Radiation: Fast physics with slow consequences in an uncertain atmosphere

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Context (i)

Compare

$$\begin{aligned}\boldsymbol{\Omega}\cdot\nabla I(\mathbf{x}) = & -\sigma(\mathbf{x})I(\mathbf{x}) \\ & +\sigma(\mathbf{x})\omega_0(\mathbf{x})\int_{4\pi} I(\mathbf{x})P(\mathbf{x},\boldsymbol{\Omega}'\rightarrow\boldsymbol{\Omega})d\boldsymbol{\Omega}' \\ & +Q\end{aligned}$$

and

$$\frac{dl}{dt} = A(l) + S_{CV} + S_{BL} + C - E - G_p - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'l'})$$

Context (ii)

Dynamical models require grid-scale radiative heating rates and fluxes at the boundaries.

This implies

- broadband (integrated over complete shortwave and longwave spectra)
- flux calculations (neglecting detailed angular structure)

Context (iii)

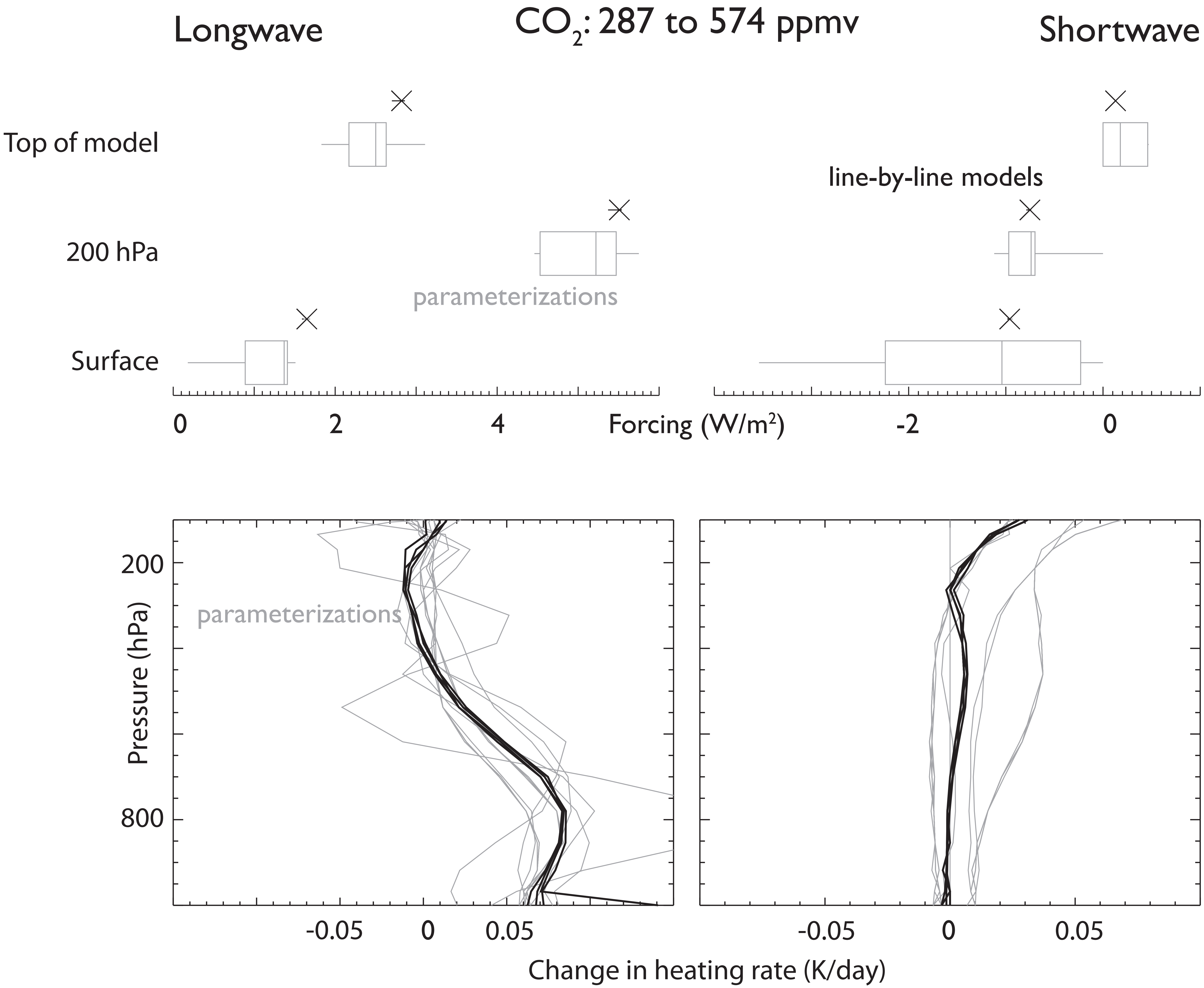
Radiation changes the circulation slowly. In most circumstances it's either a small contributor to heating rates or it's very steady

Clear-sky error budgets

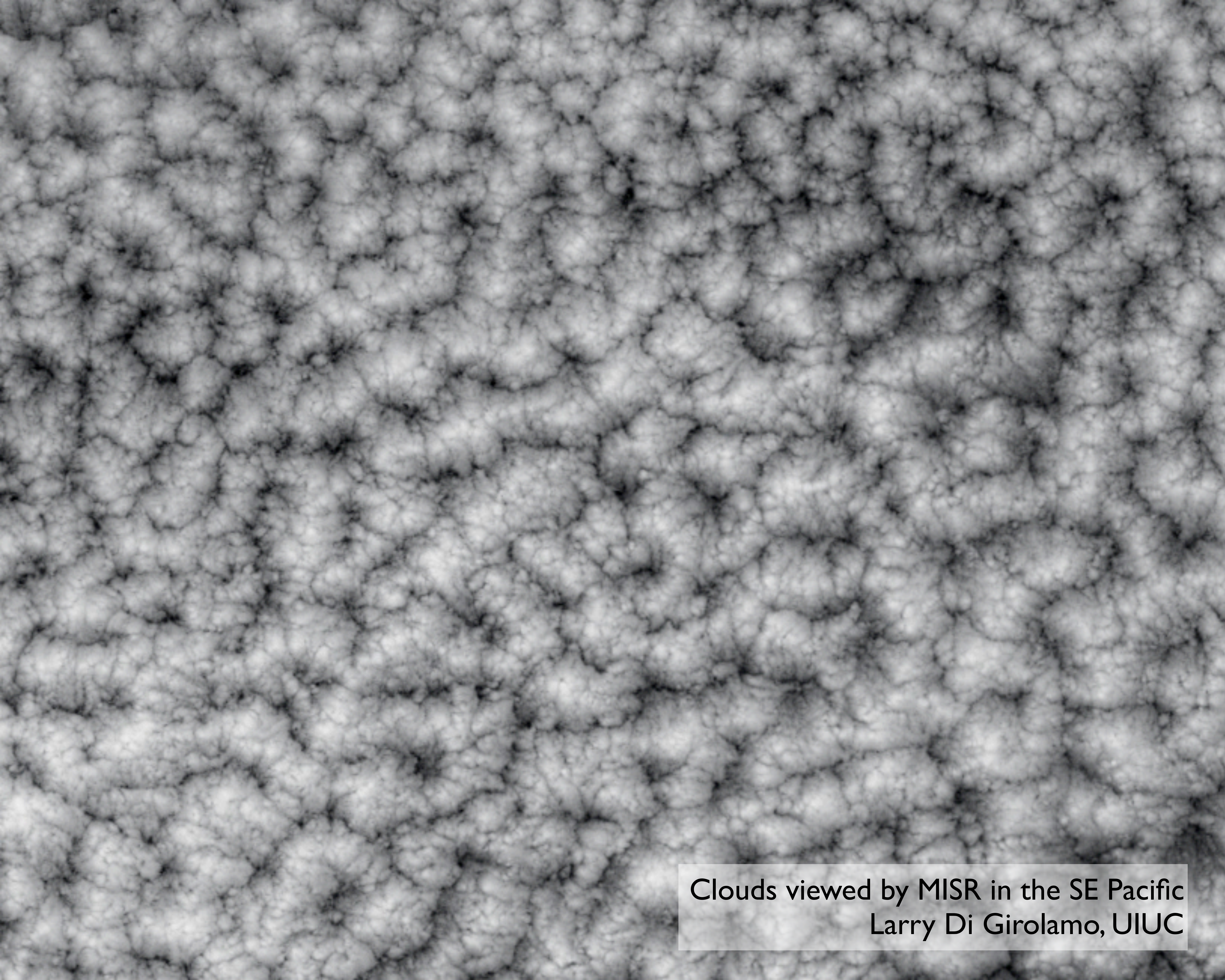
The clear sky is approximately optically homogeneous

Error sources include:

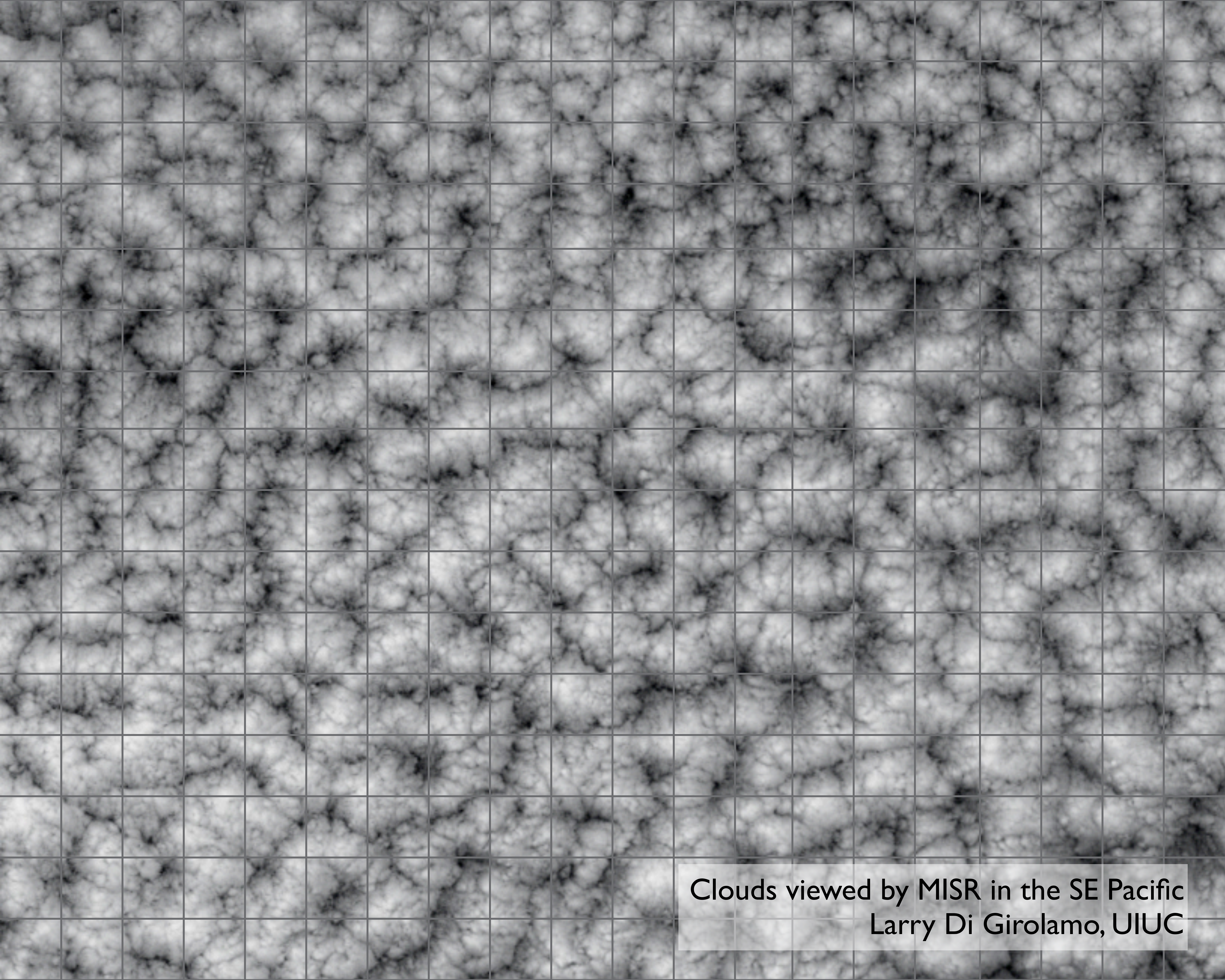
spectroscopy
angular discretization
spectral discretization
approximations (dimensionality, phenomenology)



