Radiative processes

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What does a radiation scheme do (in the IFS)?

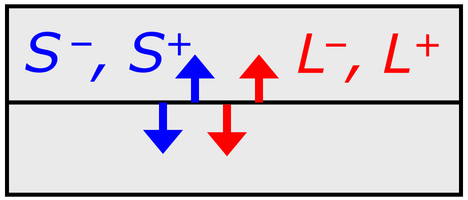
- *Prognostic variables:* temperature, humidity, cloud fraction, liquid and ice mixing ratios, surface temperature
- *Diagnostic variables:* sun angle, surface albedo, pressure, O_3, aerosol; well-mixed gases: CO_2, O_2, CH_4, N_2O, CFC-11 and CFC-12

Interpolate horizontally to radiation grid

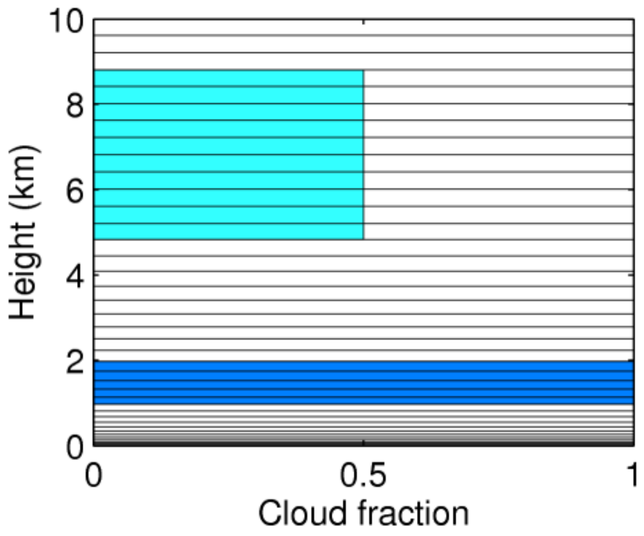
Radiation scheme ecRad

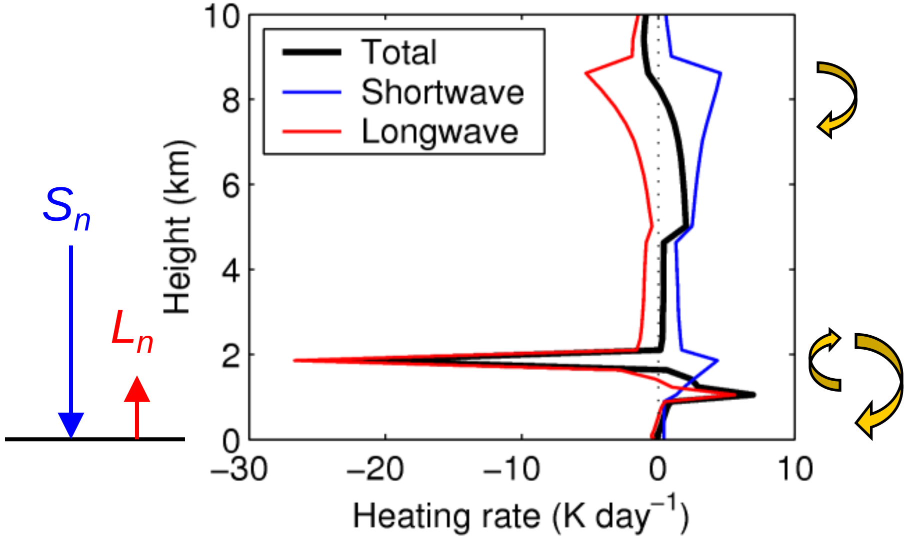
Interpolate to model grid

Radiation scheme predicts fluxes between model levels in W m^{-2}, and the net flux $R_n = S^- - S^+ + L^- - L^+$



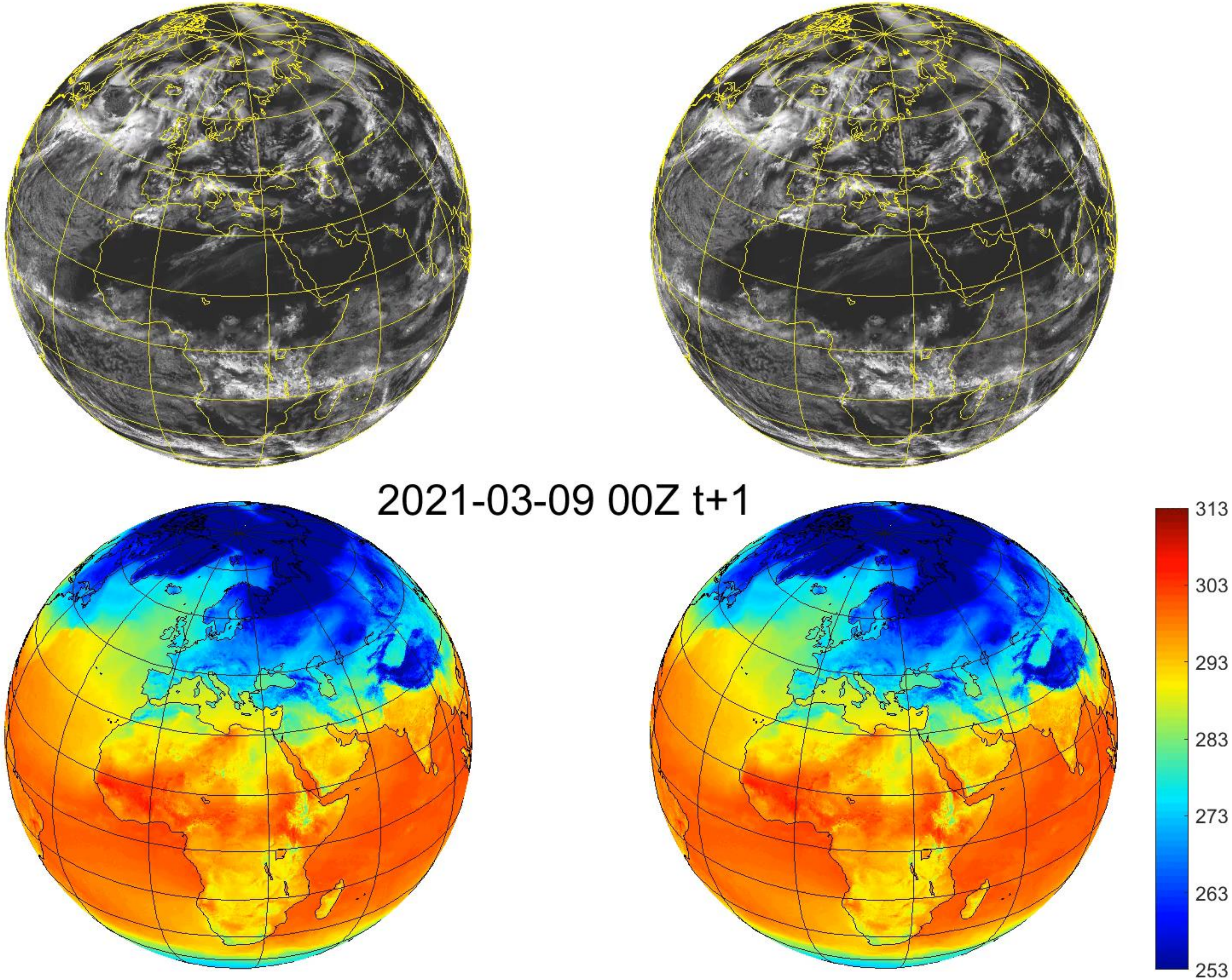
- Thermodynamic equation: $$\frac{D\bar{\theta}}{Dt} = \frac{1}{\rho C_p}\frac{\partial R_n}{\partial z} + latent + \cdots$$
- Surface energy balance: soil & sea temperatures





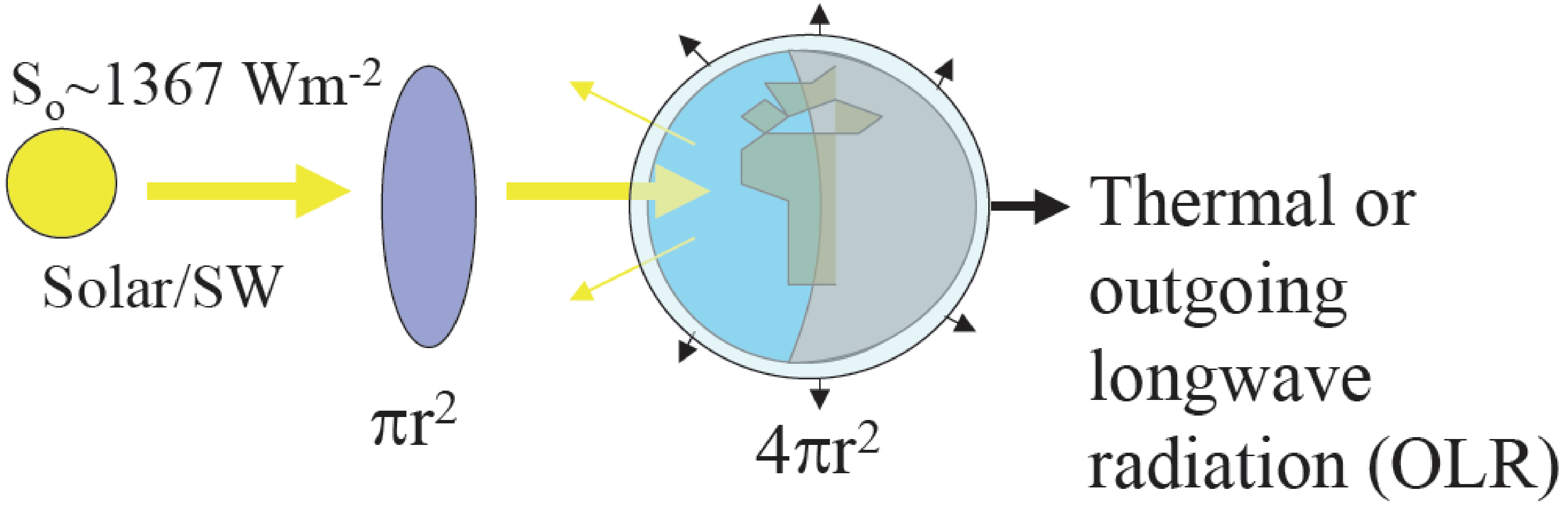
What if the sun were suddenly turned off?

- Land cools rapidly
- Atmosphere fills with cloud
- Tropical land convection disappears
- etc...



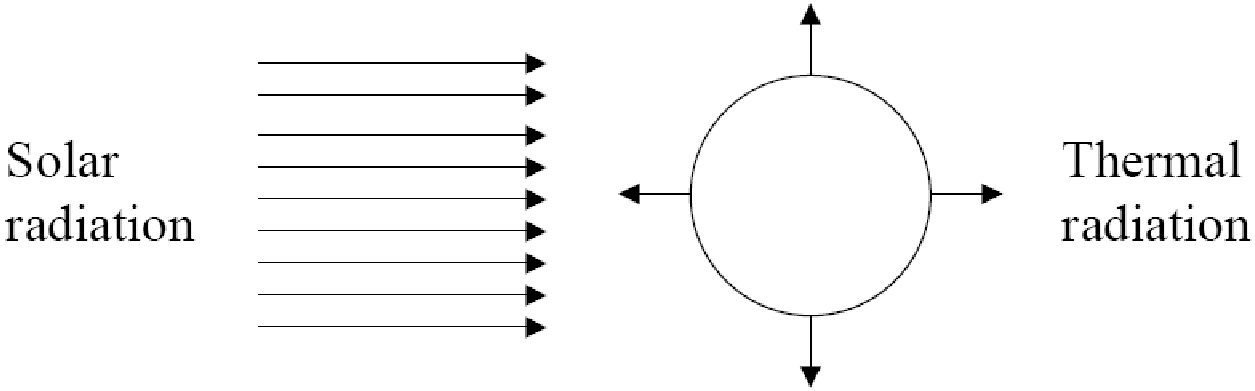
THANKS TO MARK FIELDING

Earth's radiation balance



- In equilibrium, the net absorption of solar radiation is balanced by the emission of thermal radiation back to space
- The thermal emission is controlled by the strength of the greenhouse effect
- If there is an increase in the concentrations of greenhouse gases, such as carbon dioxide, then the system warms as it tries to reach a new equilibrium

Overall energy balance of the Earth



$$(1-\alpha)\, S_o\, \pi\, r^2 = 4\, \pi\, r^2\, \sigma\, T^4_{eff}$$

Simplifying, we find that;

