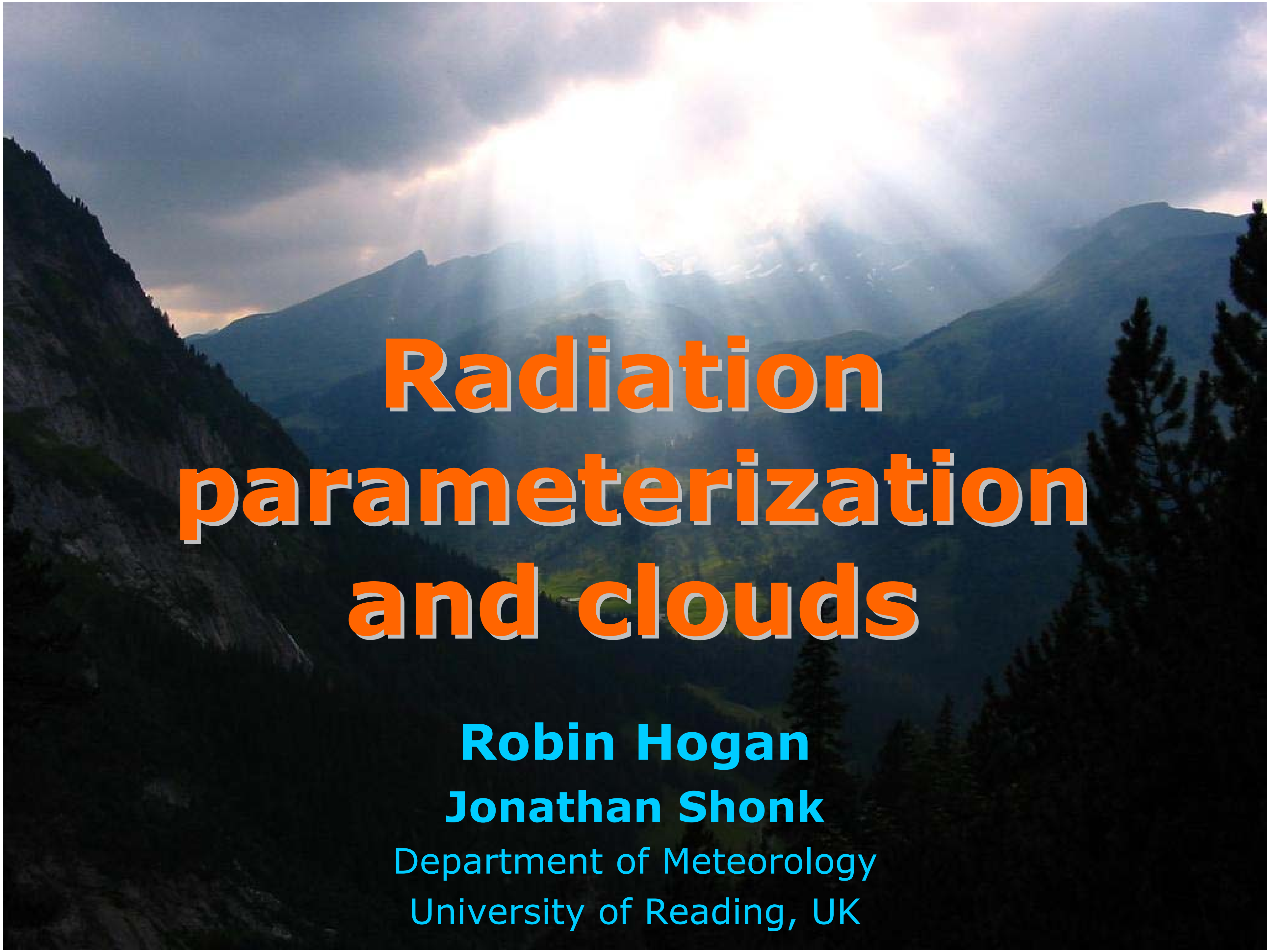


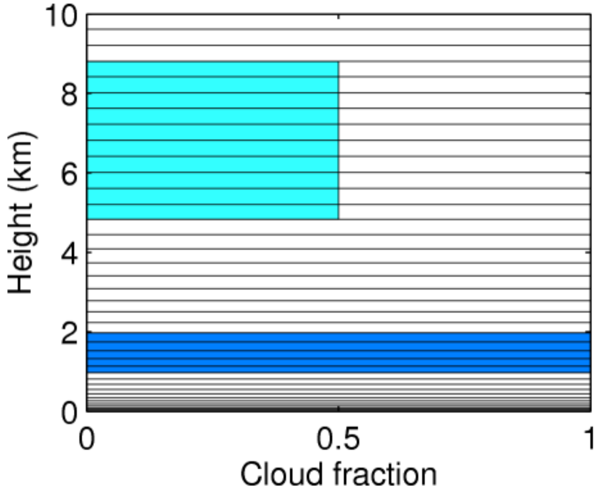
Radiation parameterization and clouds

Robin Hogan
Jonathan Shonk
Department of Meteorology
University of Reading, UK

Overview

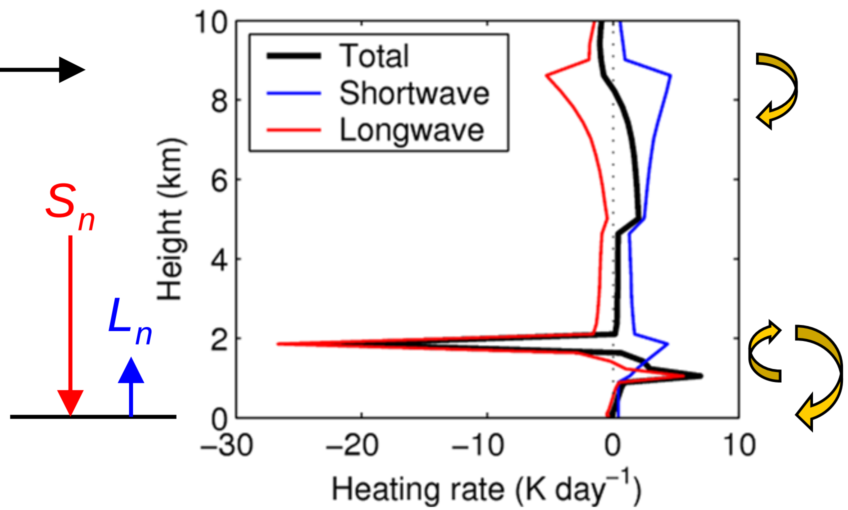
- From Maxwell to the two-stream approximation
- Quantifying sub-grid cloud structure from observations
- The challenge of representing cloud structure efficiently
- What is the global radiative impact of sub-grid cloud structure?
- Do we need to worry about 3D radiative transport?
- Are we spending our computer time wisely?
- Outlook

What does a radiation scheme do?



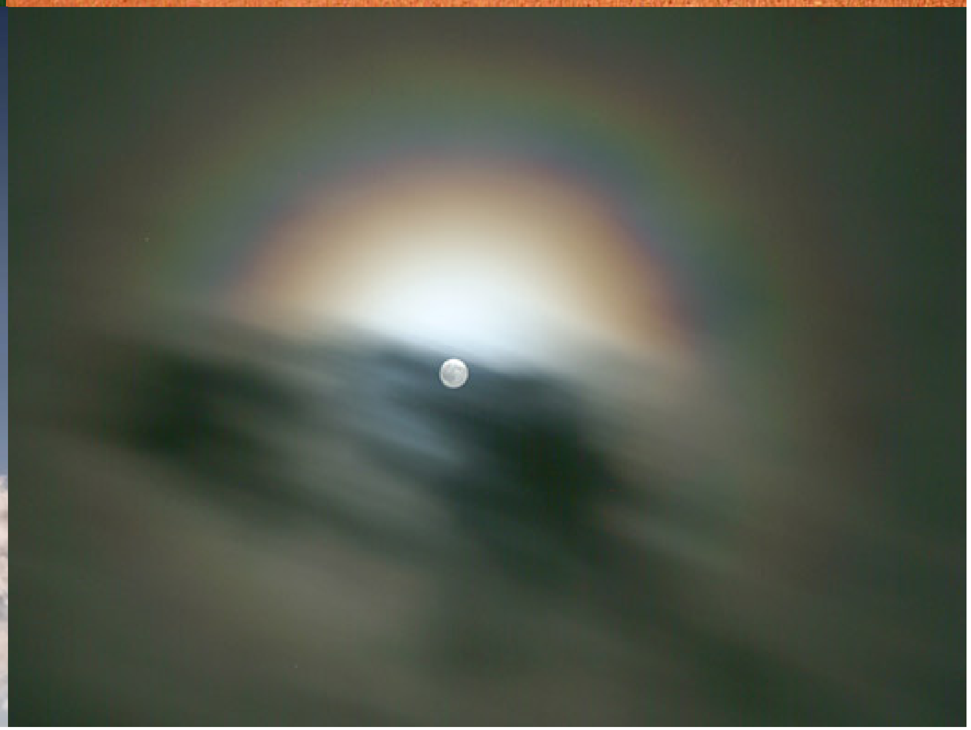
- Variables on model grid
  - Temperature, pressure, humidity, ozone
  - Cloud liquid and ice mixing ratios
  - Cloud fraction

The bit of the model that takes so long to run



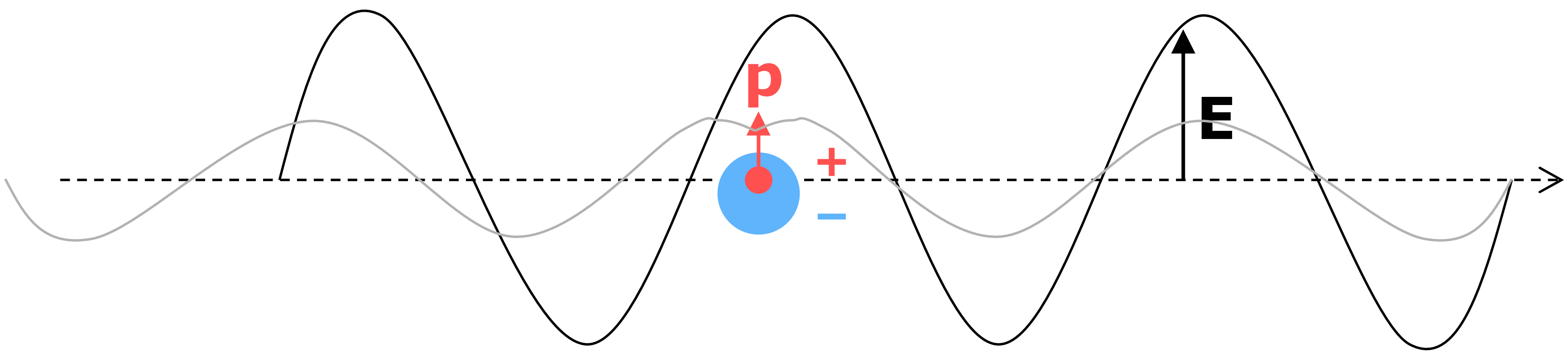
Radiation in the presence of clouds tends to destabilize the atmosphere



Building blocks of atmospheric radiation

1. Emission and absorption of quanta of radiative energy
   - Governed by quantum mechanics: the Planck function and the internal energy levels of the material
   - Responsible for complex gaseous absorption spectra
2. Electromagnetic waves interacting with a dielectric material
   - An oscillating dipole is excited, which then re-radiates
   - Governed by Maxwell's equations + Newton's 2nd law for bound charges
   - Responsible for *scattering*, *reflection* and *refraction*



Oscillating dipole p is induced, which is typically in phase with the incident electric field E

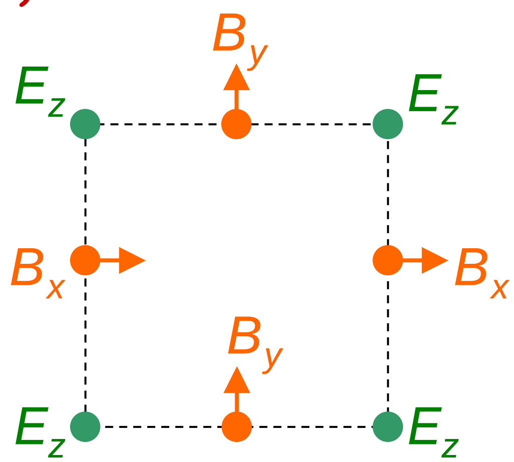
Dipole radiates in all directions (except directly parallel to its axis)

Maxwell's equations

- Almost all atmospheric radiative phenomena are due to this effect, described by the Maxwell curl equations:

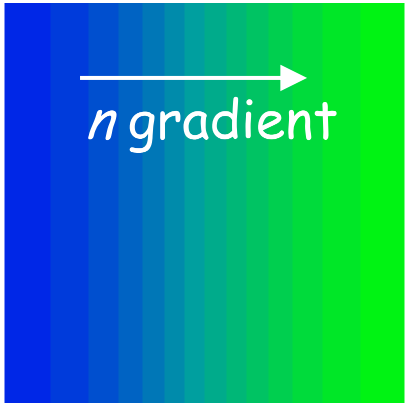
$$\frac{\partial \mathbf{E}}{\partial t} = \frac{c^2}{n^2} \nabla \times \mathbf{B} \qquad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

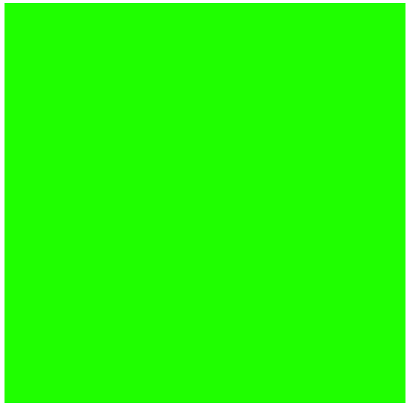
  - where *c* is the speed of light in vacuum, *n* is the complex refractive index (which varies with position), and **E** and **B** are the electric and magnetic fields (both functions of time and position);
- It is illuminating to discretize these equations directly
  - This is known as the Finite-Difference Time-Domain (FDTD) method
  - Use a staggered grid in time and space (Yee 1966)
  - Consider two dimensions only for simplicity
  - Need gridsize of ~0.02 μm and timestep of ~50 ps for atmospheric problems



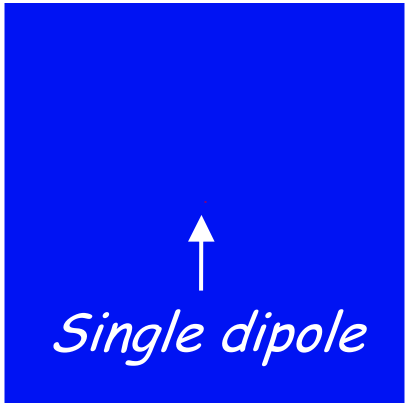
Simple examples

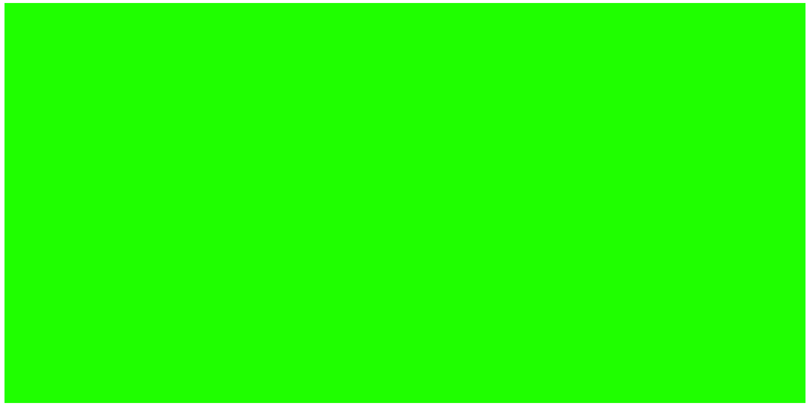
- Refraction (a mirage)





- Rayleigh scattering (blue sky)





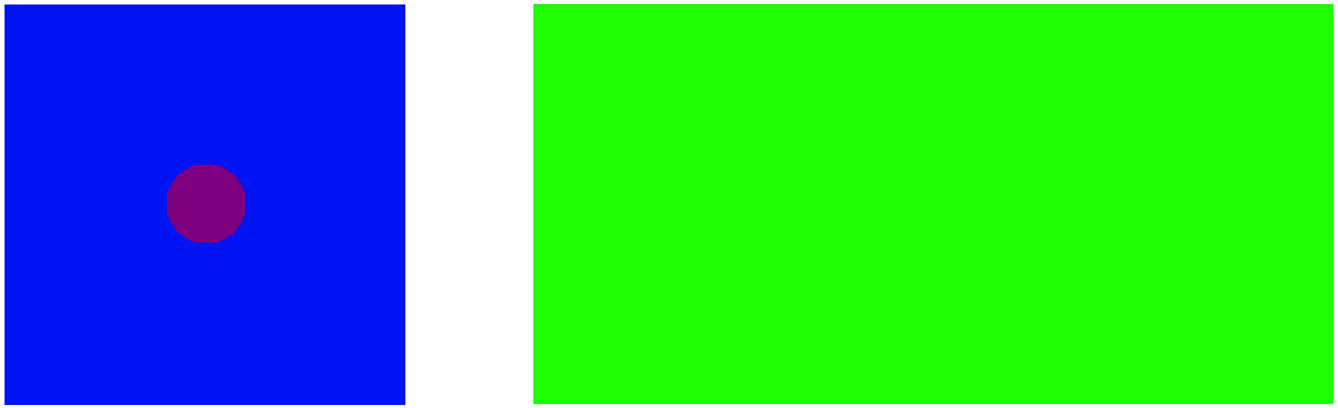
Refractive index

Total E_z field

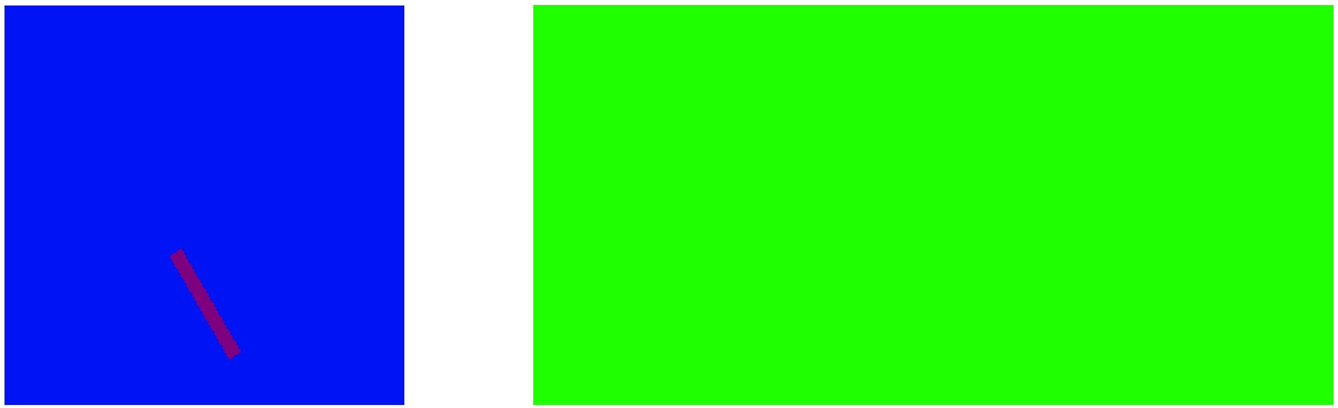
Scattered field (total − incident)

More complex examples

- A sphere (or circle in 2D)



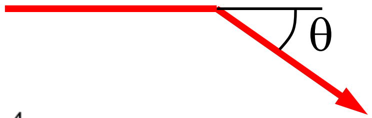
- An ice column

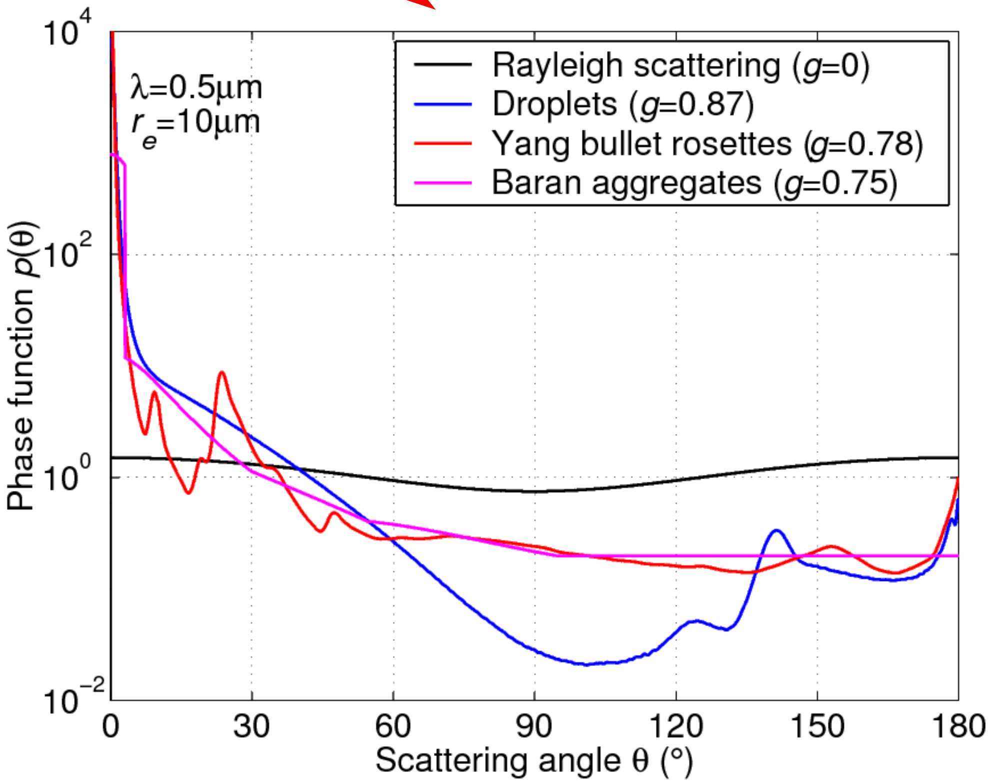


Refractive index | Total E_z field | Scattered field (total − incident)

