# Radiation

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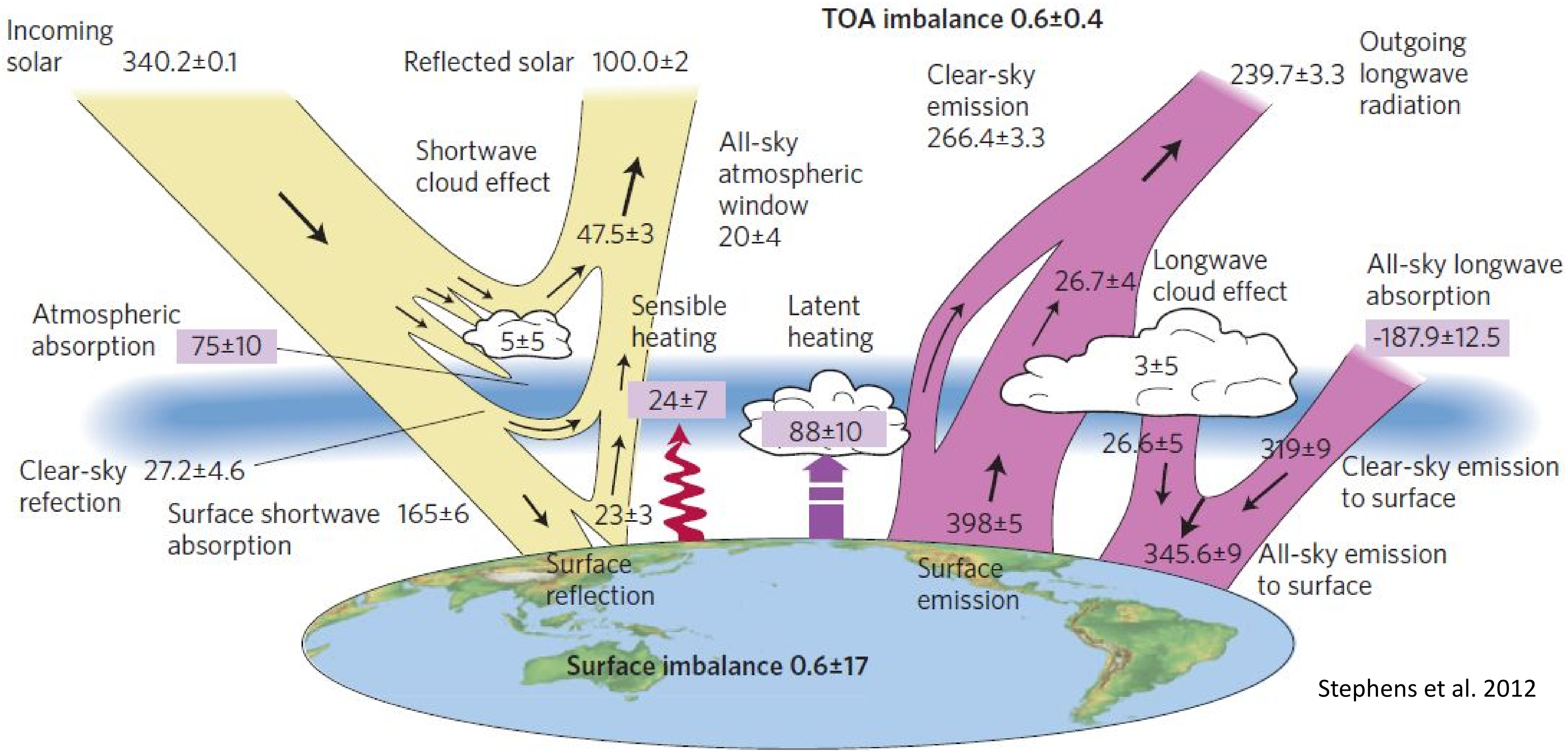
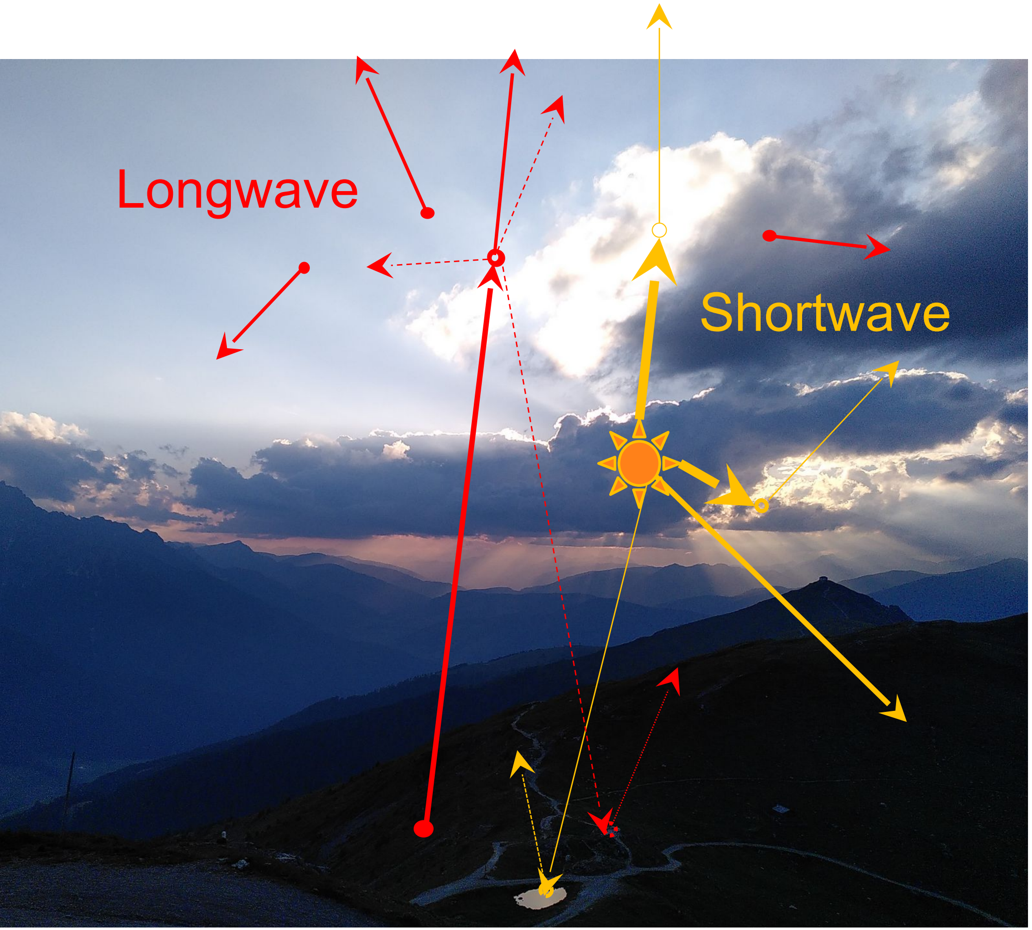
# Radiation budget drives climate and weather




