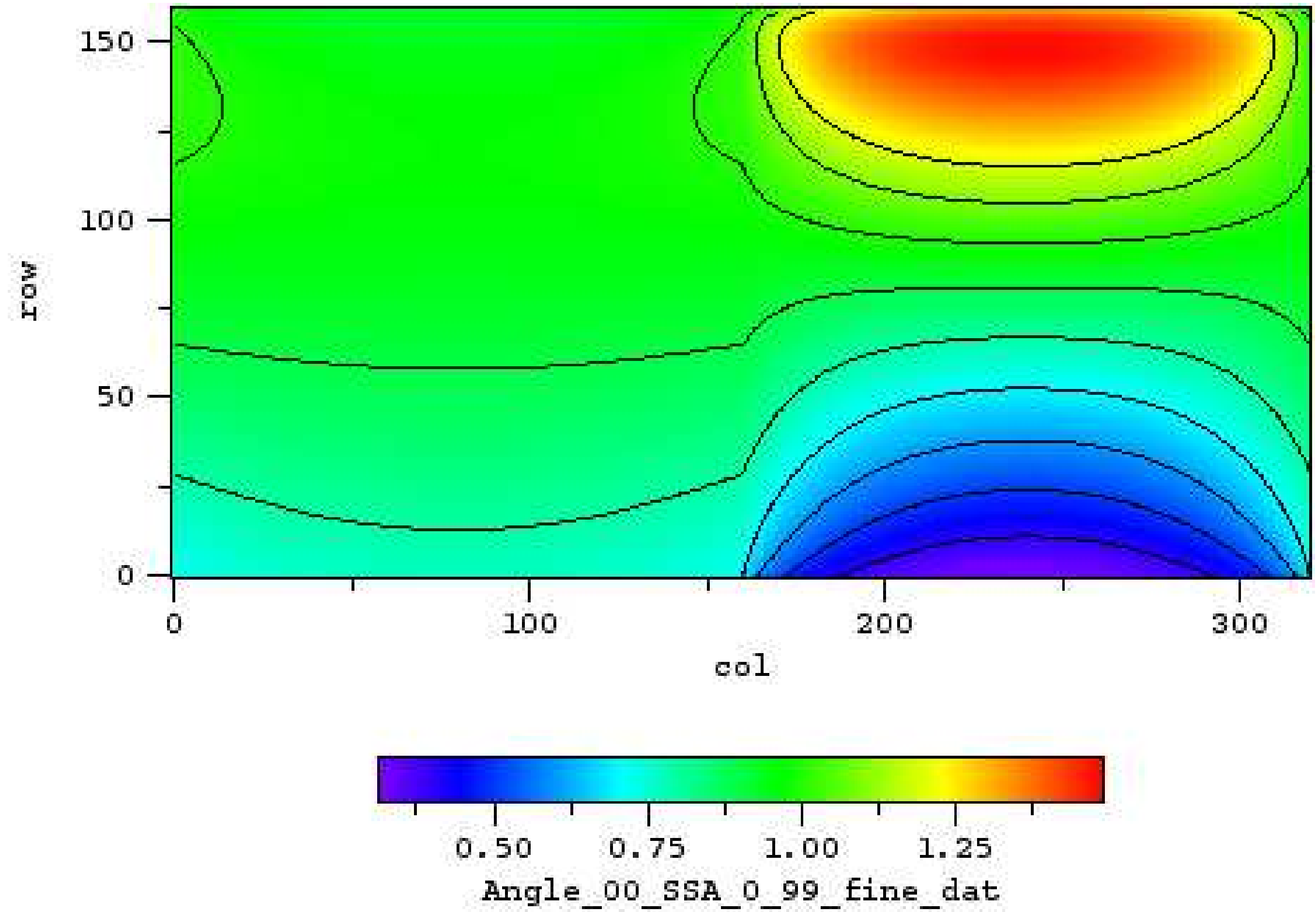
Source, $Q(x,z) = \varpi_0 \sigma e^{-\tau_0}$, $\theta = 60°$