After Collins et al, 2006
10.1029/2005JD006713



Clouds viewed by MISR in the SE Pacific
Larry Di Girolamo, UIUC



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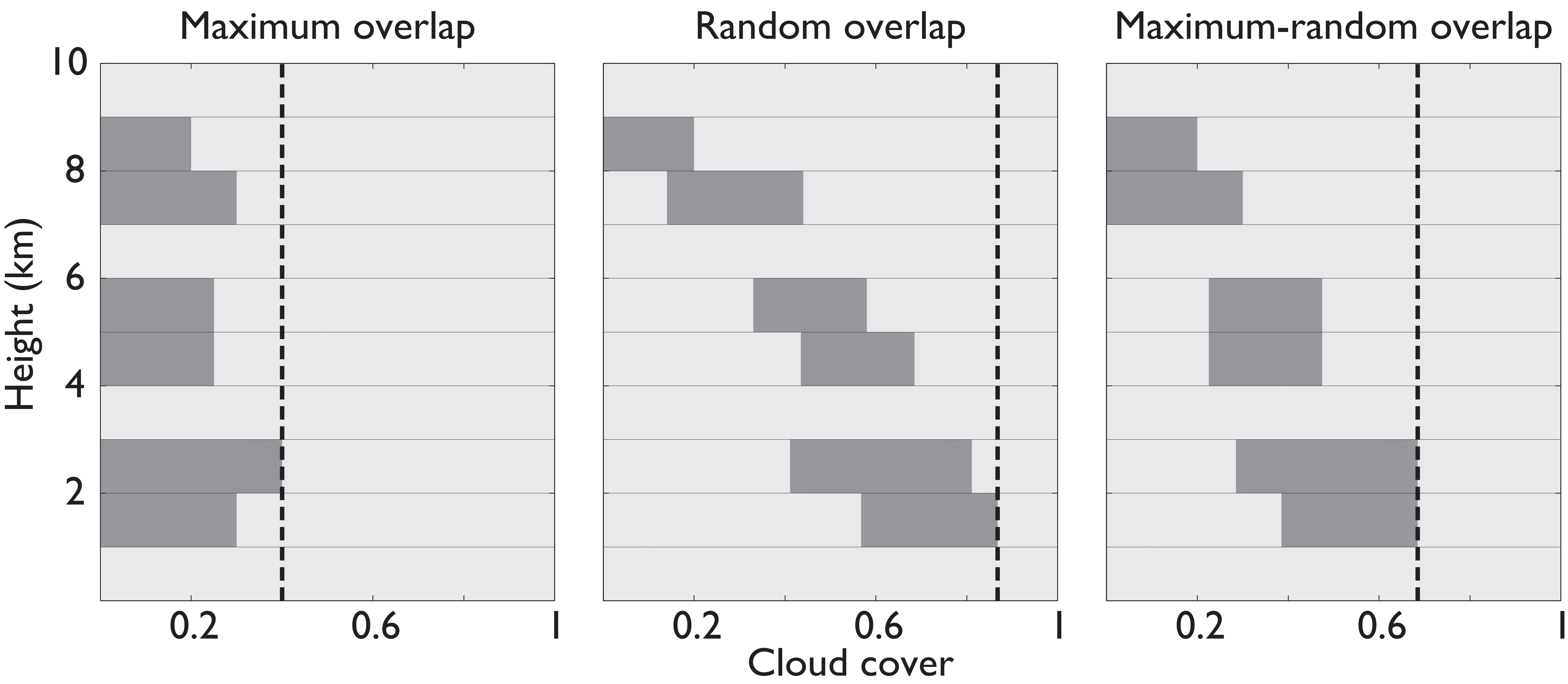
Radiation is non-linear, so fluxes and heating rates from grid-mean properties don’t produce grid-mean values

Variability arises from multiple partially-cloudy layers

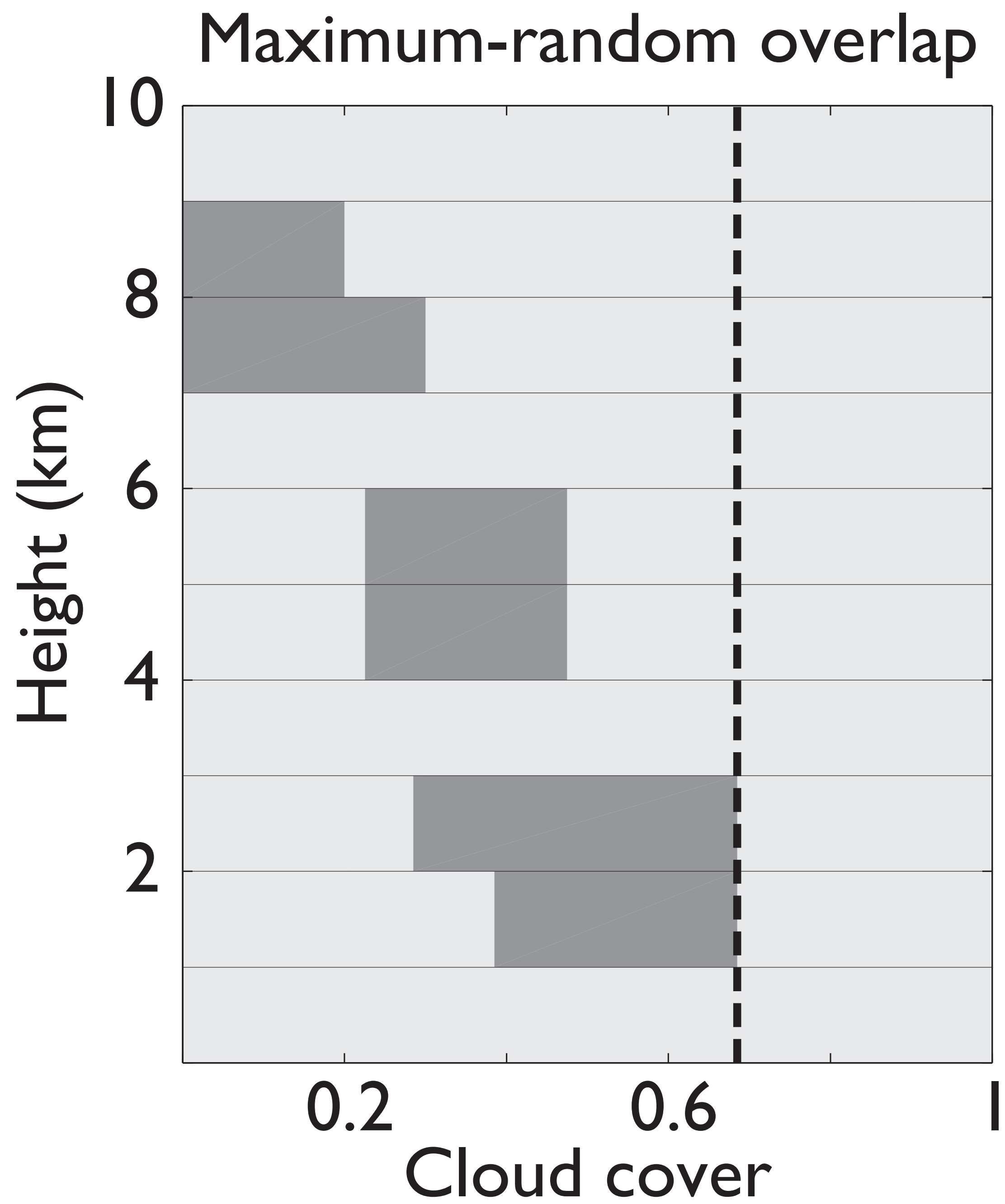
Horizontal variability is also present in nature.
In models it is normally tuned away but needn’t be (see under “assumed-PDF cloud schemes”)