Stephens et al. 2012

Top-of atmosphere radiation exchange with sun / space determines climate, measured since 1960s

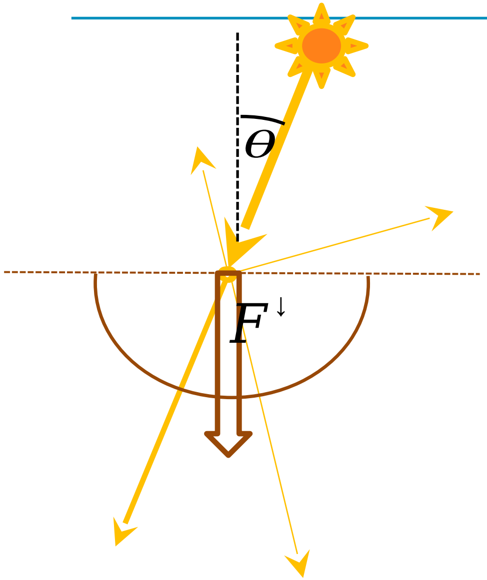
# Radiation in reality

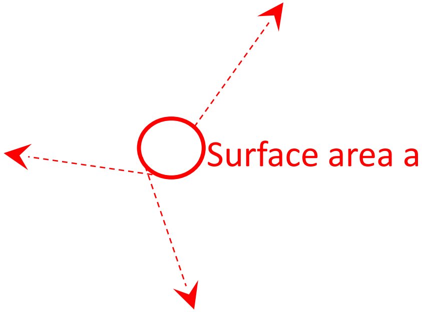



- Photons emitted by sun (**shortwave** / visible) and Earth system (**longwave** / infrared), absorbed or scattered by surface, atmospheric gases, aerosol, cloud water or ice particles

