Radiative transfer in numerical models of the atmosphere

Robin Hogan

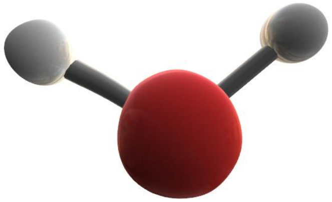
Slides contain contributions from Jean-Jacques Morcrette, Alessio Bozzo,Tony Slingo, Piers Forster and Sophia Schaefer

Outline

- Lecture 1
  1. Global context
  2. From Maxwell to the two-stream equations

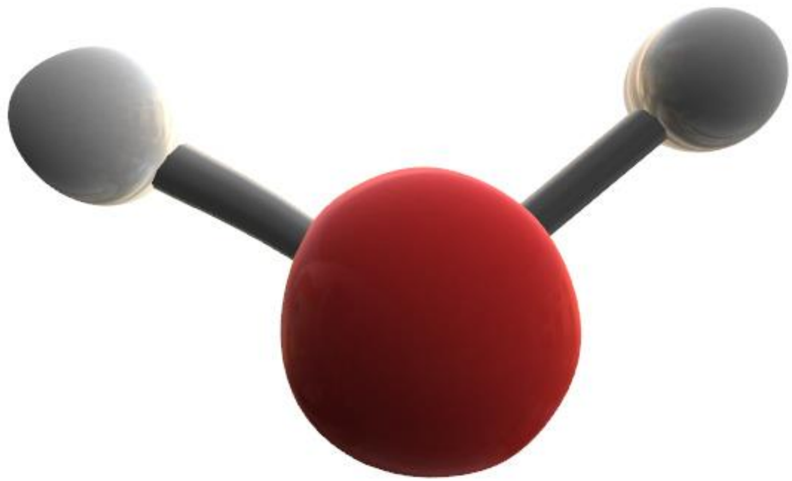
- Lecture 2
  3. Gaseous absorption and emission
  4. Representing cloud structure
  5. Some remaining challenges

- Lecture 3 (Mark Fielding)
  – The ECMWF radiation scheme



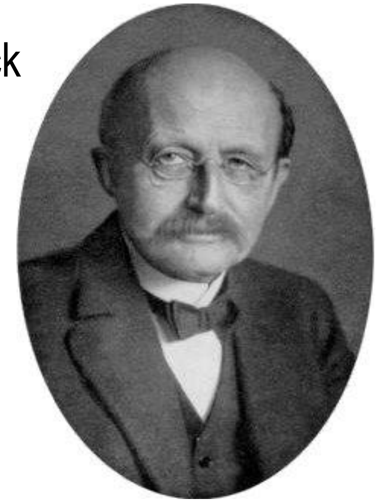
Part 3: Gaseous absorption and emission

- Part 2 considered monochromatic radiative transfer only



- What causes complex emission/absorption spectra of gases?
- *Lecture 3 will outline how we represent this efficiently in models*

Max Planck



Planck's law

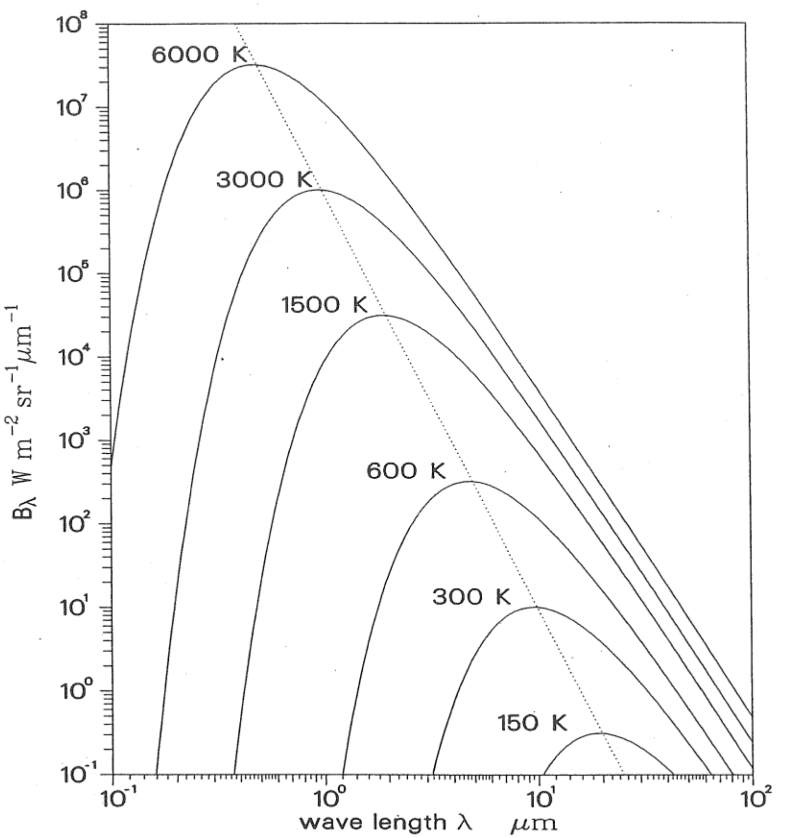
- Spectral radiance [W m^{-2} sr^{-1} Hz^{-1}] emitted by a black body at temperature T is

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\left\{\exp\left(\frac{h\nu^3}{kT}\right) - 1\right\}^{-1}$$

h = Planck's constant 6.626×10^{-34} J s
k = Boltzmann's const 1.381×10^{-23} J K^{-1}
c = speed of light 299792458 m s^{-1}

- Can change to per-unit-wavelength via $B_\nu d\nu = B_\lambda d\lambda$:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\left\{\exp\left(\frac{hc}{\lambda kT}\right) - 1\right\}^{-1}$$



Emission by gases

- Planck function has a continuous spectrum at all temperatures: maximum possible emission by medium in thermal equilibrium

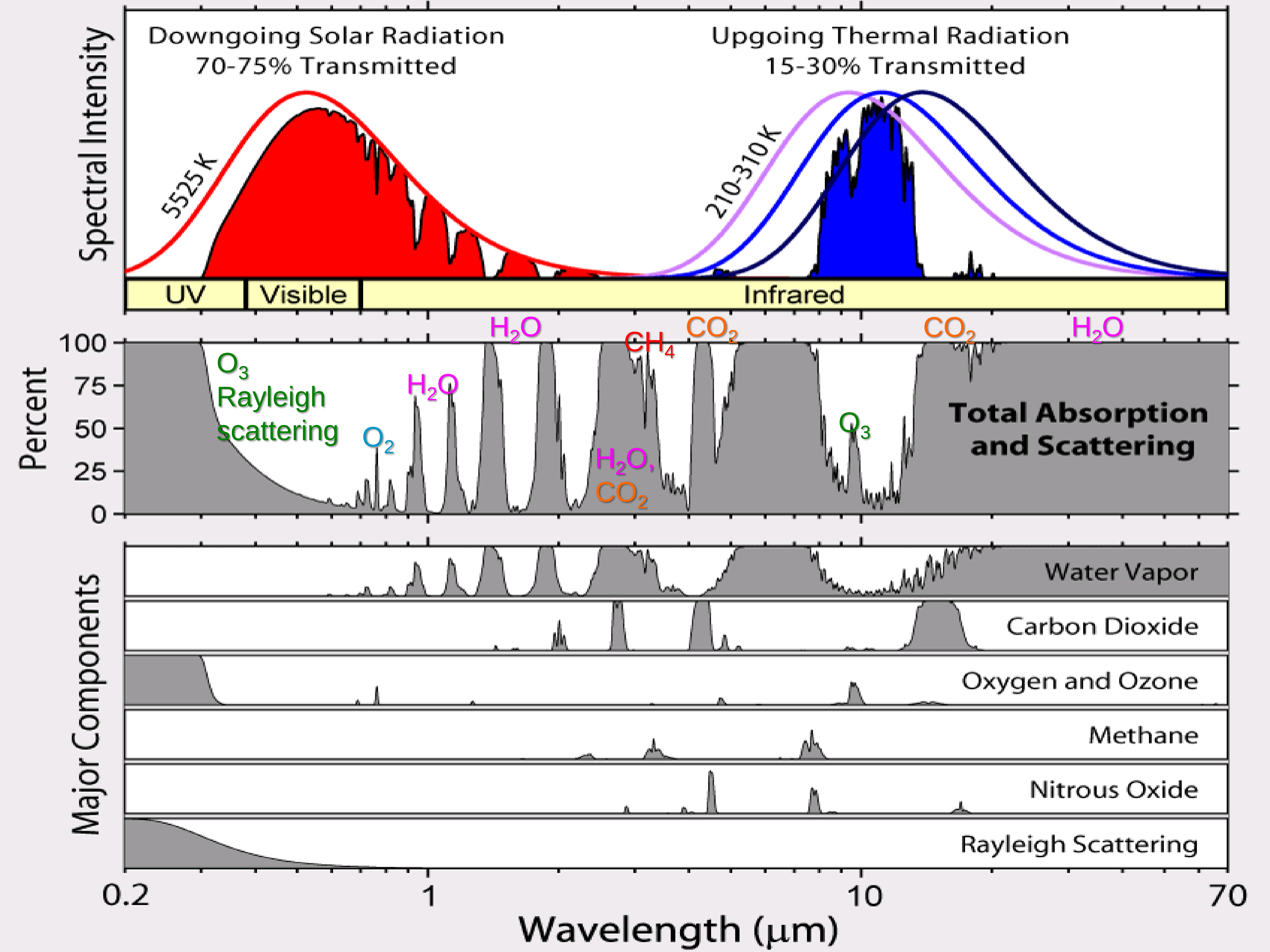
- Absorption by gases is an interaction between molecules and photons and obeys quantum mechanics
  - Not quantized: kinetic energy ~ kT/2
  - Quantized: changes in levels of energy occur by $\Delta E = h\, \Delta\nu$ steps
    - rotational energy: lines in the far infrared λ > 20μm
    - vibrational energy (+rotational): lines in the 1 - 20 μm
    - electronic energy (+vibr.+rot.): lines in the visible and UV

- Radiation schemes are benchmarked to spectroscopic databases from laboratory measurements
  - For example, HITRAN database (Rothman et al. JQSRT 2009)

Composition of the Earth's atmosphere

Gas	Parts by volume	Interaction
Nitrogen (N_2)	780,840 ppmv (78.084%)	**SW (Rayleigh)**
Oxygen (O_2)	209,460 ppmv (20.946%)	**SW (Ray+abs)**
Water vapour (H_2O)	~0.40% full atmosphere, surface ~1%-4%	**LW**, **SW (abs)**
Argon (Ar)	9,340 ppmv (0.9340%)	
Carbon dioxide (CO_2)	415 ppmv (0.042%) *rising*	**LW**, **SW (abs)**
Neon (Ne)	18.18 ppmv (0.001818%)	
Helium (He)	5.24 ppmv (0.000524%)	
Methane (CH_4)	1.88 ppmv (0.000188%) *rising*	**LW**, **SW (abs)**
Krypton (Kr)	1.14 ppmv (0.000114%)	
Hydrogen (H_2)	0.55 ppmv (0.000055%)	
Nitrous oxide (N_2O)	0.319 ppmv (0.00003%) *rising*	**LW**
Carbon monoxide (CO)	0.1 ppmv (0.00001%)	
Xenon (Xe)	0.09 ppmv (9×10^{-6}%) (0.000009%)	
Ozone (O_3)	0.0 to 0.07 ppmv (0 to 7×10^{-6}%)	**LW**, **SW (abs)**

SW "shortwave" solar radiation: Rayleigh scattering (blue sky) or absorption
LW "longwave" terrestrial infrared radiation: absorbing greenhouse gases



Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
Spectral Intensity
5525 K
210-310 K
UV
Visible
Infrared
100
75
50
25
0
Percent
H_2O
CH_4
CO_2
CO_2
H_2O
O_3
Rayleigh
scattering
H_2O
O_2
H_2O,
CO_2
O_3
Total Absorption
and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
0.2
1
10
70
Wavelength (μm)

Spectral lines

- Spectral lines are of frequency $\nu = \Delta E/h$
- Absorption cross-section per molecule: $\sigma_\nu = S\, f(\nu - \nu_0)$
  - S = line strength
  - ν_0 = centre frequency
  - $f(\nu - \nu_0)$ = line shape (normalized to unit area)
- Natural broadening
  - Due to Heisenburg's principle (negligible)
- Pressure broadening
  - Molecular collisions disrupt energy levels (troposphere and stratosphere)
- Doppler broadening
  - Due to random motion of molecules, absorption/emission is Doppler-shifted from natural line position (mesosphere)

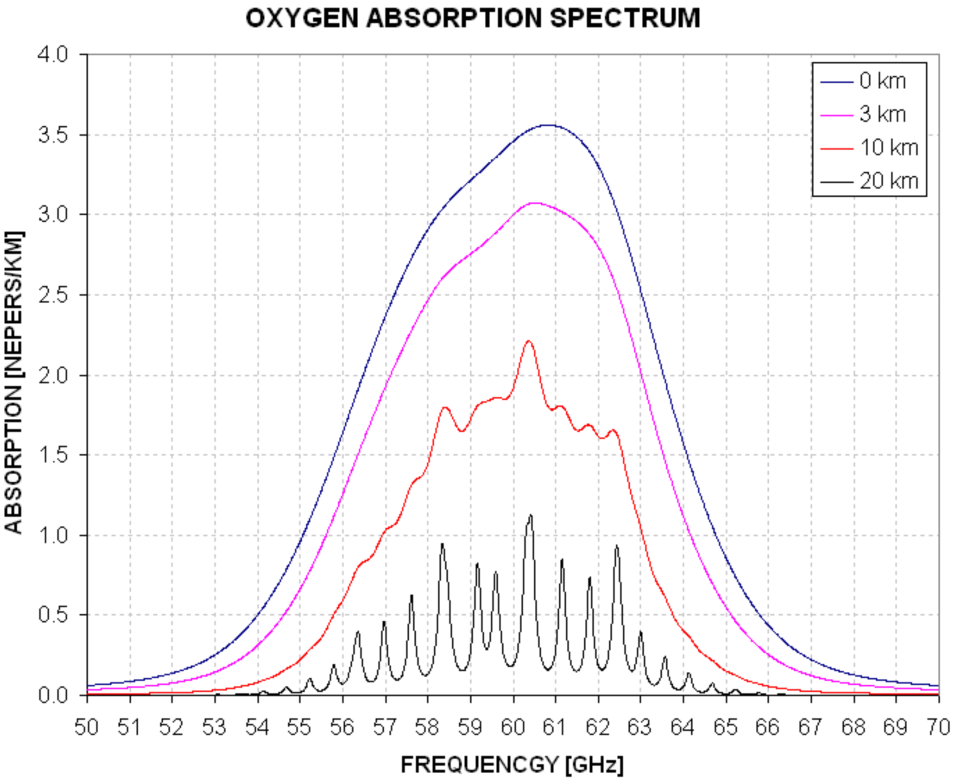
Pressure broadening

- Theory is rather heuristic; usually described adequately but not perfectly by the *Lorenz* line shape:

$$f_L(\nu) = \frac{\alpha_L}{\pi\left[\ (\nu - \nu_0)^2 + {\alpha_L}^2\ \right]}$$

- With the half-width at half the maximum roughly proportional to the frequency of collisions, modelled by:

$$\alpha_L = \alpha_{L0} \frac{P}{P_0}\left(\frac{T_0}{T}\right)^{0.5}$$



Doppler broadening

- Molecular velocity distribution is Gaussian:

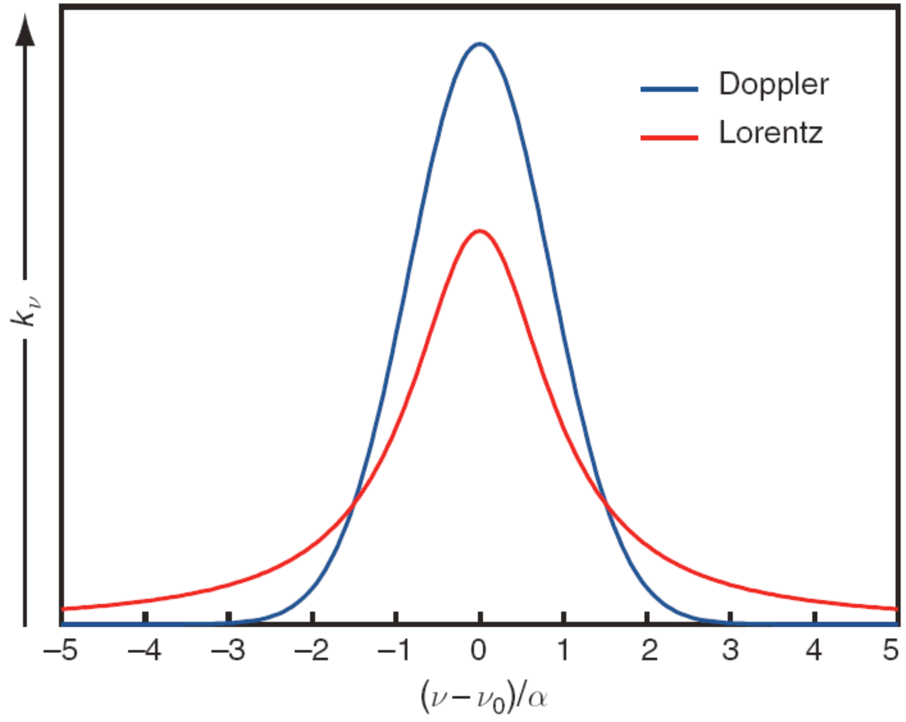
$$P(v) = \left(\frac{m}{2\pi kT}\right)^{0.5} \exp\left(-\frac{mv^2}{2kT}\right)$$

- Doppler shift $\nu' = \nu\,(1 - v/c)$ so line shape is Gaussian

$$f_D(\nu) = \frac{1}{\alpha_D(\pi)^{0.5}} \exp\left\{-\left[\frac{\nu-\nu_0}{\alpha_D}\right]^2\right\}$$

- where

$$\alpha_D = \frac{\nu_0}{c}\left(\frac{2kT}{m}\right)^{0.5}$$

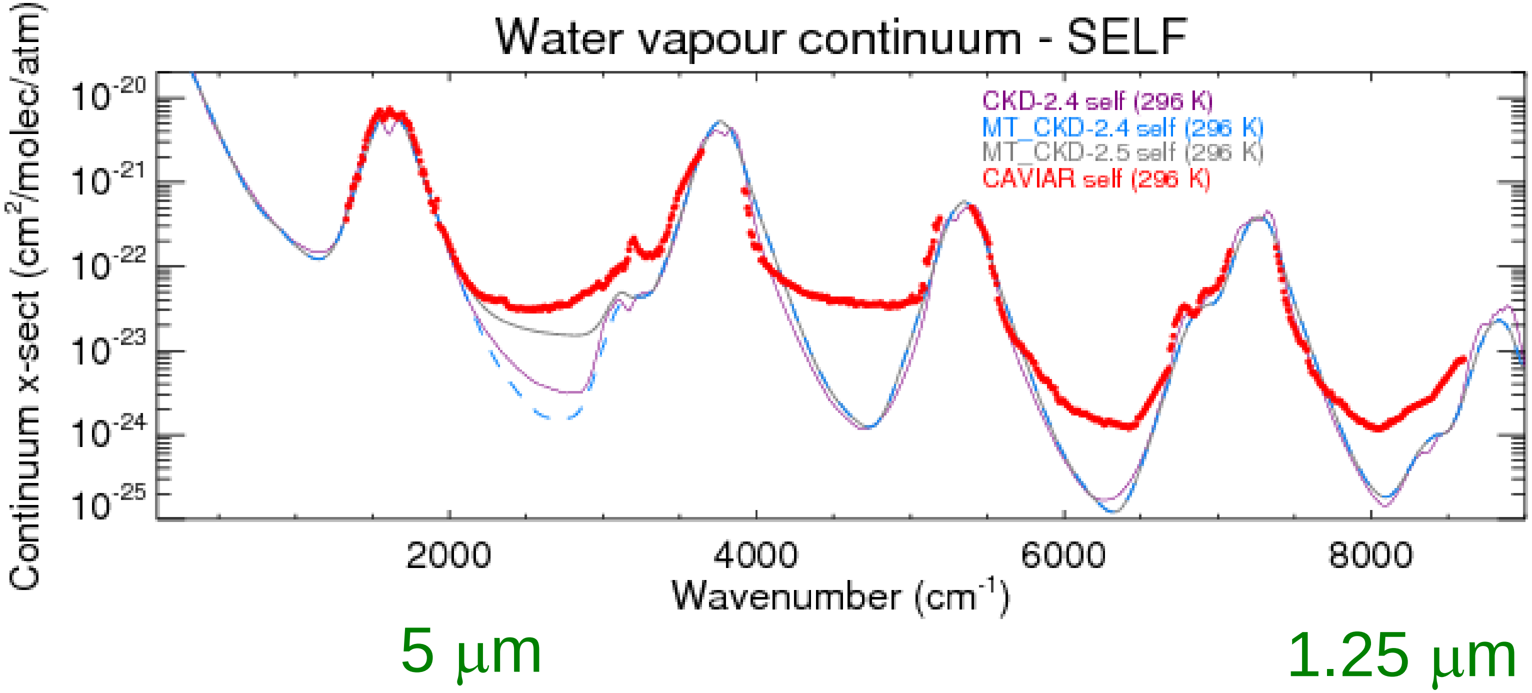


Continuum absorption

- In addition to spectral lines, some absorption does not exhibit line structure – this is due to:
- Photoionization
  - High energy photons (X/γ-rays) strip electrons from atoms
  - Kinetic energy of resulting ion and electron not quantized, so will be continuum absorption above ionization energy
- Photodissociation
  - Ultraviolet light can break molecules (e.g. $O_{2,}$ O_3) into constituent atoms: protects us from hard UV at surface
- Water vapour continuum uncertain: mechanism is either
  - Far wings of lines (due to underestimate by Lorenz shape)
  - Temporary water vapour clusters (dimers, trimers etc.)