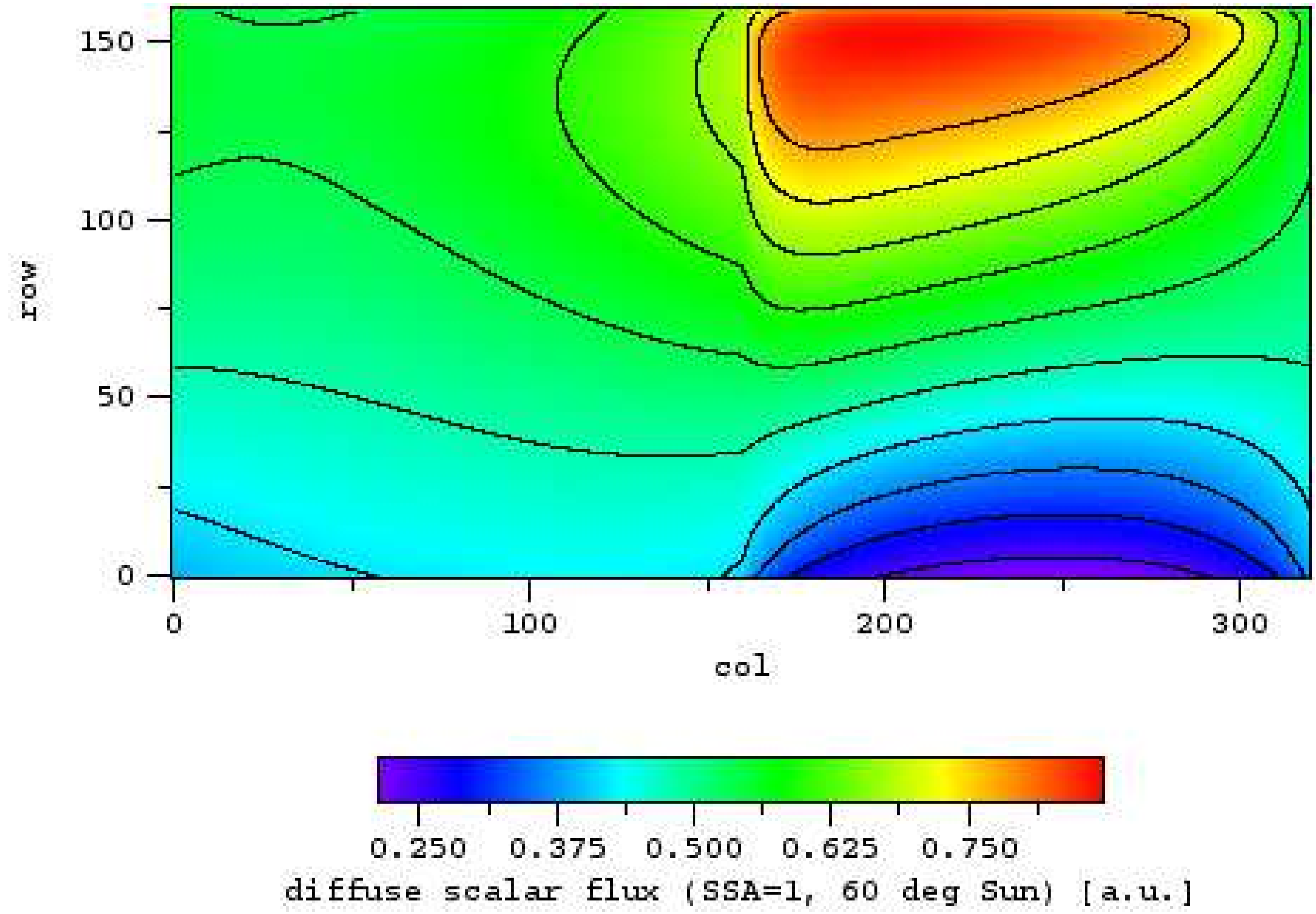
CÆSAR Results: $J\,(x, z)$, $\theta = 0°$, ϖ_0=1.00



