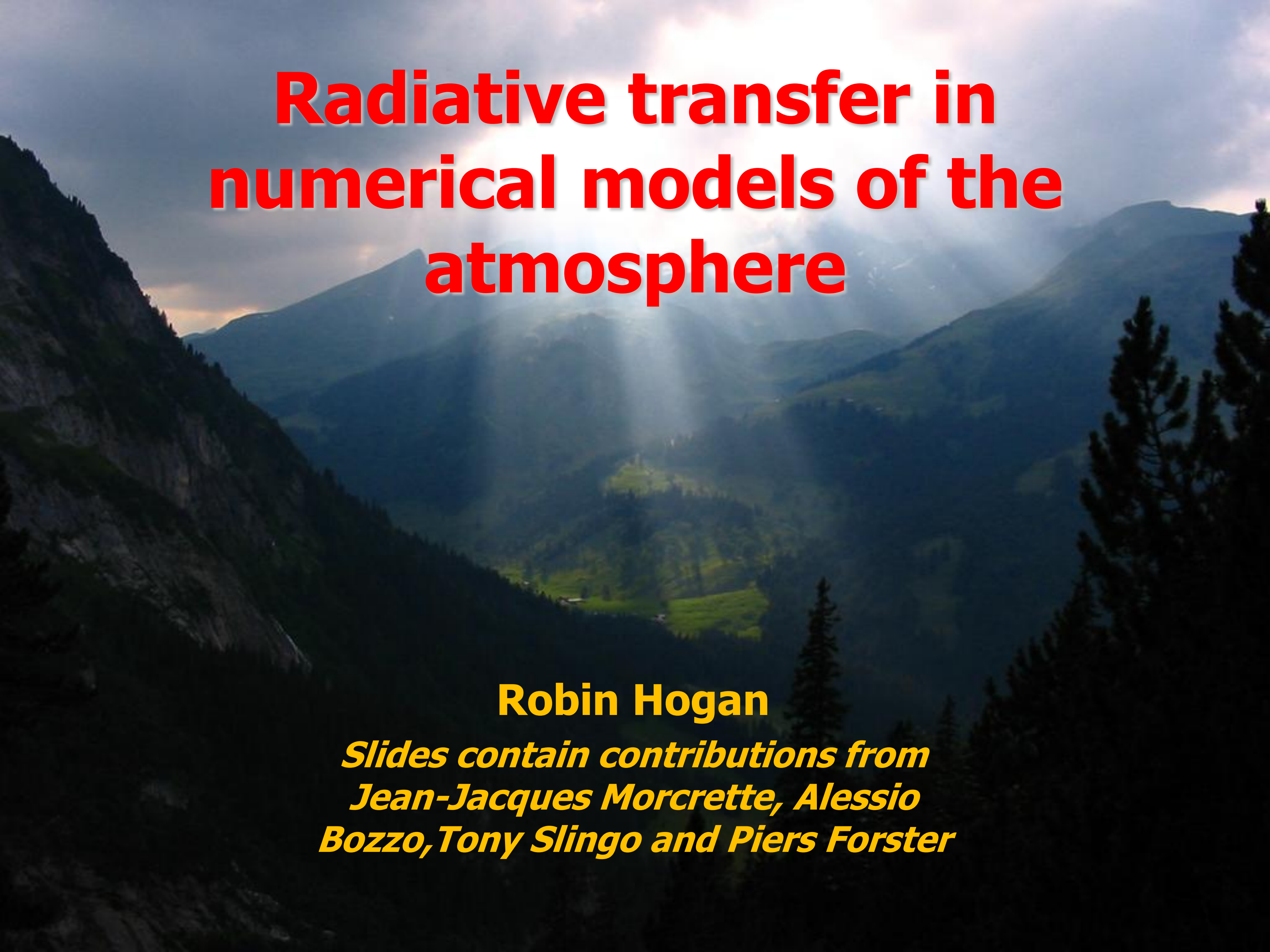


Radiative transfer in numerical models of the atmosphere

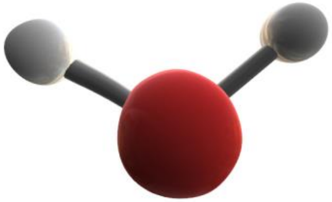
Robin Hogan

Slides contain contributions from Jean-Jacques Morcrette, Alessio Bozzo,Tony Slingo and Piers Forster

Outline

- Lectures 1 & 2
  1. Global context
  2. From Maxwell to the two-stream equations
  3. Gaseous absorption and emission

- Lecture 3 (Alessio Bozzo)
  - The ECMWF radiation scheme
- Lecture 4
  4. Representing cloud structure
  5. Some remaining challenges

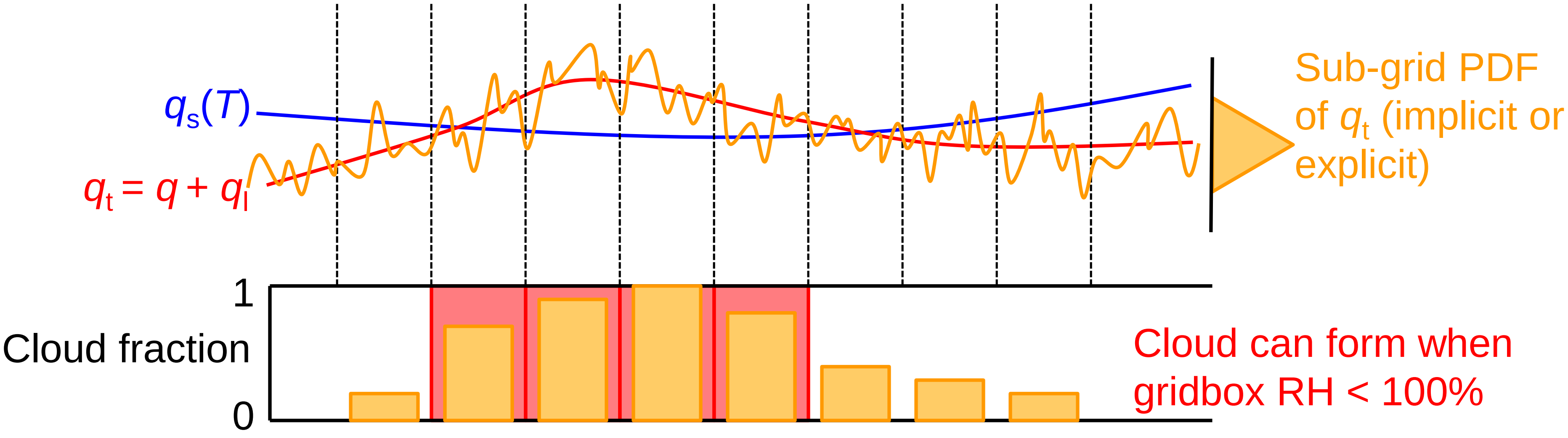


Part 4: Representing cloud structure

- Representing cloud fraction, overlap and inhomogeneity
- What is the impact of overlap and inhomogeneity on the radiation budget?

Cloud fraction parametrization

- If cloud is diagnosed only when gridbox-mean $q_t > q_s$ then resulting cloud fraction can only be 0 or 1

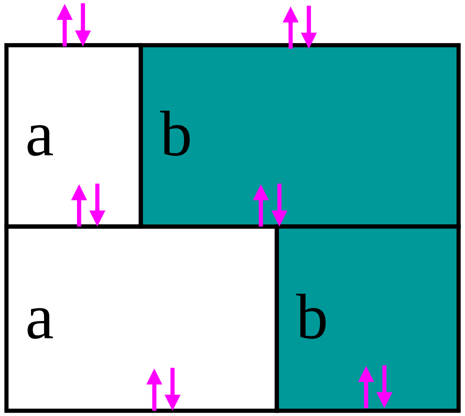


Sub-grid PDF of q_t (implicit or explicit)

Cloud can form when gridbox RH < 100%

- Cloud fraction can be diagnosed from prognostic or diagnostic sub-grid distribution of humidity and cloud
- ECMWF uses a prognostic equation for cloud fraction

Multi-region two stream



- E.g. Met Office Edwards-Slingo scheme
- Solve for two fluxes in clear and cloudy regions
  - Matrix is now denser (pentadiagonal rather than tridiagonal)

$$\begin{pmatrix}
 & & 1 & & & & & & & & & \\
 & & & 1 & & & & & & & & \\
1 & & -R_1^{aa} & -R_1^{ab} & -T_1^{a} & -T_1^{b} & & & & & & \\
 & 1 & -R_1^{ba} & -R_1^{bb} & -T_1^{a} & -T_1^{b} & & & & & & \\
 & & -T_1^{a} & -T_1^{b} & -R_1^{aa} & -R_1^{ab} & 1 & & & & & \\
 & & -T_1^{a} & -T_1^{b} & -R_1^{ba} & -R_1^{bb} & & 1 & & & & \\
 & & & & 1 & & -R_2^{aa} & -R_2^{ab} & -T_2^{a} & -T_2^{b} & & \\
 & & & & & 1 & -R_2^{ba} & -R_2^{bb} & -T_2^{a} & -T_2^{b} & & \\
 & & & & & & -T_2^{a} & -T_2^{b} & -R_2^{aa} & -R_2^{ab} & 1 & \\
 & & & & & & -T_2^{a} & -T_2^{b} & -R_2^{ba} & -R_2^{bb} & & 1 \\
 & & & & & & & & 1 & & \alpha_s & \\
 & & & & & & & & & 1 & & \alpha_s
\end{pmatrix}
\begin{pmatrix}
F_{0.5}^{a+} \\ F_{0.5}^{b+} \\ F_{0.5}^{a-} \\ F_{0.5}^{b-} \\ F_{1.5}^{a+} \\ F_{1.5}^{b+} \\ F_{1.5}^{a-} \\ F_{1.5}^{b-} \\ F_{2.5}^{a+} \\ F_{2.5}^{b+} \\ F_{2.5}^{a-} \\ F_{2.5}^{b-}
\end{pmatrix}
=
\begin{pmatrix}
S_{TOA}^{-} \\ S_{TOA}^{-} \\ S_1^{a+} \\ S_1^{b+} \\ S_1^{a-} \\ S_1^{b-} \\ S_2^{a+} \\ S_2^{b+} \\ S_2^{a-} \\ S_2^{b-} \\ S_s^{+} \\ S_s^{+}
\end{pmatrix}$$

Note that coefficients describing the overlap between layers have been omitted

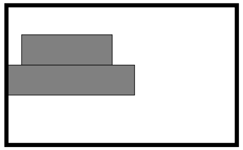
Are we using computer time wisely?

- Radiation is an integral:

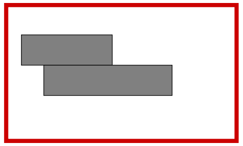
$$\overline{F^{\uparrow\downarrow}(z)} = \int_{\Delta t}\int_{\infty}\int_{\Delta \mathbf{x}}\int_{2\pi} I(z,\mathbf{\Omega},\mathbf{x},\nu,t)\,d\mathbf{\Omega}\,d\mathbf{x}\,d\nu\,dt$$

Dimension	**Typical number of quadrature points**	**How well is this dimension known?**	**Consequence of poor resolution**
Time	1/3 (every 3 h)	At the timestep of the model	Changed climate sensitivity (Morcrette 2000); diurnal cycle (Yang & Slingo 2001)
Angle	2 (sometimes 4)	Well (some uncertainty on ice phase functions)	±6 W m^{-2} (Stephens et al. 2001)
Space	2 (clear+cloudy)	Poorly (clouds!)	Up to a 20 W m^{-2} long-term bias (Shonk and Hogan 2009)
Spectrum	100-250	Very well (HITRAN database)	Incorrect climate response to trace gases?

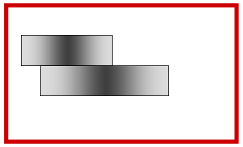
Three further issues for clouds



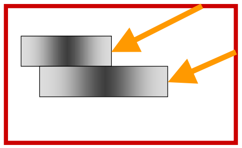
- Clouds in older GCMs used a simple cloud fraction scheme with clouds in adjacent layers being maximally overlapped



1. Observations show that vertical overlap of clouds in two layers tends towards random as their separation increases



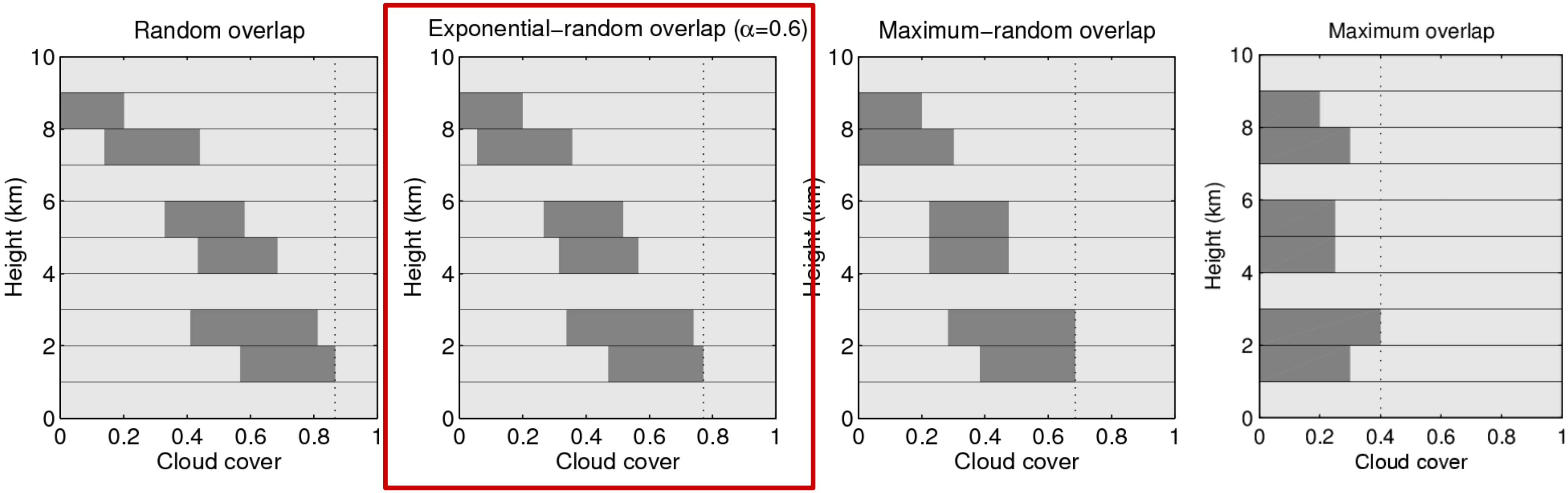
2. Real clouds are horizontally inhomogeneous, leading to albedo and emissivity biases in GCMs (Cahalan et al 1994, Pomroy and Illingworth 2000)