Many more animations at www.met.rdg.ac.uk/~swrhgnrj/maxwell
(interferometer, diffraction grating, dish antenna, clear-air radar…)

The phase function





- The distribution of scattered energy is known as the "scattering phase function"
- Different methods are suitable for different types of scatterer

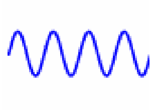
– *Spheres:* Mie theory (Mie 1908) provides a solution to Maxwell's equations as a series expansion

– *Arbitrary ice particle shapes:* depending on D/λ, use the Discrete Dipole Approximation, FDFT or ray tracing (Yang et al. 2000)

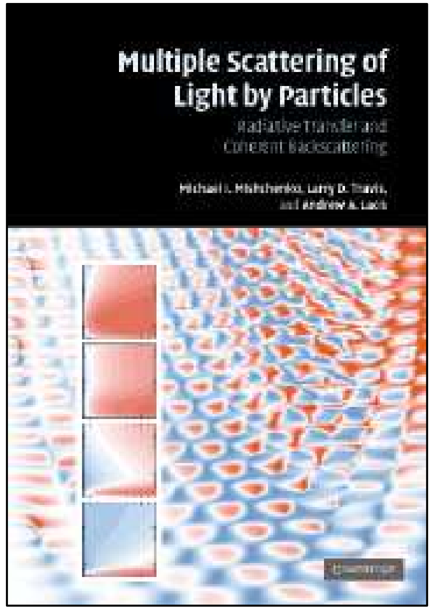
– But observations (Baran) suggest smoother phase functions implying that the surface of ice particles is "rough"

From Maxwell to radiative transfer

Maxwell's equations in terms of fields $\mathbf{E}(\mathbf{x},t)$, $\mathbf{B}(\mathbf{x},t)$



Mishchenko et al. (2007)



Reasonable assumptions:

- Ignore polarization
- Ignore time-dependence (sun is a continuous source)
- Particles are randomly separated so intensities add incoherently and phase is ignored
- Random orientation of particles so phase function doesn't depend on absolute orientation
- No diffraction around features larger than individual particles

3D radiative transfer in terms of radiances $I(\mathbf{x},\Omega,\nu)$ in W m^{-2} sr^{-1} Hz^{-1}

The 3D radiative transfer equation

- Also known as the "Boltzmann transport equation", this describes the radiance I in direction $\mathbf{\Omega}$ (where the $\mathbf{x}$ and ν dependence of all variables is implicit):

$$\mathbf{\Omega} \cdot \nabla I(\mathbf{\Omega}) = -\beta_e I(\mathbf{\Omega}) + \beta_s \int_{4\pi} p(\mathbf{\Omega}, \mathbf{\Omega}') I(\mathbf{\Omega}') d\mathbf{\Omega}' + S(\mathbf{\Omega})$$

Spatial derivative representing how much radiation is upstream

Loss by absorption or scattering

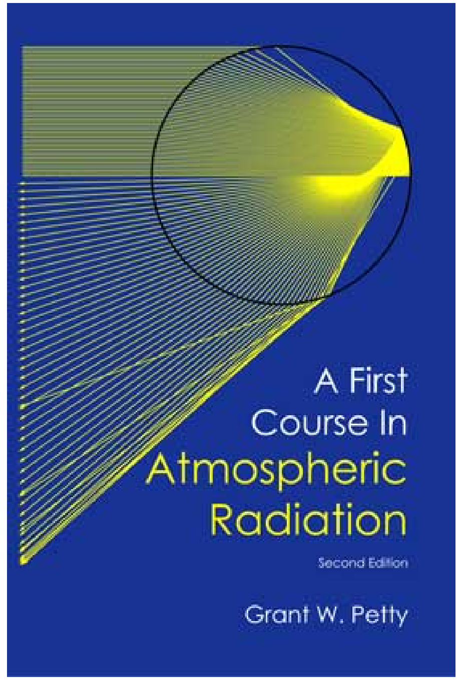
Gain by scattering Radiation scattered from all other directions

Source Such as thermal emission

- This may be solved in a 3D domain
  - Monte Carlo method most efficient for fluxes
  - As a boundary-value problem (e.g. using "SHDOM") for radiances
- Extinction coefficient β_e (m^{-1}) is a key variable
  - When particle size >> wavelength, GCM can use $\beta_e = \frac{3\rho_a q_l}{2\rho_l r_{el}} + \frac{3\rho_a q_i}{2\rho_i r_{ei}}$

Two-stream approximation

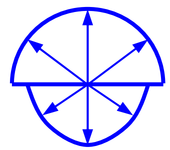
3D radiative transfer in terms of radiances $I(\mathbf{x},\Omega,\nu)$



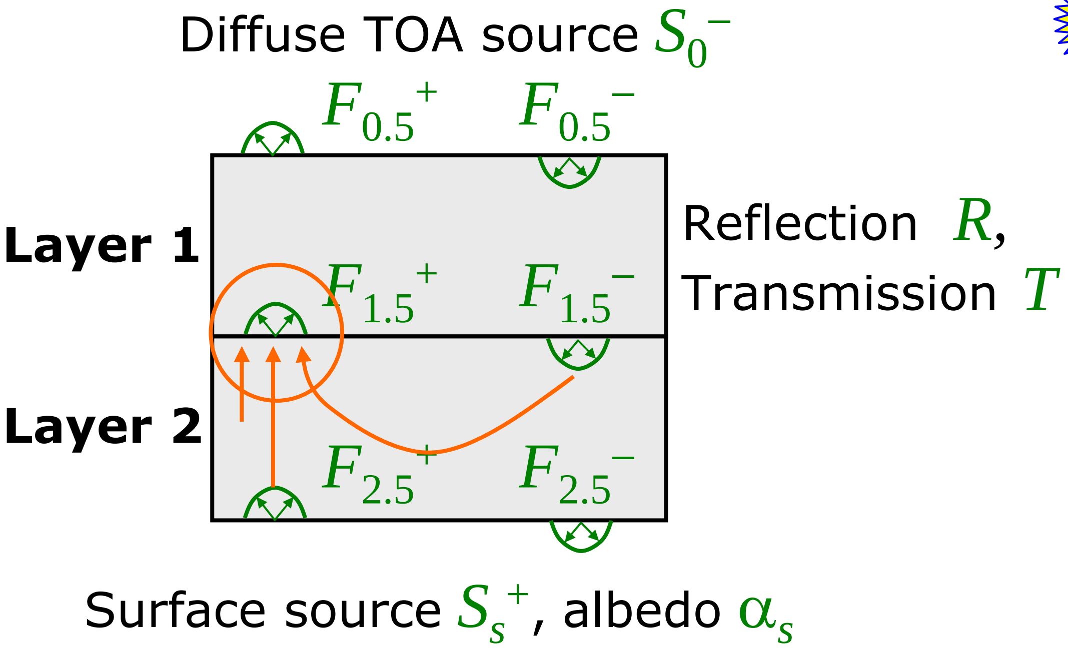
*Un*reasonable assumptions:

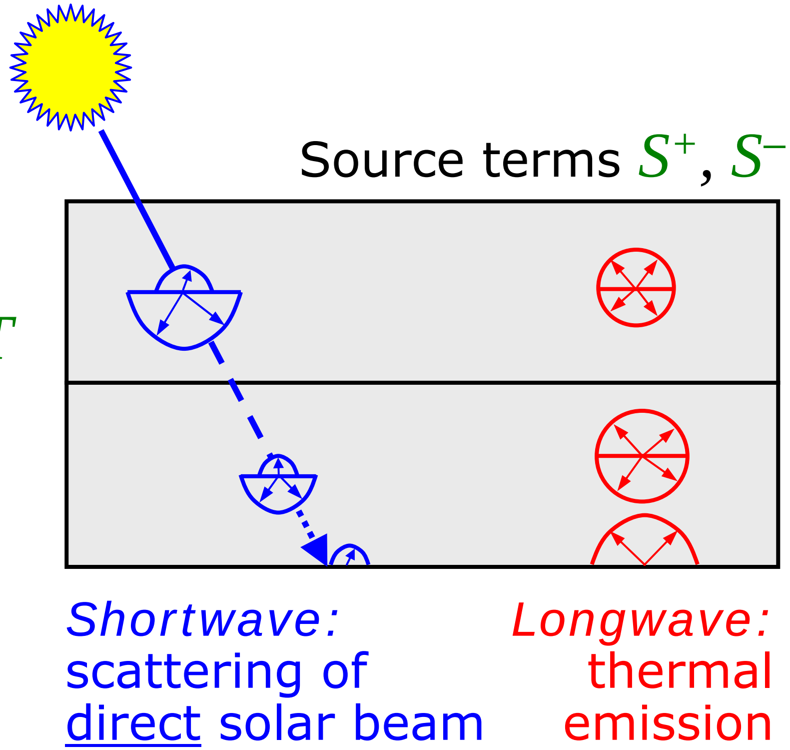
- Radiances in all directions represented by only 2 (or sometimes 4) discrete directions
- Atmosphere within a model gridbox is horizontally infinite and homogeneous
- Details of the phase functions represented by one number, the asymmetry factor $g = \cos\theta$

1D radiative transfer in terms of two fluxes $F^{\pm}(z,\nu)$ in W m^{-2} Hz^{-1}



Discretized two-stream scheme





- Equations relating diffuse fluxes between levels take the form:

$$F_{i-0.5}^+ = T_i F_{i+0.5}^+ + R_i F_{i-0.5}^- + S_i^+$$

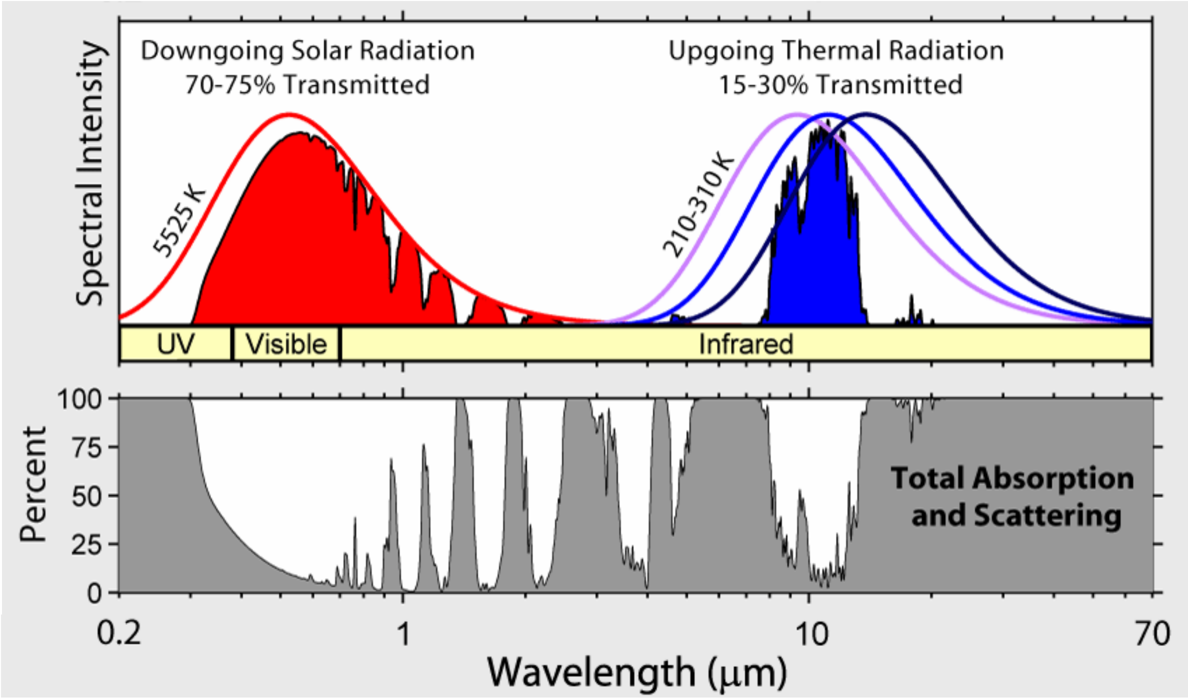
- Terms T, R and S given by Meador and Weaver (1980)

Solution for two-level atmosphere

- Solve the following tri-diagonal system of equations

$$\begin{pmatrix} & 1 & & & & & \\ 1 & -R_1 & -T_1 & & & & \\ & -T_1 & -R_1 & 1 & & & \\ & & 1 & -R_2 & -T_2 & & \\ & & & -T_2 & -R_2 & 1 & \\ & & & & 1 & -\alpha_s & \end{pmatrix} \begin{pmatrix} F_{0.5}^{+} \\ F_{0.5}^{-} \\ F_{1.5}^{+} \\ F_{1.5}^{-} \\ F_{2.5}^{+} \\ F_{2.5}^{-} \end{pmatrix} = \begin{pmatrix} S_0^{-} \\ S_1^{+} \\ S_1^{-} \\ S_2^{+} \\ S_2^{-} \\ S_S^{+} \end{pmatrix}$$

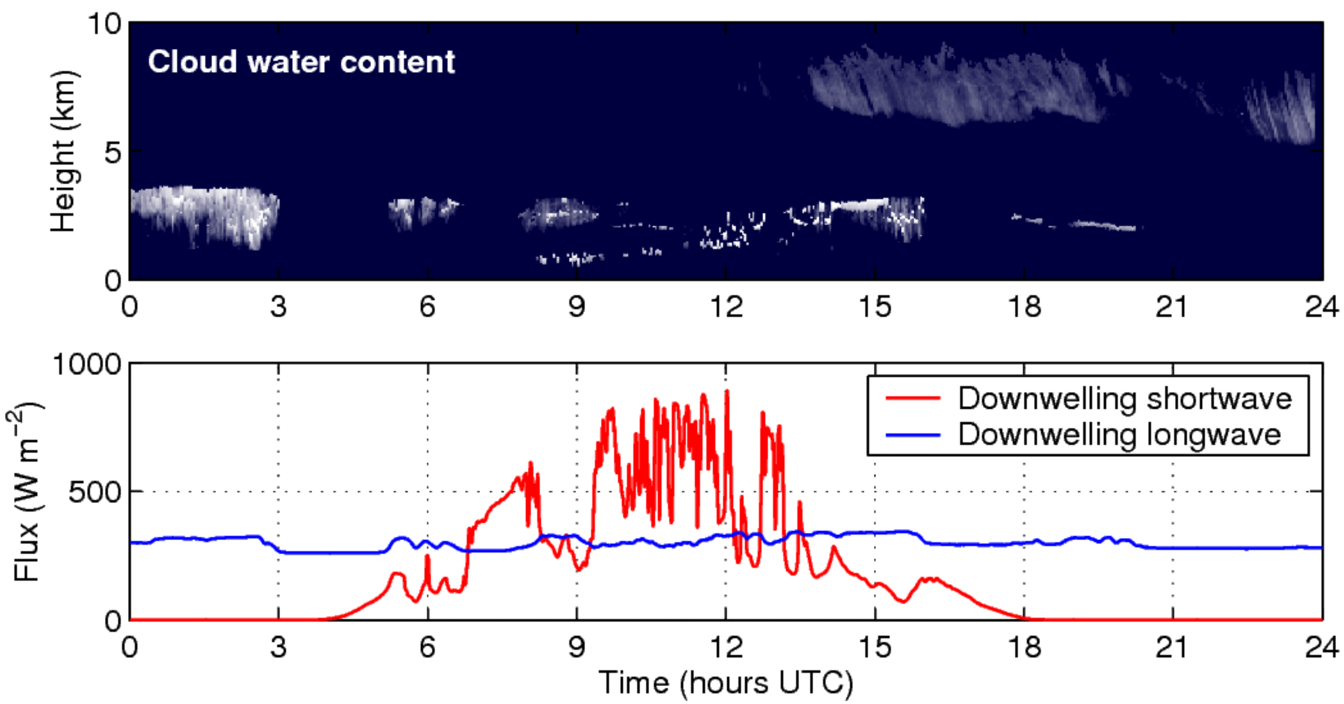
- Efficient to solve and simple to extend to more layers
- But need to account for scattering and absorption by gases and clouds
  - Next we compare the problems posed by each



Gases

- Gas absorption and scattering:
  - Varies with frequency ν but not much with horizontal position **x**
  - Strongly vertically correlated
  - Well known spectrum for all major atmospheric gases
  - No significant transfer between frequencies (except Raman - tiny)
- Correlated-k-distribution method for gaseous absorption
  - ECMWF (RRTM): 30 bands with a total of 252 independent calculations
  - Met Office (HadGEM): 15 bands with 130 independent calculations

Clouds



Radar-lidar retrievals and radiation observations from Lindenberg, 19 April 2006

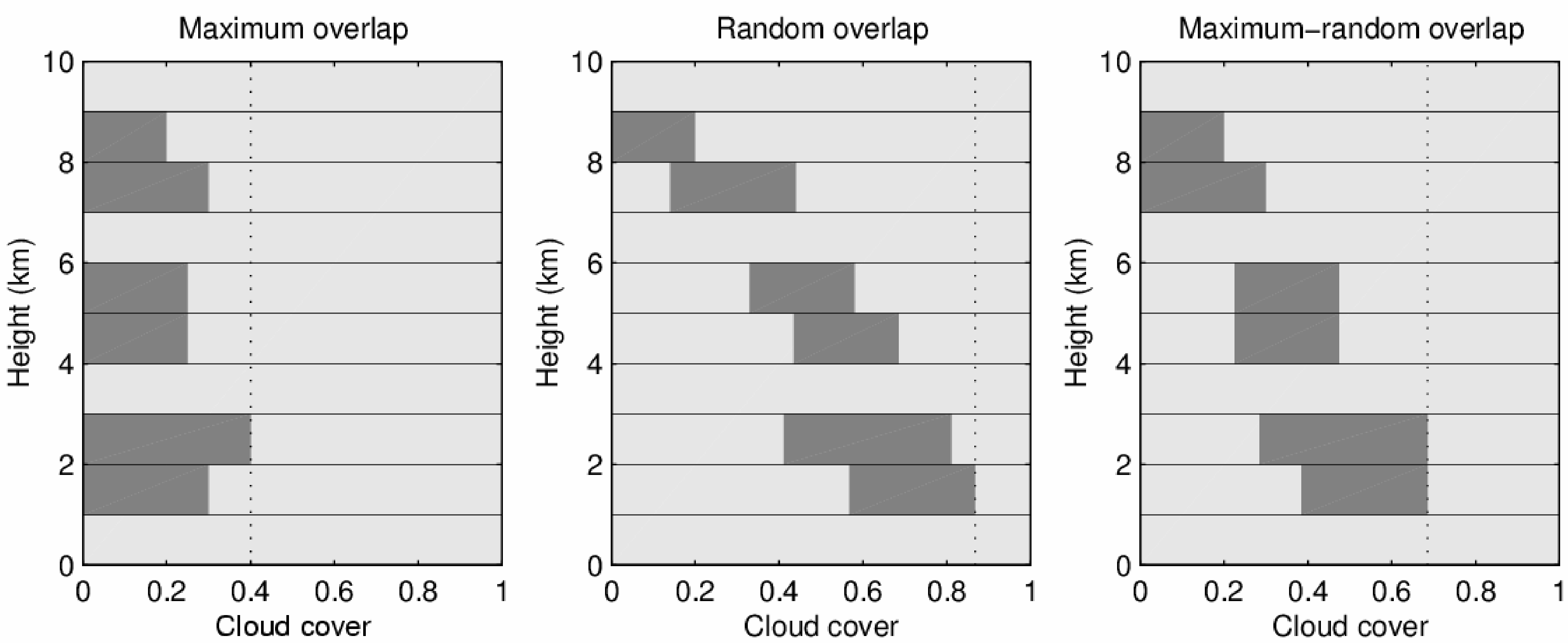
- Cloud absorption and scattering:
  - Varies with horizontal position **x** *and* (somewhat less) with frequency ν
  - *Not* very vertically correlated
  - Exact distribution within model gridbox is *unknown*
  - Horizontal transfer can be *significant*
- Independent column approximation (ICA)
  - Divide atmosphere into non-interacting horizontally-infinite columns
  - Need ~50 columns implying ~10^4 independent calculations with gases
  - *Too computationally expensive for a large-scale model!*

Many issues to resolve

- Model cloud scheme provides cloud fraction and water content but not cloud structure information
  - Some newer schemes prognose cloud variability (e.g. Tompkins 2002, Wilson et al. 2008) but they need validation
- So we need the following from observations:
  - The degree to which clouds in different layers are overlapped
  - The horizontal variability of water content within a grid box
  - The degree to which cloud inhomogeneities are overlapped
- But the independent column approximation is too expensive to use anyway
  - What tricks can we employ to represent cloud structure efficiently?
  - Is ICA OK or do we need to represent 3D effects as well?
- What is the impact of these factors on radiation globally?