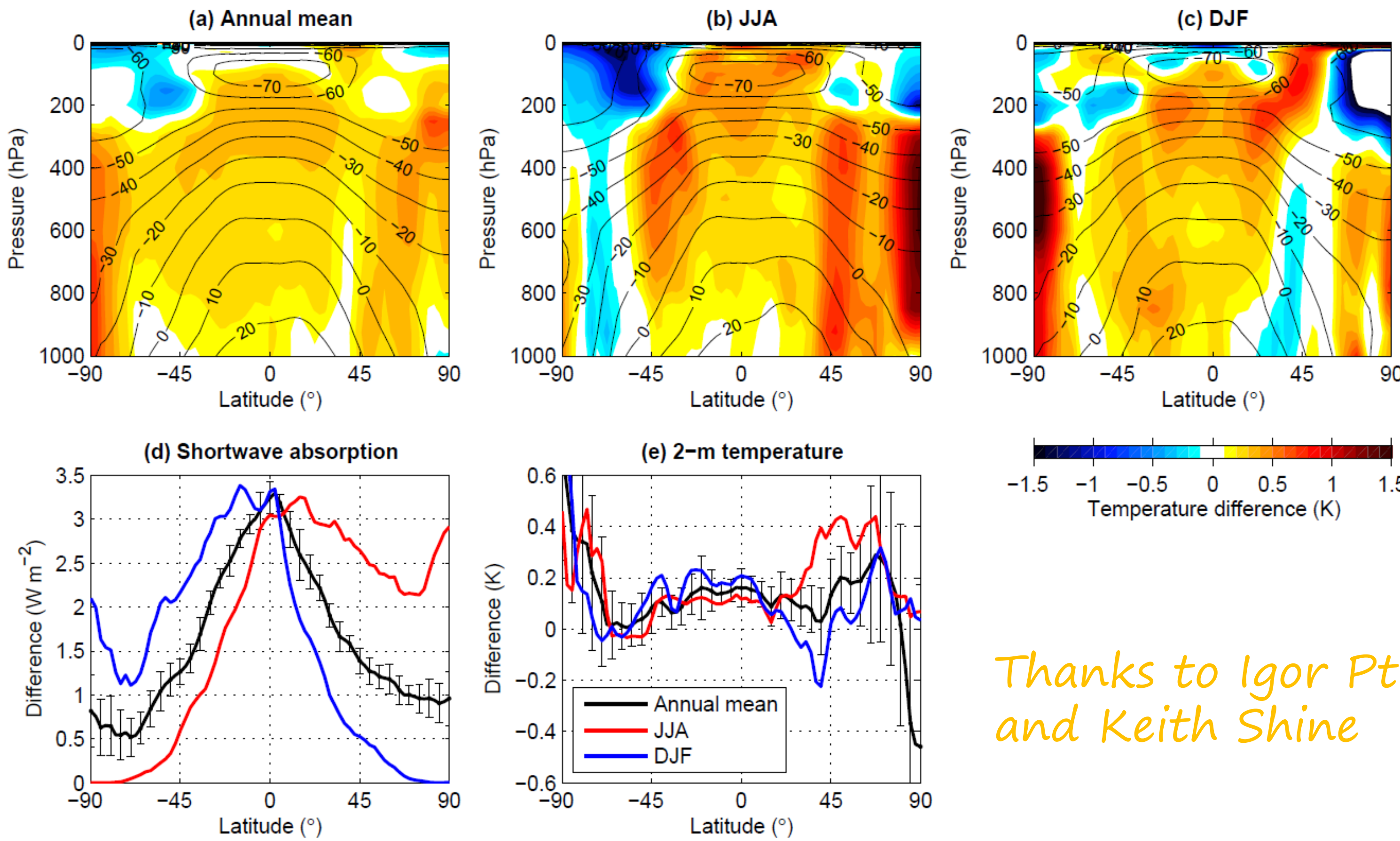
Water vapour continuum

- Shine et al. in CAVIAR project have found that current water vapour continuum models can significantly underestimate absorption in windows between bands, particularly in the near infrared

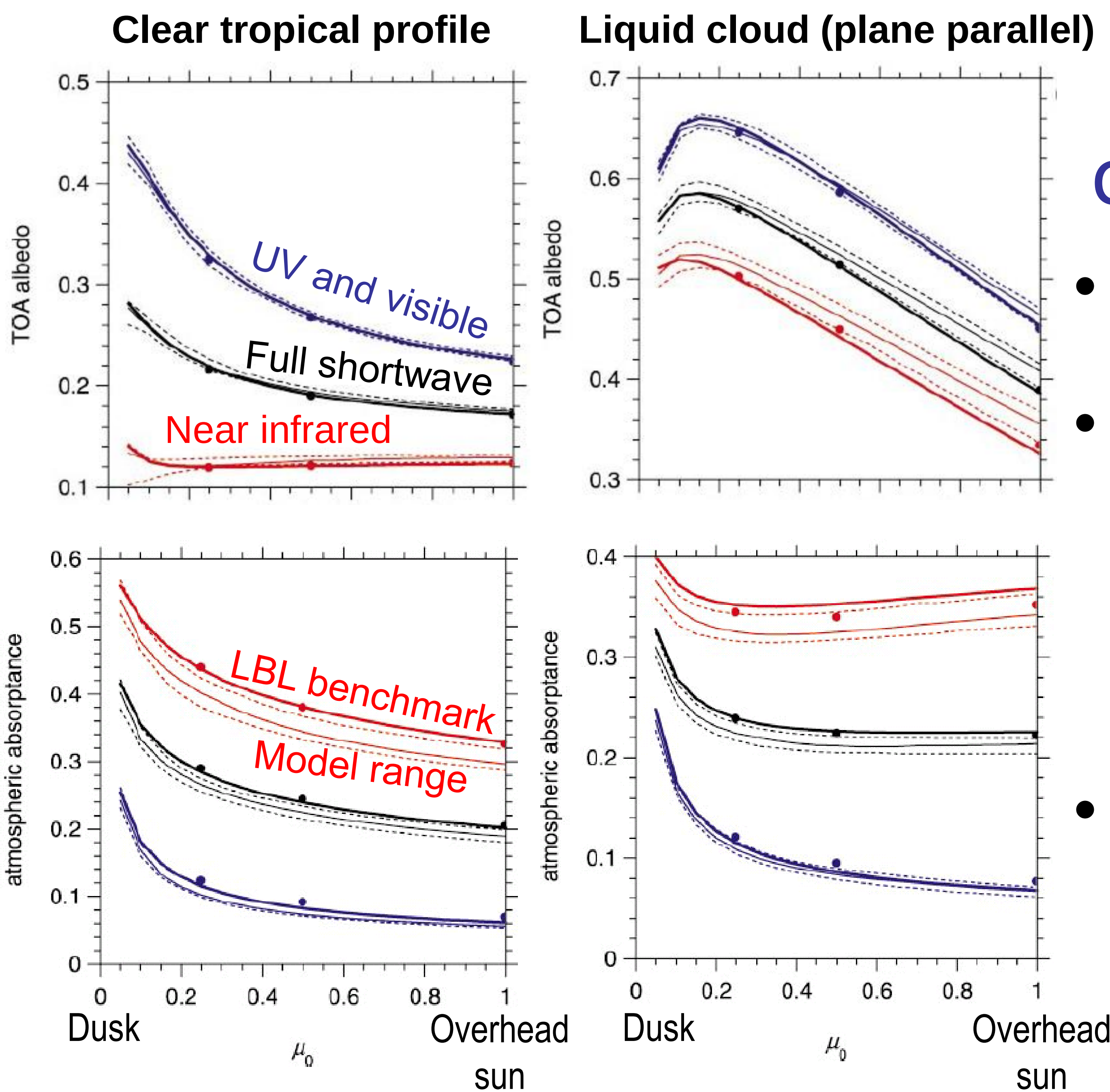


Impact of CAVIAR continuum

- Change in free-running IFS coupled to the ocean when CAVIAR continuum introduced



Thanks to Igor Ptashnik and Keith Shine



Shortwave comparison

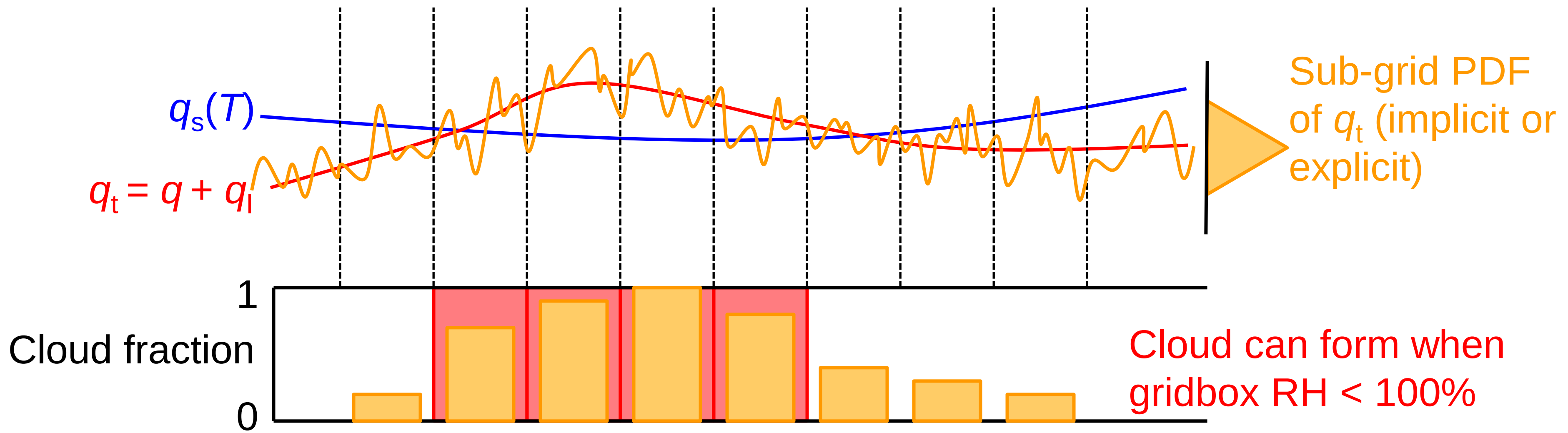
- Barker et al. (JClim 2003)
- Most models underestimate clear-sky near-IR absorption
  - Poor continuum
- Most models underestimate liquid cloud near-IR absorption

Part 4: Representing cloud structure

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

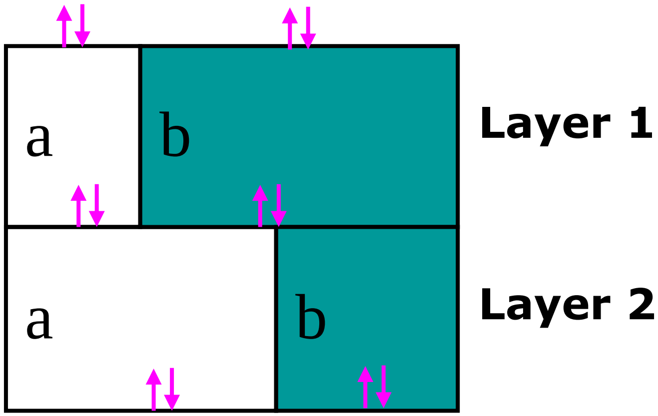
Cloud fraction parametrization

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



- 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

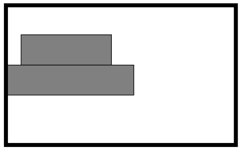
Are we using computer time wisely?

- Radiation is an integral:

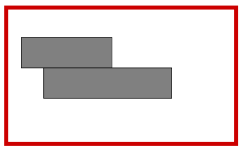
$$\overline{F^{\uparrow\downarrow}(z)} = \int_{\Delta t}\int_{\infty}\int_{\Delta \mathbf{x}}\int_{2\pi} I(z,\mathbf{\Omega},\mathbf{x},\nu,t)\,d\mathbf{\Omega}\,d\mathbf{x}\,d\nu\,dt$$

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?