3. Radiation can pass through cloud sides, but these 3D effects are negelcted in all current GCMs

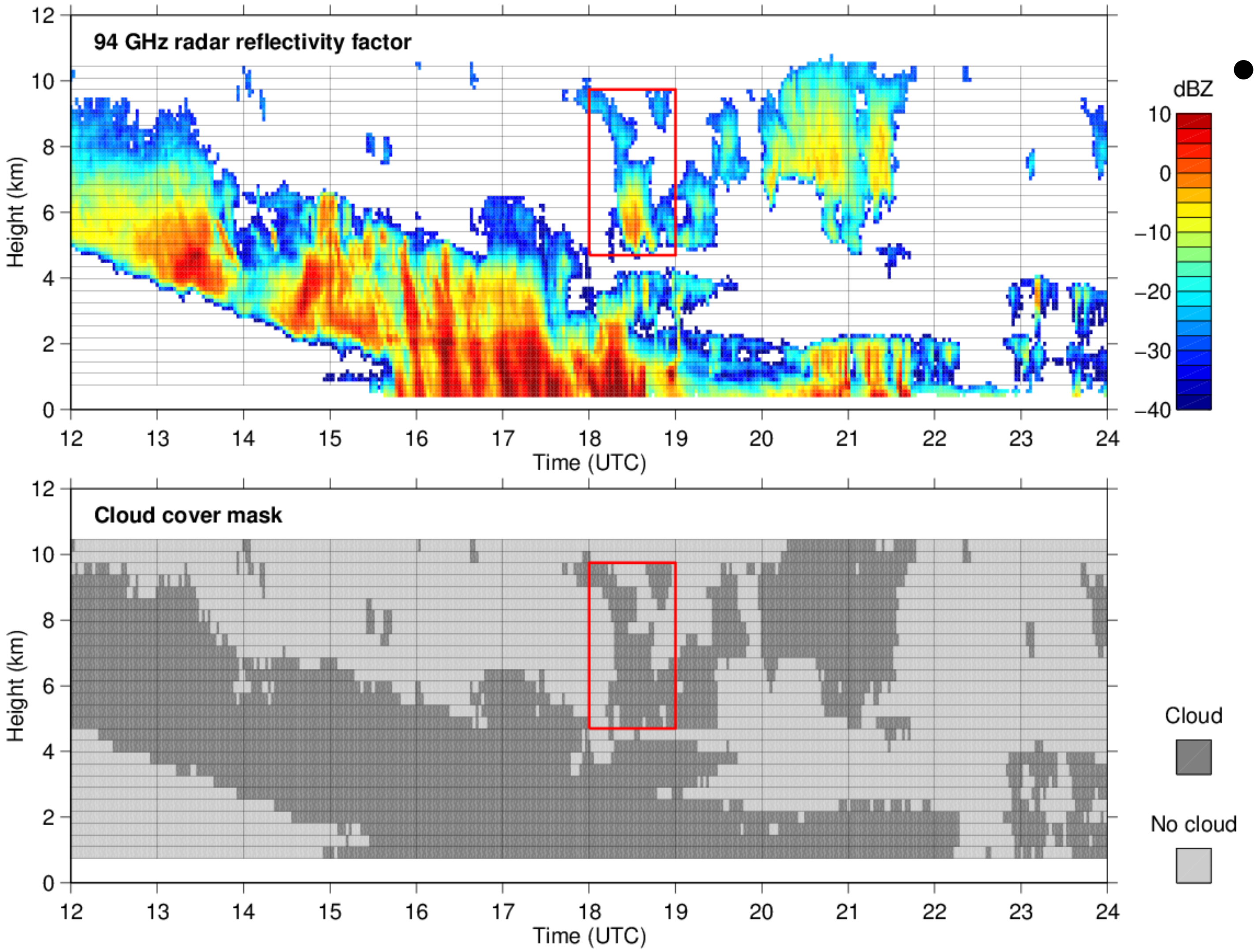
Cloud overlap parametrization

- Even if can predict cloud fraction versus height, cloud cover (and hence radiation) depends on cloud *overlap*



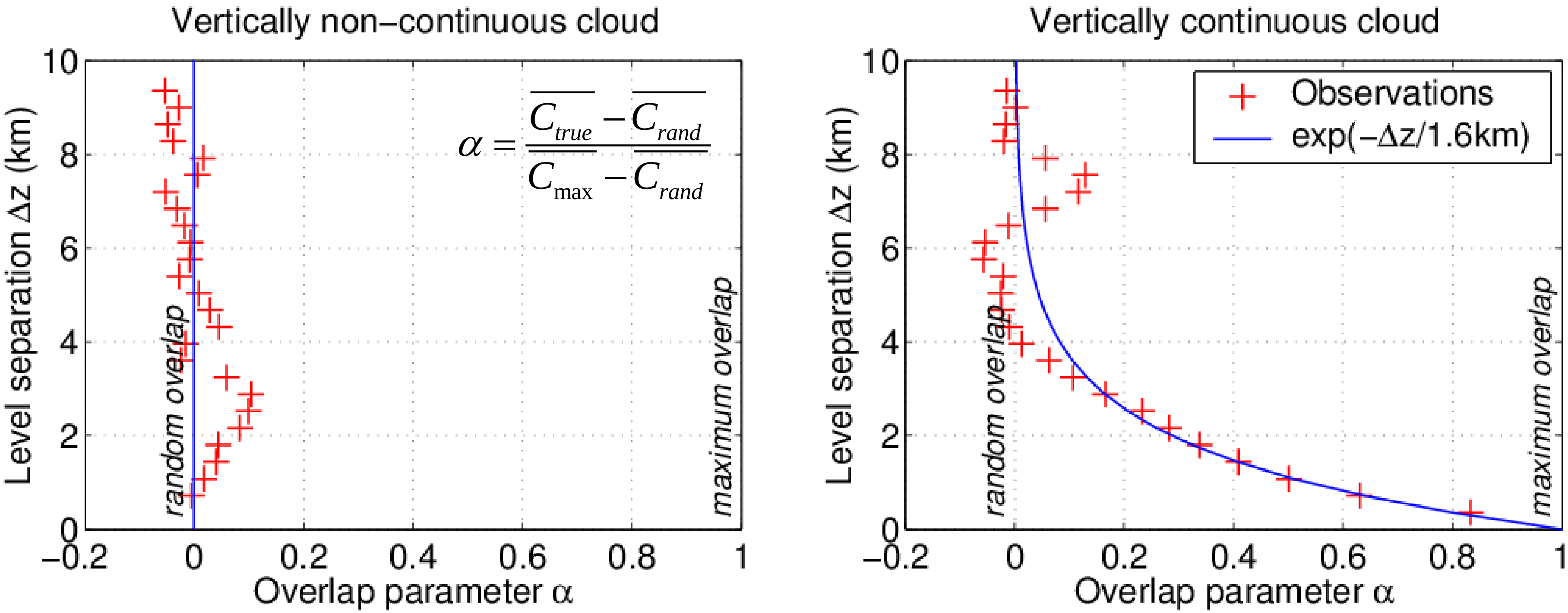
- Observations (Hogan and Illingworth 2000) support “exponential-random overlap”:
  - Non-adjacent clouds are randomly overlapped
  - Adjacent clouds correlated with decorrelation length ~2km
  - Many models still use “maximum-random overlap”

Cloud overlap from radar: example



- Radar can observe the actual overlap of clouds

Cloud overlap: results

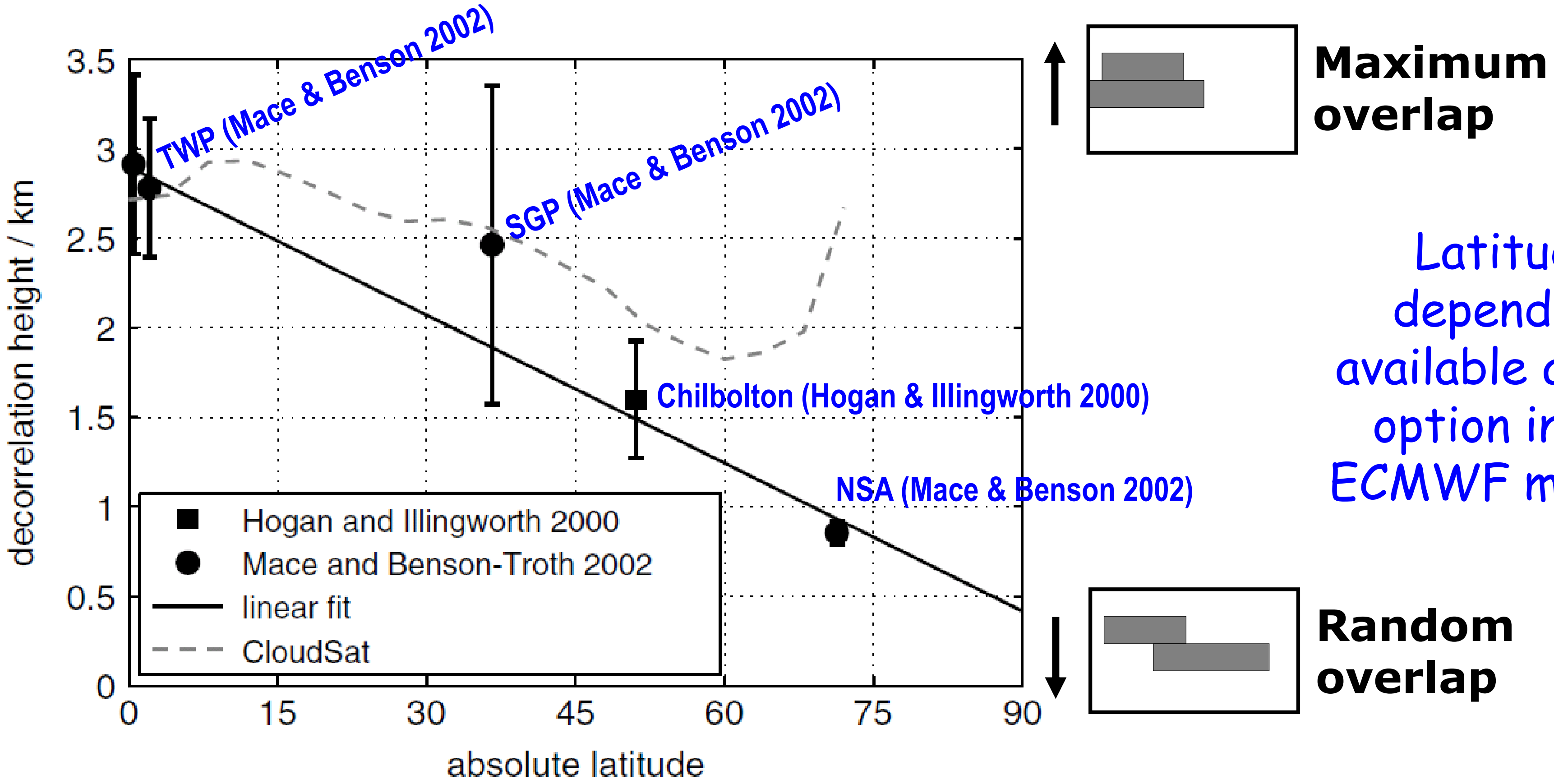


- Vertically isolated clouds are randomly overlapped
- *Overlap of vertically continuous clouds becomes rapidly more random with increasing thickness, characterized by an overlap decorrelation length* z_0 *~ 1.6 km*

Hogan and Illingworth (QJ 2000)

Cloud overlap globally

- Latitudinal dependence of decorrelation length from Chilbolton and the worldwide ARM sites
  - More convection and less shear in the tropics so more maximally overlapped



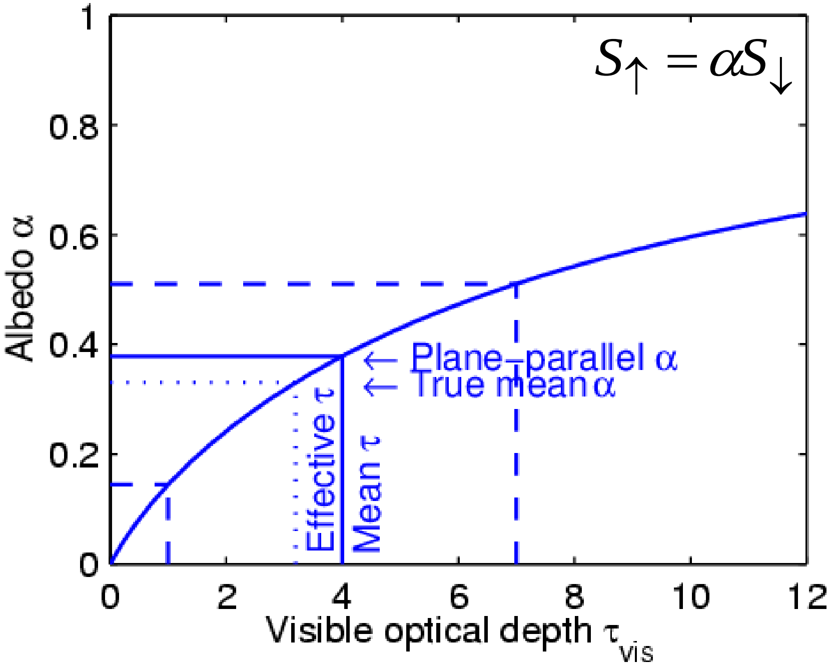
Maximum overlap

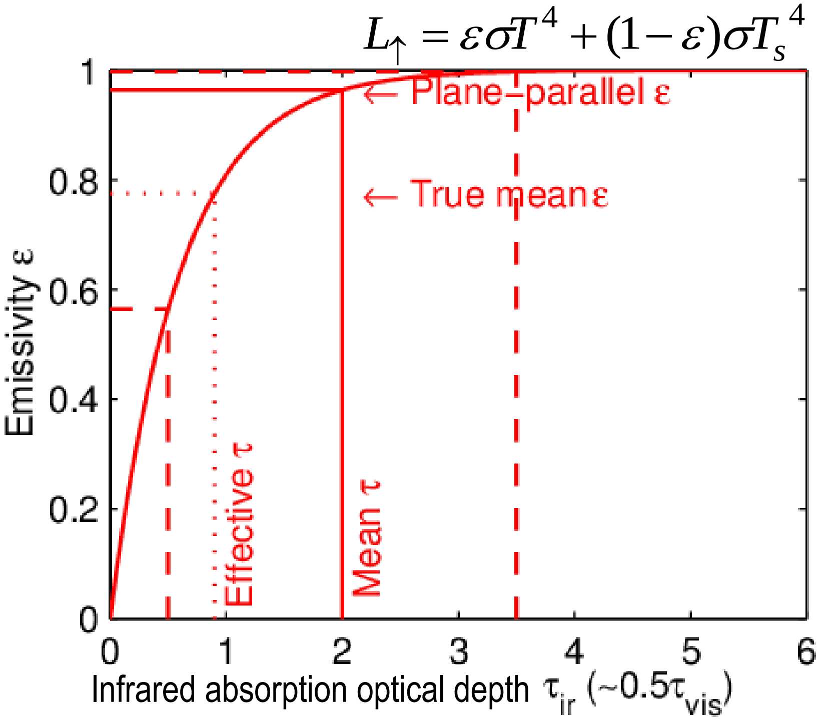
Random overlap

Latitudinal dependence available as an option in the ECMWF model

Shonk et al. (QJ 2010)

Why is cloud structure important?

