Radiation: Fast physics with slow consequences in an uncertain atmosphere

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Ω \cdot \nabla I(x) = - \sigma(x)I(x)
\quad + \sigma(x)\omega_0(x) \int_4^{4\pi} I(x)P(x, \Omega' \rightarrow \Omega) d\Omega'
\quad + Q

and

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

CO$_2$: 287 to 574 ppmv

Longwave

Shortwave

Parameterizations

Top of model

200 hPa

Surface

Forcing (W/m$^2$)

Parameterizations

Change in heating rate (K/day)

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
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## Overlap assumptions in global models

The figure shows six cloudy configurations. Each configuration is represented by a shaded area in the grid, indicating the overlap and height of cloud cover.

### Diagram Details

- **Height (km):** The y-axis represents the height in kilometers. The values range from 2 to 10 km.
- **Cloud cover:** The x-axis represents the cloud cover, ranging from 0.2 to 1.
- **Maximum-random overlap:** The grid shows the maximum_overlap and random_overlap assumptions in global models.

After Hogan and Illingworth, 2000

10.1002/qj.49712656914
Clouds viewed by MISR in the SE Pacific
Larry Di Girolamo, UIUC
After Barker et al., 2003
After Barker et al., 2003
Simplified horizontal structure

Dimensionality

Developing convection

Uniform cloud (PPH) bias

Boundary layer clouds

Squall line

Simplified horizontal and vertical structure

Trade Cu

Cosine of solar zenith angle

Error in albedo

After Barker et al., 2003

Options for treating variability ca. 2002

“Tuning” (essentially every model does this)

Closures (H. Barker’s $\Gamma$-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

Cloud fraction
Liquid water
Ice water

Pressure

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 I: 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

\[ \overline{F}(x, y, T) = \sum_{s}^{S} w_{s} \sum_{g}^{G} w_{g} F_{g}(s; x, y, T) \]
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 $O(10 - 100 \text{ m})$; 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.
Insight 2: Frequent subsets of the spectral integration are an unbiased estimate of the full calculation

\[ F(x, y, t) \approx \sum_{g} \omega_g F_g(s'_g; x, y, t) \]

This approach

samples temporal variability

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

converges like an LES
Frequency from ultraviolet to the infrared and beyond.
Monte Carlo sampling

\[ q_l \text{ [g/kg]} \]

\[ e \text{ [m}^2\text{/s}^2\text{]} \]

Cloud top [m]

Pincus and Stevens, 2009
10.3894/JAMES.2009.1.1
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).

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

In a mixed-layer model we can calculate the scale-dependent perturbation in kinetic energy due to the approximation
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
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.
Opportunities (i)

Ice crystal habits from TWP-ICE
Greg McFarquhar, UIUC
Opportunities (i)

Asymmetry Factor

Ebert & Curry (1992)
Chou et al. (2002)
McFarquar et al. (2002)
Fu (1996)
Edwards et al. (2006)
Macke et al. (1996)

Mean effective size ($D_{ge}$)

After Fu, 2007
10.1175/2007JAS2289.1
After Song and Min, 2011, 10.1016/j.jqsrt.2010.06.020

Heating rate error
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