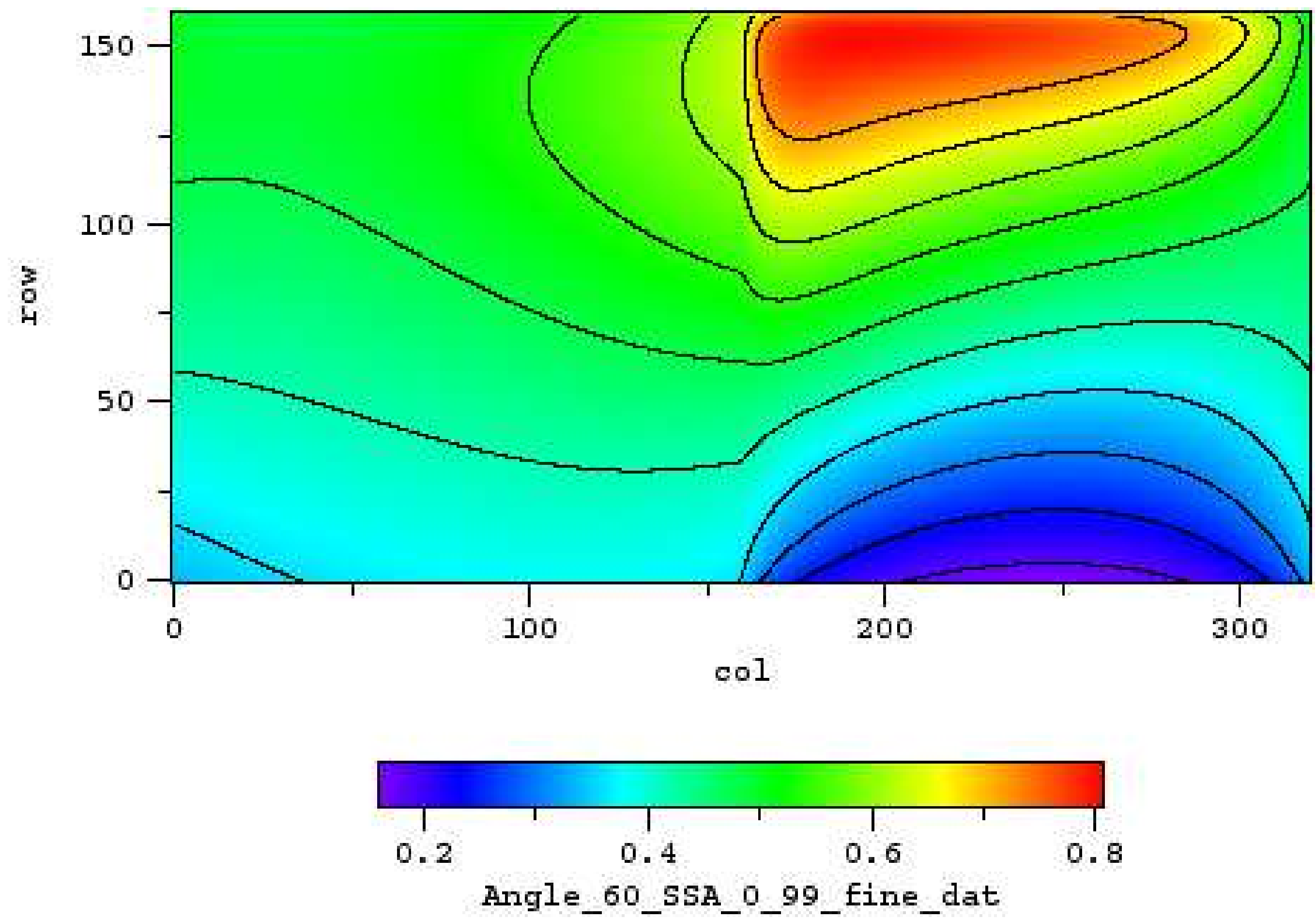
CÆSAR **Results:** $J\,(x,z)$, $\theta=0^\circ$, ϖ_0**=0.99**



