ICRCCM III, Phase 2: Longwave Model Comparisons for Inhomogeneous Clouds

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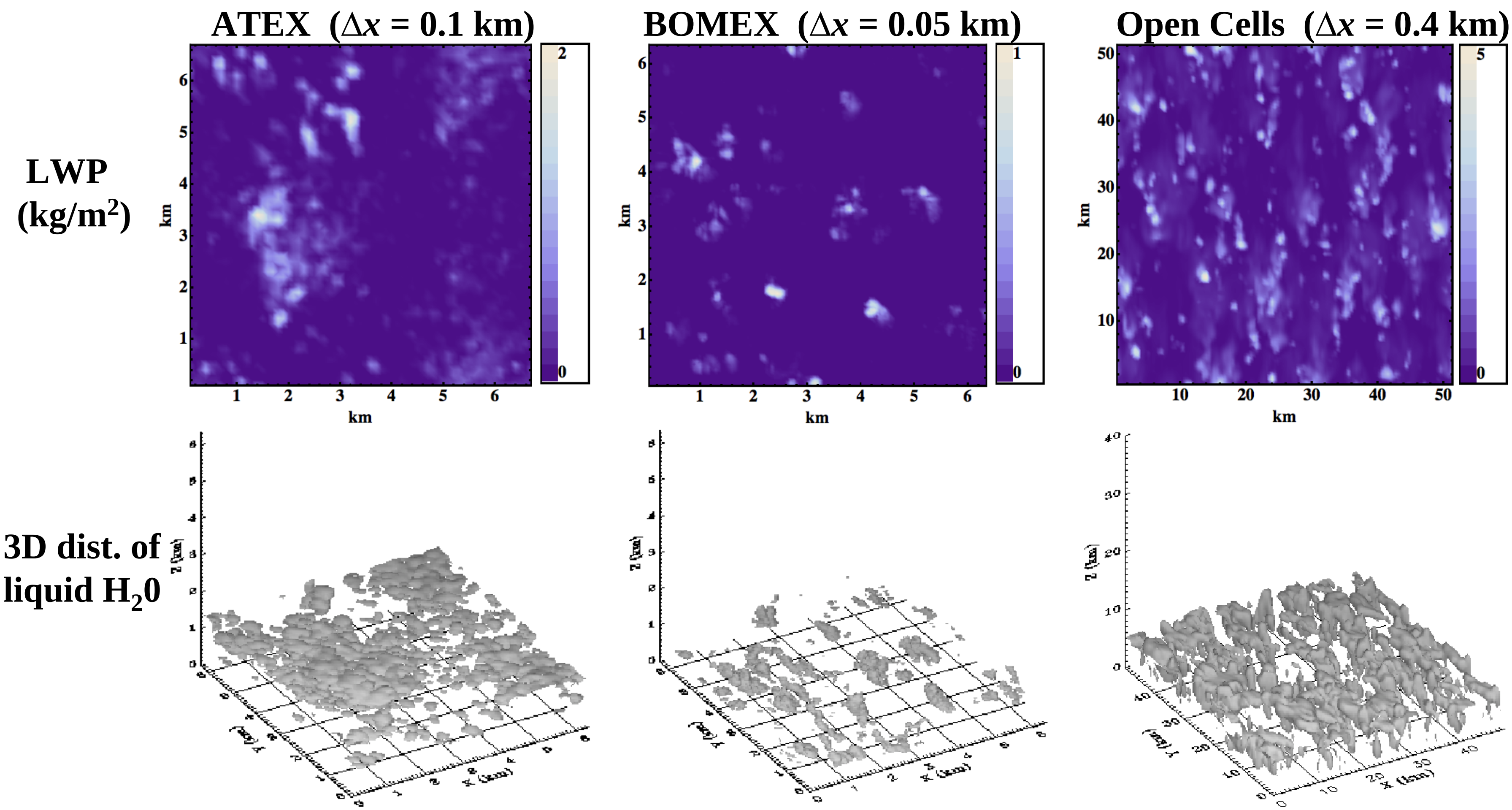
Objectives

- Establish longwave benchmarks for real cloud atmospheres using a validated, three-dimensional Monte Carlo model (3DMC)
- Calculate results with approximate radiation methods employed by general circulation models (GCMs) including:
  - independent pixel approximation (IPA)
  - maximum/random cloud-overlap (MRO)
  - random cloud-overlap (RO)
- Identify discrepancies between benchmarked "truth" and approximated radiation codes

Unresolved clouds: CRM cases following Barker et al. (2003)

- Used a variety of inhomogeneous cloud fields
- All have various domain size, resolution, and total cloud amount



Images from *Barker et al.* (2003)

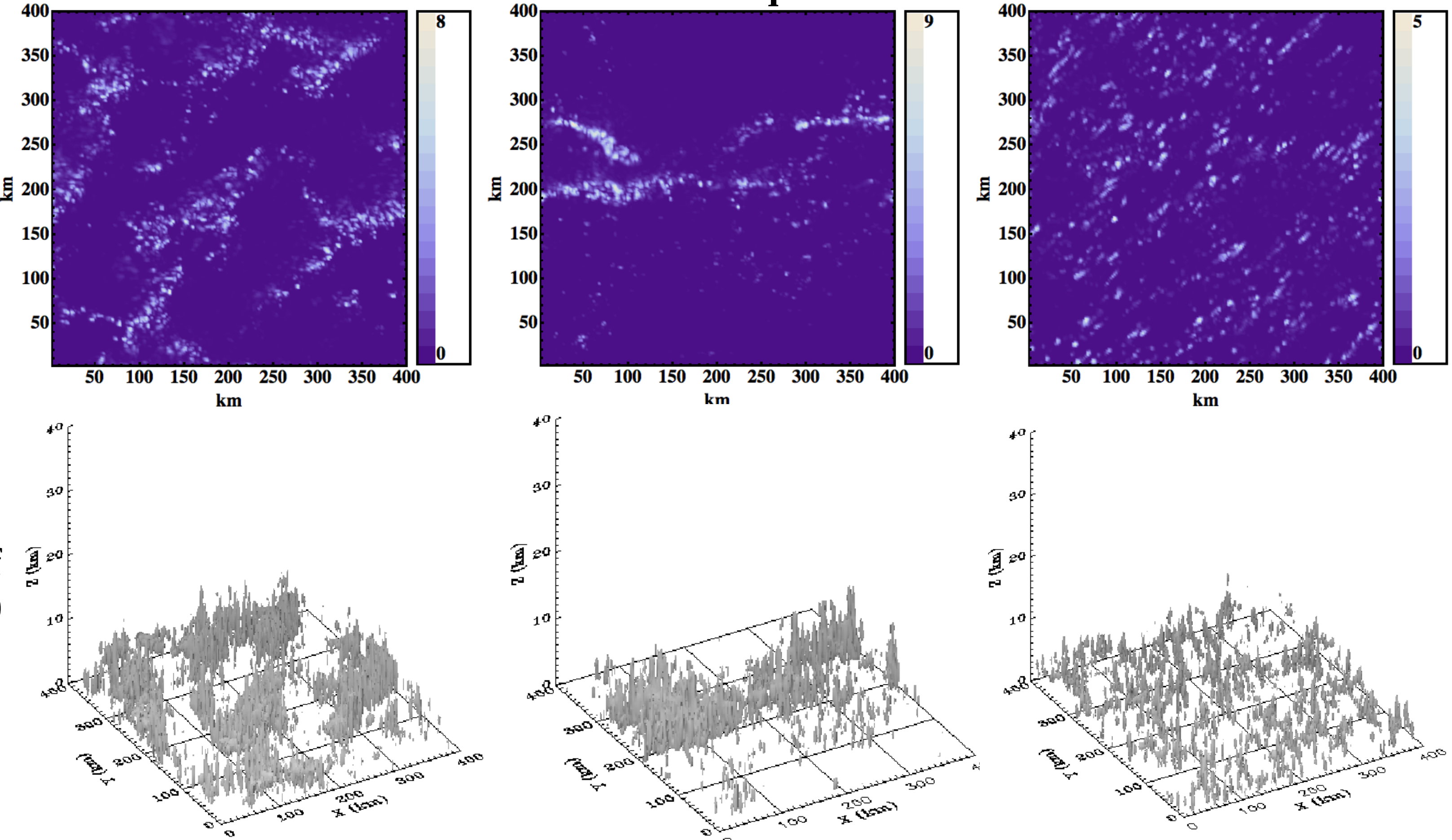
Unresolved clouds: CRM cases (cont.)

- Three large-scale cases are included from the GATE campaign
- These represent the non-CRM-scales usually employed by GCMs (each has Δx = 2 km)

GATE A - clusters | **GATE B - squall line** | **GATE C - scattered trade Cu**

LWP (kg/m^2)

3D dist. of liquid $H_2 0$



Images from *Barker et al.* (2003)

Unresolved clouds: CRM cases (cont.)