Overlap assumptions in global models



After Hogan and Illingworth, 2000
10.1002/qj.49712656914

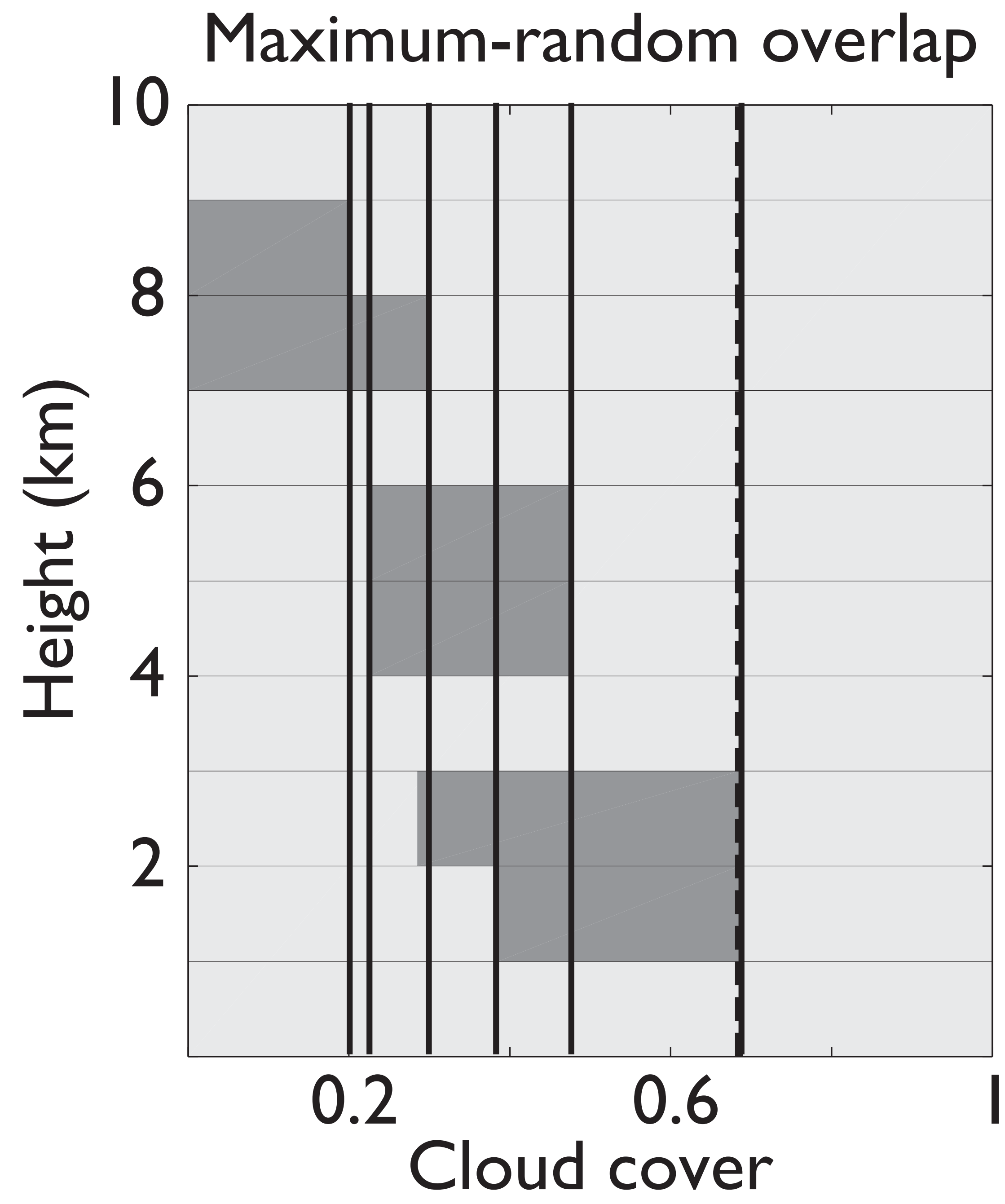
Overlap assumptions in global models



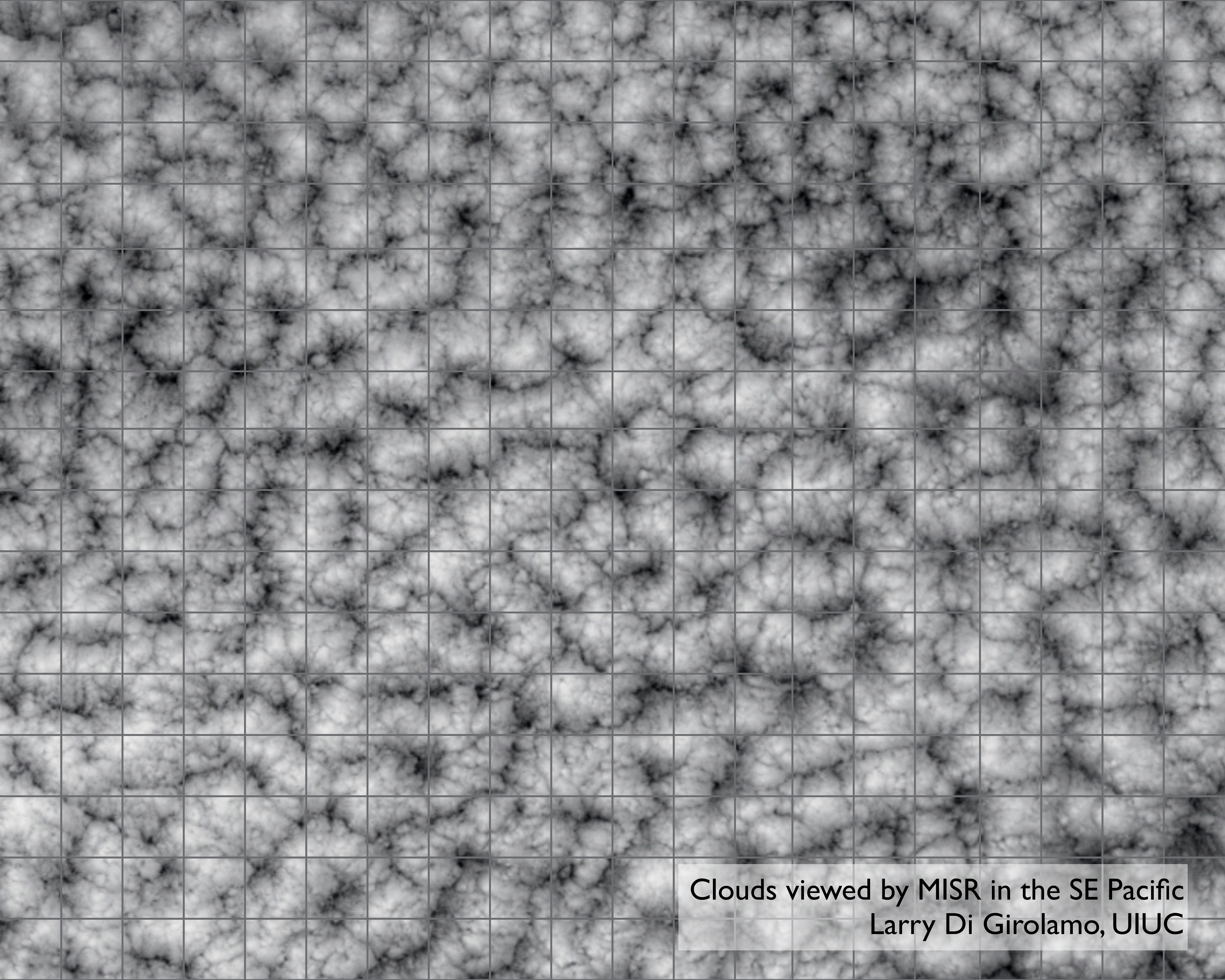
After Hogan and Illingworth, 2000
10.1002/qj.49712656914

Overlap assumptions in global models

Six cloudy configurations



After Hogan and Illingworth, 2000
10.1002/qj.49712656914



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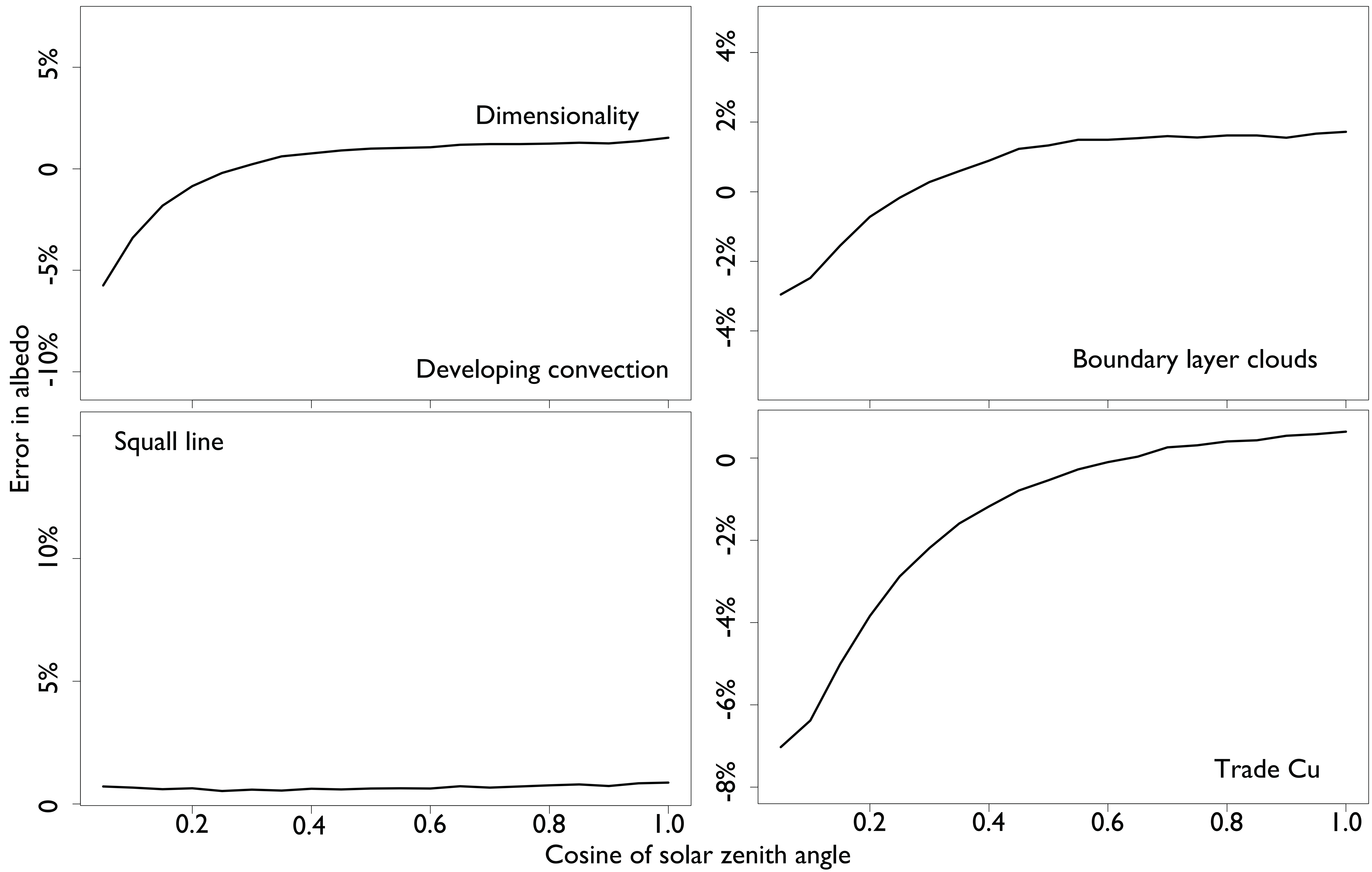
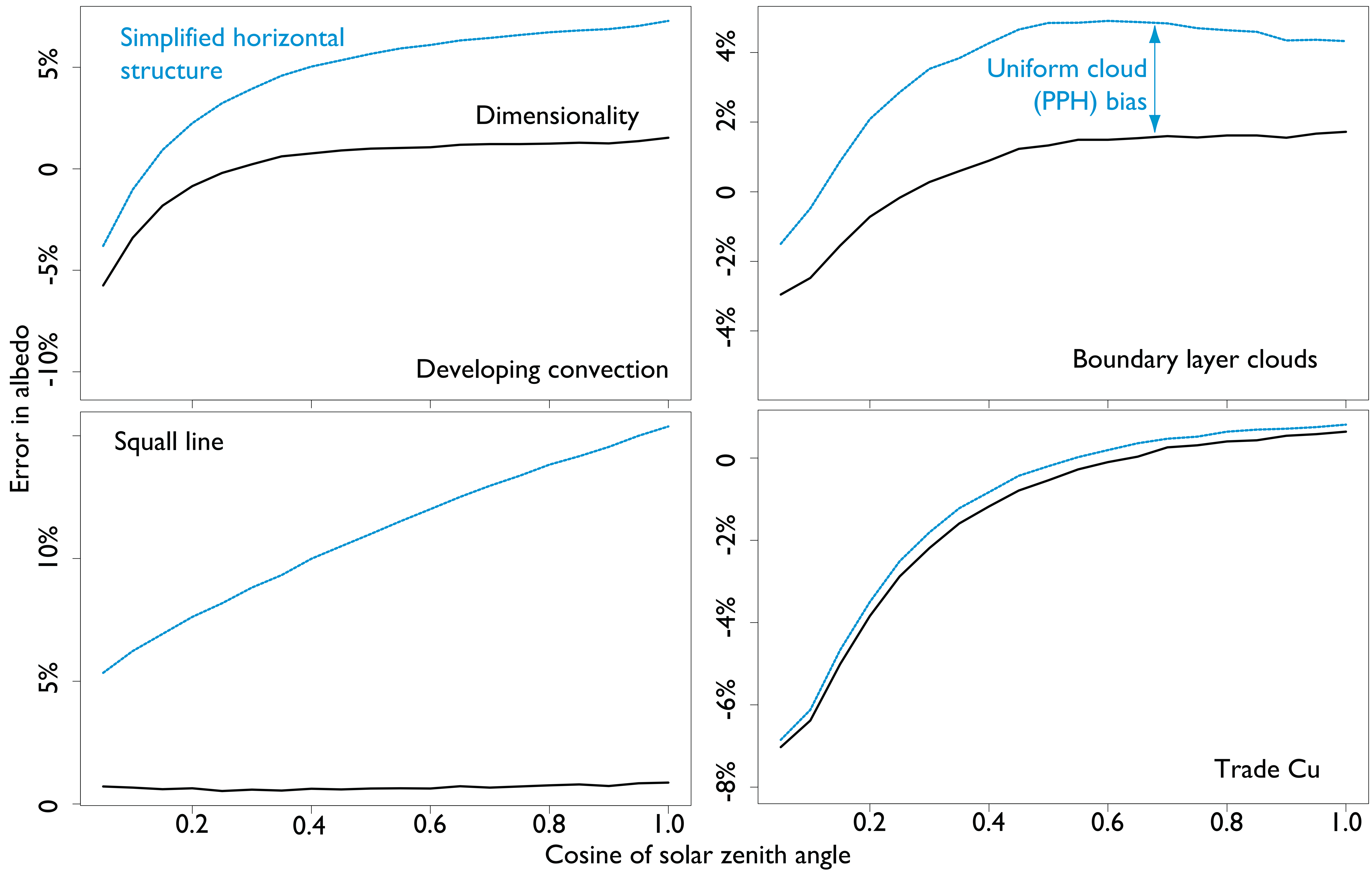


