Stochastic cloud generator for McICA radiation calculations

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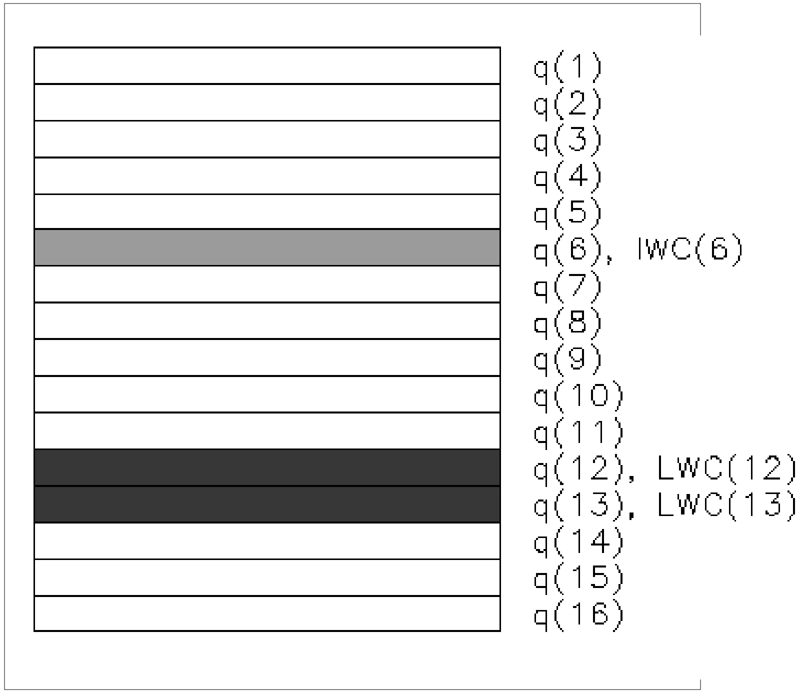
1. Motivation

- Large-scale atmospheric models (LSAMs) use 1D radiation schemes
- In its basic form, a 1D radiation code computes radiative fluxes and heating rates for a plane-parallel horizontally homogeneous (pph) column, given the vertical profile of H_2O and other trace gases, cloud water etc.
- However, the atmosphere is not horizontally homogeneous at the scale of LSAM grid cells