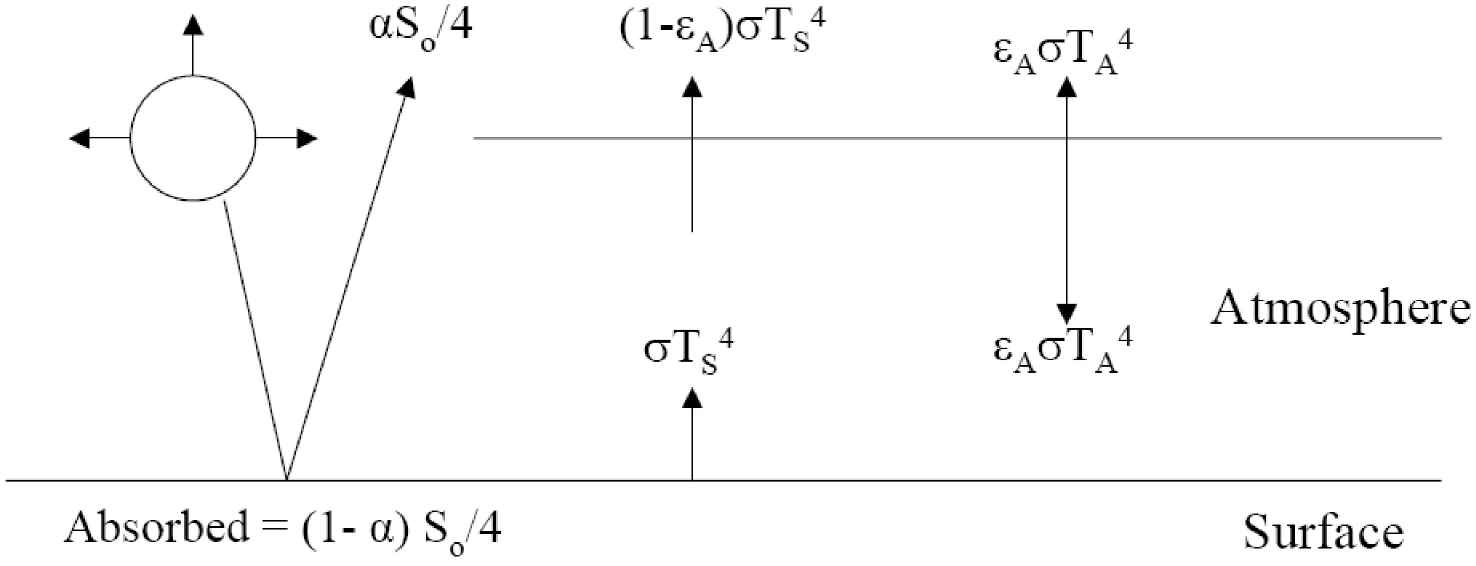
$$\sigma\, T^4_{eff} = (1-\alpha)\, S_o/4$$

and hence

$$T_{eff} \approx 255\ \text{K}$$

If the Earth was black ($\alpha=0$), T_{eff} = 278 K, still lower than observed 288 K

Overall energy balance including the greenhouse effect



Consider the equilibrium of the atmosphere and then of the surface;

$$\varepsilon_A \sigma T_S^4 = 2\varepsilon_A \sigma T_A^4 \tag{4}$$

$$(1-\alpha)S_o/4 + \varepsilon_A \sigma T_A^4 = \sigma T_S^4 \tag{5}$$

Hence

$$\sigma T_S^4 = \{(1 - \alpha)S_o/4\} / (1 - \varepsilon_A/2) \qquad (6)$$

and

$$T_A = T_S/2^{1/4} \qquad (7)$$

Note that T_S is larger than T_{eff} given by (2), because of the additional downward thermal emission from the atmosphere. So, the greenhouse effect ensures that the surface is warmer with an atmosphere than without. Secondly, the atmosphere is colder than the surface and slightly colder than T_{eff}.

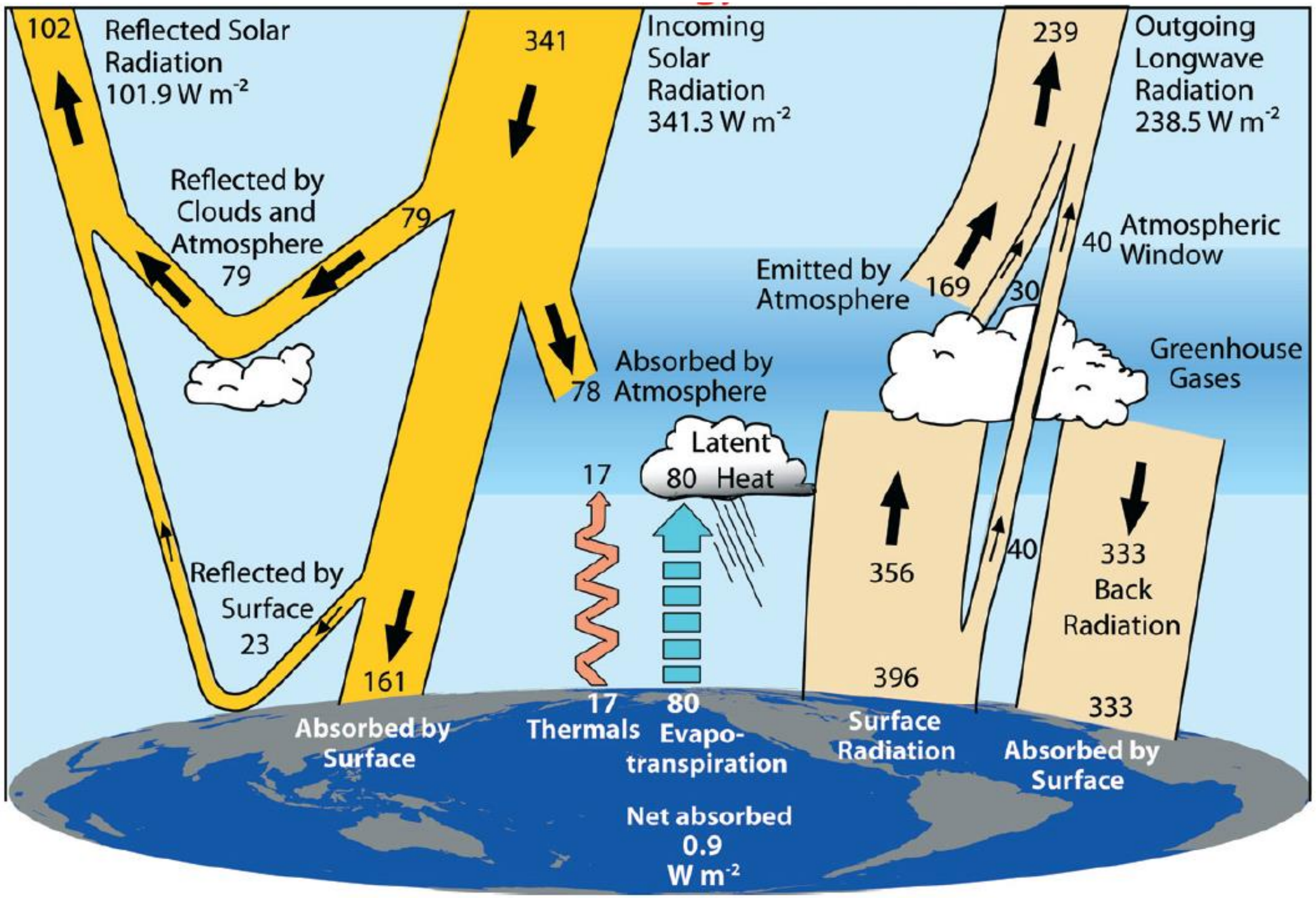
If we assume that $\alpha = 0.3$ and $\varepsilon_A = 0.8$ then we find that;

$$T_S = 289 \text{ K}$$

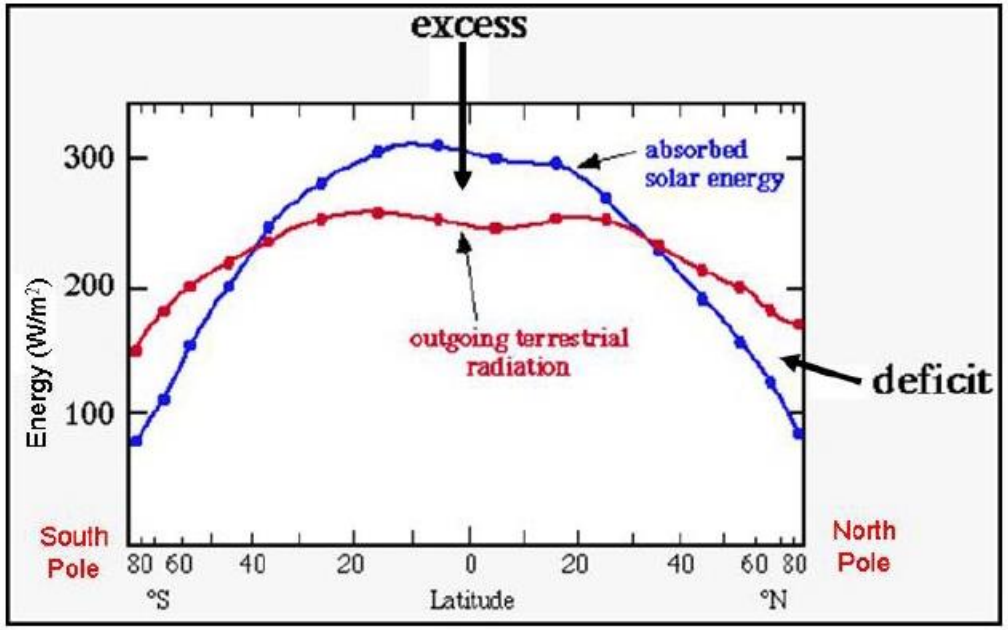
$$T_A = 243 \text{ K}$$

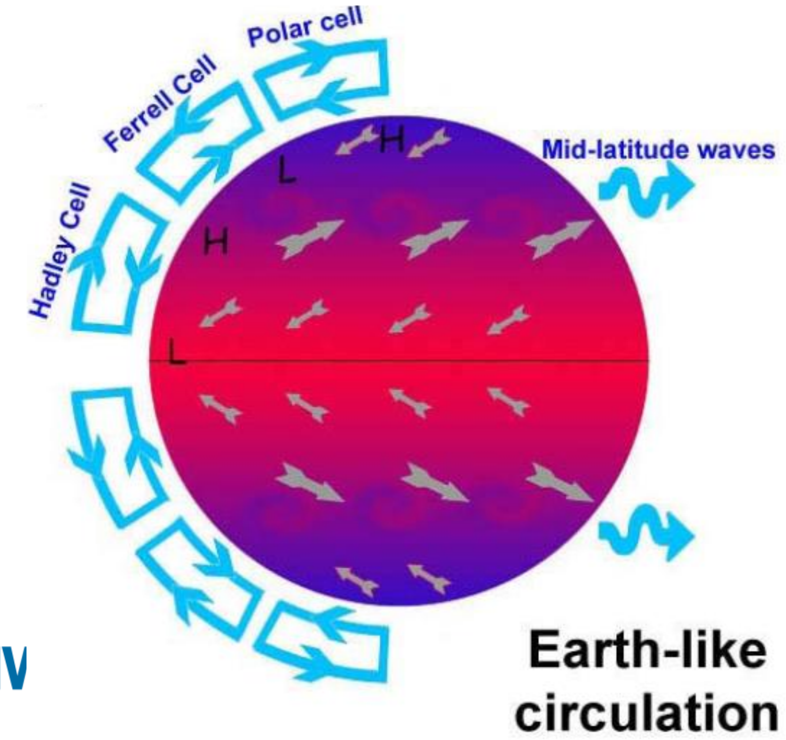
Which are reasonable values for the global mean surface and atmospheric temperatures.