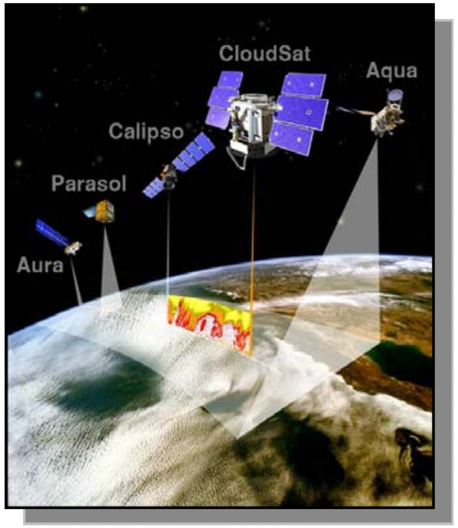
Cloud overlap assumption in models

- Three possible overlap assumptions:



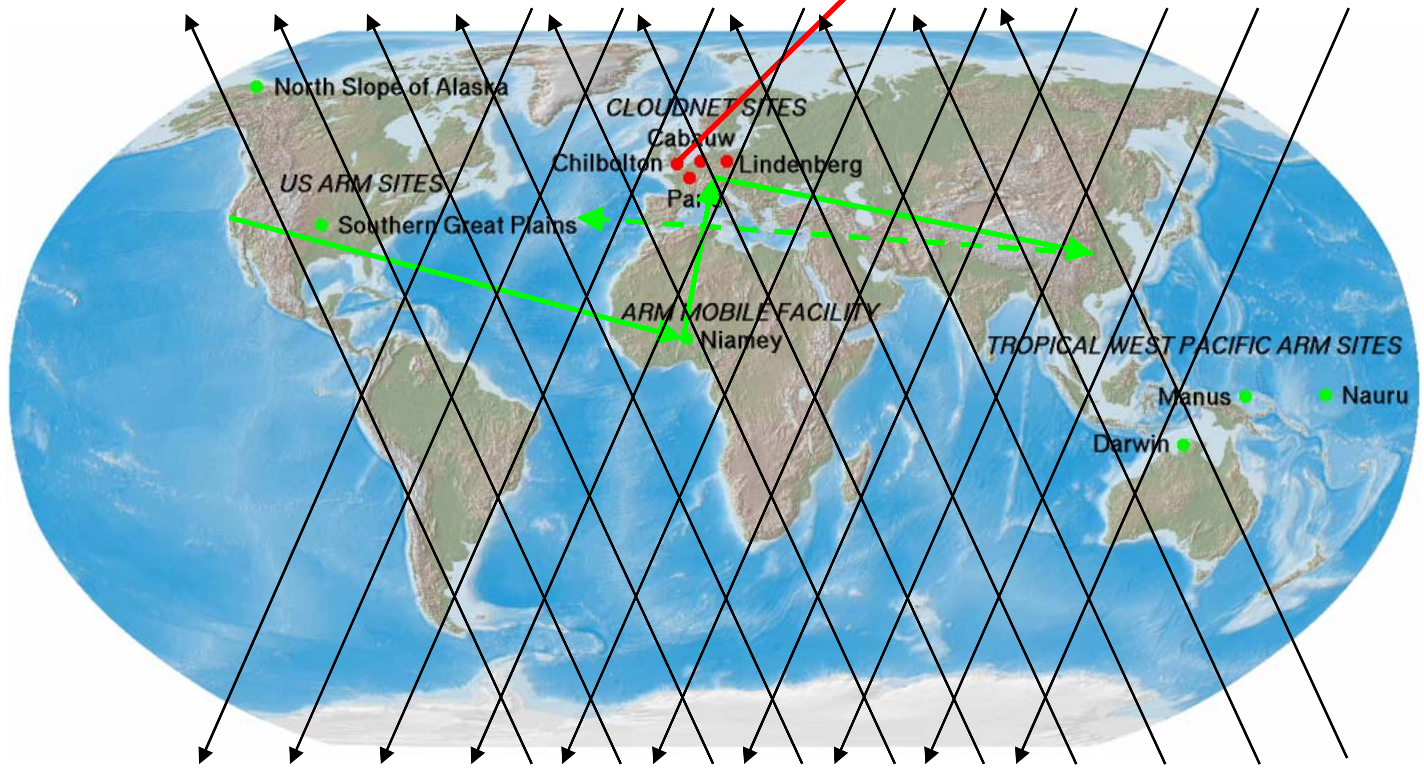
- These assumptions generate very different cloud covers
  - Different radiative properties for same water content & cloud fraction
  - Most models still use "maximum-random" overlap but, how good is it?

Cloud radar sites

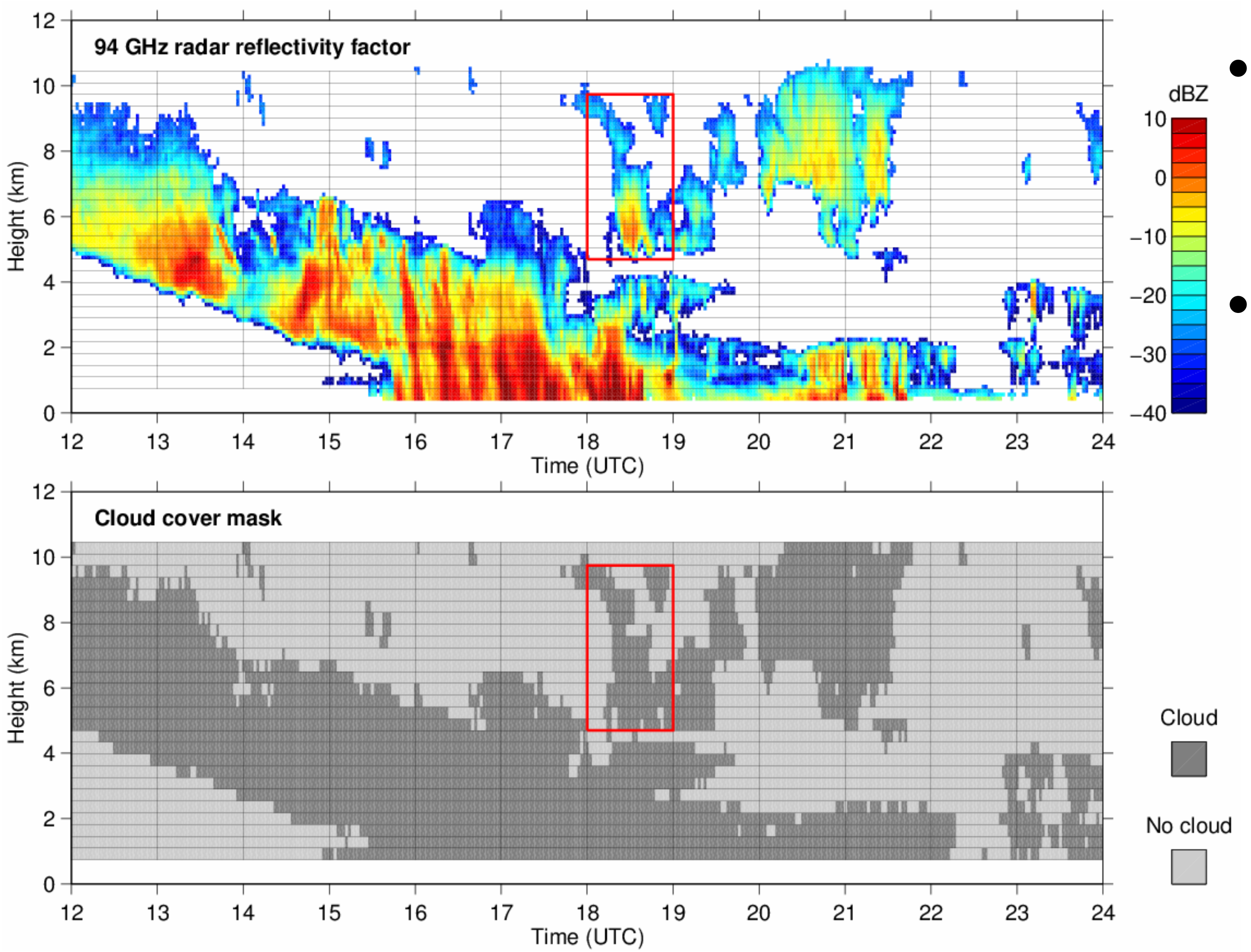


A-Train of satellites

Chilbolton 35 GHz "Copernicus" radar

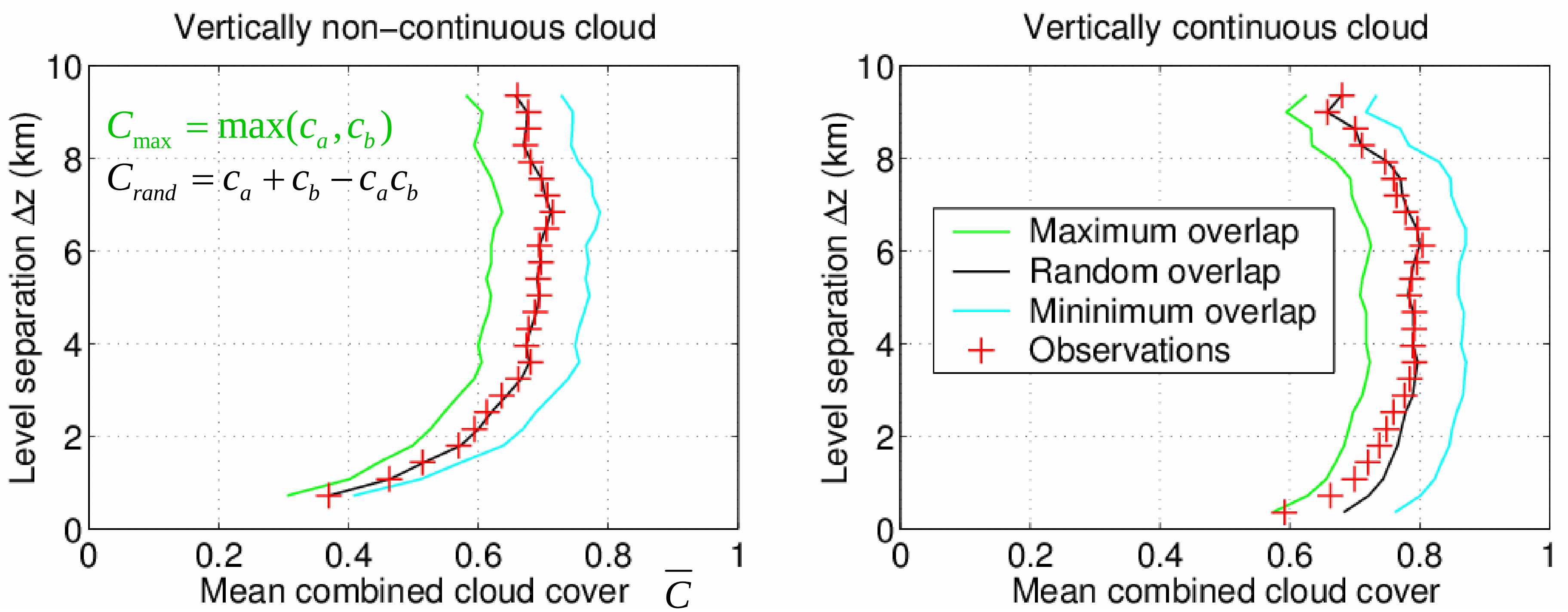


Cloud overlap from radar: example



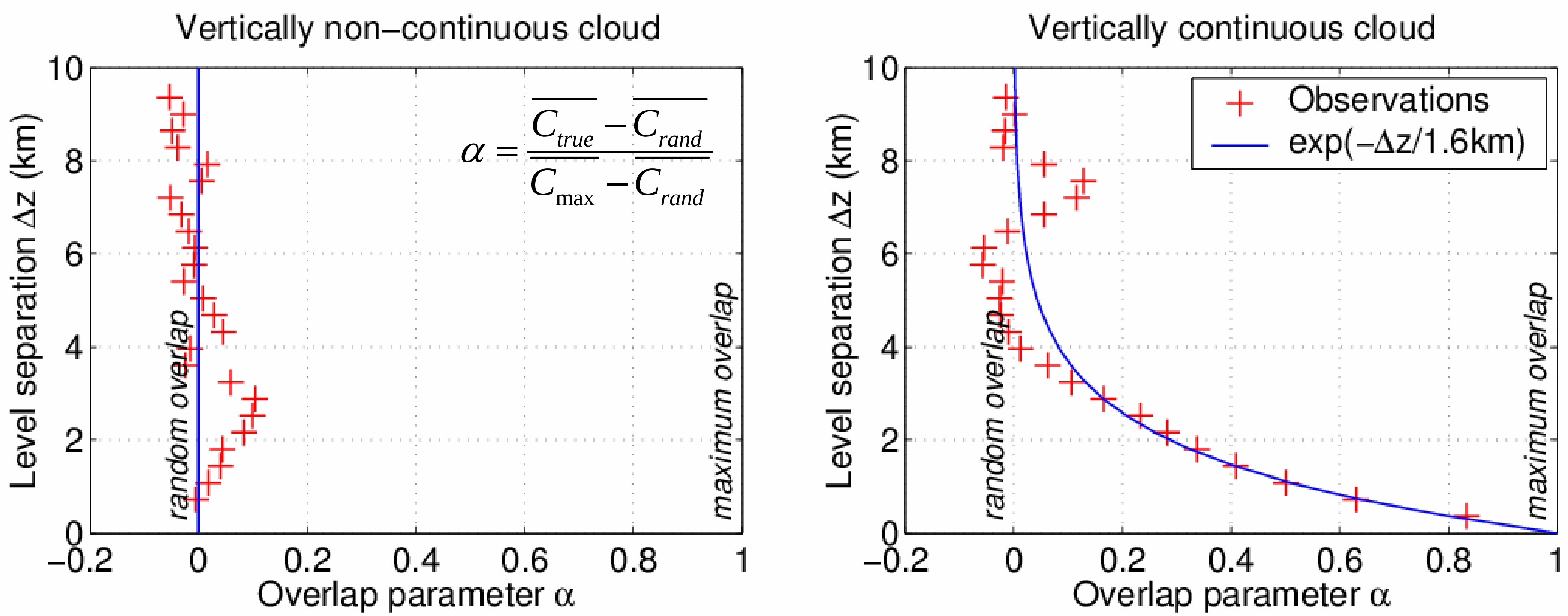
- Radar can observe the actual overlap of clouds
- We next quantify the overlap from 3 months of data

Cloud overlap: approach



- Consider combined cloud cover of pairs of levels
  - Group into vertically continuous and non-continuous pairs
  - Plot combined cloud cover versus level separation
  - Compare true cover & values from various overlap assumptions
  - Define *overlap parameter* α: 0 = random and 1 = maximum overlap

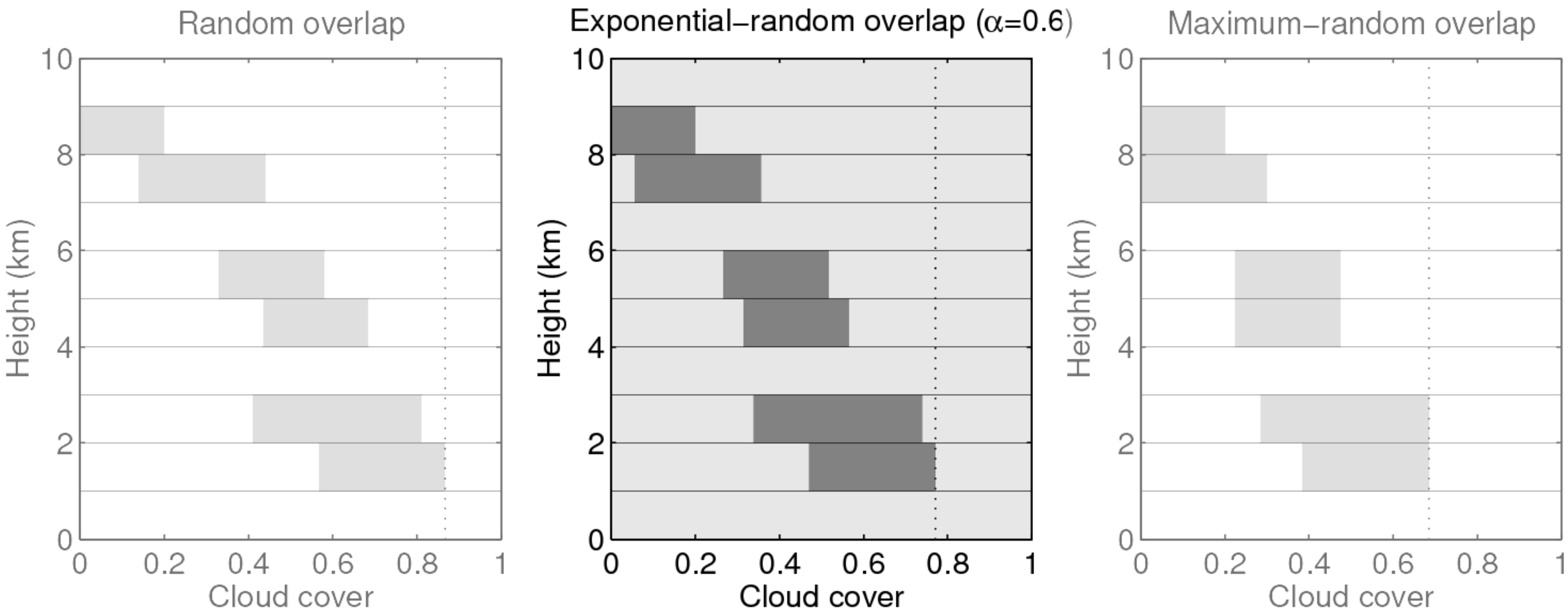
Cloud overlap: results



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

Hogan and Illingworth (QJ 2000)

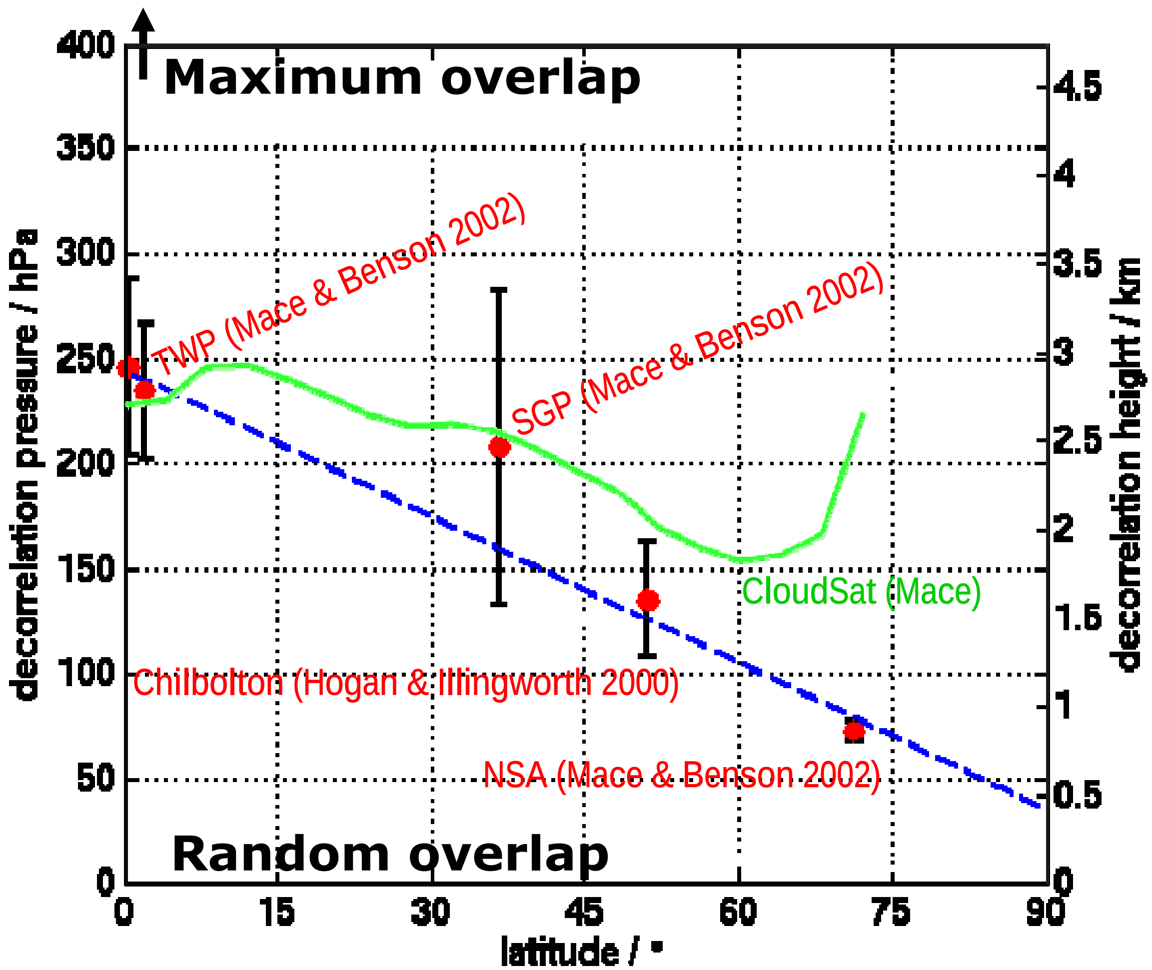
"Exponential-random overlap"



- Real atmosphere described by "exponential-random overlap" (or "decorrelation overlap")
  - This is on average; overlap can be anything in individual cases
  - Need global observations to estimate z_0 for different cloud types

Cloud overlap globally

- Latitudinal dependence of z_0 from ARM sites and Chilbolton
  - *More convection and less shear in the tropics*



- CloudSat implies clouds are more maximally overlapped
  - *But it also includes precipitation, which is more upright than clouds*