- All cases use liquid water spheres with effective radius (r_e) of 10 μm
- Using r_e and LWC, the optical properties are computed using the Mie scattering routine of SHDOM
  - absorption and scattering coefficients
  - single scattering albedo
  - Legendre polynomials
- Scattering angles are tabulated and referenced by 3DMC when a random angle is generated

Benchmark model:
quantities

- Upwelling and downwelling fluxes calculated at each (*x*,*y*,*z*)-location for 16 bands with 16 *k*-values - total of 256 simulations at each point
- Potentially up to 1000 photon bundles per simulation per gridpoint - possibly for 490 billion histories to track for largest cases
- Convergence criteria used
  - calculations stopped when solutions for photons are within 0.05σ
- Flux divergence is calculated separately
  - reduces noise introduced from using pseudorandom numbers
  - post processing converts from W/m^3 to K/day

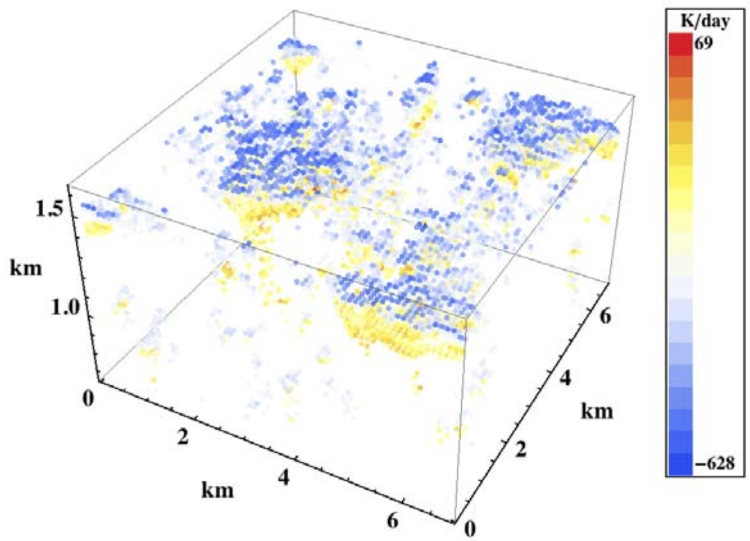
Benchmark results:

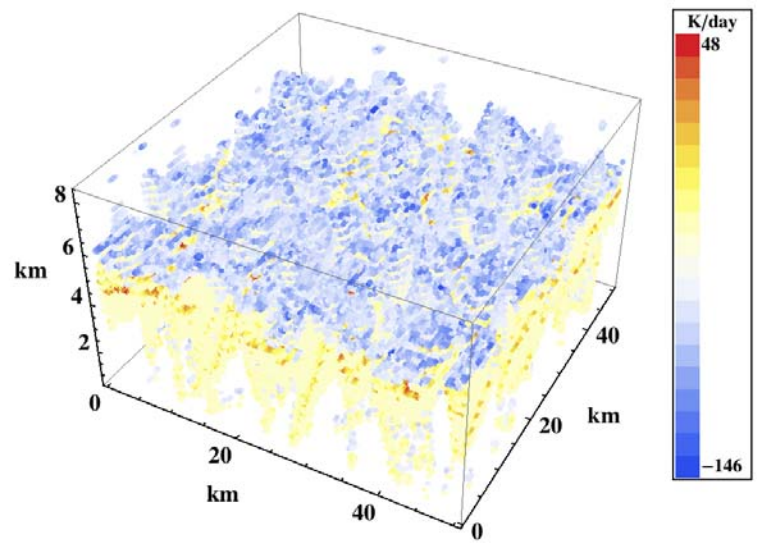
3D heating rates

These fields demonstrate the high sampling capabilities of 3DMC, and show the multidimensional heating/cooling structure of the cloud layer.

ATEX - stratiform cumulus
- heating within/below clouds
- cooling above

Open Cells - towering convection
- heating within convective columns
- cooling above (less than ATEX)





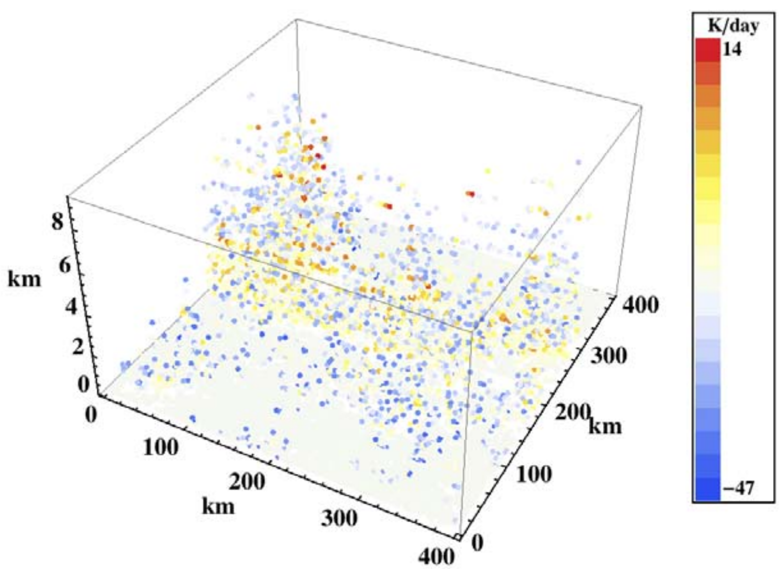
In terms of 1D: $q \propto -\frac{\partial F_{net}}{\partial z}$

Benchmark results:
3D heating rates (cont.)

GATE cases have lower resolution, making it harder to visualize the heating distribution associated with clouds

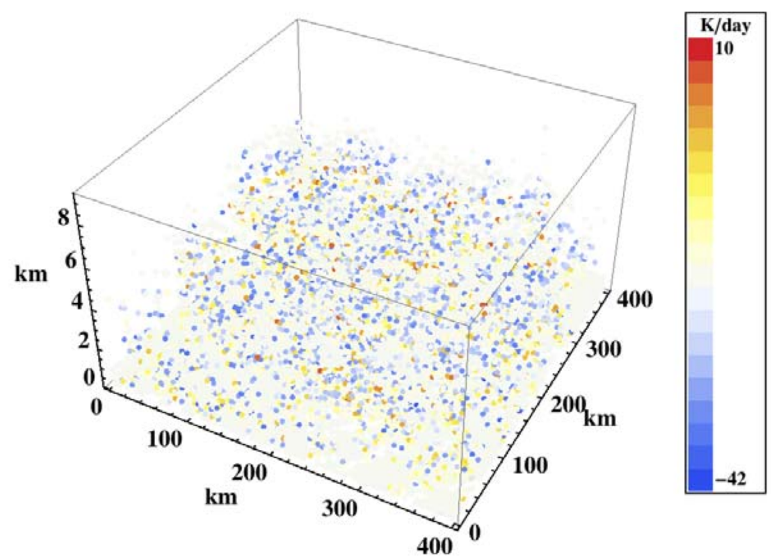
GATE B - defined squall line

- Much lower extreme values due to coarse resolution
- compute over larger volumes



GATE C - scattered convection

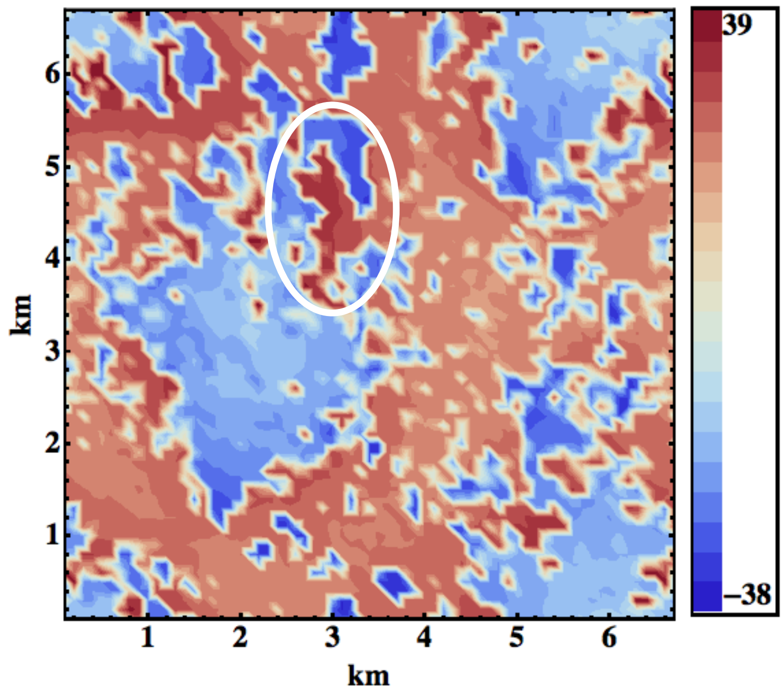
- on this scale, heating/cooling looks uniformly random
- more homogeneous looking



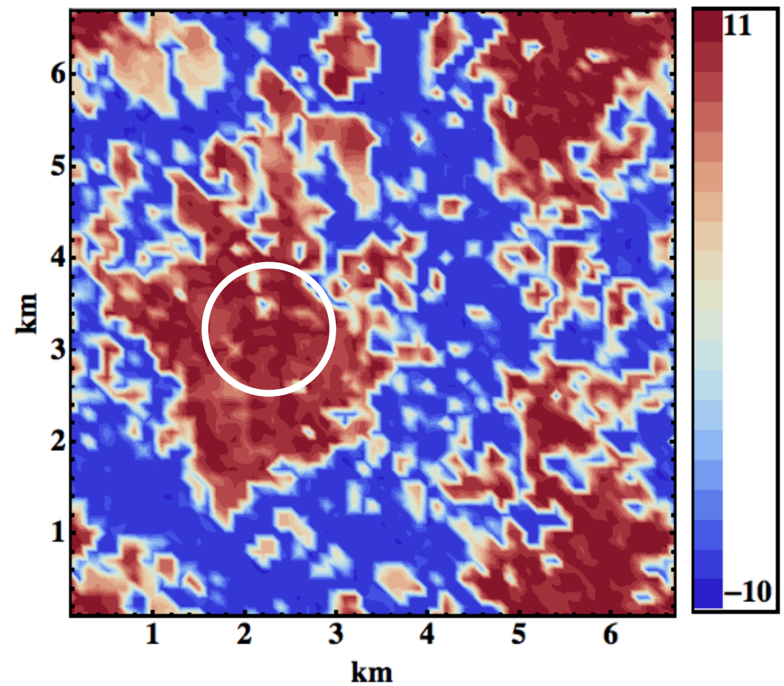
Comparisons: (3DMC-IPA)
ATEX IPA Flux errors (all values W/m^2)

• Demonstrate the local 3D effects of radiation through a broken cloud field.