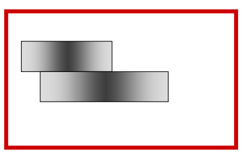
Three further issues for clouds



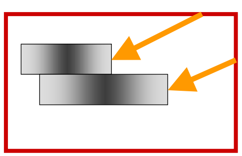
- Clouds in older GCMs used a simple cloud fraction scheme with clouds in adjacent layers being maximally overlapped



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



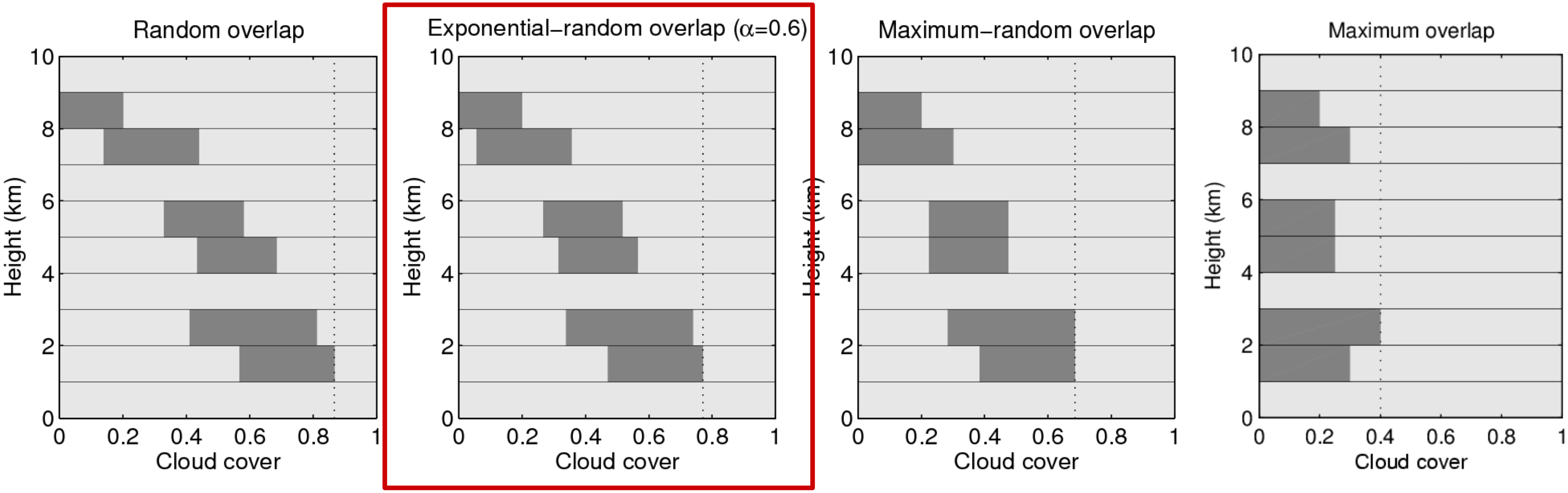
2. Real clouds are horizontally inhomogeneous, leading to albedo and emissivity biases in GCMs (Cahalan et al 1994, Pomroy and Illingworth 2000)



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

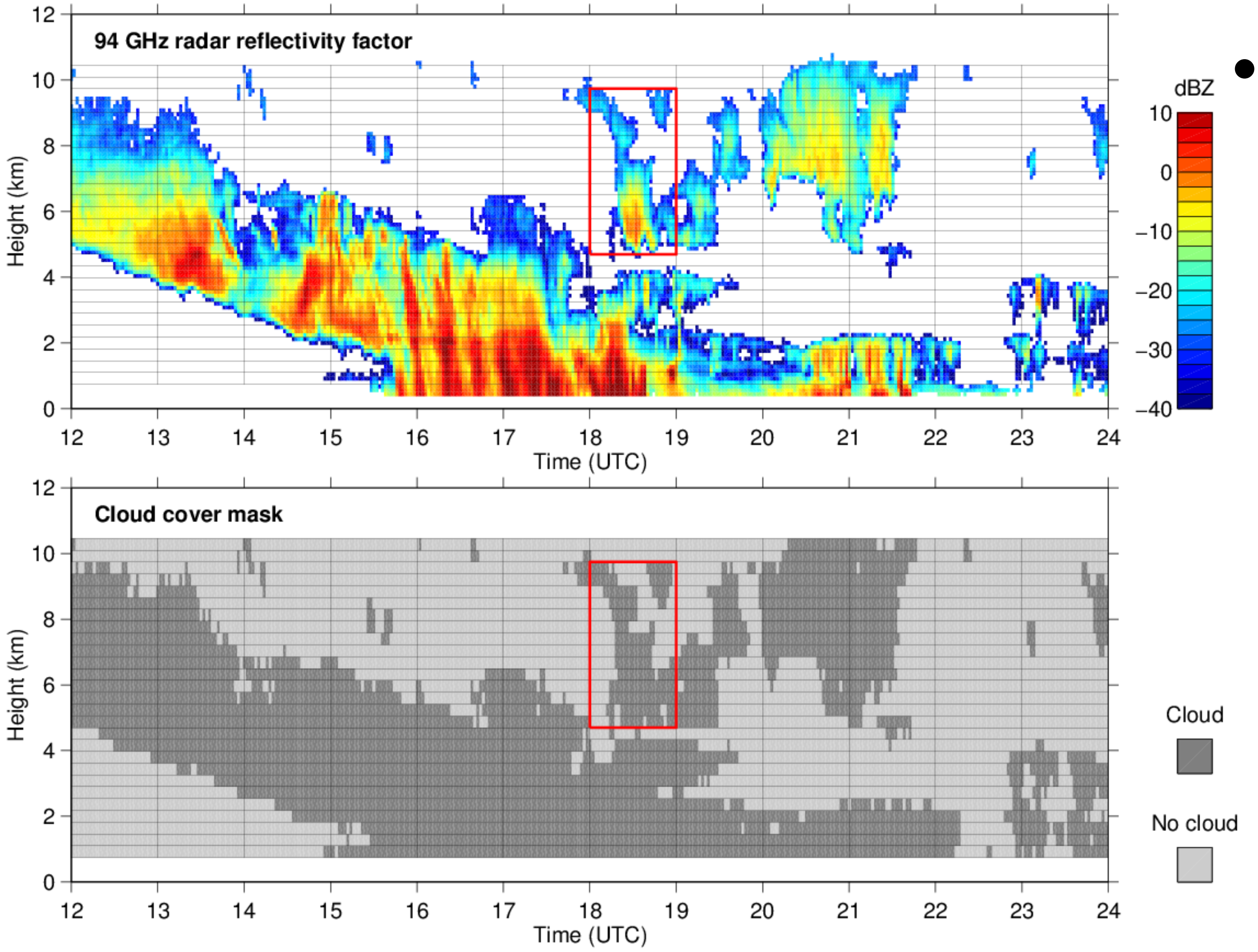
Cloud overlap parametrization

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



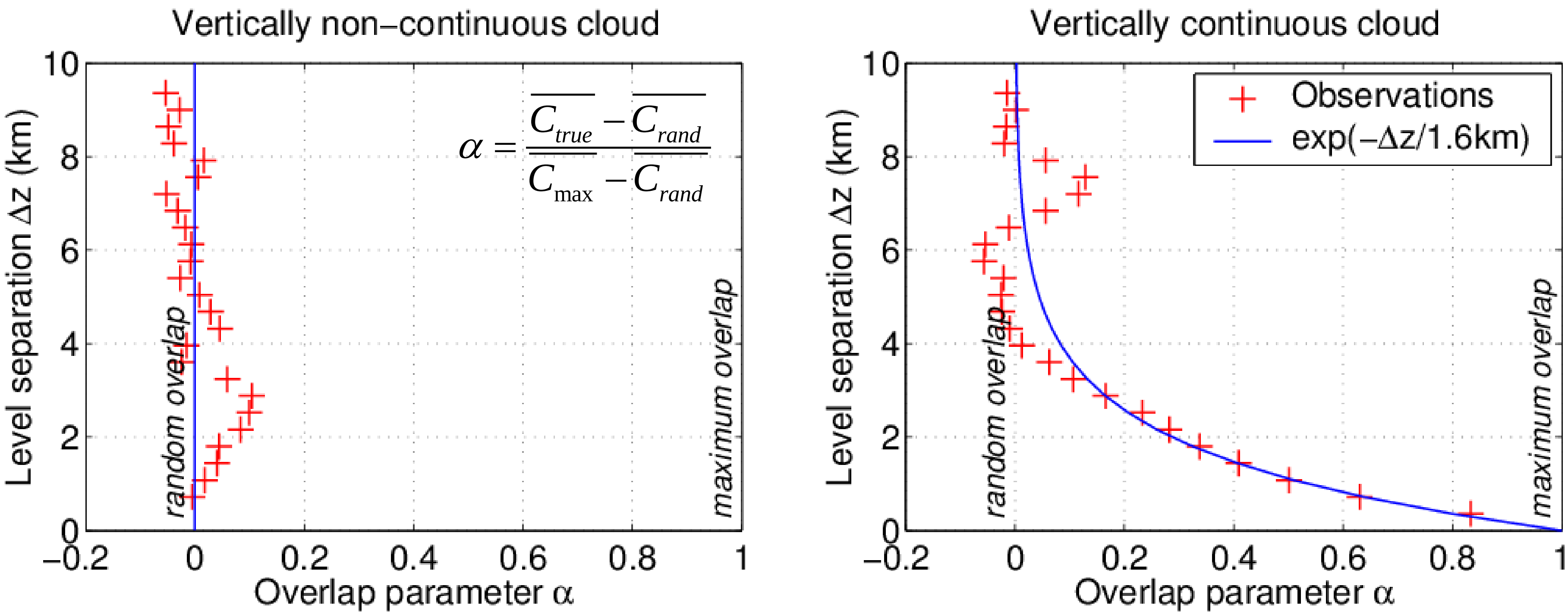
- Observations (Hogan and Illingworth 2000) support "exponential-random overlap":
  - Non-adjacent clouds are randomly overlapped
  - Adjacent clouds correlated with decorrelation length ~2km
  - Many models still use "maximum-random overlap"