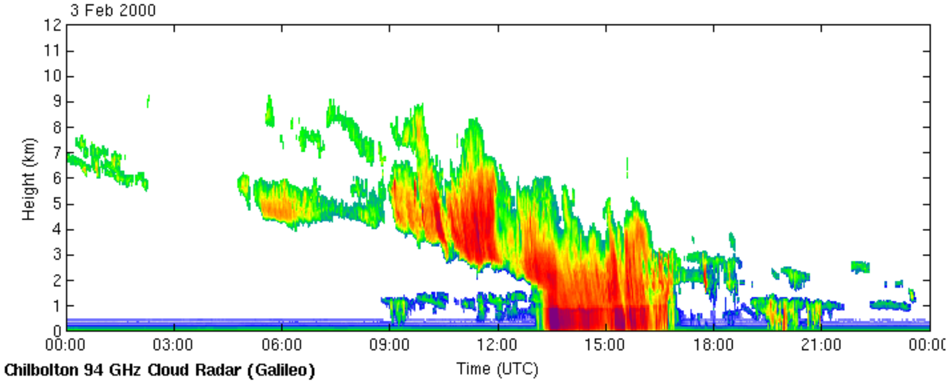
Further work required

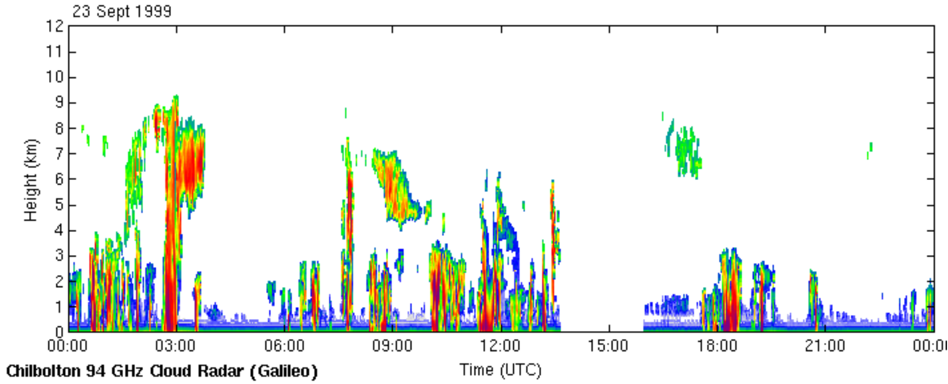
We should really define decorrelation length as a function of:

- Liquid and ice; horizontal and vertical resolution
  - Malcolm Brooks (PhD 2005): ice more maximally overlapped than liquid:

$$\alpha_{liquid} = 1 - 0.0097 \Delta x^{-0.0214} \Delta z^{0.6461} \qquad \alpha_{ice} = 1 - 0.0115 \Delta x^{-0.0728} \Delta z^{0.5903}$$

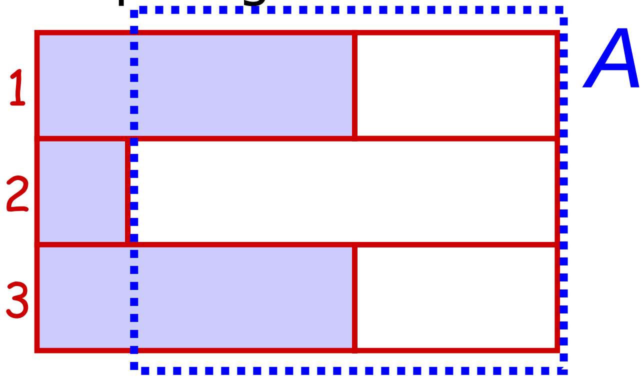
  - But what is the *global* dependence, and what is the physics behind it?
- Wind shear
  - Preliminary work suggests the dependence is weak
- Convective versus stratiform clouds…





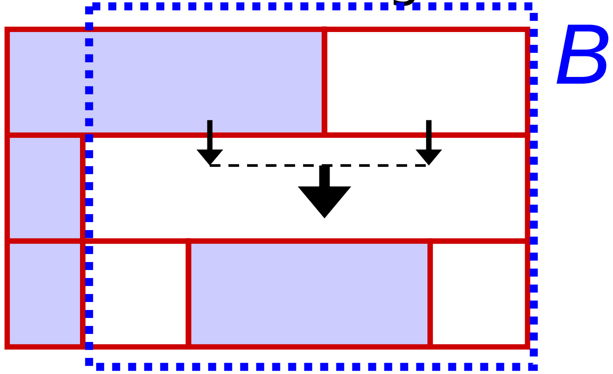
An interesting detail...

- Do we need to know the overlap of a layer with every other layer, or just with the adjacent layers?
- We might expect "max-rand" overlap to give this:



  - Layer 1 is maximally overlapped with layer 3 because the cloud is "vertically continuous"

- But most max-rand implementations give this:

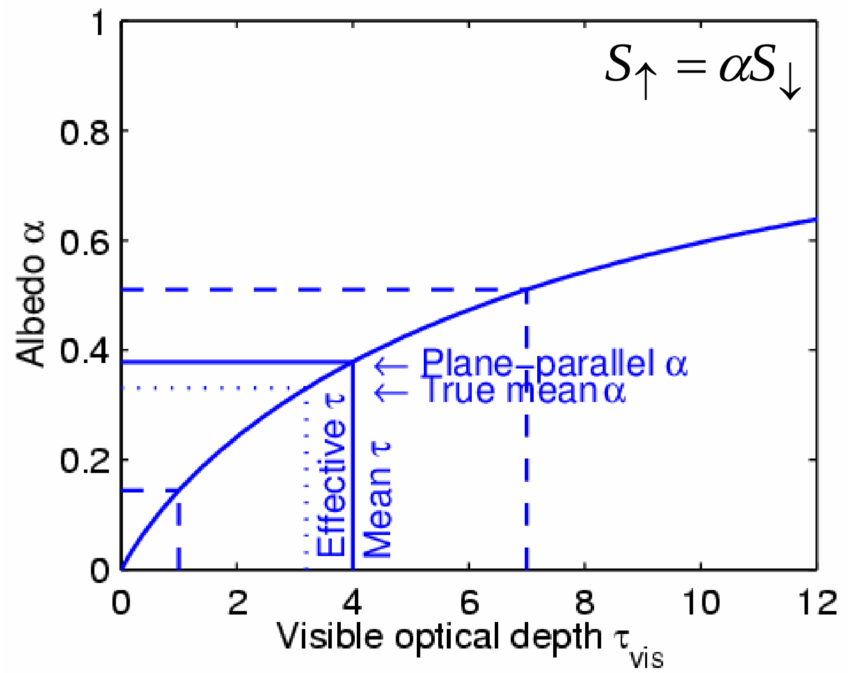


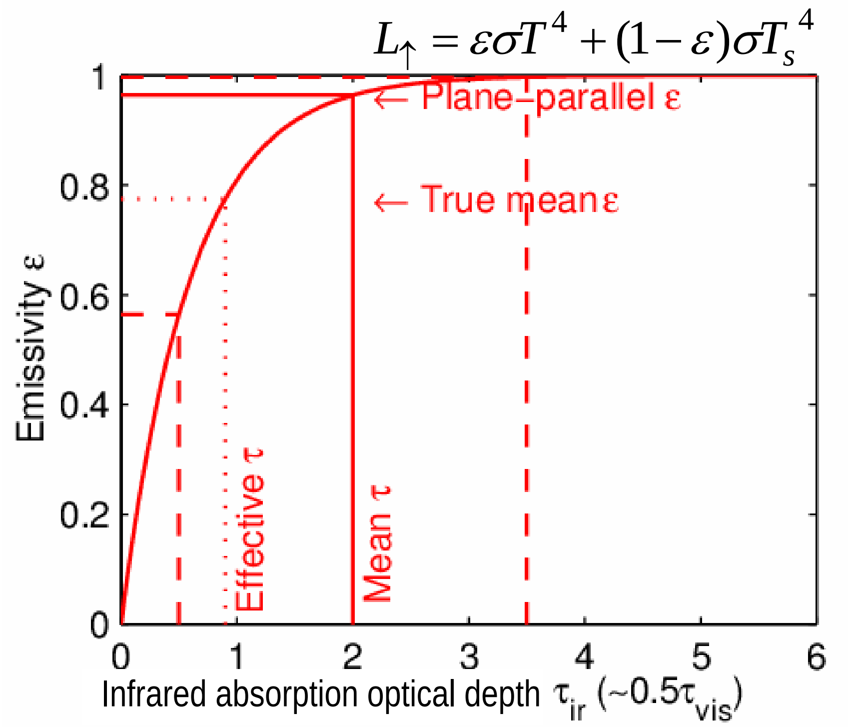
  - Fluxes are usually homogenized in a cloudy or clear-sky region so have no memory of their horizontal distribution when entering another layer

- *Which one is right?*

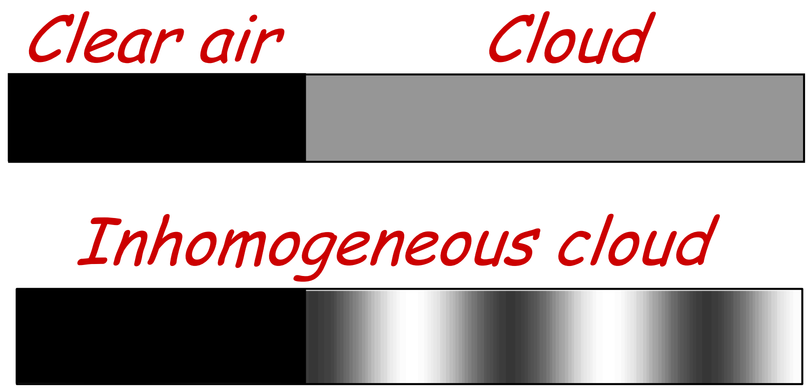
If gridbox was slightly smaller, we see that A wrongly gives maximum overlap for non-adjacent layers, so B more correct. Good news: only adjacent-level overlap parameter is required!

Why is cloud structure important?



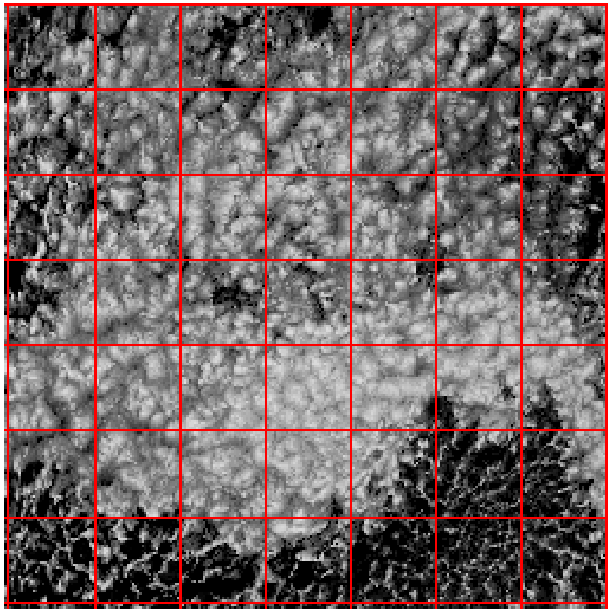


- An example of *non-linear averaging*



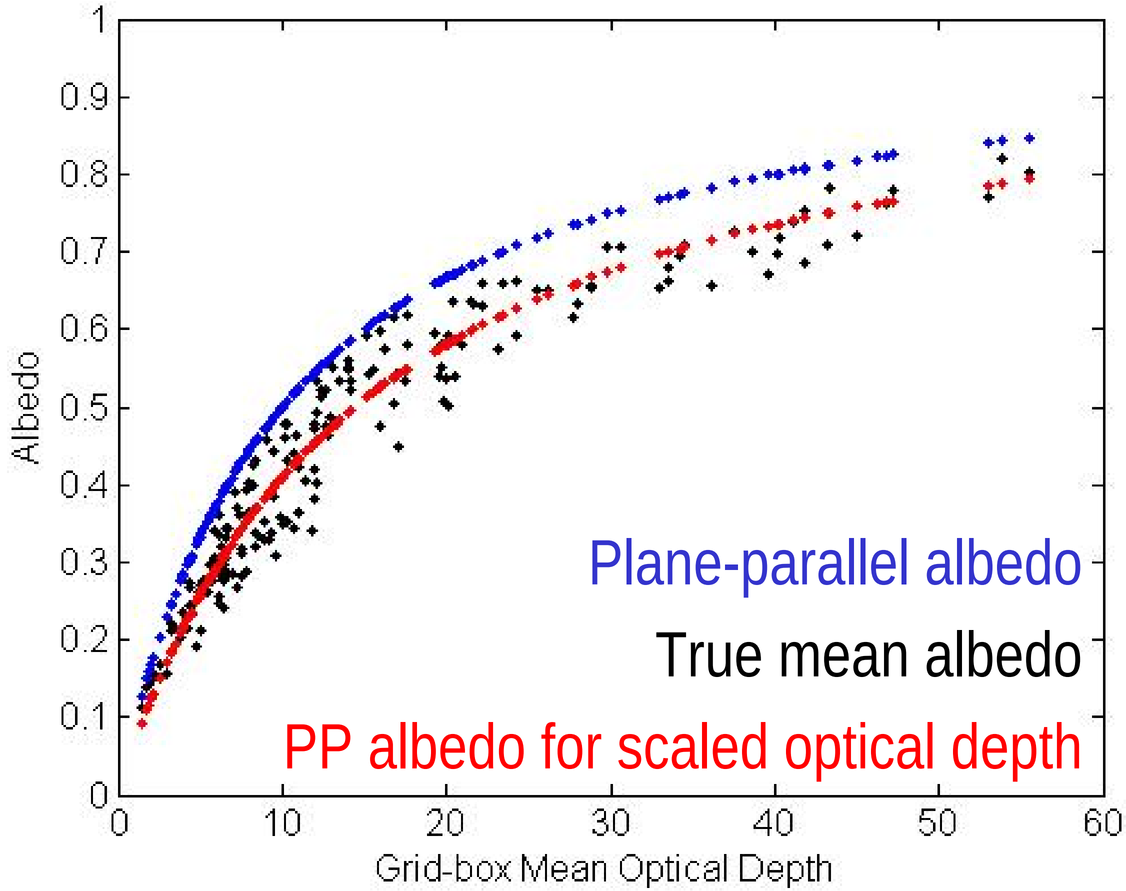
- Non-uniform clouds have lower mean emissivity & albedo for same mean optical depth due to curvature in the relationships

Example from MODIS



MODIS Stratocumulus

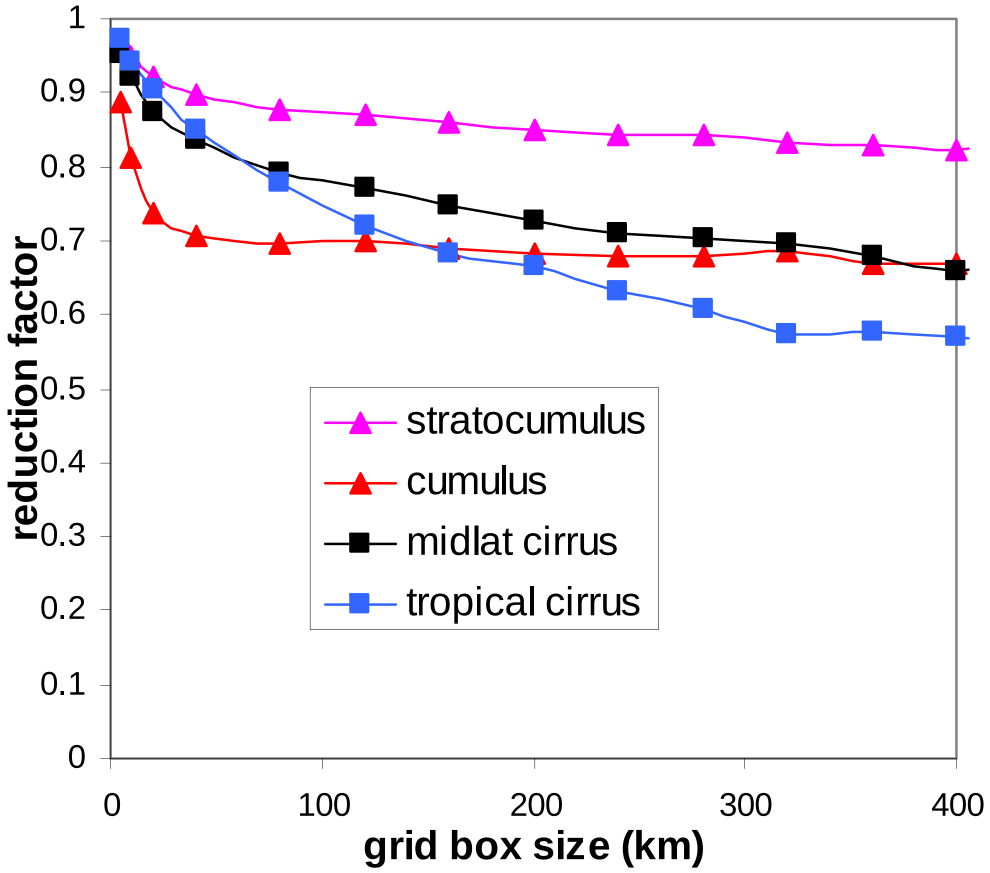
100-km boxes



- By scaling the optical depth it appears we can get an unbiased fit to the true top-of-atmosphere albedo

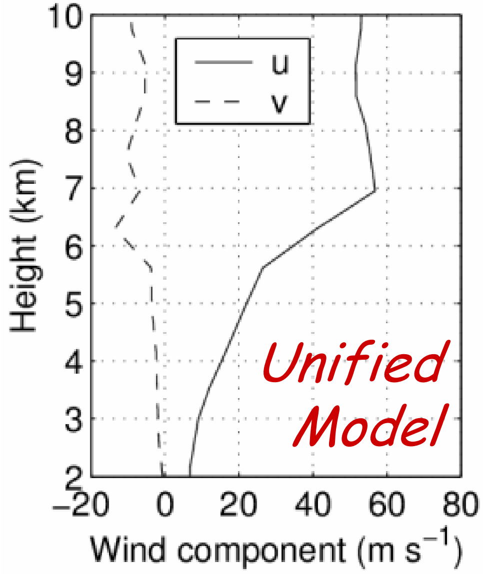
Joe Daron and Itumeleng Kgololo

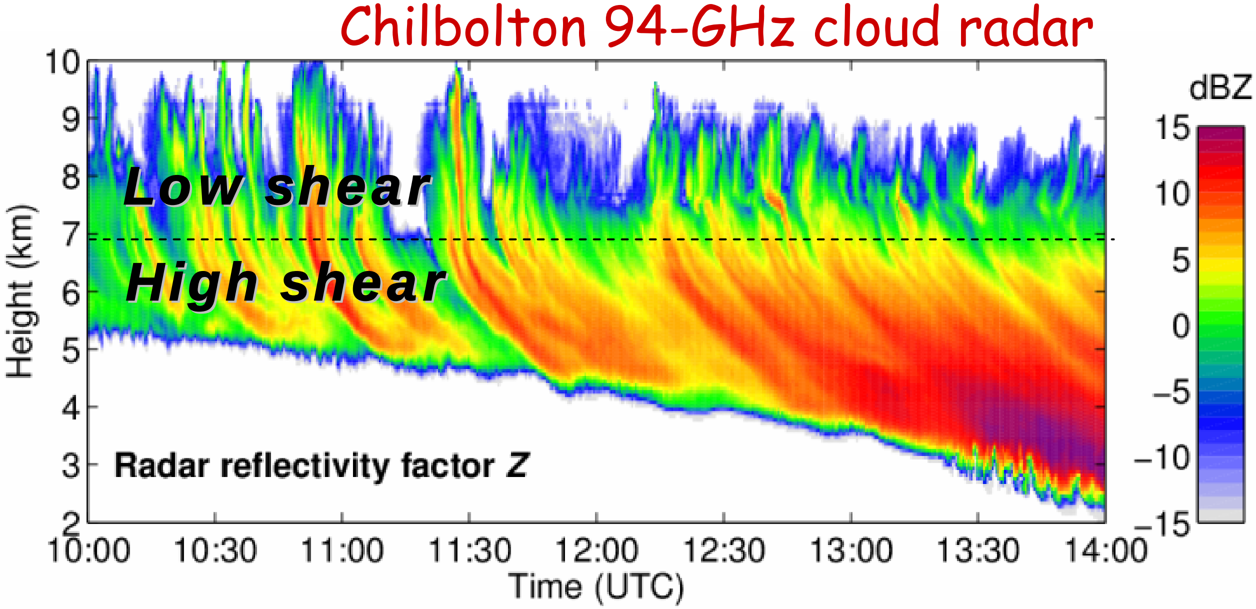
Scaling factor from MODIS

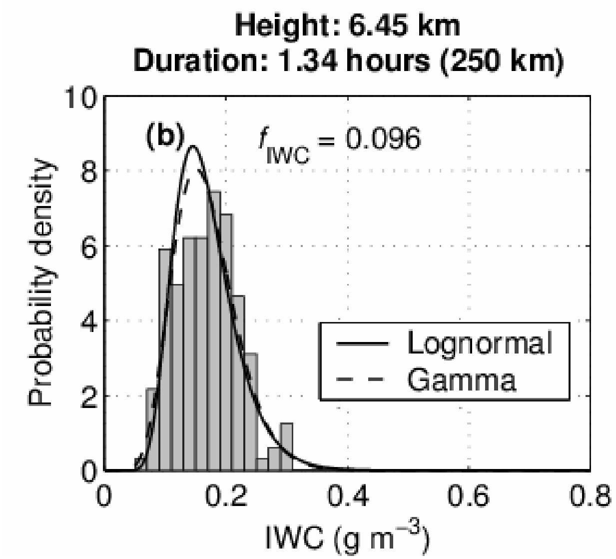


- But satellites show optimum scaling factor is sensitive to
  - Cloud type
  - Gridbox size
  - Solar zenith angle
  - Shortwave/longwave
  - Mean optical depth itself
- Also, better performance at top-of-atmosphere can mean *worse* performance in heating rate profile
- *Need to measure variance of cloud properties and apply in a more sophisticated method*