IPA surface F↓ error



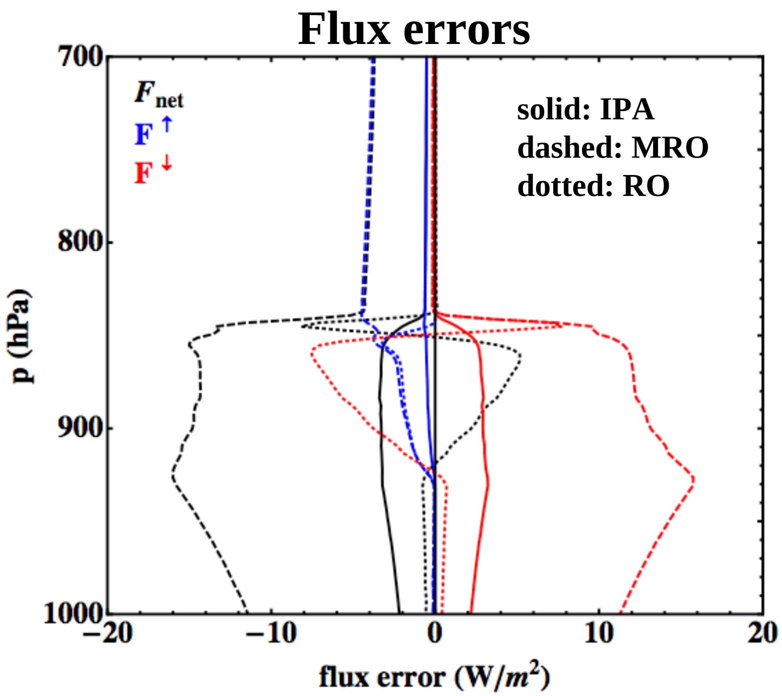
IPA TOA F↑ error

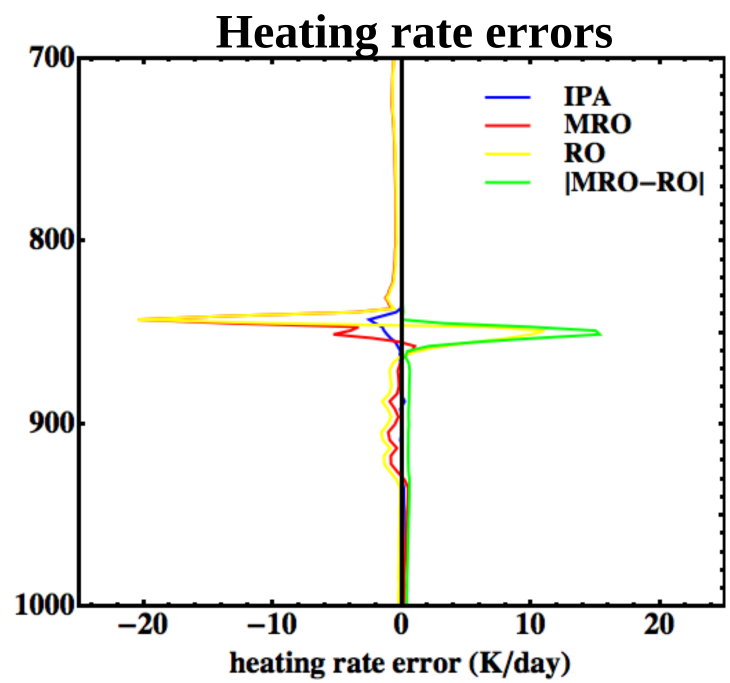


- **At surface:** clear sky pixels adjacent to clouds have larger F↓with 3DMC, whereas pixels beneath clouds have less F↓
- **At TOA:** more flux from cloud tops with 3DMC, less in clear skies

Comparisons: (3DMC-Approximate)

Domain-averaged ATEX errors





IPA:

Flux error less than 3 W/m^2

HR error less than 2 K/day

MRO:

Large flux error (11 W/m^2 at surface)

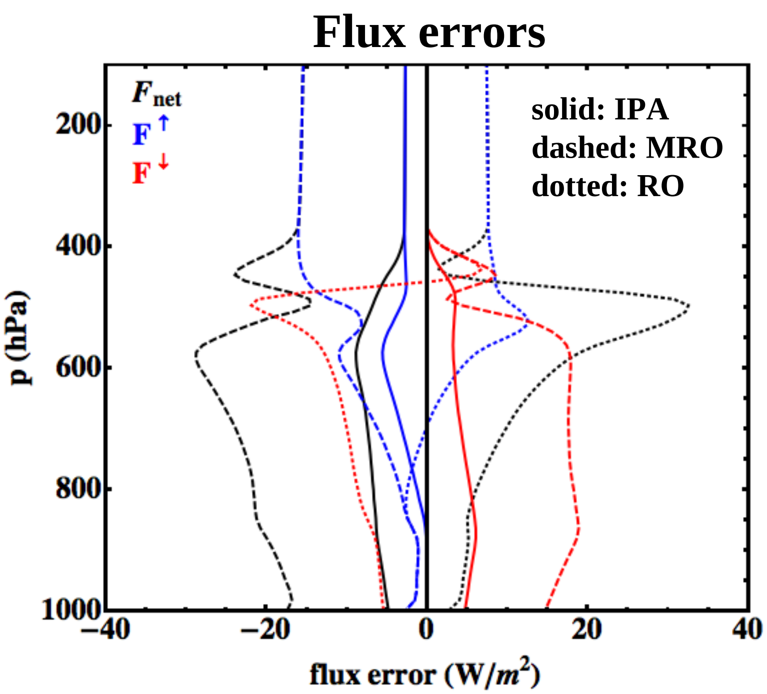
Tropospheric HR error ~20 K/day

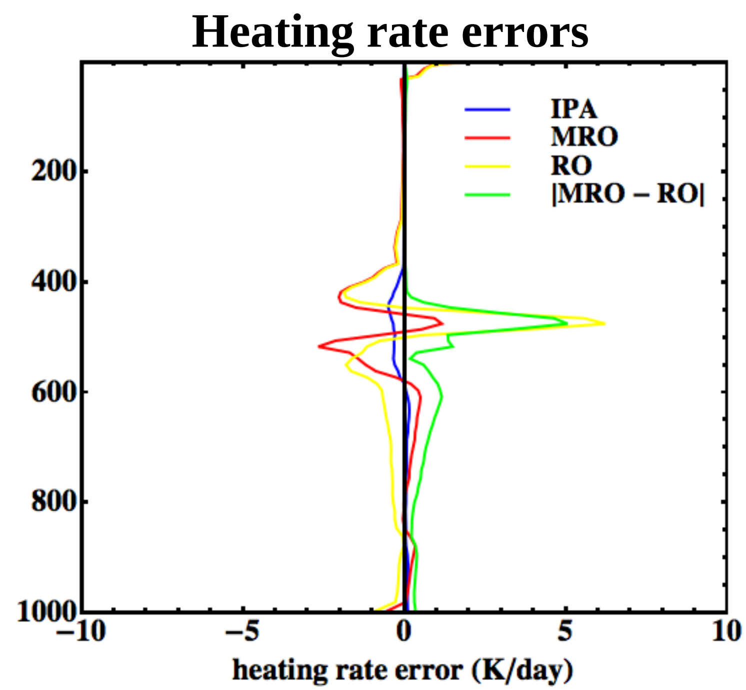
RO:

Sfc. flux error < 1 W/m^2

HR error also ~20 K/day

Comparisons: (3DMC-Approximate)
Domain-averaged Open Cells errors



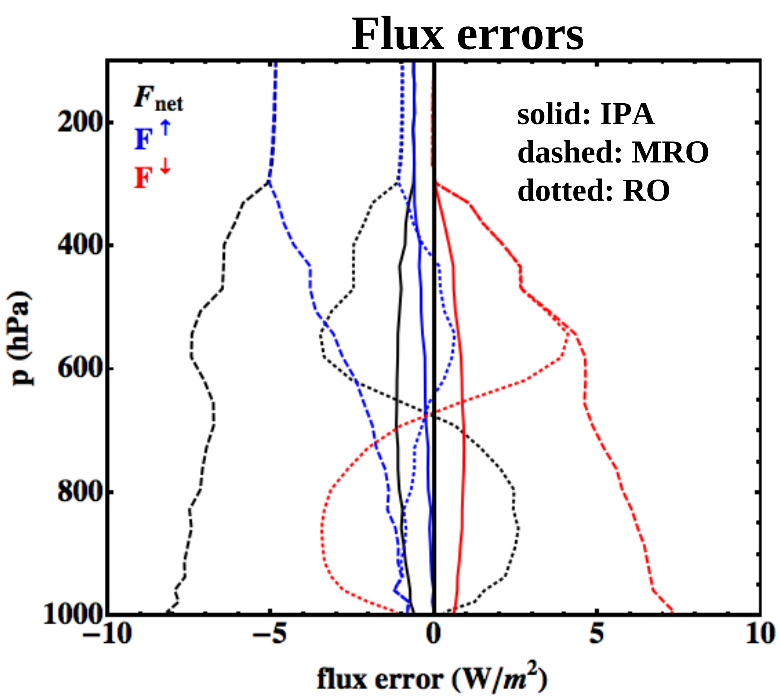


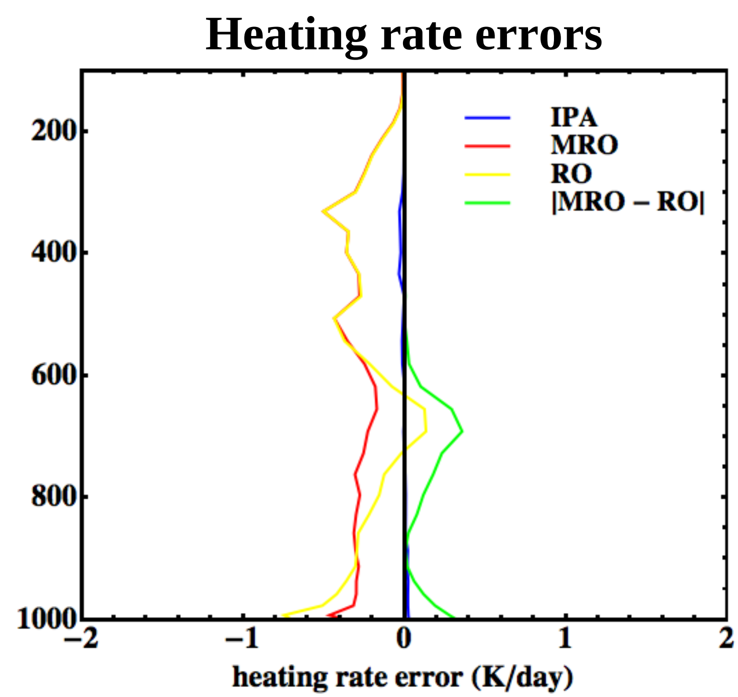
IPA:
F↓ error of about 5 W/m^2 at sfc.
HR error less than 1 K/day

MRO:
15 W/m^2 error in F↓ sfc.
Cloud layer HR error 3 K/day

RO:
F ↓ error ~ -5 W/m^2
Cloud layer HR error 6 K/day

Comparisons: (3DMC-Approximate)
Domain-averaged GATE B errors





IPA:

F↓ error of about 1 W/m^2 at sfc.

HR error less than 1 K/day

MRO:

7.5 W/m^2 error in F↓ sfc.

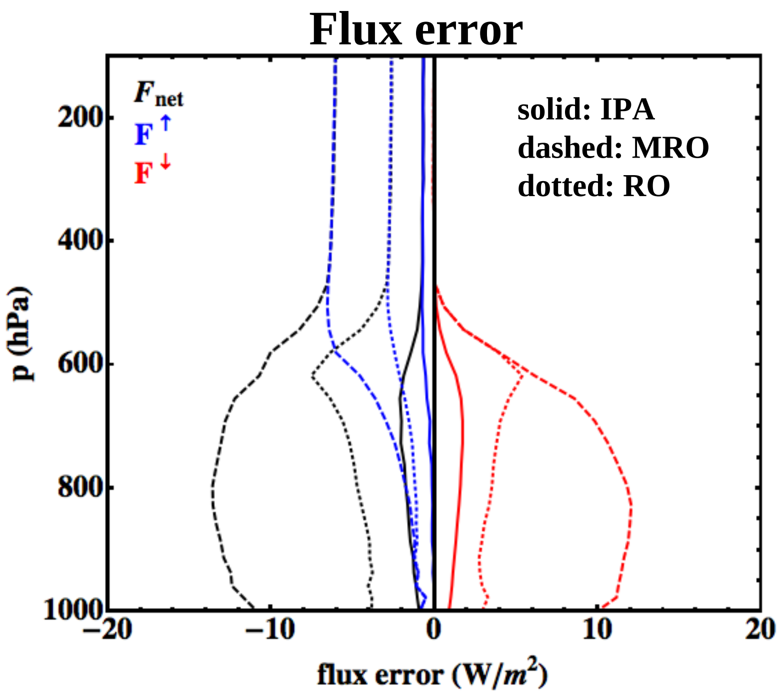
Cloud layer HR error -0.2 K/day

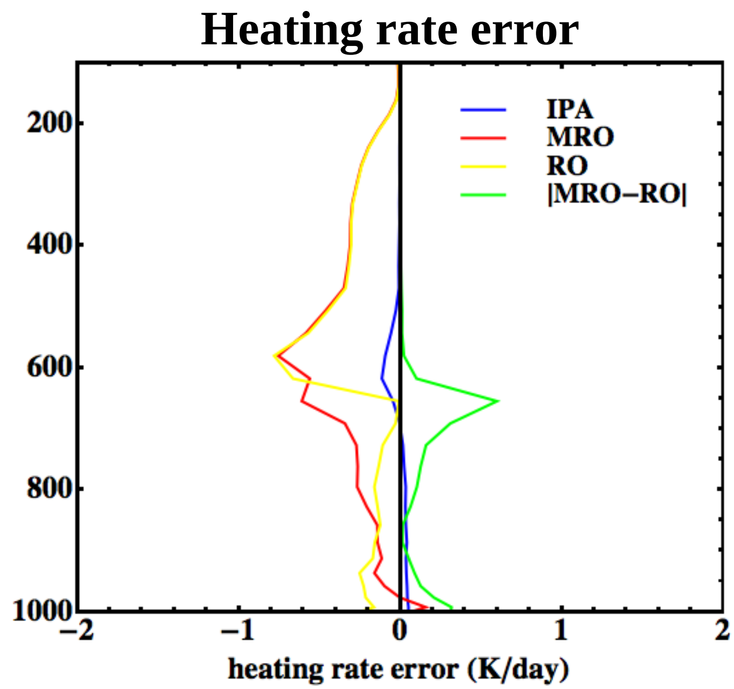
RO:

F↓ error -2 W/m^2

Cloud layer HR error 1 K/day

Comparisons: (3DMC-Approximate)
Domain-averaged GATE C errors





IPA:

F↓ error of about 1 W/m^2 at sfc.

HR error less than 1 K/day

MRO:

10 W/m^2 error in F↓ sfc.

Cloud layer HR error -0.8 K/day

RO:

F↓ error 3 W/m^2

Coud layer HR error -1 K/day

Summary and Conclusions

- Longwave benchmarks have been established for 6 inhomogeneous cloud fields using a validated multidimensional radiation model
- Comparisons to approximated models show that no 1D code performs well for all situations
- IPA performs better than RO and MRO for domain-averaged values, but has large errors for individual columns
- The non-CRM-scale GATE cases show the lowest errors for mid-level heating rates
  - This is most likely a result of a decrease in 3D effects from integrating over a larger volume

Summary and conclusions (cont.)

