Fast radiative transfer models and the representation of clouds

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Contributions from:

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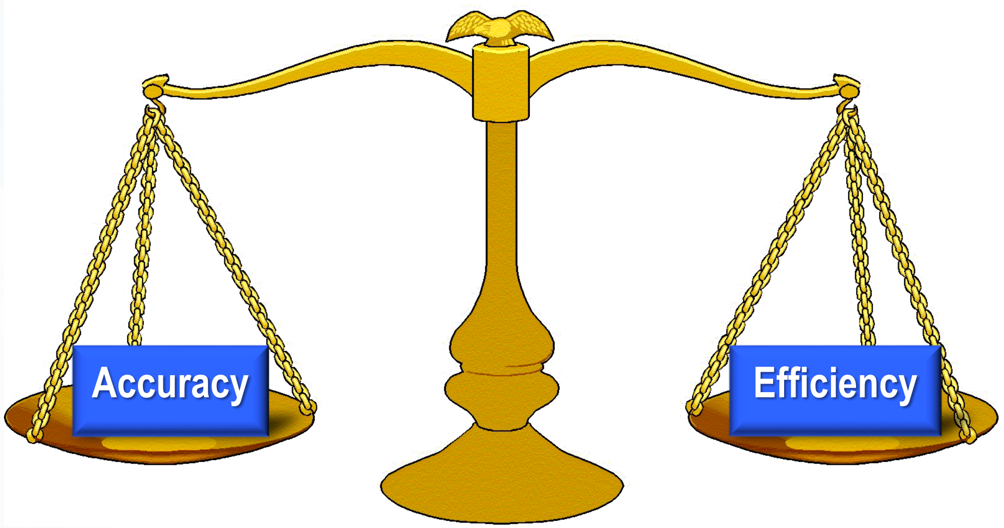
and numerous others

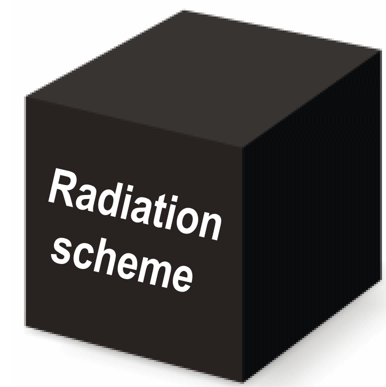
Overview

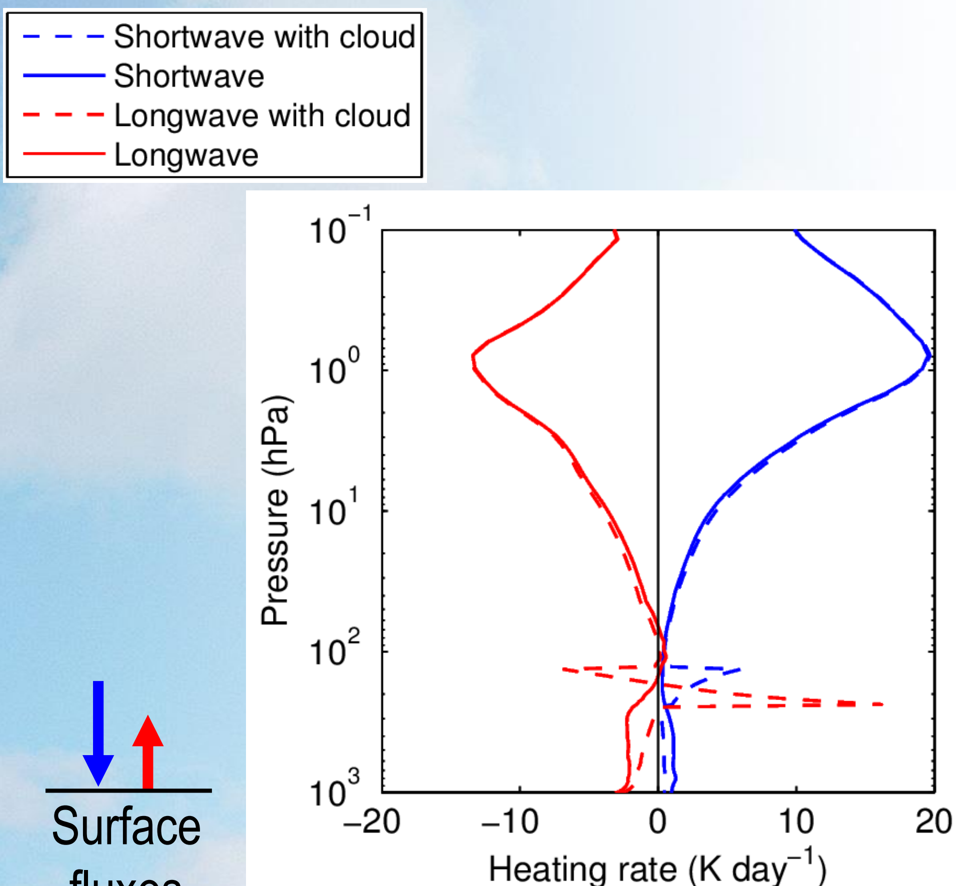
- From Maxwell to the two-stream equations
- The challenge of cloud structure
- Representing 3D effects
- Mitigating errors due to calling radiation infrequently in time and space
- Reducing the number of spectral intervals
- Outlook



What does a radiation scheme do?

- *Input profile:* temperature, pressure, gas concentrations, cloud properties…



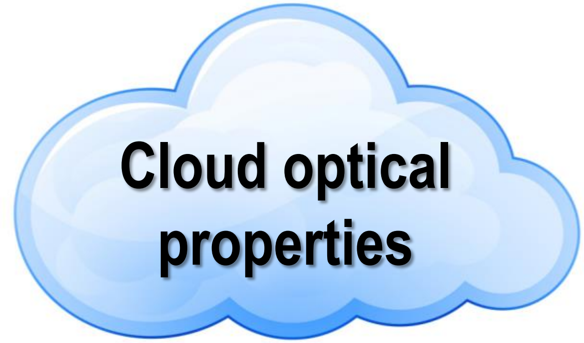


Surface fluxes

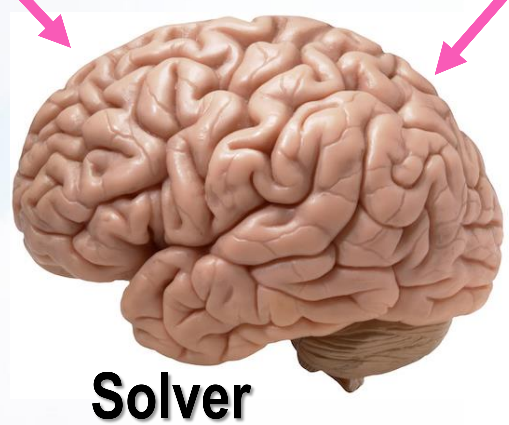
- *A term in the model's thermodynamic equation*

Clouds tend to destabilize the atmosphere

The four components of a radiation scheme



- *Determines spectral resolution*
- RRTM-G uses 252 spectral intervals



- *Determines how sophisticated interactions with clouds will be*

- Codes should be *modular*, allowing components to be changed independently

Theories of light propagation and scattering

Particle theories

- Ibn al-Haytham (1021) – *vision*
- Newton (1710) – *colour*
- Planck (1901) – *black-body radiation*
- Einstein (1905) – *photo-electric effect*

Wave theories

~ Huygens (1690) – *refraction, reflection*

~ Young (1801) – *double-slit experiment*

~ Fresnel (1821) – *polarization, diffraction*

~ Maxwell (1873) – *electricity & magnetism*

Radiative transfer

→ Lommel (1887) – *radiative transfer equation*

→ Schuster (1905) – *two-stream equations*

→ Chandrasekhar (1946) – *full 3D radiative transfer equation with polarization*

Mishchenko et al. (2002)

Quantum electrodynamics

Fenyman, Schwinger, Tomonaga, Dyson (1946-1949)

– *Lamb shift, magnetic moment of electron*

– *Describes all known properties of EM radiation exactly*

?

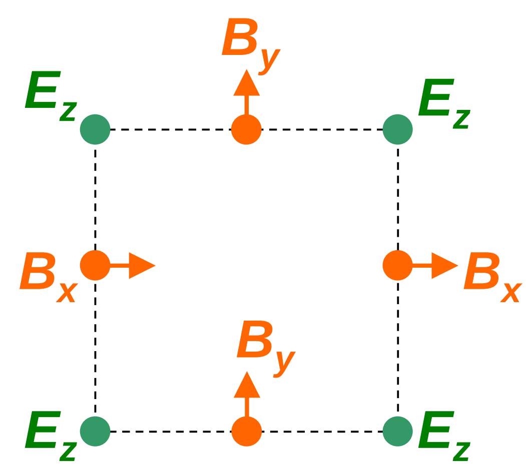
Optical phenomena explained by Maxwell's equations

- Need quantum mechanics to explain emission and absorption




- All other atmospheric optics explained by electromagnetic radiation exciting a dipole in a dielectric material which then re-radiates
  - Described by Maxwell's curl equations + Newton's 2nd law for bound charges
- Illustrated with an "Electromagnetic Weather Forecast"
  - Gridsize 0.02 μm and timestep 50 picoseconds

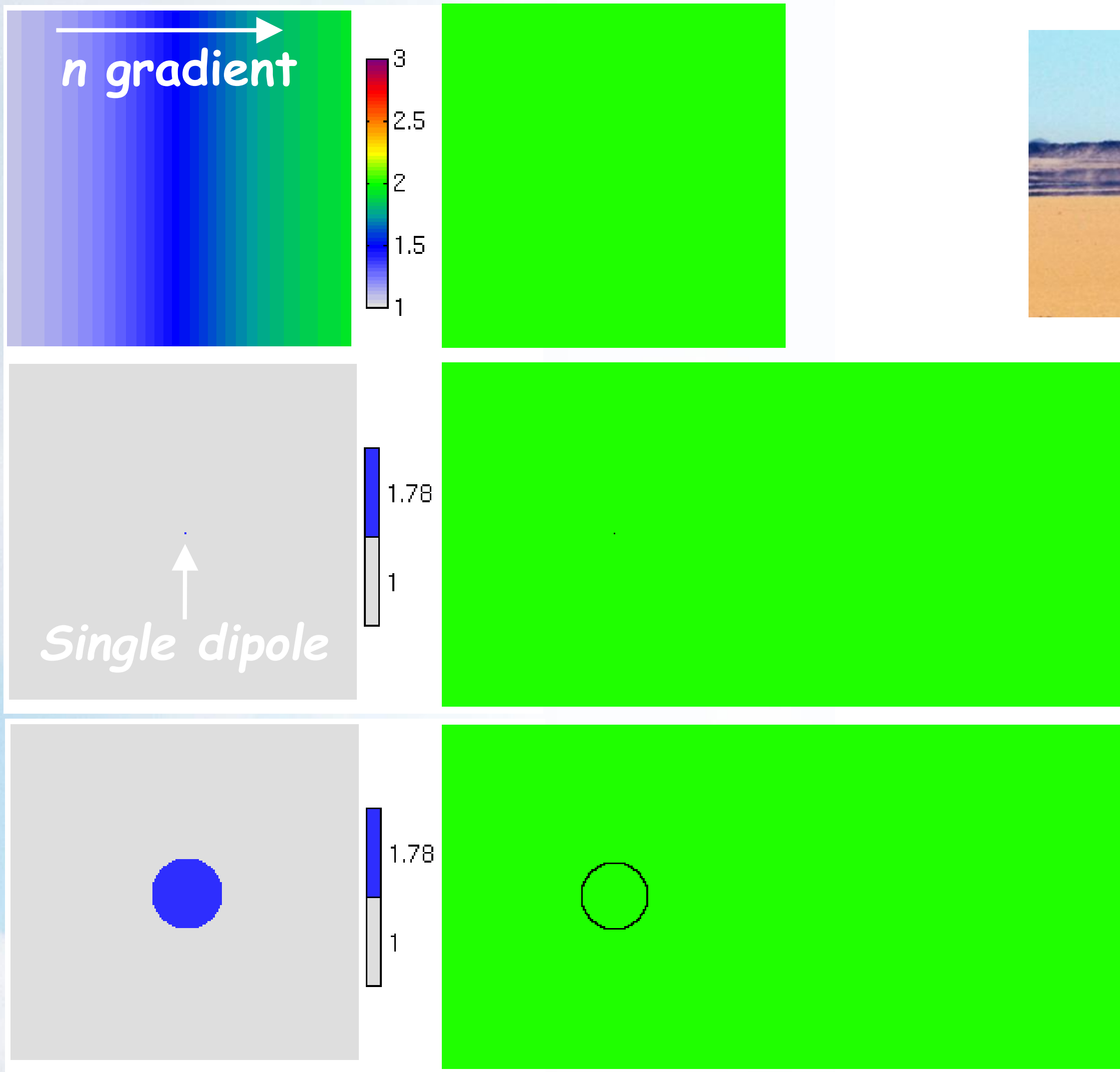
$$\frac{\partial \mathbf{E}}{\partial t} = \frac{c^2}{n^2} \nabla \times \mathbf{B} \qquad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

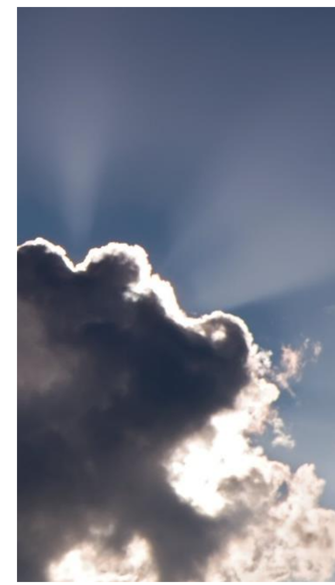


Staggered grid in time and space (Yee 1966)

The Electromagnetic Weather Forecast

- Refraction
  (a mirage)
- Rayleigh scattering
  (blue sky)
- A sphere
  (silver lining)

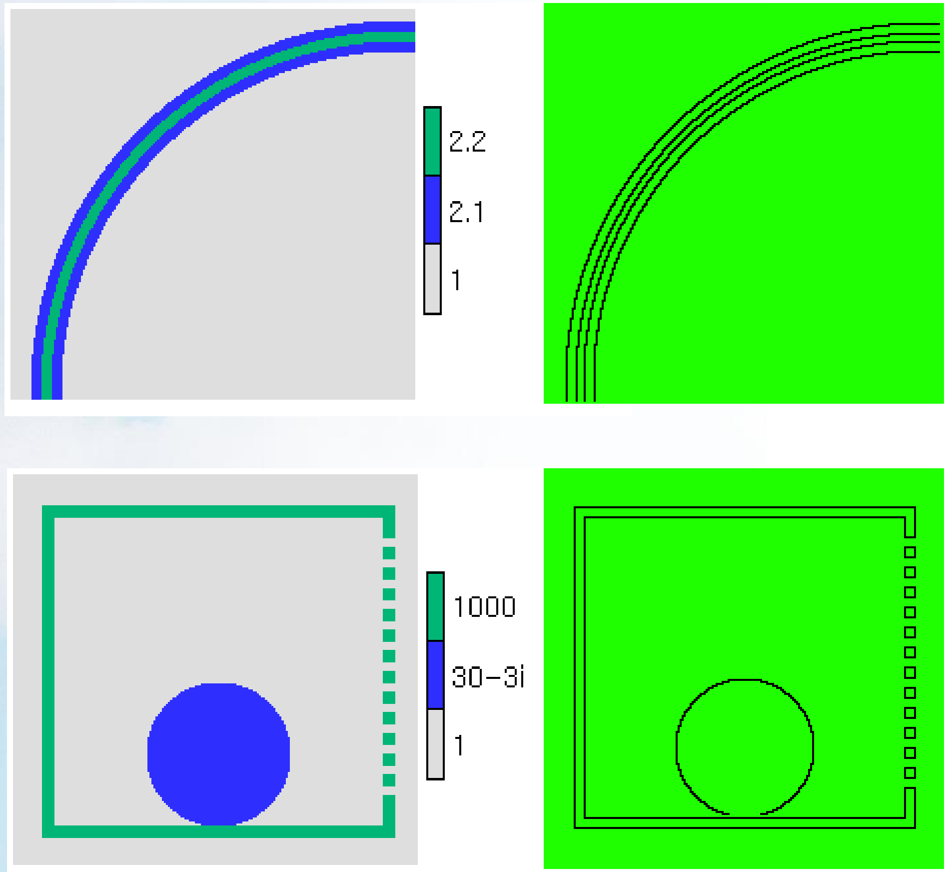




Refractive index Total E_z field Scattered field

Non-atmospheric examples

- Single-mode optic fibre
- Potato in a microwave oven

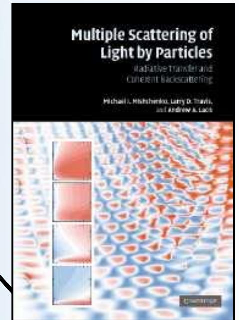


Refractive index **Total E_z field**

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

From Maxwell… …to the two-stream equations

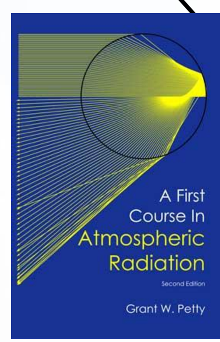
Maxwell's equations in terms of fields **E**(**x**,*t*), **B**(**x**,*t*)