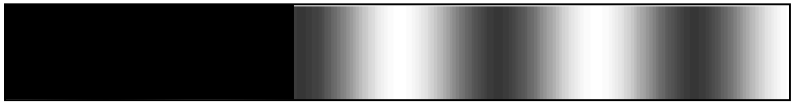




- An example of *non-linear averaging*

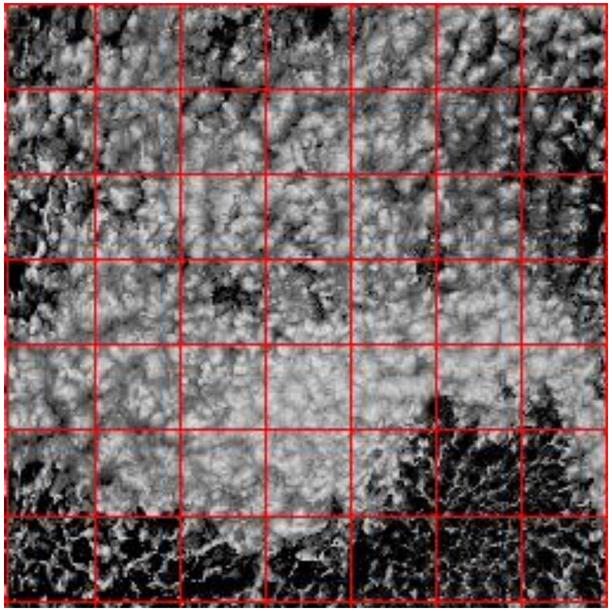
Clear air *Cloud*

Inhomogeneous cloud



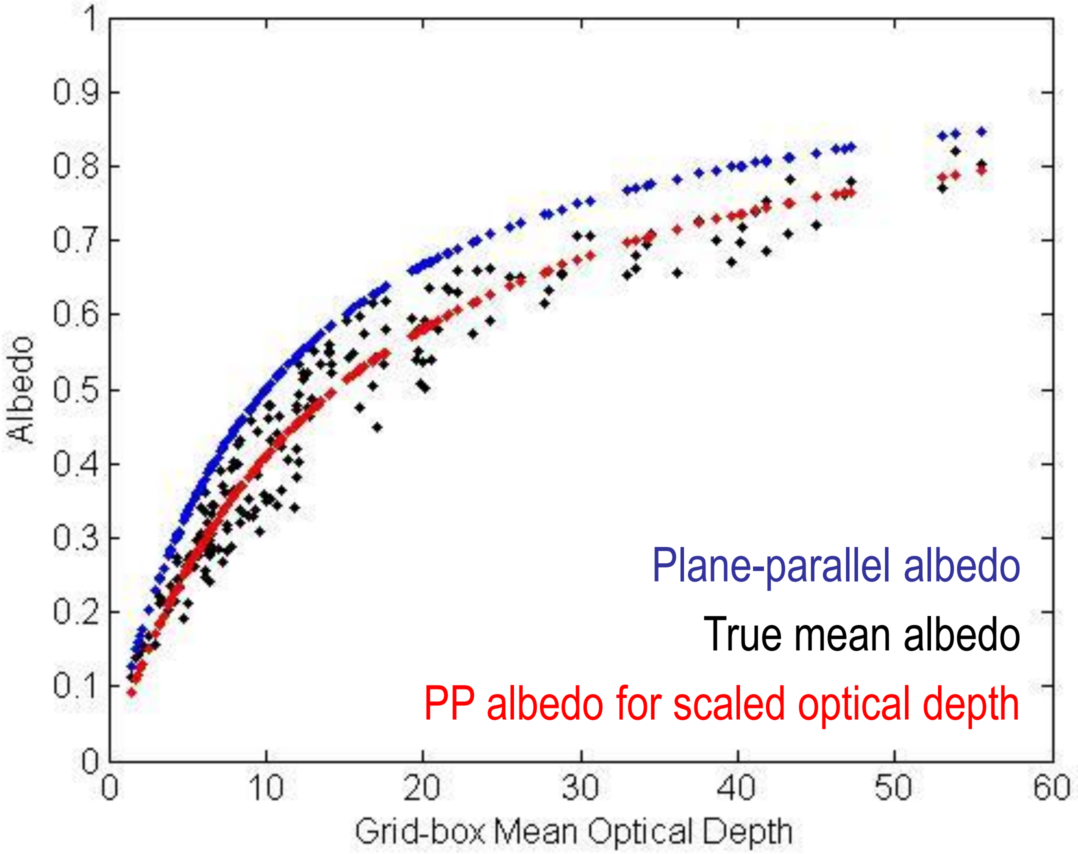
- Non-uniform clouds have lower mean emissivity & albedo for same mean optical depth due to curvature in the relationships

Example from MODIS



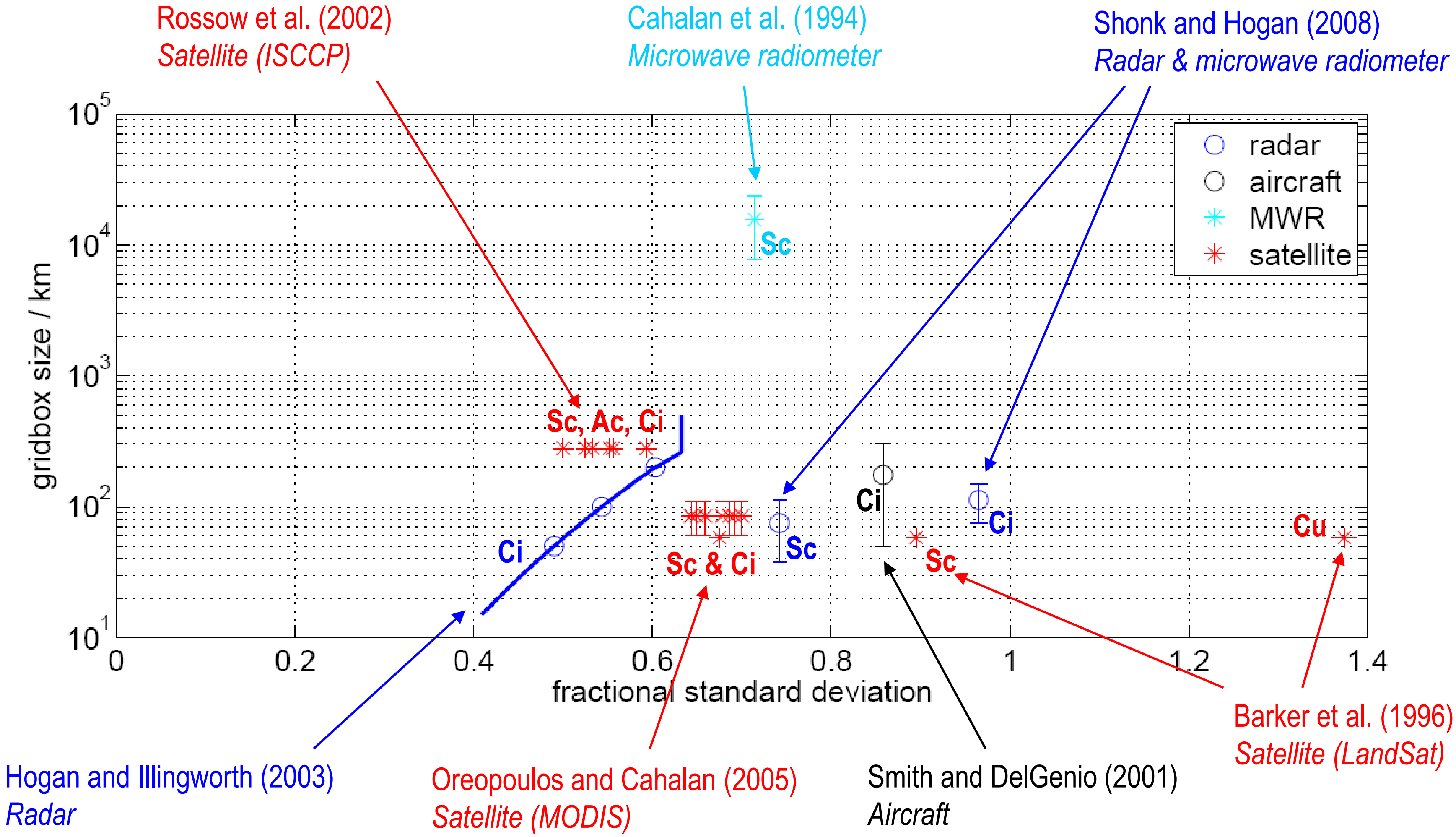
MODIS Stratocumulus

100-km boxes



- By scaling the optical depth it appears we can get an unbiased fit to the true top-of-atmosphere albedo
  - Until McRad (2007), ECMWF used a constant factor of 0.7
  - Now a more sophisticated scheme is used

Observations of horizontal structure



Rossow et al. (2002)
Satellite (ISCCP)

Cahalan et al. (1994)
Microwave radiometer

Shonk and Hogan (2008)
Radar & microwave radiometer

Hogan and Illingworth (2003)
Radar

Oreopoulos and Cahalan (2005)
Satellite (MODIS)

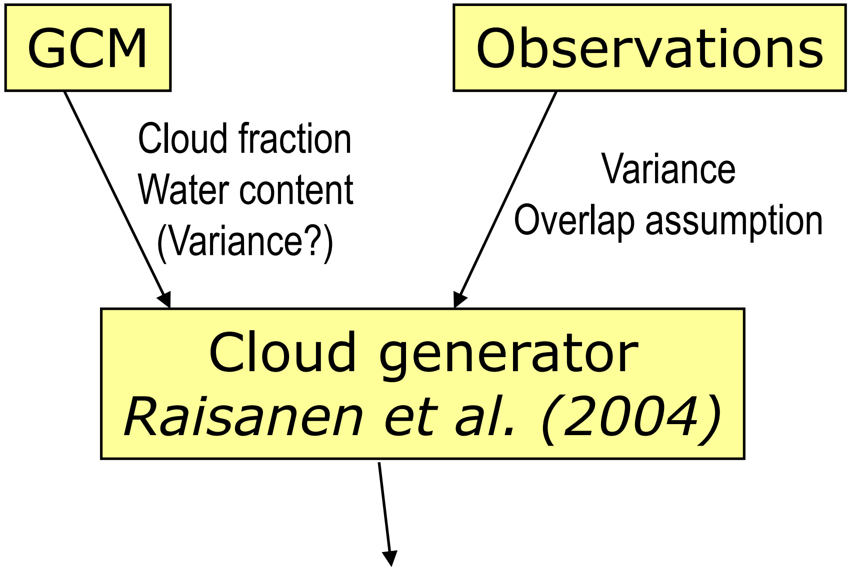
Smith and DelGenio (2001)
Aircraft

Barker et al. (1996)
Satellite (LandSat)

- Typical fractional standard deviation ~0.75

Shonk et al. (QJRMS 2012)

Monte-Carlo ICA



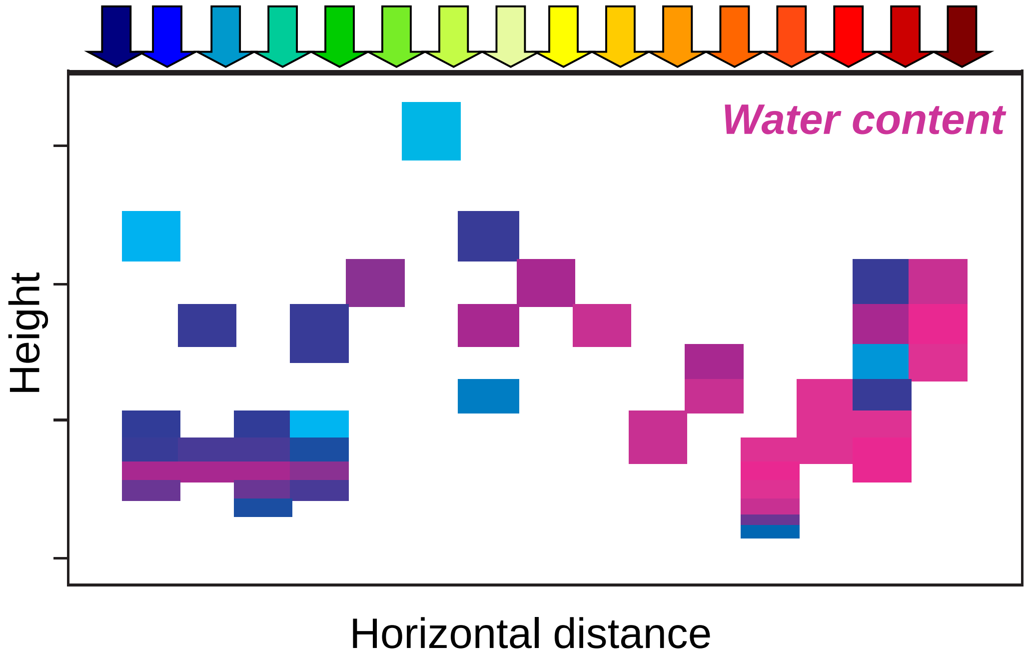
GCM

Observations

Cloud fraction
Water content
(Variance?)

Variance
Overlap assumption

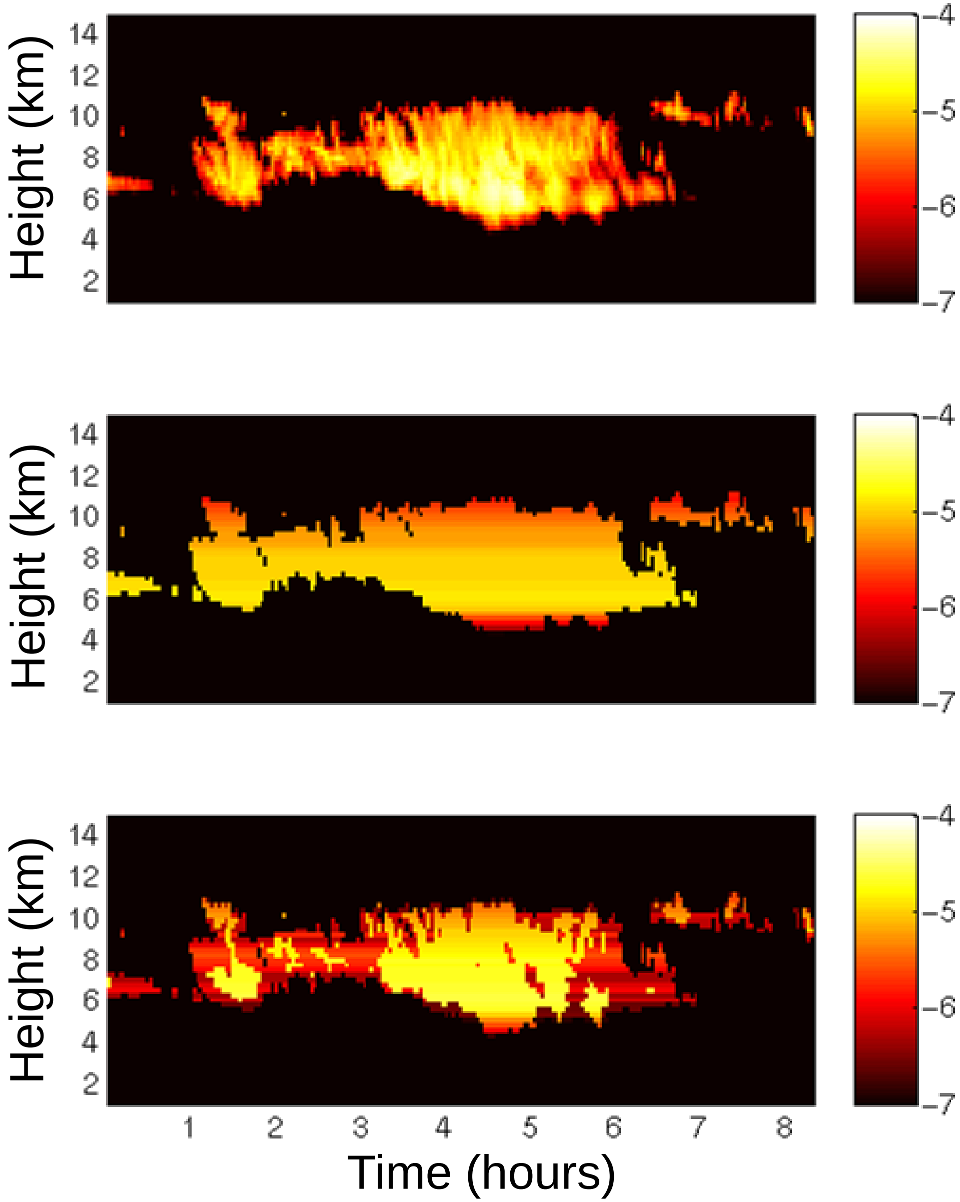
Cloud generator
Raisanen et al. (2004)



Pincus, Barker and Morcrette (2003)

- Generate random sub-columns of cloud
  - Statistics consistent with horizontal variance and overlap rules
- ICA could be run on each
  - But double integral (space and wavelength) makes this too slow (~10^4 profiles)
- *McICA solves this problem*
  - Each wavelength (and correlated-k quadrature point) receives a different profile -> only ~10^2 profiles
  - Modest amount of random noise not believed to affect forecasts