- Described by Maxwell equations + quantum-mechanics, BUT do not have necessary information – need bulk treatment

# Radiation variables and thermal emission laws




- Zenith angle $\theta$, azimuth angle $\phi$
- **Radiance** $R$: radiative power at one angle (per area)
- Irradiance or **flux** $F$: Radiative power per area integrated over angles, e.g. total up- or downward flux,

  $F^{\downarrow}(\lambda) = \int_{\pi/2}^{\pi} \int_{0}^{2\pi} R(x, \lambda, \theta, \phi)\, d\phi\, d\theta,$ $\lambda$ wavelength
- Thermal emitted power per area, (one wavelength): **Planck's law**;

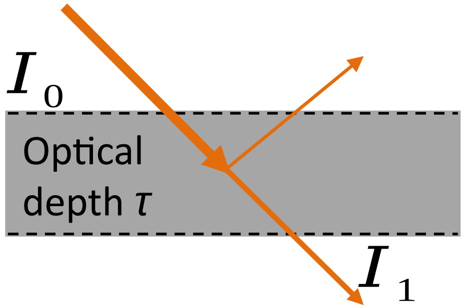
All wavelengths: **Stefan-Boltzmann law** $F = \sigma T^4$

$\sigma$ Stefan-Boltzmann constant

# Material bulk optical properties

- **Extinction coefficient** $\beta$ measures local extinction by absorption + scattering
- **Optical depth** $\tau = \int_{path\ s} \beta\ ds$ measures extinction along a path

  **Beer-Lambert-law** $I_1 = I_0 \cdot exp(-\tau)$




- **Single scattering albedo**

  $\omega$ = fraction of total extinction due to scattering = $\beta_{scat} / (\beta_{scat} + \beta_{abs})$
- **Asymmetry parameter** g**:** describes ratio of forward to backward scattering

# Radiation scheme in NWP / climate model

From NWP / climate model:

- temperature, humidity
- gases, aerosol, surface properties (usually climatology)
- Clouds: cloud fraction, liquid & ice water content, effective particle radius

Radiation scheme

- **Optical properties** for each atmospheric component: optical depth, single scattering albedo, asymmetry factor
- **Radiation solver** calculates **radiative fluxes,**
- From fluxes: **heating rates**

- Numerical efficiency: Use coarser radiation grid, long radiation timestep
- Météo-France models: ecRad (Hogan & Bozzo 2018)

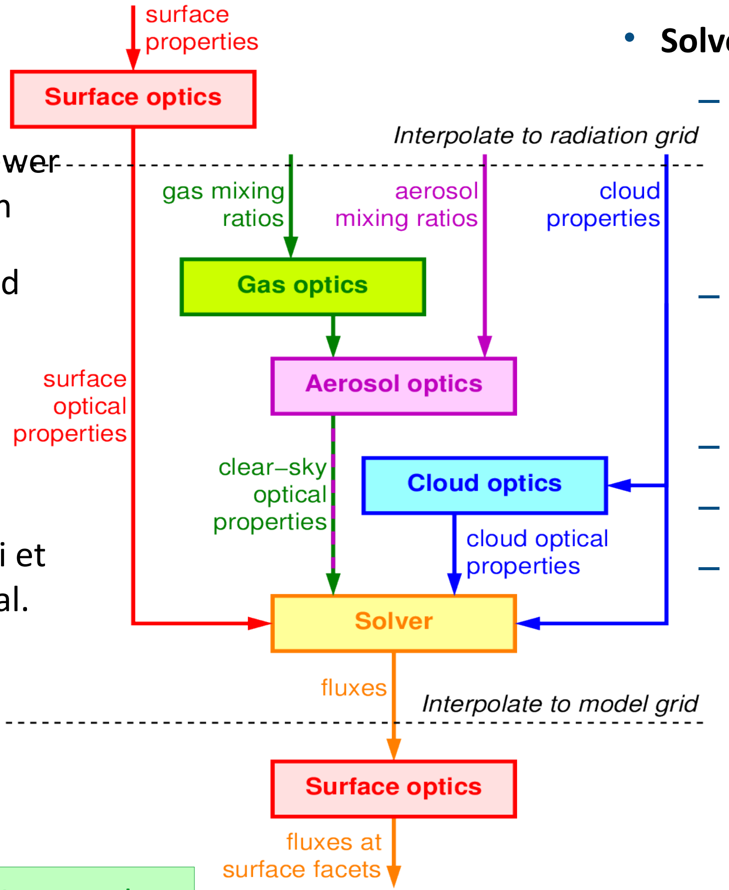
# New modular radiation scheme ecRad (Hogan & Bozzo 2018, more details Lecture 3)