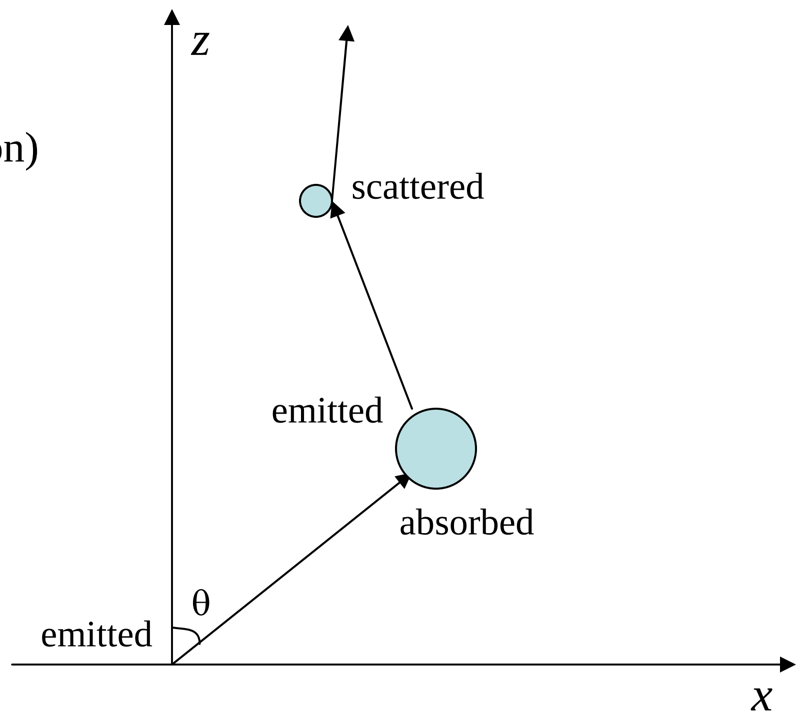
- The results presented here indicate that systematic scale-dependent flux and heating rate errors will arise from making the usual assumptions about unresolved clouds.
- *Barker et al.* (2003) showed that cloud-overlaps can lead to shortwave flux errors of 20 W/m^2, which has also been shown here in the longwave

Future work

- Test the IPA and cloud-overlap schemes with an effective cloud fraction at each layer instead of total cloud fraction
  - Accounts for cloud field geometry
- This study was not designed to be unilateral, so more models are needed to test the range of discrepancies
- McICA implementation
  - Uses a cloud generator and correlated-*k* distribution to compute the fluxes through an unresolved cloud field
  - McICA has been shown by *Räisänen et al.* (2004) to be quicker than a standard IPA without a loss of accuracy

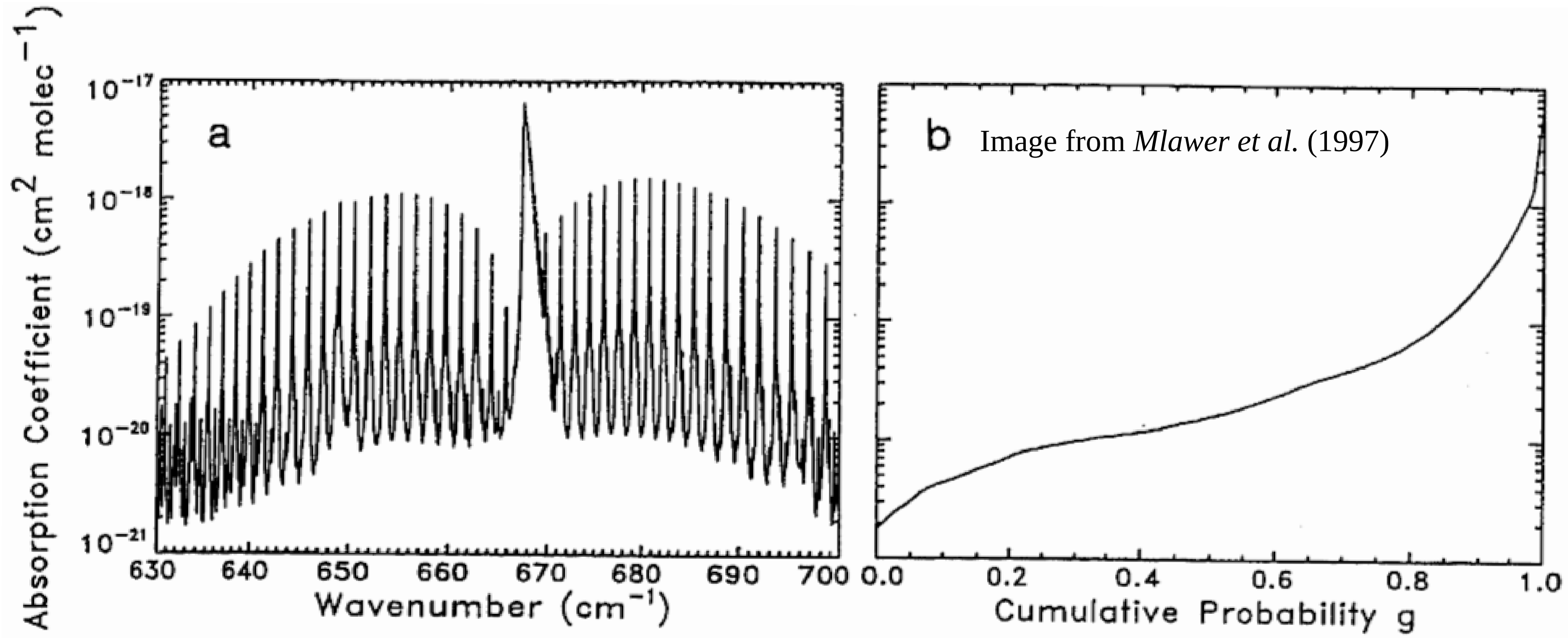
Benchmark model:
overview and importance

- Uses probabilistic transfer equations where pseudorandom numbers generate photonic events including:
  - emission
  - transmission
  - extinction (scattering or absorption)
- Emission and scattering angles found by using "random walks" through pre-computed optical properties
- Mie scattering coefficients are referenced by the model to determine new direction of travel



- The optical properties are implemented using a correlated-*k* distribution

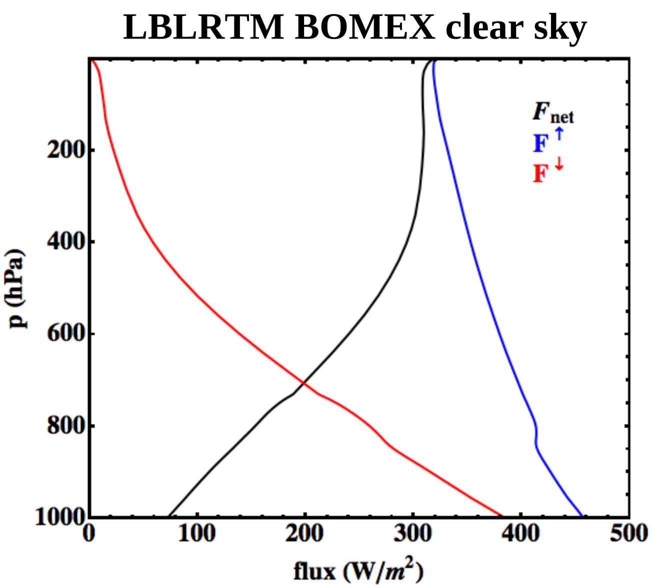
Benchmark model:
correlated-*k* distribution

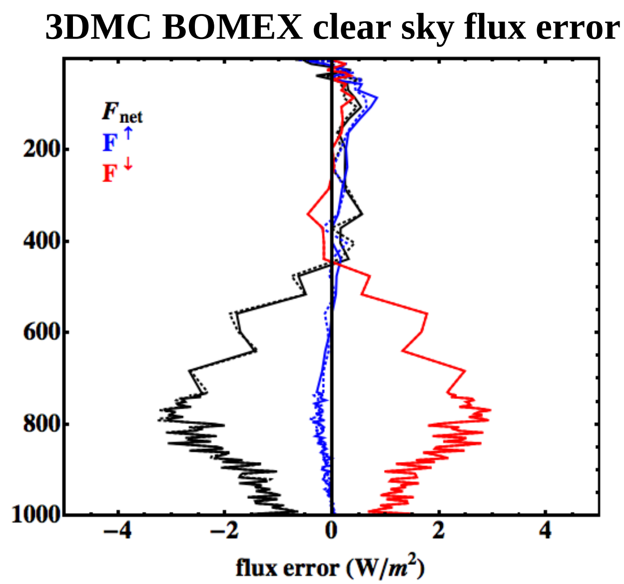


- Transforms absorption coefficients (*k*) from wavenumber space to probability space
  - correlates absorption to transmission probability at each (*x*,*y*,*z*)-location
- Sorts coefficients into a smooth function, which enables integration with fewer quasimonochromatic quadrature points
- Allows for quick integration of inhomogeneous atmospheres

Benchmark model:
validation

- 3DMC must be validated to high quality spectral calculations to give confidence in results
- This is performed by comparison to line-by-line (LBLRTM) calculations for clear sky BOMEX