Cirrus fallstreaks and wind shear





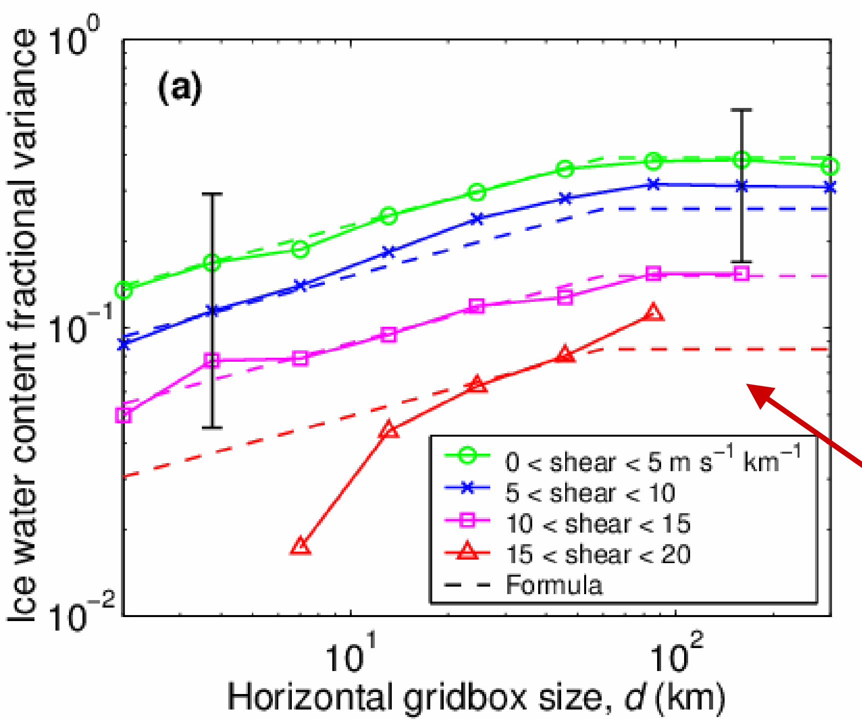


- Can estimate IWC from radar reflectivity and temperature
- PDFs of IWC within can often be fitted by a lognormal distribution with a particular *fractional variance:*

$$f_{IWC} = \nu^{-1} = \frac{\sigma_{IWC}^2}{\overline{IWC}^2} \approx \sigma_{\ln IWC}^2$$

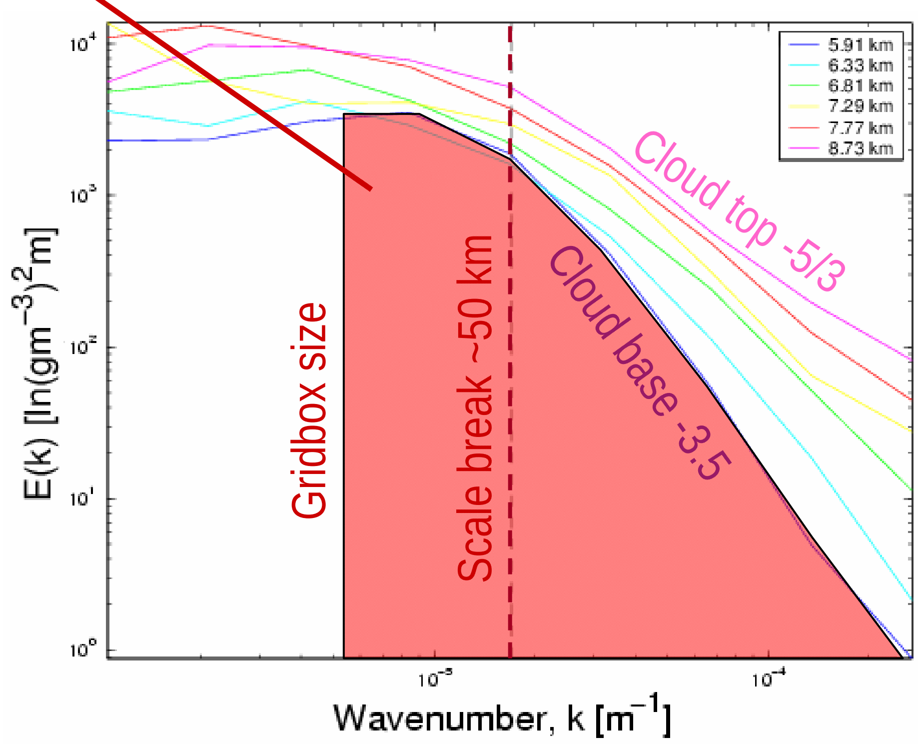
Hogan and Illingworth (JAS 2003)

18 months' data



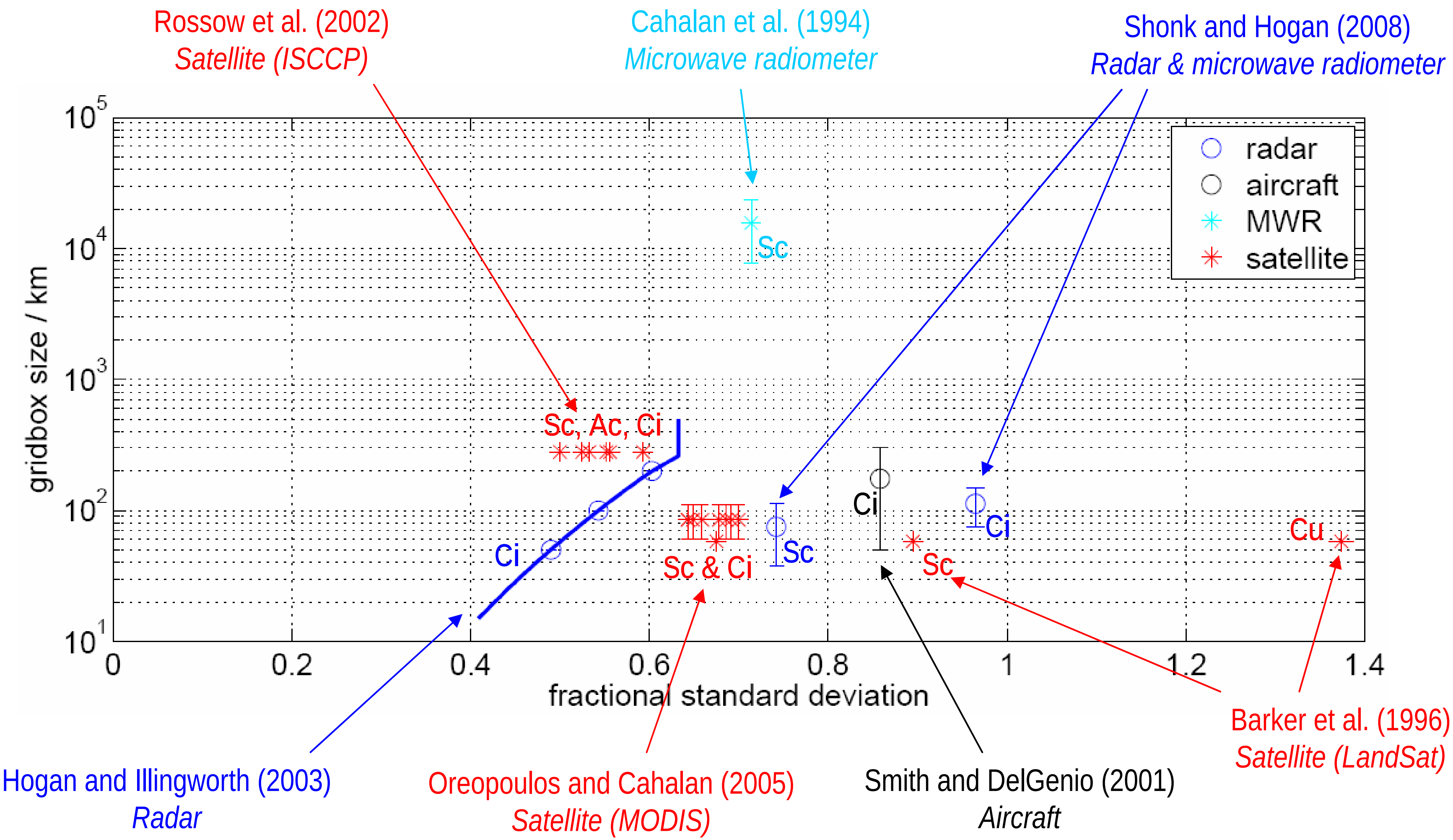
- Fractional variance increases with gridbox size *d*, decreases with wind shear *s*
  - $\log_{10} f_{IWC} = 0.3\log_{10} d - 0.04s - 0.93$
- It becomes flat for d>50 km
  - Why?

- f_{IWC} is the area under the power spectrum of ln(IWC)
- Shear-induced mixing homogenises small scales
- Scale break observed at ~50 km
  - Not sure why…



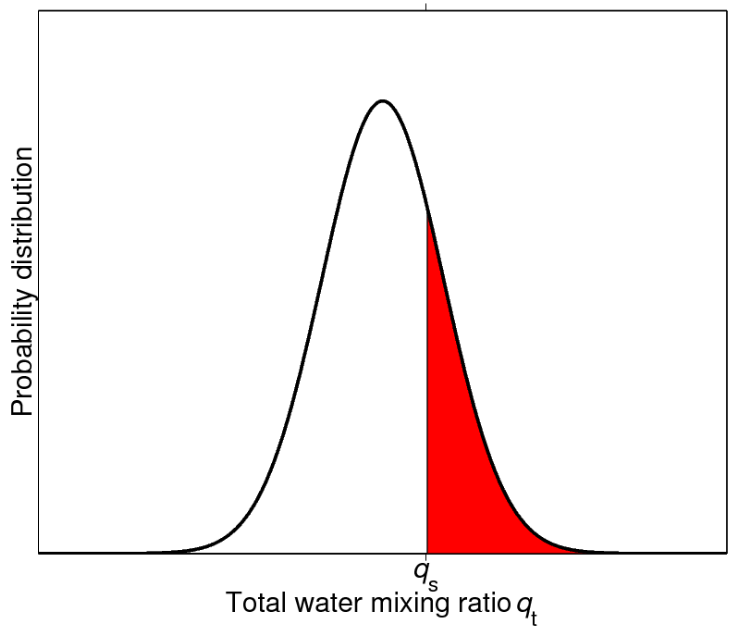
Hogan and Kew (QJ 2005)

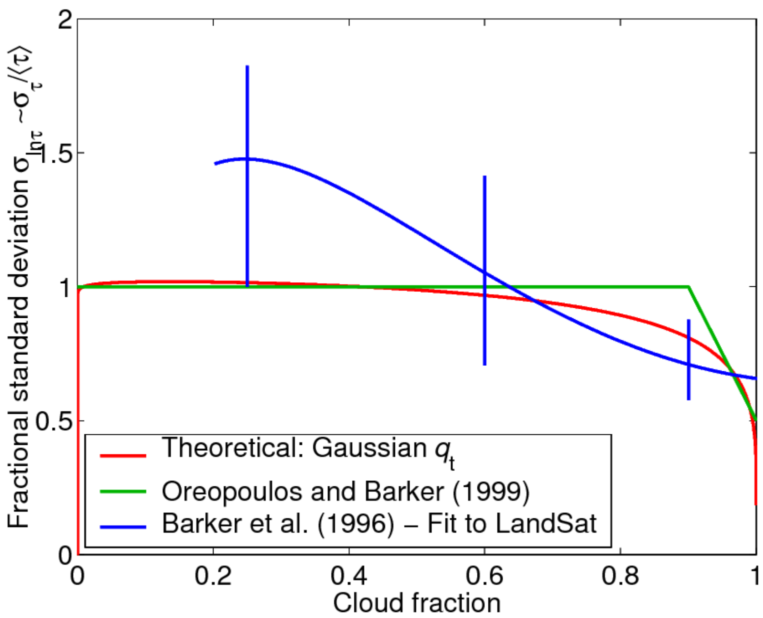
Observations of horizontal structure



- Typical fractional standard deviation ~0.75

Shonk (PhD, 2008)

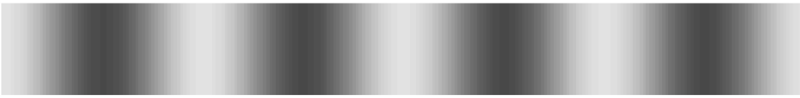




Structure versus cloud fraction

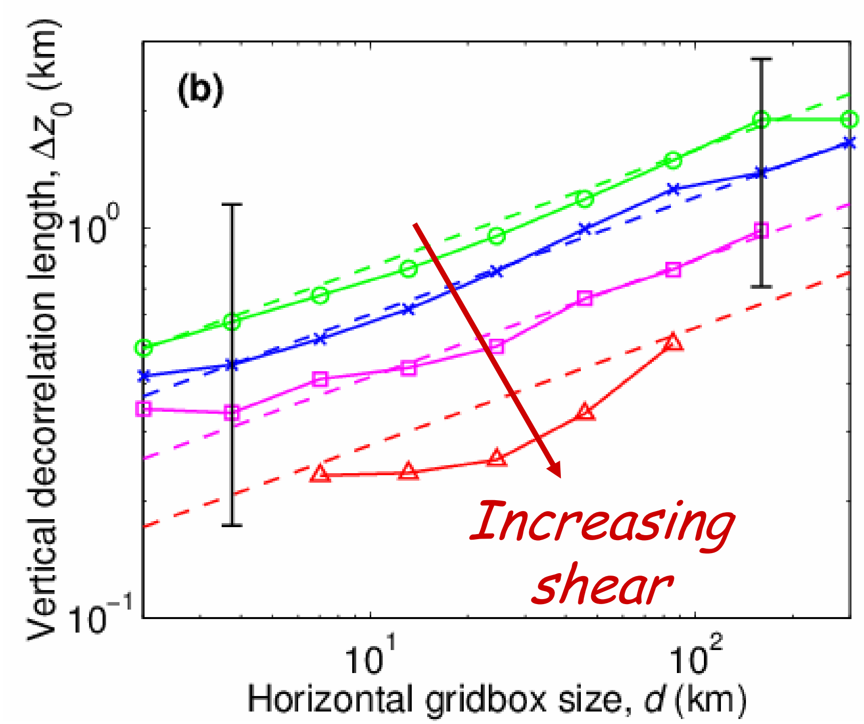
- For partially cloudy skies, cloud horizontal structure is not completely independent
- Consider an underlying Gaussian distribution of total water
- This results in fractional standard deviation tending to around unity for low cloud fractions
- This is not inconsistent with LandSat observations

Overlap of inhomogeneities

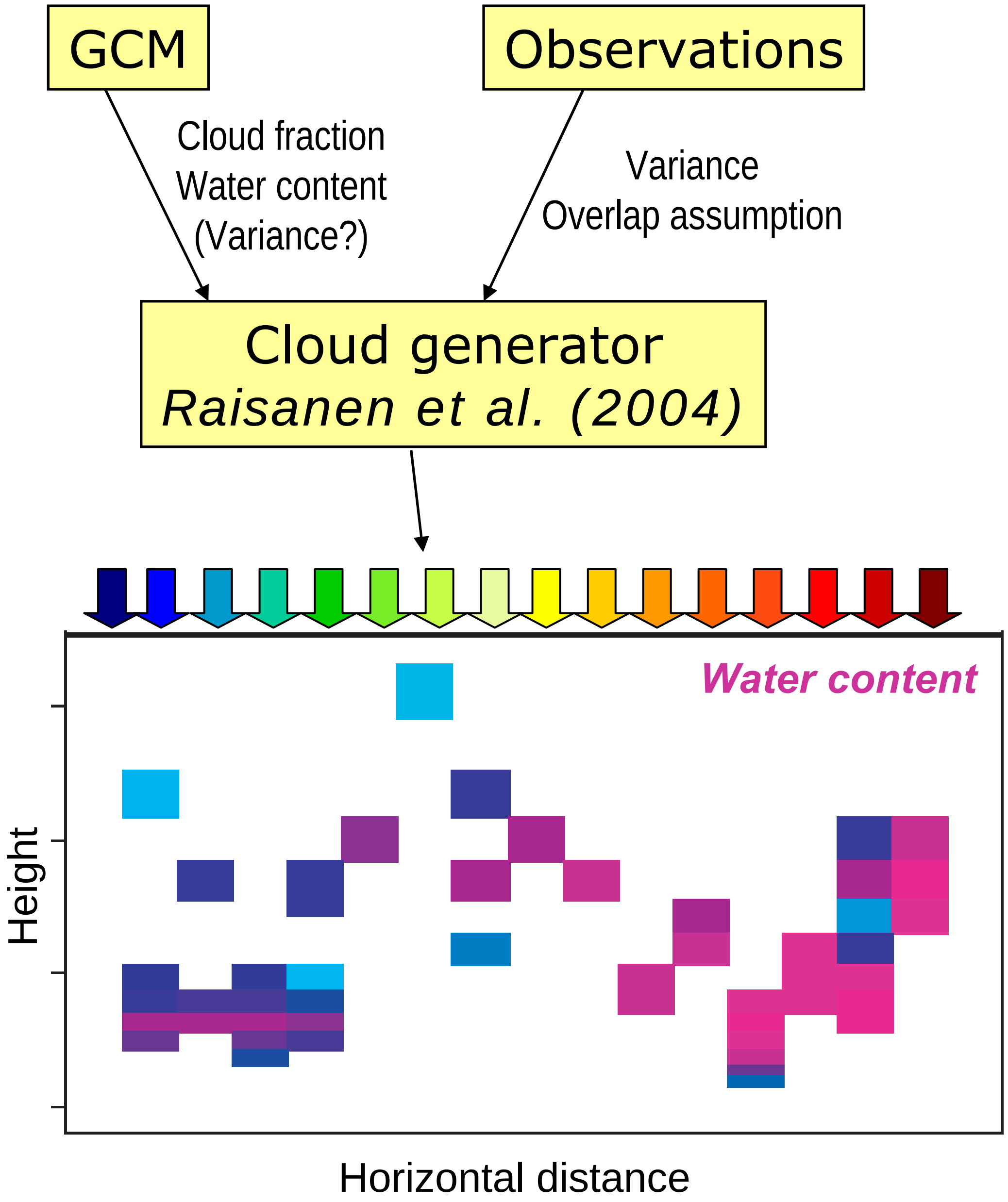


Lower emissivity and albedo

Higher emissivity and albedo



- For ice clouds, decorrelation length increases with gridbox size and decreases with shear
- Radar retrievals much less reliable in liquid clouds
  - Many sub-grid models simply assume decorrelation length for cloud structure is half the decorrelation length for cloud boundaries
- *We now have the necessary information on cloud structure, but how can it be efficiently modelled in a radiation scheme?*

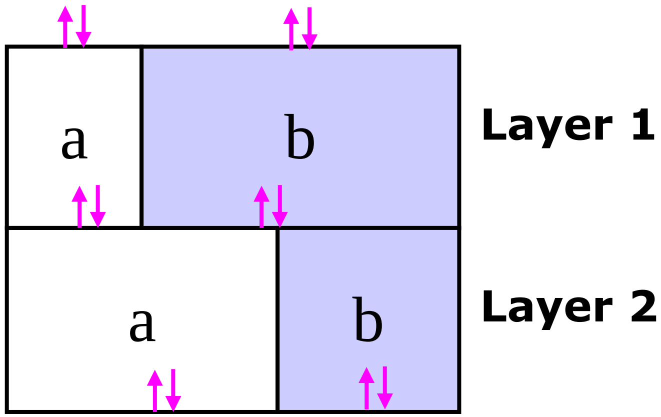


Pincus, Barker and Morcrette (2003)

Monte-Carlo ICA

- 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

Traditional cloud fraction approach

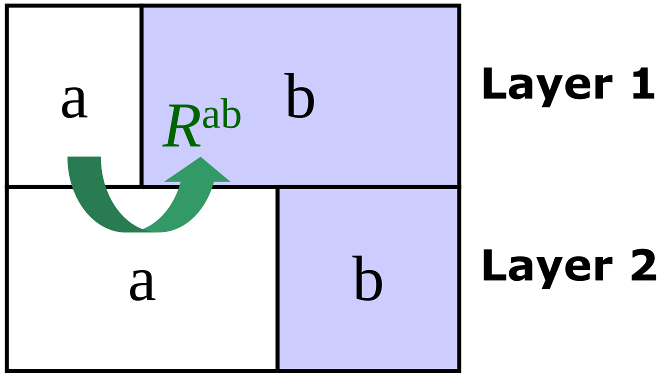


- Use Edwards-Slingo method as example
- Adapt two-stream method for two regions
  - Matrix is now denser (pentadiagonal rather than tridiagonal)

Note that coefficients describing the overlap between layers have been omitted

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

Anomalous horizontal transport

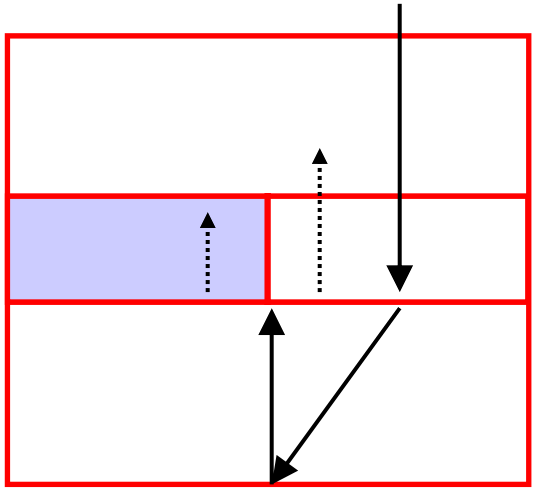


- But some elements represent unwanted anomalous horizontal transport
  - Remove them for a better solution
  - But this is not enough…