Global energy flows



- Trenberth et al. (2009); modification of Kiehl & Trenberth (1997)

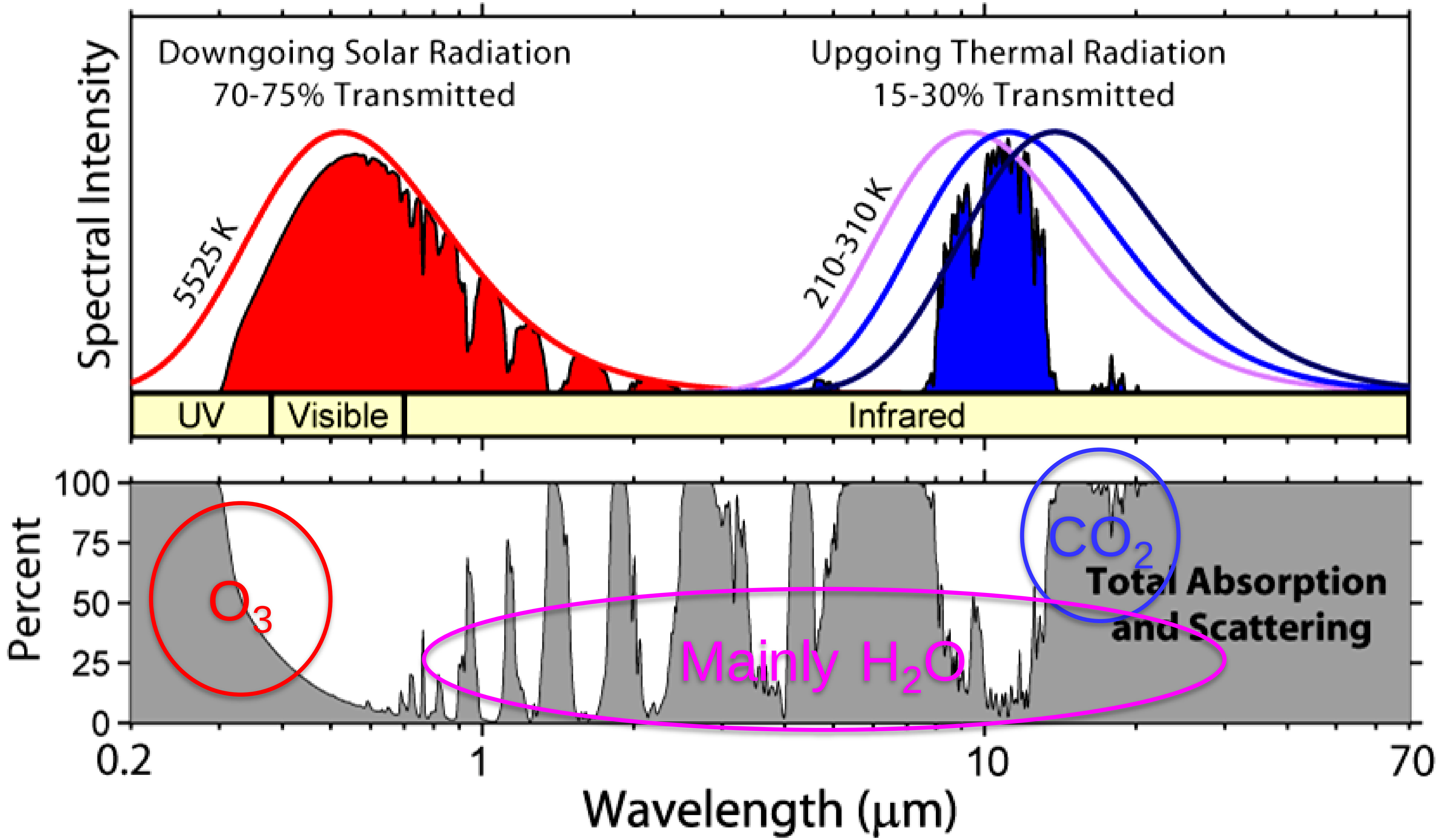




Role of radiation in the global circulation

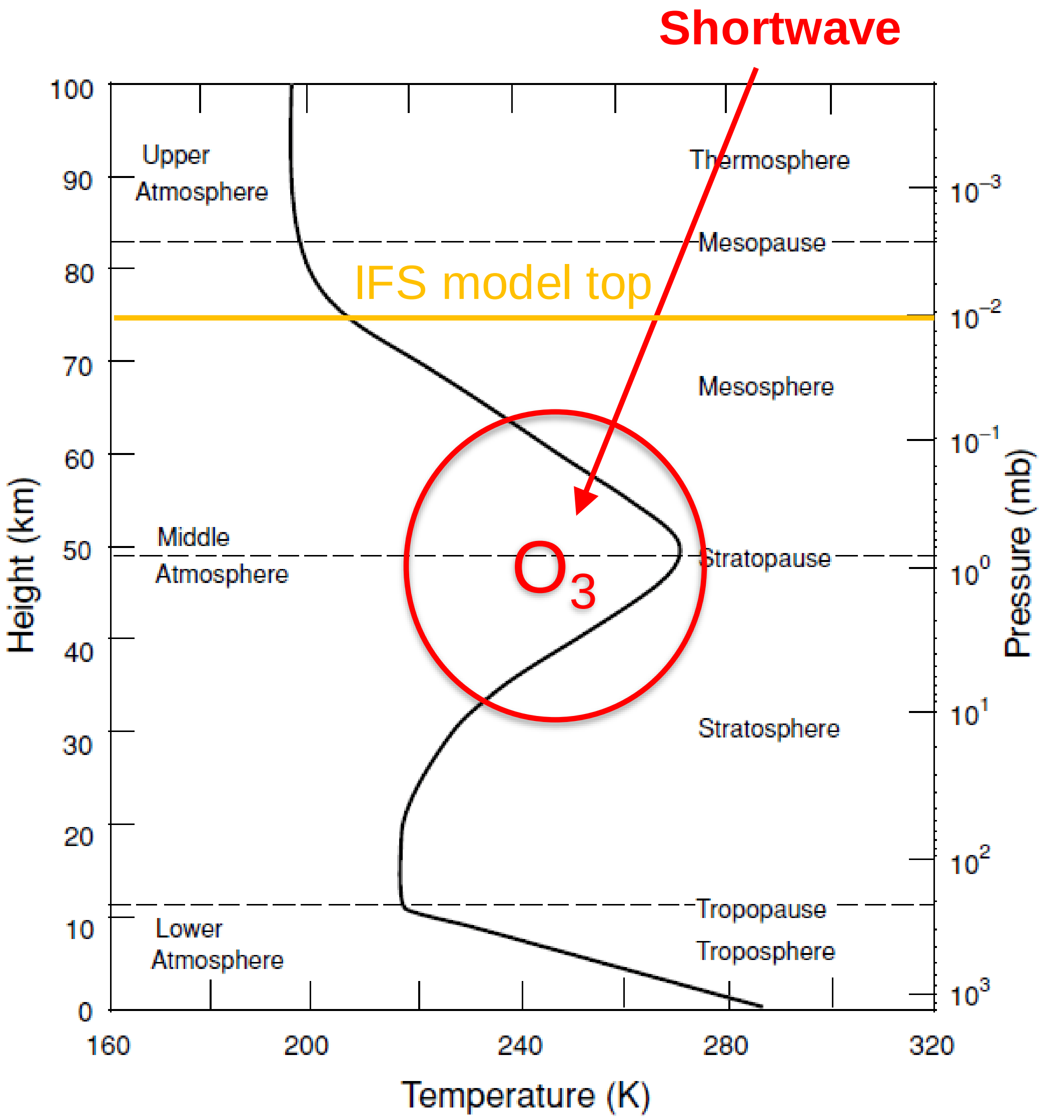
- Warmer tropics means same pressure layers are thicker at equator
- By thermal wind balance there must be westerlies
- Excess heat transported polewards by
  - Oceanic transport
  - Disturbances in these westerlies: mid-latitude weather systems!

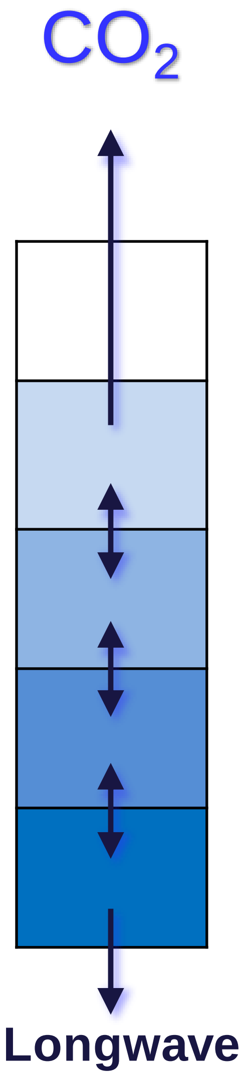
Spectral distribution of radiation



- **Shortwave: atmosphere is mostly transparent**
- **Longwave: atmosphere is mostly opaque**

Stratosphere and climate change

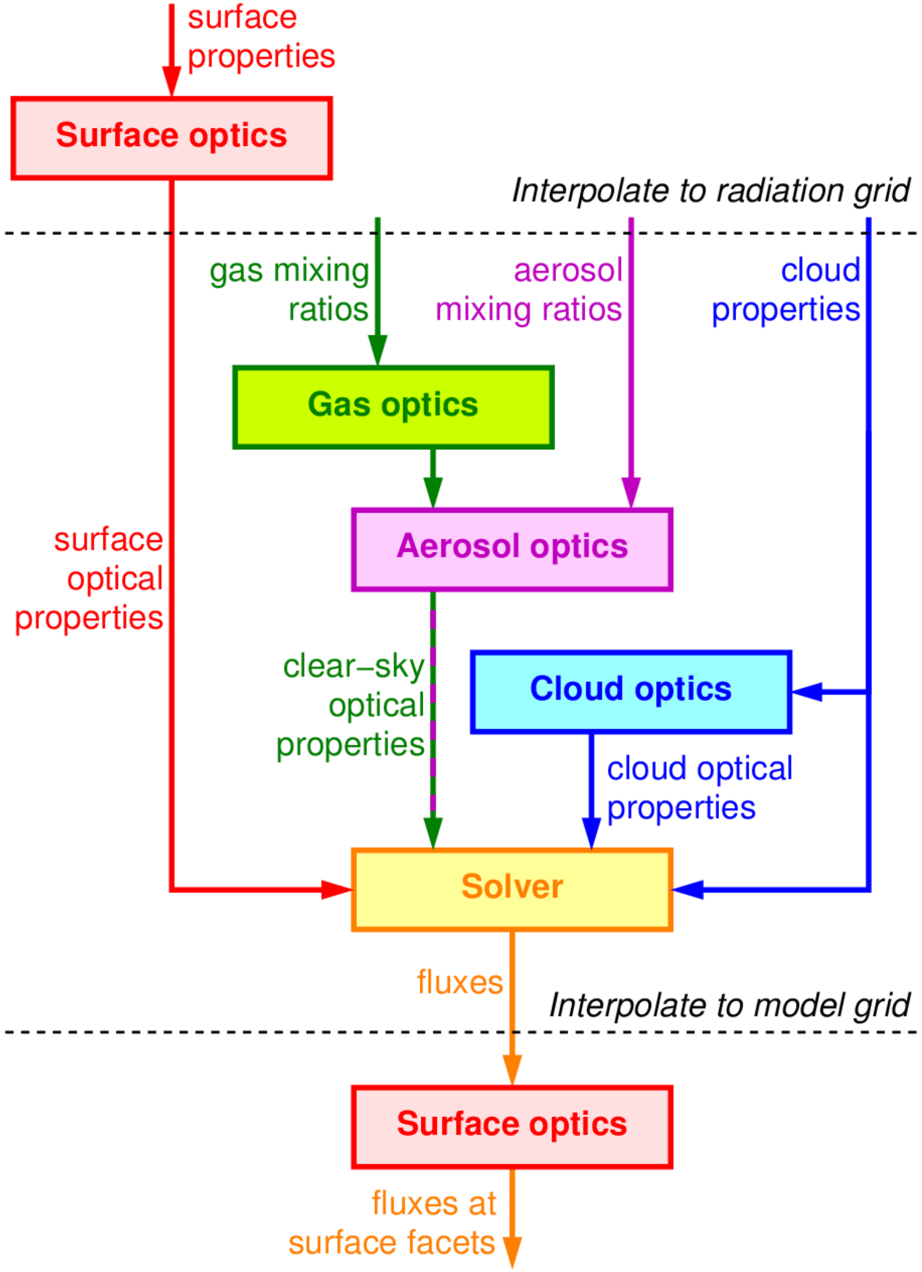




- Ozone concentrations highest in stratosphere and mesosphere: UV absorption leads to *peak shortwave warming at stratopause*
- Carbon dioxide is *well mixed* so its density decreases with height
- Adjacent layers emit and absorb longwave radiation at around 15 microns: net effect largely cancels, except in upper stratosphere where density is low enough to emit freely to space: *strong net cooling balances O_3 heating*
- Strong emission to the surface (the greenhouse effect) that increases with CO_2 concentration: *climate change*
- In the ecRad practical it is possible to investigate what happens to the stratosphere when CO_2 and O_3 concentrations are perturbed