Cloud overlap from radar: example



- Radar can observe the actual overlap of clouds

Cloud overlap: results

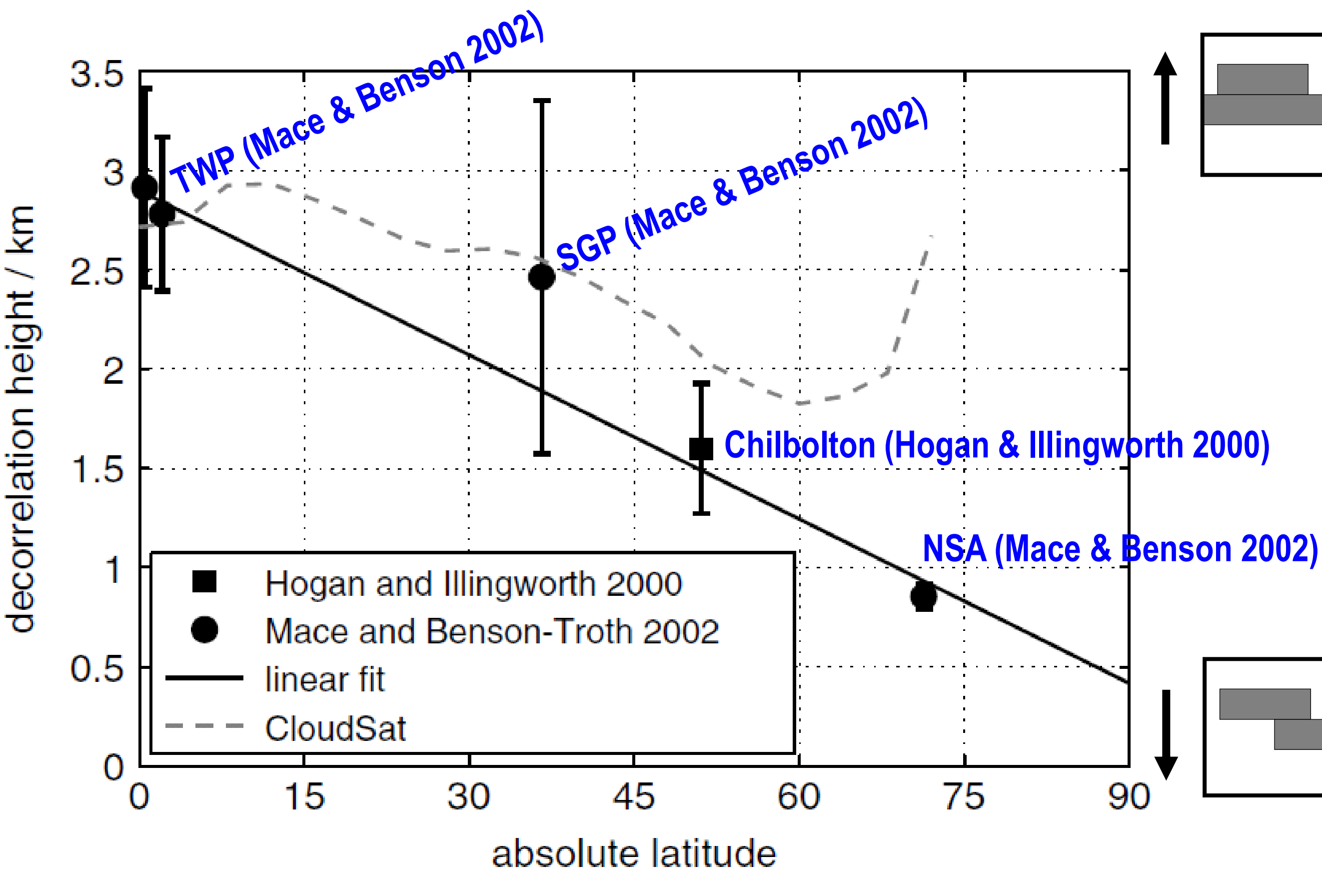


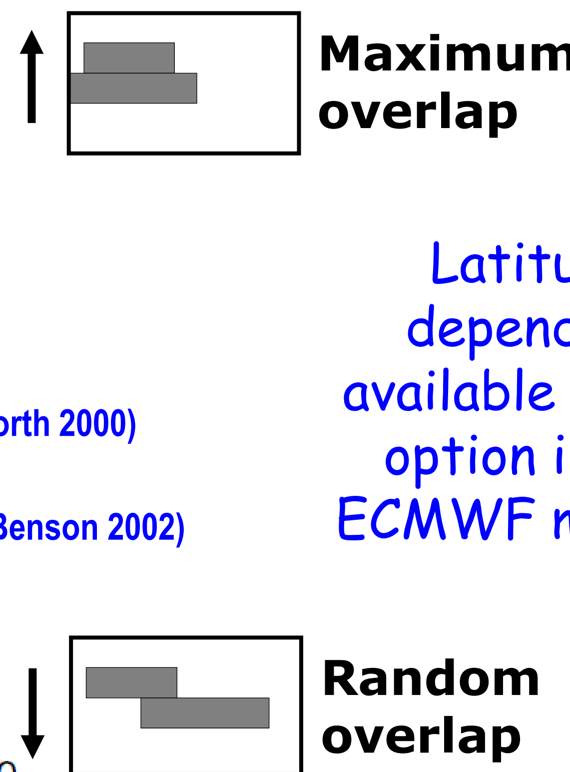
- Vertically isolated clouds are randomly overlapped
- *Overlap of vertically continuous clouds becomes rapidly more random with increasing thickness, characterized by an overlap decorrelation length z_0 ~ 2 km*

Hogan and Illingworth (QJ 2000)

Cloud overlap globally

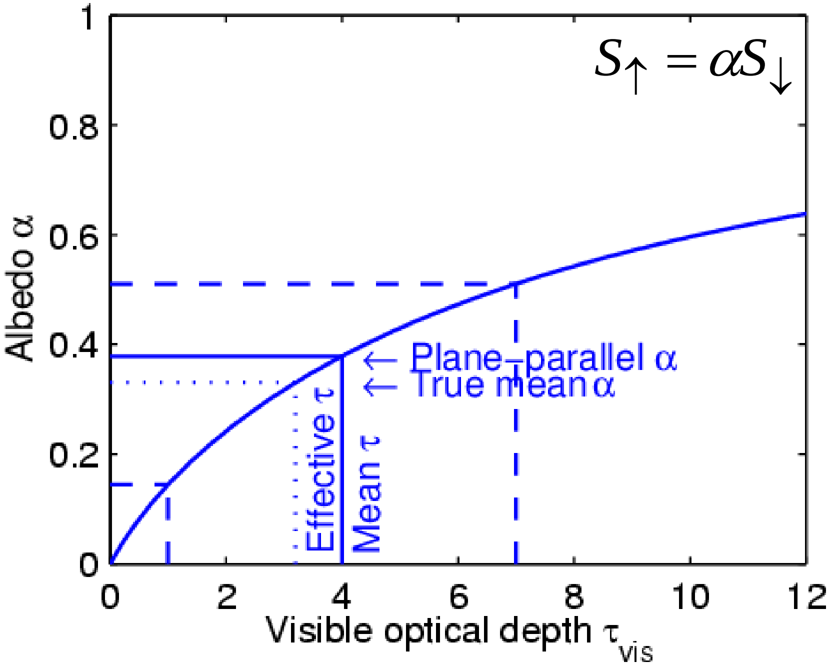
- Latitudinal dependence of decorrelation length from Chilbolton and the worldwide ARM sites
  - More convection and less shear in the tropics so more maximally overlapped

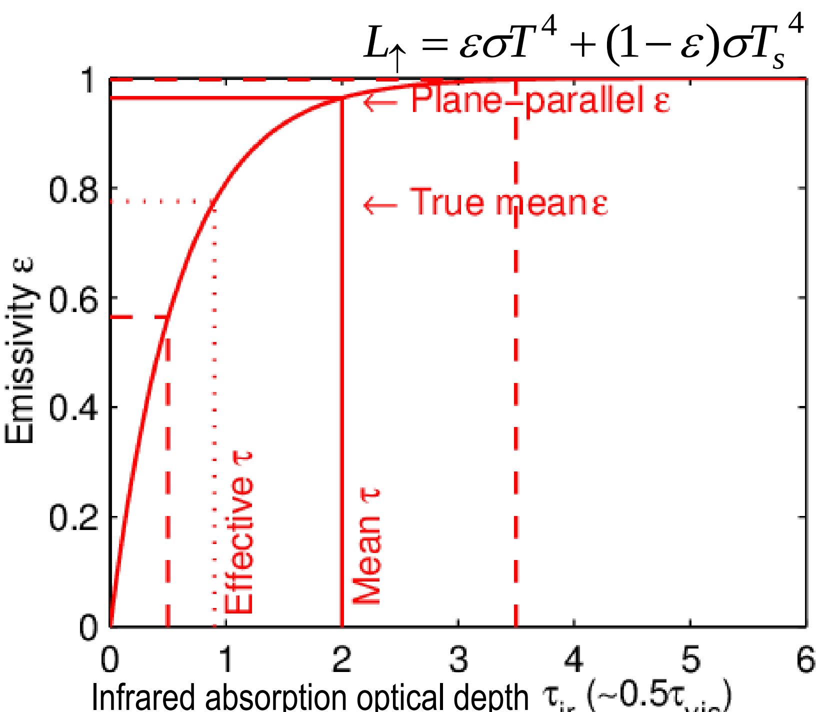




Latitudinal dependence available as an option in the ECMWF model

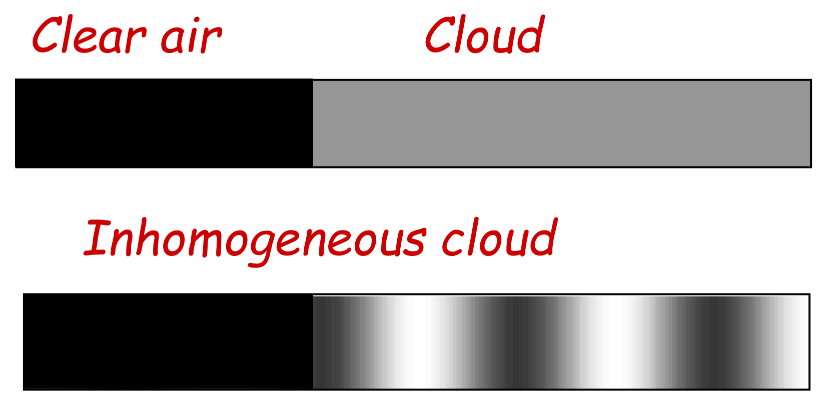
Shonk et al. (QJ 2010)



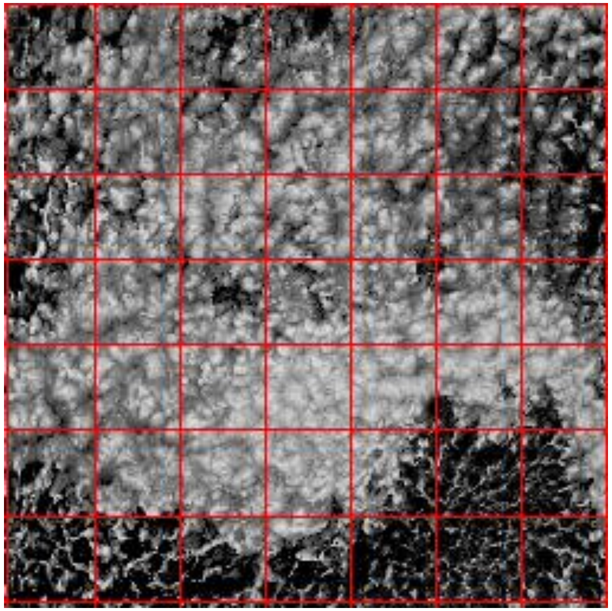


Why is cloud structure important?

- An example of *non-linear averaging*



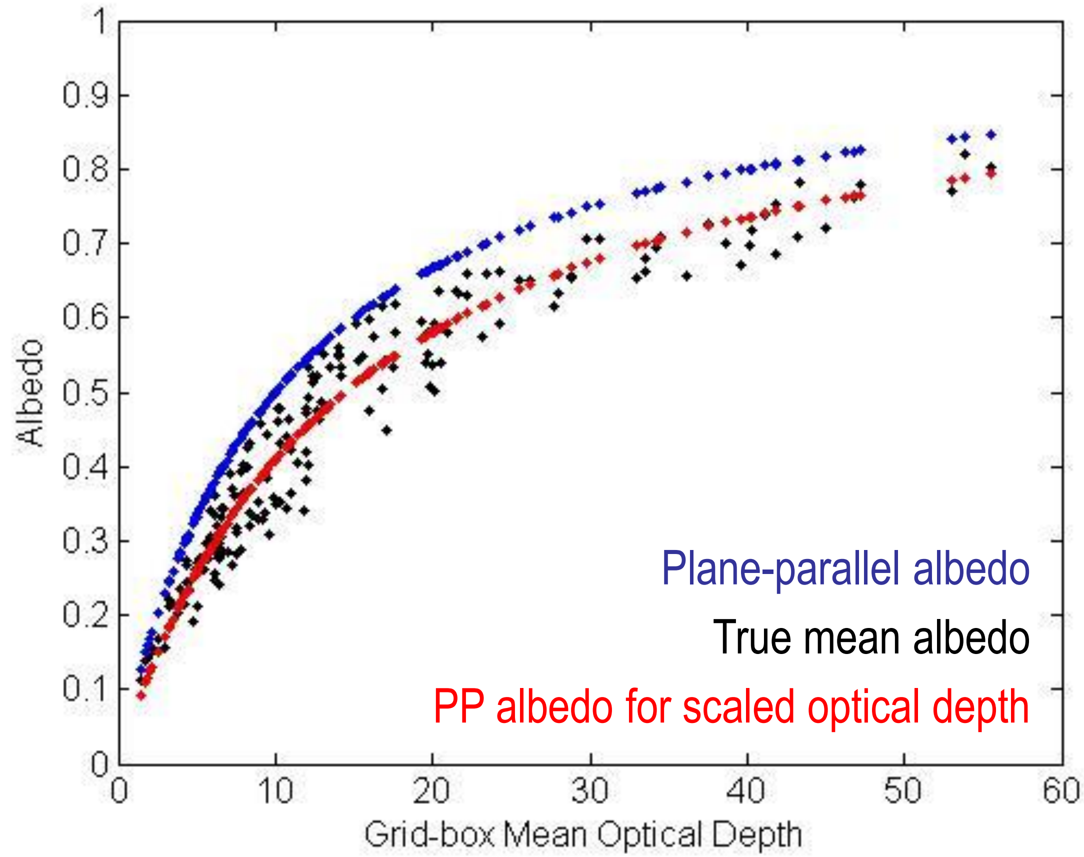
- Non-uniform clouds have lower mean emissivity & albedo for same mean optical depth due to curvature in the relationships