Alternative method: Tripleclouds



- Ice water content from Chilbolton radar, $\log_{10}(\text{kg m}^{-3})$

- Plane-parallel approx:
  - 2 regions in each layer, one clear and one cloudy

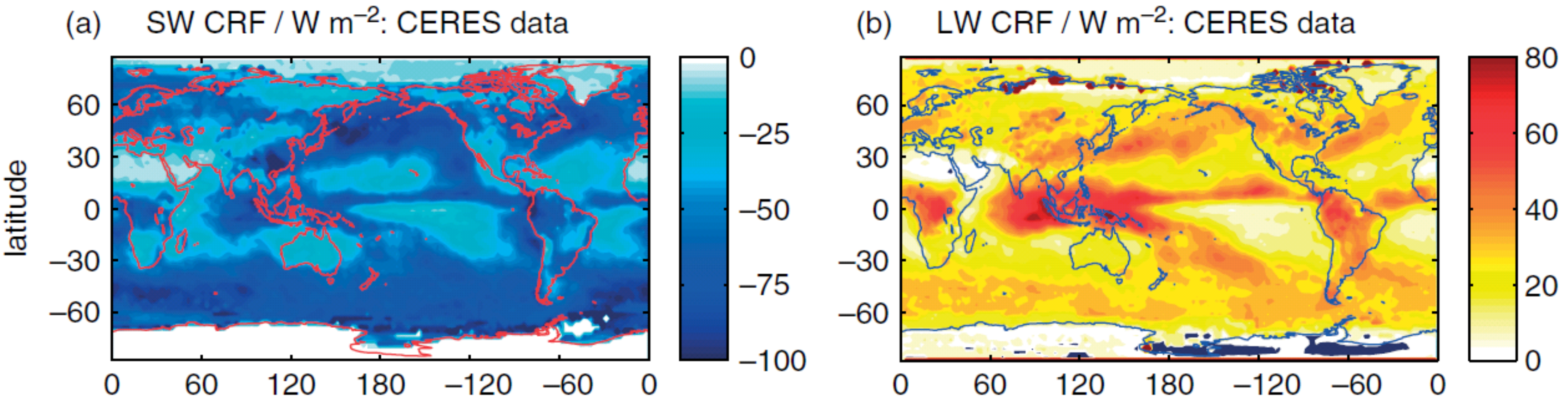
- “Tripleclouds”:
  - 3 regions in each layer
  - Alternative to McICA
  - Uses Edwards-Slingo capability for stratiform/convective regions for another purpose

Shonk and Hogan (JClim 2008)

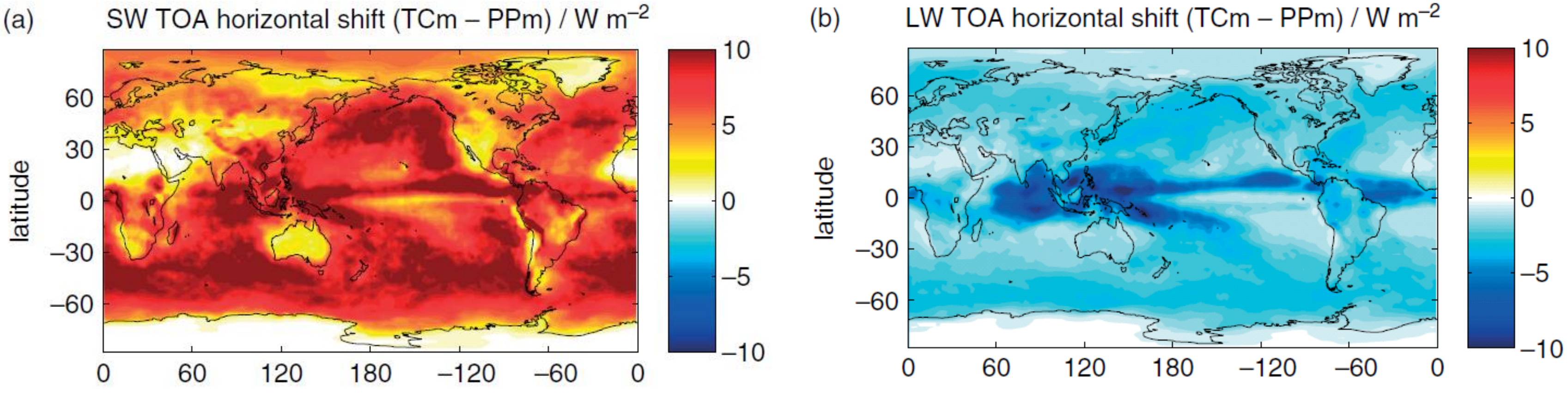
Global impact of cloud structure

Shonk and Hogan (2010)

- Cloud radiative forcing (CRF) is change to top-of-atmosphere net flux due to clouds
- Clouds cool the earth in the shortwave and warm it in the longwave:

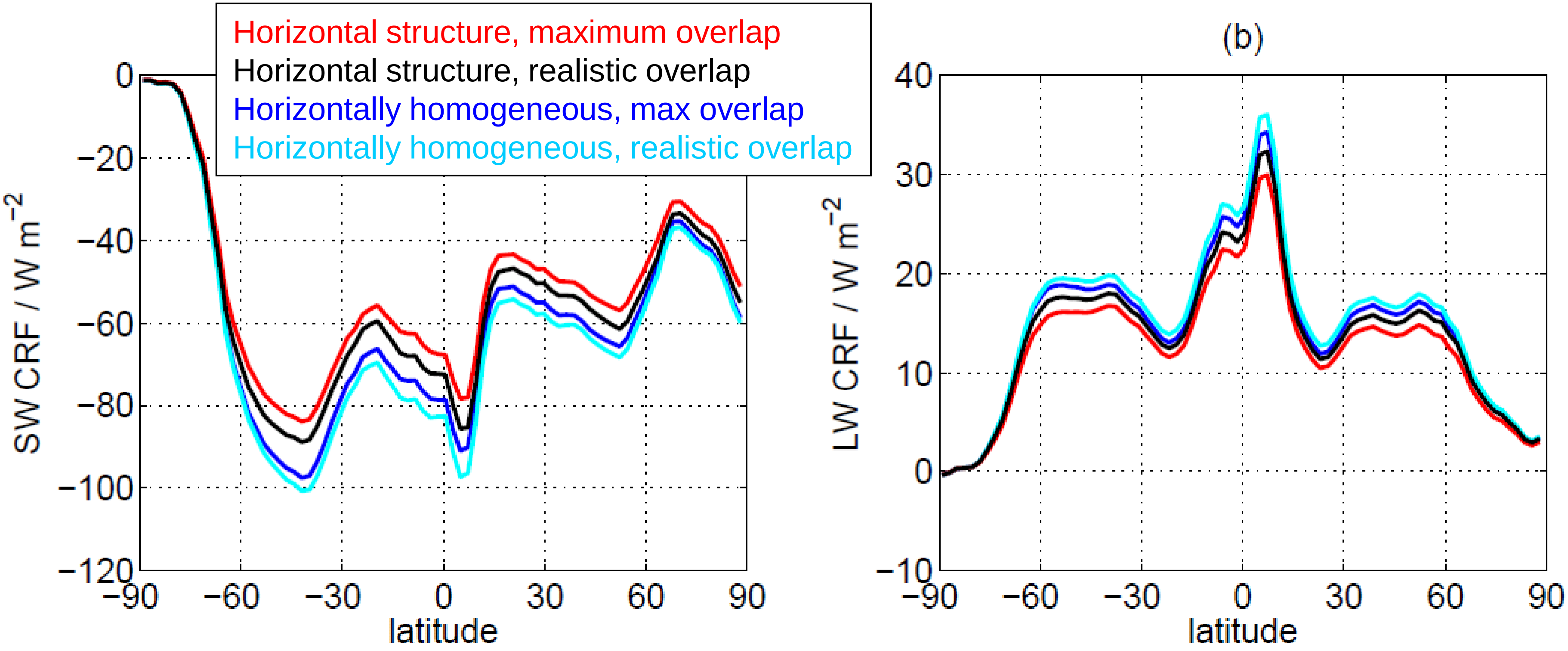

(a) SW CRF / W m^{-2}: CERES data

(b) LW CRF / W m^{-2}: CERES data


(a) SW TOA horizontal shift (TCm – PPm) / W m^{-2}

(b) LW TOA horizontal shift (TCm – PPm) / W m^{-2}

Horizontal versus vertical structure



- Correcting cloud structure changes cloud radiative effect by around 10%
- Impact of adding horizontal structure about twice that of improving vertical overlap
- Note that uncertainties in the horizontal structure effect are much larger than in the vertical overlap effect

Part 5: Remaining challenges

- Improve efficiency
  - Radiation schemes often the slowest part of the model, so may called infrequently and not in every model column
- Improve accuracy
  - Better spectroscopic data, particularly the continuum
  - Better treatment of upper stratosphere/mesosphere to enable satellite observations here to be assimilated
  - Evaluate against new observations
- Add new processes
  - Radiative properties of prognostic aerosols
  - Three dimensional radiative transfer in presence of clouds
  - Non-local-thermodynamic equilibrium for high-top models
  - Cloud inhomogeneity information from cloud scheme

Why do we need bands?

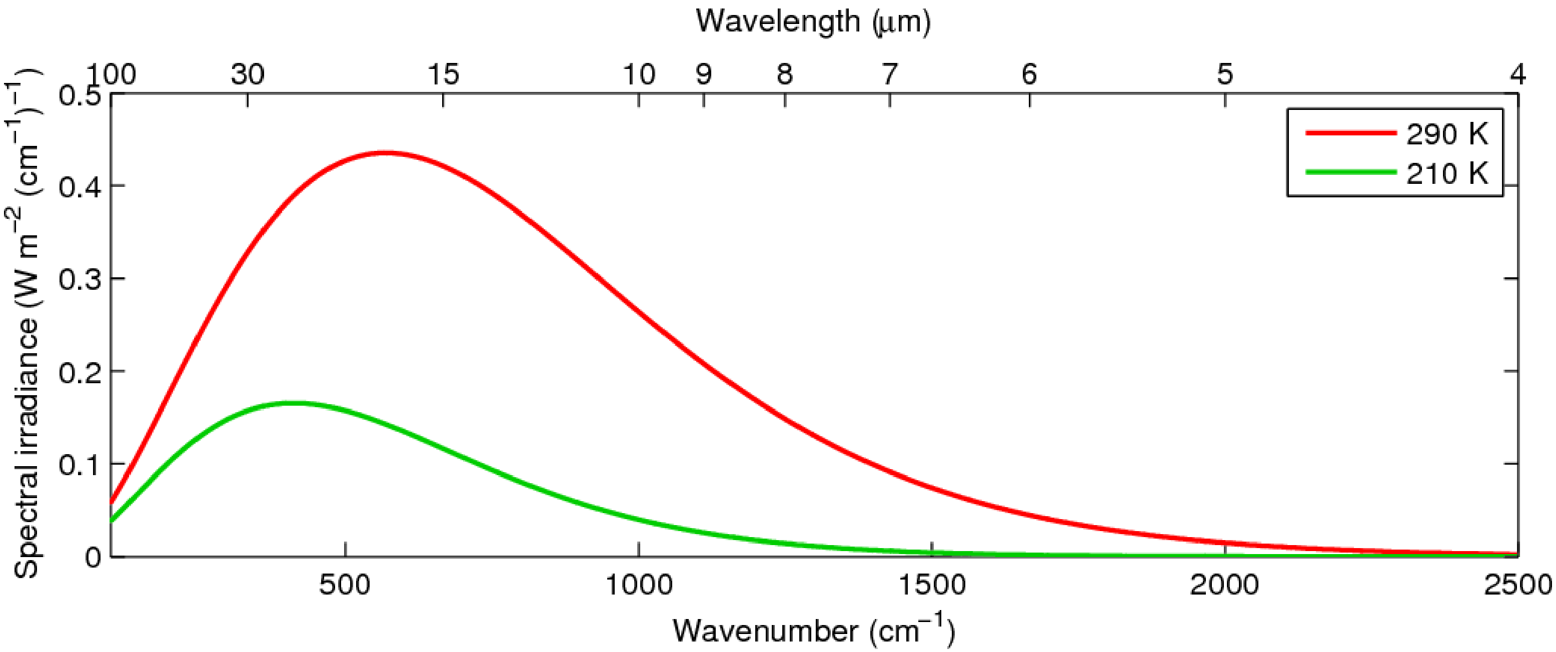
1. *Because the Planck function should not vary significantly within a band* (Fu & Liou 1992)
2. *To minimize number of active gases in each band, due to expense of treating many gases* (Mlawer et al. 1997)
3. *Because some techniques assume spectral overlap of different gases is random, not valid over large intervals* (Edwards 1996)
4. *To represent the slow variation of cloud and aerosol absorption and scattering across the spectrum* (Ritter & Geleyn 1992)

But Modest & Zhang (2002) proposed full-spectrum correlated-k (FSCK) method for combusting gases

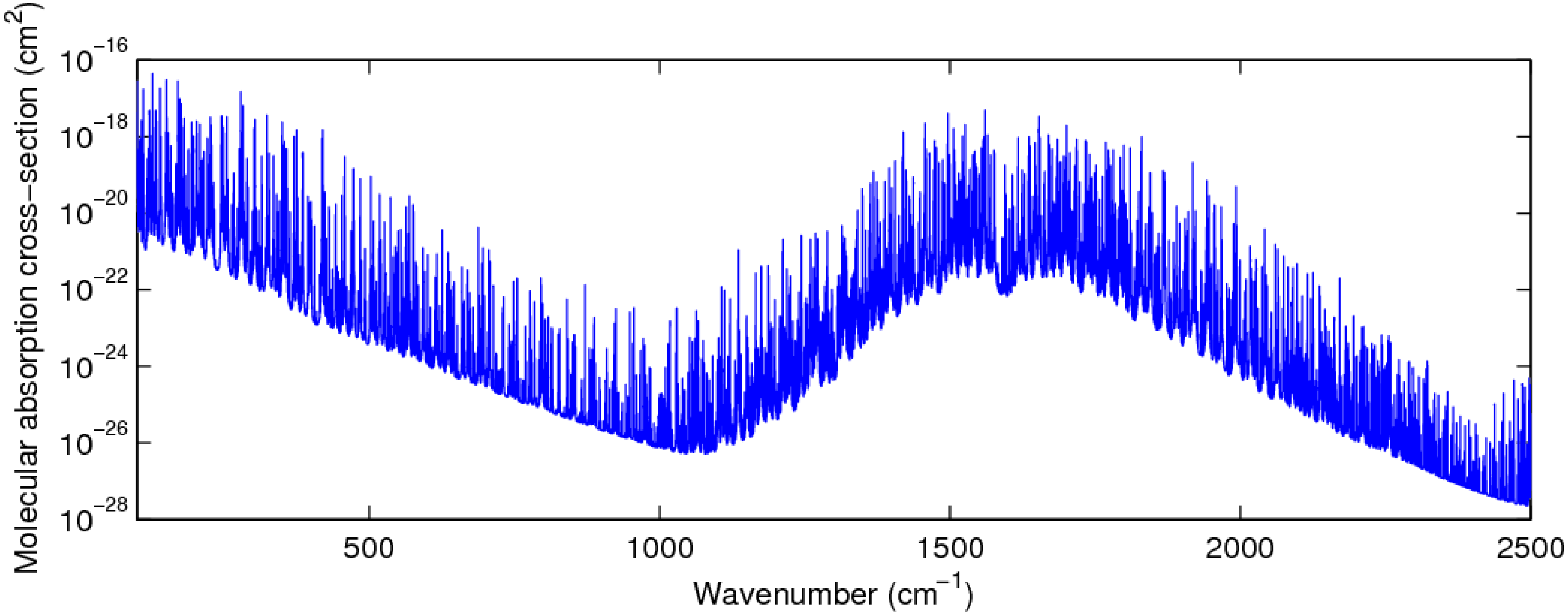
- Their formulation is unnecessarily complex and can be simplified
- Pawlak et al. (2004) showed that this method works in the shortwave
- More tricky to apply FSCK to longwave atmospheric radiative transfer, where variations in Planck function and spectral overlap are important