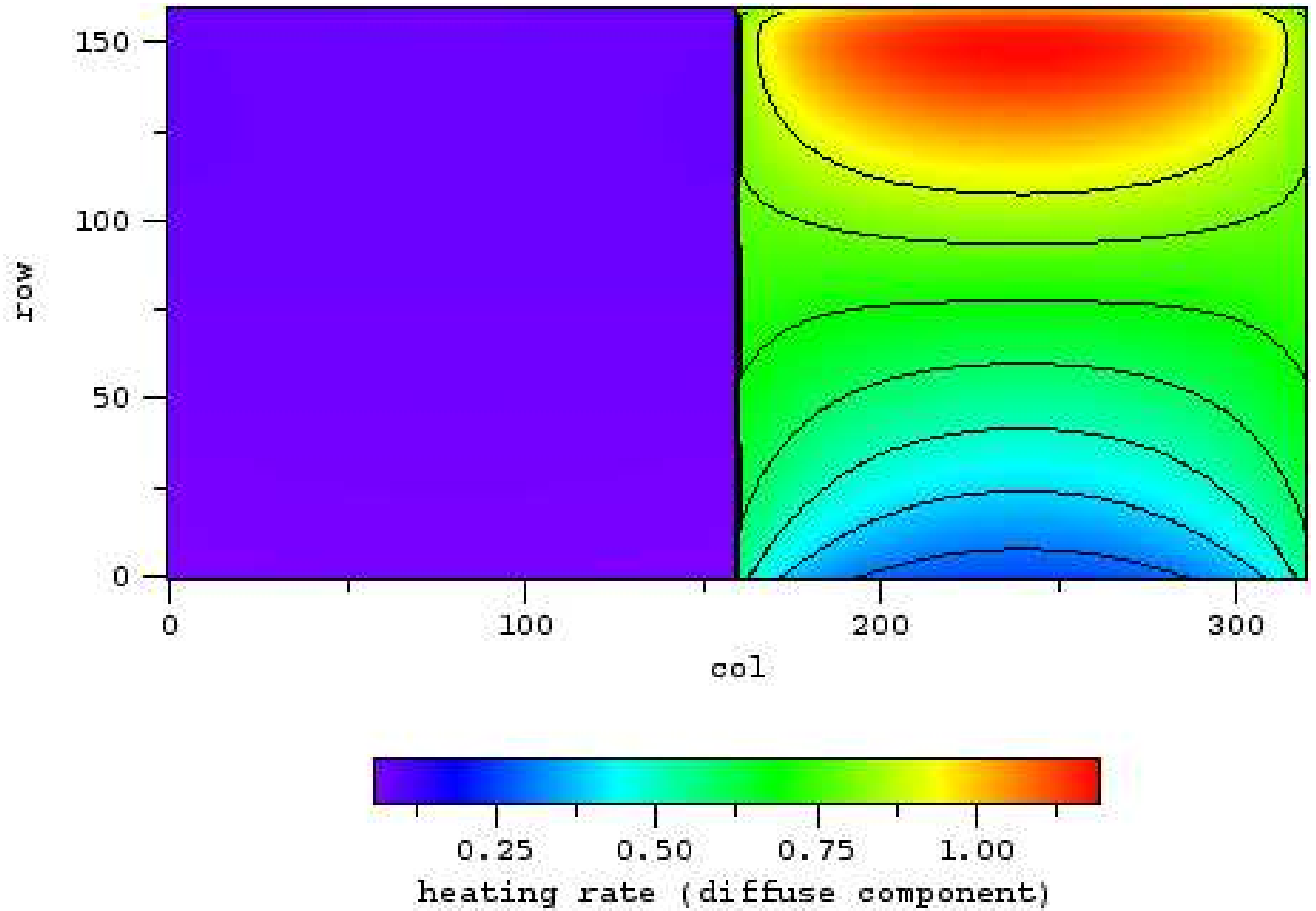
CÆSAR **Results:** $J\,(x,z)$, $\theta = 60°$, ϖ_0**=1.00**



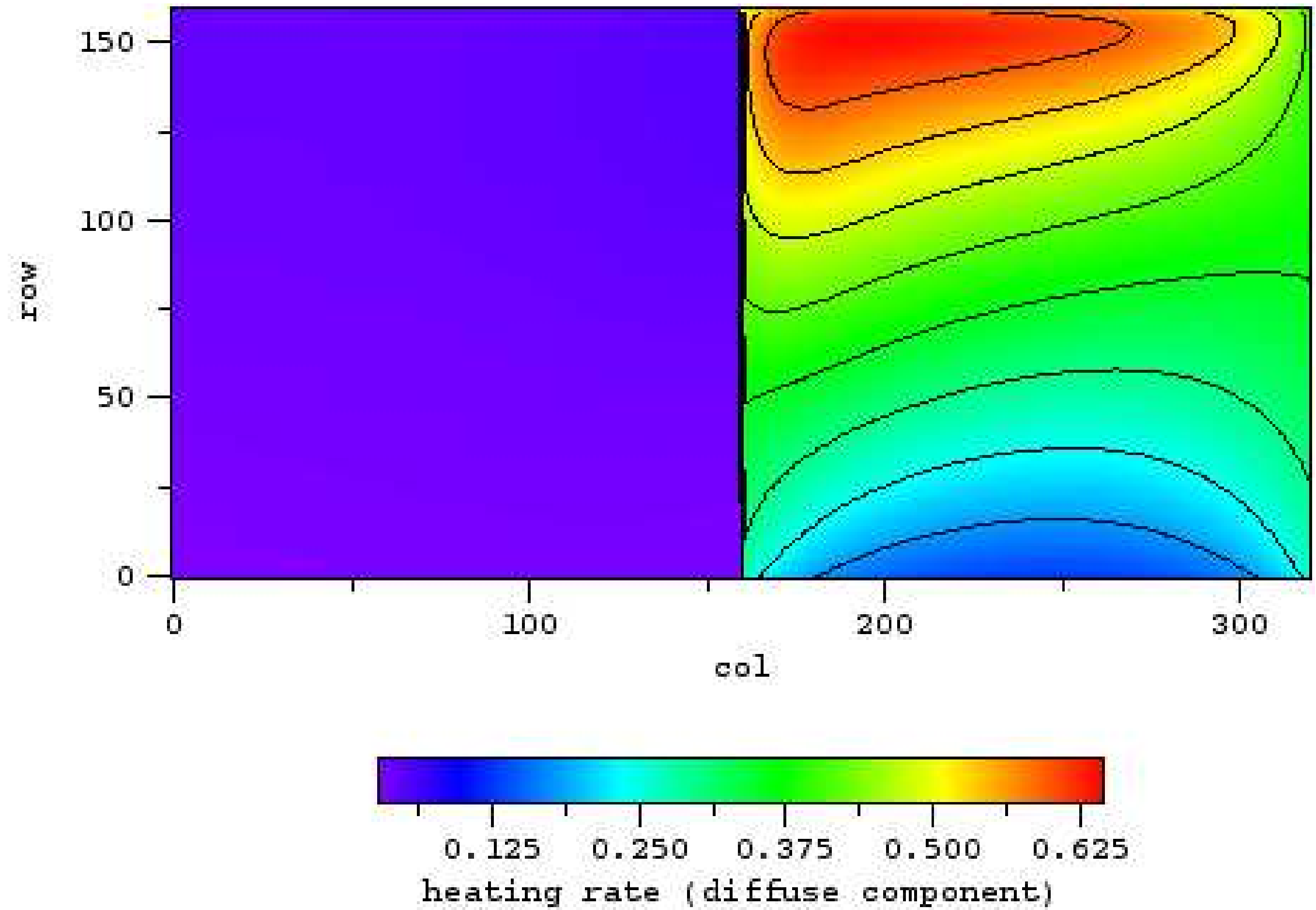
CÆSAR Results: $J\,(x,z)$, $\theta = 60°$, ϖ_0=0.99