- **Gas optics:**
  - RRTMG (Iacono et al. 2008)
  - ecCKD (Hogan & Matricardi 2020): Fewer spectral intervals but similar precision
- **Aerosol optics:** variable species number and properties (set at run-time)
- **Cloud optics:**
  - **liquid:** SOCRATES (MetOffice), Slingo (1989), Mie calculation
  - **ice:** Fu 1996, 1997, 1998 (default) , Yi et al. 2013, Baran et al. 2014, Baum et al. 2014

From ecRad 1.6: user can choose hydrometeor number + add optics

- *Surface: Consistent treatment of urban and forest canopies*

Implemented in ARPEGE, AROME and Meso-NH (default in next version)




- **Solvers** for radiative transfer equations:
  - **McICA** (Pincus et al. 2003), **Tripleclouds** (Shonk & Hogan, 2008) or **SPARTACUS** (Schäfer et al. 2016, Hogan et al. 2016)
  - SPARTACUS makes ecRad the only global radiation scheme that can do sub-grid **3D** radiative effects
  - Longwave scattering optional
  - Can configure **cloud overlap**
  - **Cloud inhomogeneity**: can configure width and shape of PDF

Info / documentation: https://confluence.ecmwf.int/display/ECRAD/ECMWF+Radiation+Scheme+Home

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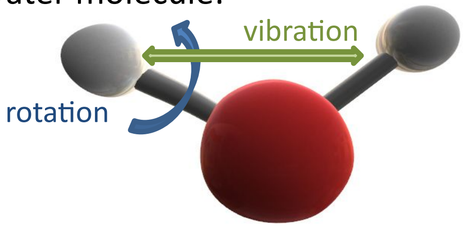
# Radiation spectra and atmospheric gases

# Atmospheric gases

- Molecules have different modes (vibration, rotation)

Water molecule:

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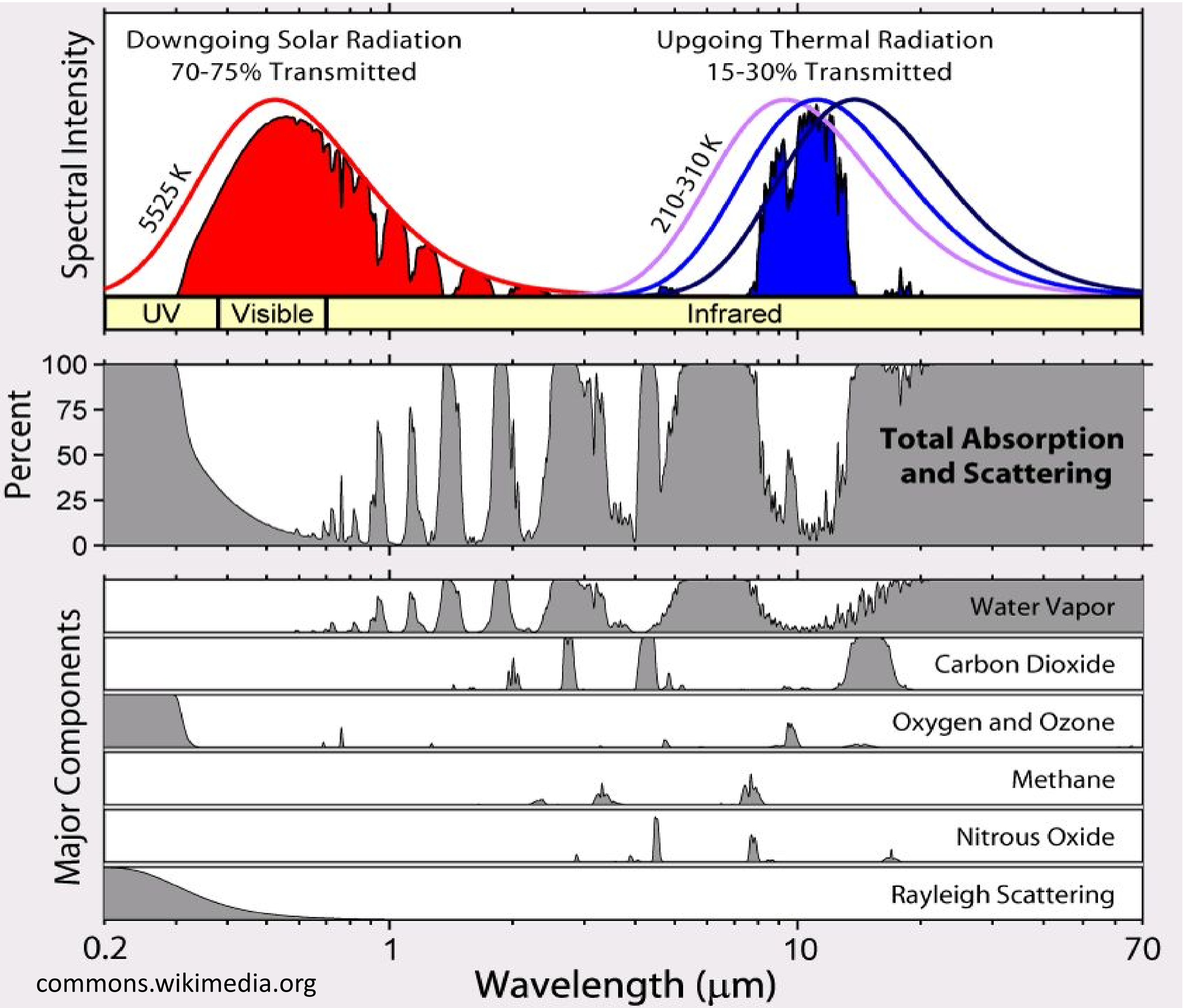
- Absorbing / emitting photons changes mode, photon wavelength corresponds to energy change

- Air molecules also scatter shortwave (especially ultraviolet / UV) radiation

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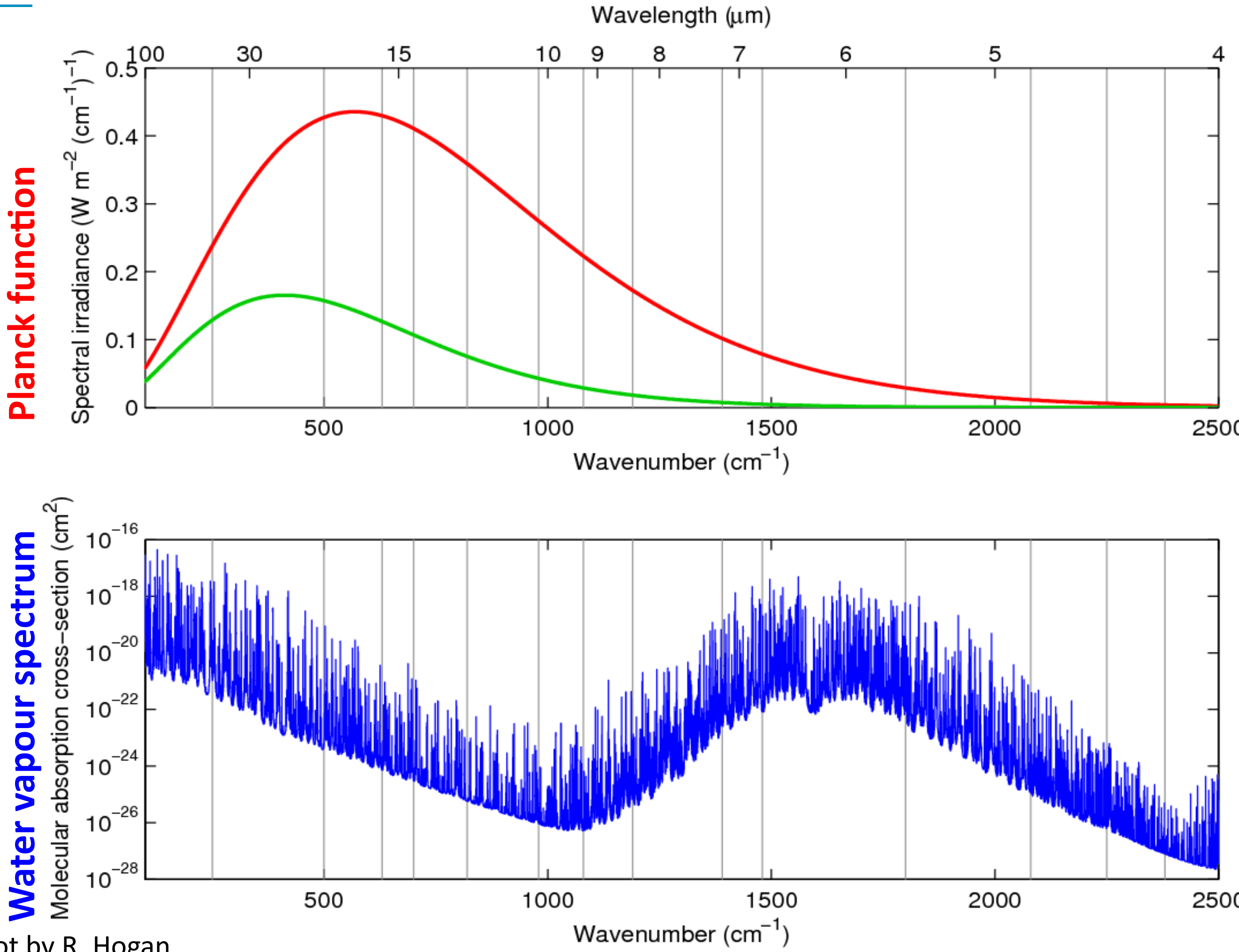
# Gas optics: bands (RRTMG)