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
  - No diffraction around features larger than individual particles

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

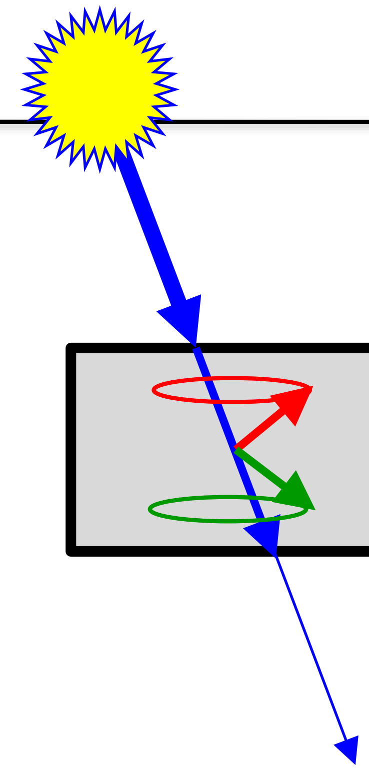


Petty (2006)

- Unreasonable assumptions:
  - Diffuse radiances in all directions represented by only 2 discrete directions
  - Atmosphere within a model gridbox is horizontally infinite and homogeneous
  - Details of the phase functions represented by one number, the asymmetry factor

1D radiative transfer in terms of two monochromatic fluxes $F^{\pm}(z,\nu)$

Two-stream equations (shortwave)



- Direct downwelling: $$\frac{dF^0}{dz} = \frac{\beta_e}{\mu_0} F^0$$
- Diffuse upwelling: $$\frac{dF^+}{dz} = \beta_e(-\gamma_1 F^+ + \gamma_2 F^- + \gamma_3 F^0)$$
- Diffuse downwelling: $$\frac{dF^-}{dz} = \beta_e(\gamma_1 F^- - \gamma_2 F^+ - \gamma_4 F^0)$$
- Or write in matrix form:

$$\frac{d}{dz}\mathbf{f} = \boldsymbol{\Gamma}\mathbf{f} \qquad \text{where} \qquad \mathbf{f} = \begin{pmatrix} F^0 \\ F^+ \\ F^- \end{pmatrix}$$

- In the longwave, no F^0 term and add Planck function on right-hand-side

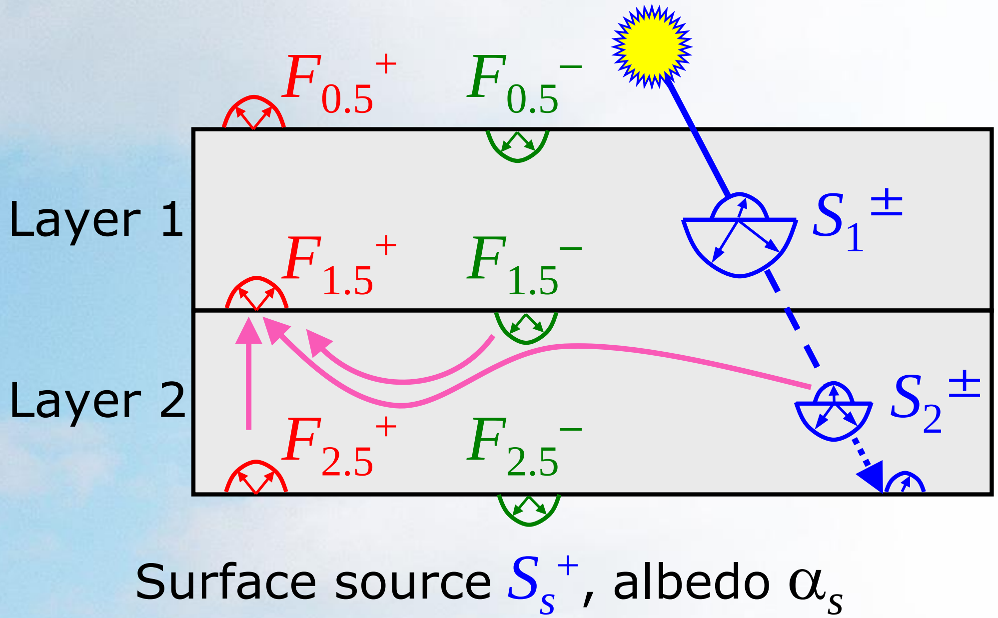
Solving the two-stream equations in a single layer

- For a homogeneous layer of thickness z_1 the general solution is:

$$\mathbf{f}(z_1) = \mathrm{e}^{\boldsymbol{\Gamma} z_1}\mathbf{f}(0)$$

where $\mathrm{e}^{\boldsymbol{\Gamma} z_1}$ is a *matrix exponential* (a 3x3 matrix)

- In the 3x3 case, analytic formulas exist for each element, from which can get diffuse reflection *R* and transmission *T* of layer (Meador & Weaver 1980)



Extension to multiple layers

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

Solution for two-level atmosphere

- Solve the following tri-diagonal system of equations

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

Top-of-atmosphere

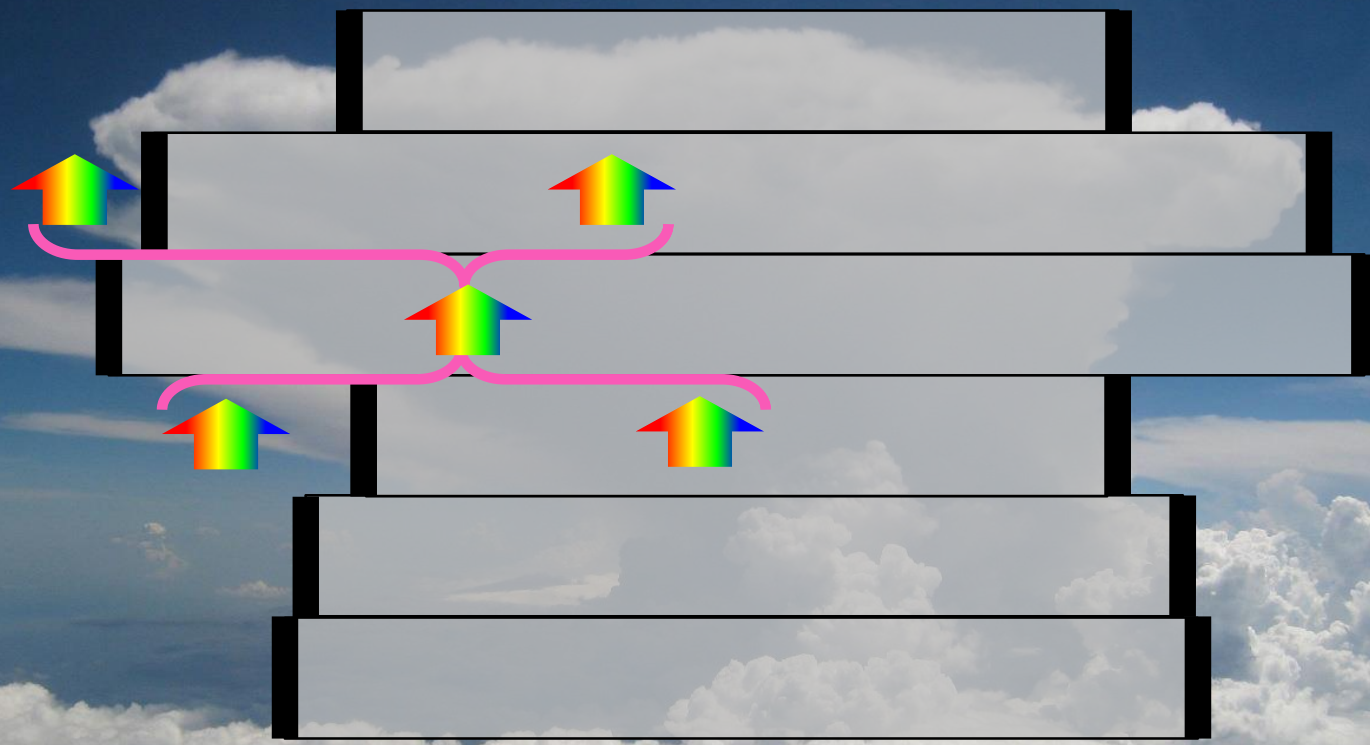
Surface

- Efficient to solve and simple to extend to more layers
  - Can't use Thomas's algorithm due to possible zeros on the diagonal
- Solution to this system is exactly equivalent to the *adding method*:
  - Gaussian elimination ≡ moving up through atmosphere & computing total albedo below each level
  - Backsubstitution ≡ moving down through atmosphere & computing fluxes from these total albedos

How do we compute how this interacts with radiation?

Plane-parallel, maximum-random overlap

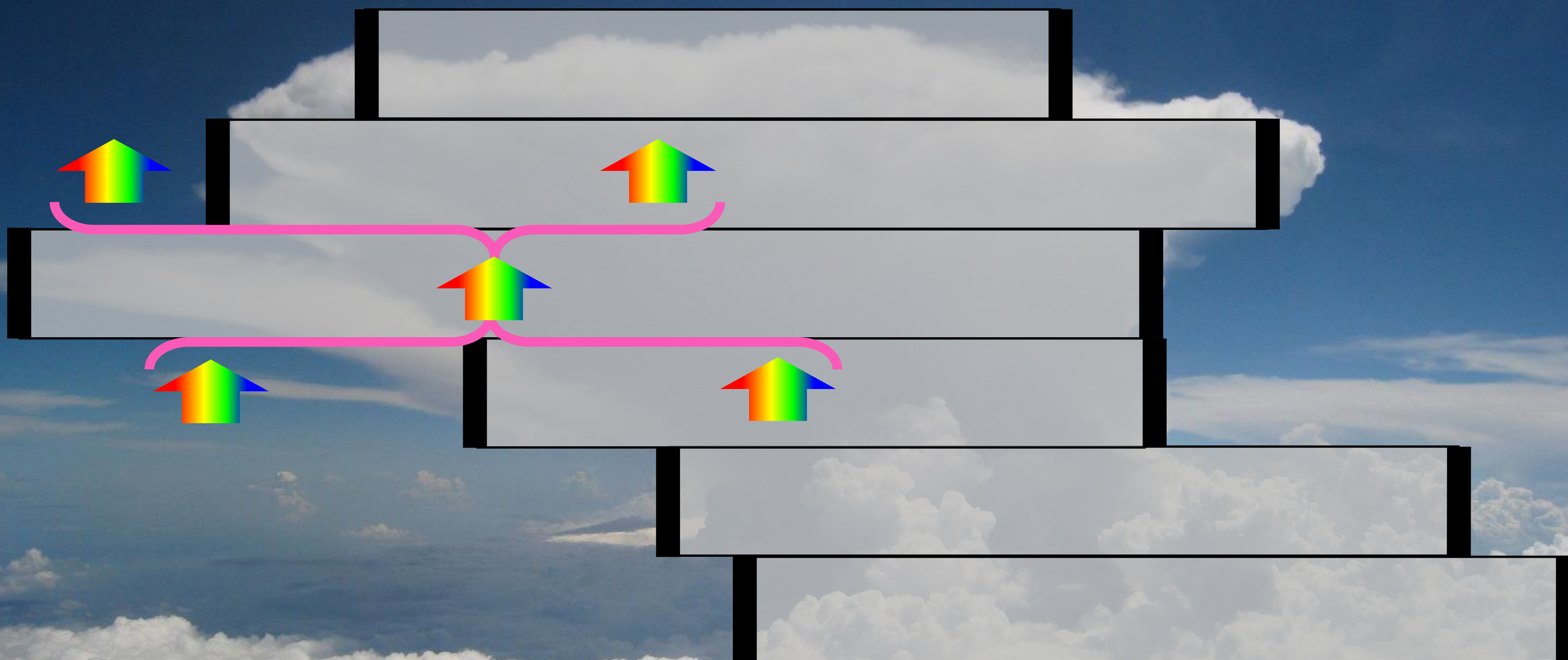
- Most models circa 2000



- *Model variables needed:* cloud fraction, water content
- Reflection & transmission computed for clear & cloudy regions separately
- Fluxes merged at layer interfaces according to cloud fraction

Realistic overlap

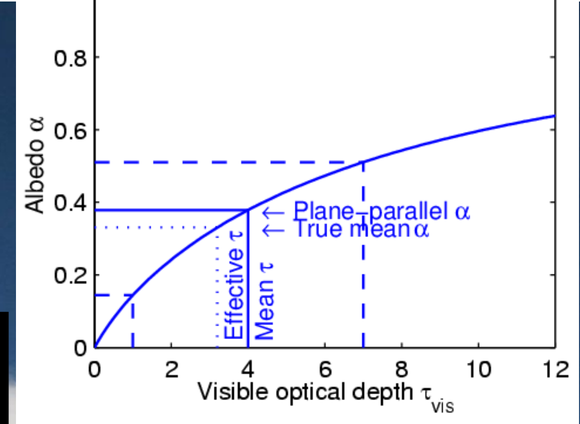
- Increases cloud cover and hence cloud radiative effect



- *Extra input:* **overlap decorrelation length** from cloud radar ~2 km
  - Ground-based (Hogan & Illingworth 2000, Mace & Benson-Troth 2002)
  - CloudSat (Barker 2008, Shonk et al. 2010)

Tripleclouds (Shonk & Hogan 2008)

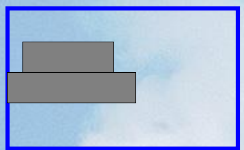
- Cloud structure *reduces* cloud radiative effect



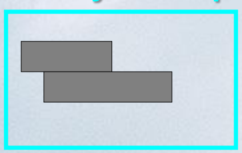
- **Cloud water fractional standard deviation** ~0.75
  - Satellite & cloud radar (Barker, Shonk, Cahalan, Oreopoulos, Rossow…)
- **Cloud water overlap decorrelation length** ~1 km
  - Ground-based cloud radar (e.g. Hogan & Illingworth 2003)