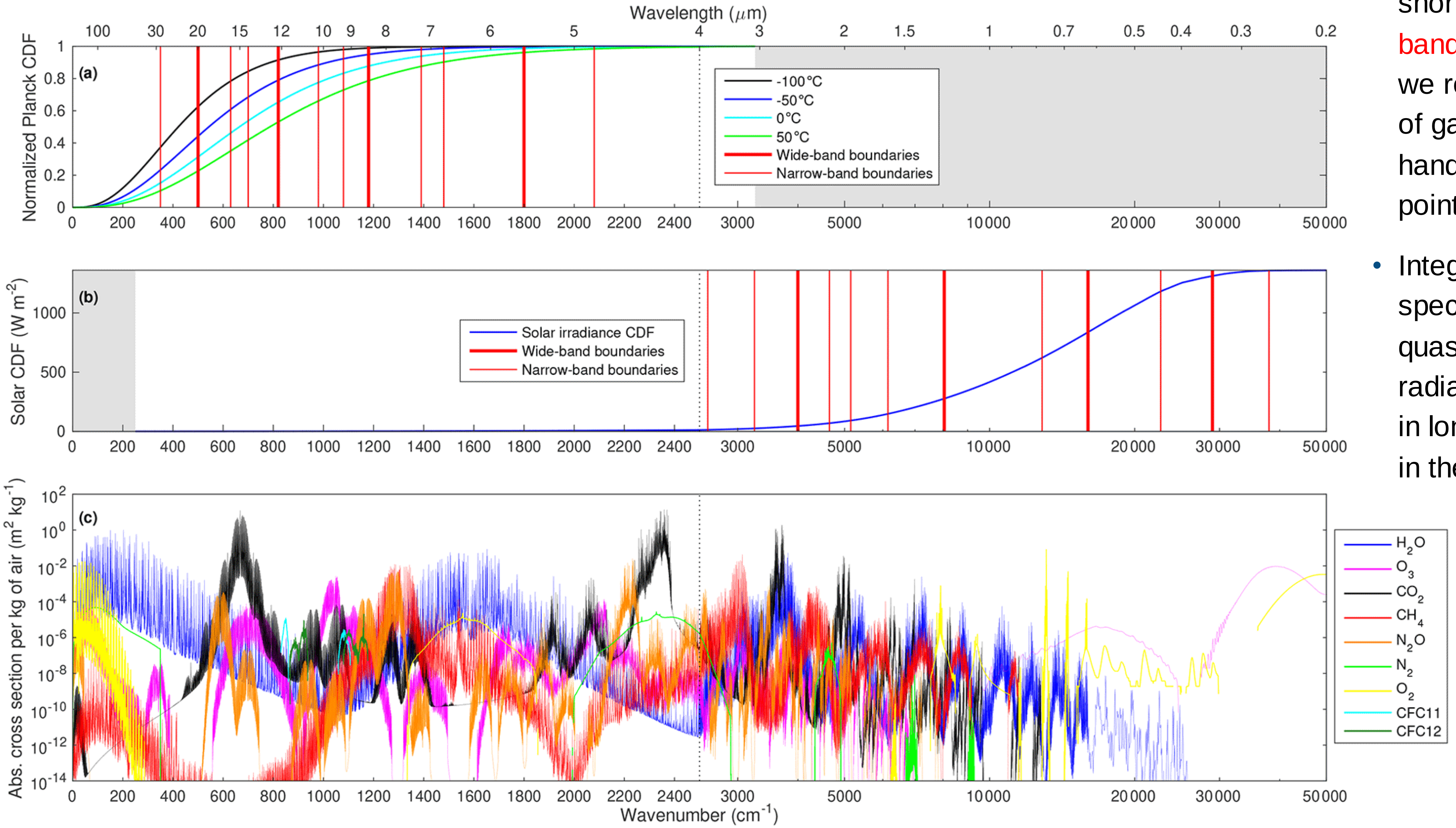
ECMWF's modular radiation scheme "ecRad"

- Gas optics
  - RRTM-G scheme computes absorption optical depth in a total of 252 spectral intervals as a function of concentration of 8 gases
- Aerosol optics
  - Compute scattering properties of various aerosol species and add them to the gas properties
  - Supports prognostic & diagnostic aerosol
- Cloud optics
  - Compute scattering properties of liquid and ice clouds



- Solver
  - Several solvers available for treating complex cloud structure, very flexible with respect to cloud overlap, and the width & shape of the PDF
  - SPARTACUS makes the IFS the only global model that can do 3D radiative effects
  - Longwave scattering optional
- Offline version available for free from GitHub and the ecRad web site

Treatment of gases

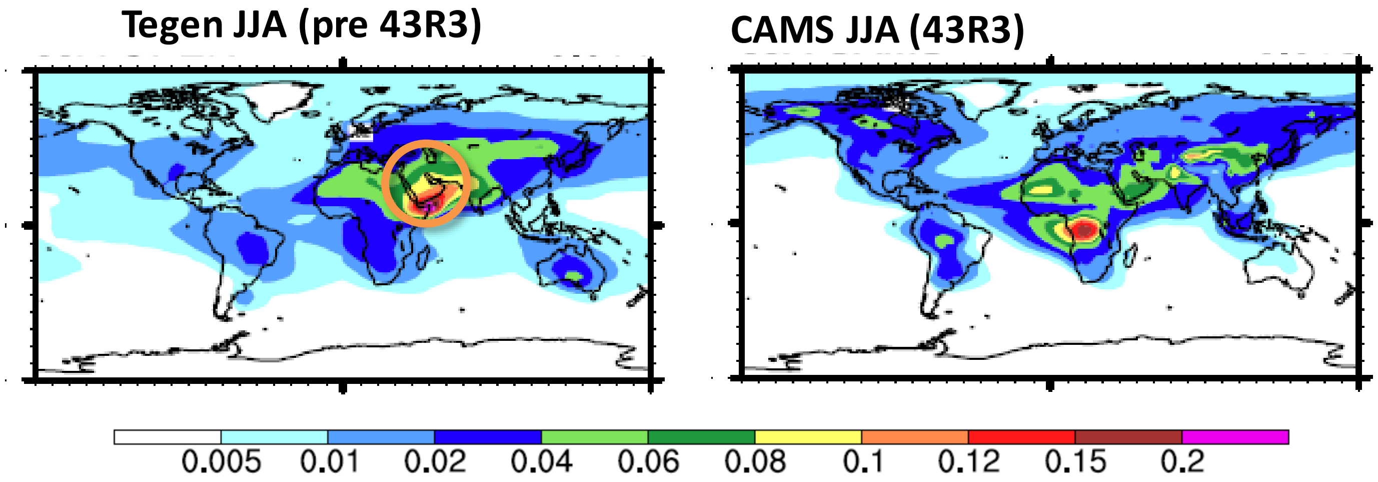


- Split longwave and shortwave spectra into bands, within which we represent the PDF of gas absorption by a handful of spectral points
- Integrate over spectrum with 140 quasi-monochromatic radiation calculations in longwave and 112 in the shortwave

Aerosols

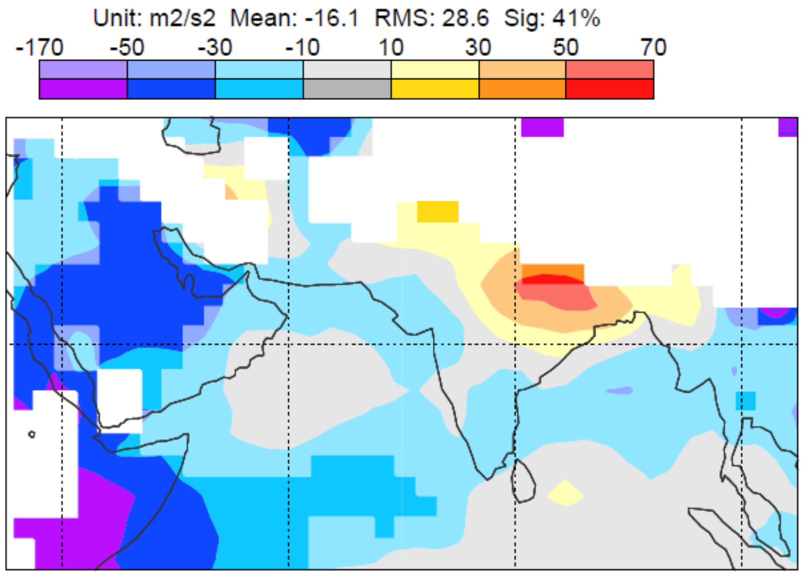
Bozzo et al. (2017)

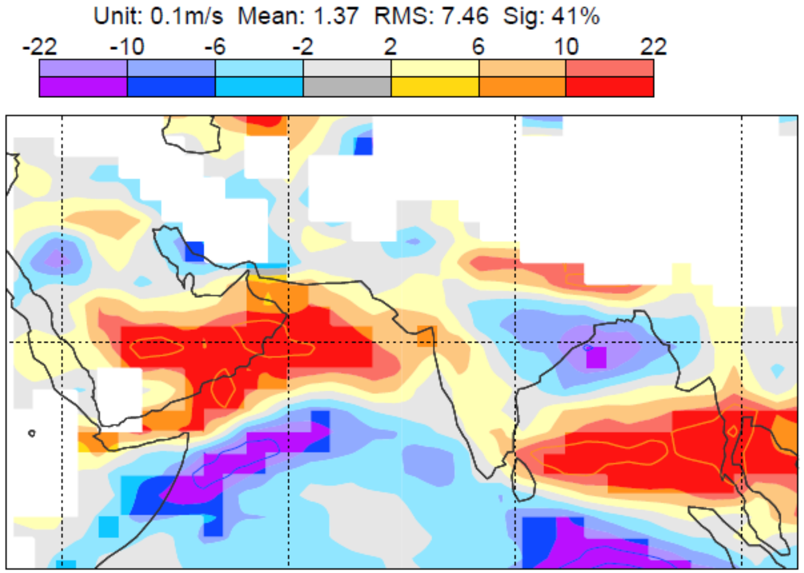
- Atmospheric forcing depends on *absorption* optical depth:


Tegen JJA (pre 43R3)

CAMS JJA (43R3)

- Strong impact on dynamics in the tropics
- A few years ago the aerosol climatology was upgraded to CAMS, which reduced absorption over Arabia, weaked the overactive Indian Summer Monsoon, and *halved the overestimate in monsoon rainfall!*


(b) CAMS climatology: geopotential *bias*


(d) CAMS climatology: zonal wind *bias*

The two-stream equations

- All weather and climate models simplify the treatment of radiation to the following:
- Direct solar beam:

$$\frac{dF_0}{d\tau} = -\frac{F_0}{\mu_0}$$

Optical depth

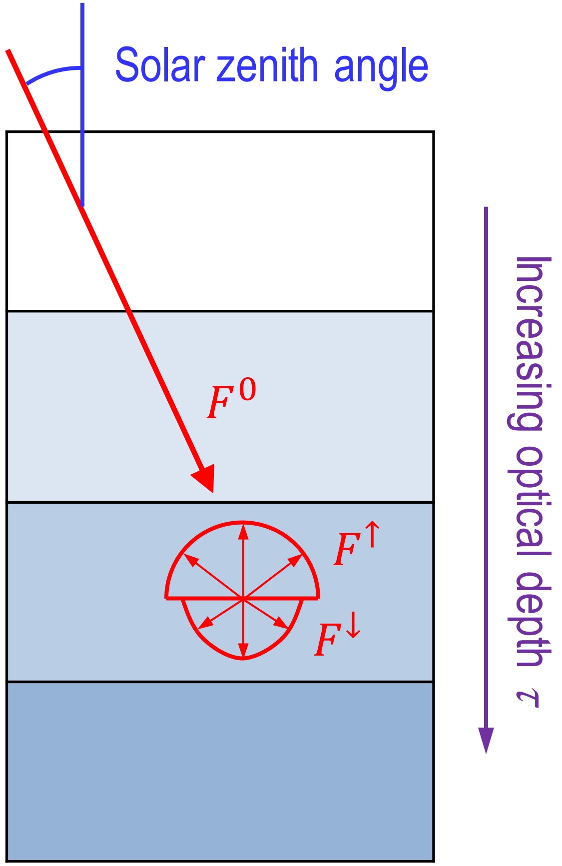
Cosine of solar zenith angle

- Two stream equations for diffuse fluxes:

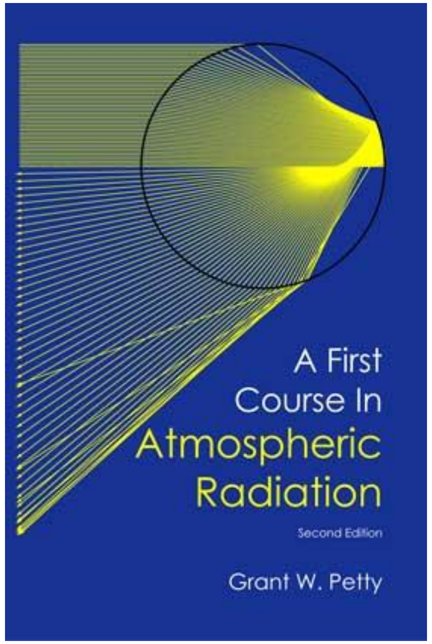
$$\frac{dF^\uparrow}{d\tau} = +\gamma_1 F^\uparrow - \gamma_2 F^\downarrow + S^\uparrow$$

$$\frac{dF^\downarrow}{d\tau} = \underbrace{-\gamma_1 F^\downarrow + \gamma_2 F^\uparrow}_{\text{Scattering between streams}} + S^\downarrow$$

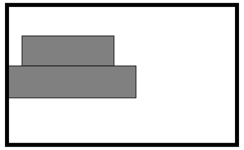
Scattering from the direct beam



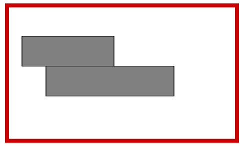
Arthur Schuster



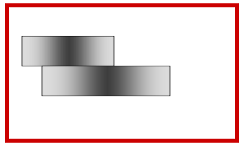
Three issues for representing clouds



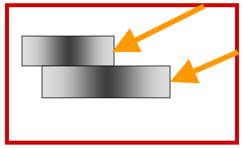
- Clouds in older GCMs used a simple cloud fraction scheme with clouds in adjacent layers being maximally overlapped