- Divide spectrum into bands with similar Planck function

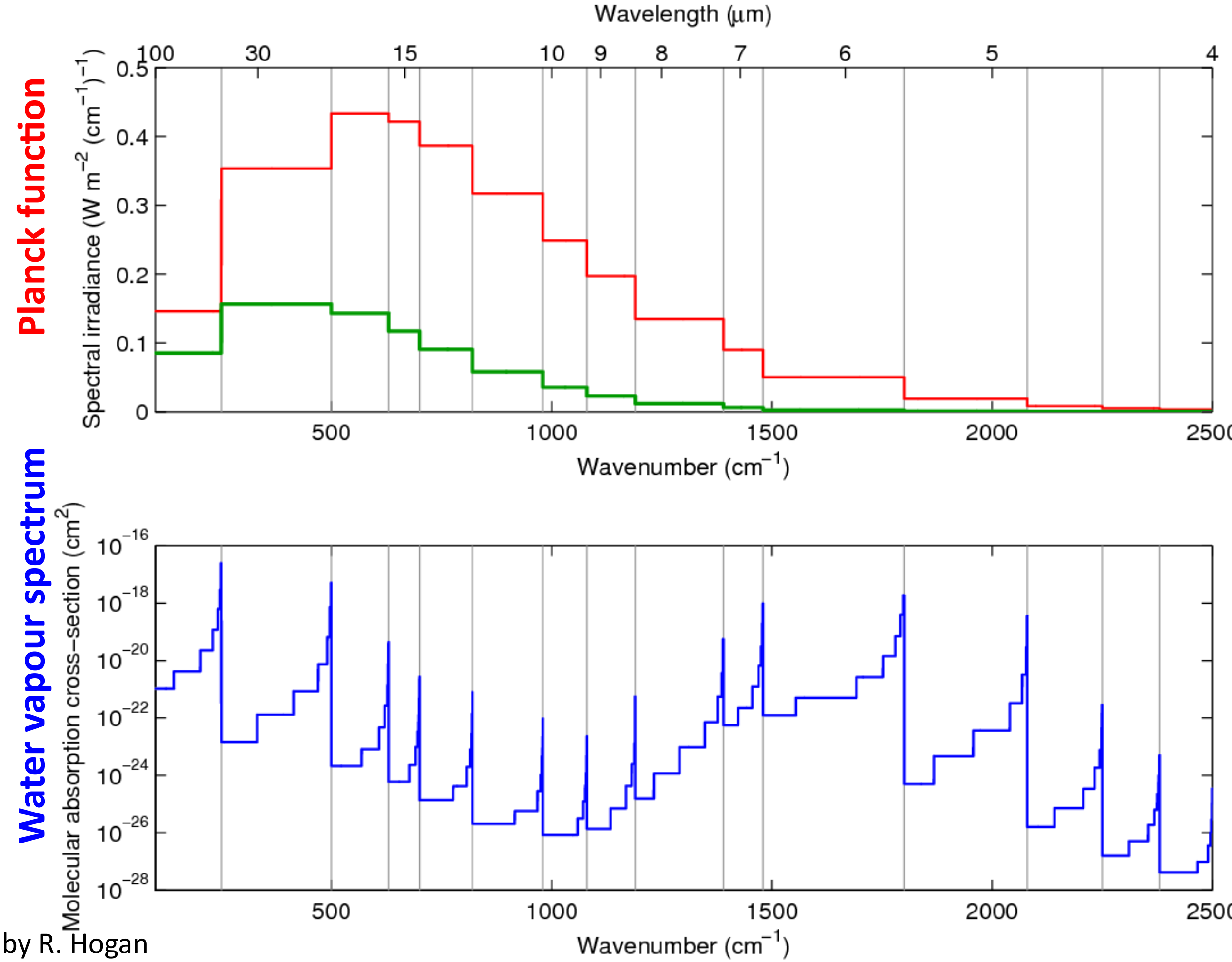
- In each band:
  - approximate Planck function
  - Gas absorption function still varies strongly