Global impact of cloud inhomogeneity and overlap

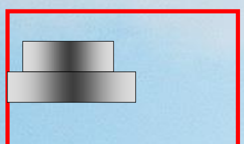
Plane-parallel, maximum-random



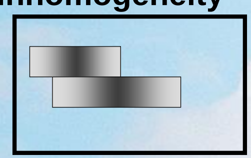
Fix only overlap



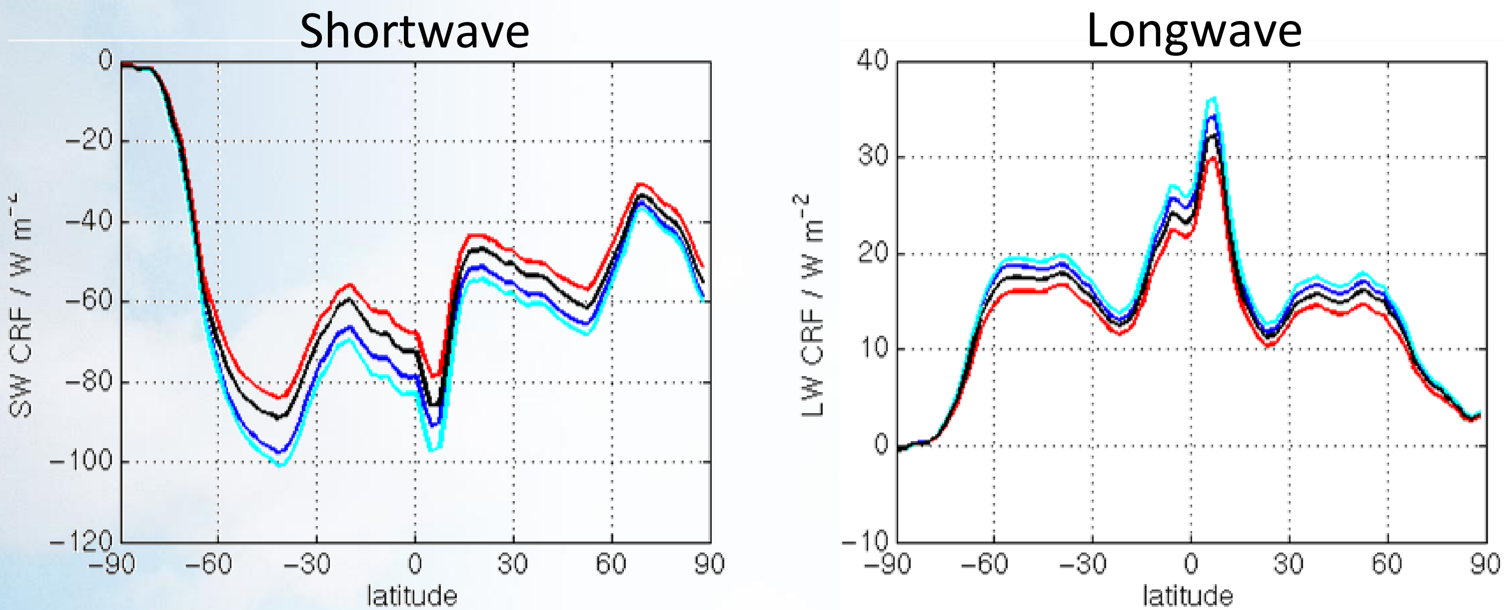
Fix only inhomogeneity



Fix overlap and inhomogeneity



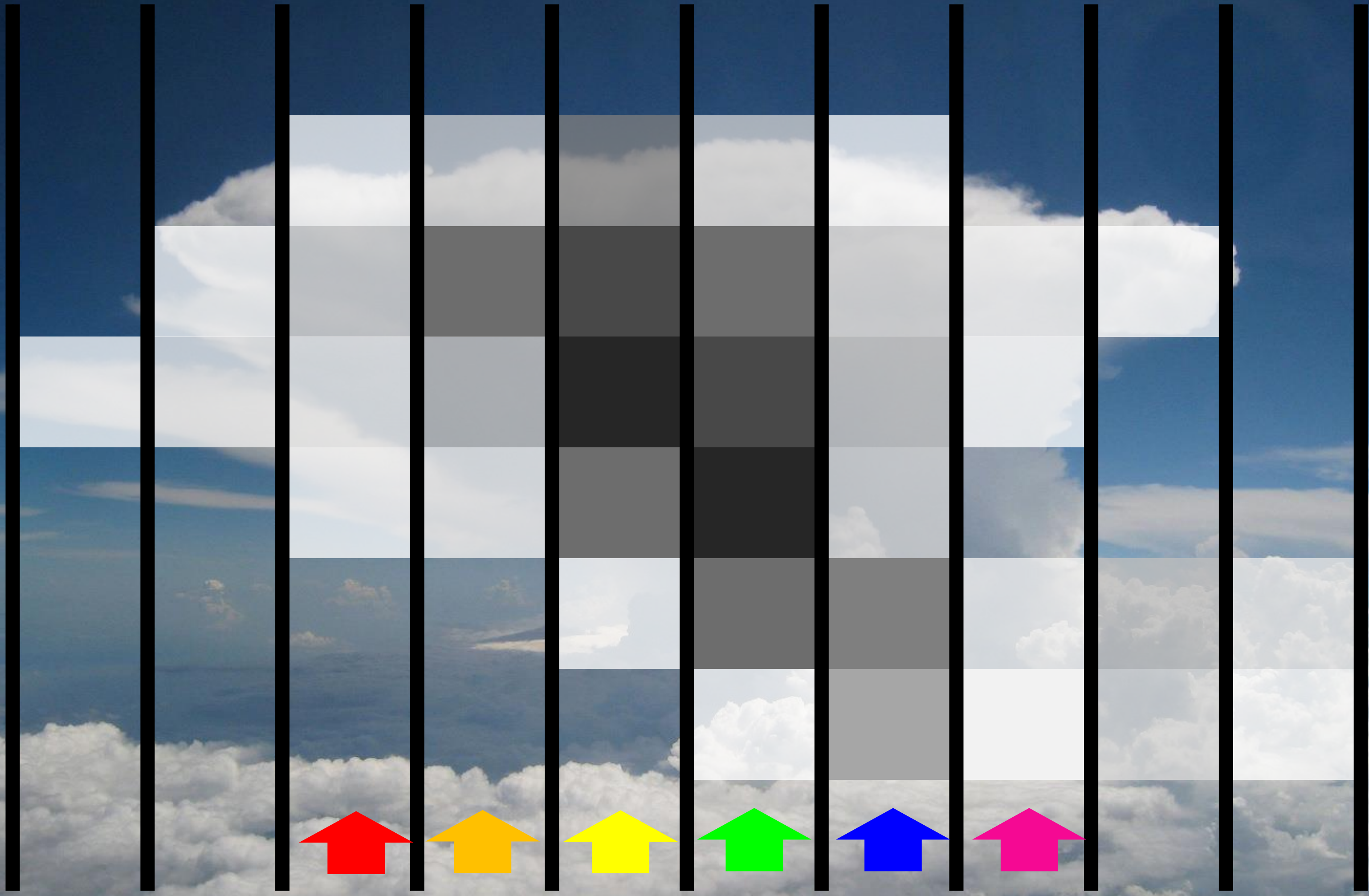
Top-of-atmosphere cloud radiative forcing



- 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*

Shonk & Hogan (2010)

Monte-Carlo Independent Column Approximation (McICA) – Pincus et al. (2005)



- Info required similar to Tripleclouds but computationally a little faster
- Use of stochastic cloud generator leads to some noise in fluxes
- Now used in many (most?) global weather and climate models

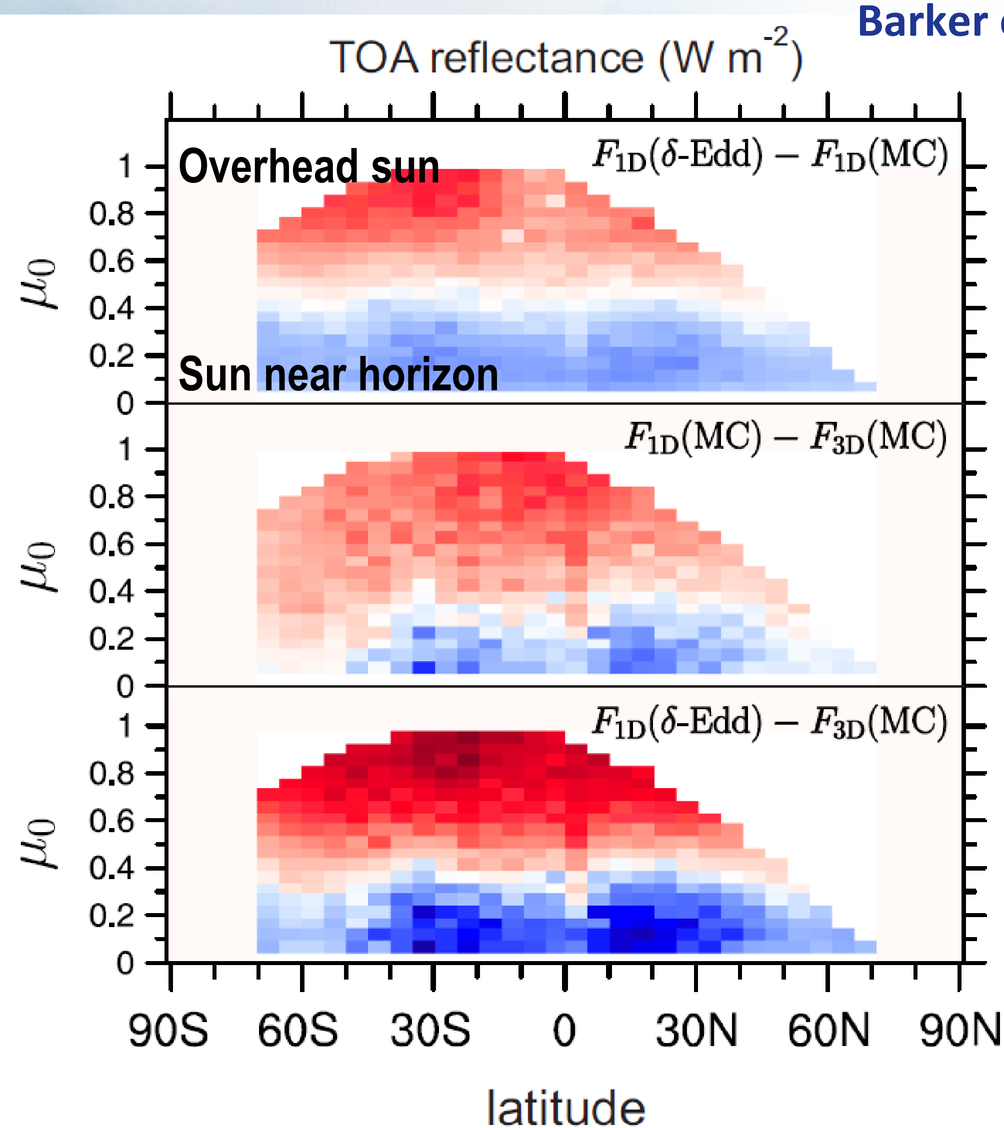
Full Monte Carlo (being investigated by Barker et al.)

- *"It's better to solve the right problem approximately than the wrong problem exactly," or "random errors are better than biases."*

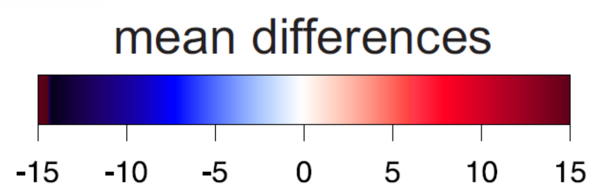
- **Use 3D cloud distribution generated by a stochastic model in each gridbox**
- How many light rays are needed for random errors to be tolerable? 500?
  - *NWP models can tolerate random errors less than climate models*
- Monte Carlo at least provides good benchmark for approximate schemes

Shortwave errors due to 2-stream and 1D approximations

Barker et al. (in press 2015) using A-Train scenes

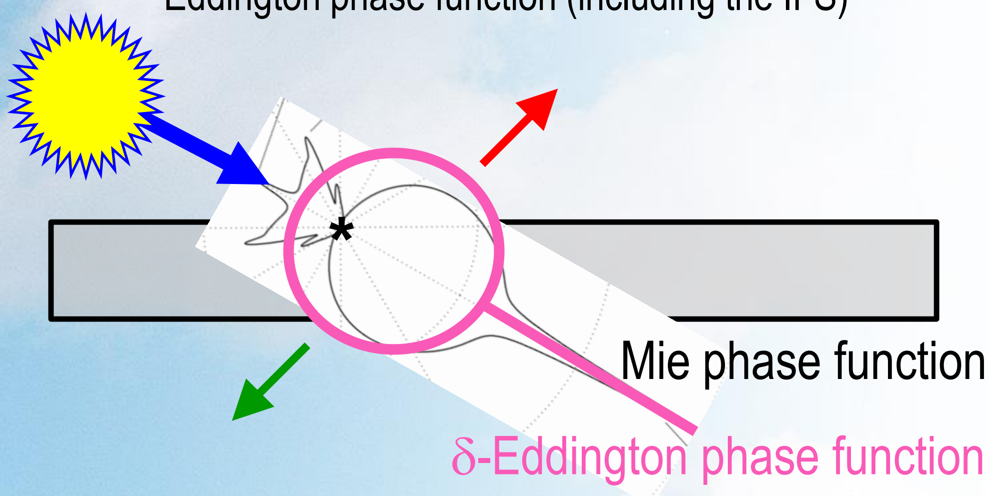


- Error due to only 2 streams
  - 2 streams minus infinite streams
  - Up to around 10% of cloud radiative effect
- Error due to neglecting 3D effects
  - 1D minus 3D
  - Up to around 10% of cloud radiative effect
  - Warning! Scenes are strictly only 2D
- Error due to both assumptions
  - Errors strongly correlated

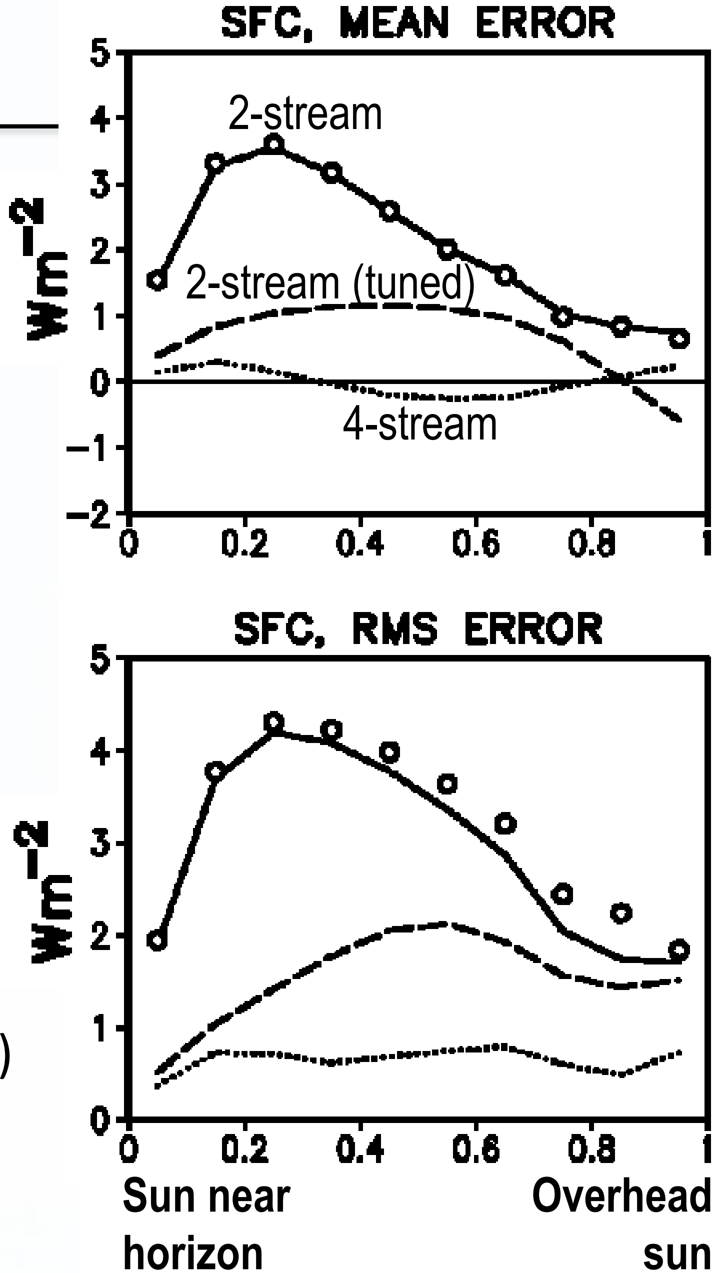


Reducing 2-stream errors

- Main problem is in *optically thin* clouds
  - Single scattering dominates, so full details of phase function needed to predict reflection/transmission at all sun angles
  - Almost all 2-stream models use the highly simplified δ-Eddington phase function (including the IFS)