Full-spectrum correlated-k (FSCK) method

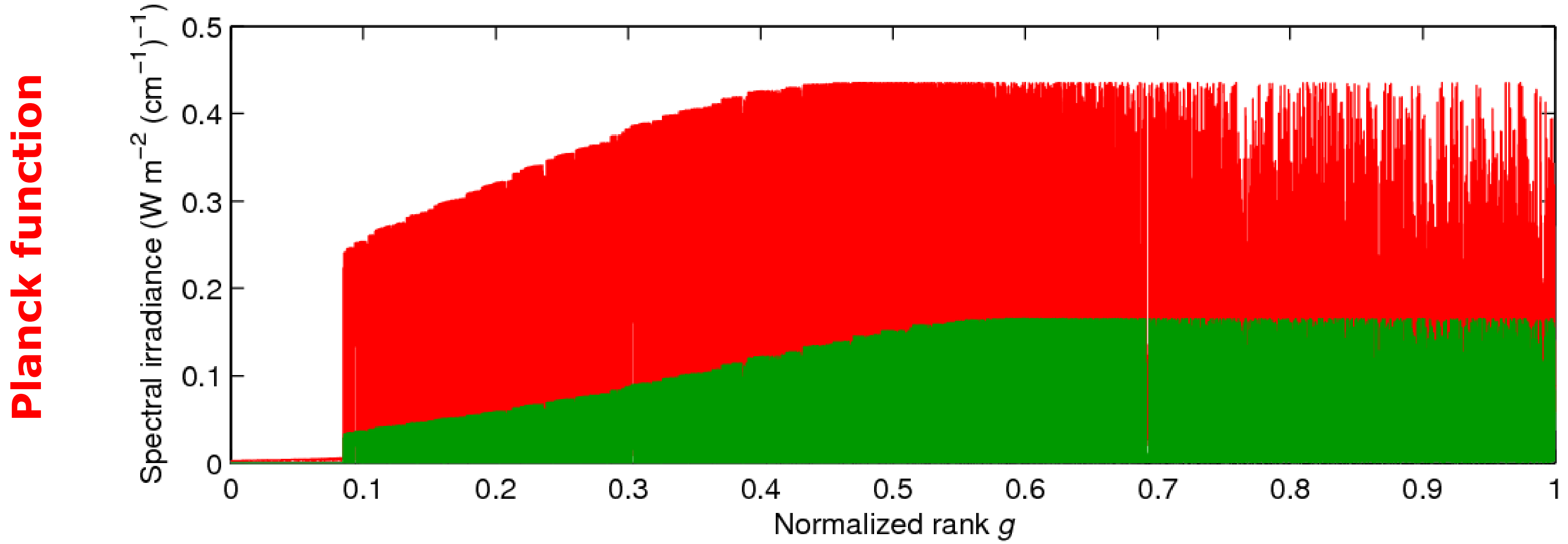
Planck function

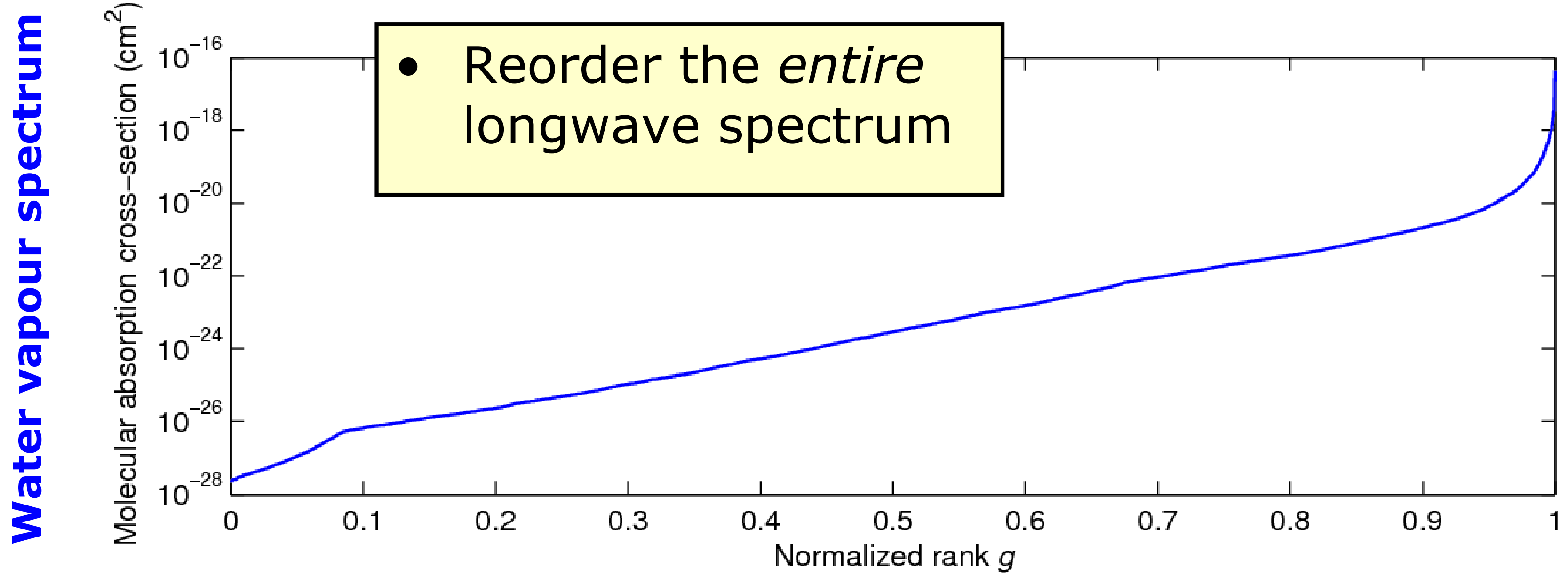


Water vapour spectrum



Full-spectrum correlated-k (FSCK) method



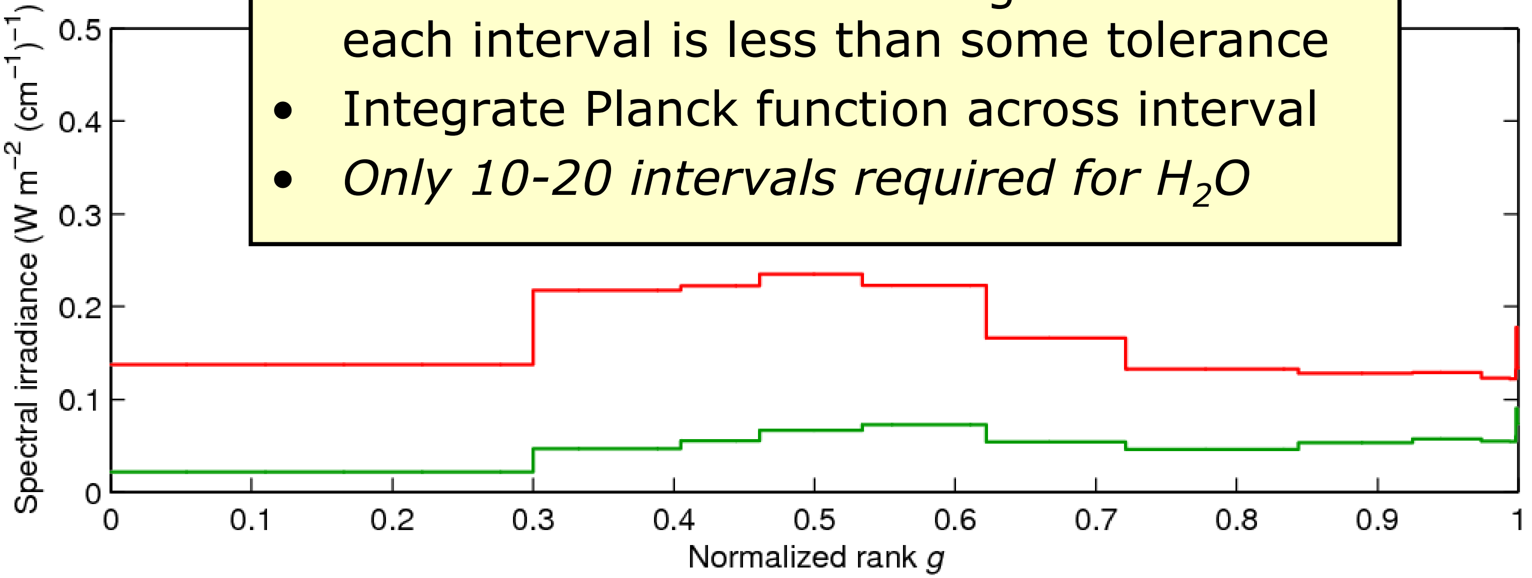


- Reorder the *entire* longwave spectrum

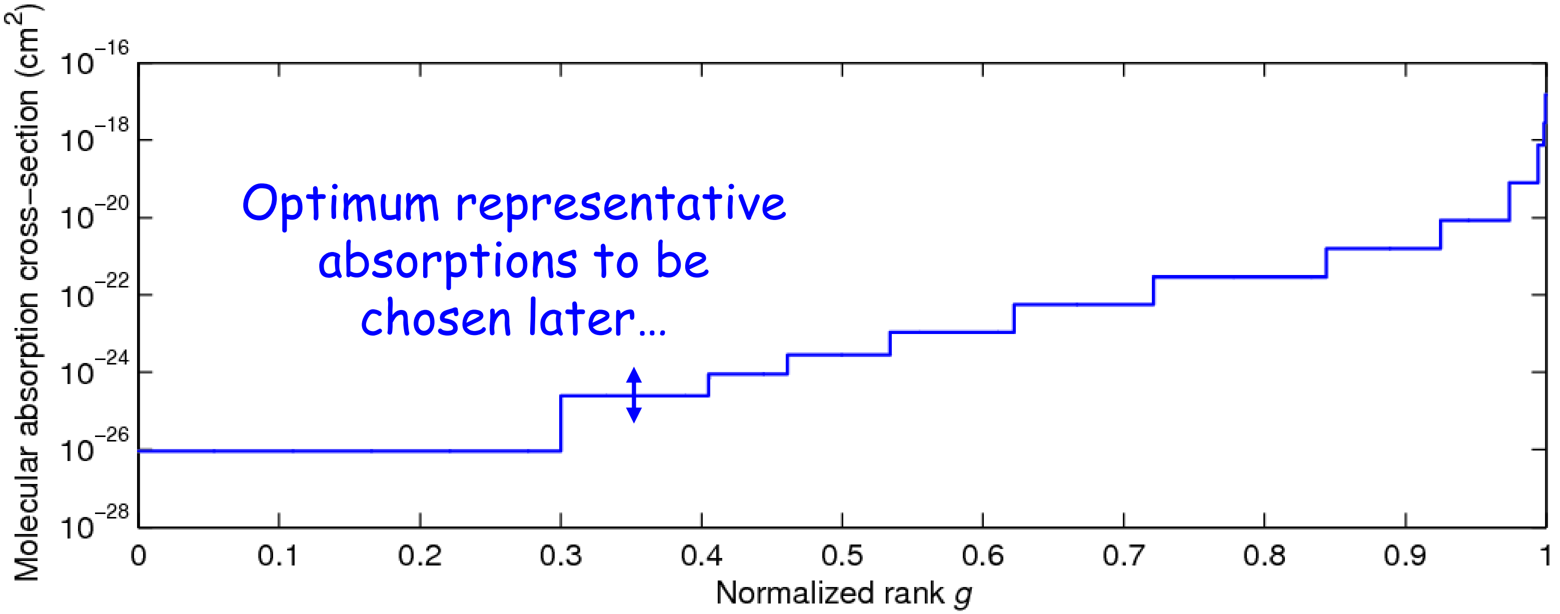
Full-spectrum correlated-k (FSCK) method

- Discretize such that heating rate error in each interval is less than some tolerance
- Integrate Planck function across interval
- *Only 10-20 intervals required for H_2O*

Planck function



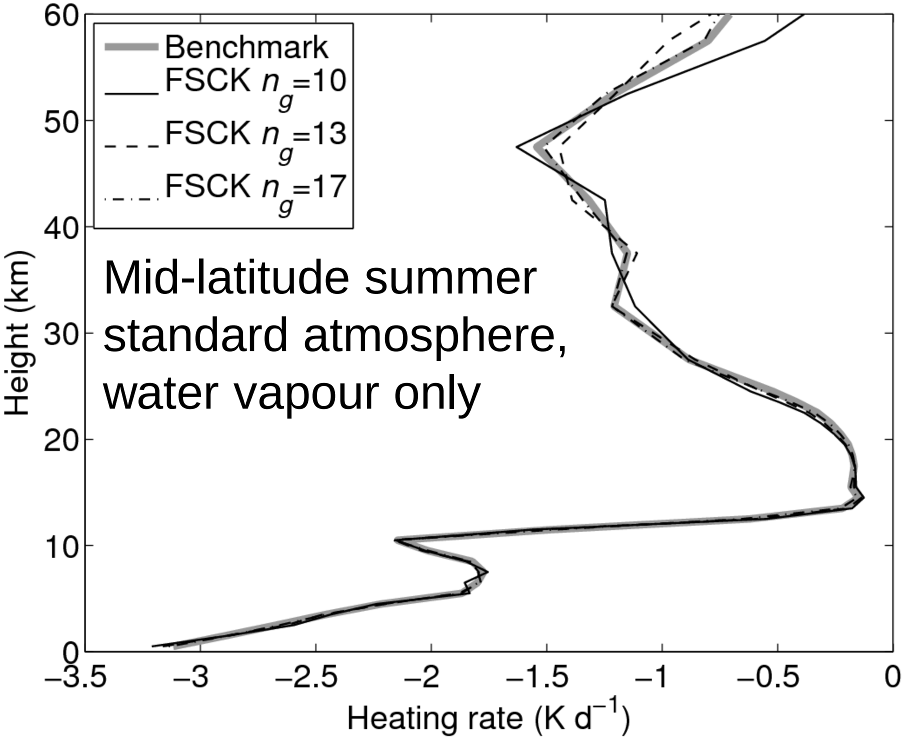
Water vapour spectrum



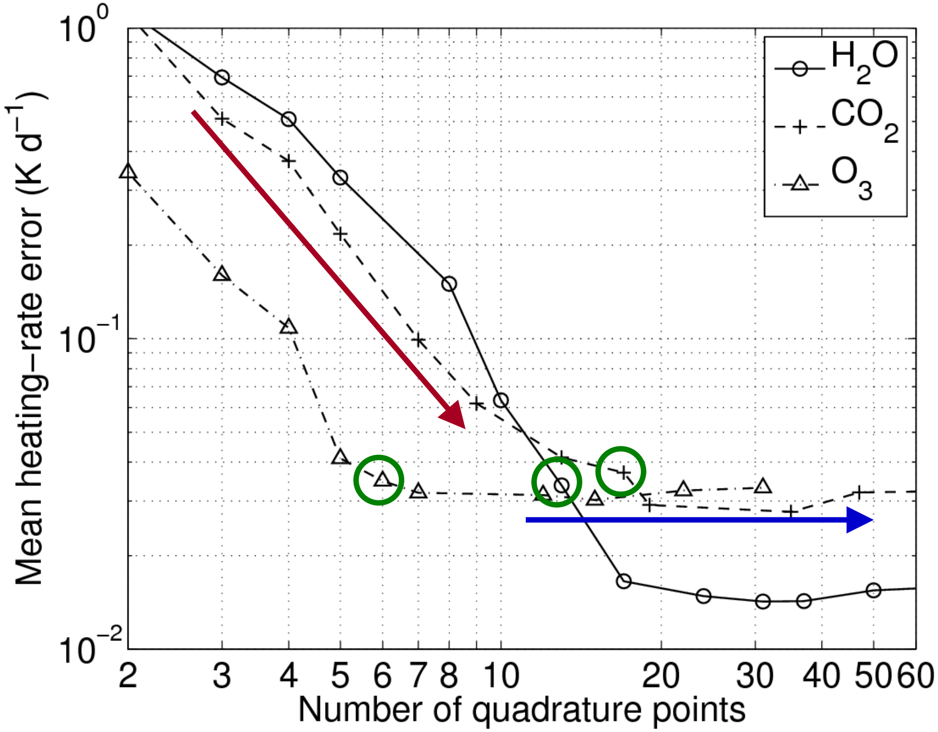
Optimum representative absorptions to be chosen later…