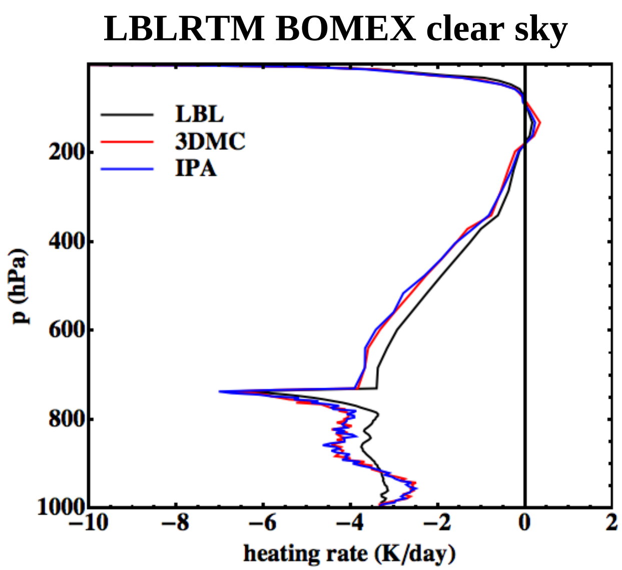


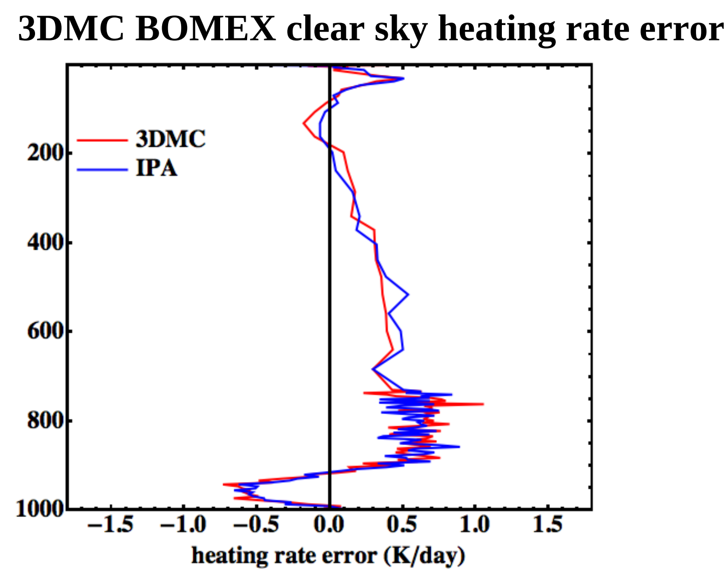


- Flux errors for 3DMC are largest in the layers with high vertical resolution - where the clouds would be if they were included
- Max. error ~ -3 W/m^2 for F_{net}, and error rarely exceeds ±2%

Benchmark model:
validation (cont.)

- 3DMC heating rate errors are similar to flux errors: main discrepancies occur in the layers where clouds would be.
- Once again, less than ±2%

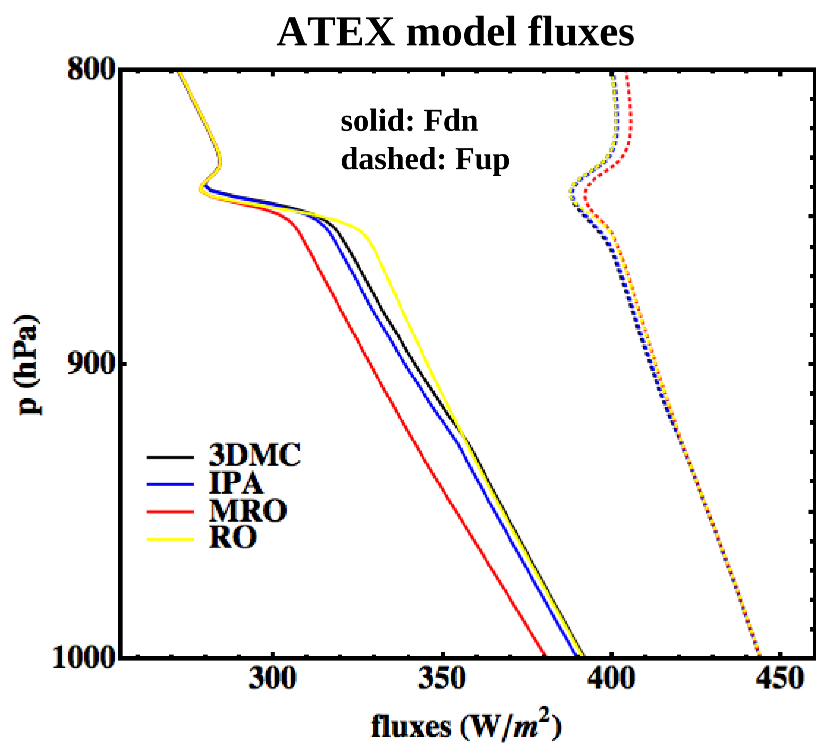




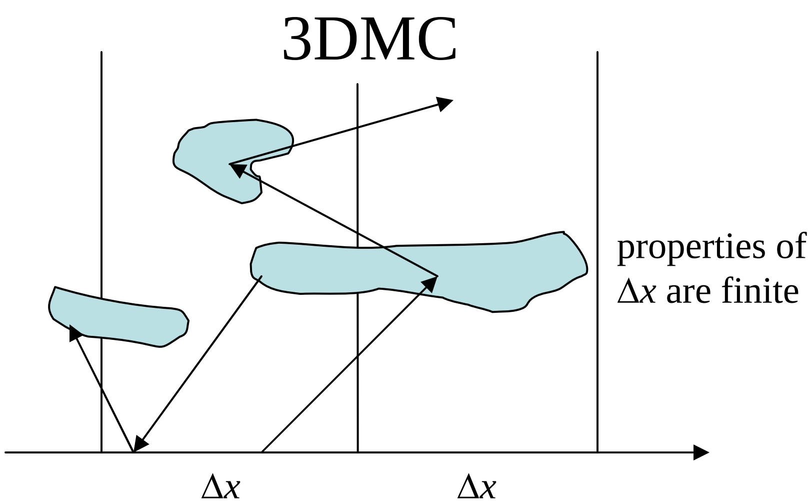
- Note that the IPA is included here for comparison
- IPA performs well for this clear sky case, closely agrees with 3DMC

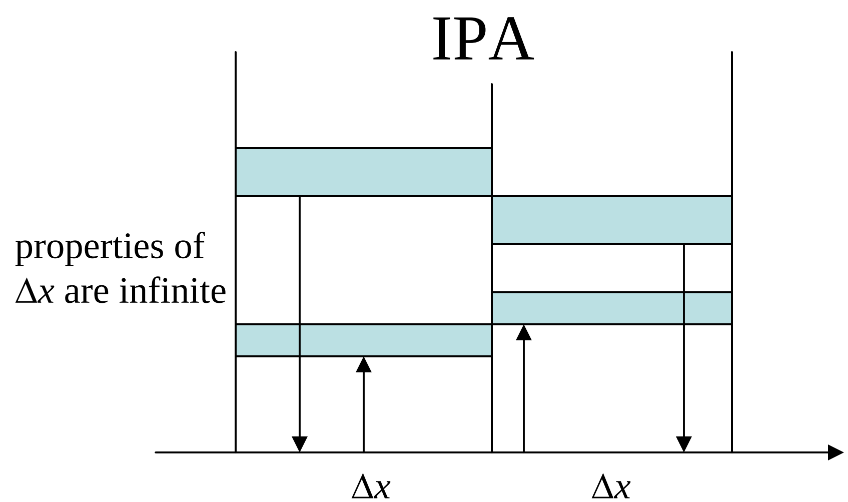
Comparisons:
RO and MRO performance

- RO consistently estimated surface downward flux better than MRO, in the ATEX case by 10 W/m^2



Benchmark model:
3D vs. 1D



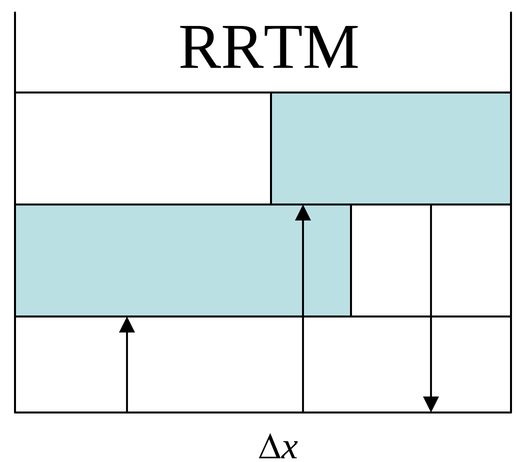


3D

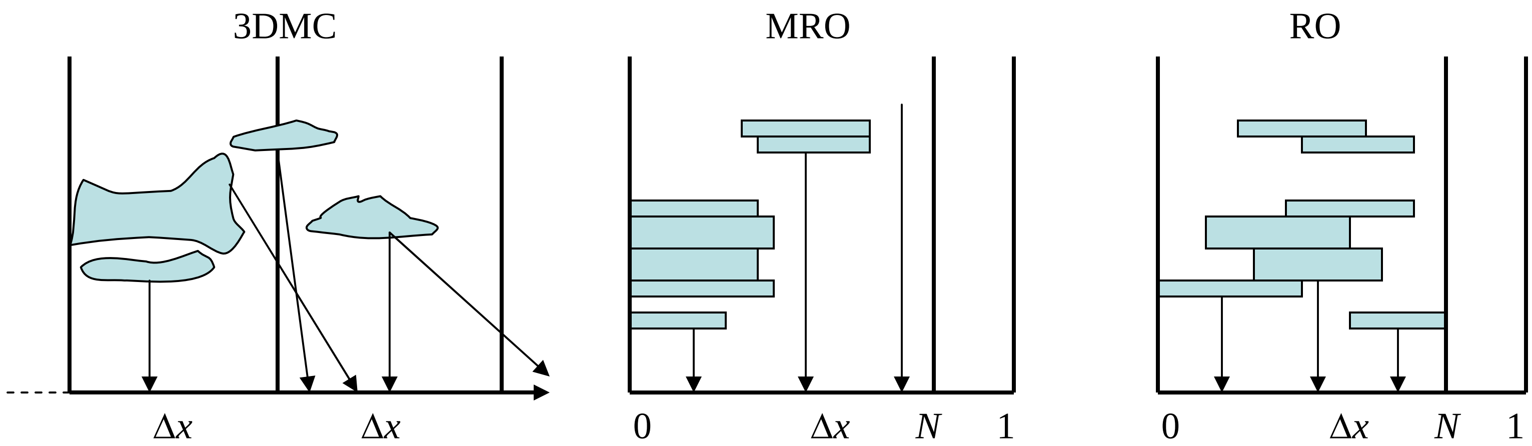
- Photons can cross pixel boundaries, contributing to flux in adjacent cells
- Ability to capture effects of broken cloudiness not seen in 1D models

1D

- IPA uses multiple subgrid columns, preserves horizontal cloud variability
- RRTM uses a single column for entire domain



Comparisons:
MRO and RO (cont.)