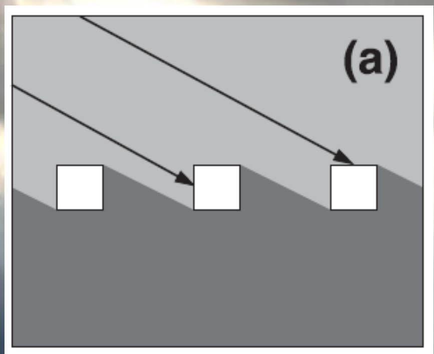


- 4 streams much more accurate (twice the cost)
- Räisänen (2002) significantly reduced error by *tuning* the 2-stream γ coefficients separately for droplets, ice crystals and aerosols

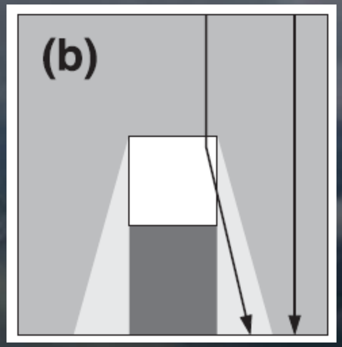


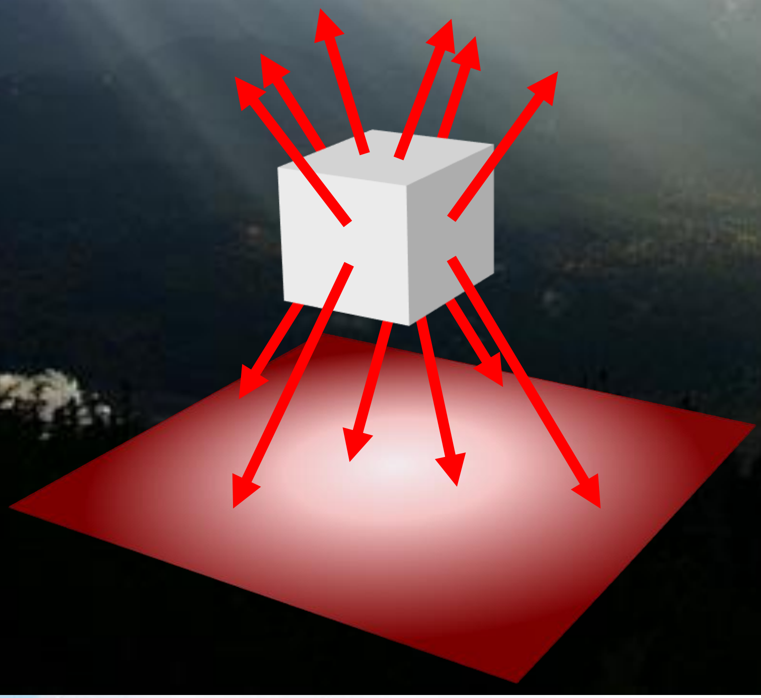
Errors due to neglecting 3D effects

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



- **Shortwave side escape**
  - Strongest when sun near zenith
  - Forward scattering leads to more sunlight reaching the ground

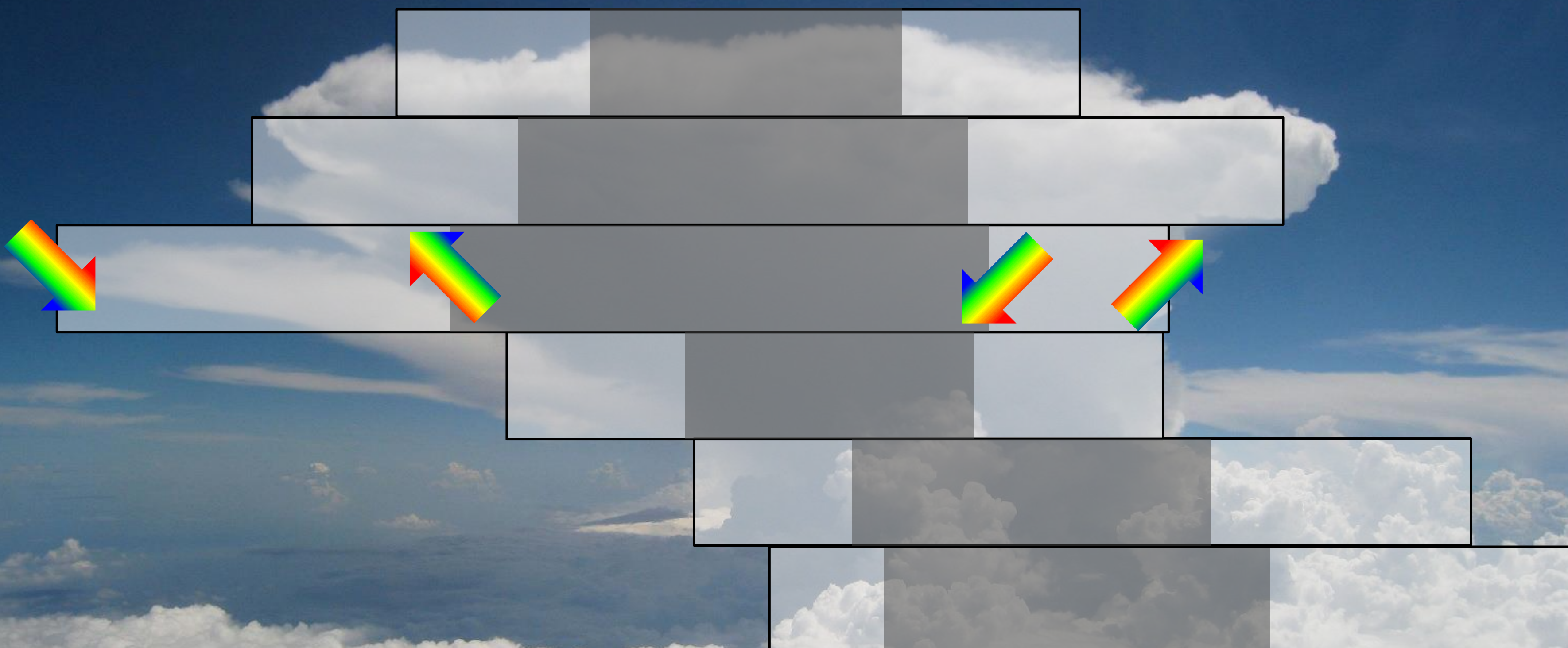




- **Longwave effect**
  - Radiation can now be emitted from the side of a cloud
  - 3D effects can increase surface cloud forcing by a *factor of 3* (for an isolated, optically thick, cubic cloud in vacuum!)

SPARTACUS (Hogan & Shonk 2014)

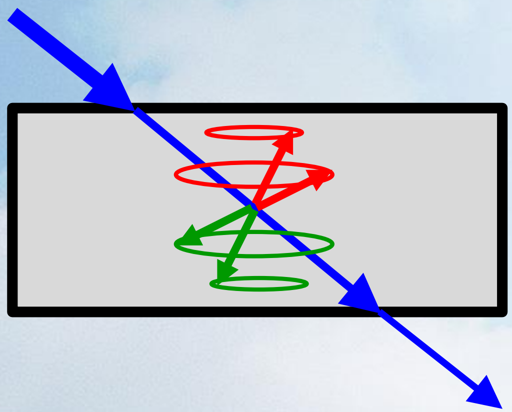
- "Speedy algorithm for radiative transfer through cloud sides"



- **Effective cloud diameter** – need more observations!
  - Stratocumulus from MODIS: ~10 km (Jensen et al. 2008)
  - Cumulus in cloud-resolving models: ~500 m (Schaefer)
  - Cumulonimbus: ~8 km (Stein et al. 2015)

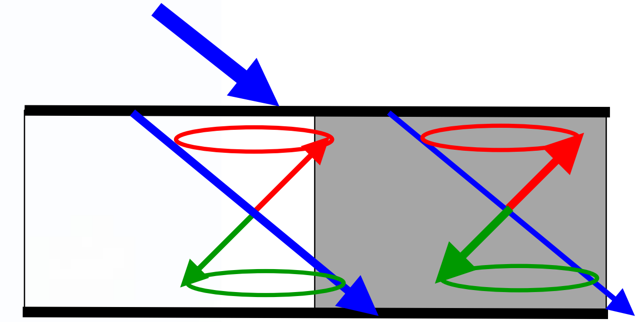
Extending the two-stream equations

- **More diffuse streams, e.g. 4**



$$\mathbf{f} = \begin{pmatrix} F^0 \\ F^1 \\ F^2 \\ F^3 \\ F^4 \end{pmatrix}$$

- **Transport through cloud sides**



$$\mathbf{f} = \begin{pmatrix} F^{a0} \\ F^{b0} \\ F^{a+} \\ F^{b+} \\ F^{a-} \\ F^{b-} \end{pmatrix}$$

- Rates of exchange between streams can be calculated from the scattering phase function

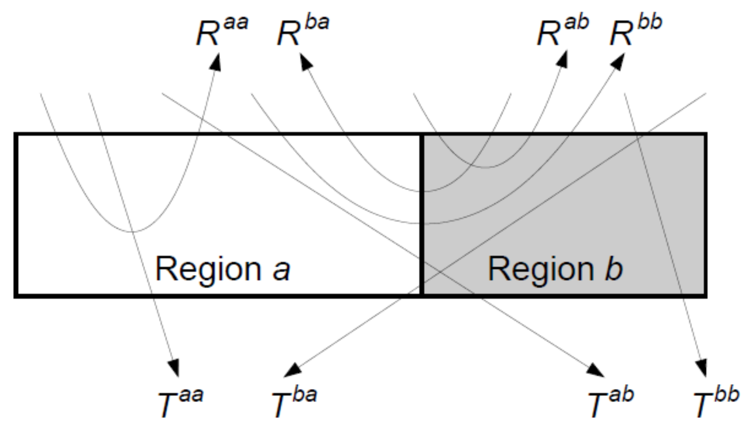
- Exchange between regions calculated from *effective cloud diameter* (Hogan & Shonk 2014)
- Use 3 regions (2 cloudy) to capture cloud inhomogeneity (Shonk & Hogan 2008)

- In both cases we have the same equation and solution as before: $\frac{d}{dz}\mathbf{f} = \mathbf{\Gamma}\mathbf{f} \longrightarrow \mathbf{f}(z_1) = e^{\mathbf{\Gamma} z_1}\mathbf{f}(0)$

Extending the two-stream equations

- Reflectance and transmittance of a layer are now matrices **R** and **T**:

$$\mathbf{T} = \begin{pmatrix} T^{aa} & T^{ba} \\ T^{ab} & T^{bb} \end{pmatrix}$$

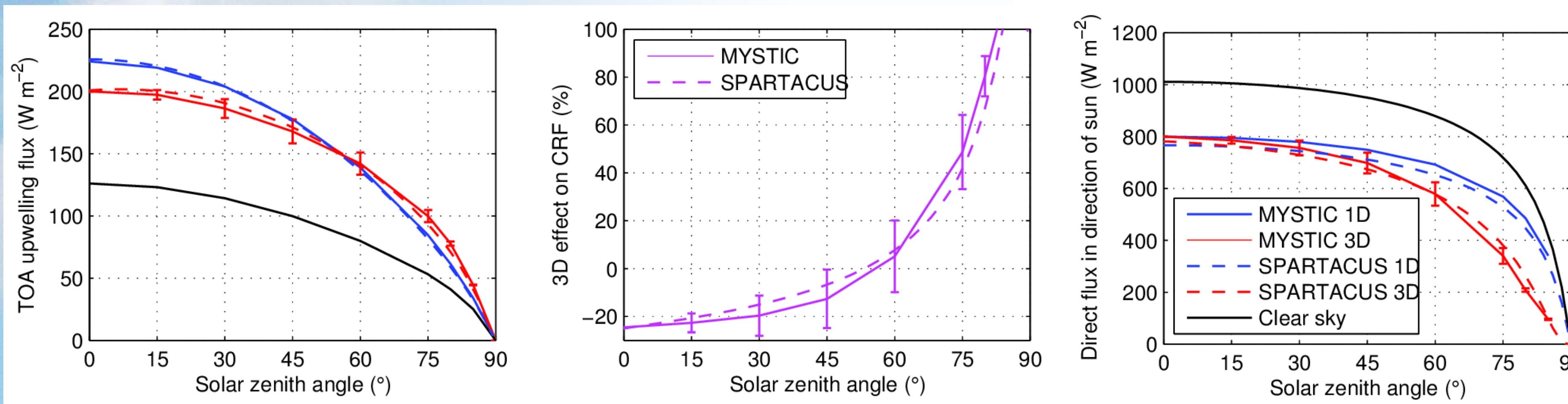


- Multi-layer problem is now *block-tridiagonal*, so still fairly efficient to solve

$$\begin{pmatrix} & \mathbf{I} & & & & & \\ \mathbf{I} & -\mathbf{R}_1 & -\mathbf{T}_1 & & & & \\ & -\mathbf{T}_1 & -\mathbf{R}_1 & \mathbf{I} & & & \\ & & \mathbf{I} & -\mathbf{R}_2 & -\mathbf{T}_2 & & \\ & & & -\mathbf{T}_2 & -\mathbf{R}_2 & \mathbf{I} & \\ & & & & \mathbf{I} & -\alpha_s \end{pmatrix} \begin{pmatrix} \mathbf{f}_{0.5}^{+} \\ \mathbf{f}_{0.5}^{-} \\ \mathbf{f}_{1.5}^{+} \\ \mathbf{f}_{1.5}^{-} \\ \mathbf{f}_{2.5}^{+} \\ \mathbf{f}_{2.5}^{-} \end{pmatrix} = \begin{pmatrix} \mathbf{s}_0^{-} \\ \mathbf{s}_1^{+} \\ \mathbf{s}_1^{-} \\ \mathbf{s}_2^{+} \\ \mathbf{s}_2^{-} \\ \mathbf{s}_s^{+} \end{pmatrix}$$