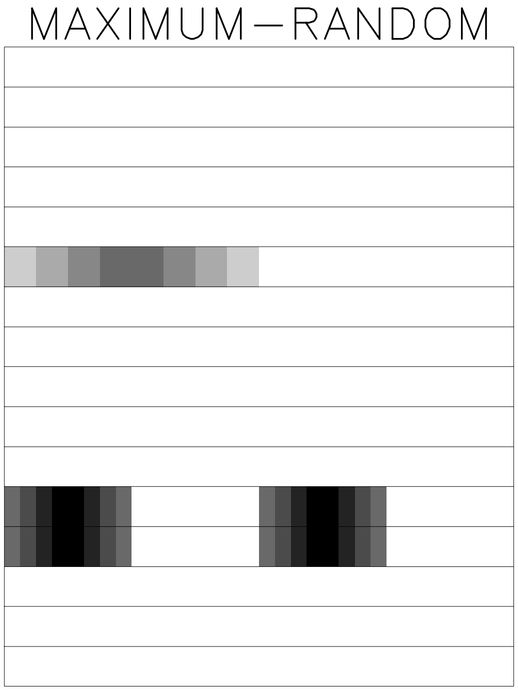


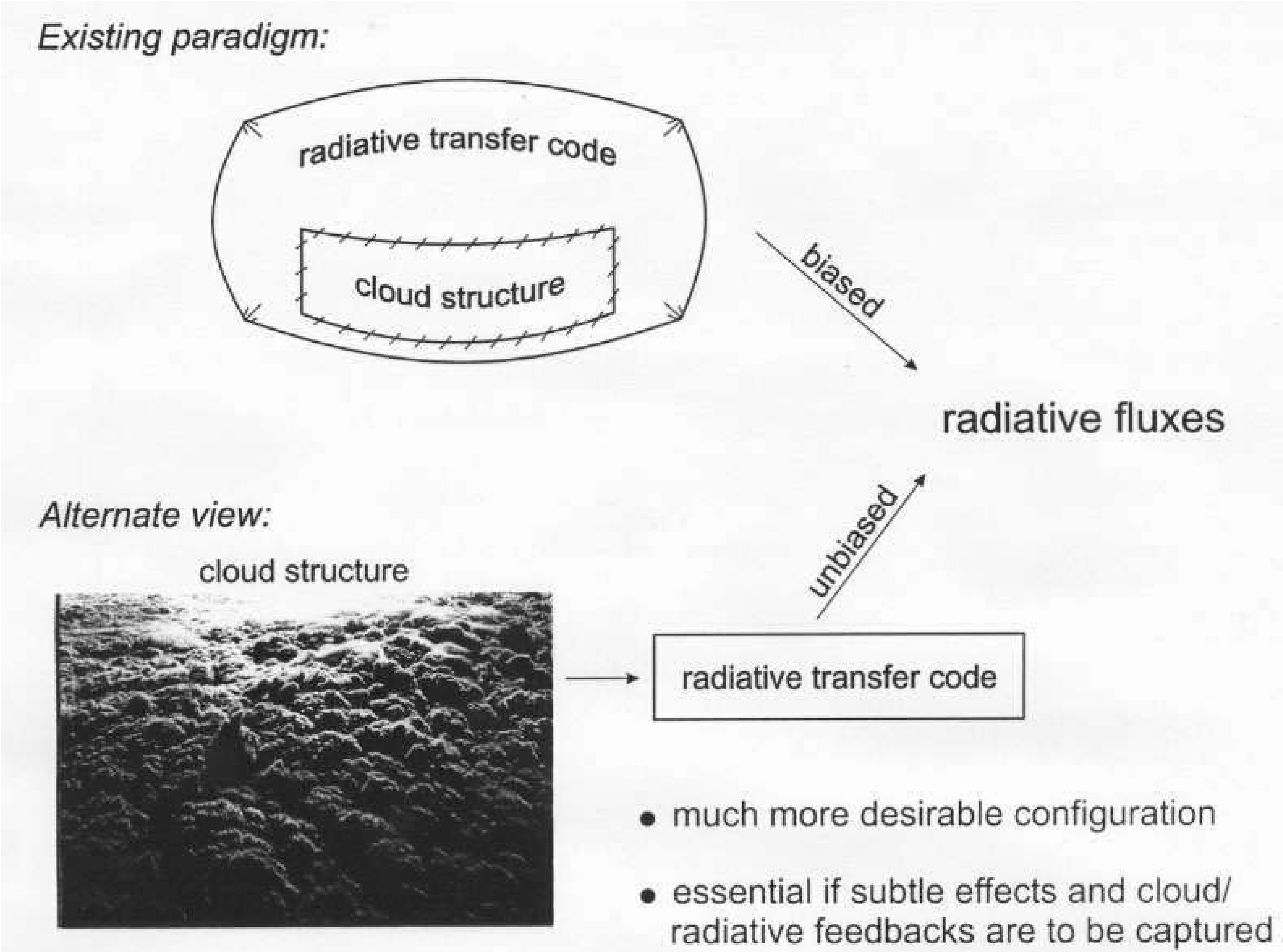
Treatment of subgrid-scale clouds: conventional approach

- Assumptions about cloud horizontal variability and cloud overlap built in the radiation code.

- E.g.: Oreopoulos and Barker (1999): attempt to combine gamma-weighted two-stream approximation with maximum-random overlap of clouds.

- Result: complex 1D radiation codes that are difficult to modify – even if the assumptions about subgrid-scale cloud structure are known to be biased!

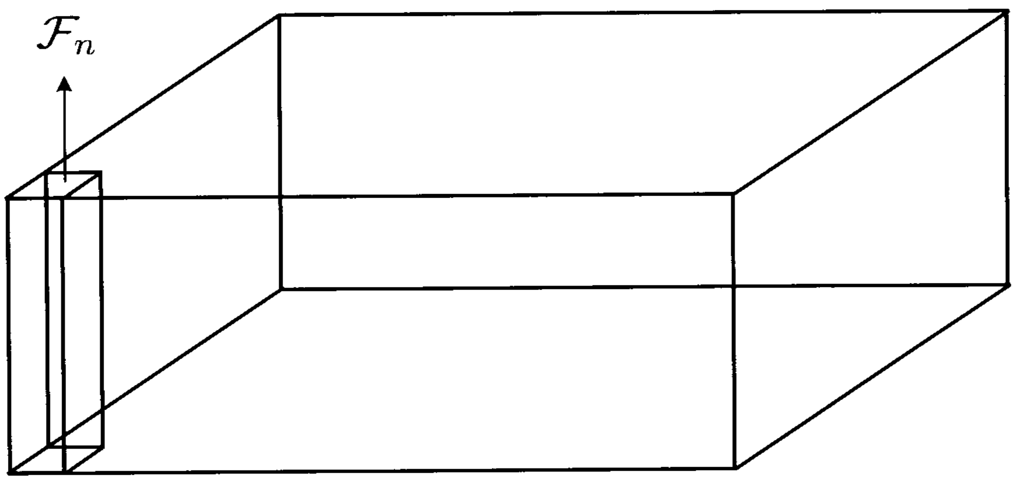



Existing paradigm:
radiative transfer code
cloud structure
biased
radiative fluxes
Alternate view:
cloud structure
radiative transfer code
unbiased
• much more desirable configuration
• essential if subtle effects and cloud/ radiative feedbacks are to be captured

2. (a) ICA = Independent Column Approximation

- ICA allows to separate subgrid-scale cloud structure from the radiation code!
- Assume zero net horizontal radiative transport (a good assumption when computing domain-average flux profiles).
- Perform the radiation calculations separately for the N independent columns

=> domain average $$\langle F \rangle_{\text{ICA}} = \frac{1}{N} \sum_{n=1}^{N} F_n$$



2(b). McICA = Monte Carlo Independent Column approximation

Most GCM-type radiation codes use the k distribution method for gas absorption

=> in effect, the spectrum is divided into *K* parts (*K ~ 50-100)*

=>

$$F = \sum_{k=1}^{K} w_k F_k$$

When using ICA, $\langle F \rangle_{\text{ICA}} = \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} w_k F_{n,k}$