- MRO maximally overlaps clouds in adjacent layers, and randomly overlaps clouds separated by two or more layers
- RO randomly aligns clouds without regard to vertical correlation
- More likely to see overcast skies with RO than MRO
- Greater downward flux at surface is a result of more cloud cover lower in the troposphere

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decompressor
are needed to see this picture.

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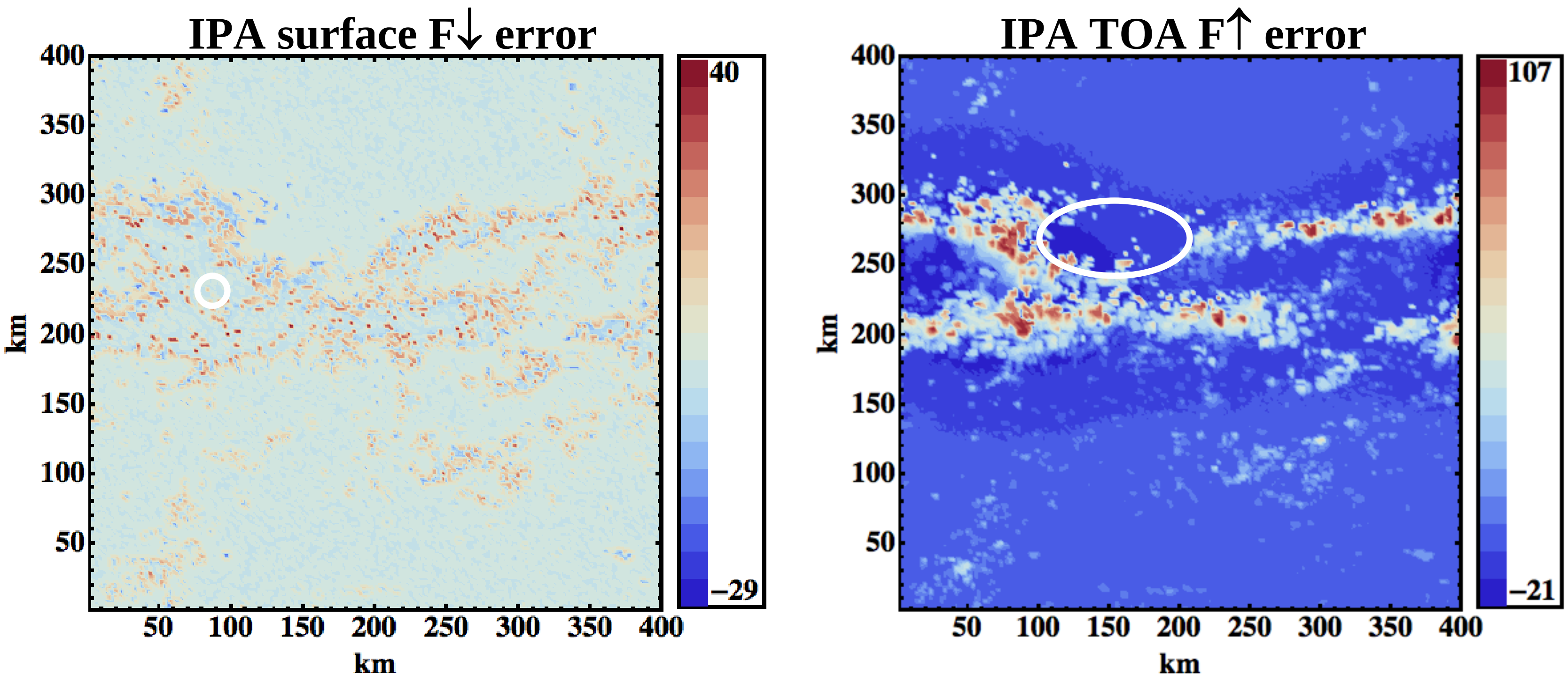
Comparisons: (3DMC-IPA)

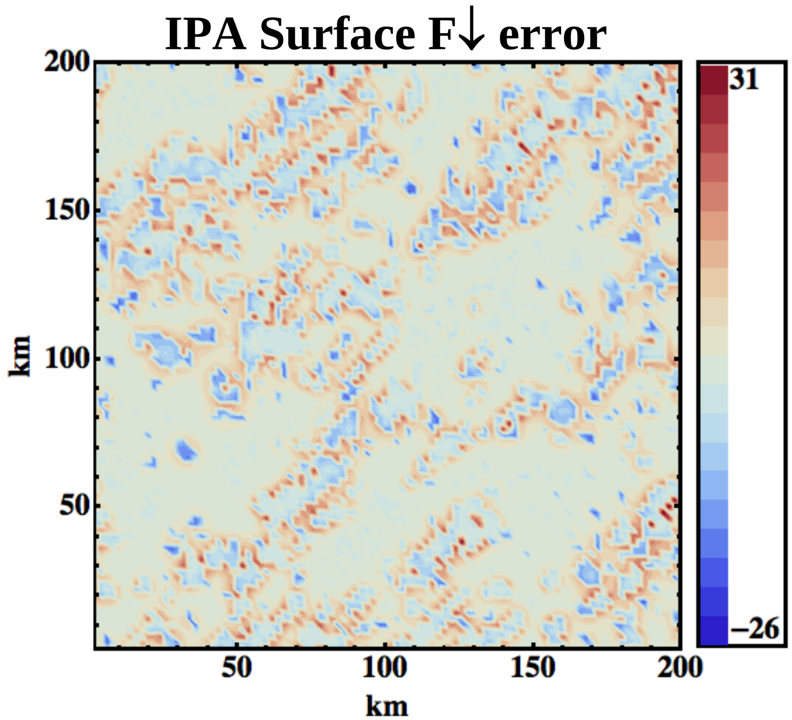
GATE B IPA Flux errors (all values W/m^2)

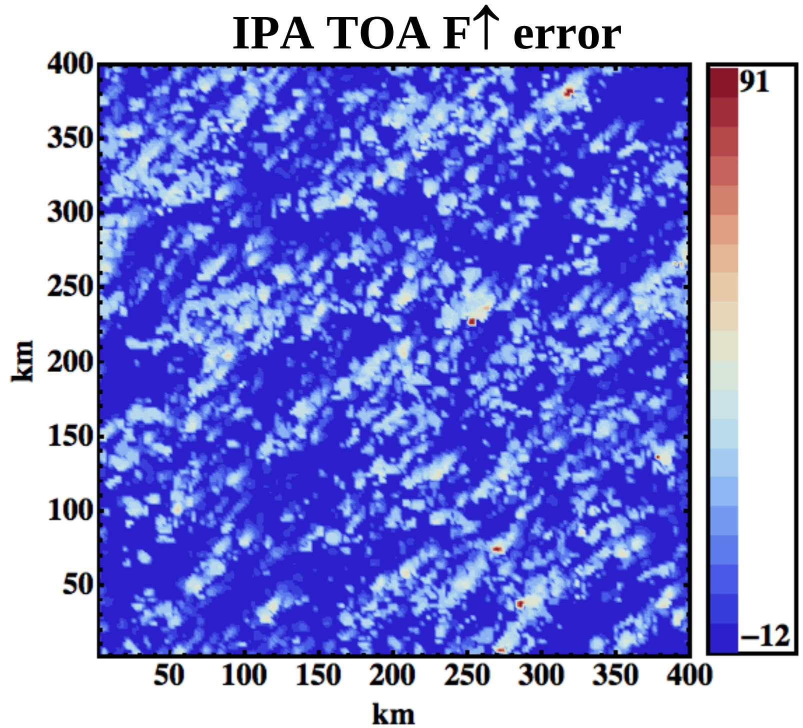


- **At surface:** differences look less extreme due to coarse domain, but there are 3D effects that cause increased F↓ in pixels adjacent to clouds
- **At TOA:** IPA underpredicts as much as 107 W/m^2 over the cloud tops due to neglect of F↑ from cloud sides, and similarly overpredicts clear sky fluxes - especially in areas close to the cloud.