Broadband shortwave SPARTACUS vs Monte Carlo

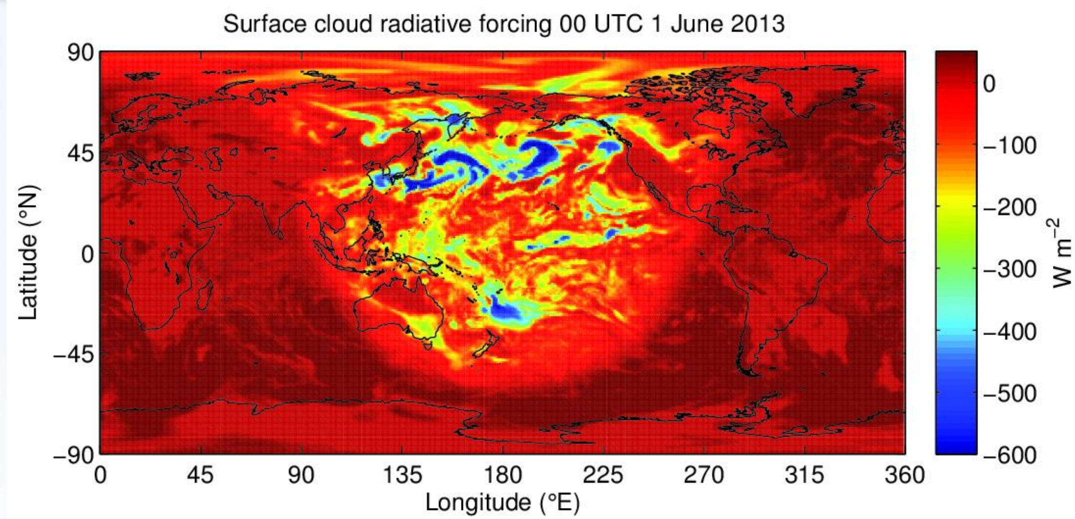
- SPARTACUS coded up in Fortran 90 with RRTM-G for gas absorption
- Compare to full 3D Monte Carlo calculation from MYSTIC in cumulus
  - Thanks to Carolin Klinger & Bernhard Mayer, LMU Munich
  - Mean of 4 solar azimuths, error bar indicates standard deviation due to sun orientation

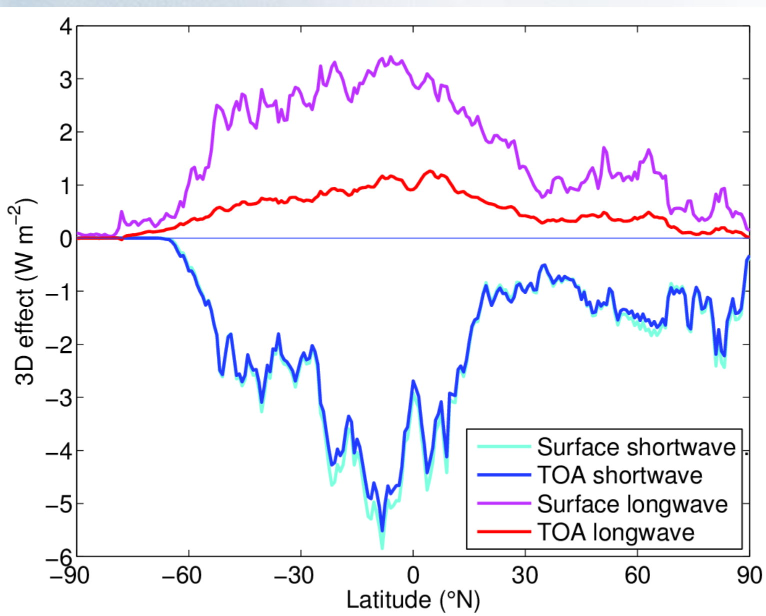


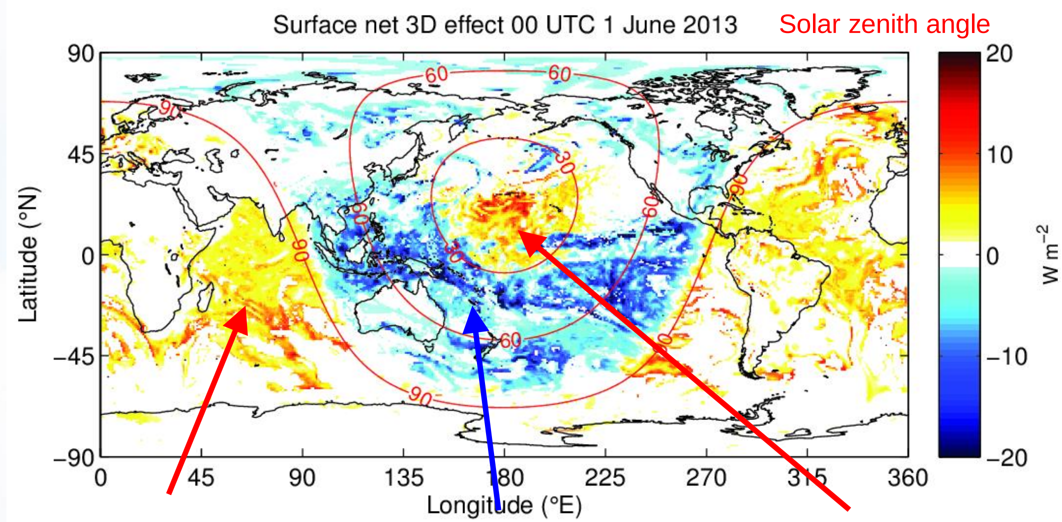
- Good match!
- 3D effect up to 20 W m^{-2}, similar to inhomogeneity effect
- Large difference in direct surface flux at large solar zenith angle
  - SPARTACUS direct fluxes agree better with ARM observations

Towards a global estimate of the impact of 3D effects

- Instantaneous cloud radiative forcing calculated by applying SPARTACUS to one ERA-Interim cloud field
- *3D effect is appreciable!*
- Next step: annual mean







Night-time:
positive LW effect

Low sun:
negative SW effect

High sun:
positive SW effect

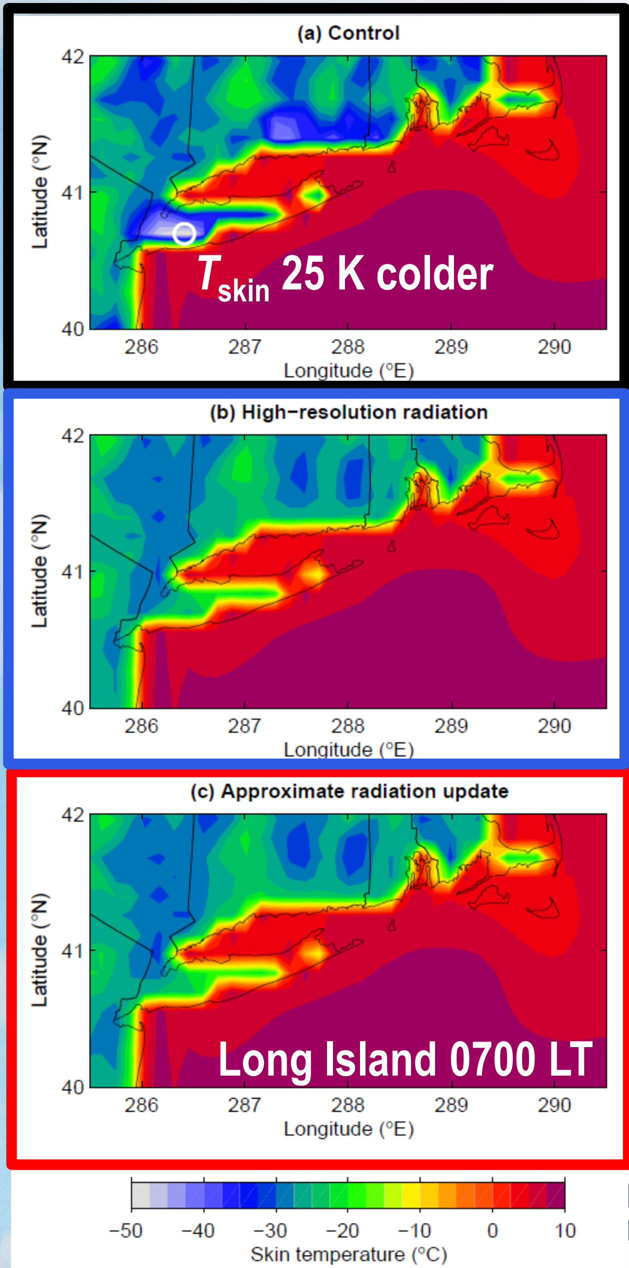
Are we using computer time wisely?

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

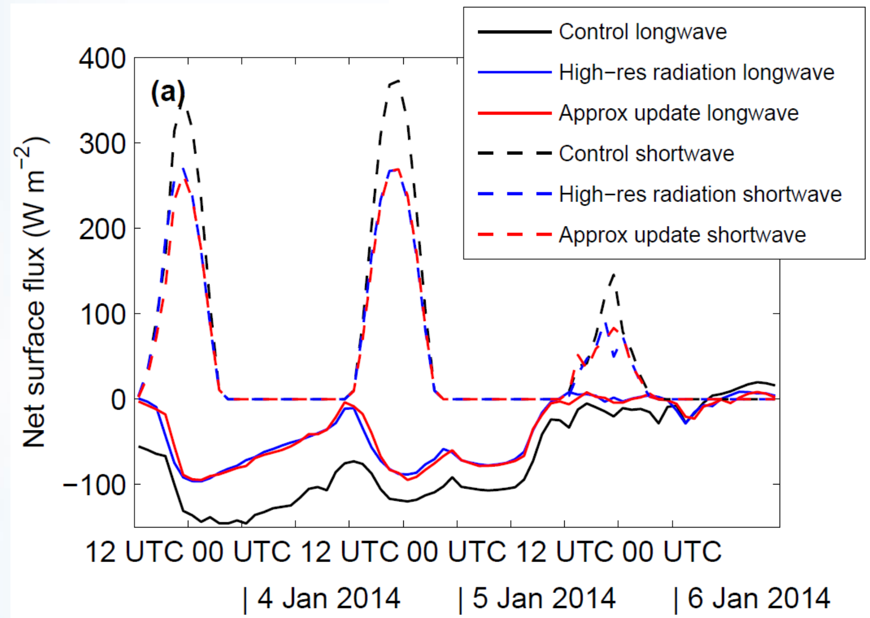
Dimension	Typical number of quadrature points	How well is this dimension known?	Consequence of poor resolution
Time	1 every 3 hours	At the timestep of the model	Changed climate sensitivity (Morcrette 2000); diurnal cycle (Yang & Slingo 2001)
Angle	2 (sometimes 4)	Well (some uncertainty on ice phase functions)	±6-8 W m^{-2} (Stephens et al. 2001, Barker et al. 2015)
Space But only every 6^{th} gridpoint!	2 (clear+cloudy) *McICA: equal to spectral intervals*	Poorly (clouds!)	Up to a 20 W m^{-2} long-term bias (Shonk and Hogan 2010)
Spectrum	70-260	Very well (HITRAN database)	Incorrect climate response to trace gases?

Approximate radiation updates

Hogan & Bozzo (JAMES 2015)



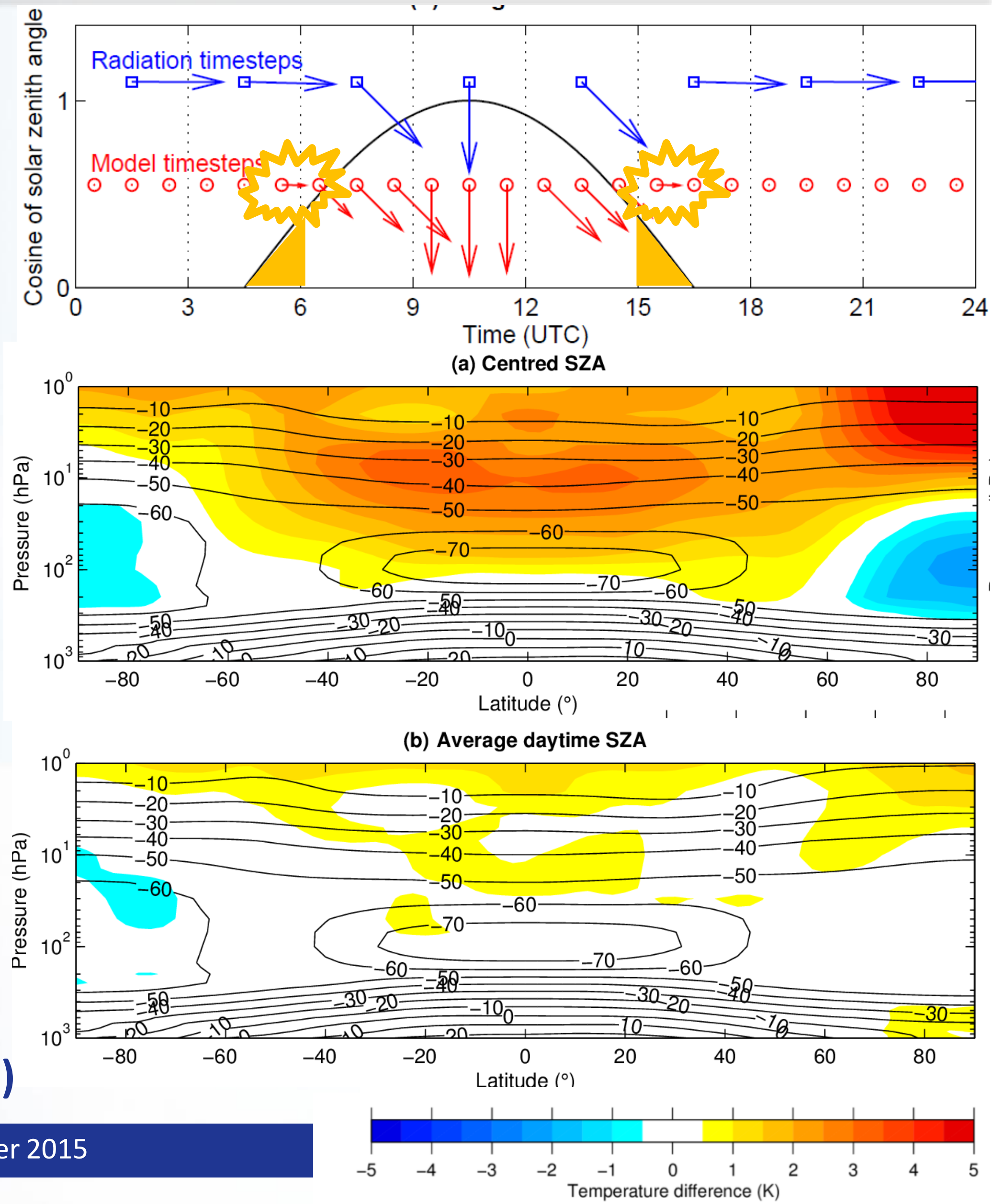
- IFS can have large temperature errors at coasts due to running radiation at coarser resolution



- New scheme updates longwave and shortwave fluxes every timestep and gridpoint in response to surface albedo and skin temperature
- Fixes errors due to spatial interpolation at a cost of only around 2% that of the radiation scheme