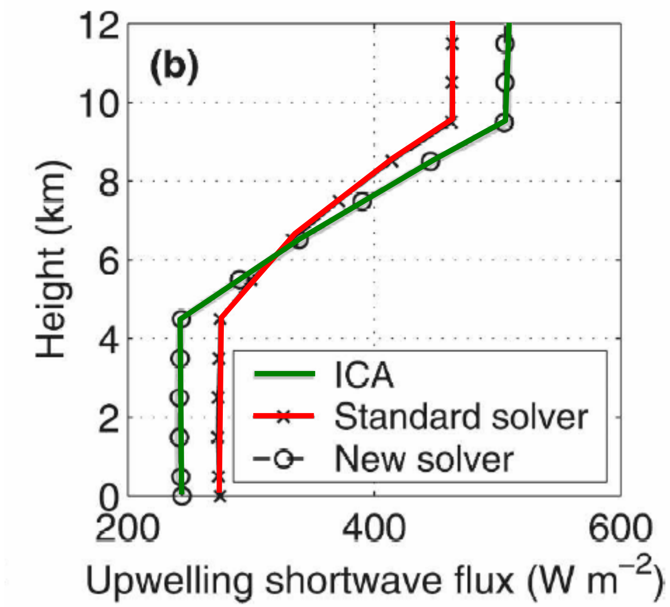
R^{ab} is the reflection from region a to region b at the same level

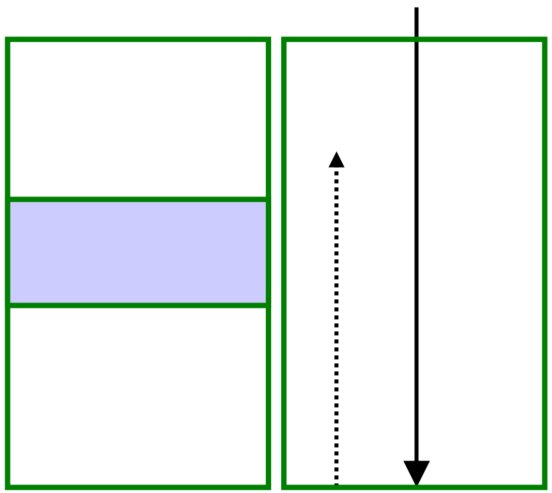
$$
\begin{pmatrix}
 & & 1 & & & & & & & & & \\
 & & & 1 & & & & & & & & \\
1 & & -R_1^{aa} & -R_1^{ab} & -T_1^{a} & -T_1^{b} & & & & & & \\
 & 1 & -R_1^{ba} & -R_1^{bb} & -T_1^{a} & -T_1^{b} & & & & & & \\
 & & -T_1^{a} & -T_1^{b} & -R_1^{aa} & -R_1^{ab} & 1 & & & & & \\
 & & -T_1^{a} & -T_1^{b} & -R_1^{ba}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

Anomalous horizontal transport



Cloud-fraction representation

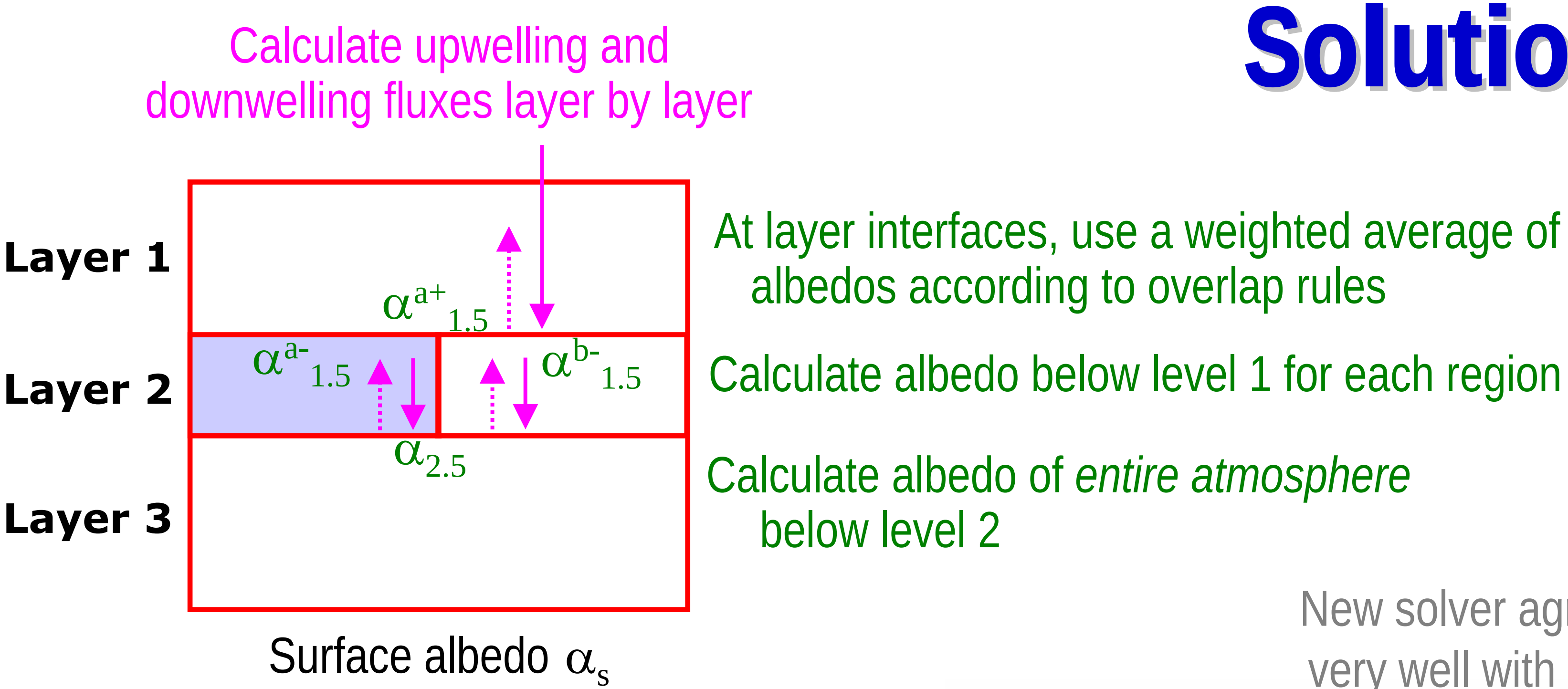




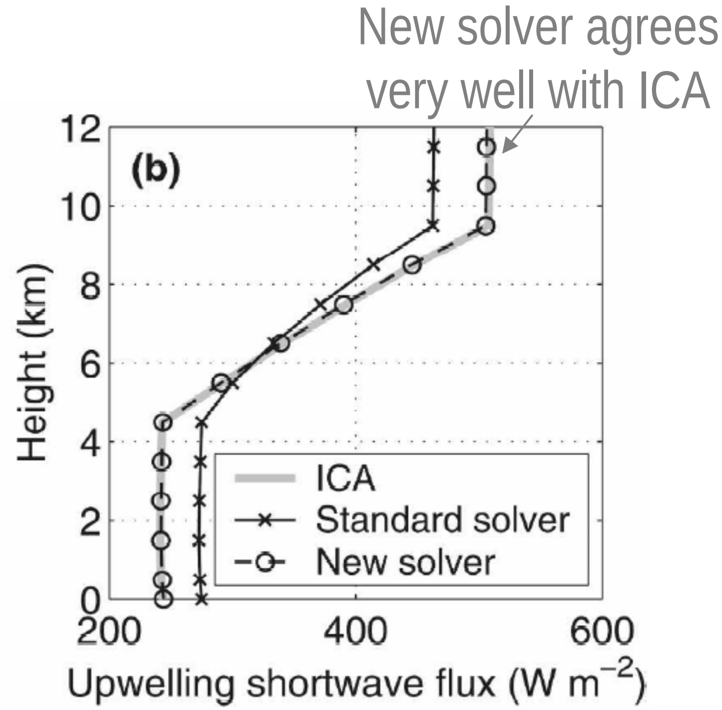
Independent column approximation

- Homogenization of clear-sky fluxes:
  - Reflected radiation has more chance to be absorbed -> TOA shortwave bias
  - Effect is very small in the longwave
- This problem can be solved in a way that makes the code more efficient

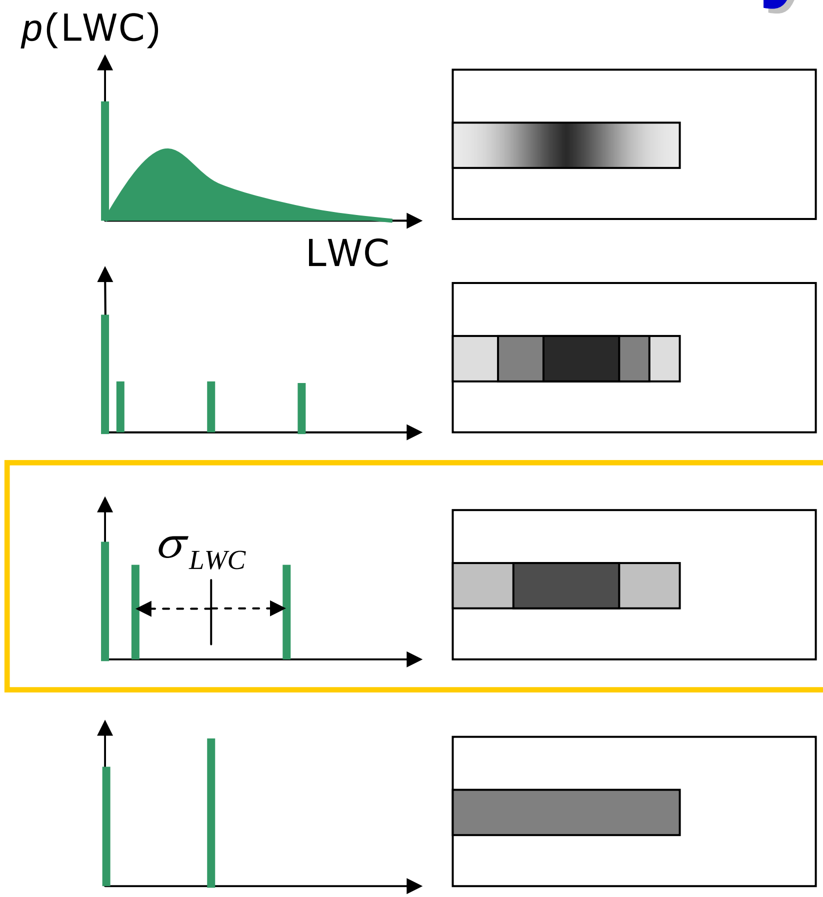
Solution



- Anomalous horizontal transport almost entirely eliminated
  - Works in longwave and shortwave
  - Procedure is identical to Gaussian elimination and back-substitution in the case of 1 region
  - New solvers now available in Edwards-Slingo code
  - *Easily extended to 3 or more regions*



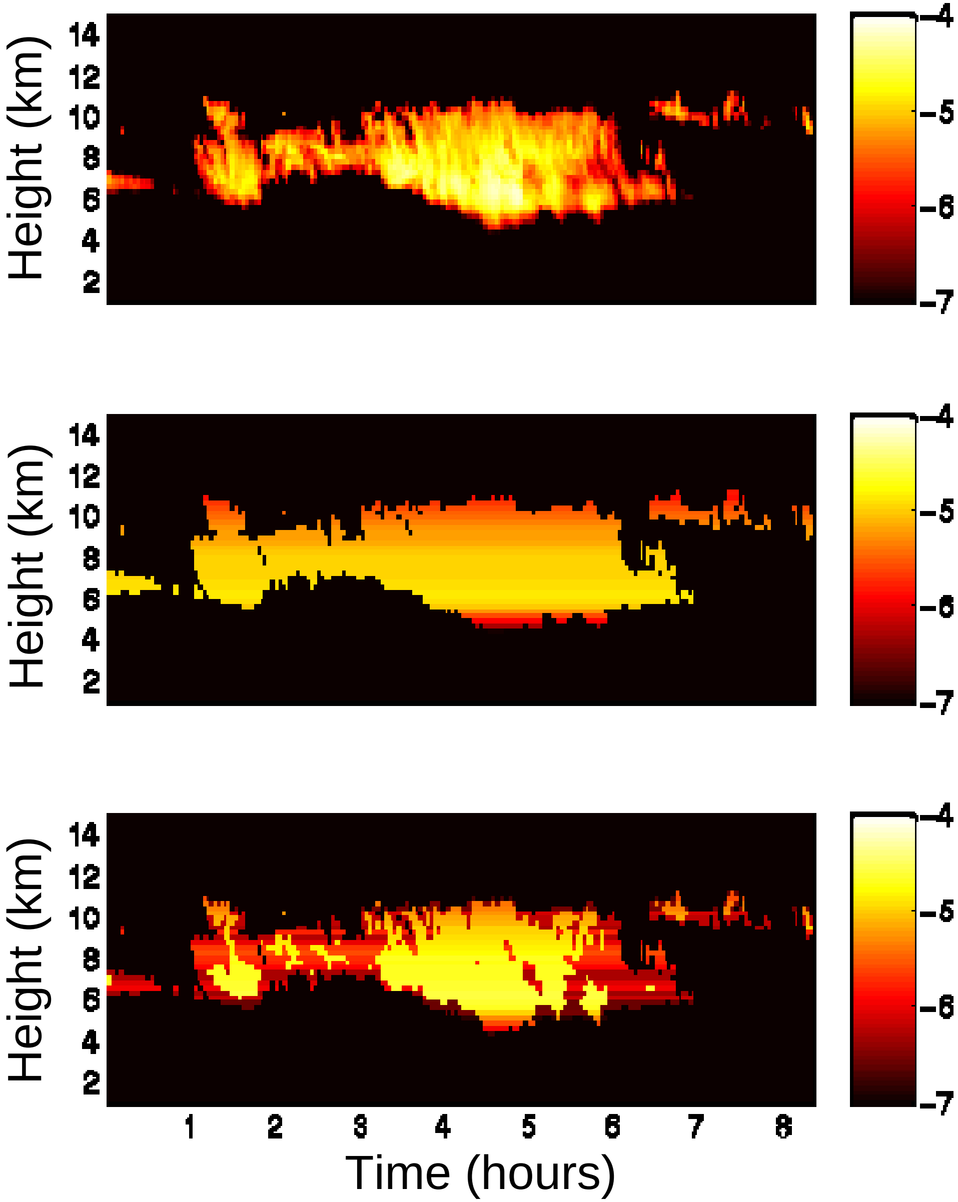
How many regions are needed?



- Continuous distribution
- Four regions?
- Three regions?
- Two regions?
  - Standard plane-parallel approach

- *Lets try three regions first...*
  - If the full PDF is known, use the 16th percentile for lower region
  - If we know only variance σ^2_{LWC}, then use $LWC = \overline{LWC} \pm \sigma_{LWC}$

A new approach

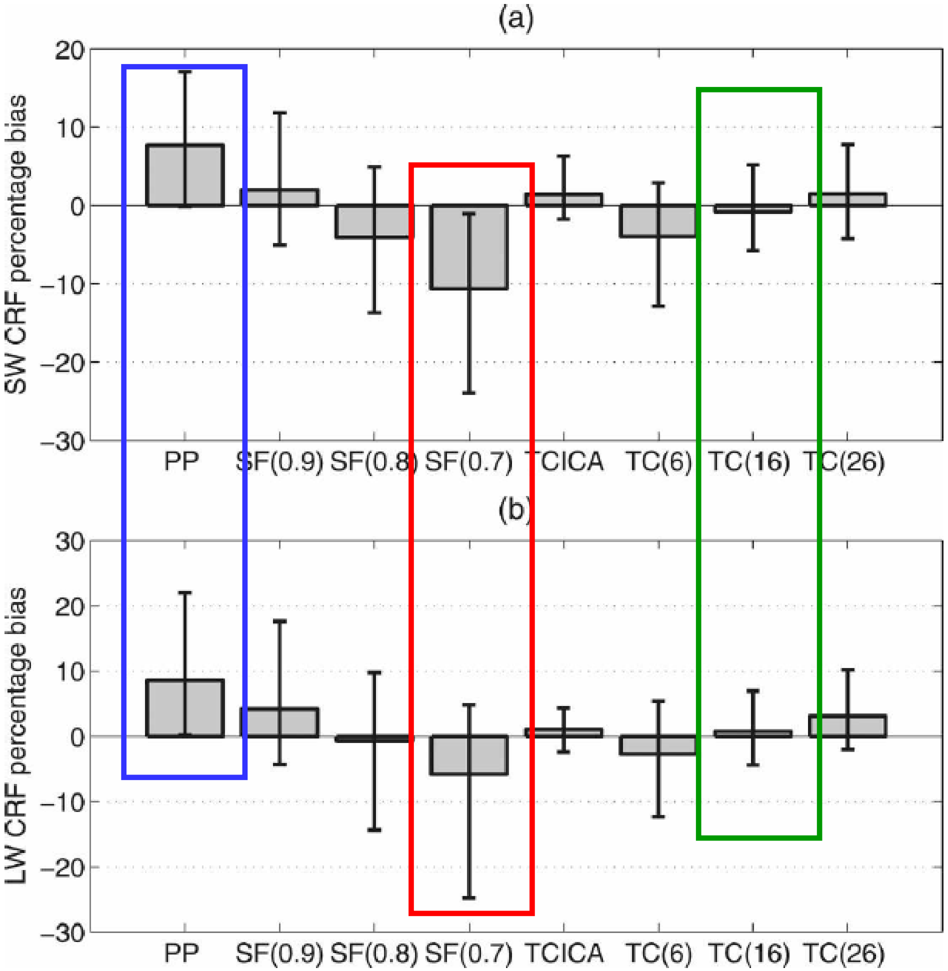


- Ice water content from Chilbolton, $\log_{10}(\text{kg m}^{-3})$
- Plane-parallel approx:
  - 2 regions in each layer, one clear and one cloudy
- "Tripleclouds":
  - 3 regions in each layer
  - Alternative to McICA
  - Uses Edwards-Slingo capability for stratiform/convective regions for another purpose

Shonk and Hogan (JClim 2008)

Testing on 98 cloud radar scenes

Bias in top-of-atmosphere cloud radiative forcing



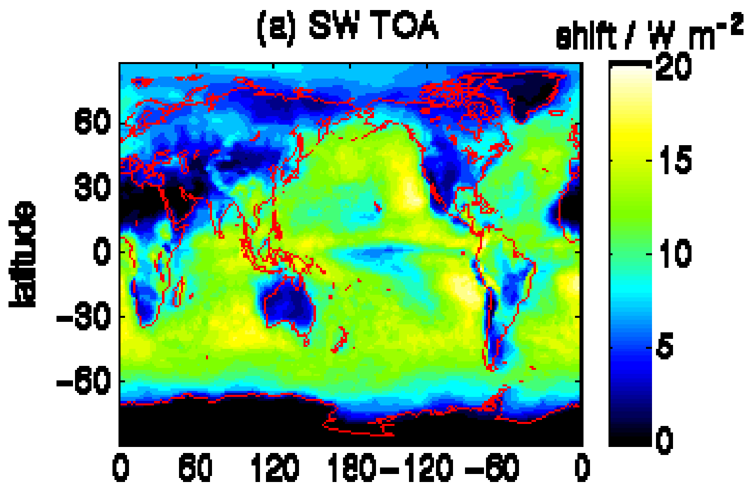
Triplecloud: less than 1% bias and a smaller random error

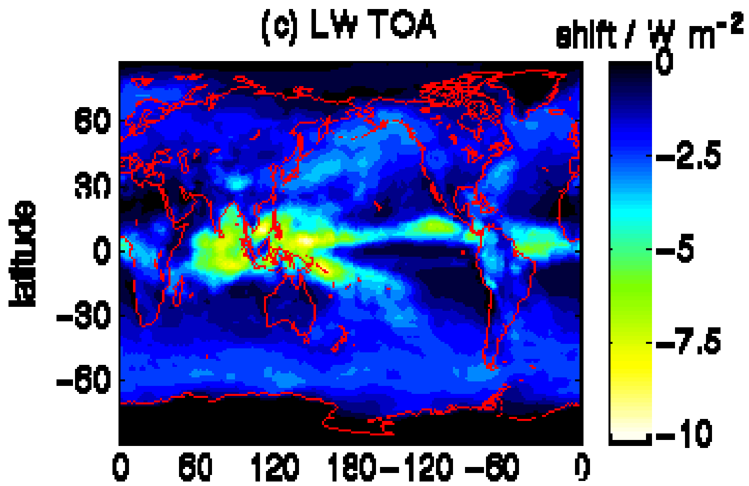
Plane-parallel assumption: 8% bias

Scaling factor of 0.7: error overcompensated

- Next step: test on ERA-40 clouds over an annual cycle

Global effect of horizontal structure

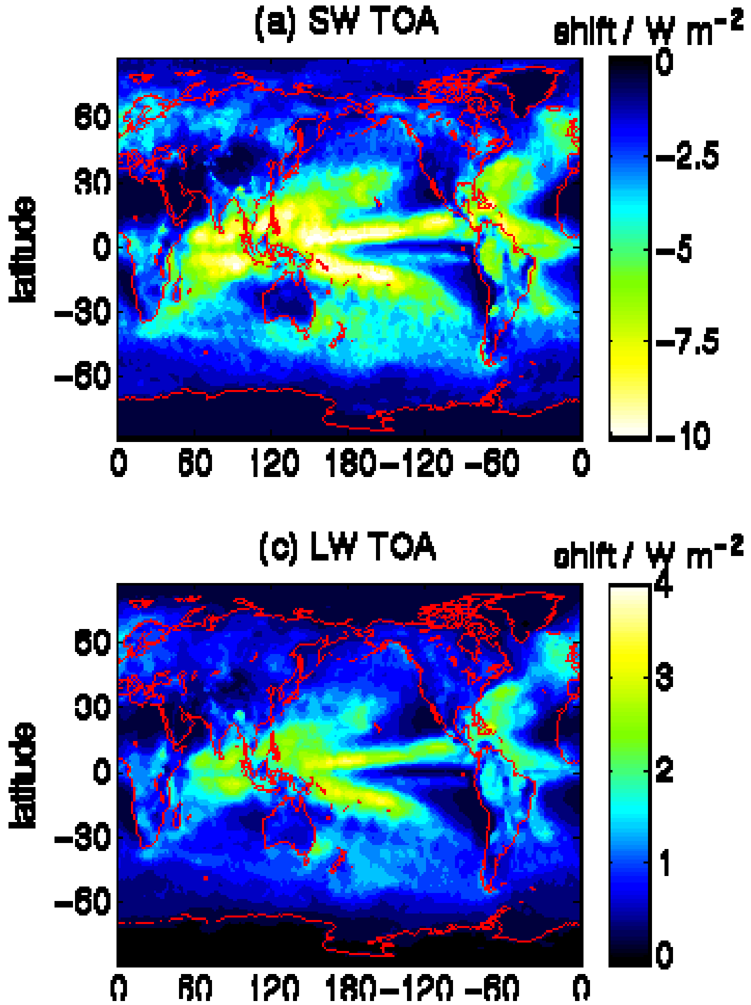




Change in top-of-atmosphere cloud radiative forcing when using fractional standard deviation of 0.8 globally