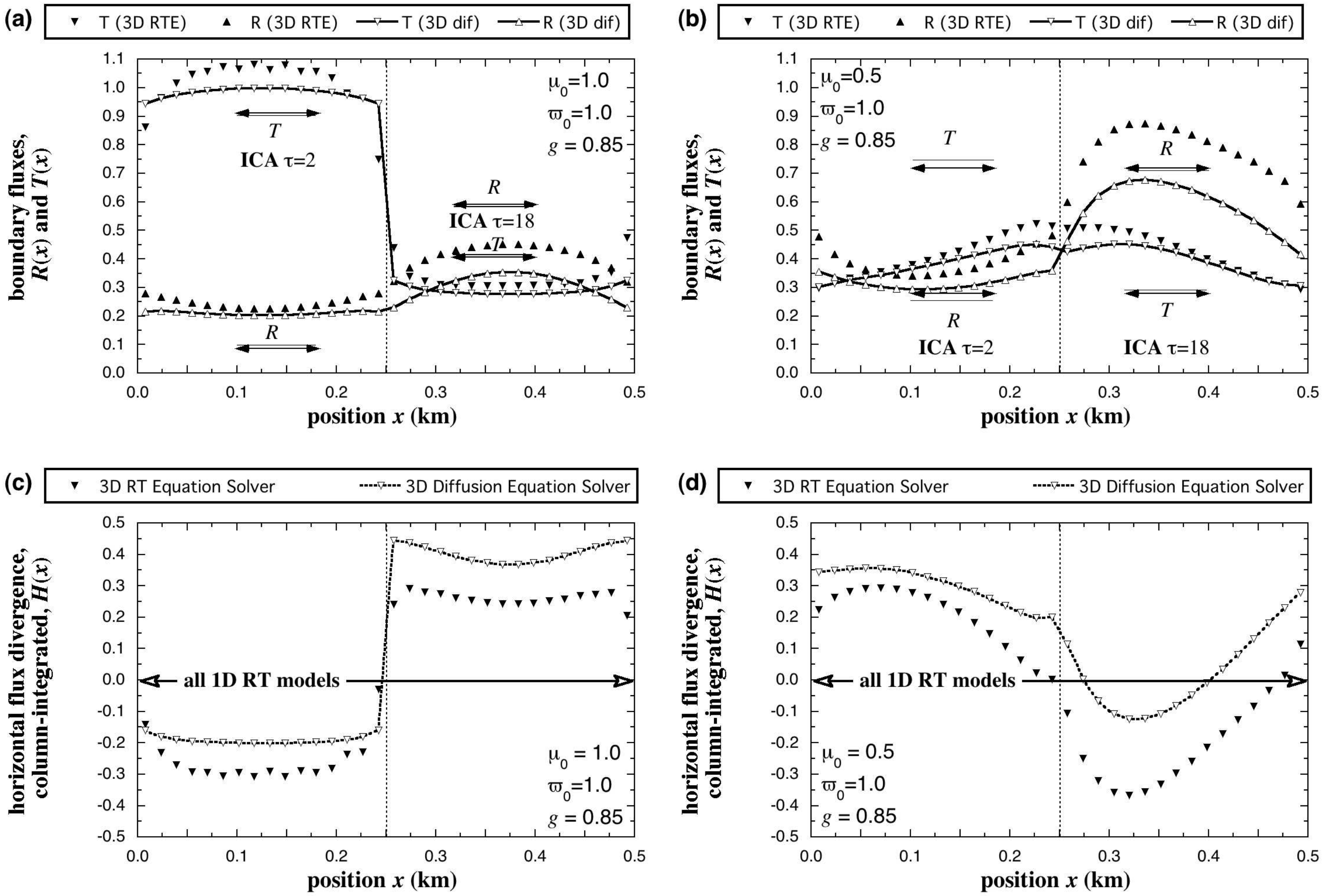
CÆSAR Results: Heating Rate, $q_{rad} = (1 - \varpi_0)\,\sigma J\,(x, z)$, $\theta = 0^\circ$, ϖ_0=0.99