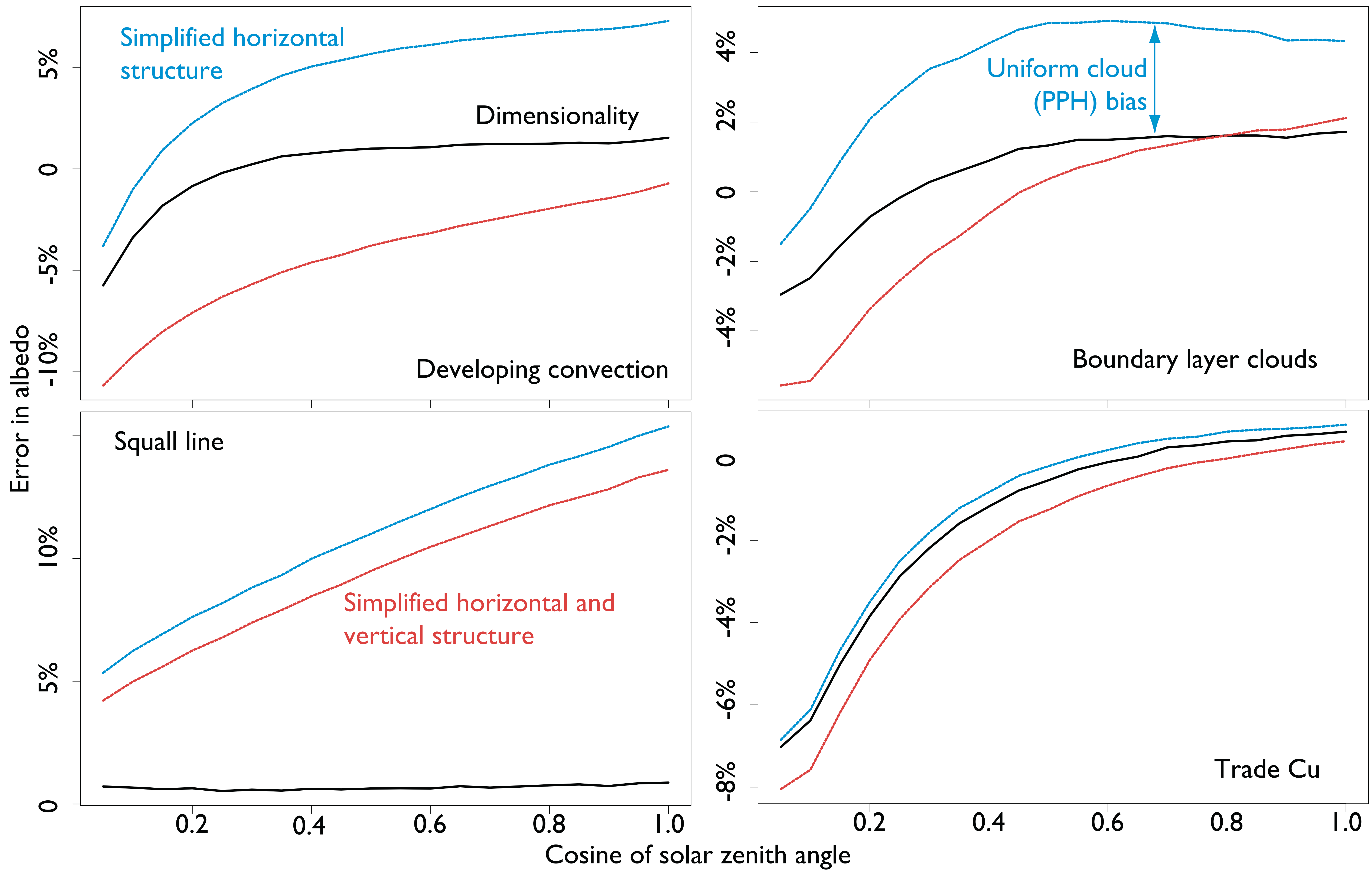
After Barker et al., 2003

10.1175/1520-0442(2003)016<2676:ADASRT>2.0.CO;2



After Barker et al., 2003

10.1175/1520-0442(2003)016<2676:ADASRT>2.0.CO;2



After Barker et al., 2003
10.1175/1520-0442(2003)016<2676:ADASRT>2.0.CO;2

Options for treating variability ca. 2002

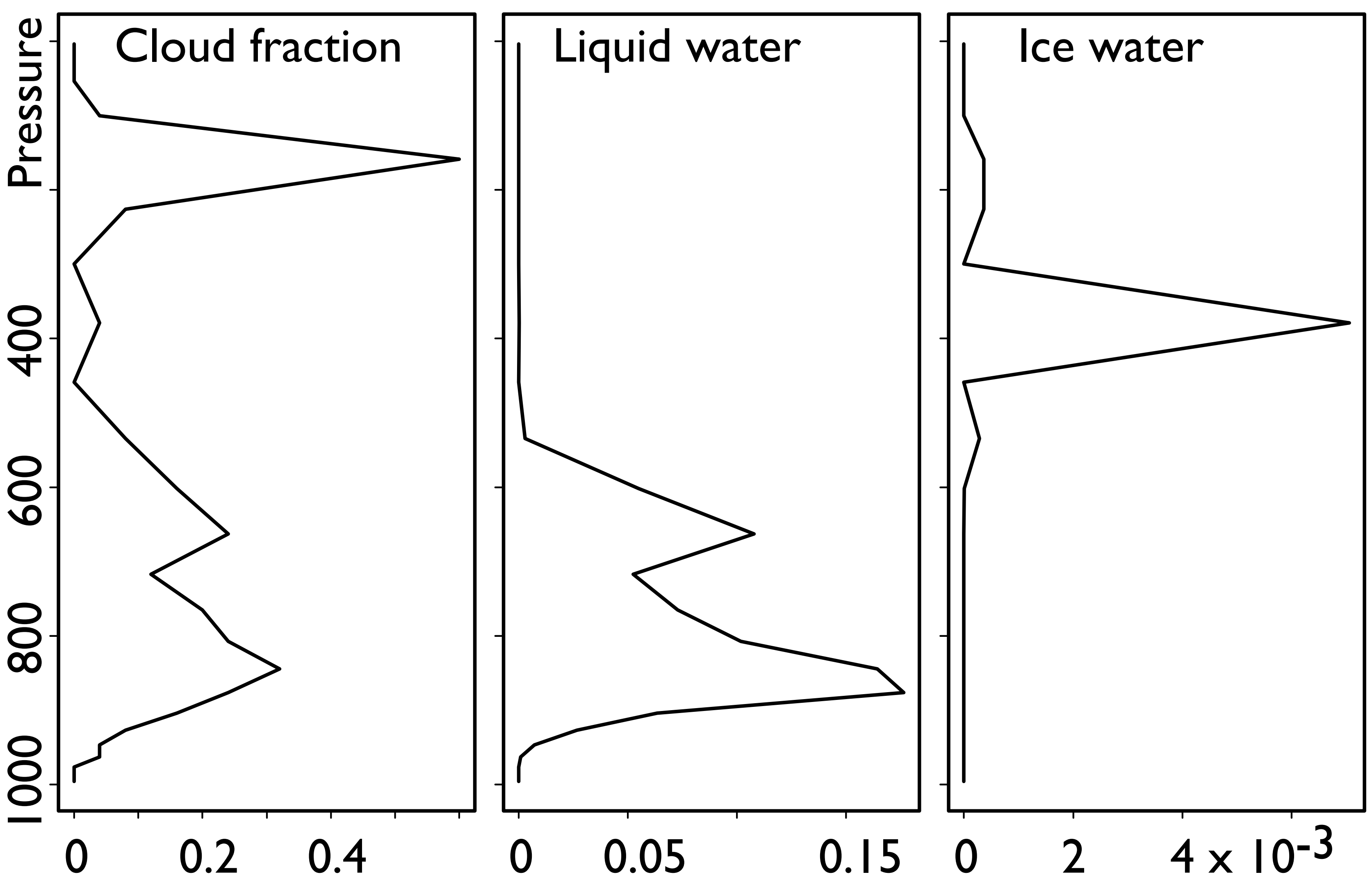
"Tuning" (essentially every model does this)

Closures (H. Barker's Γ-weighted two-stream approx.)

Analytic treatments,
incl. rescaling for internal variability (B Cairns, GW Petty, ...)
and treatments for overlap (none agreeing with benchmarks)

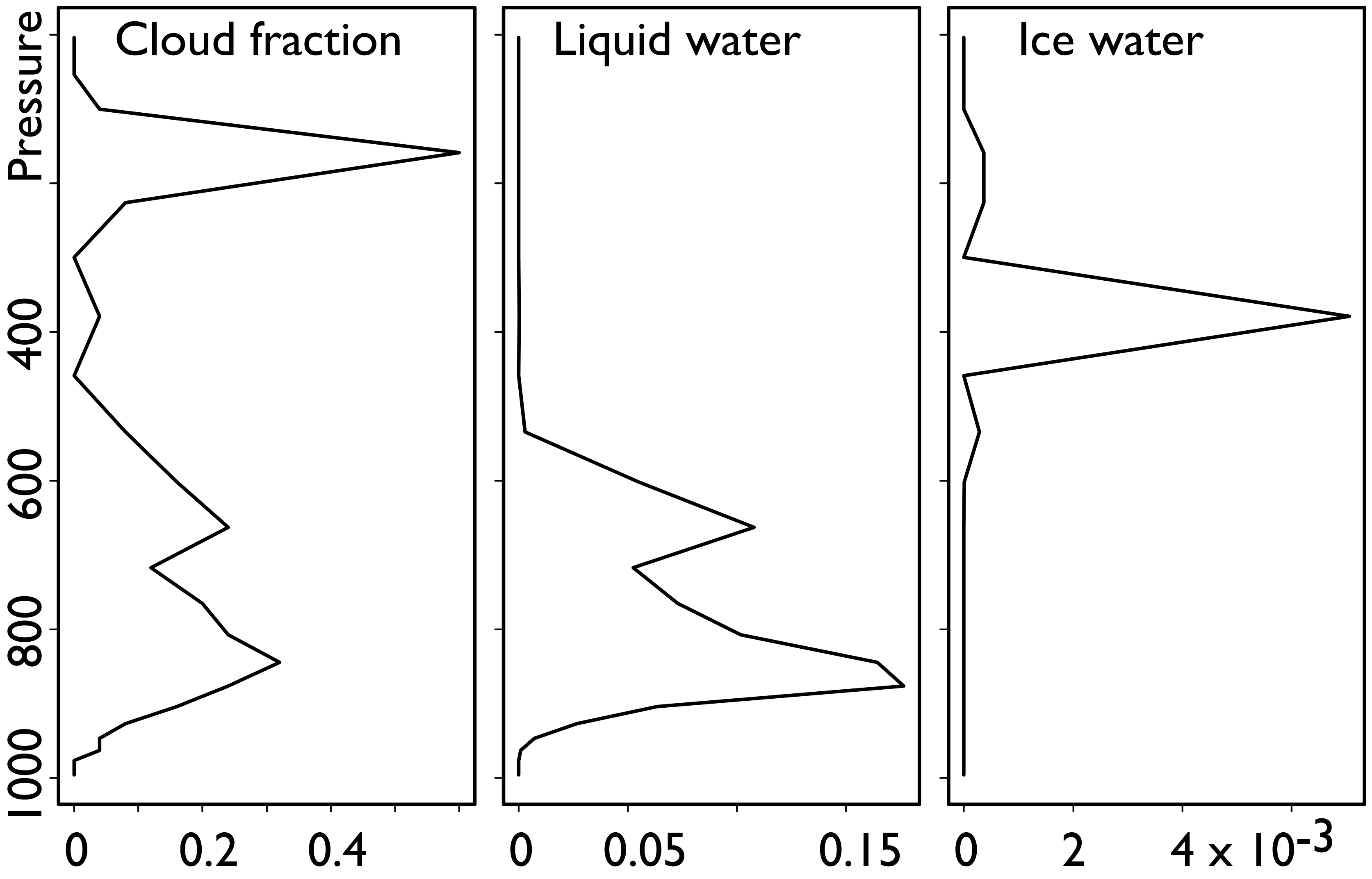
Enumeration/ICA (C Stubenrauch, WD Collins)