- Largest shortwave effect in regions of marine stratocumulus, but also storm tracks and tropics
- Largest longwave effect in regions of tropical convection

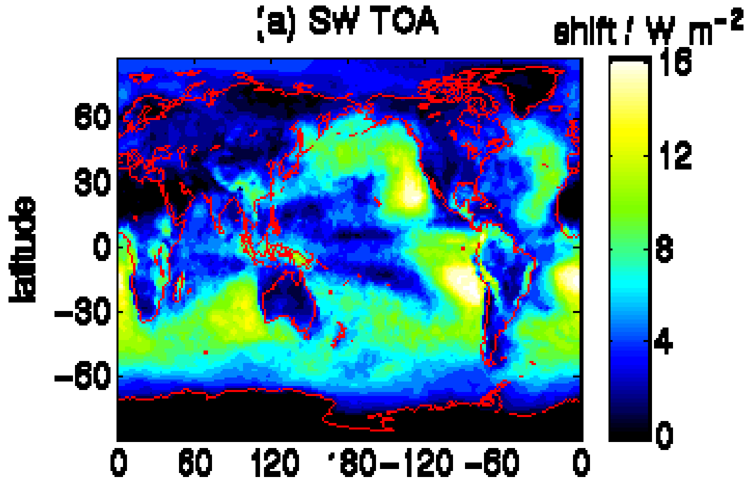
Global effect of realistic overlap



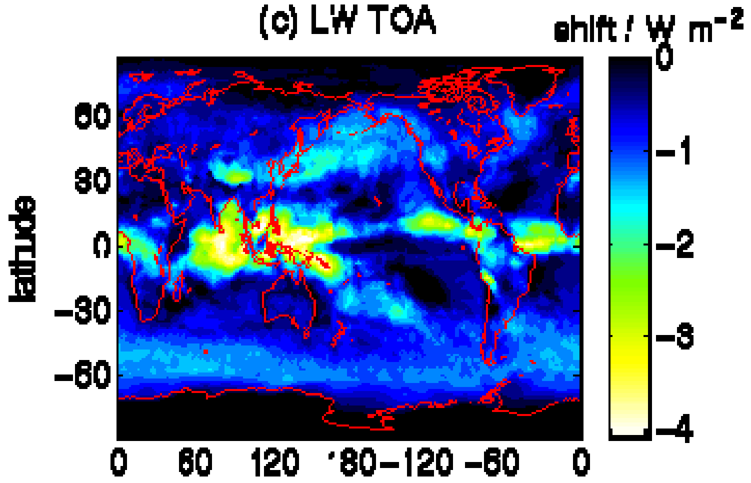
Change in top-of-atmosphere cloud radiative forcing when using a latitudinally varying decorrelation length

- Change is of the opposite sign and of lower magnitude to that from horizontal structure
- Largest effect in the tropics in both the shortwave and the longwave

Total global effect



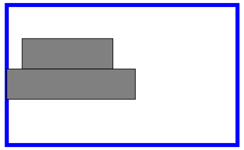
Change in top-of-atmosphere cloud radiative forcing when improving both horizontal structure and overlap



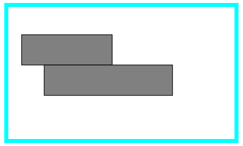
- Shortwave change strongest in the marine stratocumulus regions, but in the tropics the two effects cancel
- Longwave effect is dominant in regions of tropical convection

Zonal mean cloud radiative forcing

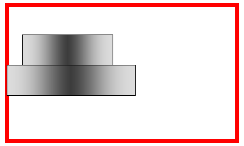
Current models: Plane-parallel



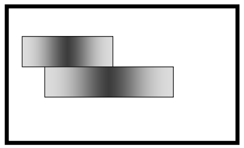
Fix only overlap



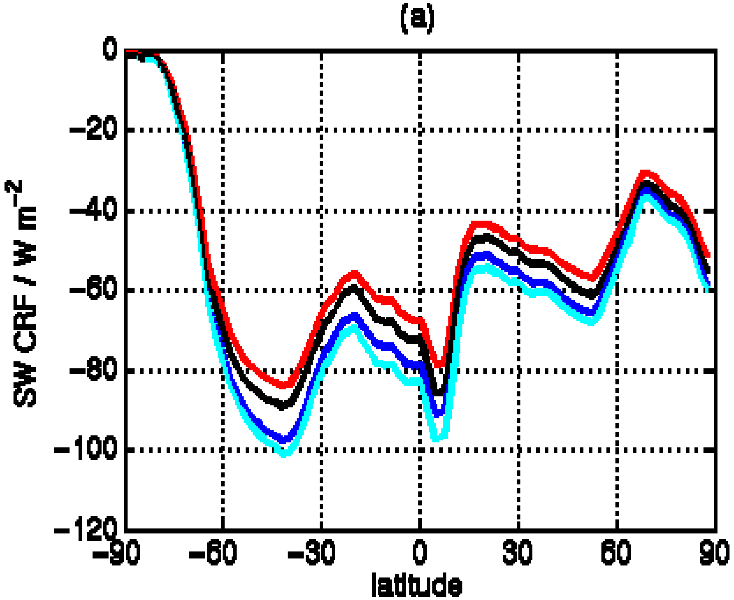
Fix only inhomogeneity



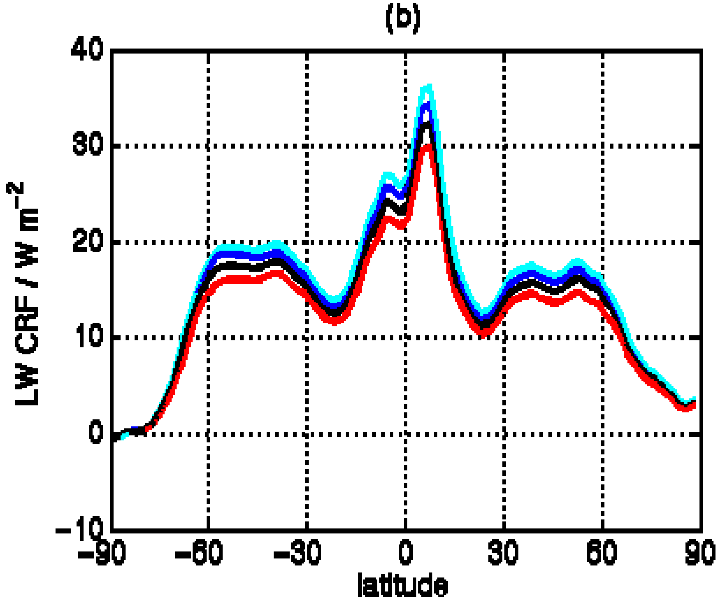
New Tripleclouds scheme: fix both!



TOA Shortwave CRF



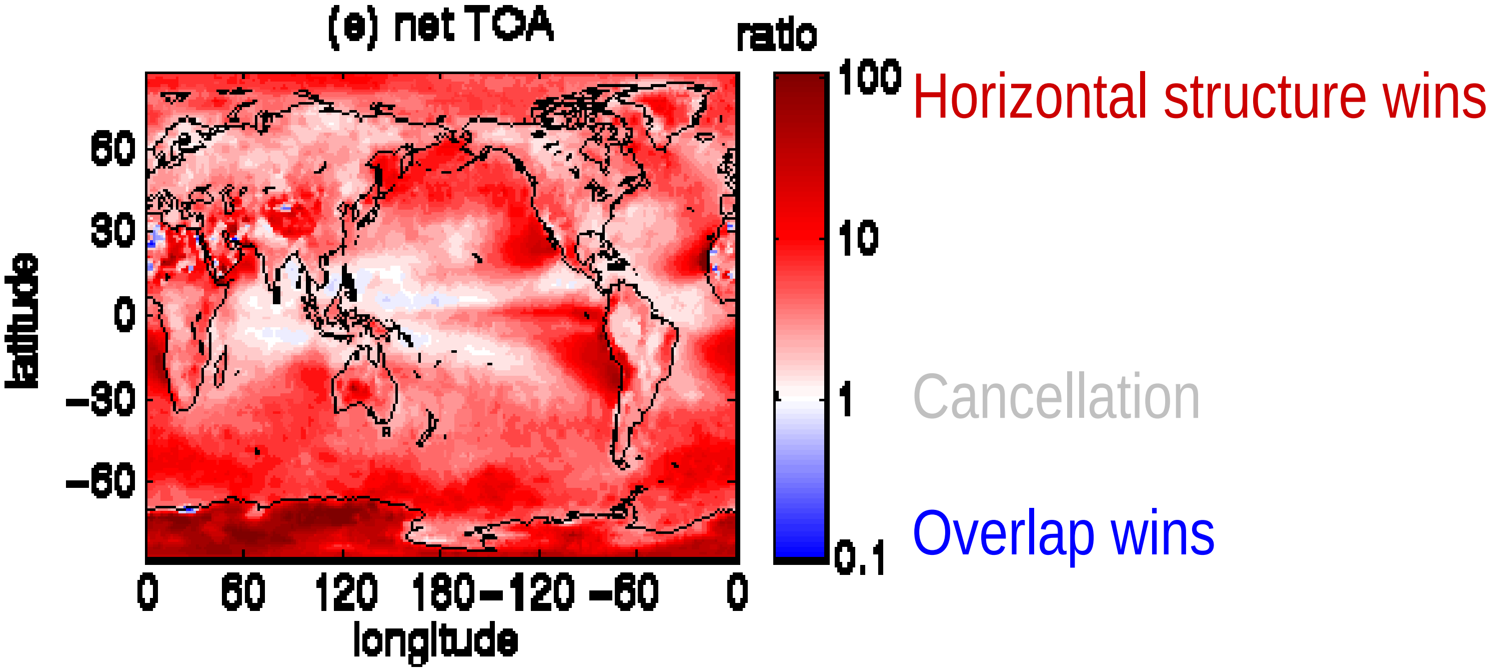
TOA Longwave CRF



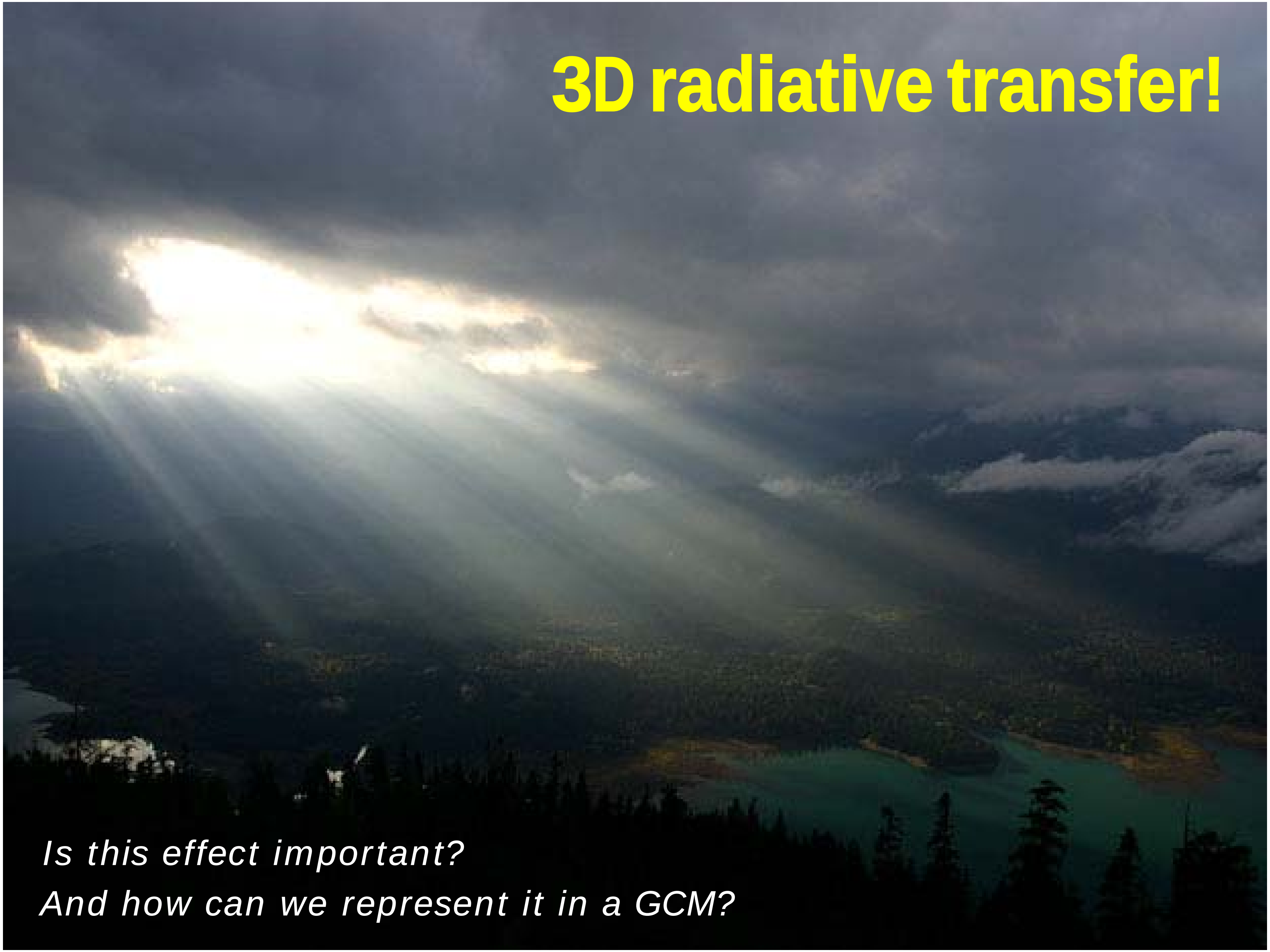
- Fixing just horizontal structure (blue to red) would overcompensate the error
- Fixing just overlap (blue to cyan) would increase the error
- *Need to fix both overlap and horizontal structure*

Relative importance

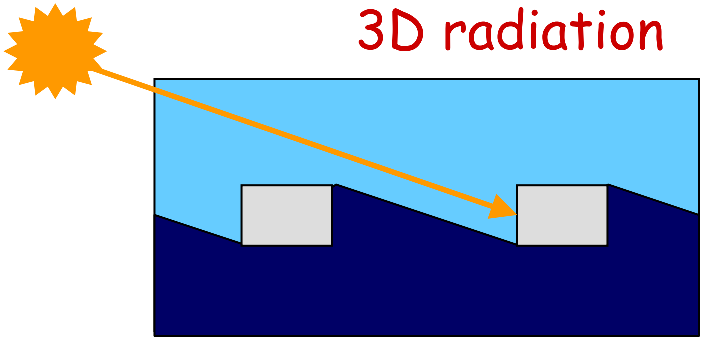
- Ratio of the horizontal-structure effect and the overlap effect in net radiation (shortwave plus longwave)

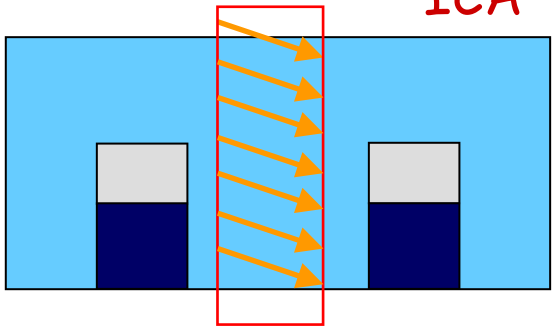


- In marine stratocumulus the horizontal structure effect is completely dominant
- In tropical convection the two effects approximately cancel
- *Tripleclouds shortly to be implemented in Unified Model*


3D radiative transfer!
Is this effect important?
And how can we represent it in a GCM?

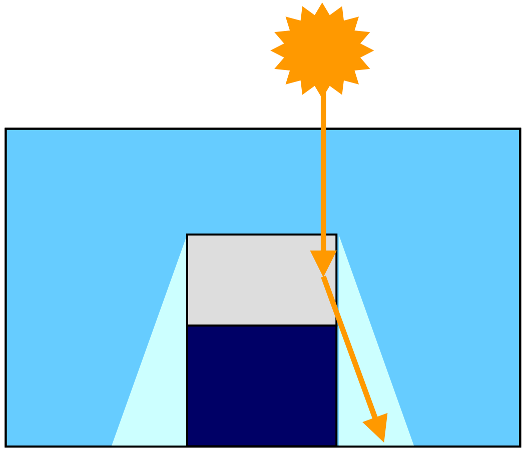
Three main 3D effects



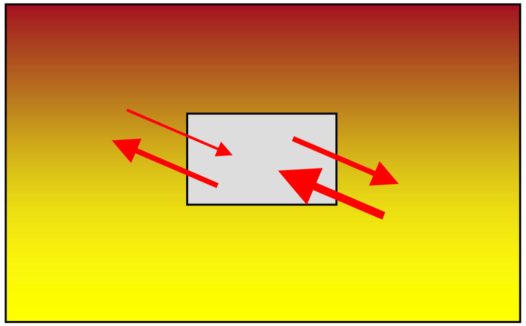


- Effect 1: Shortwave cloud side illumination
  - Incoming radiation is more likely to intercept the cloud
  - Affects the direct solar beam
  - Always increases the cloud radiative forcing
  - Maximized for a low sun (high solar zenith angle)
  - But remember that the flux is less for low sun, so diurnally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

Three main 3D effects continued



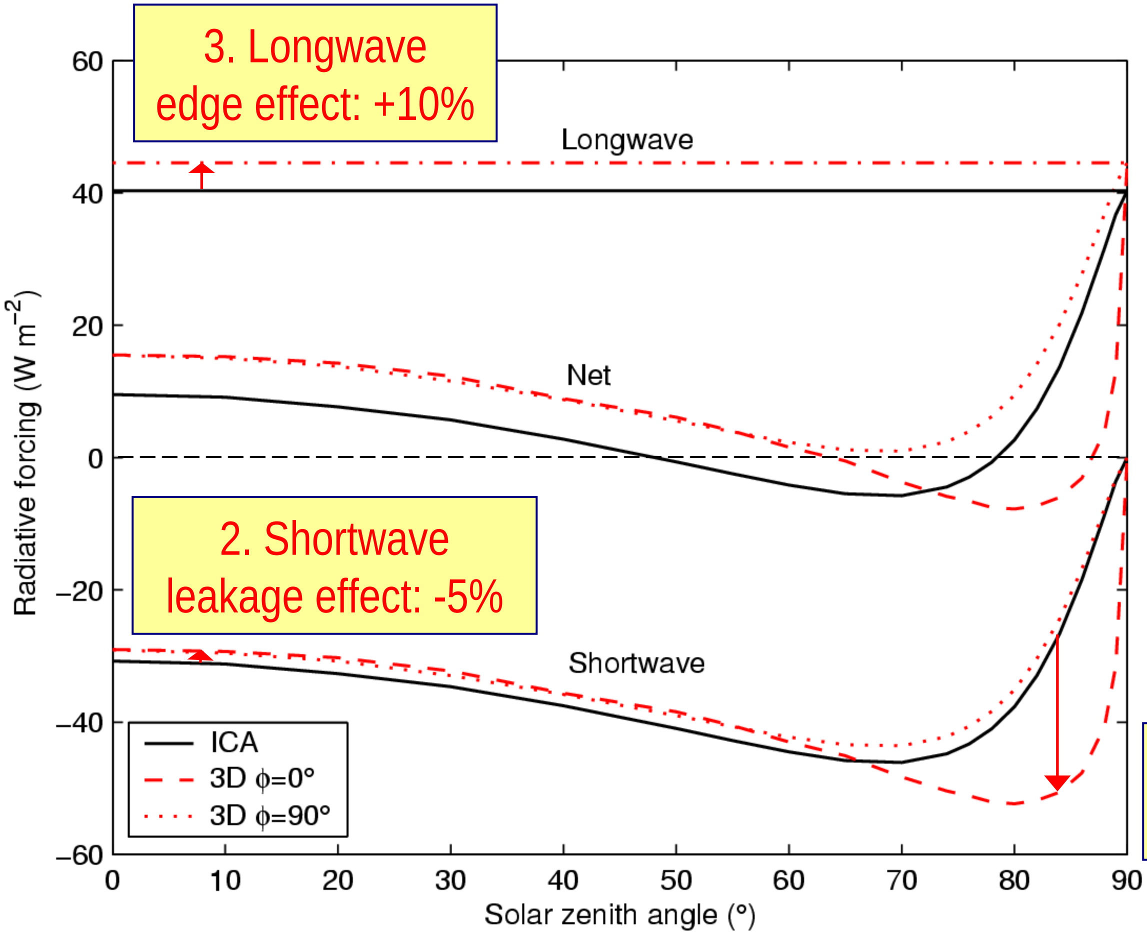
- Effect 2: Shortwave side leakage
  - Maximized for high sun and isolated clouds
  - Results from forward scattering
  - Usually decreases cloud radiative forcing
  - But depends on specific cloud geometry
  - Affects the <u>diffuse</u> component