CÆSAR Results: Heating Rate, $q_{rad} = (1 - \varpi_0)\, \sigma J\,(x, z)$, $\theta = 60°$, ϖ_0=0.99



Boundary Fluxes $(R(x), T(x))$ and Horizontal Flux Divergence $(H(x))$



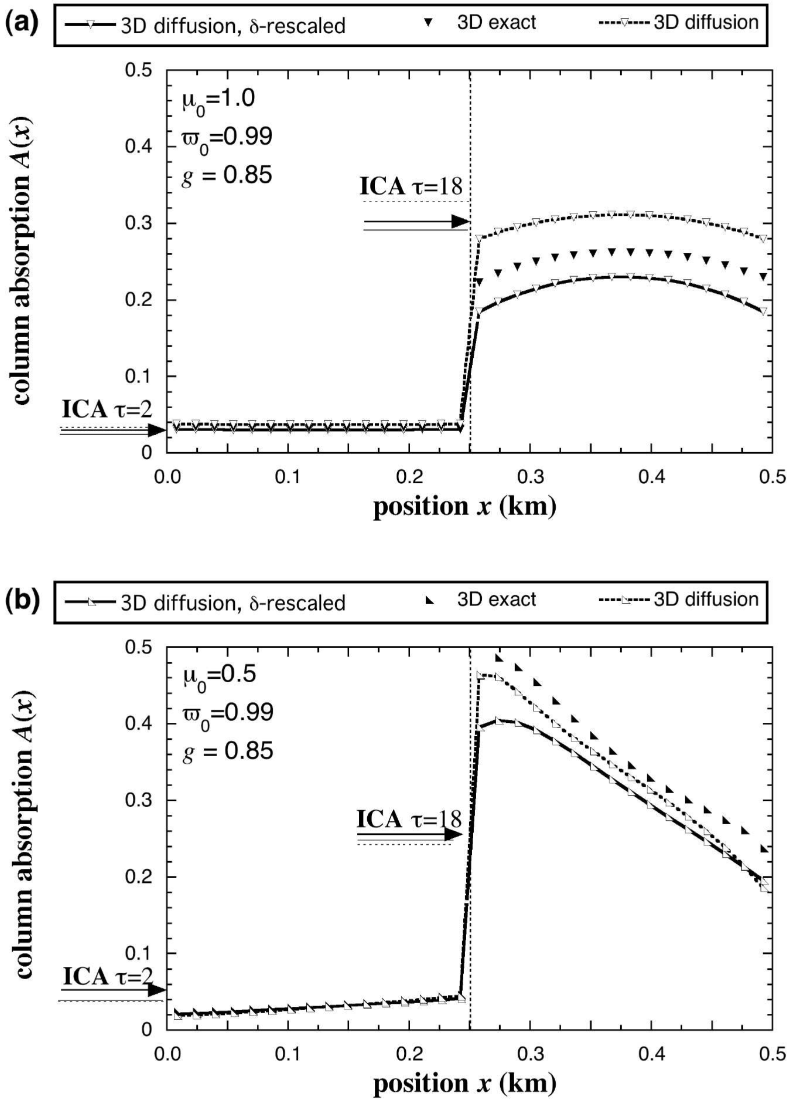
Caption on next slide.

Boundary Fluxes $(R(x), T(x))$ and Horizontal Flux Divergence $(H(x))$ (cont.)