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



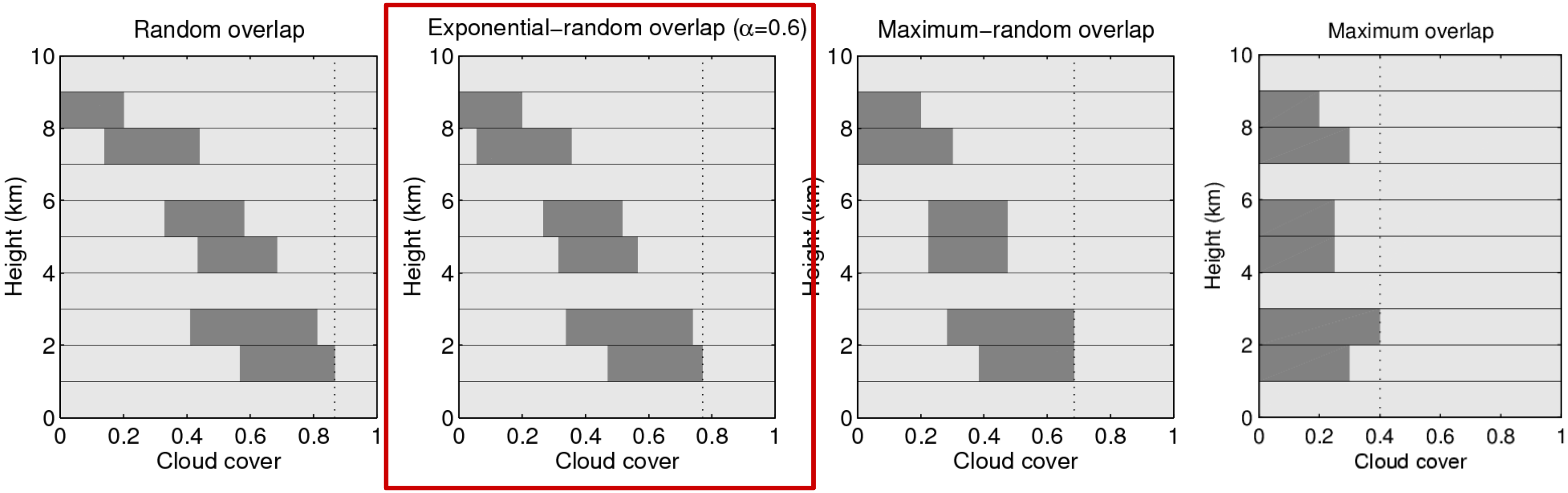
2. Real clouds are horizontally inhomogeneous, leading to albedo and emissivity biases in GCMs (Cahalan et al 1994, Pomroy and Illingworth 2000)



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

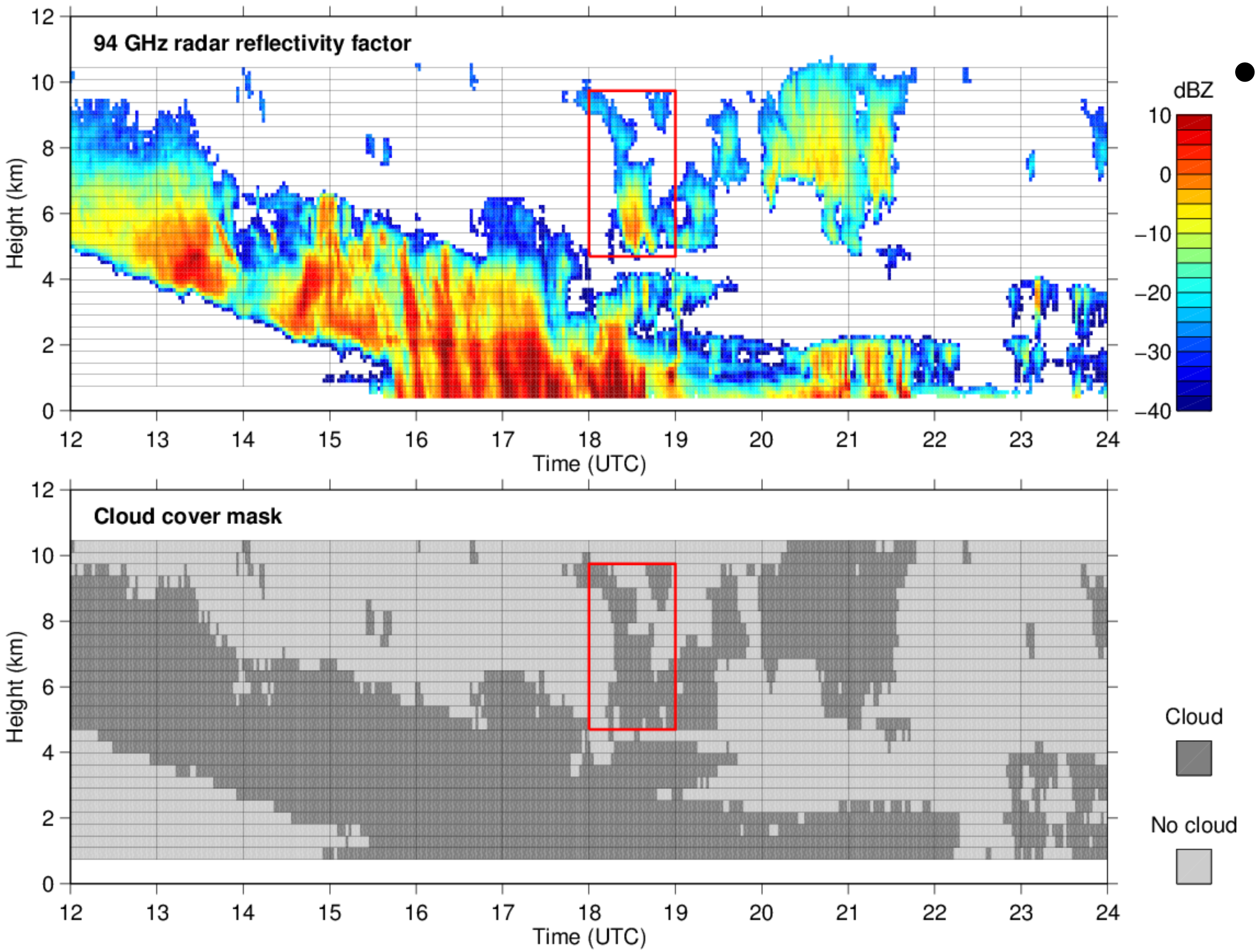
Cloud overlap parametrization

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



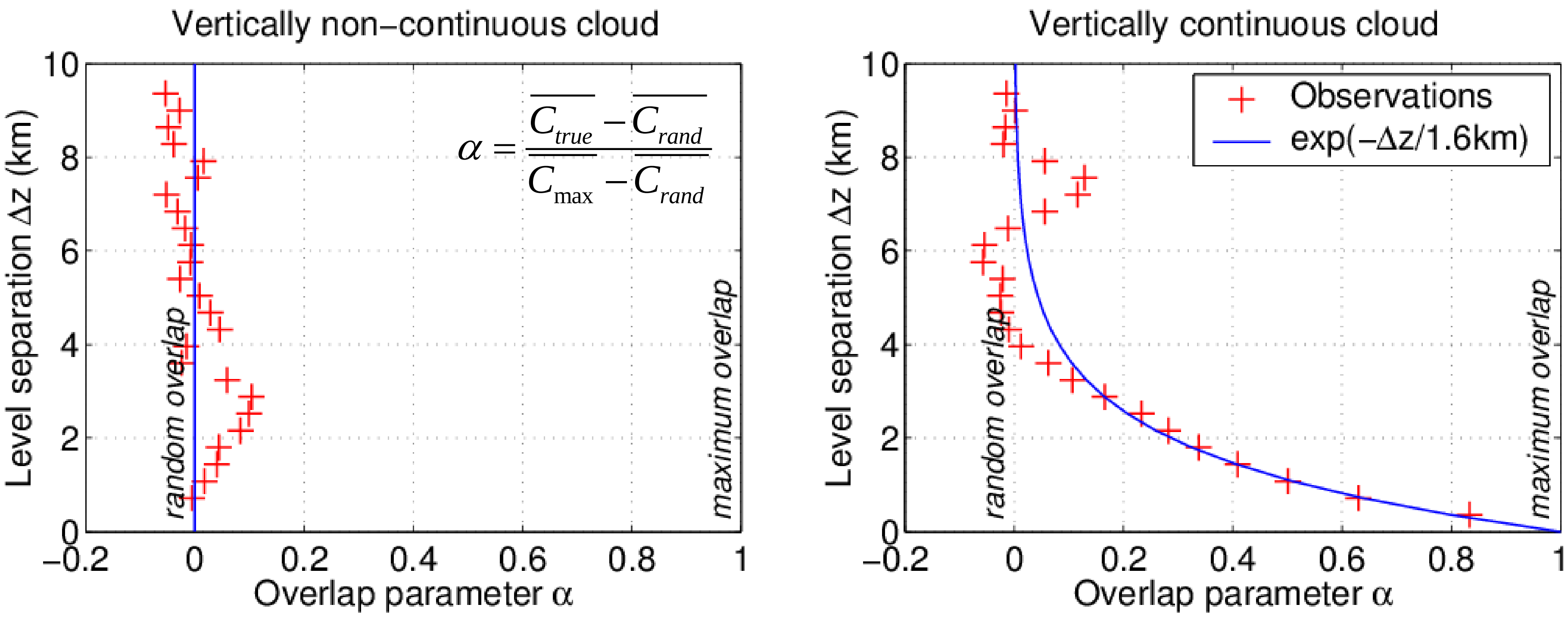
- Observations (Hogan and Illingworth 2000) support "exponential-random overlap":
  - Non-adjacent clouds are randomly overlapped
  - Adjacent clouds correlated with decorrelation length ~2km
  - Many models still use "maximum-random overlap"

Cloud overlap from radar: example



- Radar can observe the actual overlap of clouds

Cloud overlap: results



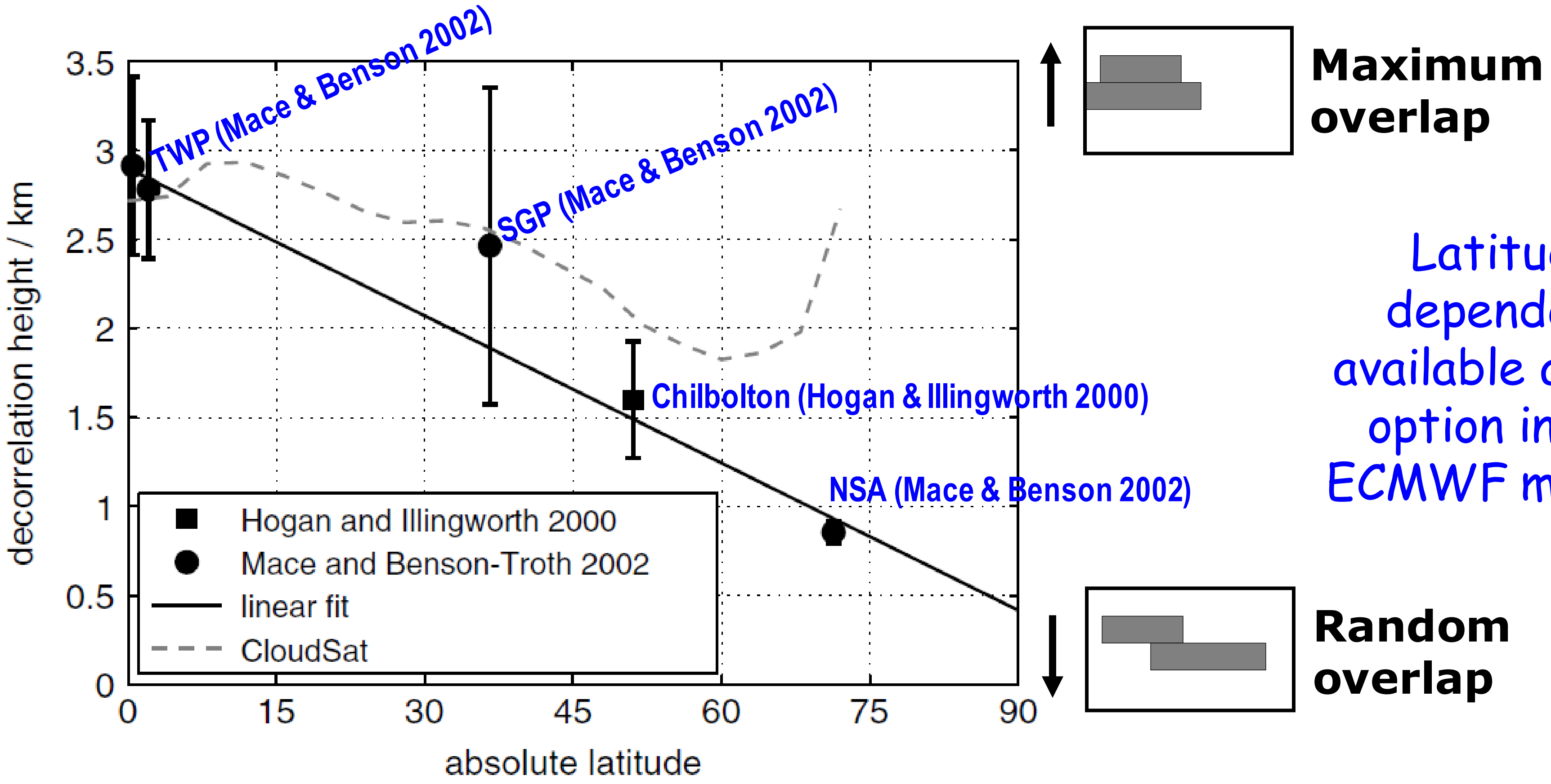
$$\alpha = \frac{\overline{C_{true}} - \overline{C_{rand}}}{\overline{C_{\max}} - \overline{C_{rand}}}$$