Climate errors due to infrequent calls to radiation scheme

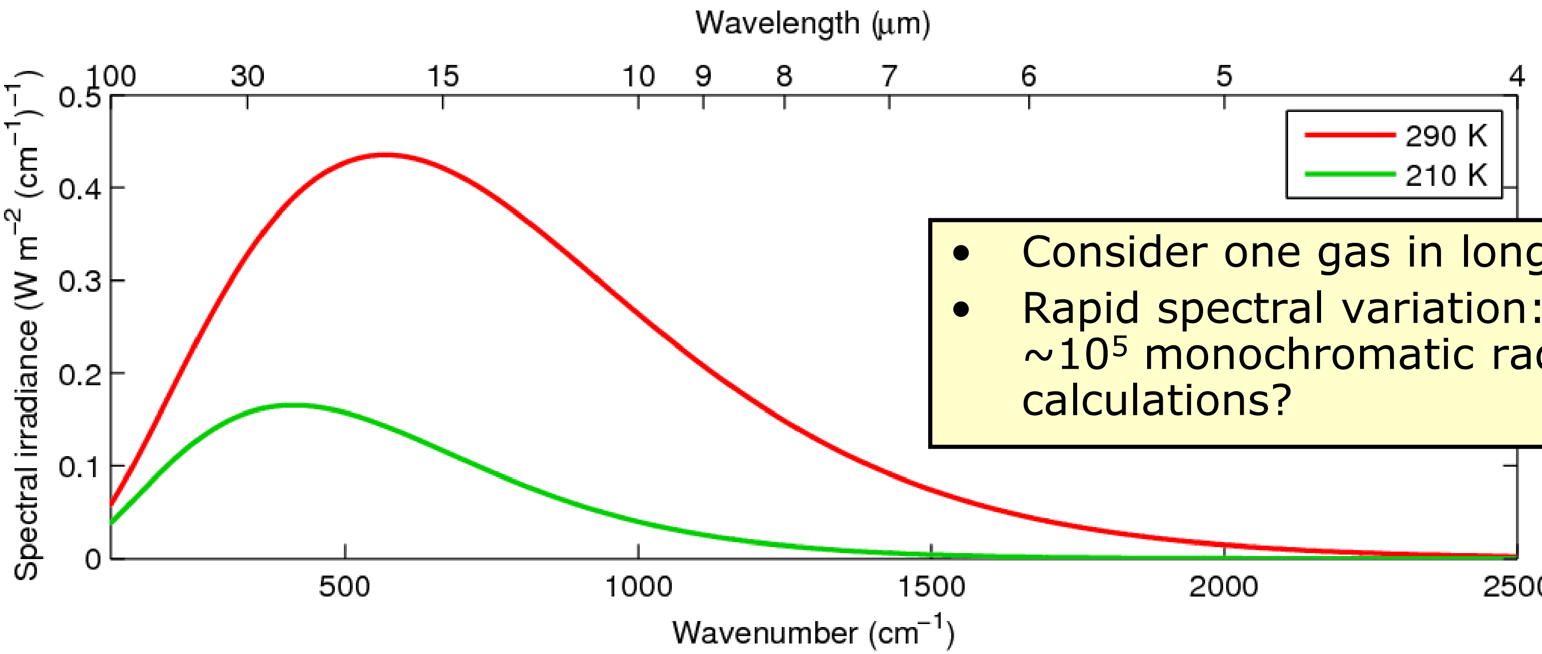
- All but one operational IFS configurations call radiation scheme only every 3 h
- At dawn & dusk, sun angle at centre of 3-h period too shallow: absorption *too high*
- Stratosphere too warm by 3-5 K (compared to running radiation scheme every timestep)
- Fix by averaging cosine of solar zenith angle over *sunlit part* of radiation timestep



Hogan & Hirahara (ECMWF memo 2015)

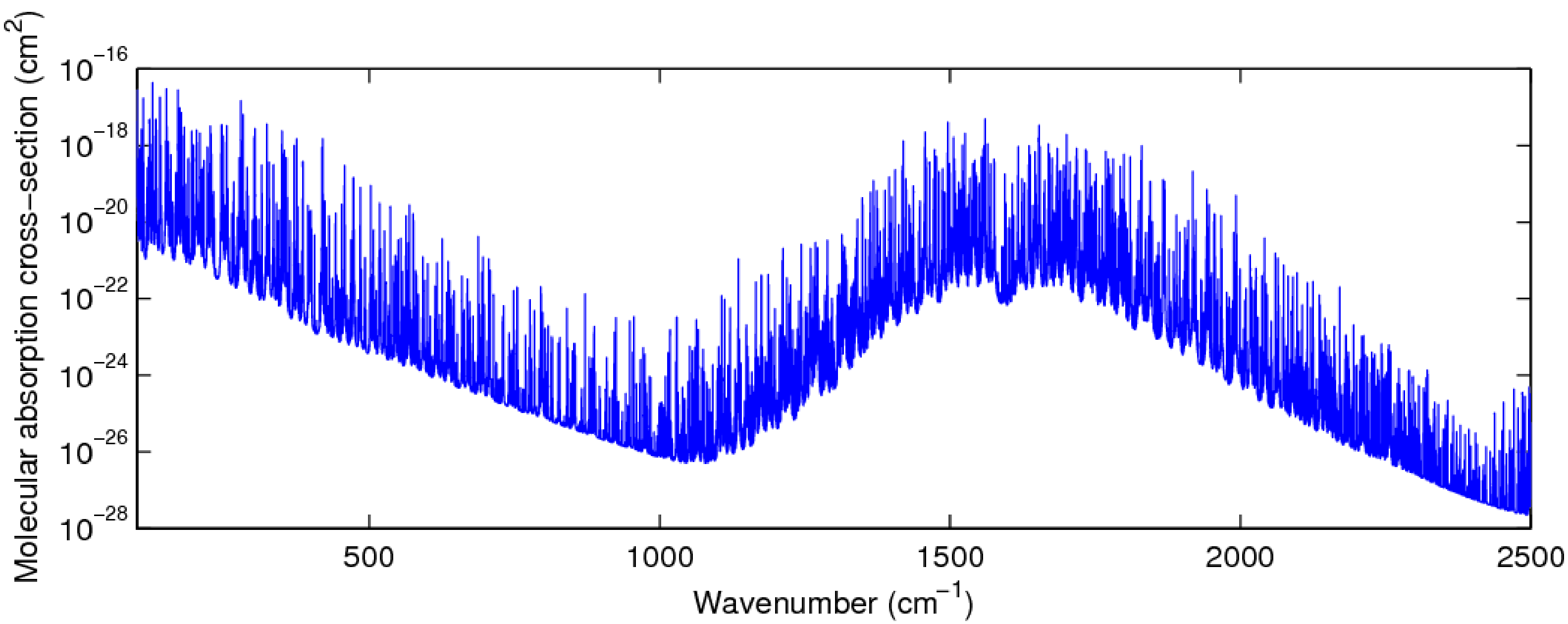
How do we integrate across the spectrum?

Planck function



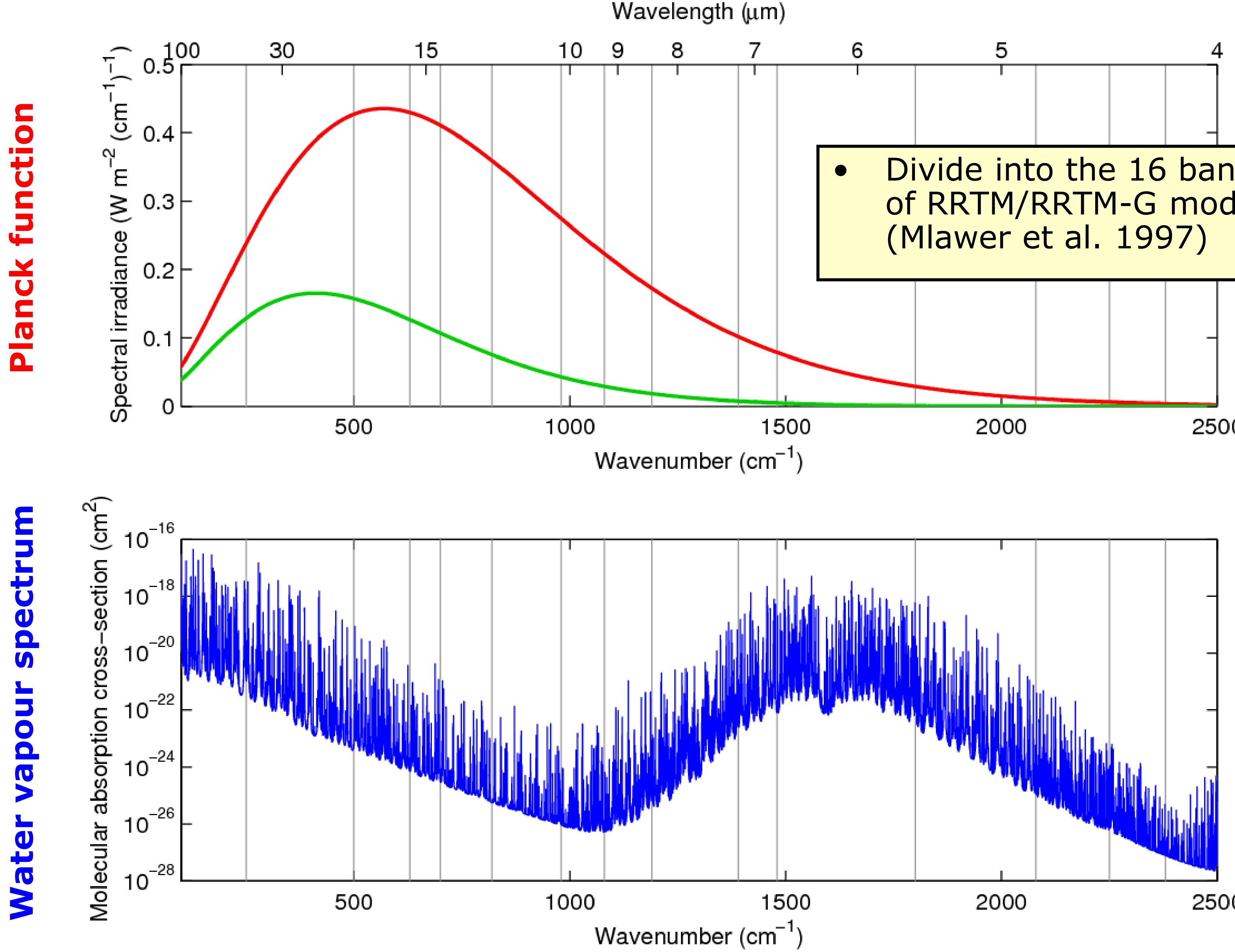
- Consider one gas in longwave
- Rapid spectral variation: need ~10^5 monochromatic radiation calculations?

Water vapour spectrum



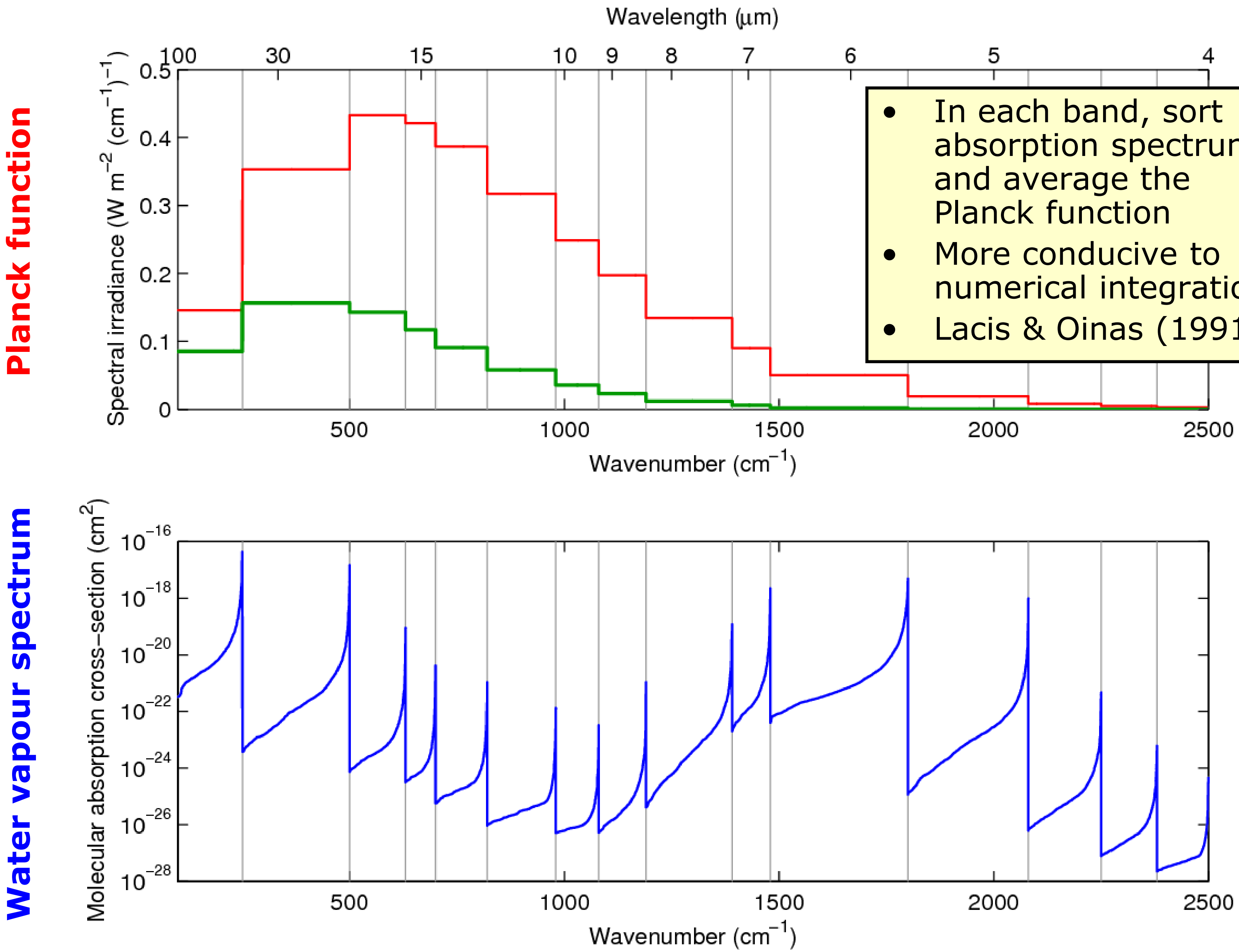
Divide into bands

- Divide into the 16 bands of RRTM/RRTM-G model (Mlawer et al. 1997)



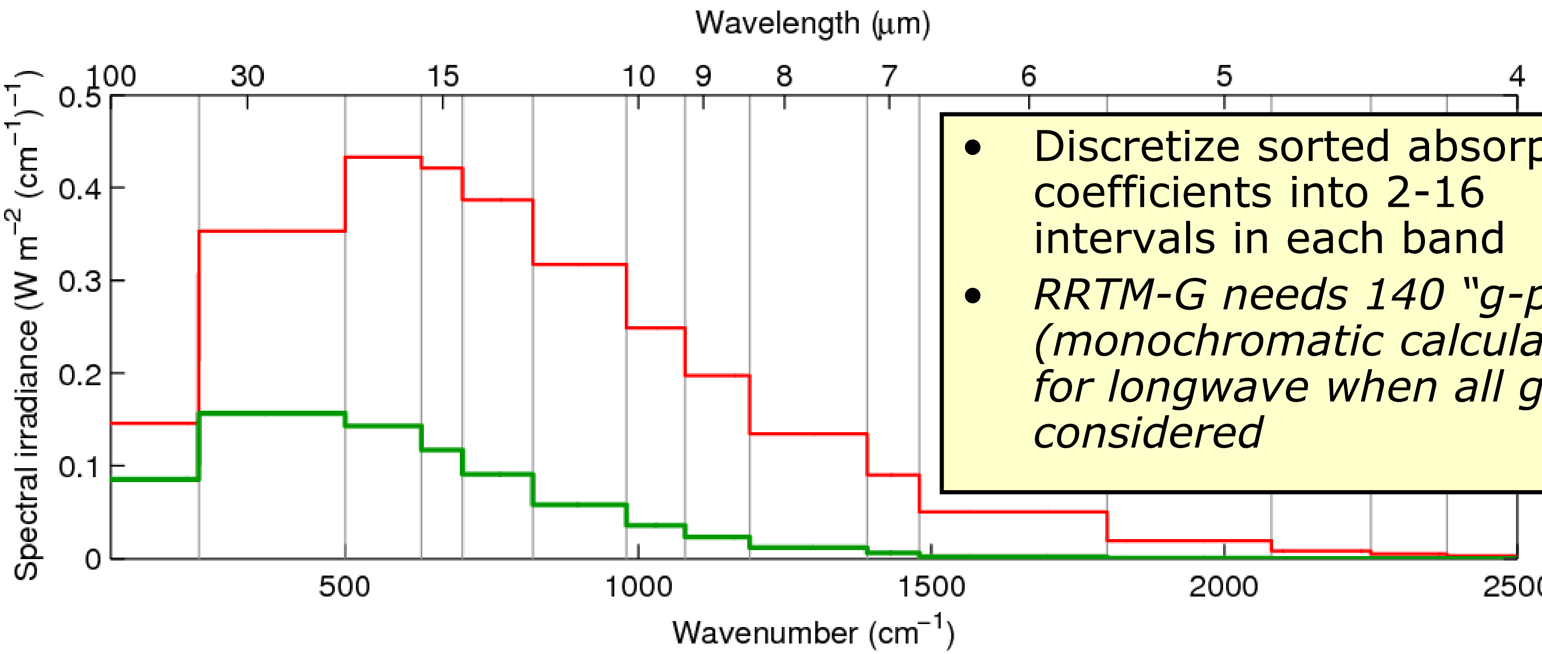
The correlated k-distribution method

- In each band, sort absorption spectrum and average the Planck function
- More conducive to numerical integration
- Lacis & Oinas (1991)