In McICA this is approximated as $\langle F \rangle_{\text{McICA}} = \sum_{k=1}^{K} w_k F_{\{\text{random}\},k}$

where $F_{\{\text{random}\},k}$ is the radiative flux for *k* term *k* for a randomly selected subcolumn

Properties of McICA

- Much faster than ICA. In fact, as fast (or faster than) present 1D radiation codes
- Unbiased with respect to ICA.
- Significant random errors. Does this matter?
    * A non-trivial question
    * Errors are spatially and temporally localized
    * GCM estimates of large-scale variables are not perfect
    * There is no one-to-one correlation between large-scale variables and (large-scale) radiative fluxes
    * Random errors can be reduced by doing more than one loop over the *k* distribution

3. Stochastic cloud generator

Unless a super parameterization (2D CRM for each GCM grid cell) is used, the columns needed by McICA have to be generated using model large-scale variables. A simple stochastic cloud generator was developed for that purpose.

GENERATION OF CLOUD FRACTION

Define a variable $x \in [0,1]$ ("cumulative frequency") such that

$$\begin{cases} x_j \le 1 - C_j \Leftrightarrow \text{layer } j \text{ clear for this subcolumn} \\ x_j > 1 - C_j \Leftrightarrow \text{layer } j \text{ cloudy for this subcolumn} \end{cases}$$

The algorithm for generating x depends on cloud overlap assumptions. For example,

$$\begin{cases} x_j = \text{RND} \Leftrightarrow \text{random overlap} \\ x_j = x_{j-1} \Leftrightarrow \text{maximum overlap} \end{cases}$$

Preferred approach: generalized cloud overlap

(Hogan & Illingworth, 2000)

Total cloud fraction for clouds in layers *j* and *k*

$$C_{jk} = \alpha_{jk} C_{jk,\max} + (1 - \alpha_{jk}) C_{jk,\mathrm{ran}}$$

$$C_{jk,\max} = \max(C_j, C_k)$$

$$C_{jk,\mathrm{ran}} = C_j + C_k - C_j C_k$$

This can be generated stochastically, subject to two assumptions:

(a) The true overlap is between random and maximum $(0 \le \alpha \le 1)$

(b) It is sufficient to consider parameter α for adjacent layers

$$\alpha_{jk} = \alpha_{j,j+1} \times \alpha_{j,j+1} \times \ldots \times \alpha_{k-1,k}$$

- This is consistent with the decorrelation depth (L_c) approach by Bergman and Rasch (2002):

$$\alpha_{jk} = \exp[-(z_j - z_k)/L_c]$$

Resulting algorithm for generating the profile of x

Uppermost layer ($j = 1$):

$$x_1 = \mathrm{RND}$$

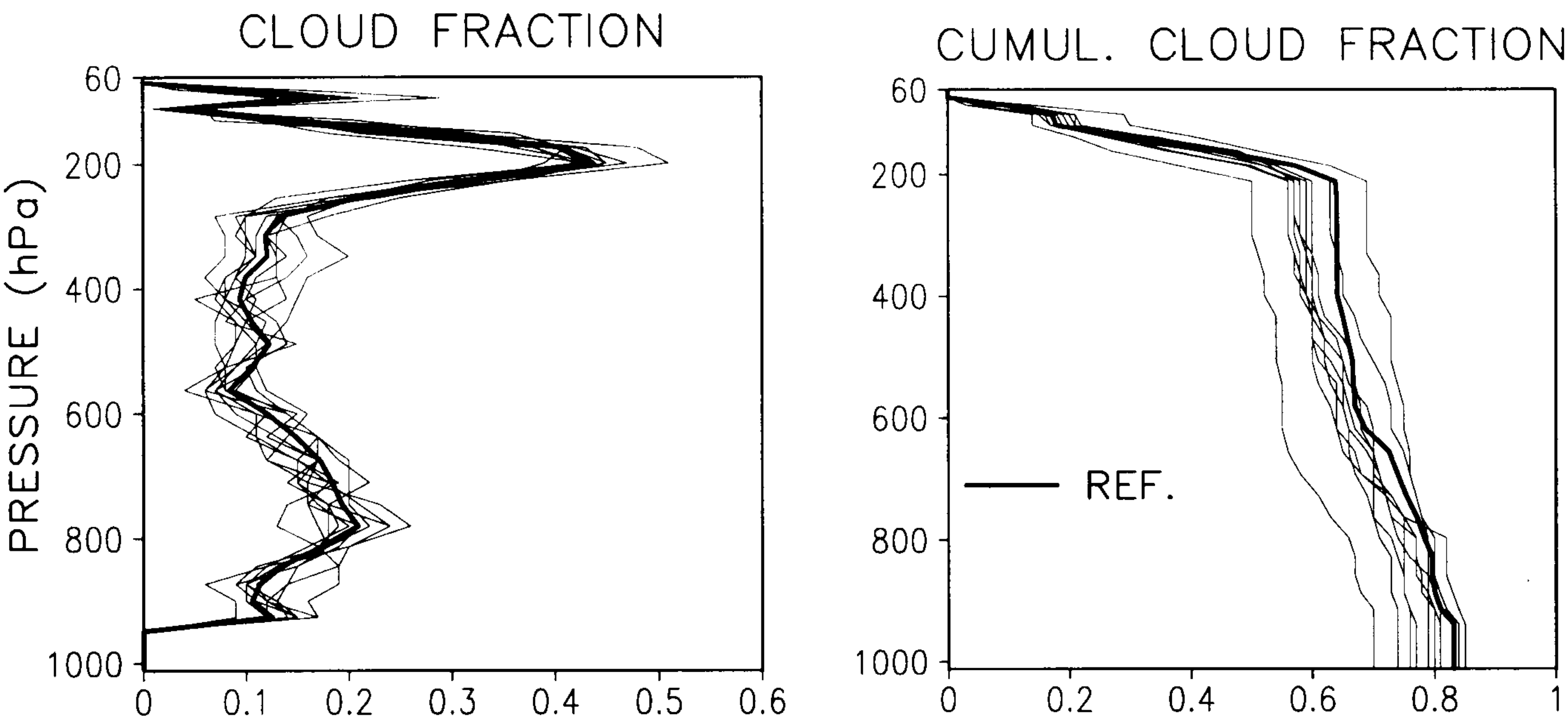
Other layers ($j > 1$):