Atmospheres containing one gas

- Heating-rate error converges rapidly (~2nd order) with number of points in integration
- Flattens off because of imperfect spectral correlation at different heights due to pressure broadening



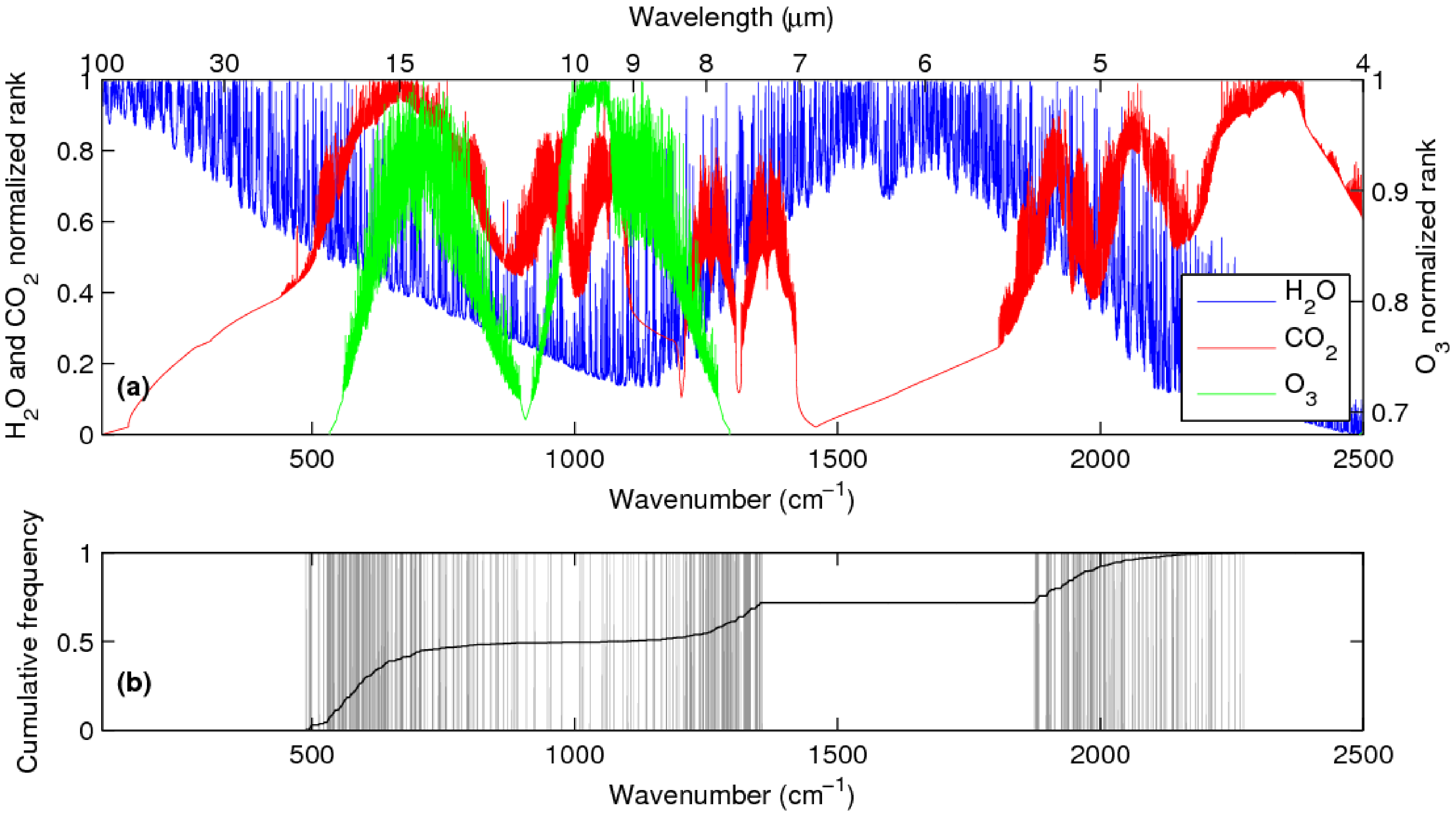
Mid-latitude summer standard atmosphere, water vapour only



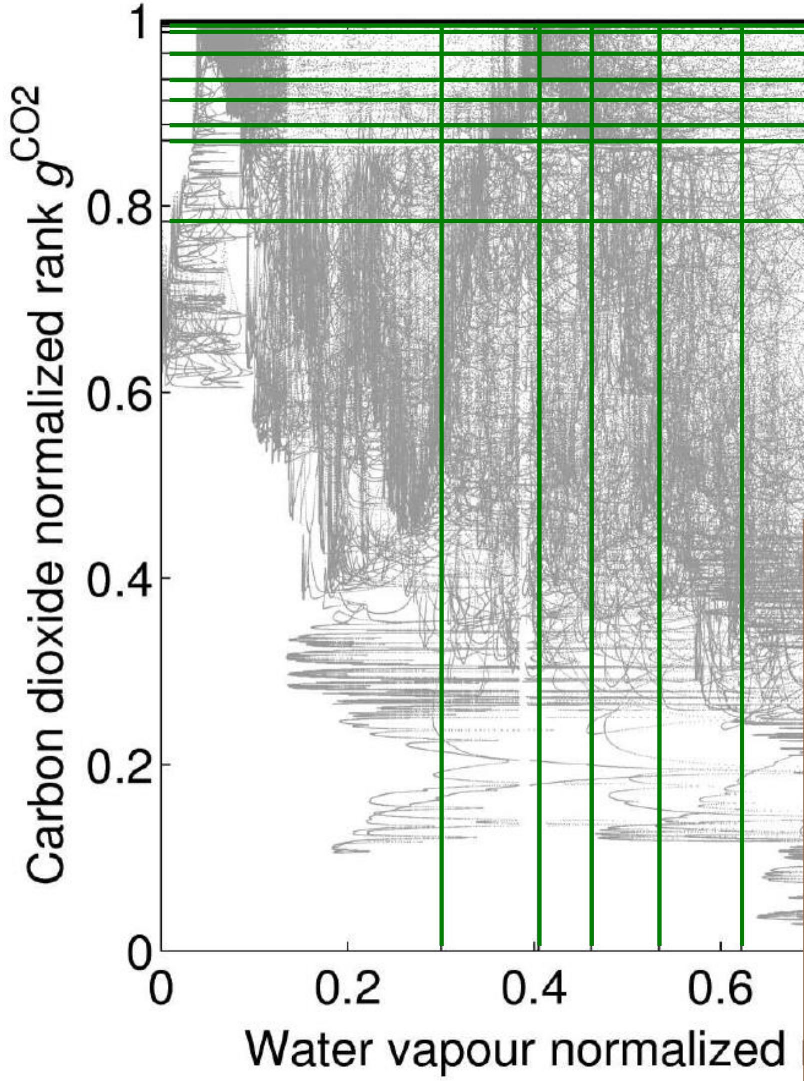
- Select discretizations of the spectrum of each gas with similar error: 0.035 K d^{-1} → n_{H2O}=13, n_{CO2}=15, n_{O3}=6

How can we treat overlapping gases?

- Gases with important contribution over a substantial part of the spectrum are water vapour, carbon dioxide and ozone

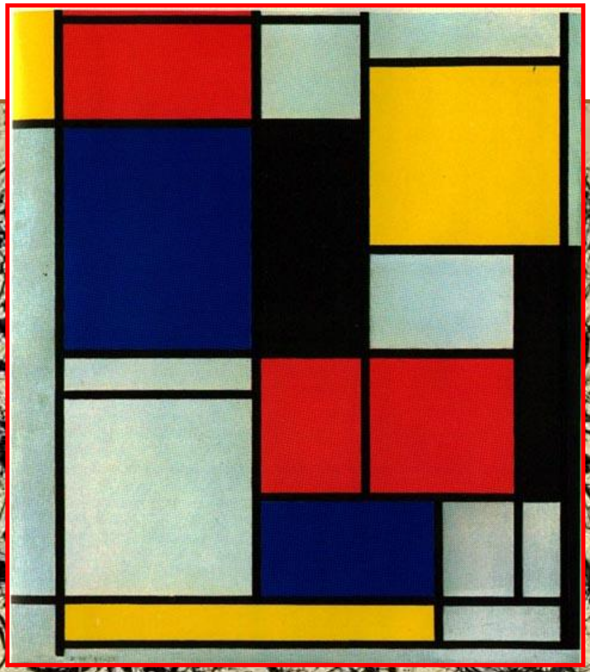


Overlap of two gases...



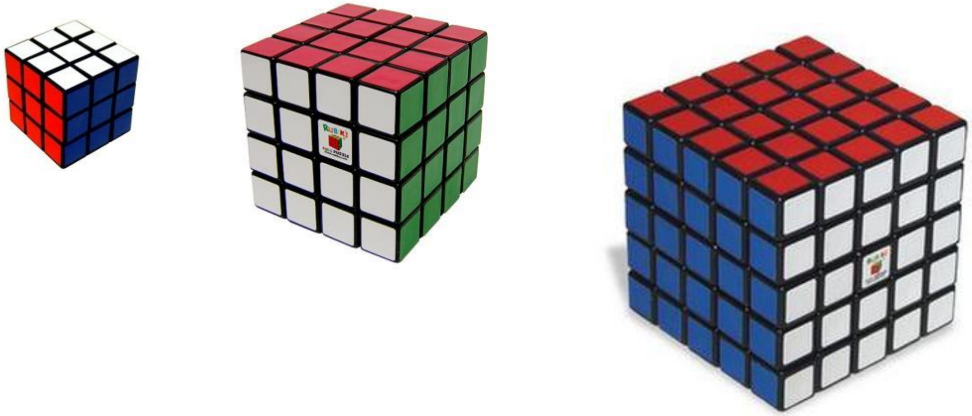
- Inefficient method: $n_{H2O} \times n_{CO2} = 195$
- Efficient method: often one gas dominates: $n_{H2O} + n_{CO2} - 1 = 27$

Piet Mondrian, 1921-25: Tableau 2

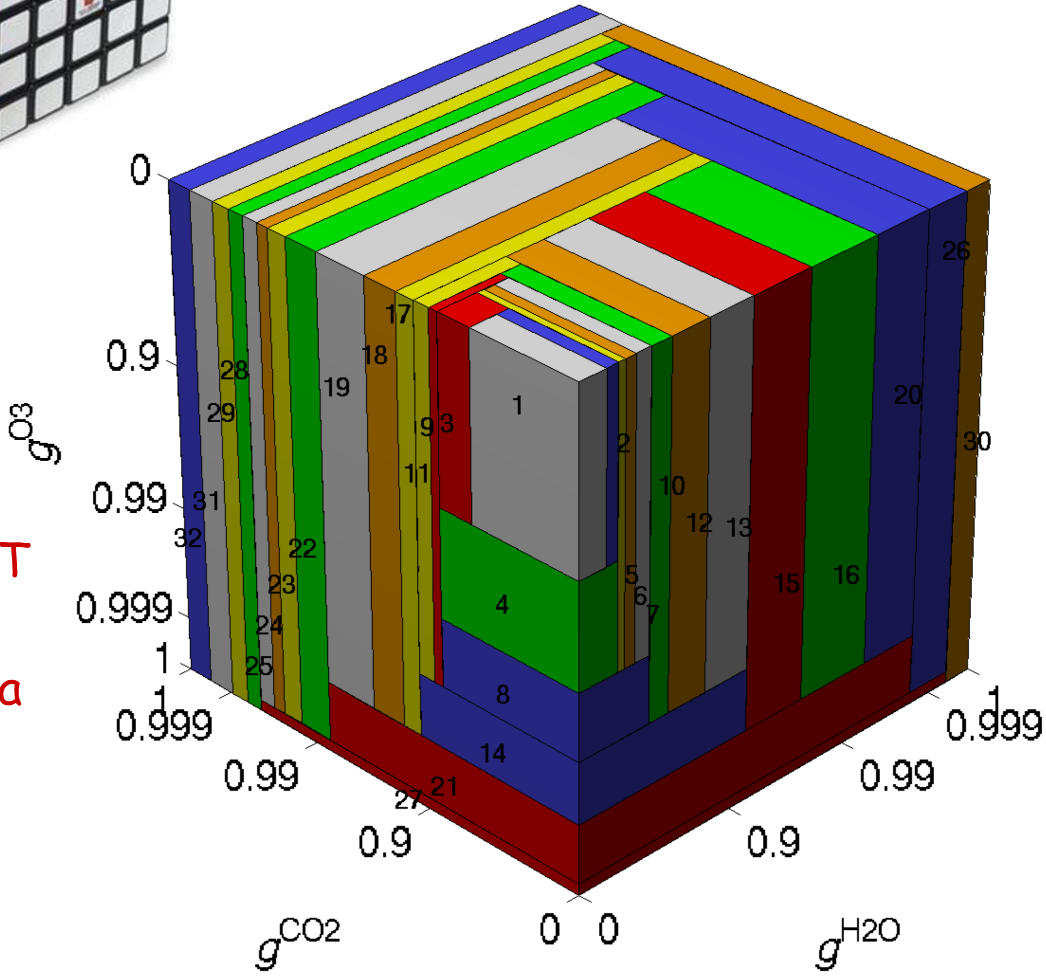


Jackson Pollock, 1950: Number 32, Enamel on canvas

Overlap of many gases



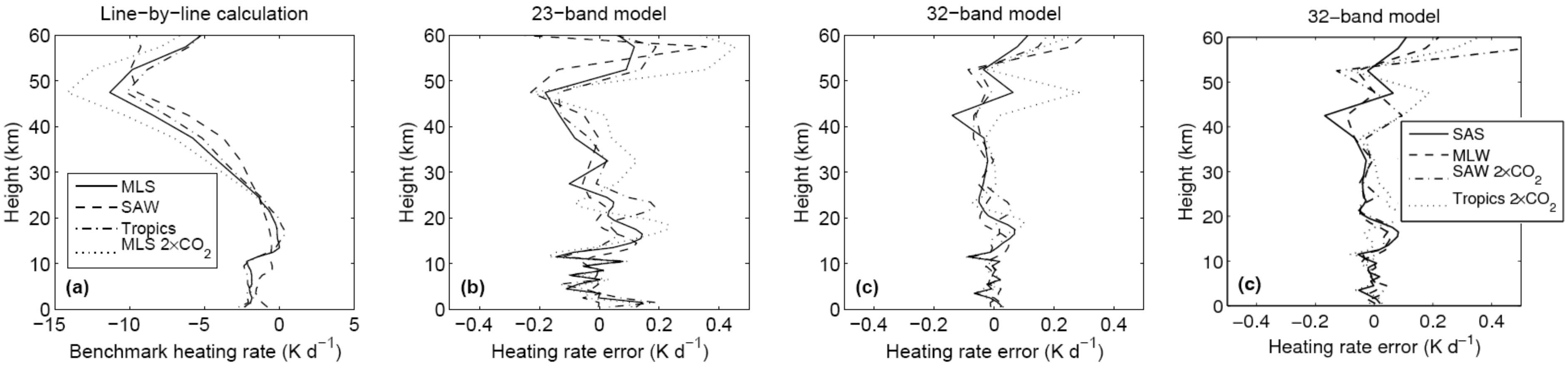
- Use a cube for 3 gases
  - $n_{H2O}+n_{CO2}+n_{O3}-2=32$ regions
  - "Hypercube" for more
- Properties in each region
  - Integral of Planck function stored as a lookup table vs T
  - Gas absorptions in each regions chosen to minimize a cost function expressing difference in heating-rate and flux profile from line-by-line benchmark in a number of test profiles