Comparisons: (3DMC-IPA)

GATE C IPA Flux errors (all values W/m^2)



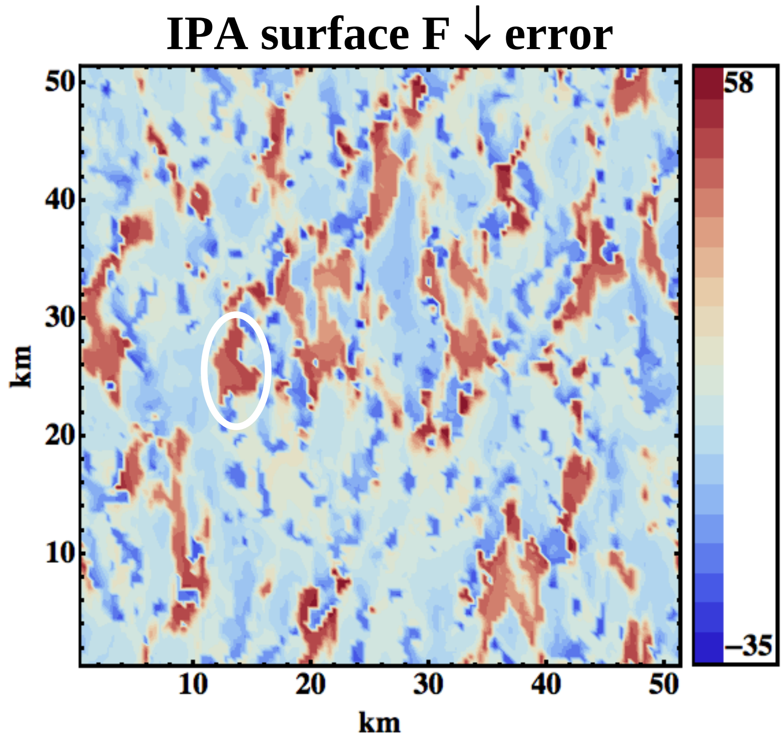


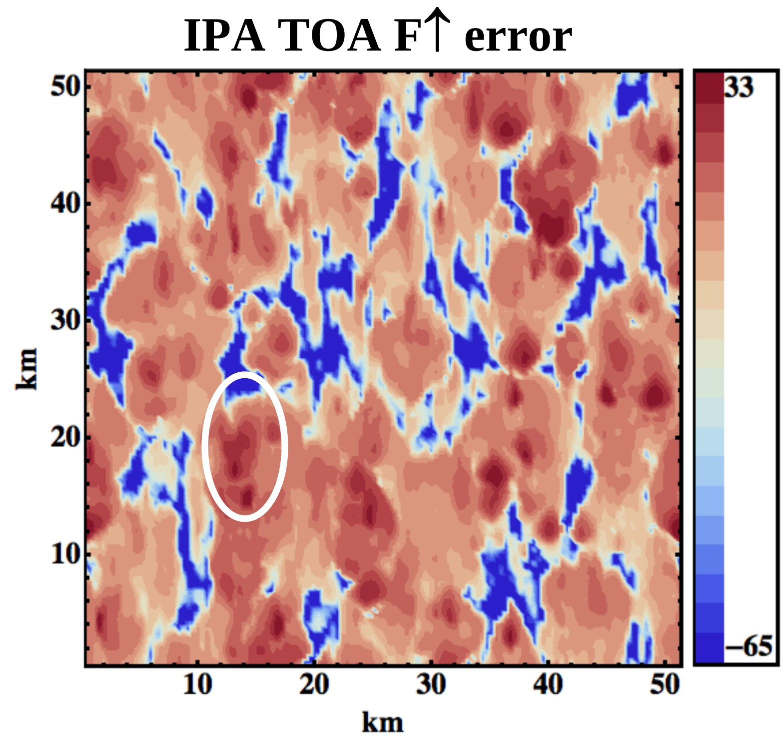
- **At surface:** Once again, error is less extreme due to coarse domain, but 3D effects increase F↓ by up to 31 W/m^2 in pixels adjacent to clouds, and IPA underpredicts beneath the clouds by as much as 26 W/m^2
- **At TOA:** IPA error is as much as 91 W/m^2 over the cloud tops due to neglect of 3D radiation, and also overpredicts clear sky fluxes

Comparisons: (3DMC-IPA)

Open Cells IPA flux errors (all values W/m^2)

- Larger, vertically-correlated clouds have increased cloud-side radiation

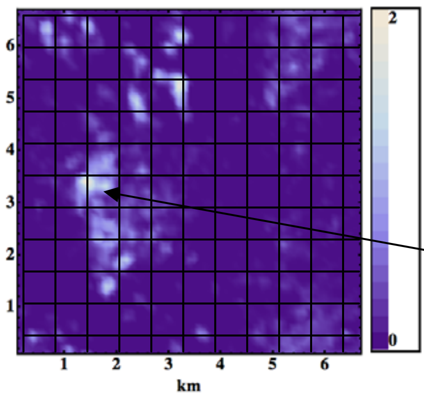


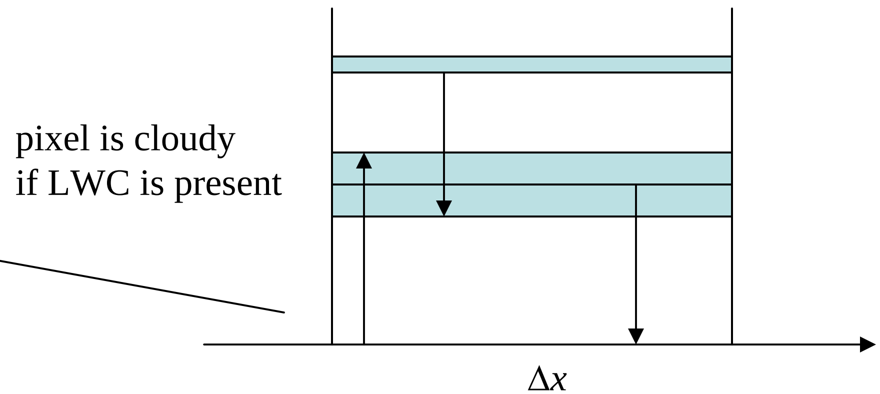


- **At surface:** clear sky show an increase of up to 58 W/m^2 in F ↓ from 3D effects
- **At TOA:** up to 33 W/m^2 more flux over cloud tops, and 65 W/m^2 less flux in clear skies

Approximate models:
IPA

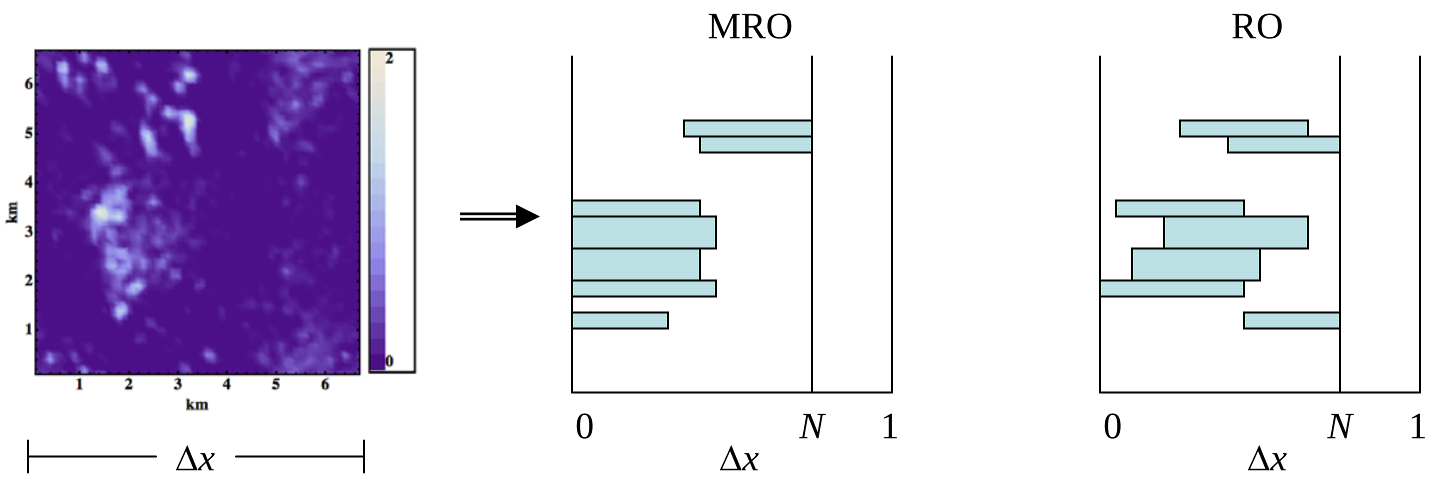
ATEX
- 68x68 pixels
- 32 cloud layers





- Calculates 1D Monte Carlo simulation for each subgrid column, or pixel
  - Same idea as 3DMC, but properties of Δx are infinite (no trans-boundary radiation)
- Assumes plane-parallel homogeneous (PPH) atmosphere within the pixel, and allows for total cloud fraction = 0 or 1
- Sacrifices 3D effect across boundaries, but preserves cloud inhomogeneity
- Has been shown to outperform single-column calculations for same atmospheric conditions

Approximate models:
MRO and RO



- Convert inhomogeneous field into PPH, single-column (GCM-like)
- Cloud-overlap assumptions are necessary in single-column models with fractional cloudiness
- MRO maximally overlaps clouds in adjacent layers, and randomly overlaps clouds separated by two or more layers
- RO randomly aligns clouds without regard to vertical correlation