$$\begin{cases} \mathrm{RND}_1 < \alpha_{j-1,j} \Rightarrow x_j = x_{j-1} \text{ (maximum overlap)} \\ \mathrm{RND}_1 \geq \alpha_{j-1,j} \Rightarrow x_j = \mathrm{RND}_2 \text{ (random overlap)} \end{cases}$$

RND, RND_1 and RND_2 are random numbers $\in [0,1]$

EXAMPLE

Ten samples for a cloud fraction profile from a tropical squall line CRM simulation (simulated area mean layer cloud fraction and cumulative cloud fraction, 100 subcolumns per sample)



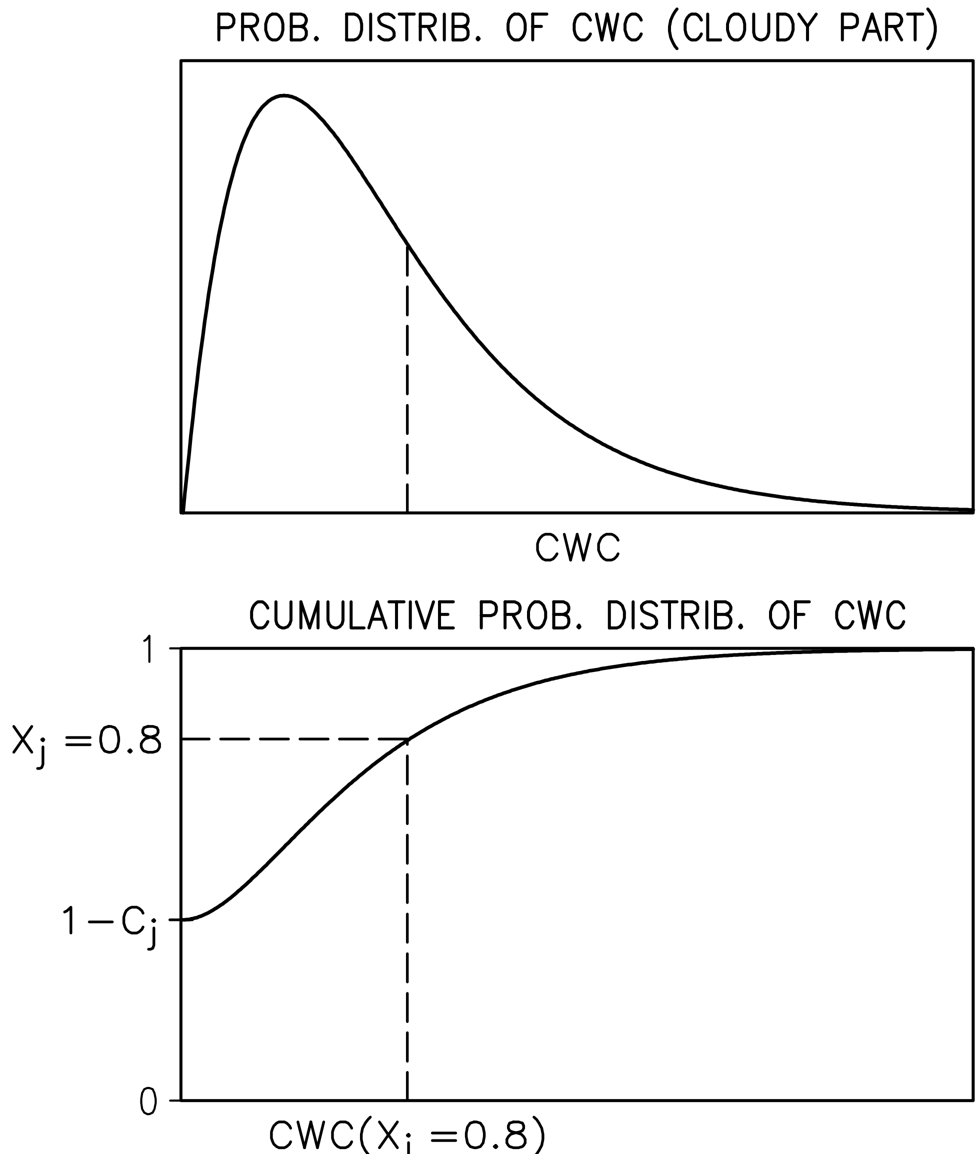
Generation of cloud water content (CWC)