MODIS Stratocumulus

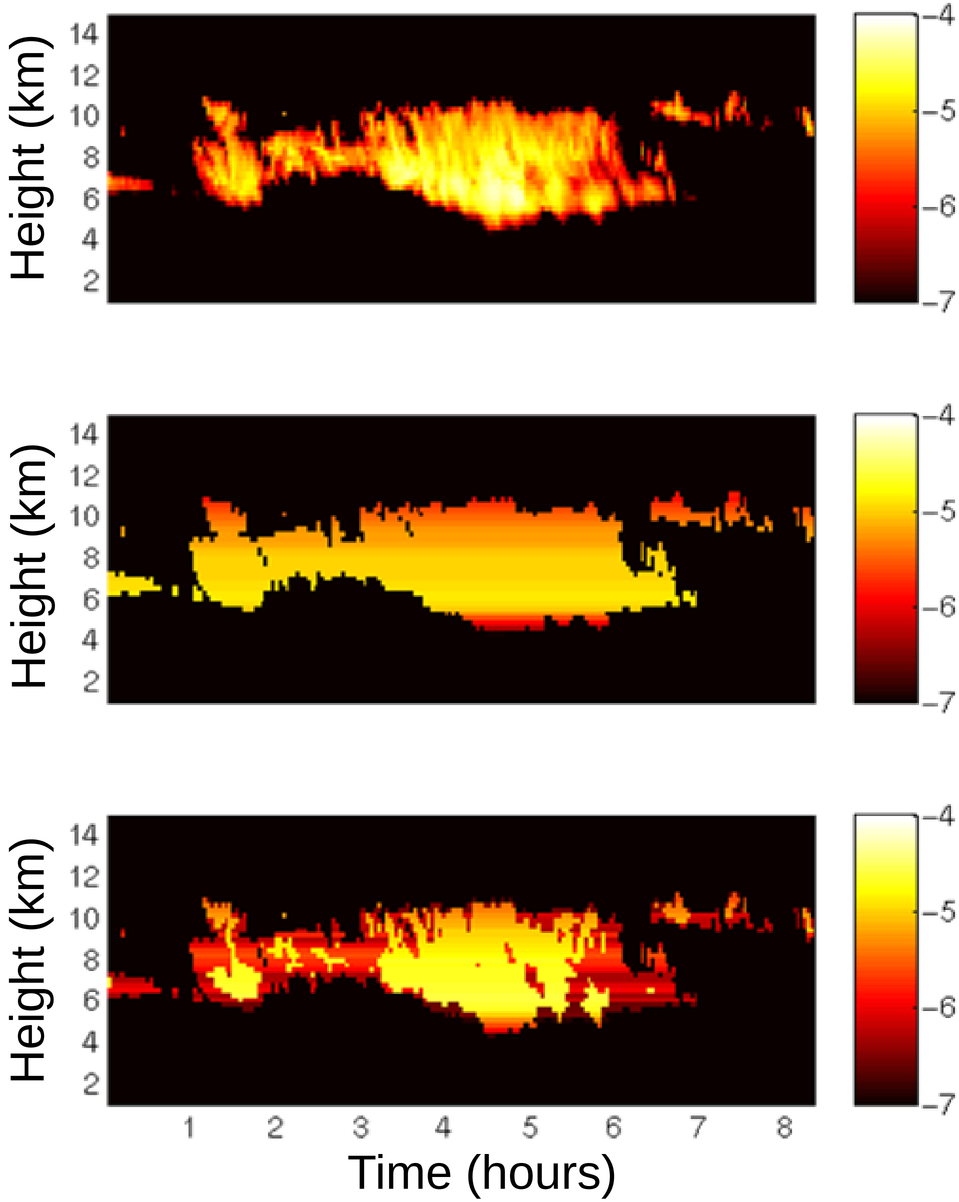
100-km boxes

Example from MODIS



- 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

Representing cloud structure: Tripleclouds



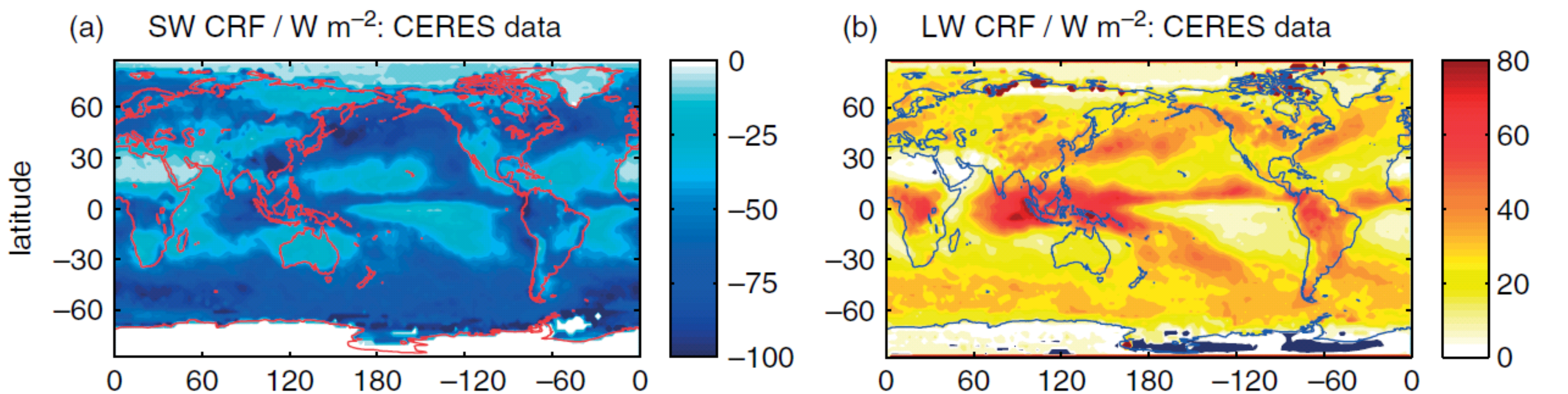
- Ice water content from Chilbolton radar, $\log_{10}(\text{kg m}^{-3})$
- Plane-parallel approx:
  - 2 regions in each layer, one clear and one cloudy
- "Tripleclouds":
  - 3 regions in each layer
  - Alternative to McICA
  - Uses Edwards-Slingo capability for stratiform/convective regions for another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

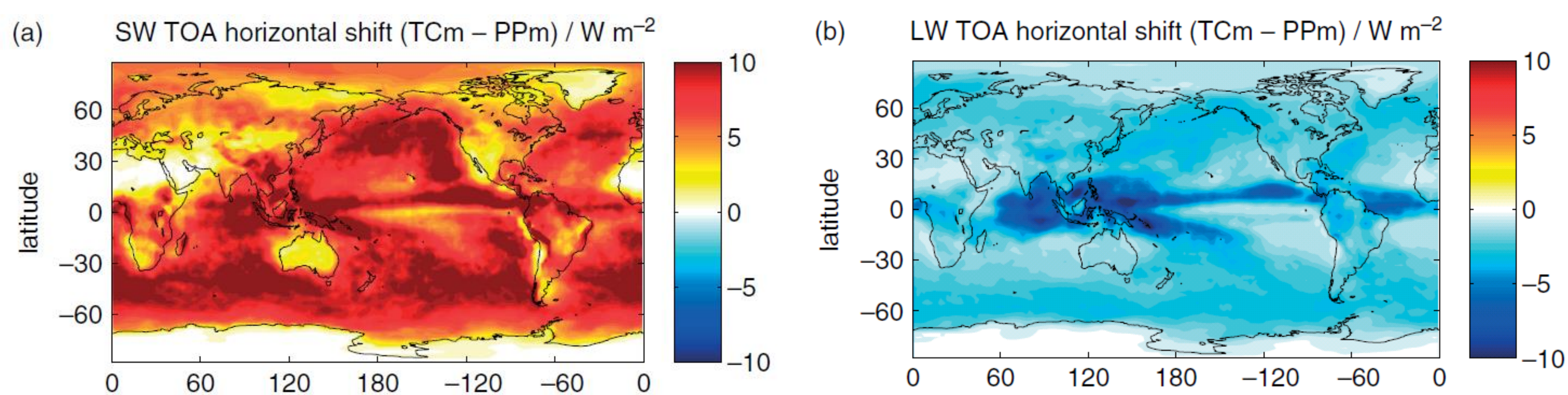
Shonk and Hogan (JClim 2008)

Global impact of cloud structure

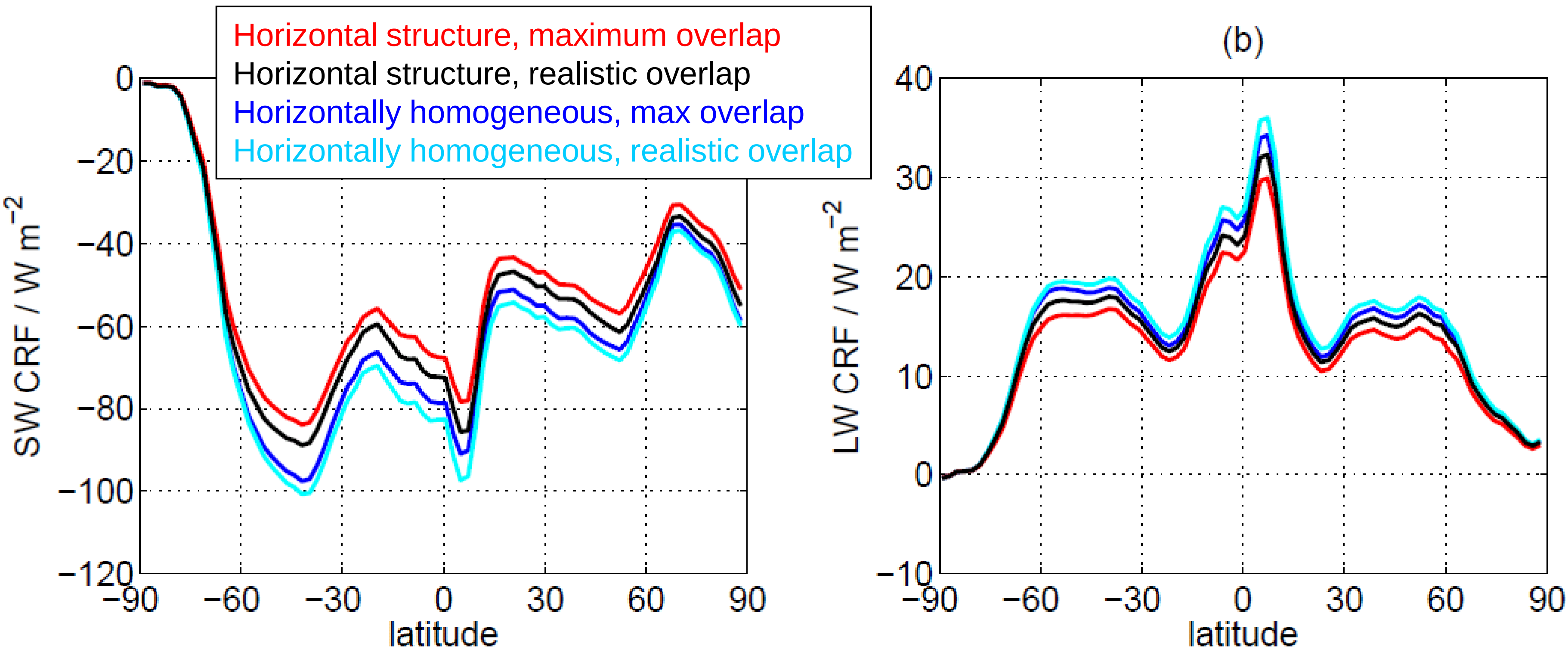
Shonk and Hogan (2010)