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

Hogan and Illingworth (QJ 2000)

Cloud overlap globally

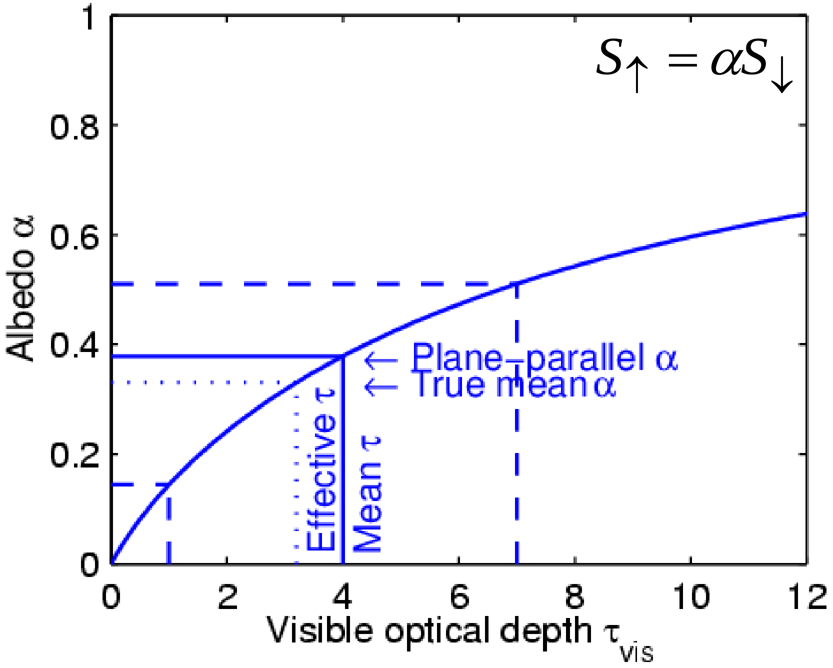
- Latitudinal dependence of decorrelation length from Chilbolton and the worldwide ARM sites
  - More convection and less shear in the tropics so more maximally overlapped

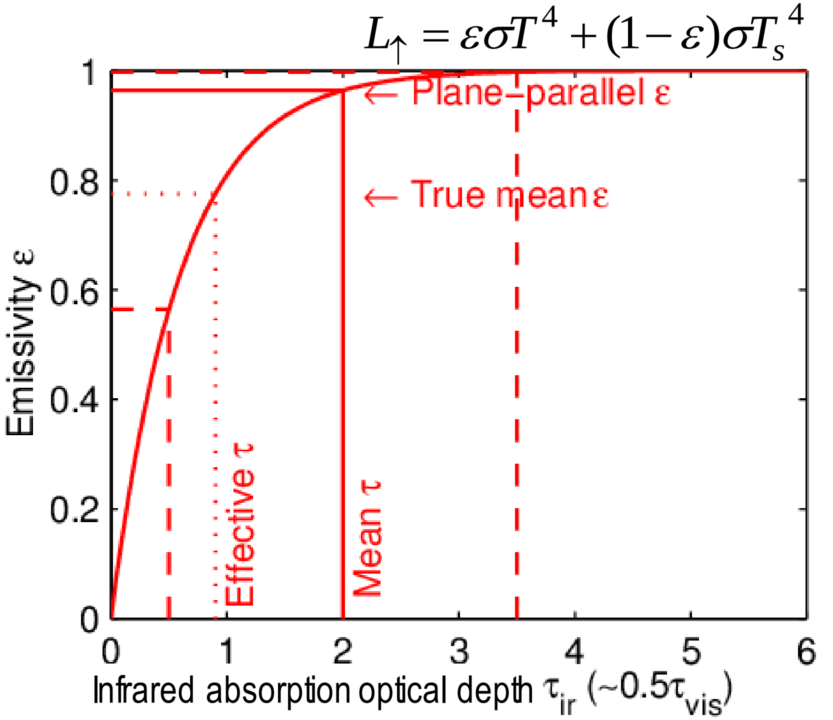


Latitudinal dependence available as an option in the ECMWF model

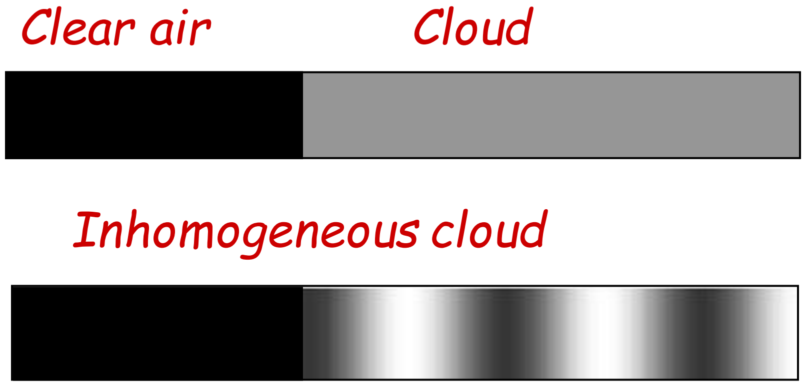
Shonk et al. (QJ 2010)

Why is cloud structure important?





- An example of *non-linear averaging*

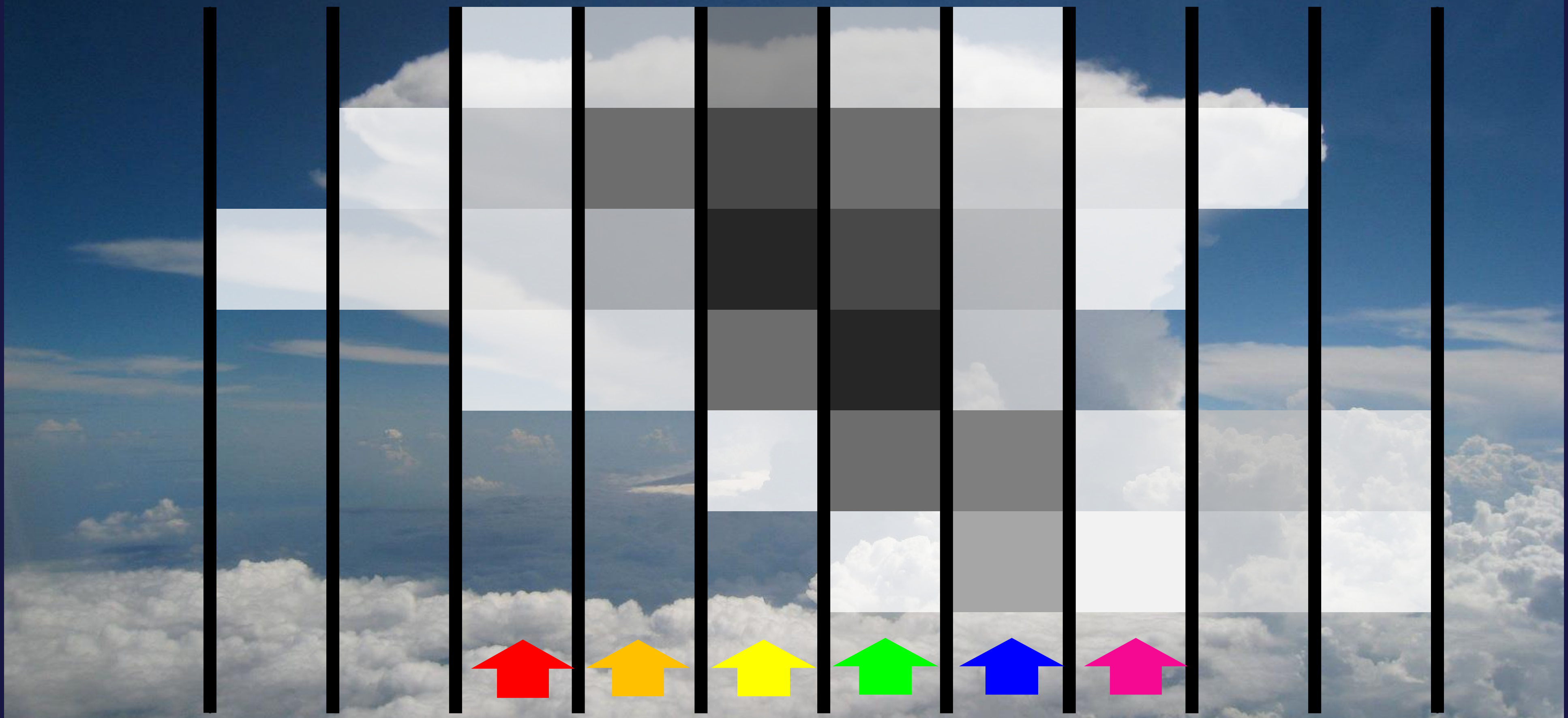


- Non-uniform clouds have *lower* mean emissivity & albedo for the same mean optical depth due to curvature in the relationships

How do the three solvers compute how clouds interact with radiation?

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

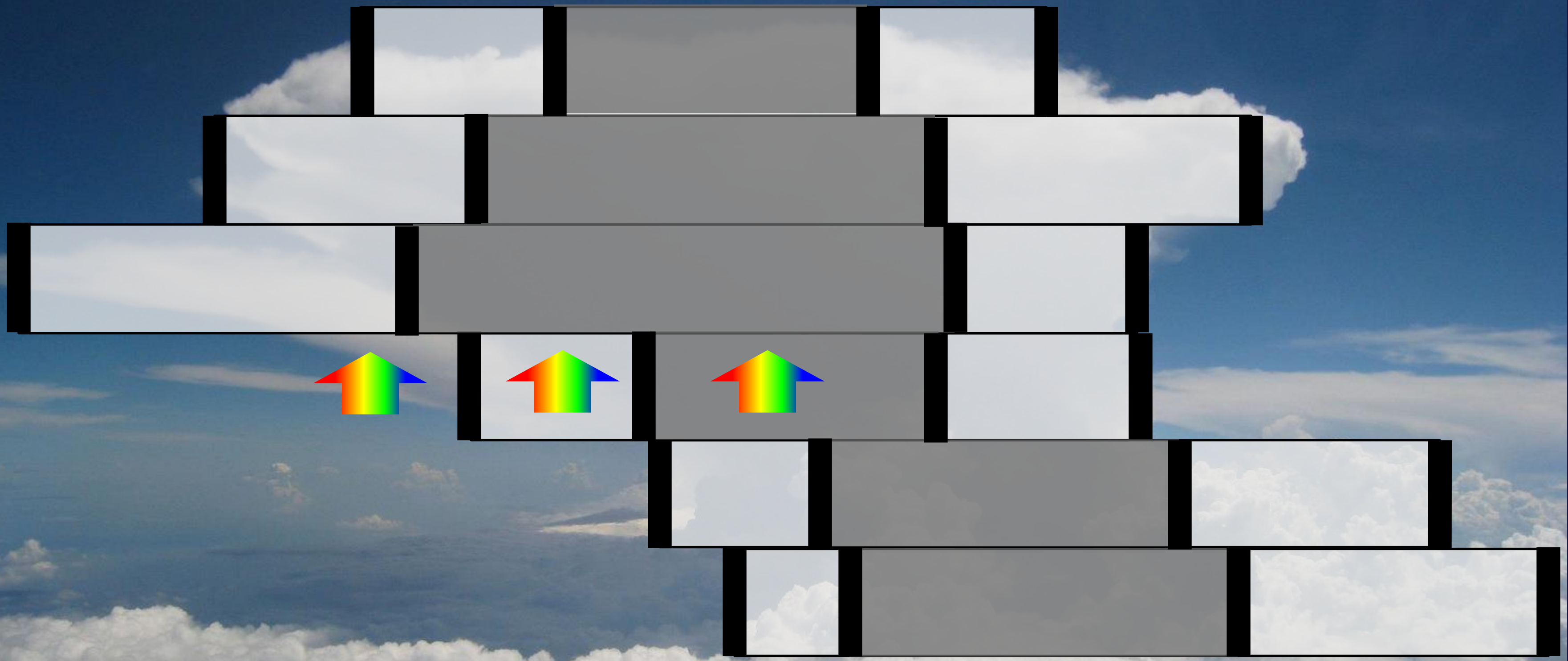
Each wavelength sees a different cloud realization (OPERATIONAL)



- Use prognostic cloud fraction and assumed standard deviation of cloud water
- Stochastic cloud generator is fast but leads to some noise in fluxes
- McICA now used in many (most?) global weather and climate models

Tripleclouds (Shonk & Hogan 2008)