Flux fields for the I3RC "Case 1" square-wave cloud in the conservative ($\varpi_0 = 1$) case. Benchmarks for comparison with the 3D diffusion theoretical results (ED3D code) are: a full 3D RT equation solution (TWODANT code), and the ICA (using both the 1D RT equation and the analytical diffusion solution). Two solar illumination angles and two boundary fluxes $\{R(x), T(x)\}$ are considered along with the "horizontal fluxes" (or apparent absorption) $H(x) = 1 - R(x) - T(x)$: **(a)** $R(x), T(x), \theta_0 = 0°$, **(b)** $R(x), T(x), \theta_0 = 60°$ **(c)** $H(x), \theta_0 = 0°$, and **(d)** $H(x), \theta_0 = 60°$. In spite of the mirror symmetry of cloud structure around the vertical planes at $x = 0.125$ and 0.375 km, the uniform $\mu_0 = 1$ illumination and the angularly-integrated response, we note a minor asymmetry in the results from TWODANT. That is because 3D RT equation solvers based on a grid proceed by "sweeps" in a given direction and iterations. This gives an indication of the residual numerical error.

Column Absorption $(A(x))$

Same as previous figure but for column absorption (when $\varpi_0 = 0.99$). Here, the 1D and 3D diffusion results distinguish between with (thin solid line) and without (thin dashed line) the δ-rescaling. Two solar illumination angles are again considered: **(a)** $A(x), \theta_0 = 0°$, and **(b)** $A(x), \theta_0 = 60°$, both with and without δ-rescaling (same visual encodings but thick lines). In the former case, δ-rescaling helps, not in the latter. To appreciate the potential dynamical effect of the bias caused by the ICA assumption, we note that the local solar heating rate can be off by as much as a factor of 2. This happens near the strong gradients when the illumination is significantly off-zenith. By comparison, the error induced by the diffusion approximation is less than ≈10%.



CÆSAR Physics Description

- General Diffusion Code, applied to Atmospheric Radiation
- Multiple Dimensionality (1-D, 2-D, 3-D)
- Uniform Mesh
- Second-Order Convergent Diffusion Discretizations
- Parallel, written in Fortran 90
- Based on earlier Augustus (P-1) and Spartan (SP_N) codes
- Future: Unstructured Hexahedral Meshes, Polyhedral Meshes, Multigroup, Tensor Diffusion, Mixed Cells, Transport

CÆSAR Coding Description

- Written in Fortran-90, preprocessed by Gnu m4.
- Object-based, as close as possible to object-oriented in Fortran-90.
- Both parallel and serial versions.
- Completely levelized design; no dependency loops between classes or modules.
- Extensive use of Design by Contract to verify the behavior of all procedures.
- Complete unit testing to certify all classes.
- Uses the ideas of literate programming to generate documentation (in HTML, PostScript and PDF) from comments included in the code, via the Document Package.

CÆSAR Documentation

Making use of the capabilities of **`Document`**, LaTeX and LaTeX2**`HTML`**, the CÆSAR Code documentation has these features:

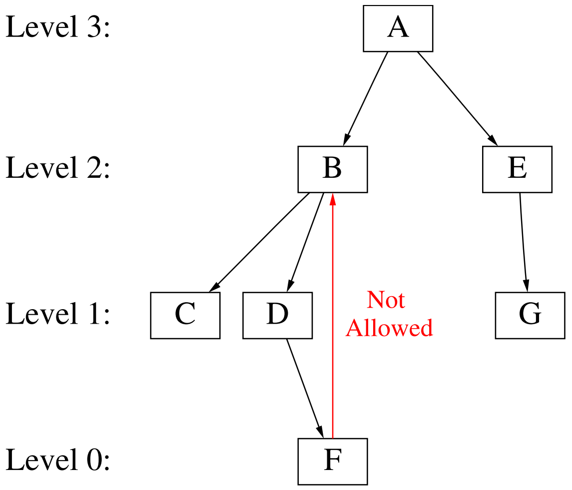
- Hardcopy *and* HTML versions from a single source, which is collocated with the source code
- Multiple output files and source languages (f90, gm4)
- Graphics, equations, code listings easily included
- Automatic table of contents (hyperlinked in HTML)
- Semi-automatic indexing (hyperlinked in HTML)
- Items included in only LaTeX or HTML version
- Automatic navigation tools for HTML (Next, Up, Previous, Contents, and Index links on every page)
- Hyper references (e.g. "see Section 3.2" becomes a link)
- External HTML links (e.g. to related presentations, papers, packages or projects)
- Level 6 Documentation — User's Manual, Code Manual, Methods Discussion and Code Listing in Hardcopy and Hyperlinked HTML via Literate Programming

Unit Testing / Levelized Design

Basic Idea of Unit Testing: Each component is tested in isolation – only components that have been previously tested may be included.

Basic Idea of Levelized Design: Each component depends only on components that are at a lower level – no feedback or circular designs.