- 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:





Horizontal versus vertical structure



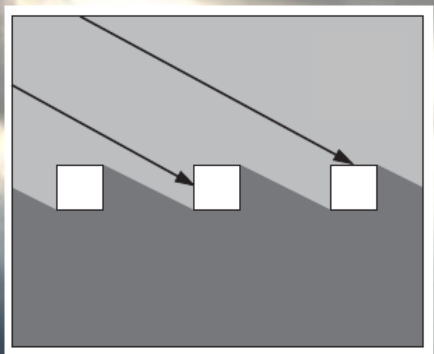
- Correcting cloud structure changes cloud radiative effect by around 10%
- Impact of adding horizontal structure about twice that of improving vertical overlap
- Note that uncertainties in the horizontal structure effect are much larger than in the vertical overlap effect

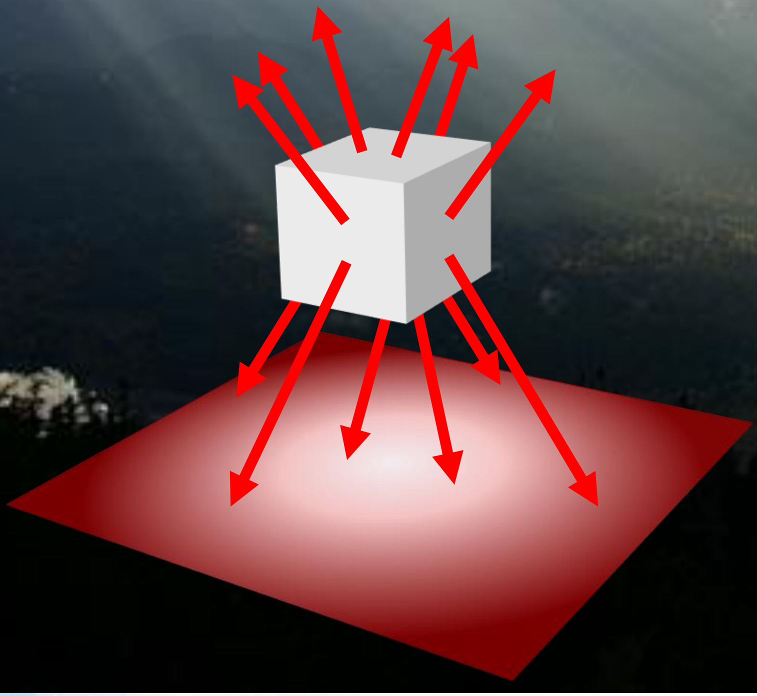
Part 5: Remaining challenges

- Improve efficiency
  - Radiation schemes often the slowest part of the model, so may be 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
  - Non-local-thermodynamic equilibrium for high-top models
  - Cloud inhomogeneity information from cloud scheme
  - Consistent radiative treatment in forests and urban areas
  - *Three dimensional radiative transfer in presence of clouds*

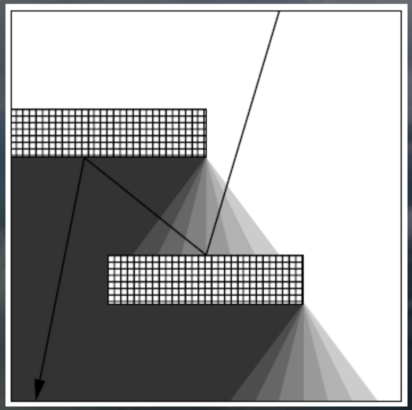
Errors due to neglecting 3D effects

- **Shortwave side illumination**
  - Strongest when sun near horizon
  - Increases chance of sunlight intercepting cloud





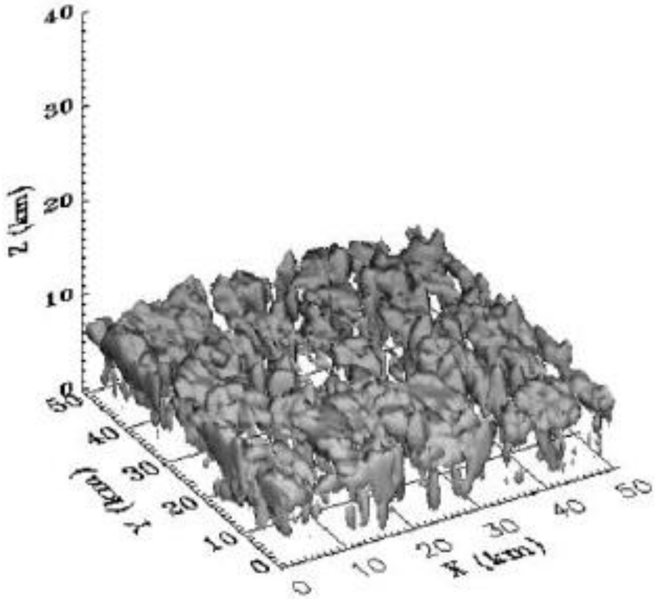
- **Shortwave entrapment**
  - Horizontal transport beneath clouds makes reflection to space less likely

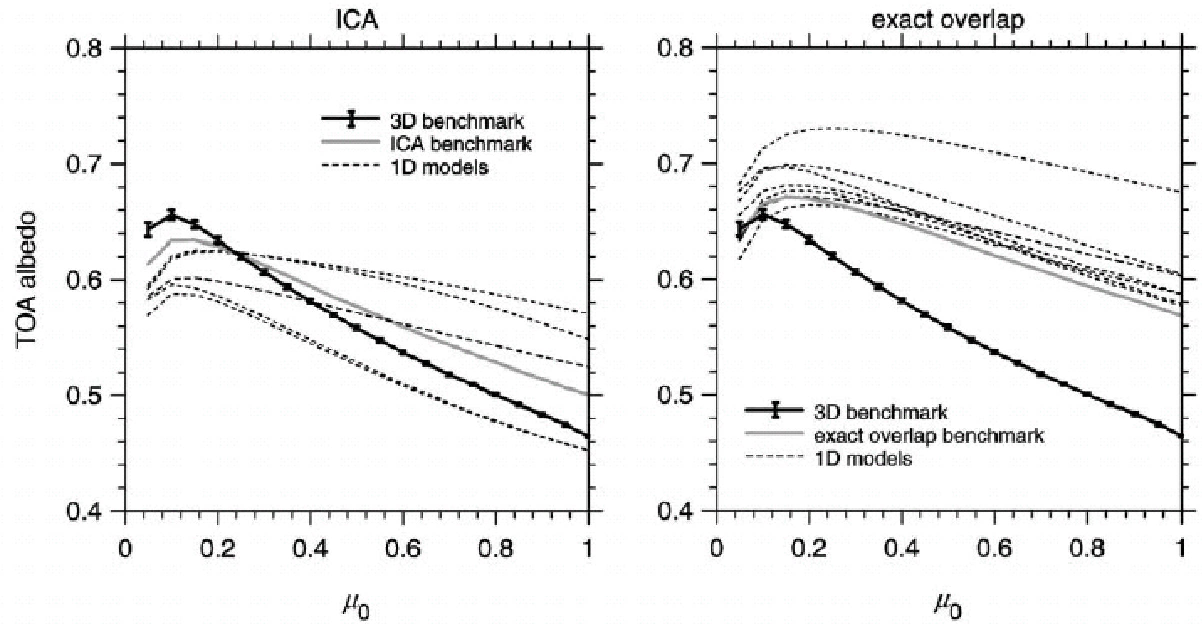


- **Longwave effect**
  - Radiation can now be emitted from the side of a cloud
  - 3D effects can increase surface cloud forcing by a *factor of 3* (for an isolated, optically thick, cubic cloud in vacuum!)

3D cloud benchmark

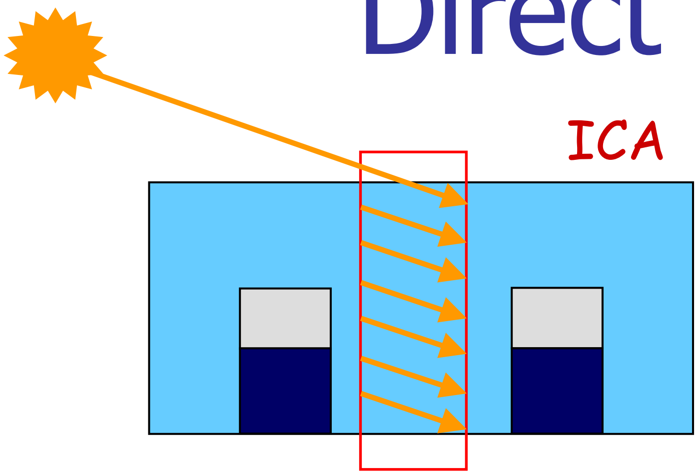
- Large spread in 1D models, whether used in ICA mode or with cloud-fraction scheme Barker et al. (JClim 2003)



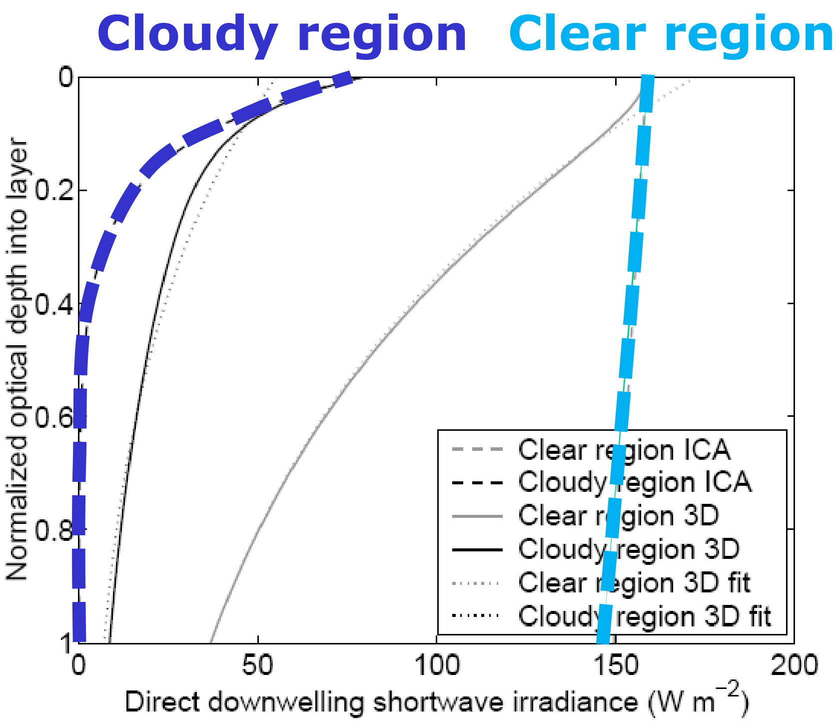


How can we represent this effect in GCM radiation schemes?