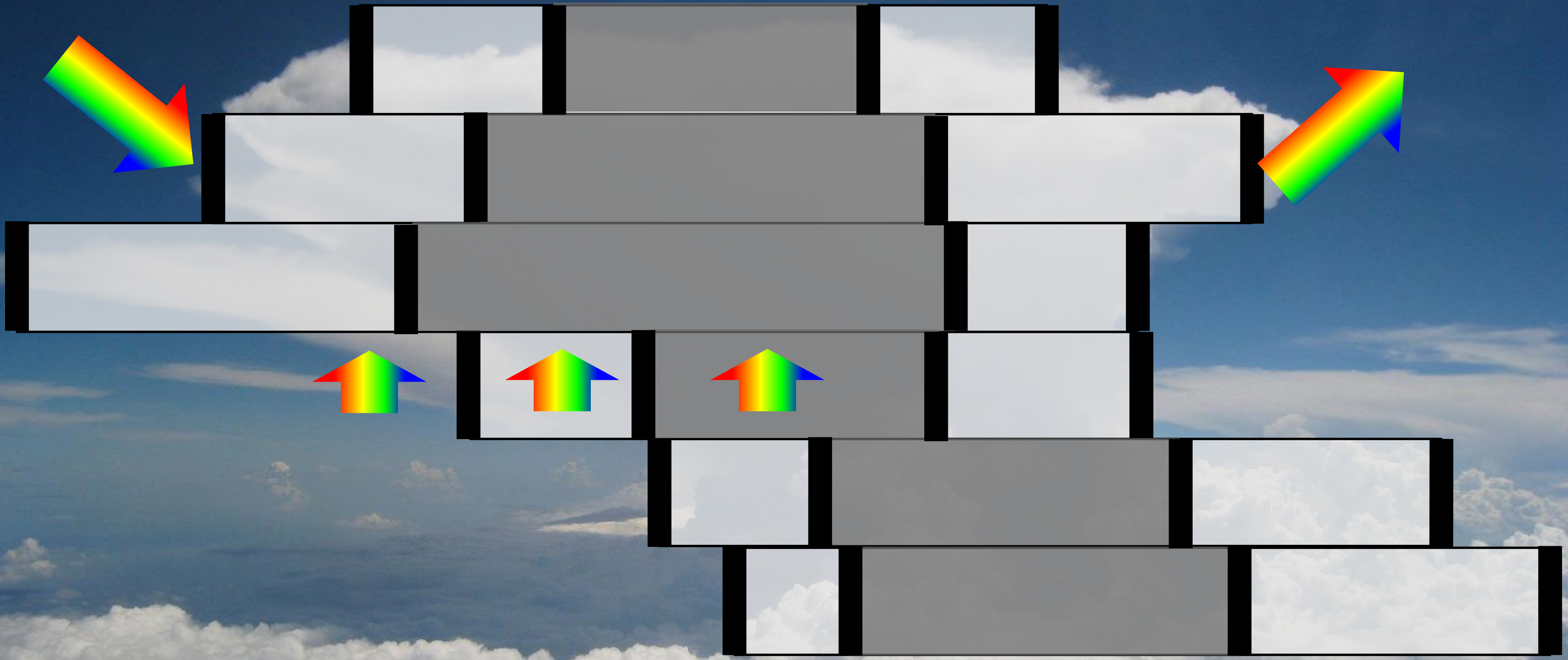
Approximate cloud variability by three regions: one clear and two cloudy



- Cloud overlap rules govern how radiation enters different regions at layer interfaces
- Fluxes and heating rates are noise-free, but this solver is slower than McICA

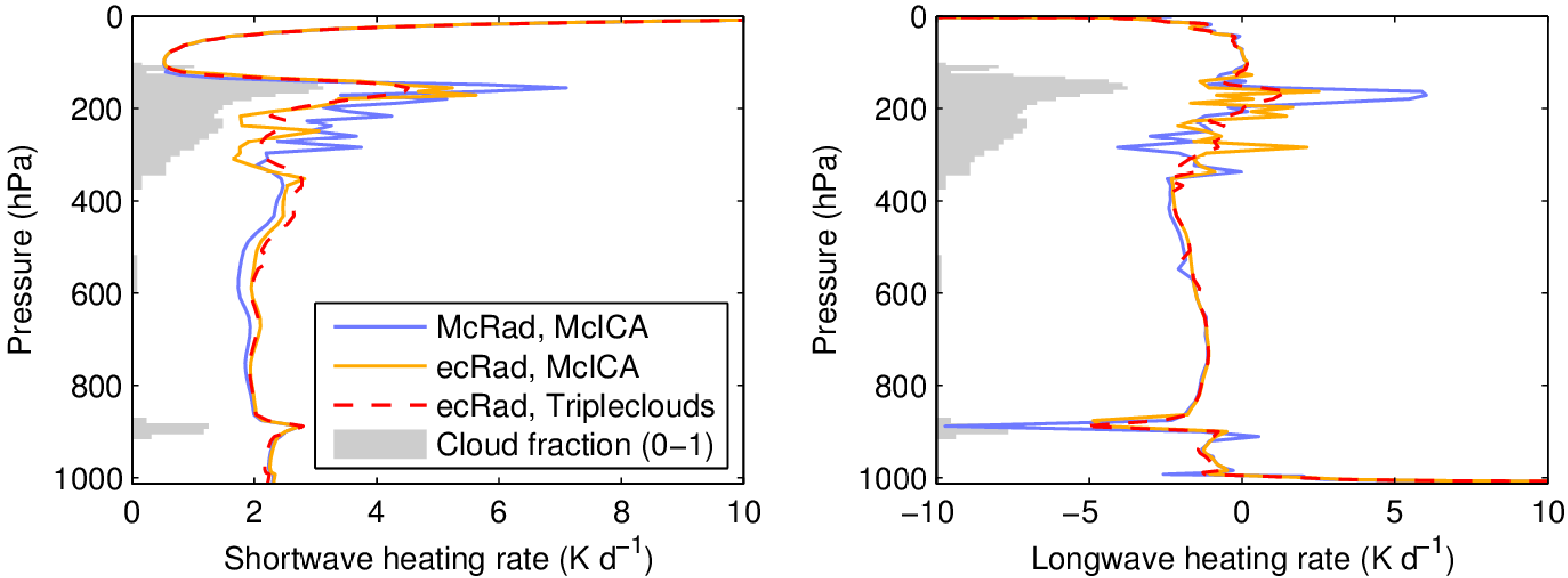
SPARTACUS (Hogan et al., Schäfer et al. 2016)

Tripleclouds with lateral radiation exchange between regions



- SPARTACUS makes ecRad the first GCM radiation scheme that can simulate 3D radiative effects
- Slower than Tripleclouds, and still under development and evaluation

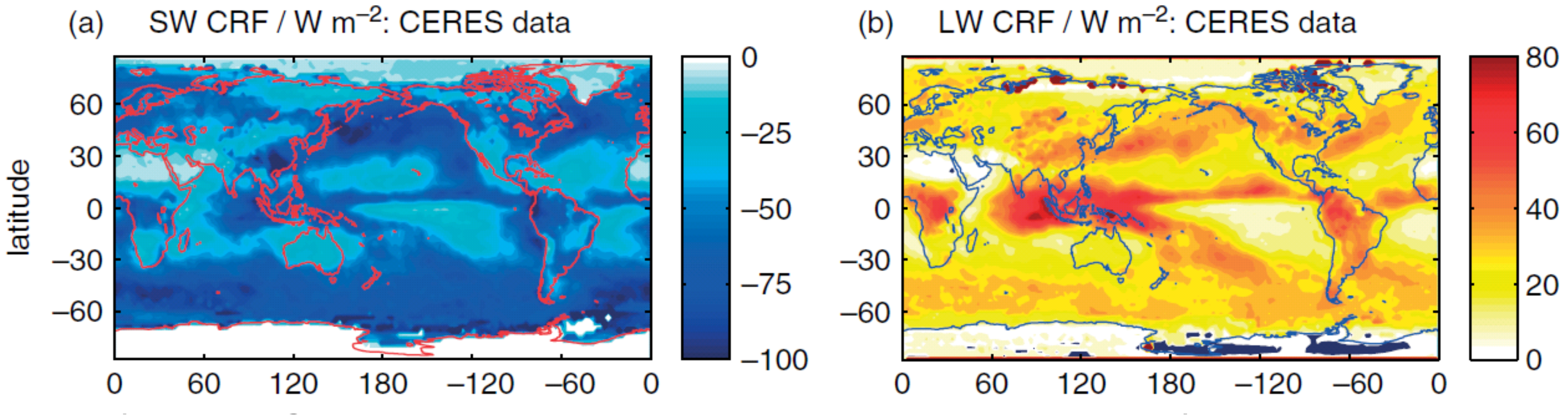
Noise in ecRad’s McICA solver compared to older McRad scheme



Global impact of cloud structure

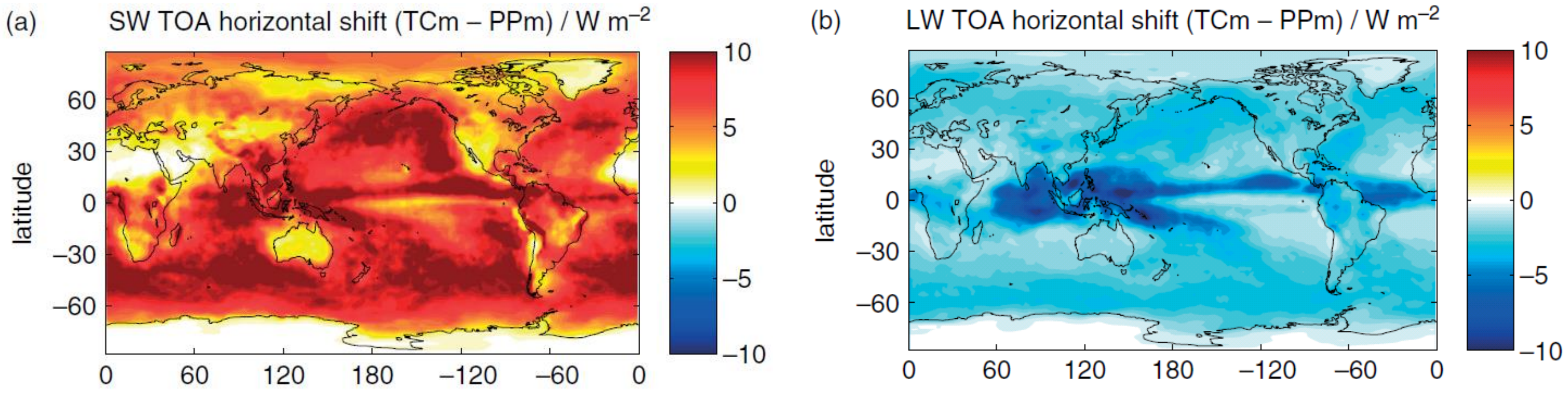
Shonk and Hogan (2010)