- Assumption: cumulative frequency for cloud fraction (x) can also be used for that:

$$x_j = 1 - C_j \Rightarrow \text{smallest CWC}$$
$$x_j = 1 \Rightarrow \text{largest CWC}$$

- Mean value and standard deviation of CWC from host model (here: CRM data)

- In principle, any form can be assumed for the probability distribution of CWC (β and γ distributions implemented)



4. Cloud data

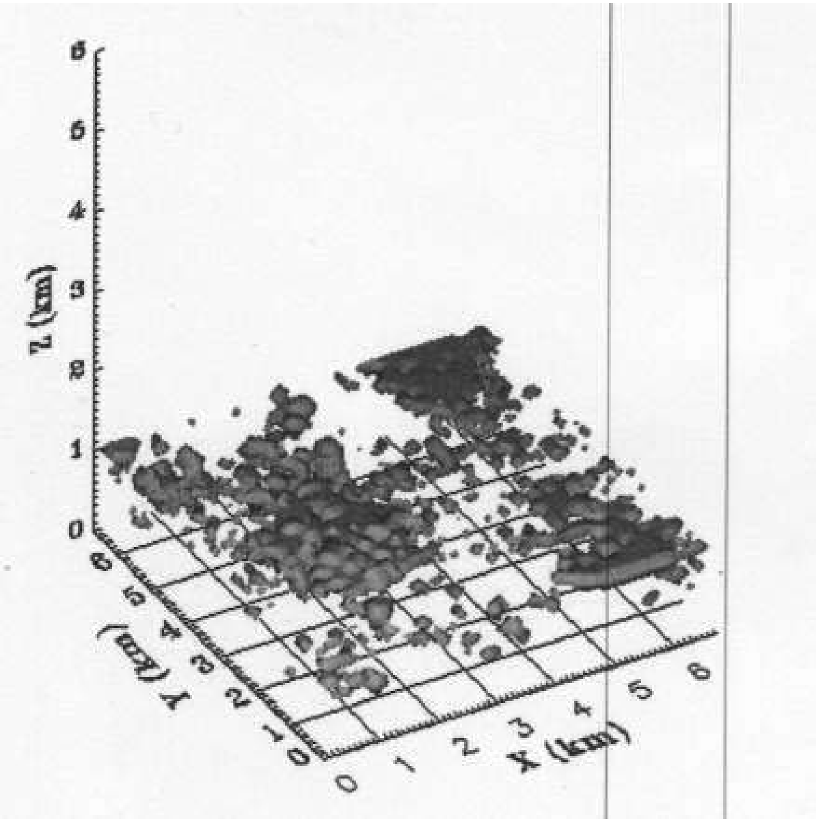
- Cloud condensate fields taken from 3D cloud-resolving model (CRM) simulations

- Boundary layer clouds: ATEX, BOMEX
- Vigorous shallow convection: OPEN CELLS
- Deep tropical convection: GATE_A, GATE_B
  GATE_A-liq, GATE_B-liq

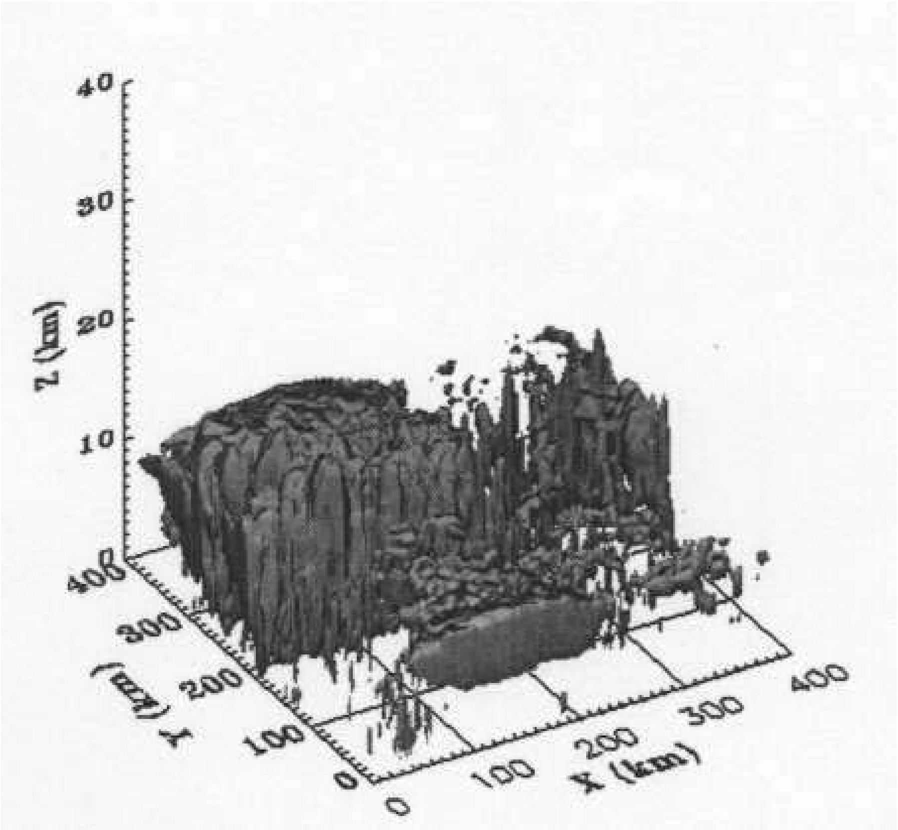
Cloud field statistics

	ΔL (km)	C_{tot}	$\bar{\tau}$	$\sigma_{\tau} / \bar{\tau}$
ATEX	6.8	0.565	15.3	1.49
BOMEX	6.4	0.150	6.3	1.63
OPEN CELLS	50	0.903	55.8	1.38
GATE A	400	0.996	54.9	1.95
GATE B	400	0.999	40.2	2.32
GATE A-liq	400	0.462	62.7	1.99
GATE B-liq	400	0.251	67.1	2.21