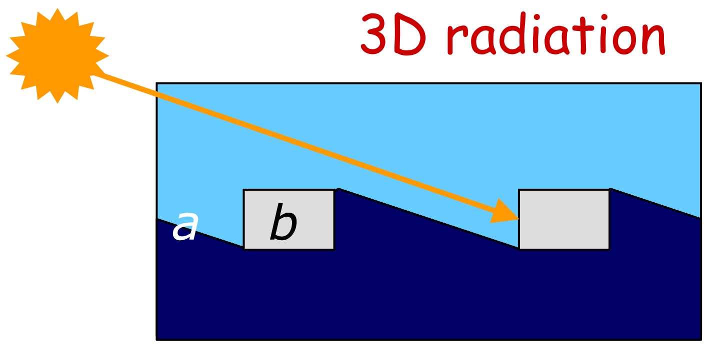
Direct shortwave calculation



- 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

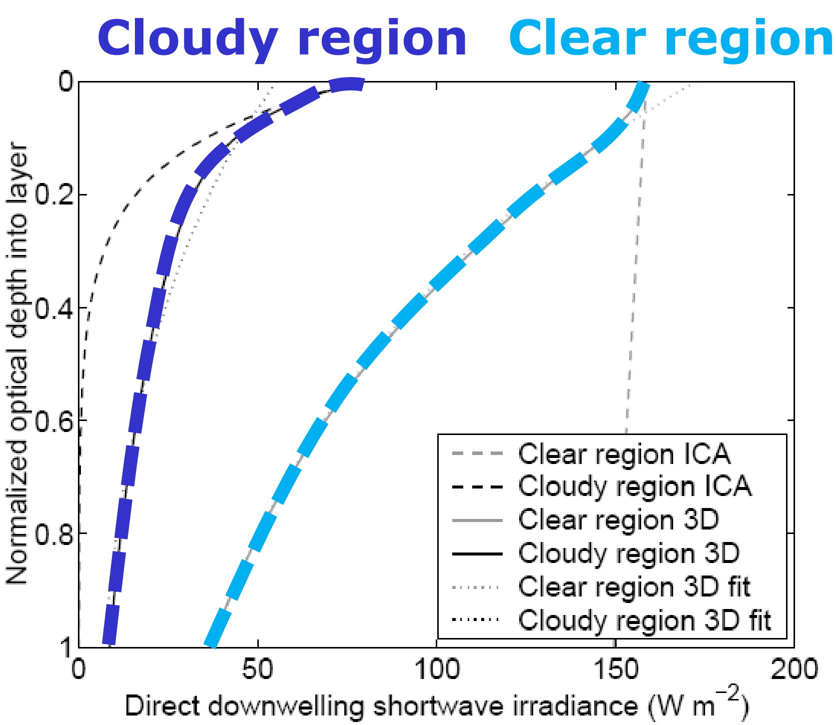


- *Alternative: add terms expressing exchange between regions a & b:*

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

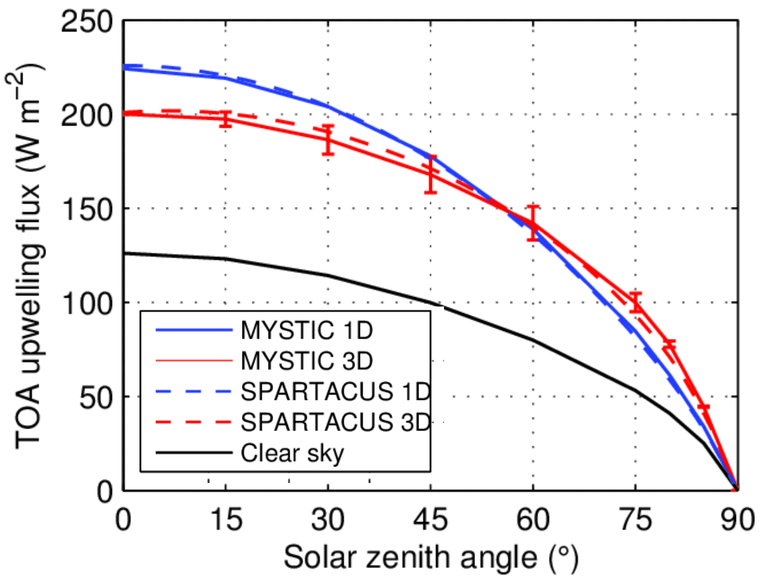
$$\frac{dF^b}{d\delta'} = -\frac{\delta^b}{\mu_0}F^b - f_{\mathrm{dir}}^{ba}F^b + f_{\mathrm{dir}}^{ab}F^a$$

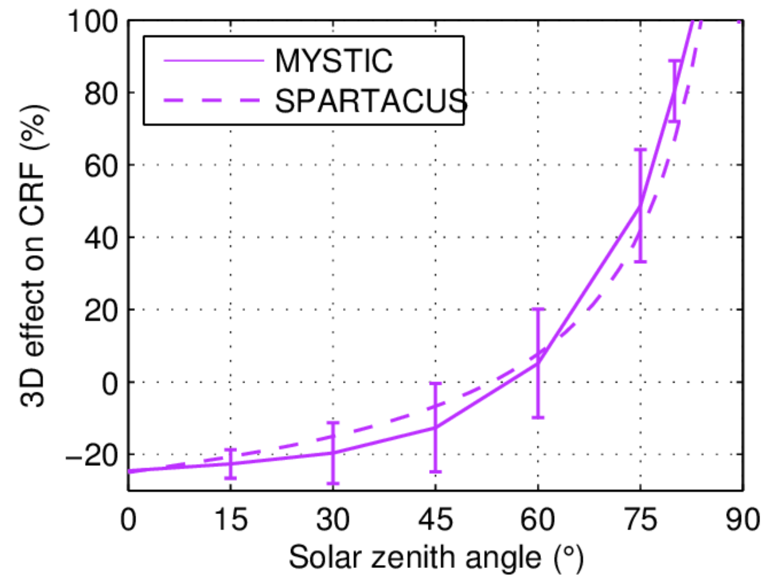
  - New terms depend on geometric constants f^{ab} and f^{ba}
  - Solution more complicated!
  - Result: much less radiation gets through to next atmospheric layer!



Evaluation of fast 3D scheme

- New solver implementing these ideas: SPARTACUS (Speedy algorithm for radiative transfer through cloud sides)
- Compare to full 3D Monte Carlo calculation in cumulus
  - *Mean of 4 solar azimuths, error bar indicates standard deviation due to sun orientation*



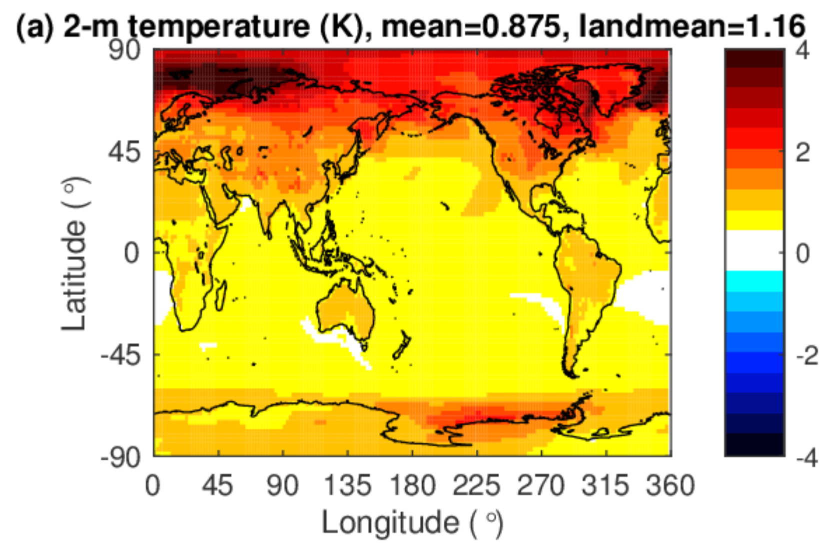


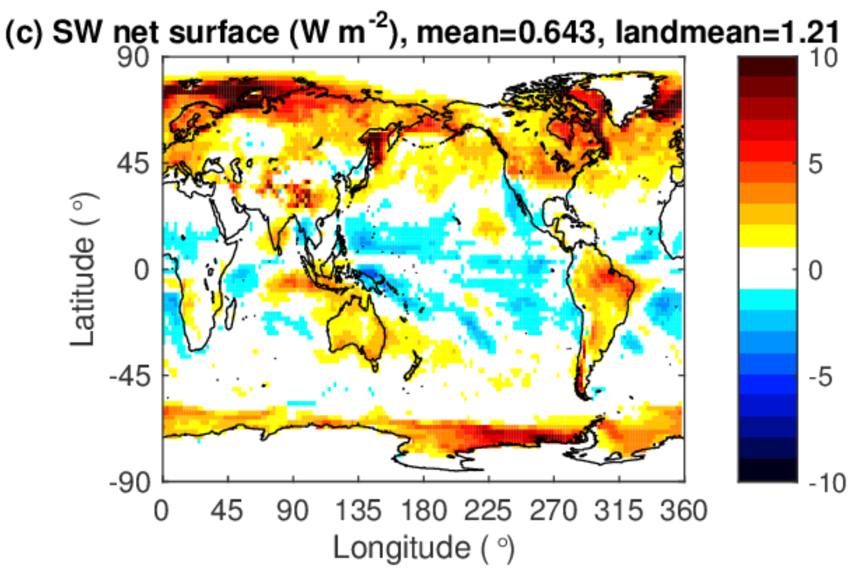
- Good match!
- 3D effect up to 20 W m^{-2}, similar to inhomogeneity effect

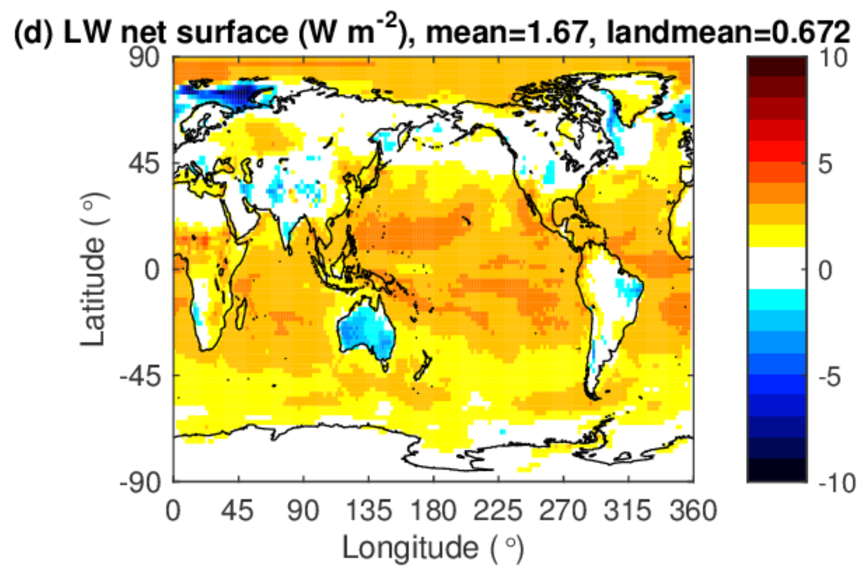
Hogan et al. (JGR 2016)

Estimate of global impact of 3D radiation

- Compare 20-year coupled IFS (constant 2000 gas & aerosol) with and without 3D effects
- Surface shortwave and longwave changes both act to warm the surface
- Land warms by over 1 K







Summary so far

- Complex absorption spectra arise due to quantum mechanics
  - Discrepancies remain between models, especially in representing the water vapour continuum and stratosphere/mesosphere infrared cooling rates
  - The correlated-k-distribution is the state-of-the-art for representing gaseous absorption spectra in models
- Observations of clouds from cloud radar have had a significant impact on the way they are represented in radiation schemes
  - Significant errors still remain, e.g. representation of 3D effects
  - Challenge to know whether we are allocating our computational resources wisely

- *Next lecture: what we currently implement in the ECMWF radiation scheme*