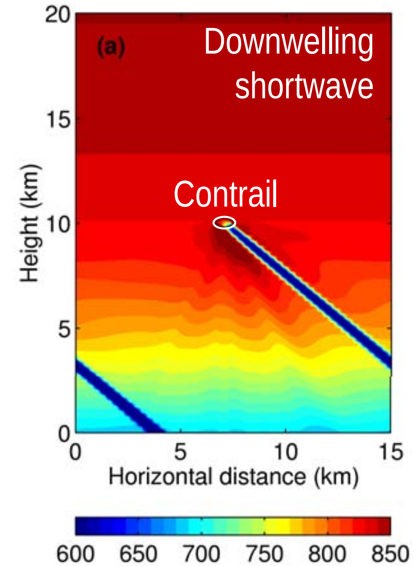


- Effect 3: Longwave side effect
  - Cloud is bathed in upwelling and downwelling radiation of a particular mean radiation temperature
  - If cloud temperature is less, then net flux is into cloud sides, increasing radiative forcing
  - Depends on other clouds in the profile

Simple geometry: aircraft contrails

- SHDOM 3D radiation code run on an idealized contrail with optical depth of 0.4





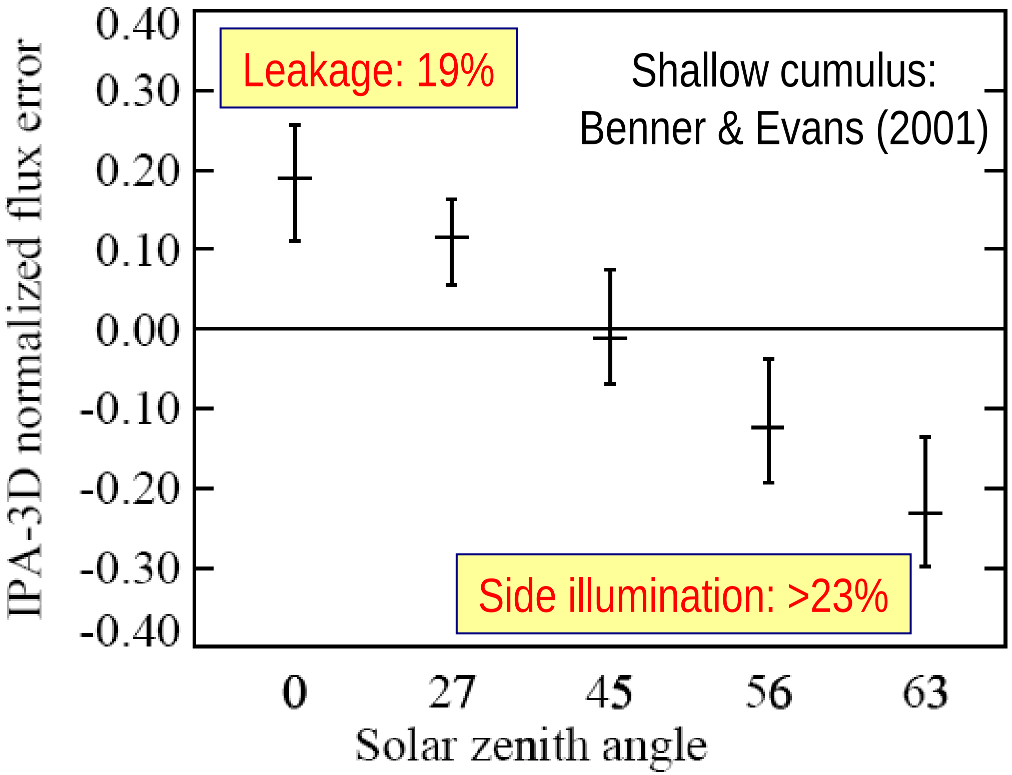
Net forcing can be doubled or its sign reversed!

1. Shortwave side illumination: 50%

Gounou and Hogan (JAS 2007)

3D radiation in natural clouds

- 3D effects significant in convective clouds
  - Cumulus (Benner & Evans 2001, Pincus et al. 2005)
  - Deep convection (DiGiuseppe & Tompkins 2003)

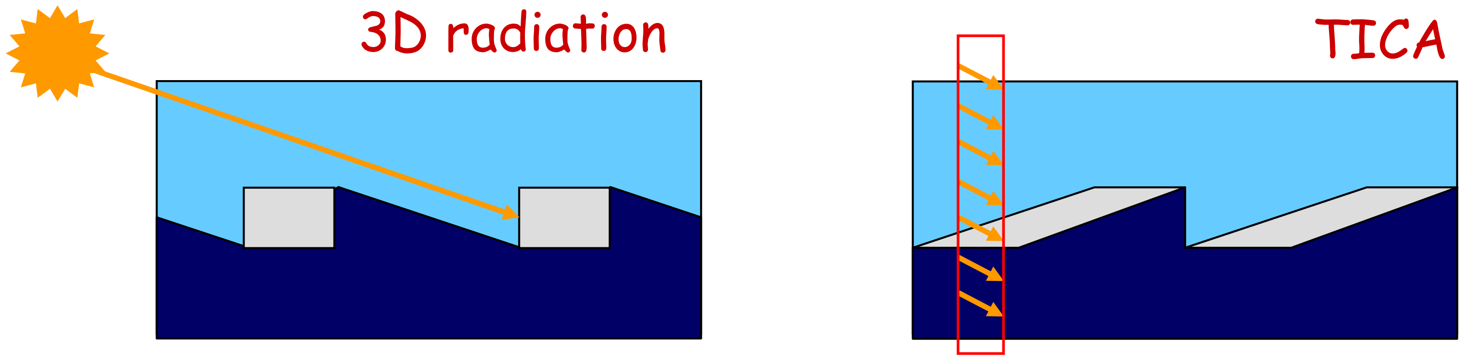


- 3D effects much smaller in layer clouds
  - In cirrus, SW and LW effects up to 10% for optical depth ~1, but negligible for optically thicker clouds (Zhong, Hogan and Haigh 2008)

- *Overall is much less important than horizontal inhomogeneity*

How can we represent this in GCMs?

- Varnai and Davies (1999) proposed the *Tilted ICA* (TICA)



- Apply in GCM radiation scheme by randomising overlap with higher solar zenith angle (Tompkins & DiGiuseppe 2007), but:
  - Need high vertical resolution; won't work for a single-level cloud
  - Only direct solar source calc. should use changed overlap (Effect 1)
  - In principle, Effects 2 and 3 could be represented by slightly randomising the overlap in the two-stream calculation of diffuse fluxes
  - Need observational information on the horizontal scale of the clouds
- Hope to modify Tripleclouds solver at a fundamental level to include horizontal transport (Effects 1-3)
  - Note that this is more difficult to do with McICA!

Are we using computer time wisely?

- Radiation is an integral:

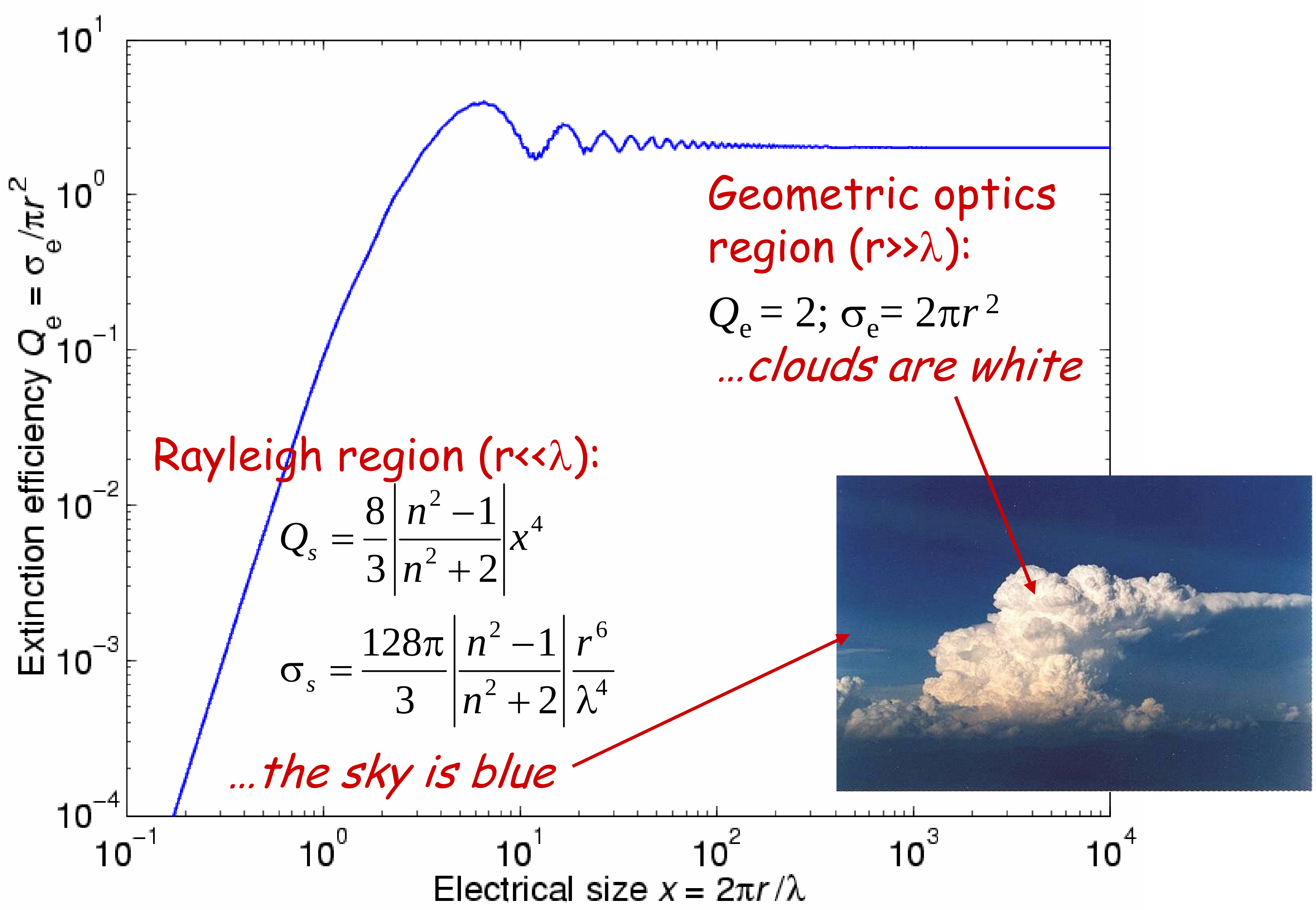
$$\overline{F^{\uparrow\downarrow}(z)} = \int_{\Delta t} \int_{\infty} \int_{\Delta \mathbf{x}} \int_{2\pi} I(z, \mathbf{\Omega}, \mathbf{x}, \nu, t) d\mathbf{\Omega} d\mathbf{x} d\nu dt$$

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 (plus heating rate biases)
Spectrum	100-250	Very well (HITRAN database)	Incorrect climate response to trace gases?

Closing remarks

- *We now have methods for efficiently representing the leading-order cloud-structure effects in GCMs*
- Can we make radiation & microphysical schemes consistent?
  - Cloud variability and overlap not only affect radiation, but also precipitation formation and evaporation
  - Effective radius should also be consistent
- We always apply *mean* overlap and *mean* variability
  - Do we need a stochastic element to represent the known fluctuations in these properties from case to case?
- Cloud structure information should be gridbox-size dependent
  - Important to include for models run at many resolutions
- Can we get away from brainless empirical relationships?
  - What is the underlying physics behind them and can it be modelled?
- *The largest error in a radiation calculation is actually from the cloud variables provided by the GCM*
  - The most substantial task is to evaluate model cloud fields from observations and improve the model…

The limits of Mie theory



Edwards-Slingo solution

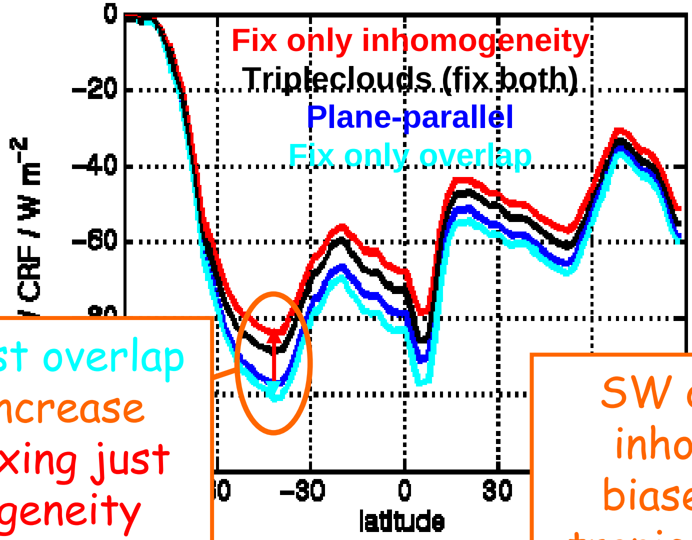
- It is conceptually convenient to solve the system by
  - Working up from the surface calculating the albedo α_i and upward emission G_i of the whole atmosphere below half-level i.

$$\begin{pmatrix} 1 & -\alpha_{0.5} & & & & \\ & 1 & & & & \\ & \beta_1\alpha_1 T_1 & 1 & & & \\ & -T_1 & -R_1 & 1 & & \\ & & & \beta_2\alpha_2 T_2 & 1 & \\ & & & -T_2 & -R_2 & 1 \end{pmatrix} \begin{pmatrix} F_{0.5}^+ \\ F_{0.5}^- \\ F_{1.5}^+ \\ F_{1.5}^- \\ F_{2.5}^+ \\ F_{2.5}^- \end{pmatrix} = \begin{pmatrix} G_{0.5} \\ S_{TOA}^- \\ \beta_1\left(G_{1.5} + S_1^-\alpha_{1.5}\right) \\ S_2^- \\ \beta_2\left(S_s^+ + S_2^-\alpha_s\right) \\ S_2^- \end{pmatrix}$$

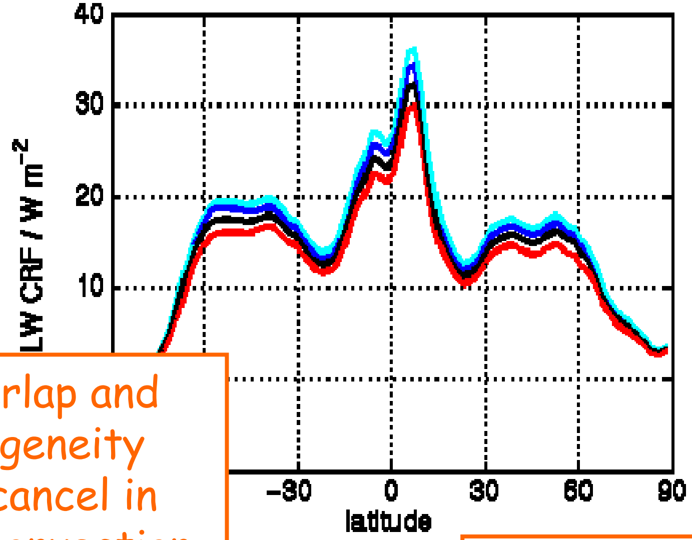
  - Then working down from TOA, calculating the upwelling and downwelling fluxes from α_i and G_i.

Calculations on ERA-40 cloud fields

TOA Shortwave CRF



TOA Longwave CRF

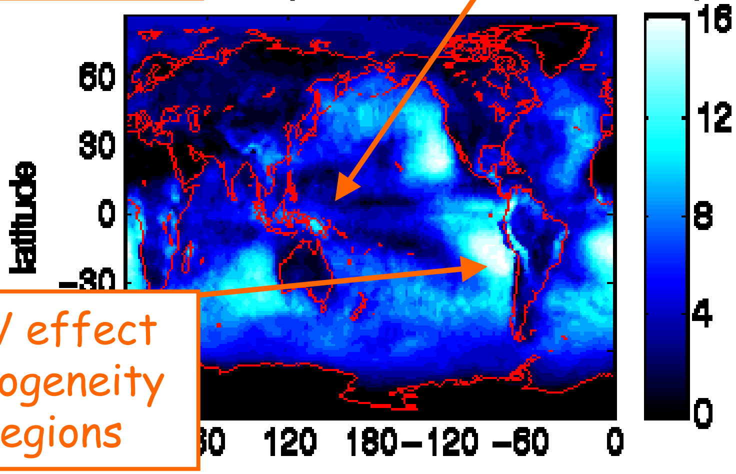


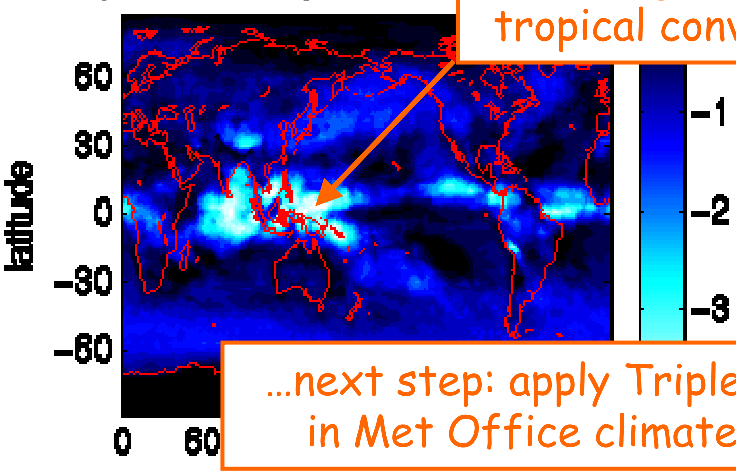
Fixing just overlap would increase error, fixing just inhomogeneity would over-compensate error!

SW overlap and inhomogeneity biases cancel in tropical convection

Main LW effect of inhomogeneity in tropical convection

Tripleclouds minus plane-parallel (W m^{-2})



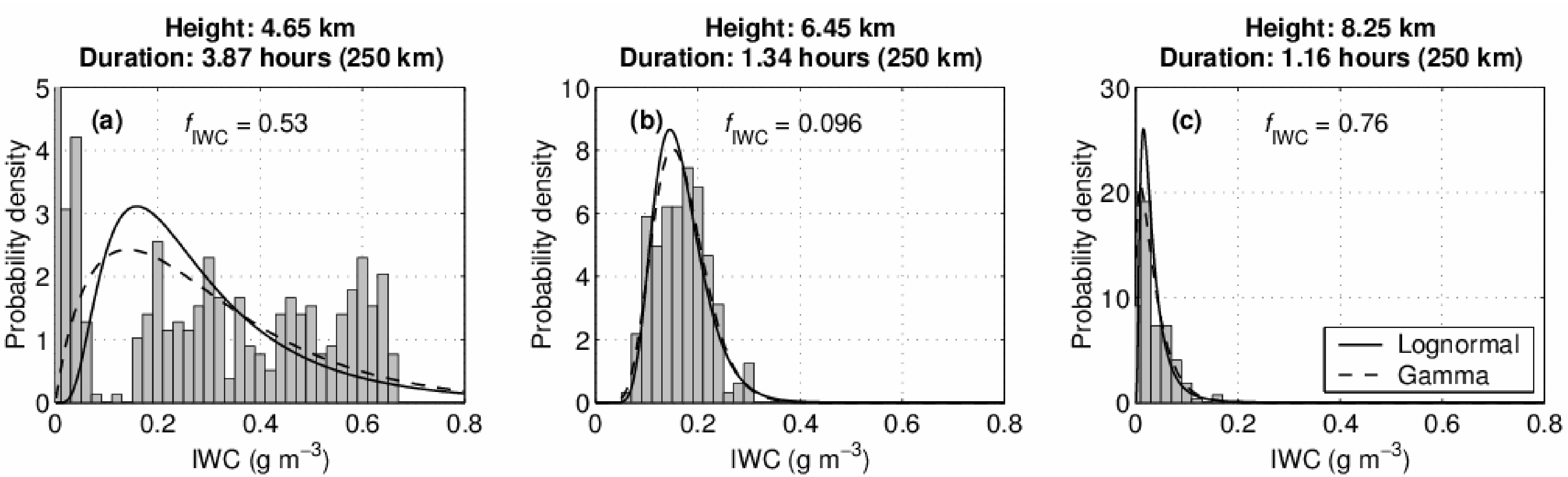


Main SW effect of inhomogeneity in Sc regions

...next step: apply Tripleclouds in Met Office climate model

Ice water content distributions

Near cloud base *Cloud interior* *Near cloud top*



- PDFs of IWC within a model gridbox can often, but not always, be fitted by a lognormal or gamma distribution
- Fractional variance tends to be higher near cloud boundaries

3D effect in natural clouds?

- Shallow cumulus (Benner and Evans 2001; Pincus et al. 2005)
  - SW side illumination: +23% to +35% albedo change for SZA=63°
  - SW side leakage: -19% to -30% for overhead sun (SZA=0°)
- Stratocumulus
- Cirrus (Zhong, Hogan and Haigh 2008)
  - LW: 10% change for τ=1, falling to 0.5% for τ=20
  - SW side illumination: 10% for τ<2 and SZA>80°, negligible otherwise
  - SW side leakage: very small effect of both signs