Plot by R. Hogan

# Gas optics: g-points / correlated k-method (RRTMG)

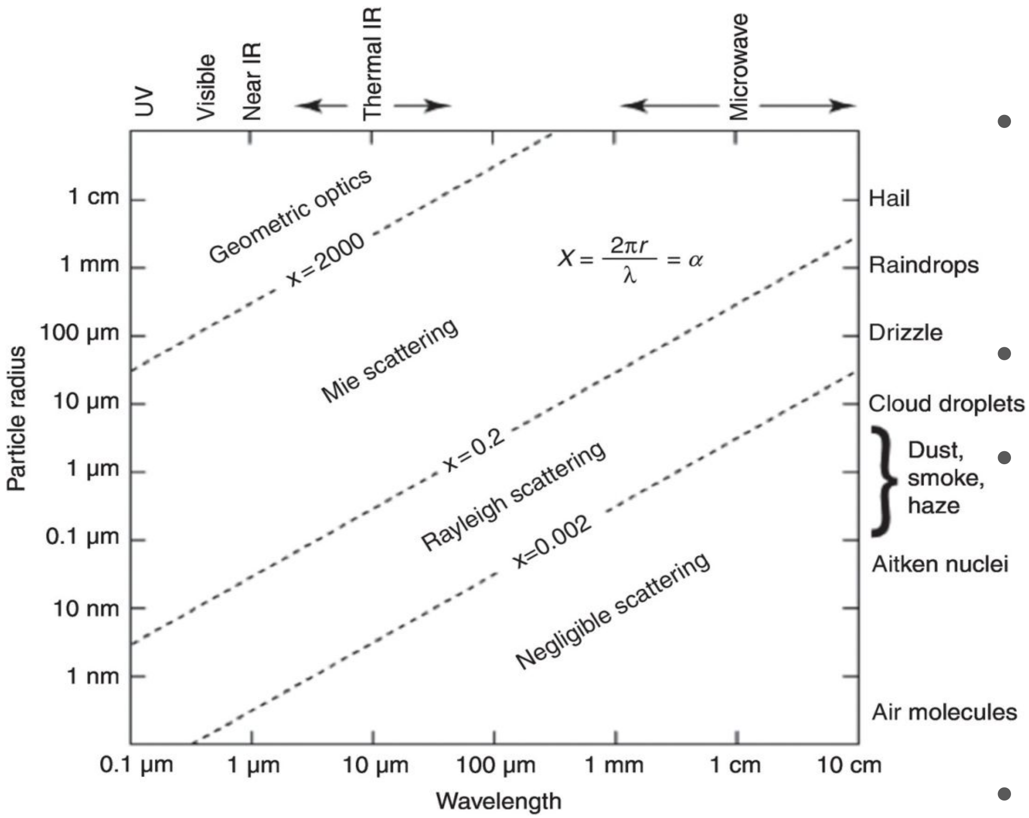
- In each band: Approximate Planck function, cloud+aerosol optics on bands: in RRTMG 14 SW + 16 LW
- Re-order in band by gas absorption, approximate on g-points
  → > 200 g-points
- Determines spectral dimension and code structure of most radiation schemes (incl. older ecRad versions)
- New more precise scheme with only 64 g-points available: ecCKD