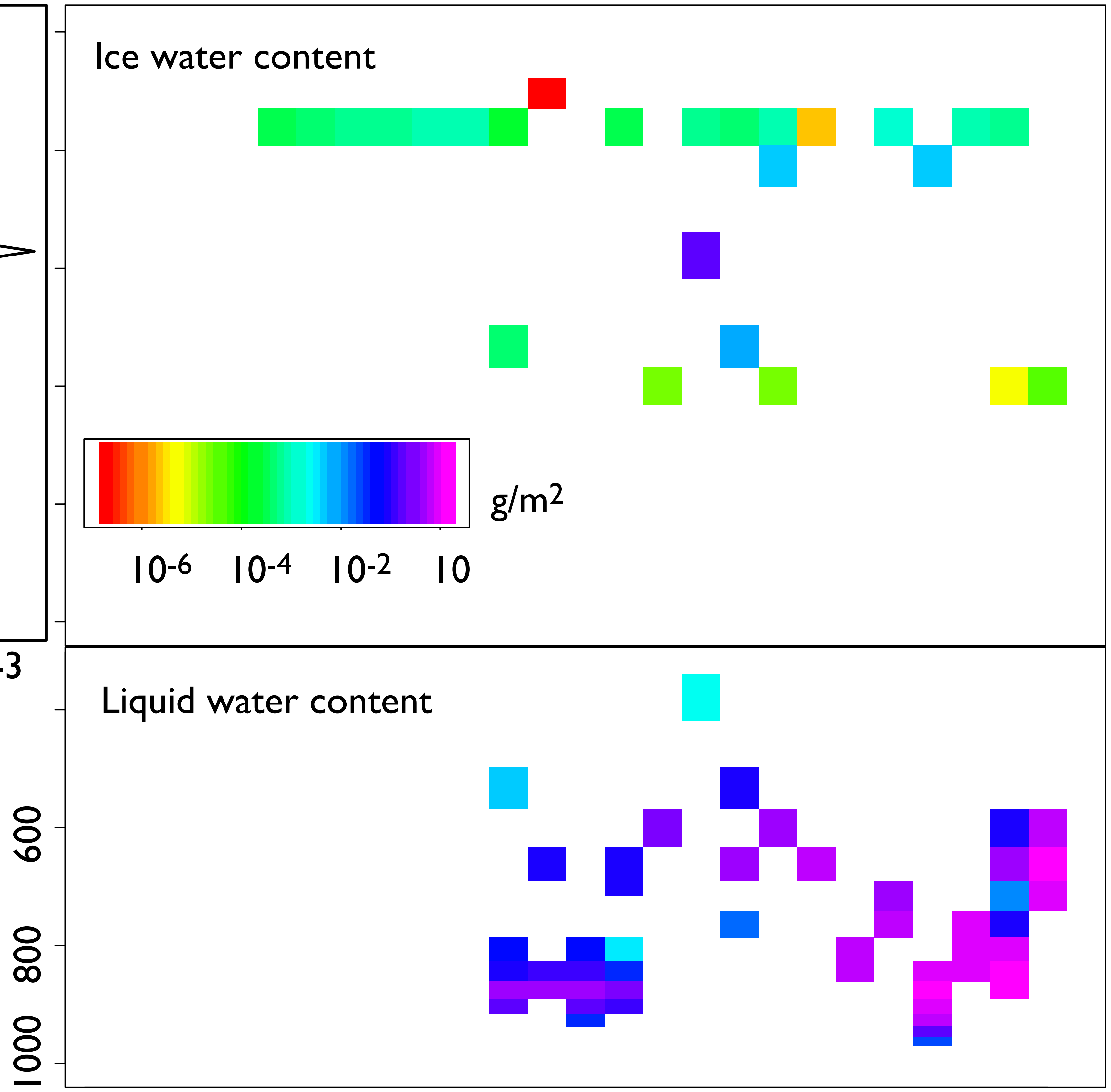
Sampling variability



Pincus et al., 2006
10.1175/MWR3257.1

Sampling variability





PDF diagnosed from cloud fraction and condensate amounts

Pincus et al., 2006
10.1175/MWR3257.1

Stochastic solution 1: Treating variability

Spectral integration requires hundreds of calculations

$$\overline{F}(x,y,T) = \sum_{g}^{G} w_g F_g(x,y,T)$$

Broadband fluxes in variable clouds require a 2D integral

$$\overline{F}(x,y,T) = \sum_{s}^{S} w_s \sum_{g}^{G} w_g F_g(s;x,y,T)$$

Stochastic solution 1: Treating variability

Insight 1: We can get away with a subset of the full integral

$$\overline{F}(x, y, T) \approx \sum_{g}^{G} w_g F_g(s'_g; x, y, T)$$

This is McICA (Monte Carlo Independent Column Approximation)

It's a time-saving approximation. Success means *not* changing model evolution

McICA introduces Monte Carlo sampling noise

- The amount of noise depends on the cloud fields, and so on the model being used
- Single-sample estimates from global models are O(10) W/m^2 in TOA fluxes
  (Heating rates are a few percent)
- Noise is limited because spectral dimension is completely sampled

For the algorithm to "work" the host model must not be sensitive to shaking at small scales

- More than half-a-dozen global models have been robust

Radiation for cloud scale models

At the other end of the spectrum are large-eddy simulations. Mesh sizes are *O*(10 - 100 m); grid cells are internally homogeneous. At smallest scales 3DRT is strictly required

Large eddy simulations often use idealized radiation (in keeping with idealized scenarios)

This is limiting but radiation calculations are time-consuming

Radiation for random samples (iii)

Insight 2: Frequent subsets of the spectral integration are an unbiased estimate of the full caluculation

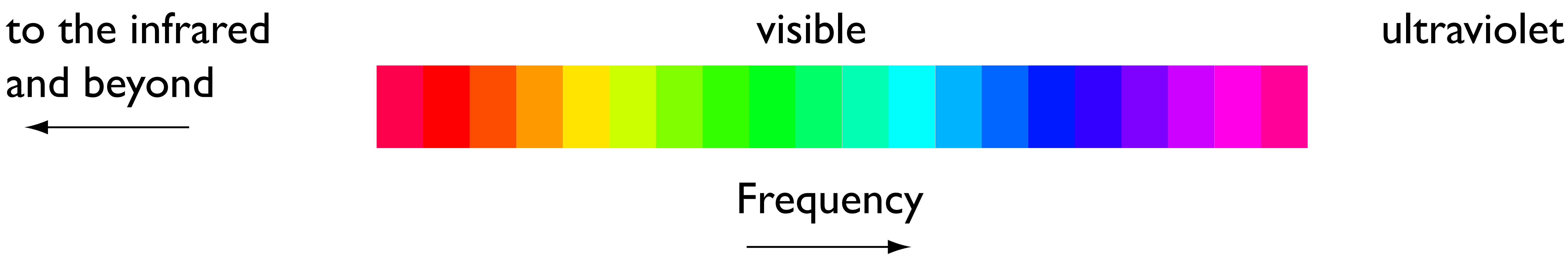
$$\overline{F}(x,y,t) \approx \sum_{g}^{\tilde{G}} w_g F_g(s'_g; x, y, t)$$