Hogan (JAS 2010)

Evaluation of FSCK

- 4 training profiles: mid-lat summer, sub-arctic winter, tropical and MLS 2xCO_2



4 other profiles

- Top-of-atmosphere flux errors (W m^{-2}):

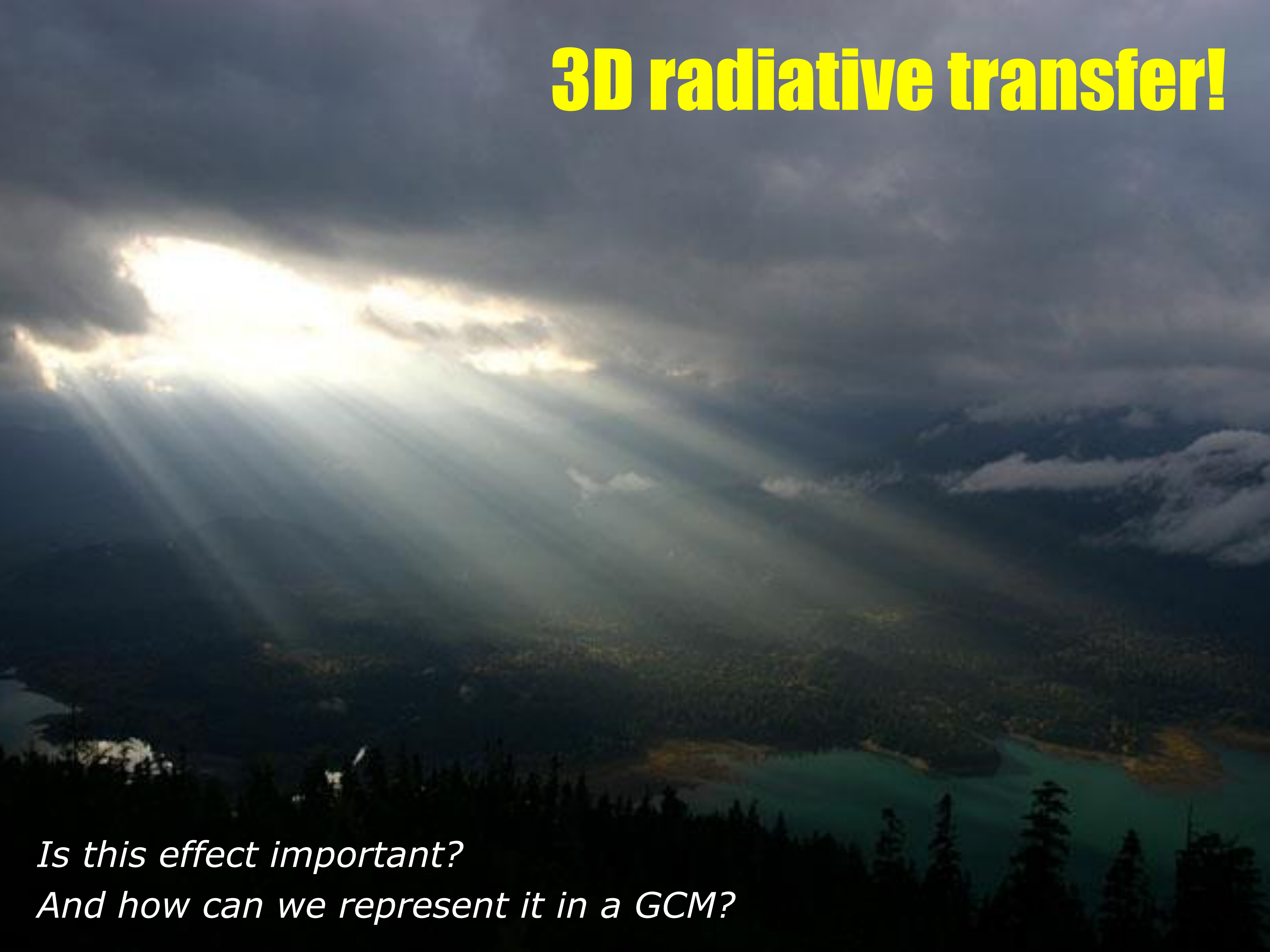
	Benchmark	23-point FSCK	32-point FSCK
MLS	281.75	-0.18	-0.03
SAW	196.69	0.41	0.19
Trop	291.89	0.09	0.04

- Error in change to top-of-atmosphere flux due to doubling CO_2:

MLS	2.87 W m^{-2}	-17%	-8%
SAW	1.82 W m^{-2}	-29%	-12%
Trop	3.31 W m^{-2}	-20%	-10%

Not part of training dataset

3D radiative transfer!

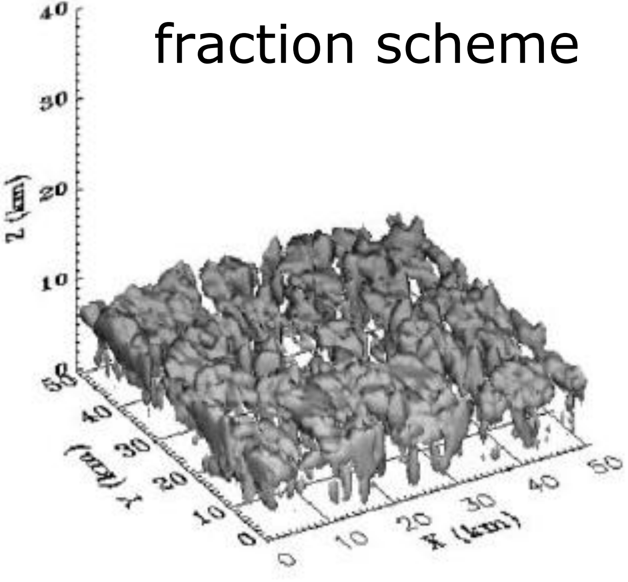


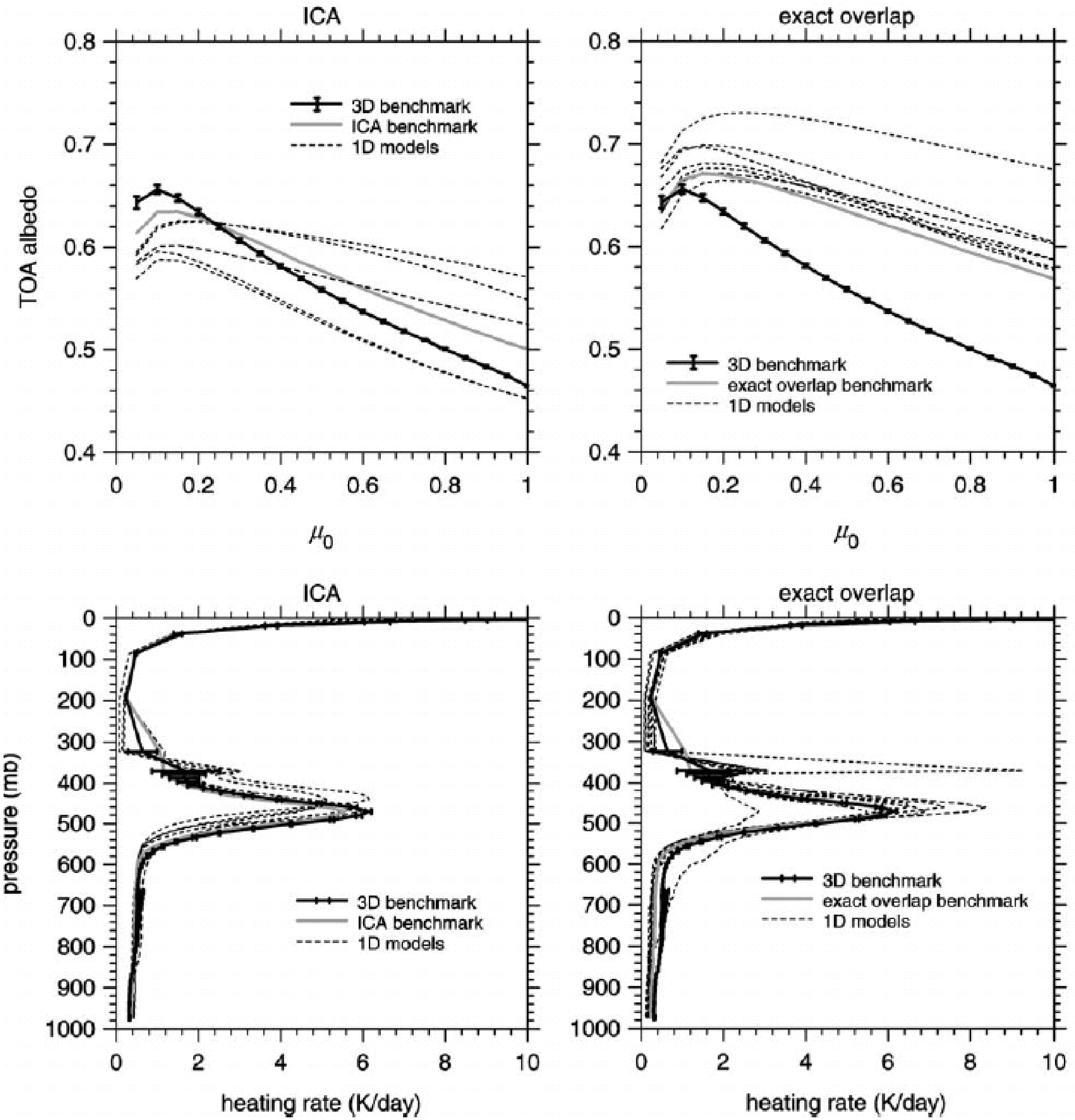
Is this effect important?

And how can we represent it in a GCM?

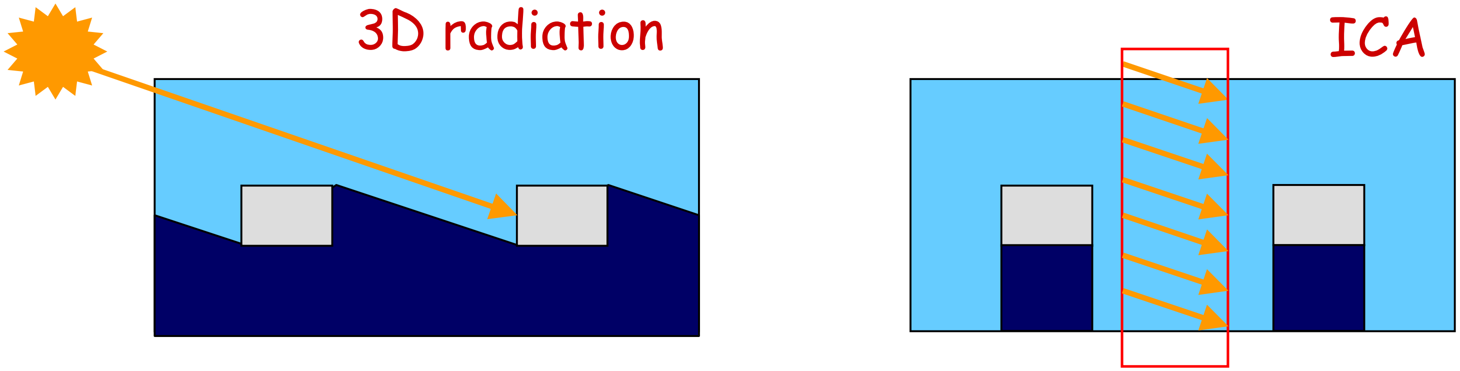
3D cloud benchmark

- Barker et al. (JClim 2003)
- Large spread in 1D models, whether used in ICA mode or with cloud-fraction scheme



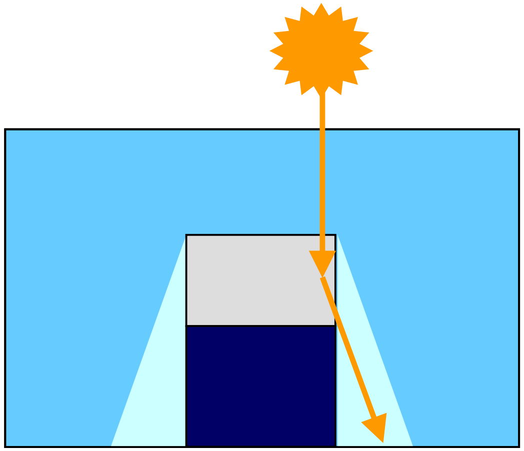


The three main 3D effects

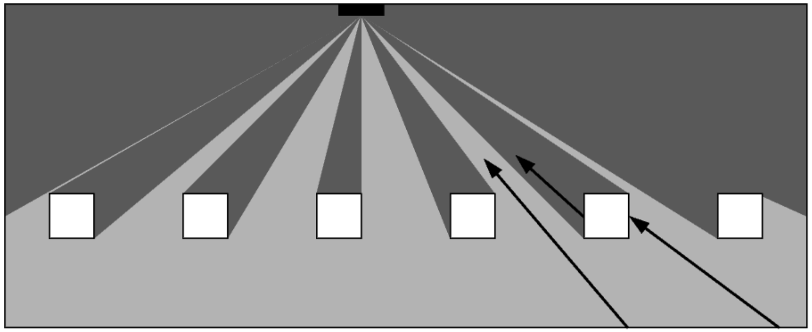


- Effect 1: Shortwave cloud side illumination
  - Incoming radiation is more likely to intercept the cloud
  - Affects the direct solar beam
  - Always increases the cloud radiative forcing
  - Maximized for a low sun (high solar zenith angle)
  - Flux is less for low sun, so diurnally averaged effect may be small