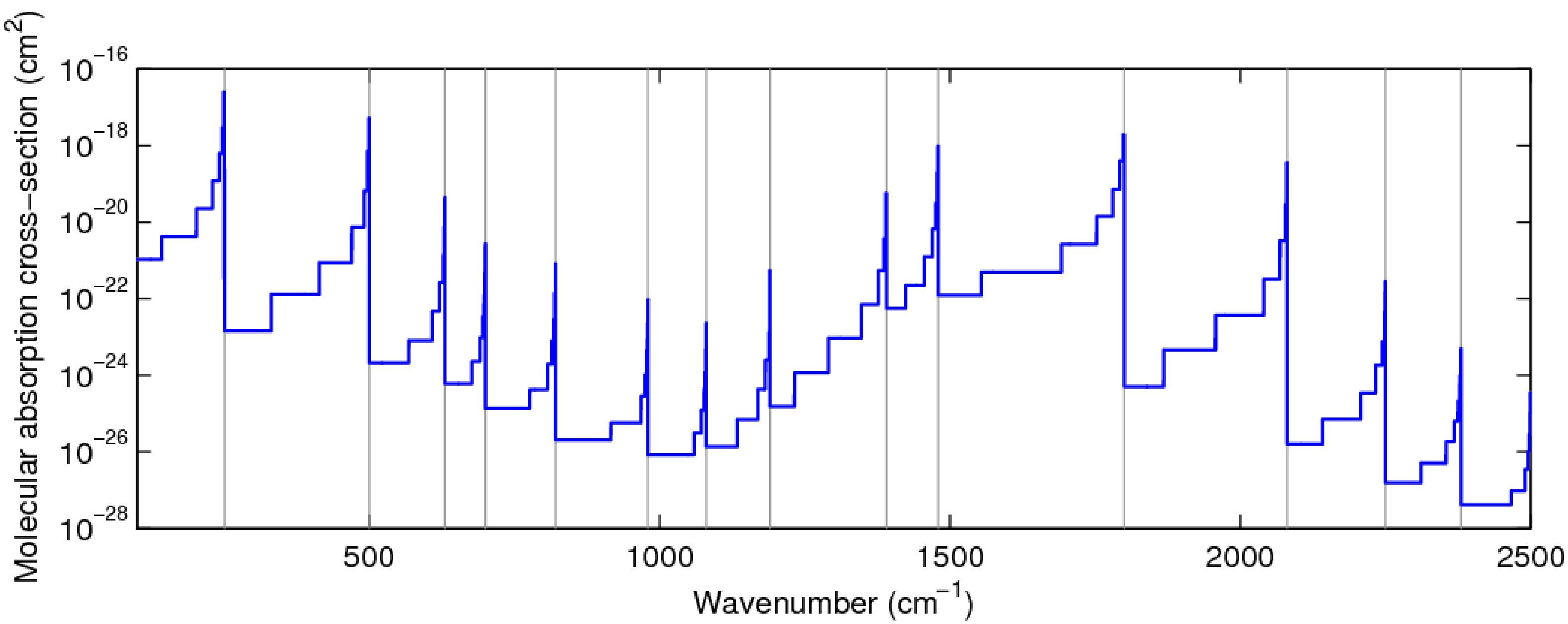
The correlated k-distribution method

Planck function

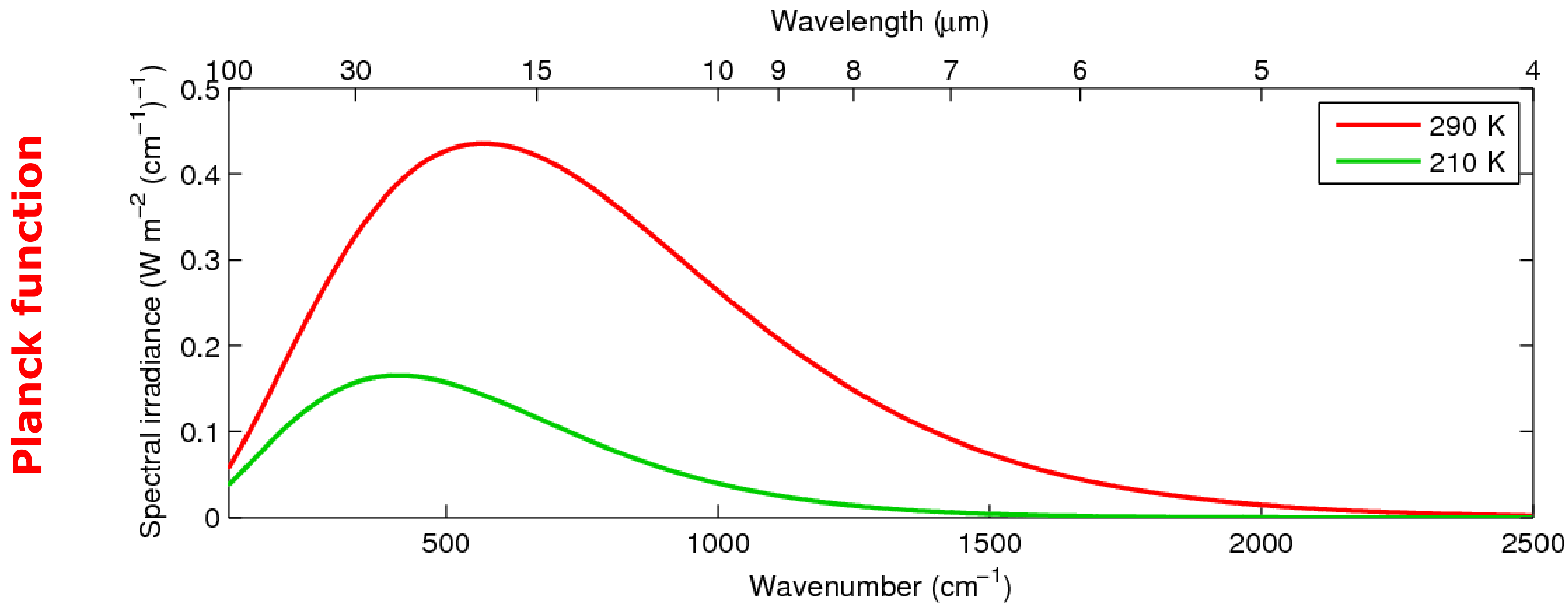


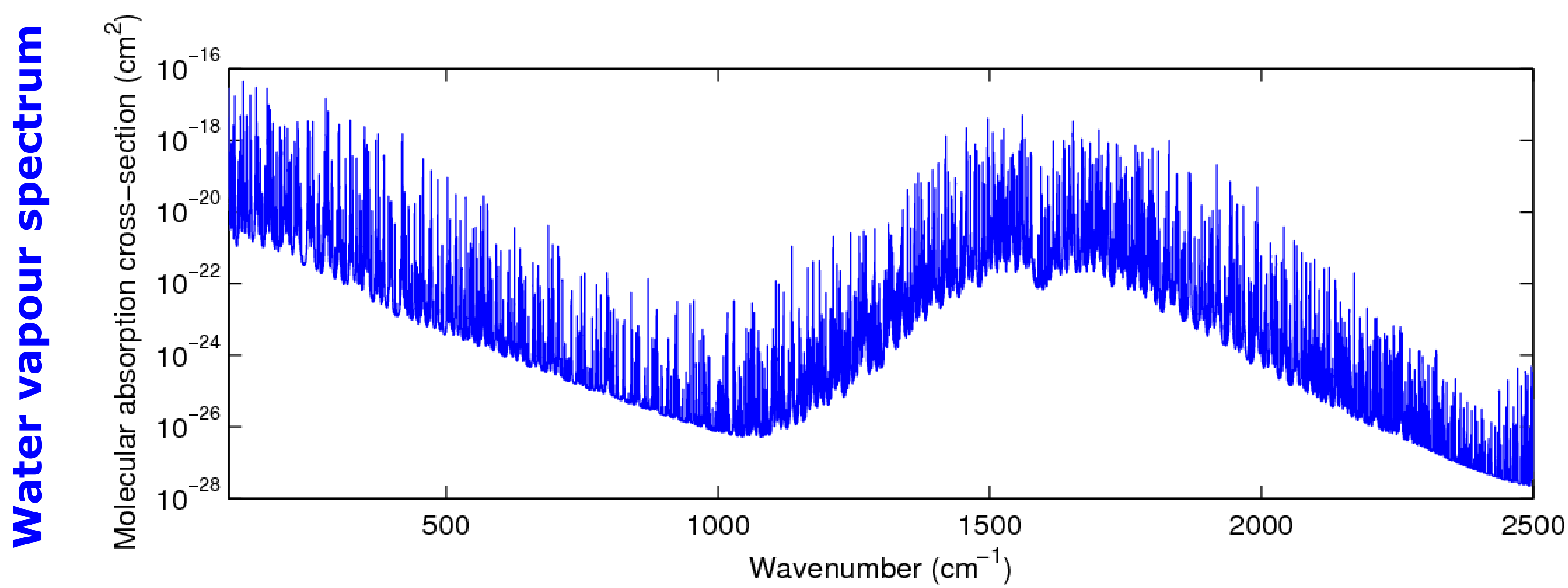
- Discretize sorted absorption coefficients into 2-16 intervals in each band
- *RRTM-G needs 140 "g-points" (monochromatic calculations) for longwave when all gases considered*

Water vapour spectrum

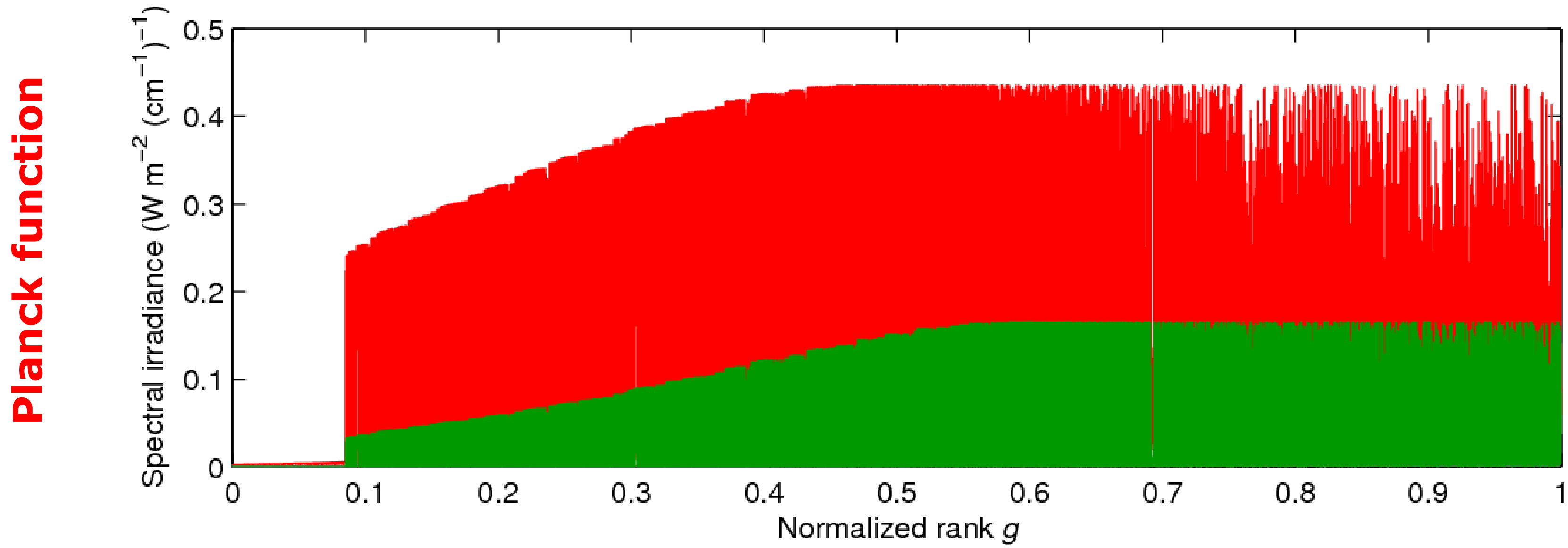


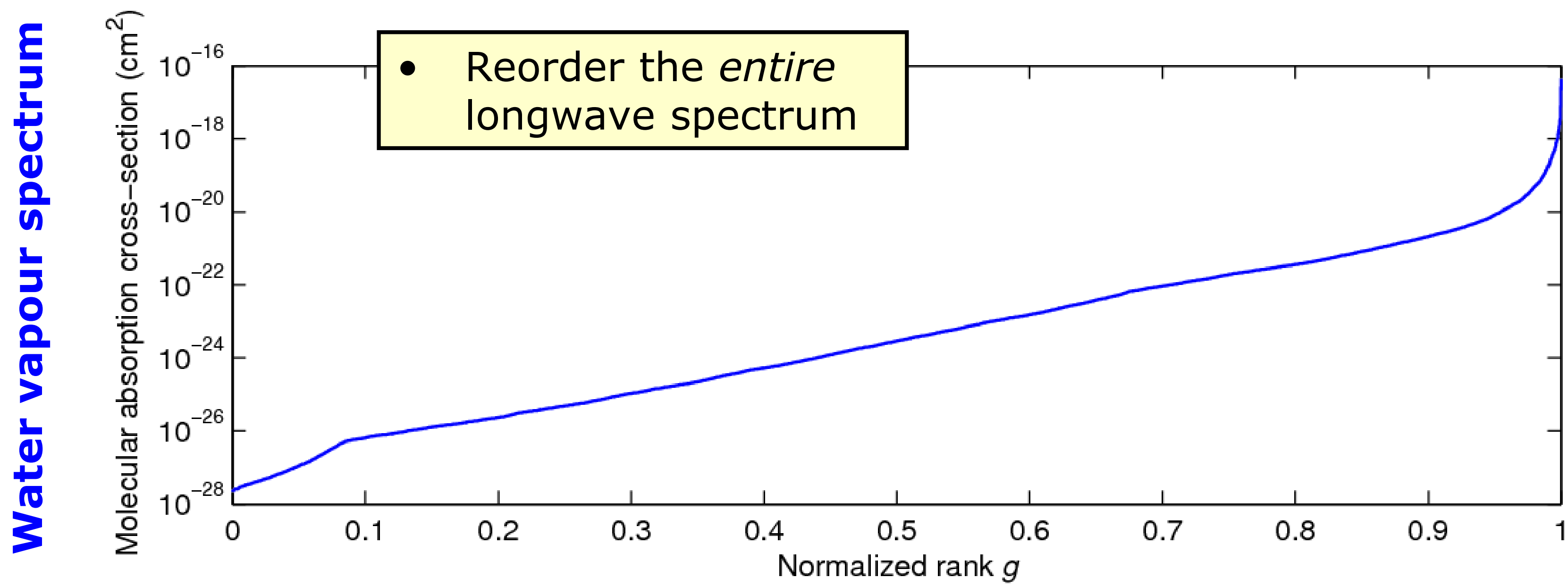
Full-spectrum correlated-k (FSCK) method