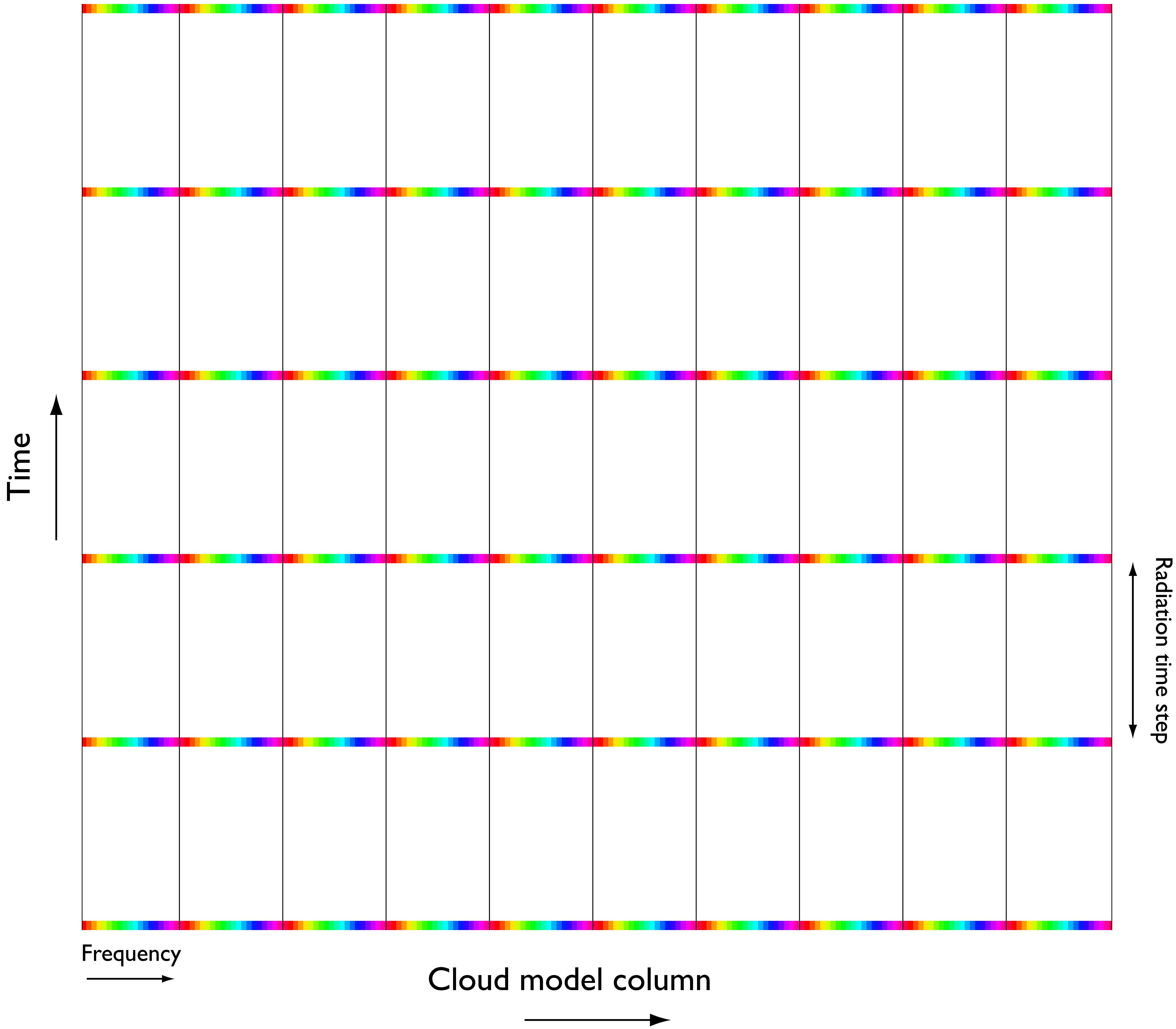
This approach

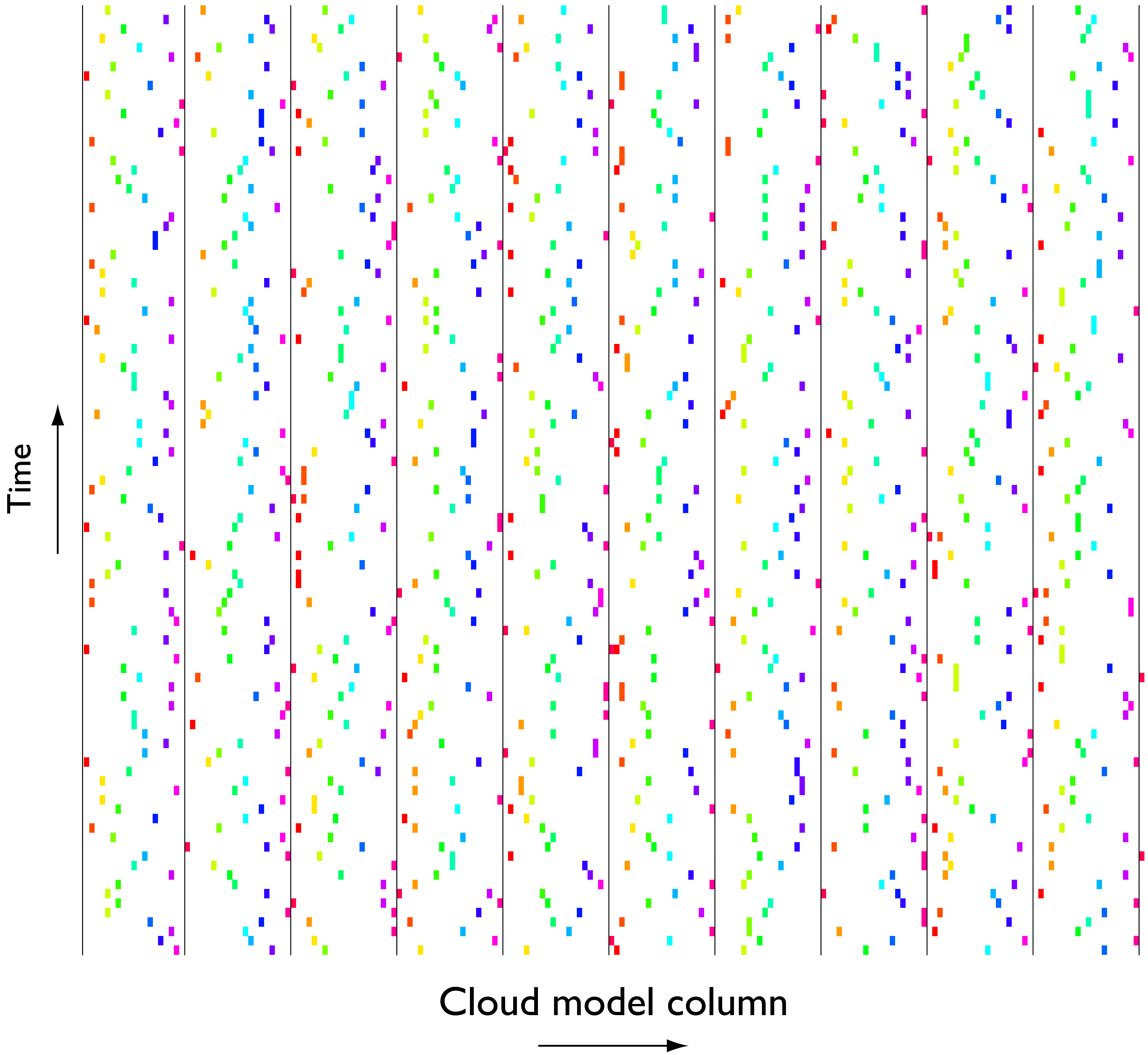
samples temporal variability

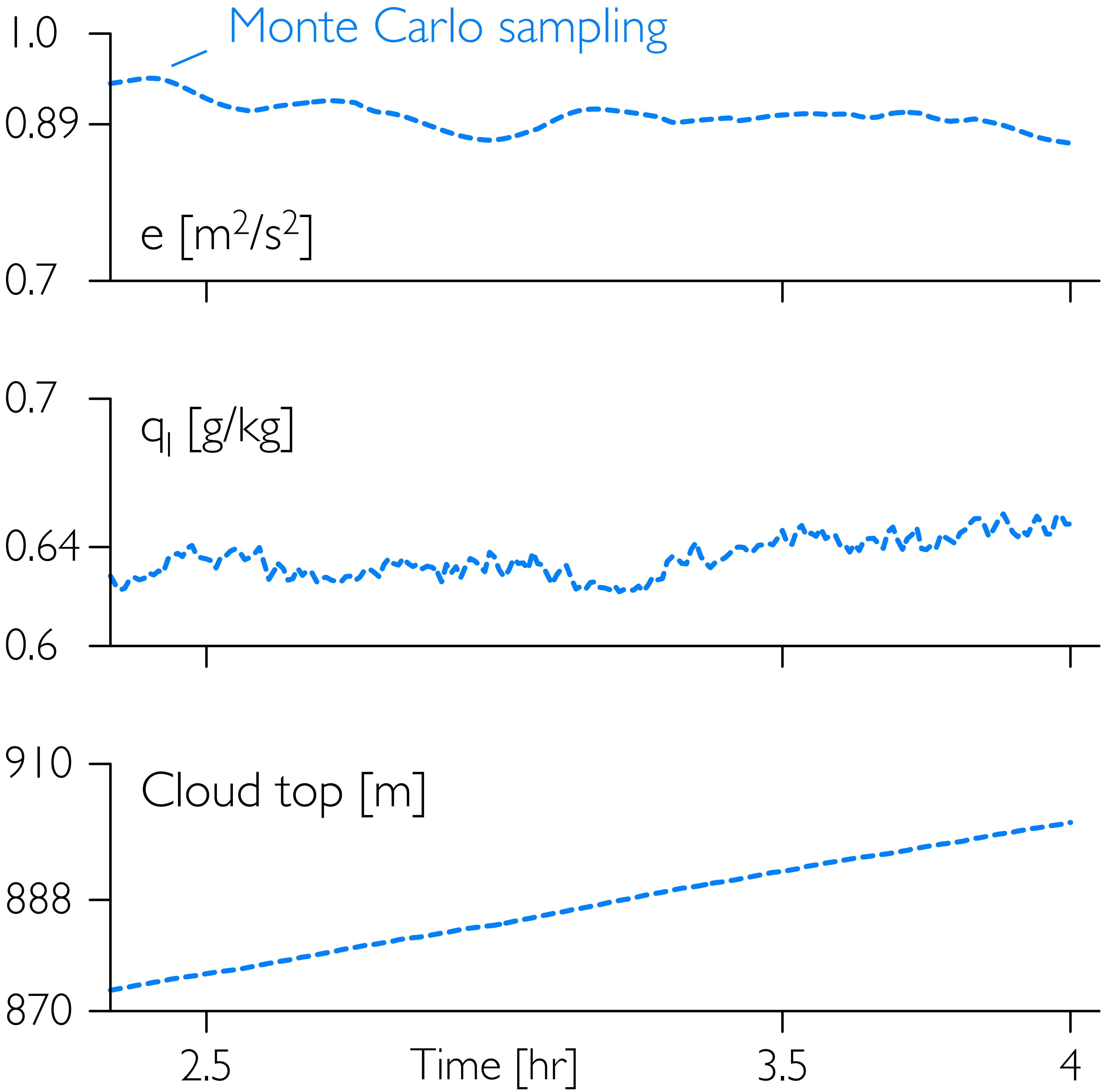
saves computation time if $\tilde{G}(T/t) < G$

converges like an LES

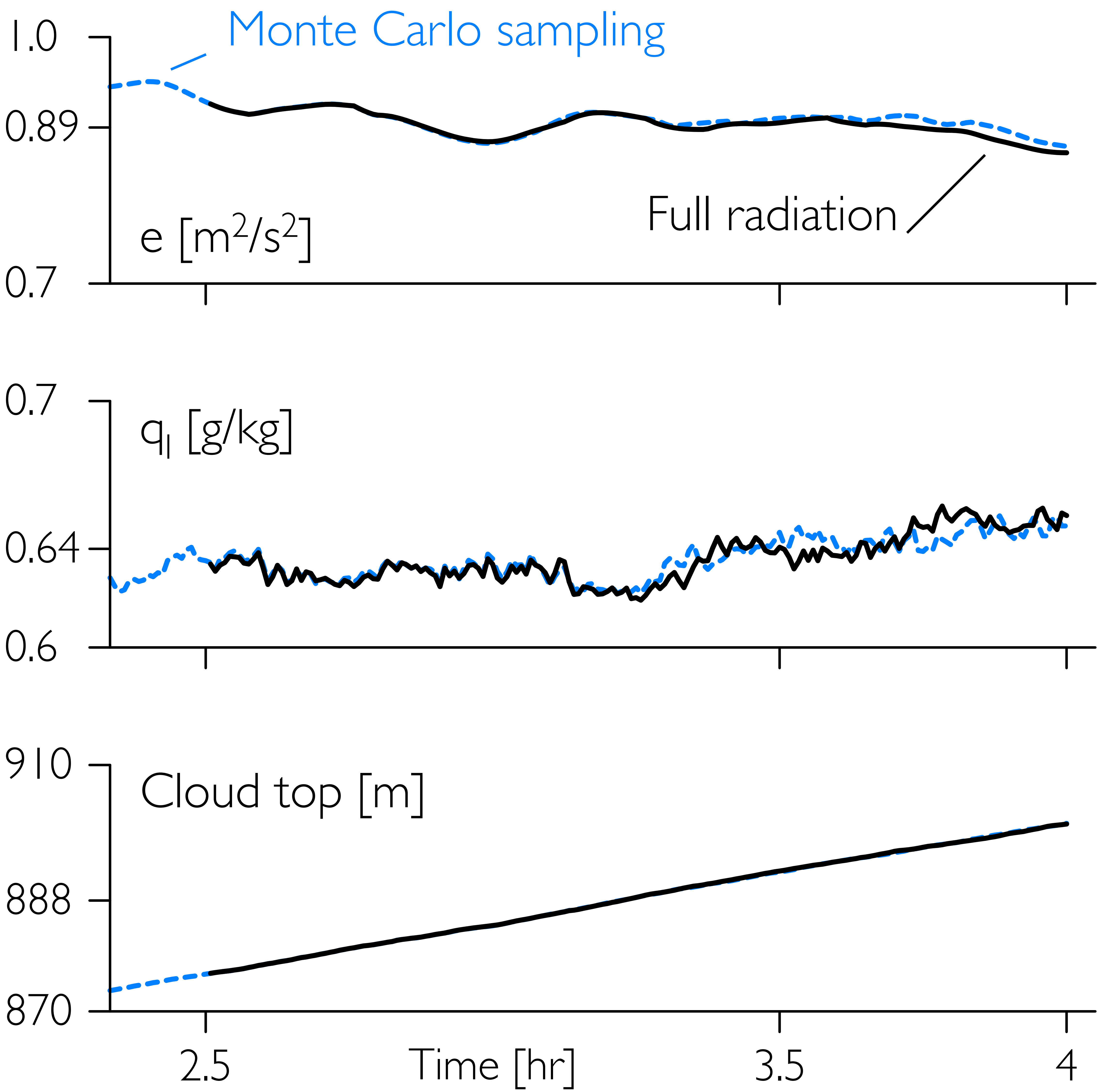

to the infrared
and beyond
visible
ultraviolet
Frequency


Time
Radiation time step
Frequency
Cloud model column


Time
Cloud model column



Pincus and Stevens, 2009
10.3894/JAMES.2009.1.1



Pincus and Stevens, 2009
10.3894/JAMES.2009.1.1

In a mixed-layer model we can calculate the scale-dependent perturbation in kinetic energy due to the approximation

$$\frac{e'_\ell}{\overline{e}_\ell} \propto \alpha^{2/3} \frac{\delta x}{\ell} \left(\frac{\ell}{h} \right)^{1/9} .$$

Monte Carlo spectral integration introduces noise in heating rates, but that noise is

large at the smallest scales (where it diffuses away quickly)

small at resolved scales (relative to the energy from other sources)

Comments

Here there is no PDF of cloud properties to sample, but spectral sampling is incomplete

Once in a while this produces very large single-step perturbations in heating rates and surface fluxes

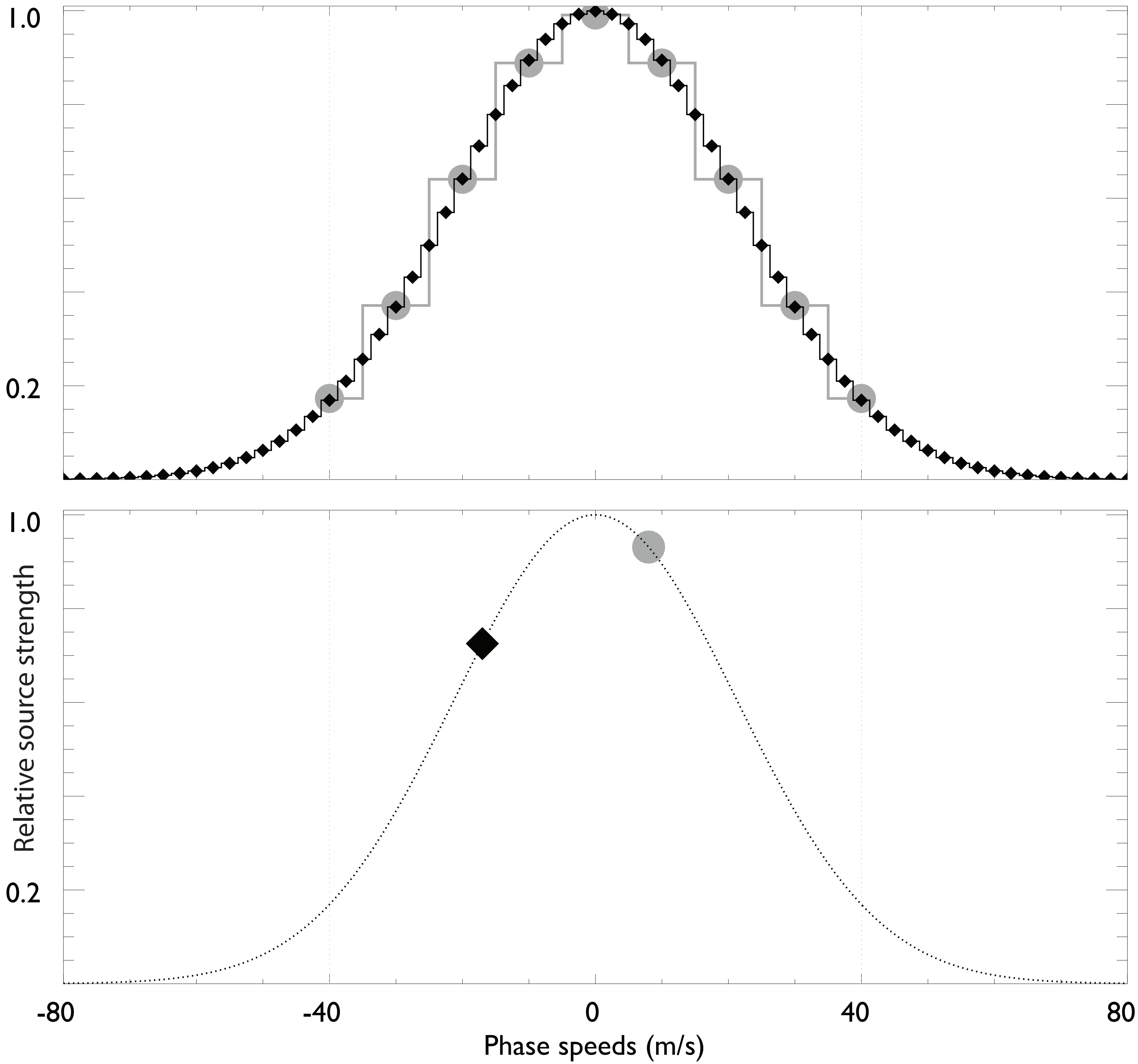
Large perturbations "break" GCMs because