Three main 3D effects continued

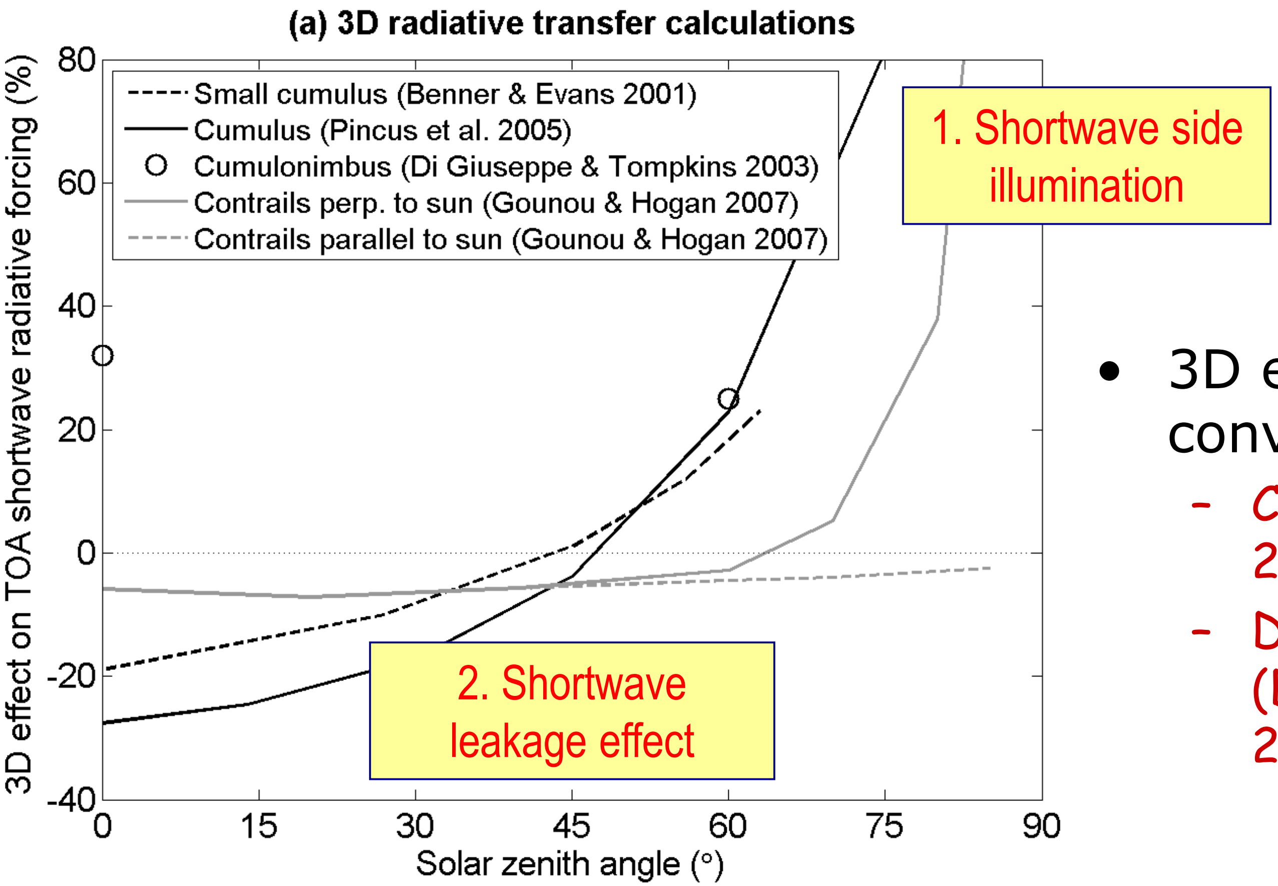


- Effect 2: Shortwave side leakage
  - Maximized for high sun and isolated clouds
  - Results from forward scattering
  - Usually decreases cloud radiative forcing
  - But depends on specific cloud geometry
  - Affects the diffuse component



- Effect 3: Longwave side effect
  - Above a field of clouds, the clouds subtend a larger fraction of the downward-looking hemisphere than the areal cloud coverage (accounting for cos θ dependence of contribution to upwelling irradiance)
  - Hence longwave cloud radiative forcing is typically increased

3D shortwave effects

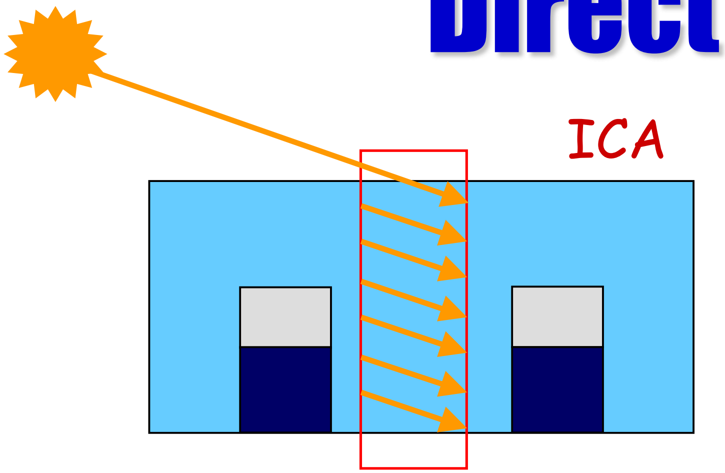

(a) 3D radiative transfer calculations

1. Shortwave side illumination

2. Shortwave leakage effect

- 3D effects significant in convective clouds
  - Cumulus (Benner & Evans 2001, Pincus et al. 2005)
  - Deep convection (DiGiuseppe & Tompkins 2003)
- 3D effects much smaller in stratiform clouds
  - In cirrus, SW and LW effects up to 10% for optical depth ~1, but negligible for optically thicker clouds (Zhong, Hogan and Haigh 2008)
- *How can we represent this effect in GCM radiation schemes?*

Direct shortwave calculation

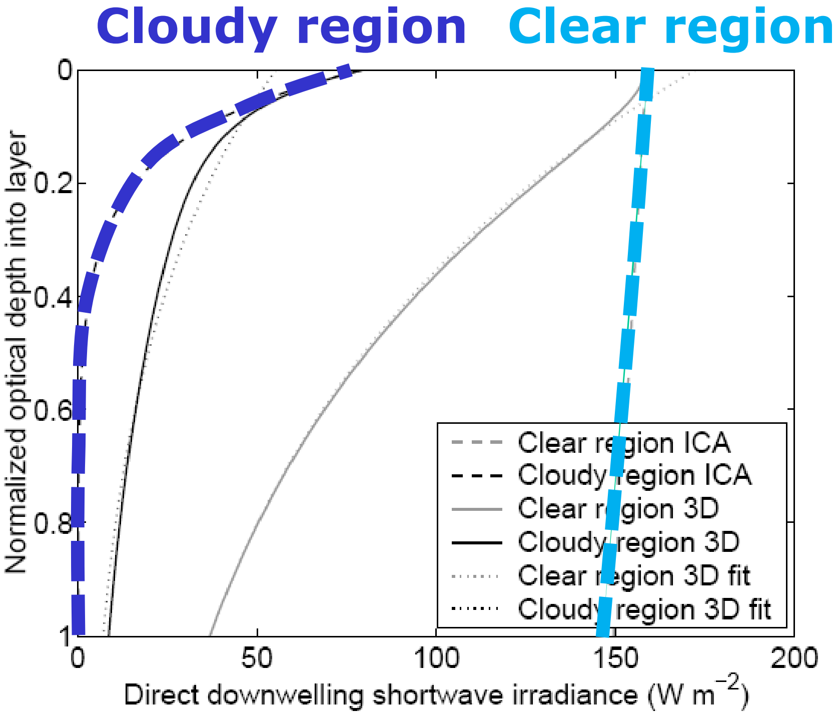


- First part of a shortwave calculation is to determine how far direct (unscattered) beam penetrates
  - Solve this equation independently in the clear and cloudy regions (δ is optical depth):

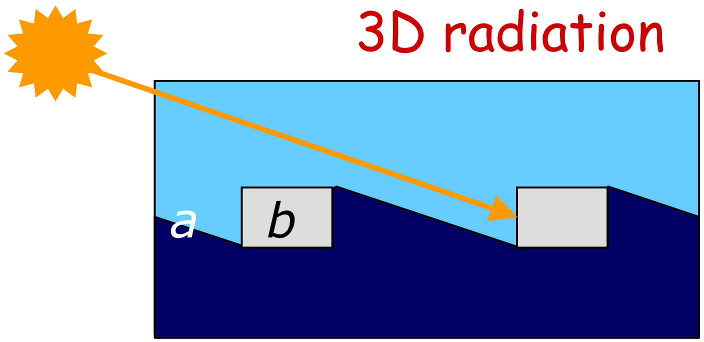
$$\frac{dF}{d\delta} = -\frac{F}{\mu_0}$$

  - The solution is Beer's law:

$$F = F_0 \exp(-\delta/\mu_0)$$



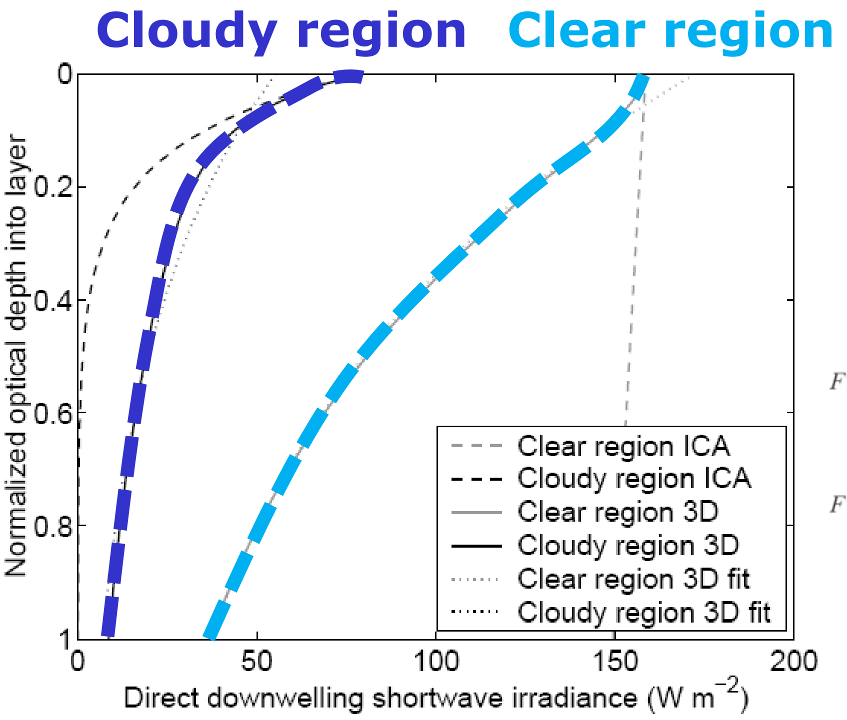
Direct shortwave calculation



- *Alternative: add terms expressing exchange between regions a & b:*

$$\frac{\mathrm{d}F^a}{\mathrm{d}\delta'} = -\frac{\delta^a}{\mu_0}F^a - f_{\mathrm{dir}}^{ab}F^a + f_{\mathrm{dir}}^{ba}F^b$$

$$\frac{\mathrm{d}F^b}{\mathrm{d}\delta'} = -\frac{\delta^b}{\mu_0}F^b - f_{\mathrm{dir}}^{ba}F^b + f_{\mathrm{dir}}^{ab}F^a$$



- New terms depend on geometric constants *f* ^{ab} and *f* ^{ba}
- Solution of pair of coupled ODEs:

$$\begin{aligned} F^a(\delta') &= \frac{(r+a-b)F^a(0) - 2f_{\mathrm{dir}}^{ab}F^b(0)}{2r}\mathrm{e}^{k_1\delta'} \\ &+ \frac{(r-a+b)F^a(0) + 2f_{\mathrm{dir}}^{ab}F^b(0)}{2r}\mathrm{e}^{k_2\delta'} \\ F^b(\delta') &= \frac{(r-a+b)F^b(0) - 2f_{\mathrm{dir}}^{ba}F^a(0)}{2r}\mathrm{e}^{k_1\delta'} \\ &+ \frac{(r+a-b)F^b(0) + 2f_{\mathrm{dir}}^{ba}F^a(0)}{2r}\mathrm{e}^{k_2\delta'} \end{aligned}$$

$$\begin{aligned} a &= \delta^a/\mu_0 + f_{\mathrm{dir}}^{ab}; \\ b &= \delta^b/\mu_0 + f_{\mathrm{dir}}^{ba}; \\ r &= \left(a^2 + b^2 - 2ab + 4f_{\mathrm{dir}}^{ab}f_{\mathrm{dir}}^{ba}\right)^{1/2}; \\ k_1 &= -(a+b+r)/2; \\ k_2 &= -(a+b-r)/2. \end{aligned}$$

- Result: much less radiation gets through to next atmospheric layer!

Diffuse calculation

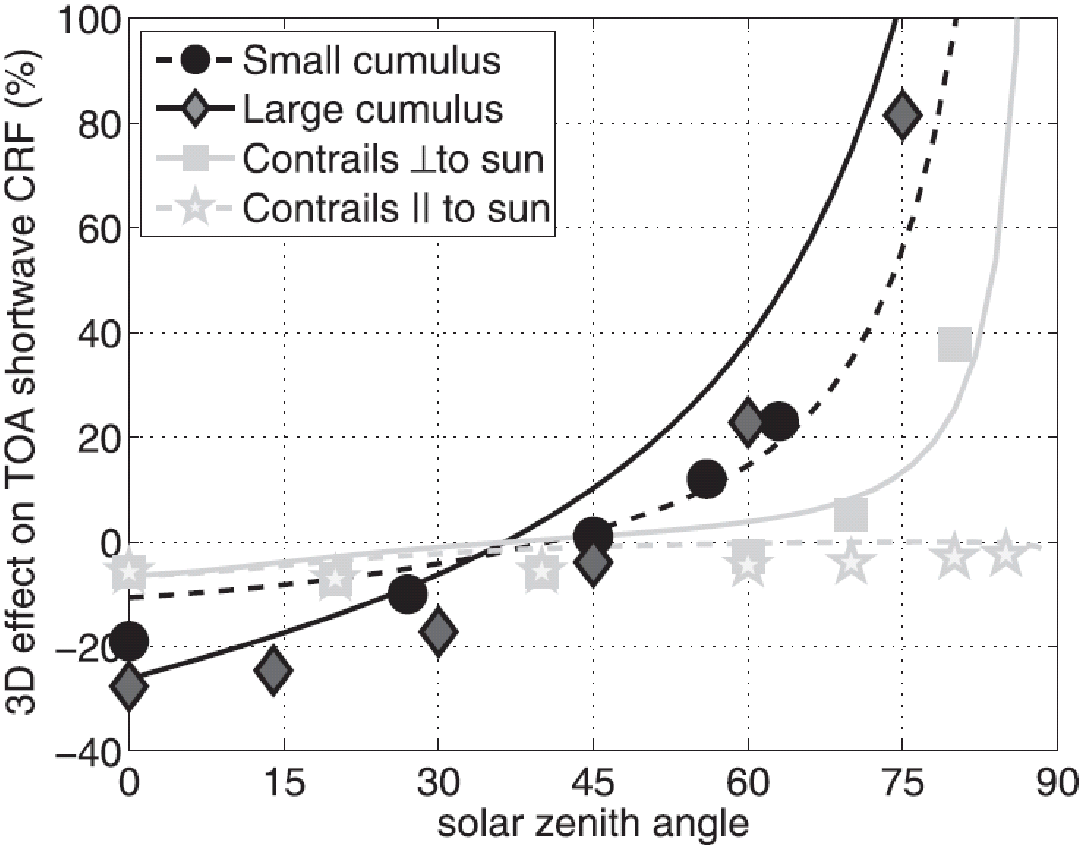
- The next step is to use the two-stream equations to calculate the diffuse part of the radiation field
  - Downwelling stream: $$\frac{\mathrm{d}I^{a-}}{\mathrm{d}\delta'} = \delta^a\left[-\gamma_1^a I^{a-} + \gamma_2^a I^{a+} + S^{a-}\right]$$
  - Upwelling stream: $$-\frac{\mathrm{d}I^{a+}}{\mathrm{d}\delta'} = \delta^a\left[-\gamma_1^a I^{a+} + \gamma_2^a I^{a-} + S^{a+}\right]$$

New terms
Represent exchange
between regions

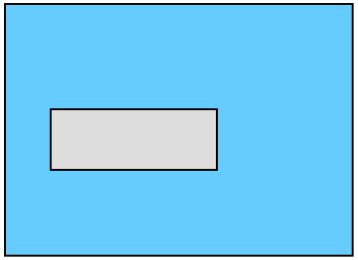
Source terms
Shortwave: direct solar beam
Longwave: Planck function

  - Solution a little more complex when integrated across a layer, but efficient enough to be implemented in a GCM

Results of new scheme



- New idea tested using a single layer of homogeneous cloud illuminated by a monochromatic beam
  - Performs surprisingly well against 3D calculations
- Next step: longwave



Cloud fraction *f*
Aspect ratio *r*
Optical depth δ

Hogan and Shonk (2013)

Summary

- The radiation scheme is a key part of both weather, seasonal and climate forecasts
- While the physics is known, there are still challenges in implementing this accurately and efficiently in models
- Significant errors still remain, particularly in the representation of clouds