Full-spectrum correlated-k (FSCK) method

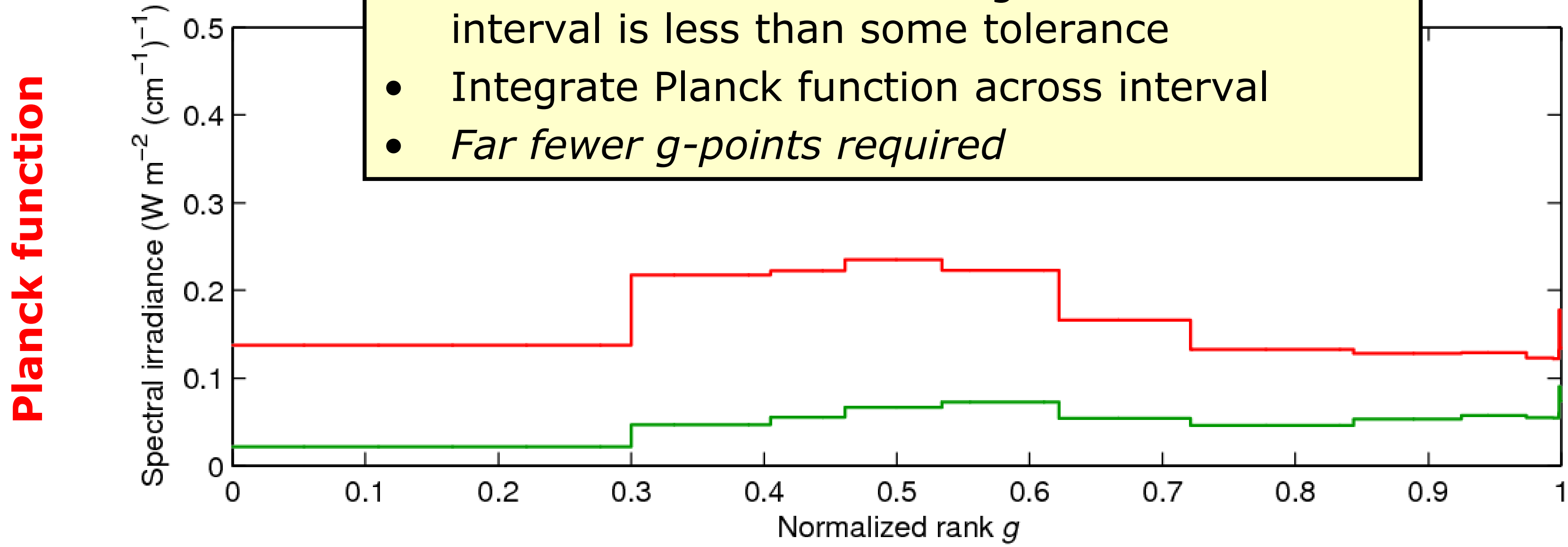


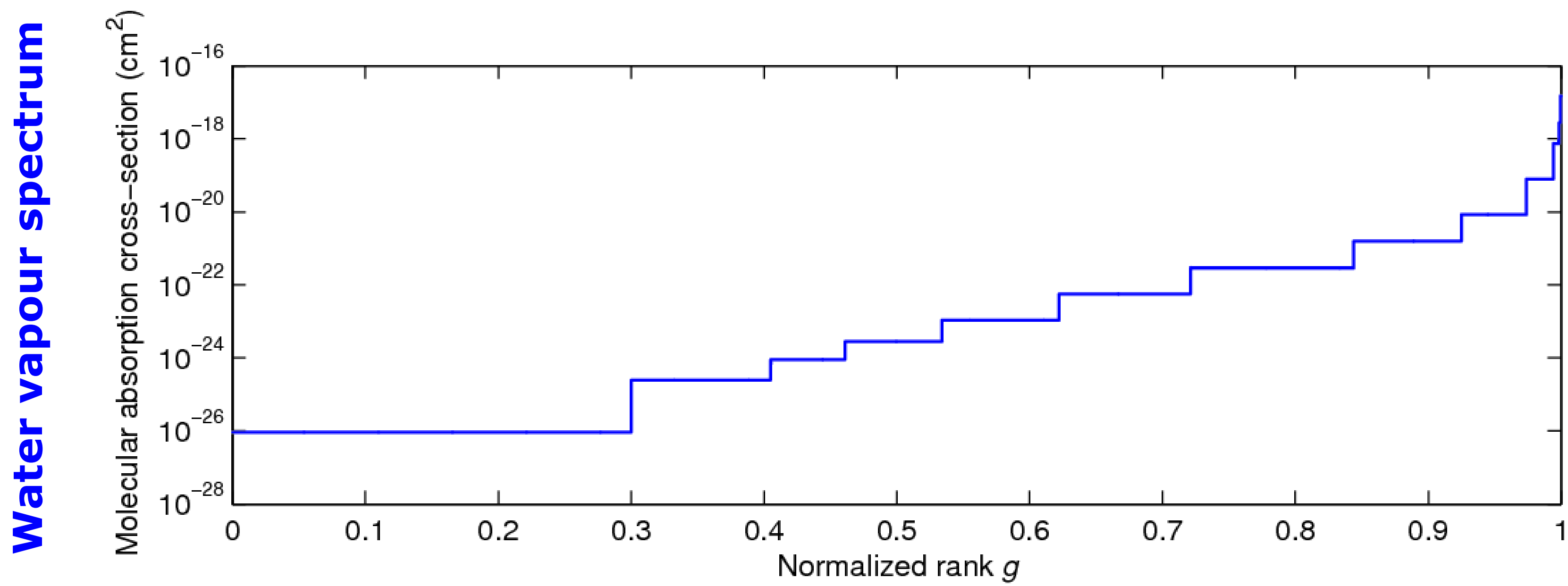


- Reorder the *entire* longwave spectrum

Full-spectrum correlated-k (FSCK) method

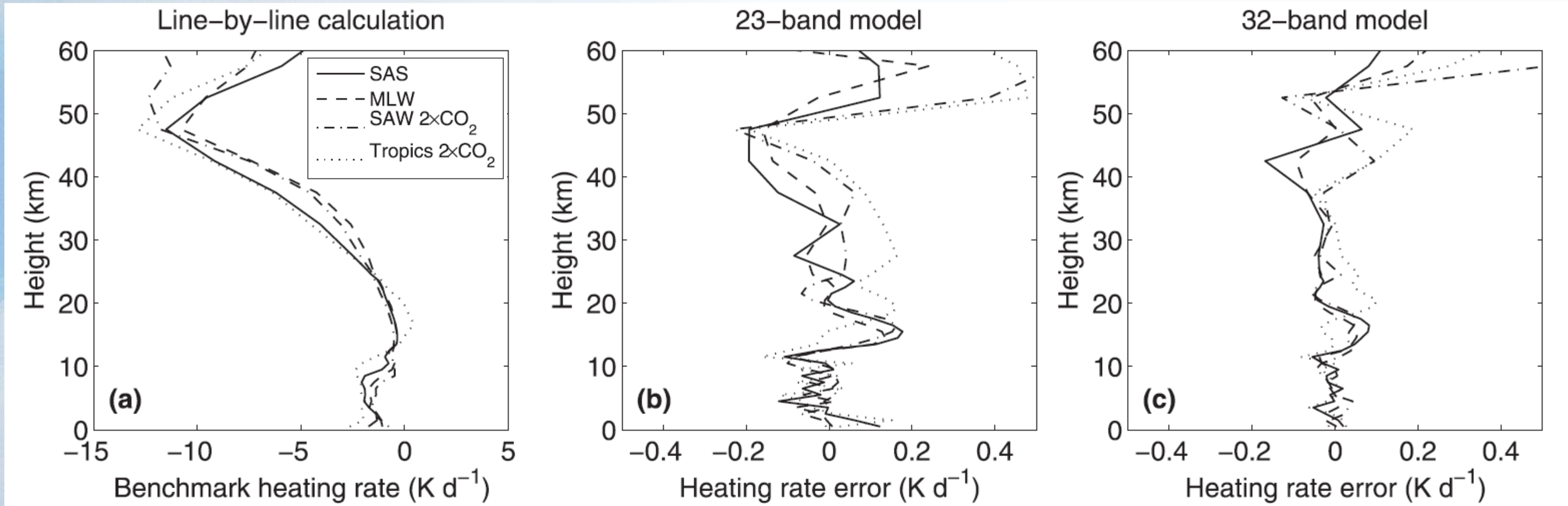
- Discretize such that heating rate error in each interval is less than some tolerance
- Integrate Planck function across interval
- *Far fewer g-points required*



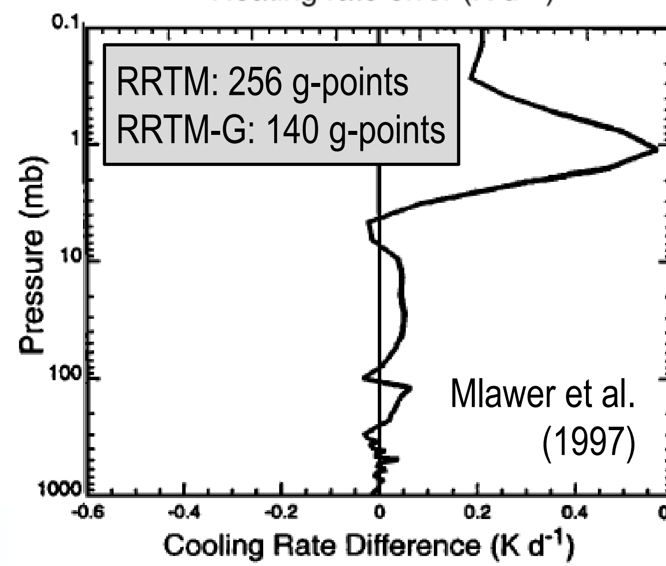


Performance of longwave FSCK on test profiles

Hogan (2010)



- FSCK performance apparently similar to RRTM-G but with 25% the number of spectral intervals
- FSCK possible in shortwave (Pawlak et al. 2004)
- More work needed!
  - Only considered longwave with H_2O, CO_2, O_3 so far
  - Need to include clouds and aerosols
- Good enough for NWP?

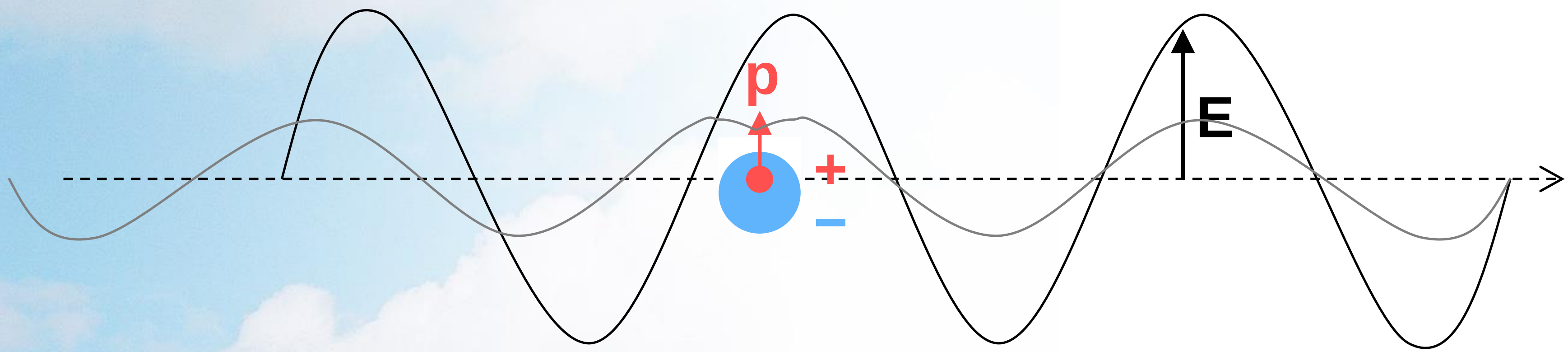


Summary and outlook

- Representation of cloud structure and overlap in radiation schemes is much improved compared to 15 years ago
  - McICA is now the de facto standard for radiation schemes in weather and climate models
- Look for opportunities to improve accuracy with no increase in cost
  - "Tuned" 2-stream method; better continuum absorption models
  - Approximate updates to fluxes to mitigate errors due to radiation calls infrequent in time and space
- Opportunities to represent new physical processes with modest cost increase
  - 3D effects with SPARTACUS
- Large number of spectral intervals limits what we can afford in other areas
  - Faster implementation of RRTM-G, e.g. on GPUs
  - Alternative approaches such as FSCK?
- Plans for a new ECMWF radiation scheme
  - Modular: solver and cloud, aerosol & gas optical models can be interchanged independently
  - Open source off-line version to be released
- *Remember that radiative fluxes are only as good as the cloud and aerosol data coming from the host model!*

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, typically in phase with incident electric field E

Dipole radiates in (almost) all directions

The 3D radiative transfer equation

- This describes the radiance I in direction $\mathbf{\Omega}$ (where the position and frequency dependence of all variables is implicit):

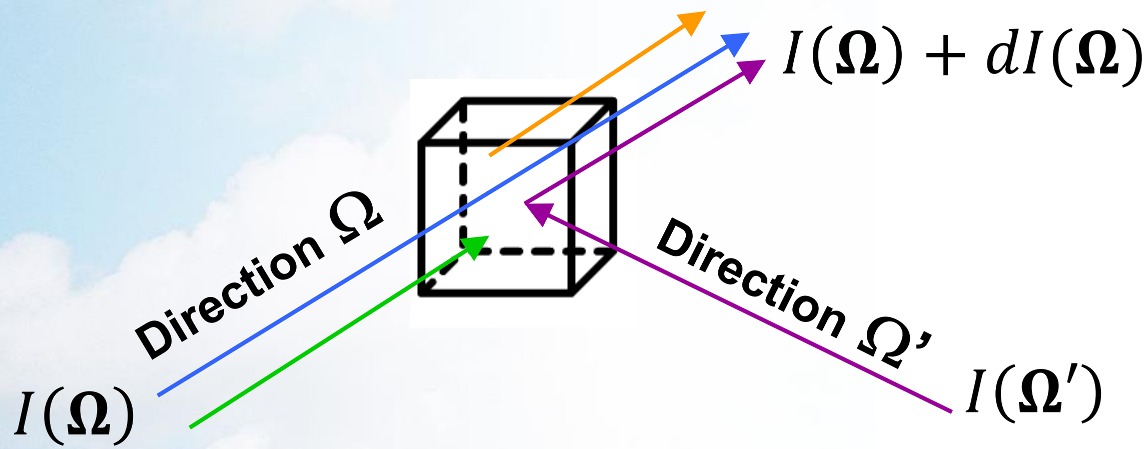
$$\mathbf{\Omega}\cdot\nabla I(\mathbf{\Omega}) = -\beta_e I(\mathbf{\Omega}) + \beta_s \int_{4\pi} p(\mathbf{\Omega},\mathbf{\Omega}')I(\mathbf{\Omega}')d\mathbf{\Omega}' + S(\mathbf{\Omega})$$

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



Forecast skill from temporal frequency of radiation calls

- Forecast skill improves if radiation called every 1 h rather than every 3 h
  - Half of this improvement is due to response of radiation fields to surface temperature; can be represented by keeping 3-h radiation but using approximate radiation updates in between (Hogan & Bozzo 2015)
  - Half is due to interaction with clouds
- Almost half spectral intervals important only in stratosphere and mesosphere
  - Could run troposphere channels more frequently to capture response to fast changing surface and clouds (Manners et al. 2009)