ATEX



GATE B



5. Radiation code

- CCC radiation code by Jiagnan Li
- 31 *k* terms in the SW and 46 *k* terms in the LW region

Input for radiation calculations

From CRM data: Cloud fraction

mean LWC, IWC and CWC (=LWC+IWC)

std. dev. of CWC

overlap parameter α

Assumed: fixed effective size for water droplets and ice crystals

$(r_e = 9.9\ \mu\text{m},\ D_{ge} = 50\ \mu\text{m})$

surface albedo = 0.1, solar zenith angle = 60 deg

6. Results

Two sources of error

(a) Cloud generator: not able to simulate cloud field structure perfectly => biases

(b) McICA: incomplete sampling of the cloud field => random errors

6(a). Errors due to the cloud generator

Reference: ICA calculations with original CRM data

Compute errors for McICA with a very large number of columns from the stochastic cloud generator (620 000 for SW, 920 000 for LW) => sampling errors $\rightarrow 0$.

=> denoted as "Stoch_20000"

For comparison, compute errors for

- MRO_pph – maximum random overlap, plane-parallel horizontally homogeneous (pph) clouds
- MRO_var – maximum random overlap, cloud horizontal variations included
- RAN_pph – random overlap, pph clouds
- RAN_var – random overlap, horizontally variable clouds

Errors in total cloud fraction

	Stoch_20000	MRO	RAN
ATEX	0.002	-0.067	0.015
BOMEX	0.000	-0.032	0.033
OPEN CELLS	-0.011	-0.216	0.097
GATE A	-0.002	-0.079	0.004
GATE B	-0.001	-0.019	0.001
GATE A-liq	0.025	-0.265	0.365
GATE B-liq	0.026	-0.170	0.358

Upward SW flux at the TOA (W m^{-2})

(reference values and errors)

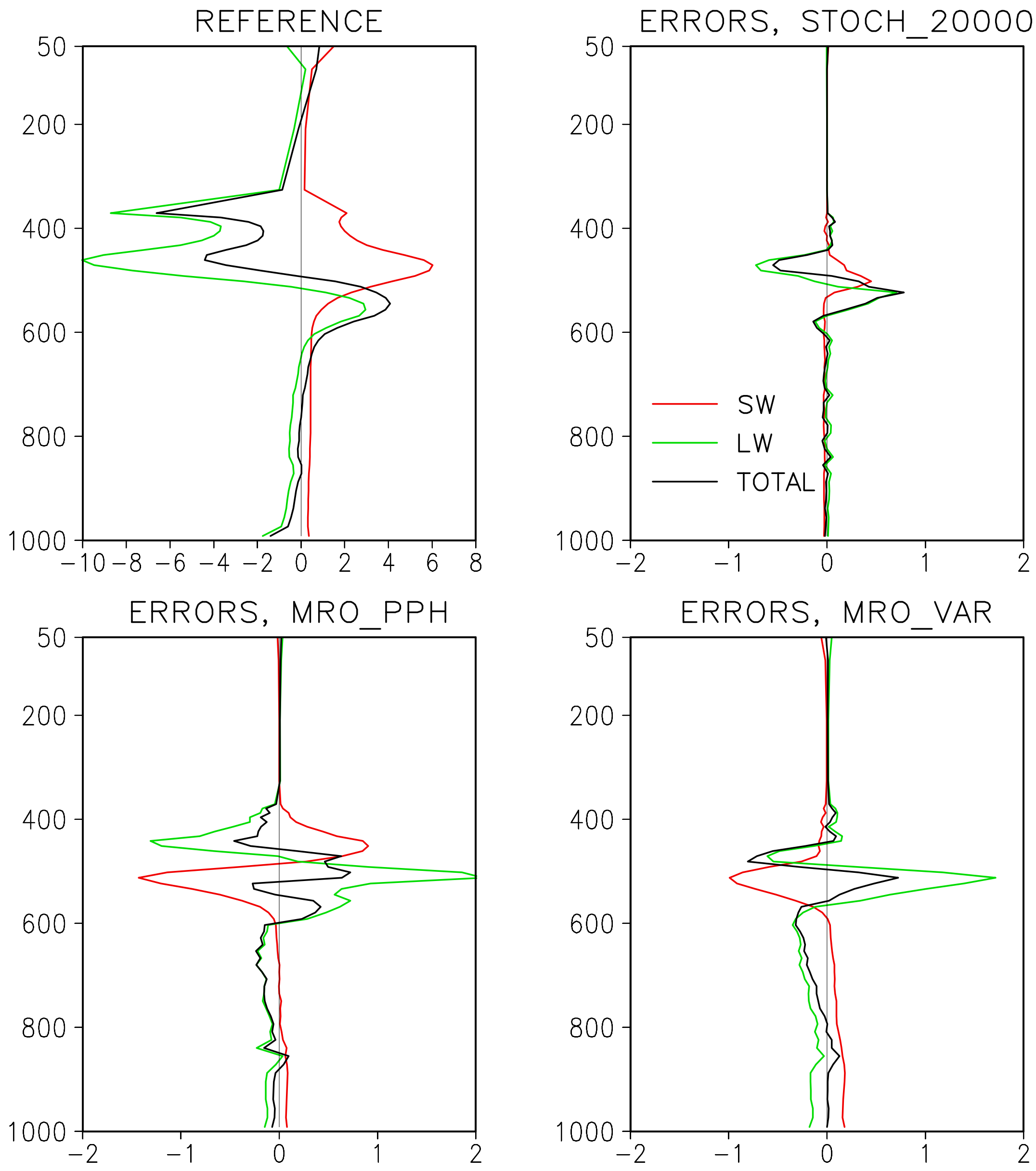
	Ref.	Stoch _20000	MRO _pph	MRO _var	RAN _pph	RAN _var
ATEX	204.1	-2.8	28.3	-21.6	44.4	-0.3
BOMEX	113.8	-0.4	2.8	-4.4	10.5	4.2
OPEN CELLS	388.5	9.9	-26.1	-64.8	99.3	94.8
GATE A	354.2	7.4	18.6	-90.2	118.3	101.8
GATE B	350.1	3.8	67.7	-77.6	112.4	93.2
GATE A-liq	208.3	17.0	-41.4	-58.0	147.1	114.7
GATE B-liq	152.1	12.6	-29.2	-35.3	117.8	93.9