- the surface temperature is affected by the surface flux, and
- parameterizations in GCMs are more non-linear than in LES

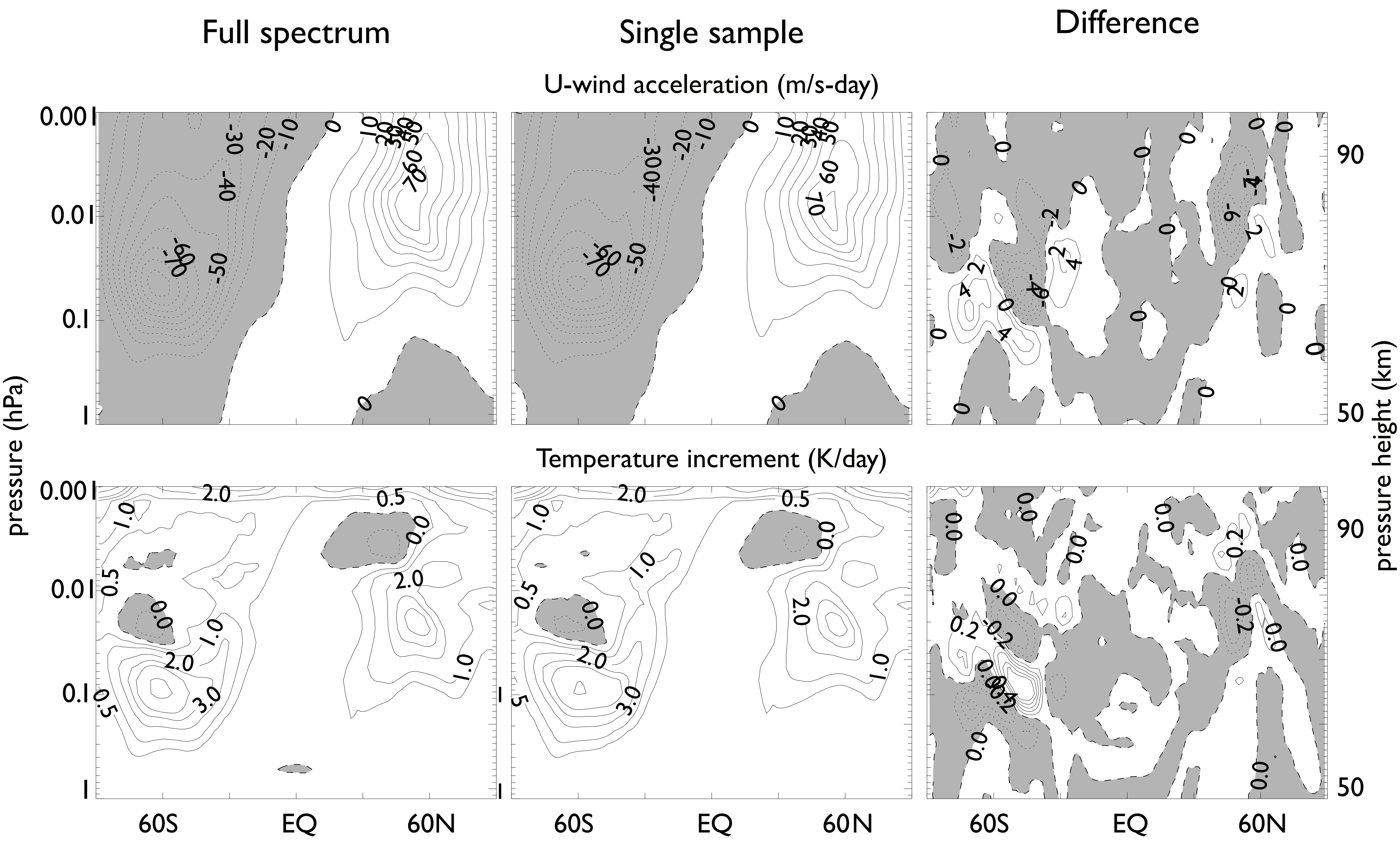
(We're working on ways around this)

These two radiation algorithms are stochastic (non-deterministic) but they are aimed at reducing model error, not representing uncertainty

“... the equilibrium spectrum and source intermittency should emerge only over a volume and time both large and long enough, respectively, for the full ensemble of sources and waves to form and equilibrate. The deterministic parameterization assumes that this equilibrium state exists within each GCM grid box. Yet, given gravity-wave horizontal wavelengths of up to 1000 km and periods and group-propagation times of up to a day, typical GCM grid-box dimensions of 10-1000 km and time steps of 1-60 min would not appear to be either large or long enough, respectively, for this wave ensemble to emerge.” Steve Eckerman (2011, doi:10.1175/2011JAS3684.1)



After Eckerman, 2011
10.1175/2011JAS3684.1



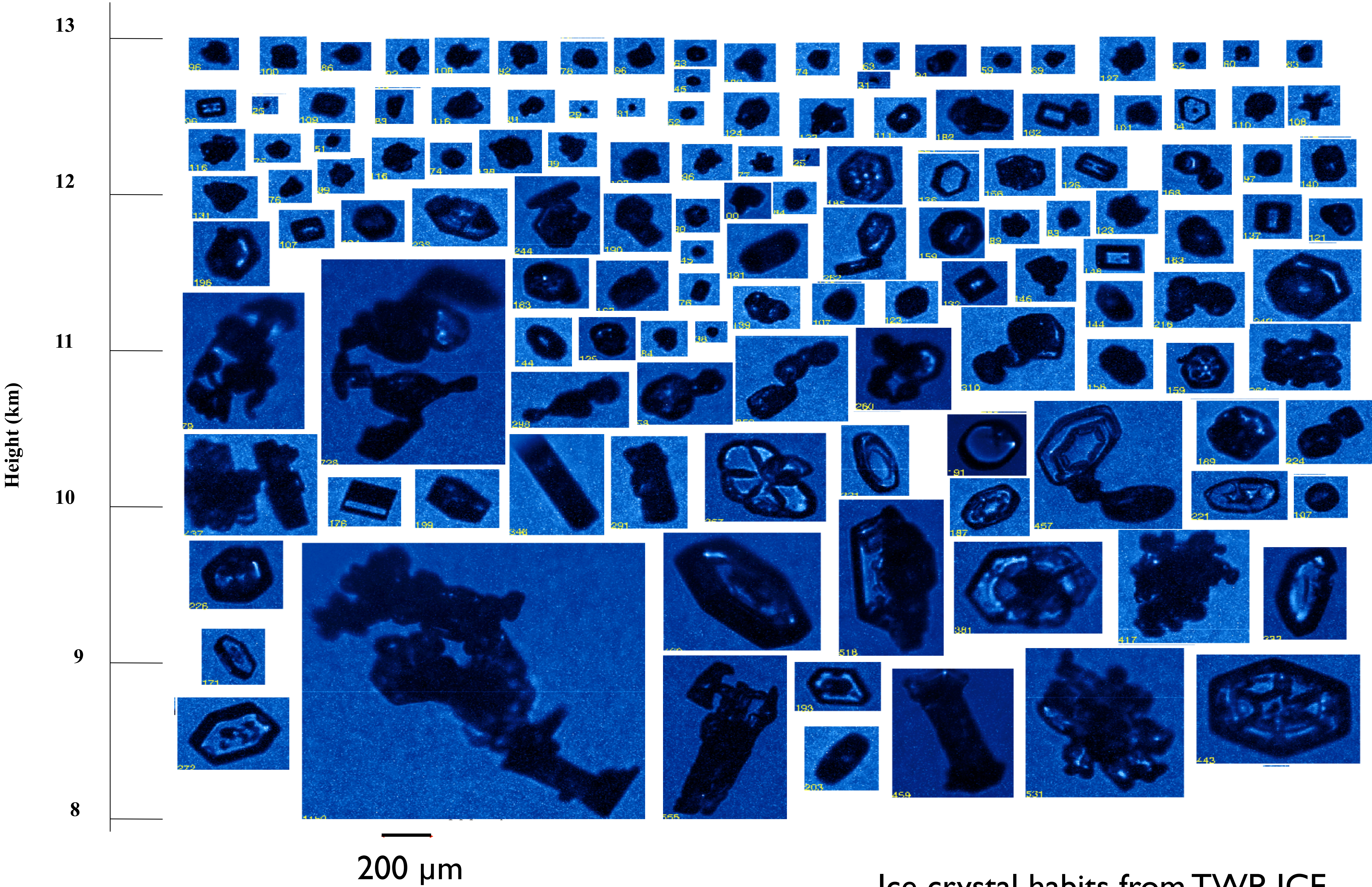
After Eckerman, 2011
10.1175/2011JAS3684.1

A common thread:

In general, random noise introduced at the grid scale doesn't affect model evolution

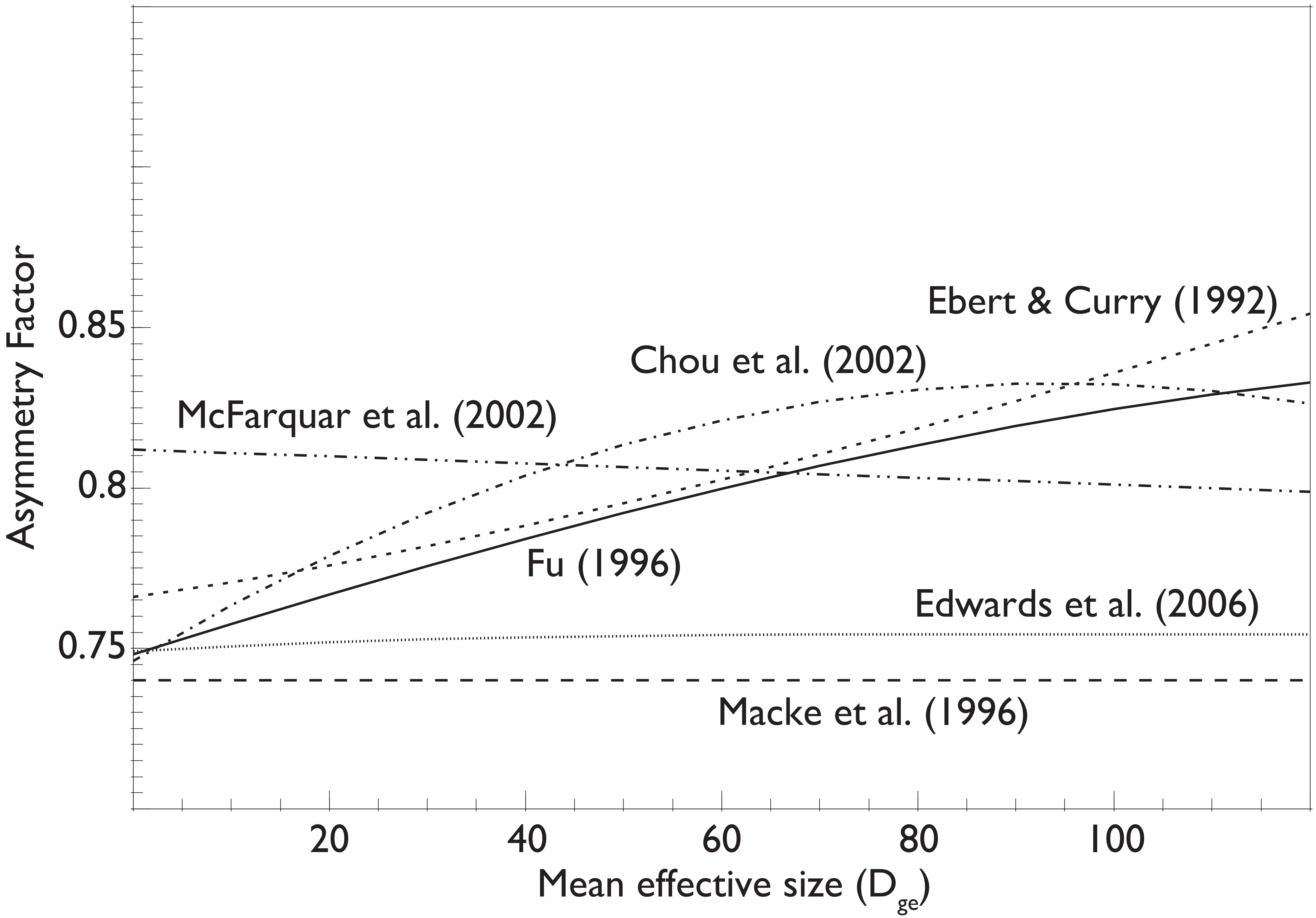
This means that stochastic schemes to treat model error must impose large-scale correlations