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



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

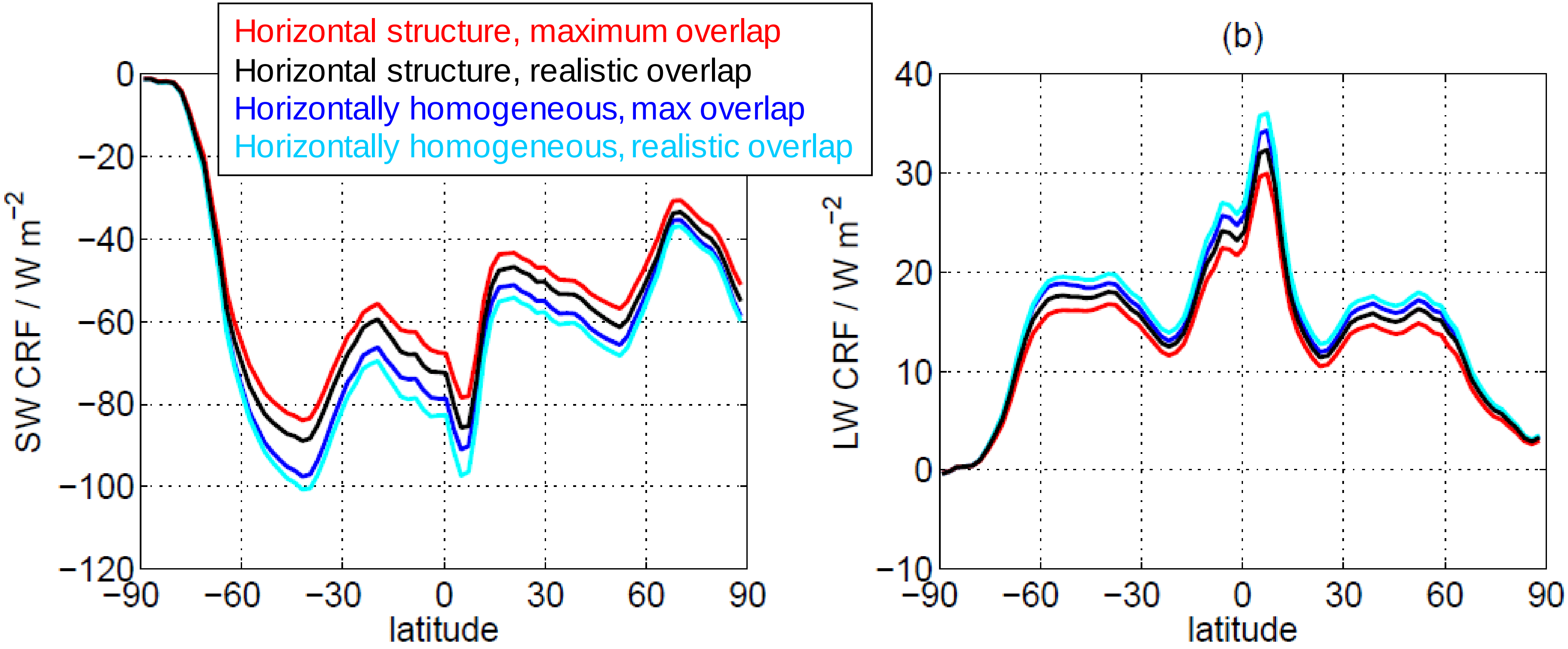
(b) LW CRF / W m^{-2}: CERES data



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

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

Horizontal versus vertical structure



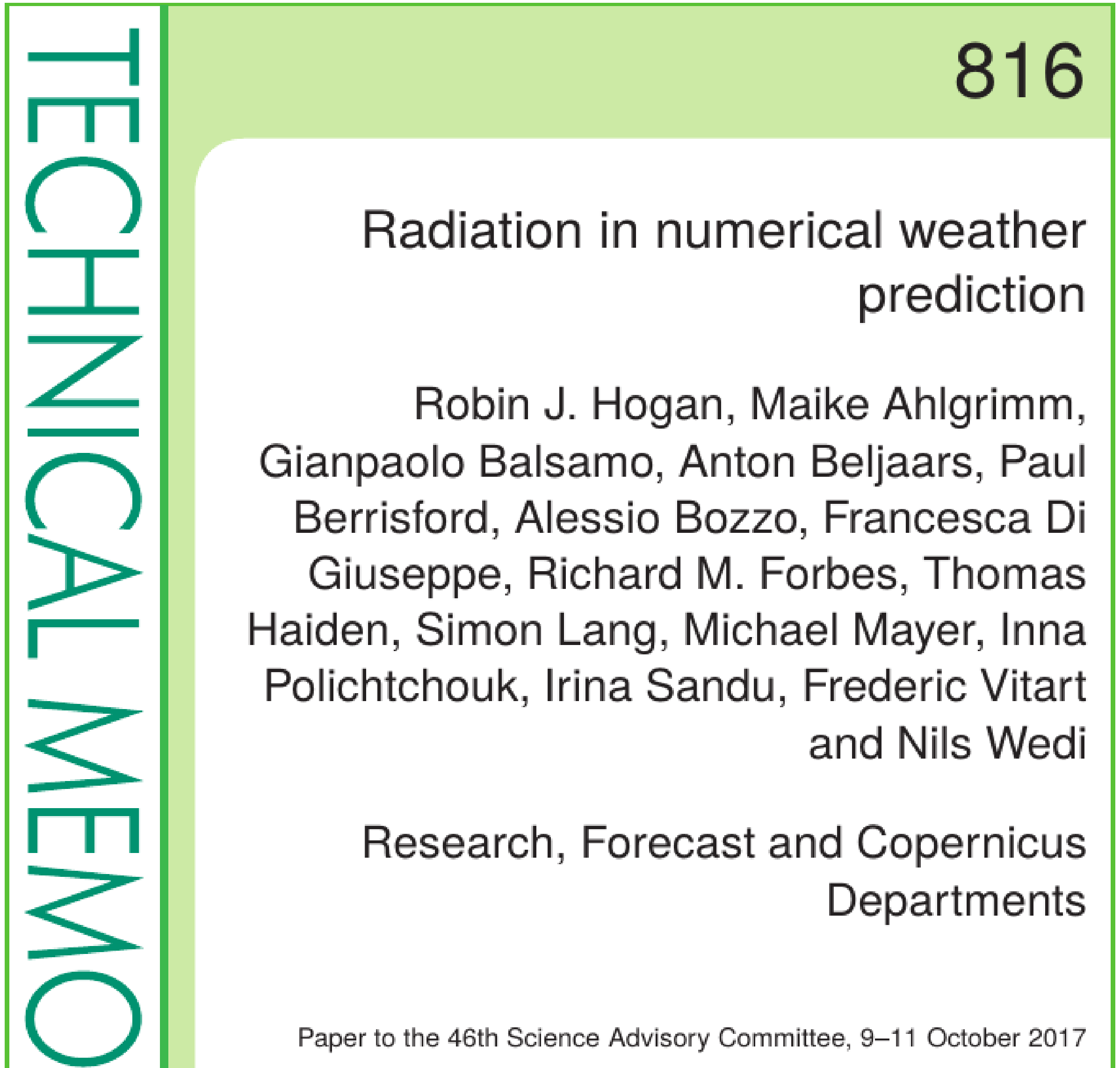
- Correcting cloud structure changes cloud radiative effect by around 10%
- Impact of adding horizontal structure about twice that of improving vertical overlap
- Note that uncertainties in the horizontal structure effect are much larger than in the vertical overlap effect

Summary and outlook

- Modular design of ecRad makes it well suited for research and operational use
  - We can test alternative modules (e.g. new solvers) while keeping everything else fixed
  - ecRad has been implemented in IFS, MesoNH, ICON, LMDZ, AROME, ISAC and MAR models
- Offline version freely available (Apache 2.0 open-source license)
  - https://confluence.ecmwf.int/display/ECRAD
  - https://github.com/ecmwf-ifs/ecrad
- **If you compile it you can try the exercises in the "practical" directory**
- Outlook for radiation developments
  - Much more efficient gas optics and spectral integration
  - Remove middle-atmosphere temperature bias via new UV solar spectrum
  - Prognostic ozone and aerosols interactive with radiation
  - Overhaul surface treatment, including 3D interactions with cities and forests
  - Orographic effects at high resolution

Further reading

- **Radiation in NWP (ECMWF Technical memo, 2017)**



TECHNICAL MEMO

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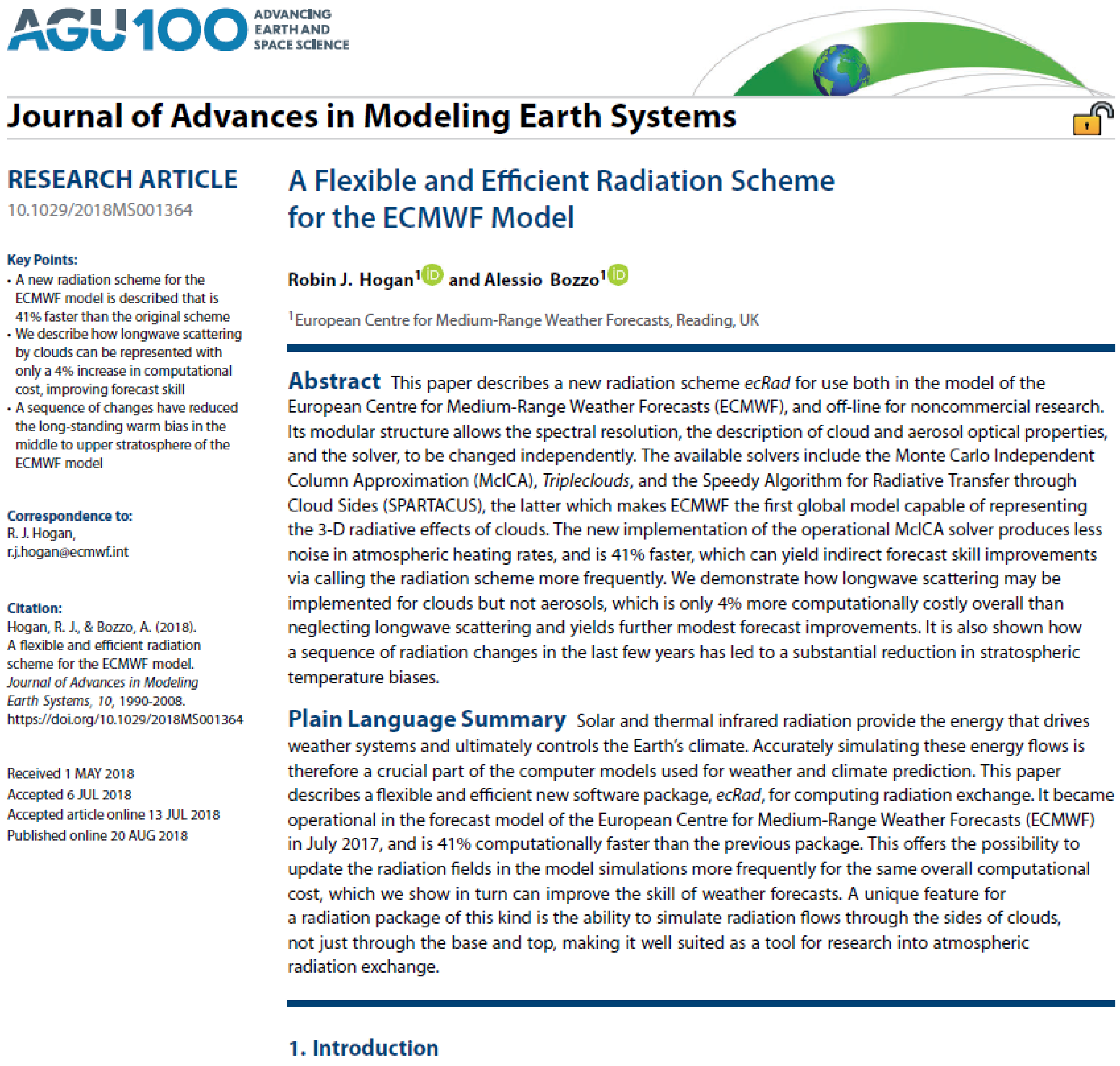
Radiation in numerical weather prediction

Robin J. Hogan, Maike Ahlgrimm, Gianpaolo Balsamo, Anton Beljaars, Paul Berrisford, Alessio Bozzo, Francesca Di Giuseppe, Richard M. Forbes, Thomas Haiden, Simon Lang, Michael Mayer, Inna Polichtchouk, Irina Sandu, Frederic Vitart and Nils Wedi

Research, Forecast and Copernicus Departments

Paper to the 46th Science Advisory Committee, 9–11 October 2017

- **ecRad (JAMES 2018)**



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RESEARCH ARTICLE

10.1029/2018MS001364

Key Points:

- A new radiation scheme for the ECMWF model is described that is 41% faster than the original scheme
- We describe how longwave scattering by clouds can be represented with only a 4% increase in computational cost, improving forecast skill
- A sequence of changes have reduced the long-standing warm bias in the middle to upper stratosphere of the ECMWF model

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Citation:
Hogan, R. J., & Bozzo, A. (2018). A flexible and efficient radiation scheme for the ECMWF model. *Journal of Advances in Modeling Earth Systems, 10*, 1990-2008. https://doi.org/10.1029/2018MS001364

Received 1 MAY 2018
Accepted 6 JUL 2018
Accepted article online 13 JUL 2018
Published online 20 AUG 2018

A Flexible and Efficient Radiation Scheme for the ECMWF Model

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Abstract This paper describes a new radiation scheme *ecRad* for use both in the model of the European Centre for Medium-Range Weather Forecasts (ECMWF), and off-line for noncommercial research. Its modular structure allows the spectral resolution, the description of cloud and aerosol optical properties, and the solver, to be changed independently. The available solvers include the Monte Carlo Independent Column Approximation (McICA), *Tripleclouds*, and the Speedy Algorithm for Radiative Transfer through Cloud Sides (SPARTACUS), the latter which makes ECMWF the first global model capable of representing the 3-D radiative effects of clouds. The new implementation of the operational McICA solver produces less noise in atmospheric heating rates, and is 41% faster, which can yield indirect forecast skill improvements via calling the radiation scheme more frequently. We demonstrate how longwave scattering may be implemented for clouds but not aerosols, which is only 4% more computationally costly overall than neglecting longwave scattering and yields further modest forecast improvements. It is also shown how a sequence of radiation changes in the last few years has led to a substantial reduction in stratospheric temperature biases.

Plain Language Summary Solar and thermal infrared radiation provide the energy that drives weather systems and ultimately controls the Earth's climate. Accurately simulating these energy flows is therefore a crucial part of the computer models used for weather and climate prediction. This paper describes a flexible and efficient new software package, *ecRad*, for computing radiation exchange. It became operational in the forecast model of the European Centre for Medium-Range Weather Forecasts (ECMWF) in July 2017, and is 41% computationally faster than the previous package. This offers the possibility to update the radiation fields in the model simulations more frequently for the same overall computational cost, which we show in turn can improve the skill of weather forecasts. A unique feature for a radiation package of this kind is the ability to simulate radiation flows through the sides of clouds, not just through the base and top, making it well suited as a tool for research into atmospheric radiation exchange.

1. Introduction