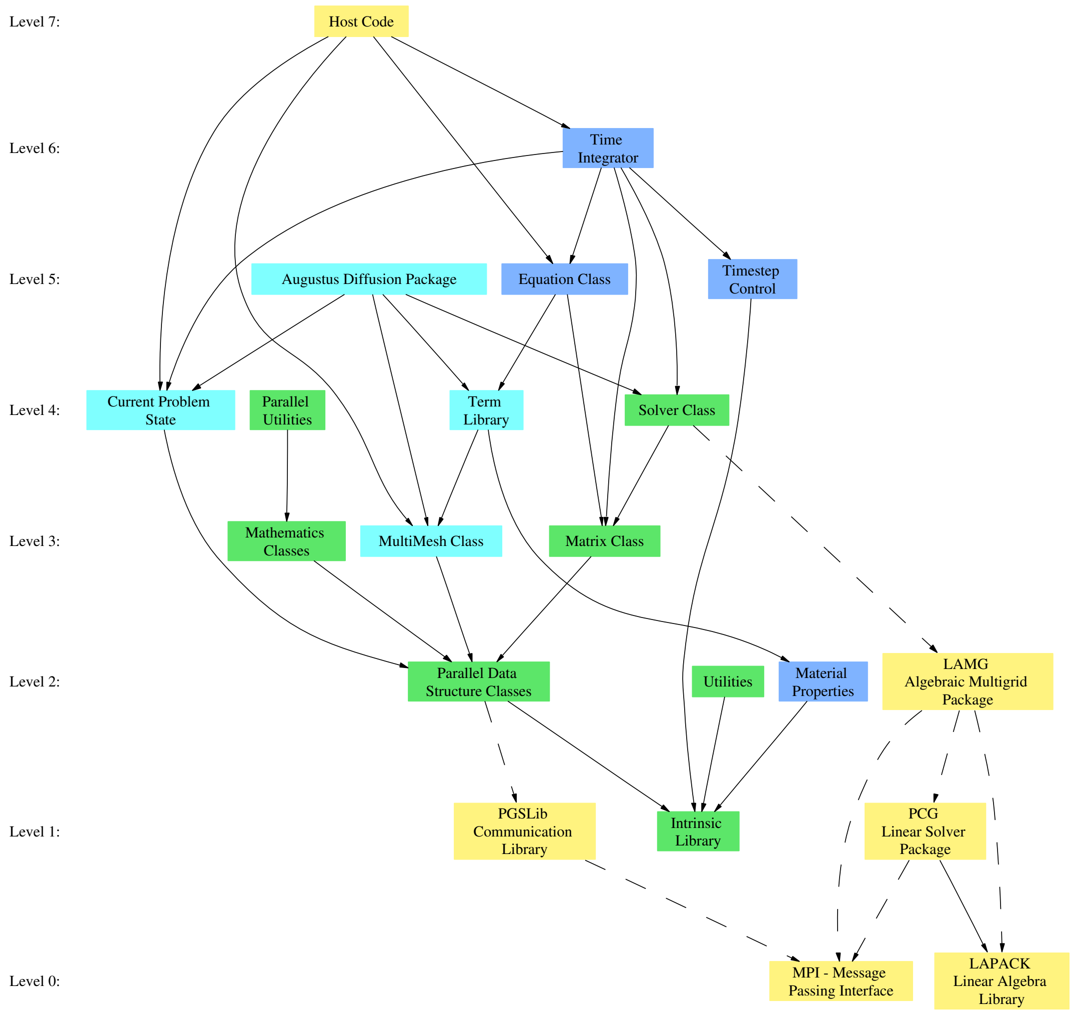
Example:



Why is a Levelized Design desirable?

- Necessary for incremental compilation in F90 if dependency is via "use association"
- Makes Unit Testing possible

Current Levelized Design for CÆSAR



Summary

The Caesar diffusion package has been used to model 2D diffusion in an atmospheric radiation model, making use of an uncollided flux for an isotropic scattering source term. The model has exposed limitations of the commonly used Independent Column Approximation (ICA).

The CÆSAR diffusion package employs many of the latest ideas in software design:

- Literate Programming - source and documentation stored together.
- The **`Document`** Package is used to extract documentation from code source, which is processed by LaTeX into hardcopy and LaTeX2**`HTML`** into hyperlinked HTML.
- A Levelized Design is used to facilitate Unit Testing, which is accomplished using the **`gm4`** preprocessor and the self-test feature of the **`Document`** Package.
- Verification **`gm4`** macros are used to implement Design By Contract.

Future Work

- Time dependence.
- 3D test problems (Caesar is already working and tested in 3D).
- Broken clouds.
- Spherical cloud.