Opportunites (i)



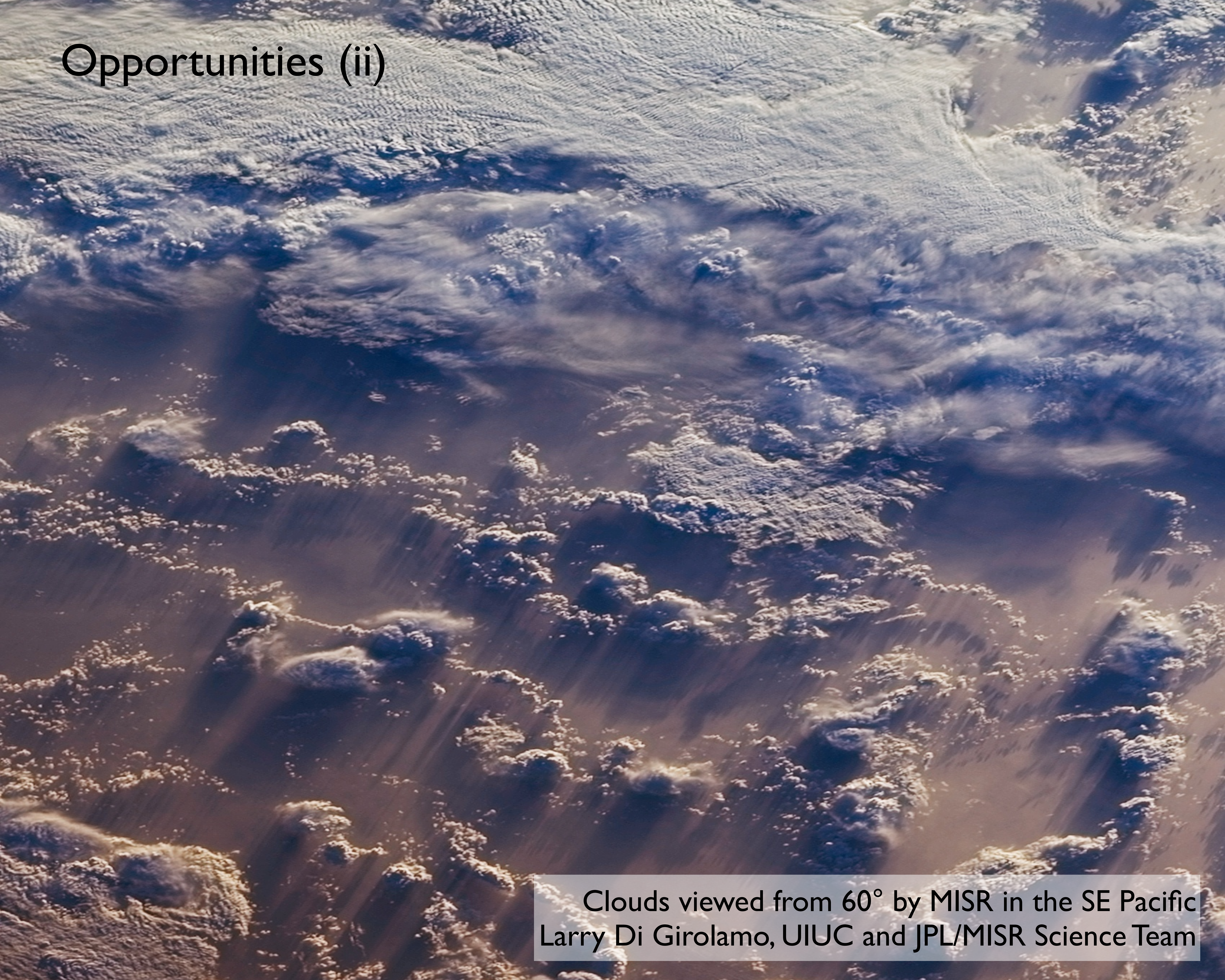
Ice crystal habits from TWP-ICE
Greg McFarquhar, UIUC

Opportunities (i)



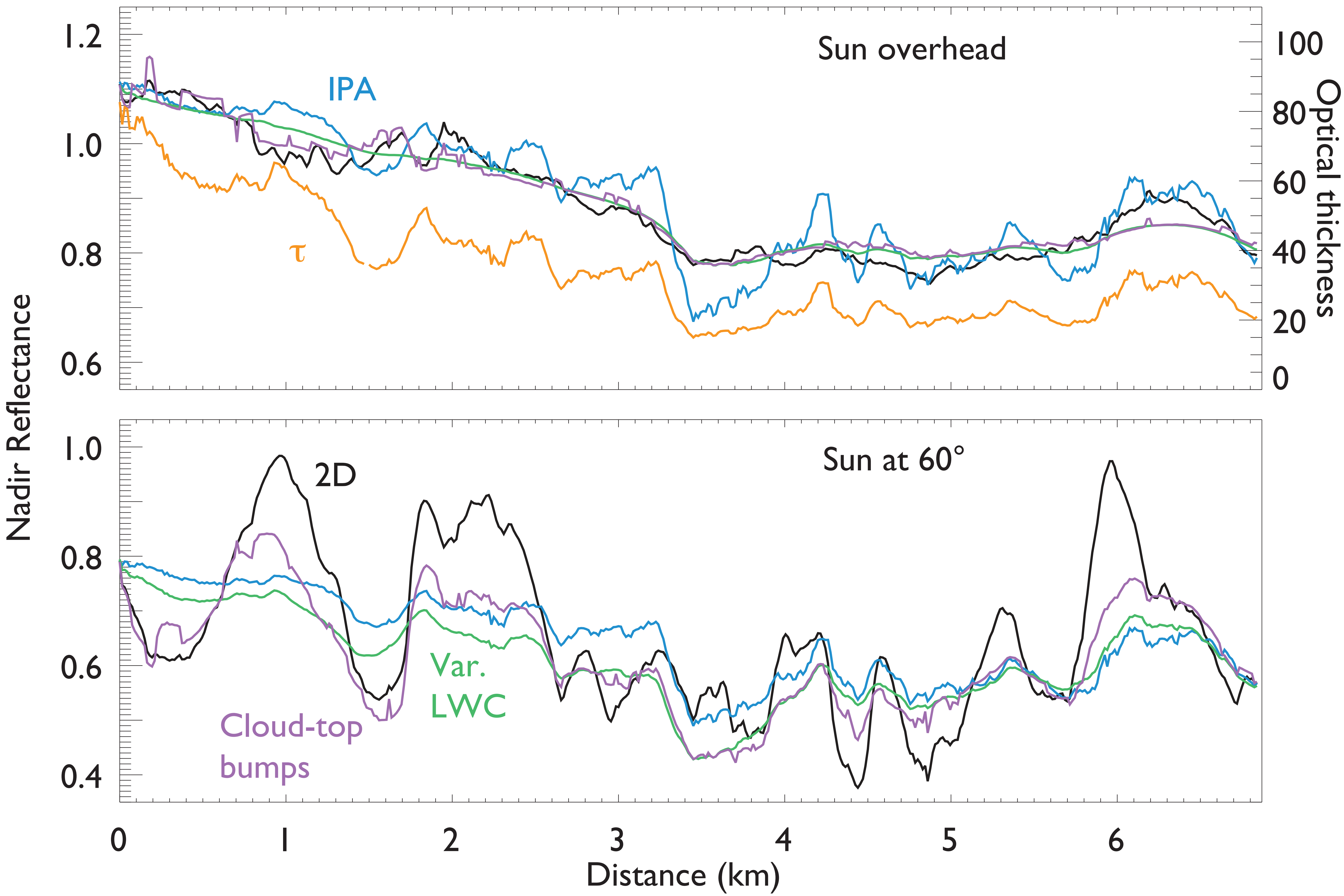
After Fu, 2007
10.1175/2007JAS2289.1

Opportunities (ii)

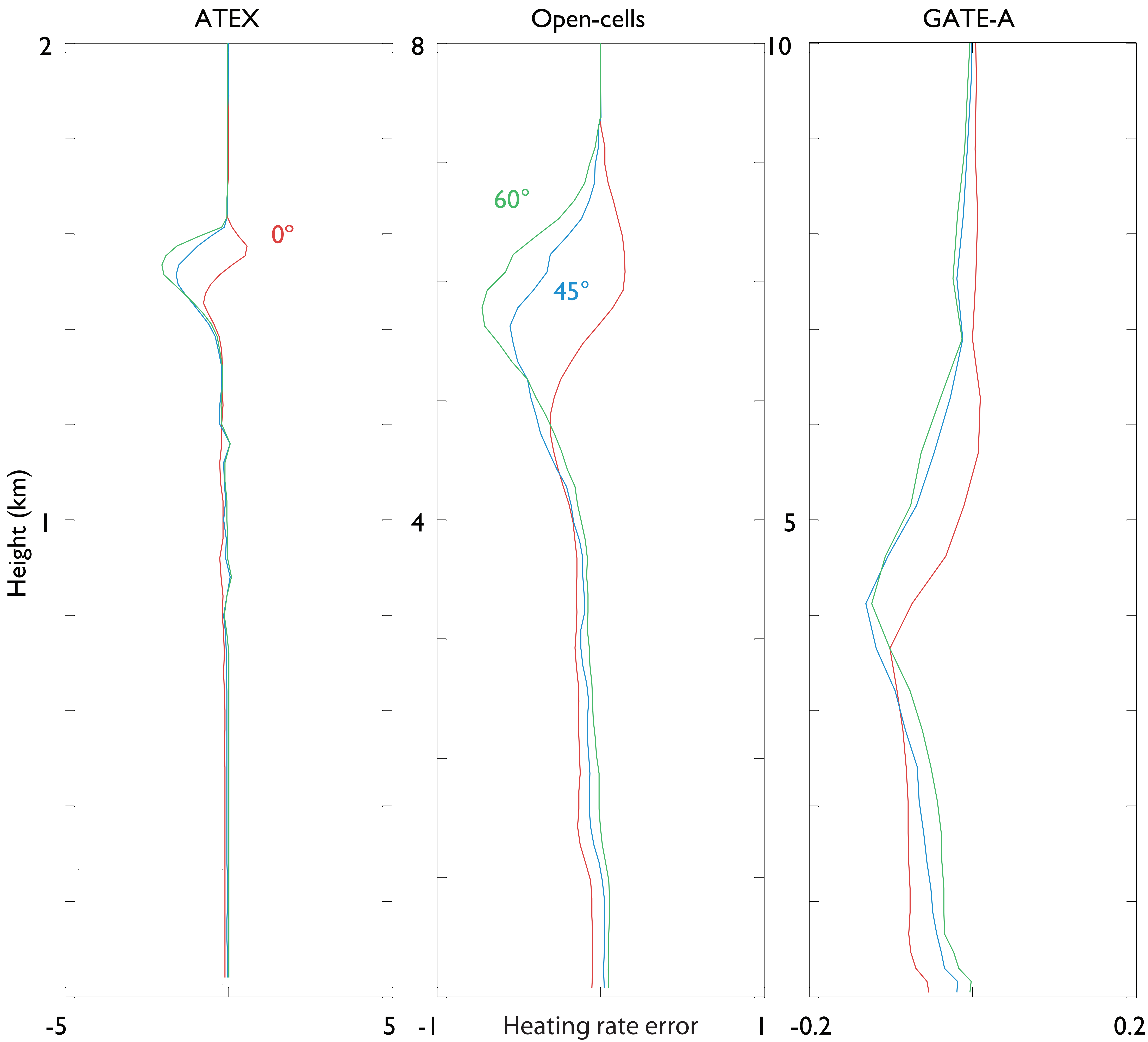


Clouds viewed from 60° by MISR in the SE Pacific
Larry Di Girolamo, UIUC and JPL/MISR Science Team

Opportunities (ii)



After Zuidema and Evans, 1998
10.1029/98JD00080



After Song and Min, 2011, 10.1016/j.jqsrt.2010.06.020

Treating 3D effects would require

a model for the 2-point statistics of cloud structure at the sub-grid scale

a model for the 3-d effects depending on cloud structure

... a lot of work and uncertainty for impacts that may not affect the circulation

“What is there to say? Radiation is the boring part of the atmospheric sciences.” -- Frank Evans