Outgoing LW radiation (W m^{-2})

(reference values and errors)

	Ref.	Stoch _20000	MRO _pph	MRO _var	RAN _pph	RAN _var
ATEX	326.8	0.3	-1.0	1.0	-1.8	0.2
BOMEX	340.8	0.0	-0.1	0.2	-0.5	-0.2
OPEN CELLS	188.4	-0.8	8.7	11.5	-16.6	-15.1
GATE A	178.2	6.3	-4.9	25.9	-16.9	-9.6
GATE B	168.9	16.1	-16.9	36.1	-20.6	-5.4
GATE A-liq	261.4	-0.2	3.4	4.1	-11.6	-9.3
GATE B-liq	270.5	-0.3	1.9	2.2	-9.6	-7.9

HEATING RATES FOR OPEN CELLS (K/d)



6(b). Sampling errors

Reference: McICA calculations with a very large number of columns from the stochastic cloud generator ("Stoch_20000")

Make a sample of 2000 calculations so that there is only one loop over the *k* distribution (i.e., one subcolumn per *k* term) ("Stoch_1").

Compute error statistics compared to Stoch_20000.

RMS sampling errors for Stoch_1 (W m^{-2} or K day^{-1})

	$F^{\uparrow}_{SW}$	$F^{\uparrow}_{LW}$	$(\partial T / \partial t)_{SW}$	$(\partial T / \partial t)_{LW}$
ATEX	73.9	3.3	0.59	0.88
OPEN_CELLS	72.9	10.4	1.18	2.15
GATE B	73.6	14.8	0.98	1.14
GATE B-liq	76.3	6.9	0.61	0.89

Reduction of sampling errors:
Trick 1: Use only cloudy columns for McICA

Estimate all-sky fluxes as

$$F_{\mathrm{all}} = C_{tot} F_{\mathrm{cloudy}} + (1 - C_{tot}) F_{\mathrm{clear}}$$

This is not expensive because

-- Clear-sky fluxes F_{clear} are computed for diagnostics

-- Total cloud fraction C_{tot} can be estimated rapidly using the cloud generator (here, 300 columns used for that)

These results are denoted as "Stoch_1*"

RMS sampling errors for Stoch_1* (W m^{-2} or K day^{-1})

(relative differences to (%) Stoch_1 in blue.)

	$F^{\uparrow}_{SW}$	$F^{\uparrow}_{LW}$	$(\partial T/\partial t)_{SW}$	$(\partial T/\partial t)_{LW}$
ATEX	39.5 (-47)	1.5 (-55)	0.39 (-34)	0.54 (-38)
OPEN_CELLS	46.1 (-37)	4.6 (-56)	1.09 (-8)	1.95 (-9)
GATE B	74.3 (1)	14.7 (-1)	0.96 (-2)	1.13 (-1)
GATE B-liq	20.5 (-73)	2.7 (-61)	0.32 (-48)	0.45 (-49)

Reduction of sampling errors: Trick 2: Improved spectral sampling

The best strategy is not to use equally many subcolumns for every k term but to add the extra subcolumns for those k terms that are associated with large cloud radiative effects.

Test: Use 50% more subcolumns (47 in the SW, 69 in the LW)
(and include Trick 1: only cloudy columns for McICA)

=> Stoch_1.5*

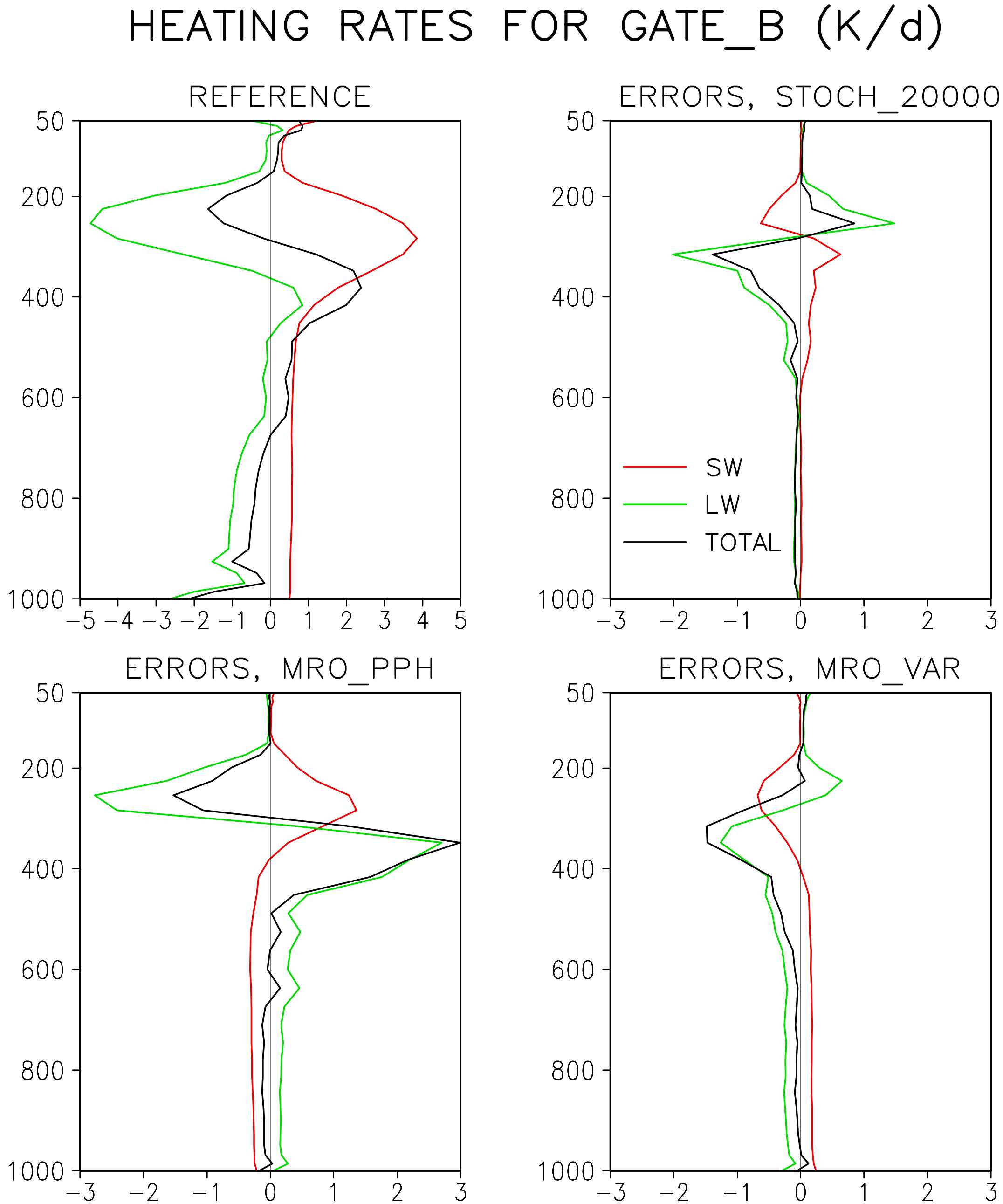
RMS sampling errors for Stoch_1.5* (W m^{-2} or K day^{-1})

(relative differences (%) to Stoch_1* in red and to Stoch_1 in blue.)

	$F^{\uparrow}_{SW}$	$F^{\uparrow}_{LW}$	$(\partial T/\partial t)_{SW}$	$(\partial T/\partial t)_{LW}$
ATEX	18.1 (-54 / -76)	0.7 (-53 / -79)	0.16 (-57 / -72)	0.20 (-63 / -77)
OPEN_CELLS	20.8 (-55 / -71)	2.1 (-54 / -80)	0.58 (-46 / -51)	0.99 (-49 / -54)
GATE B	32.4 (-56 / -56)	6.1 (-59 / -59)	0.48 (-50 / -51)	0.59 (-47 / -48)
GATE B-liq	10.7 (-48 / -86)	1.2 (-56 / -83)	0.14 (-55 / -77)	0.19 (-58 / -78)

7. Conclusions

- A simple stochastic cloud generator has been developed for use in McICA radiation calculations
- Systematic errors in cloud cover, radiative fluxes and heating rates are significantly smaller than for traditional cloud overlap assumptions
- Random errors can be reduced substantially by improved sampling of the cloud field and improved spectral sampling



HEATING RATES FOR GATE_B (K/d)
REFERENCE
ERRORS, STOCH_20000
ERRORS, MRO_PPH
ERRORS, MRO_VAR
SW
LW
TOTAL
50
200
400
600
800
1000
−5 −4 −3 −2 −1 0 1 2 3 4 5
−3 −2 −1 0 1 2 3