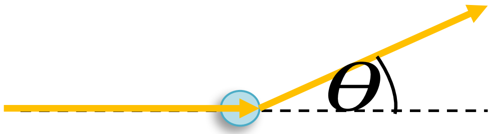

Plot by R. Hogan

# Cloud particles

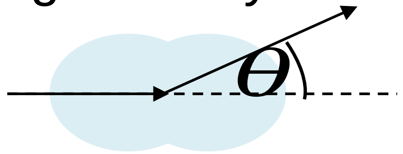
# Scattering by particles clouds, aerosol, air molecules




Petty (2006)

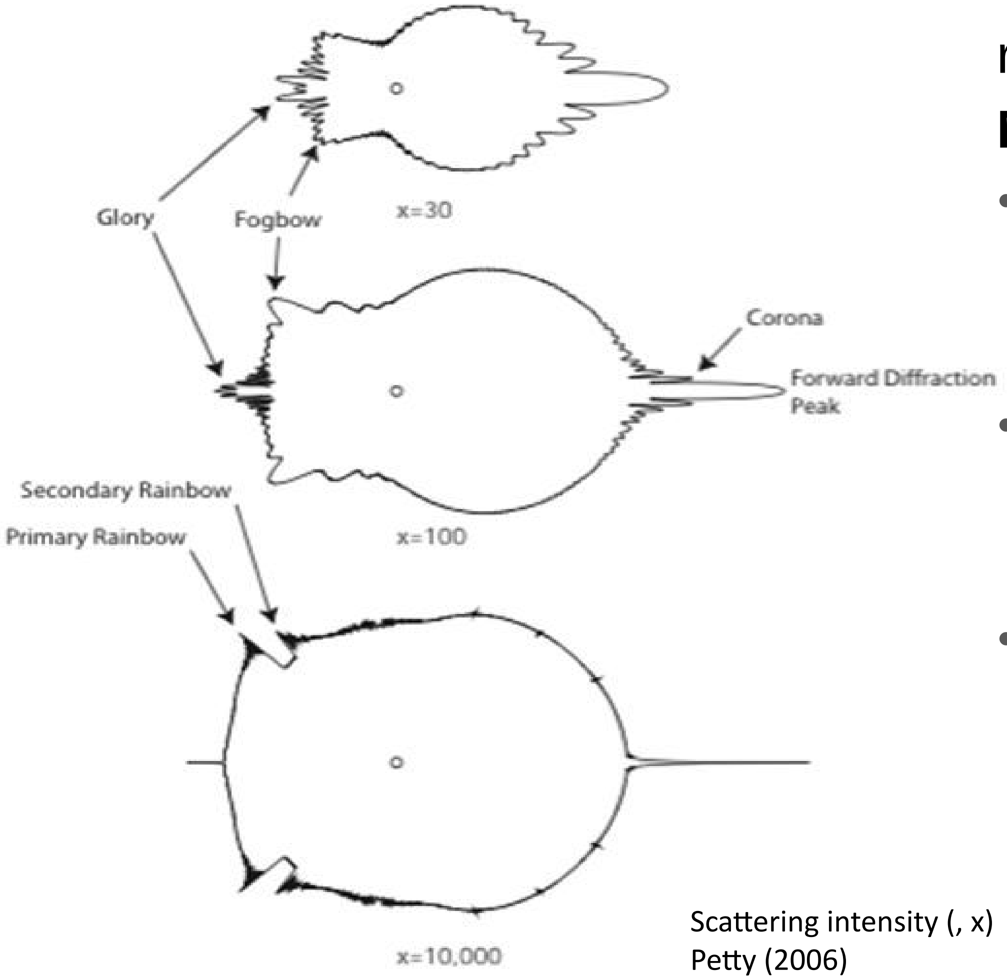



- Scattering intensity at scattering angle θ depends on size parameter x=2πr/λ: ratio of particle radius r and wavelength λ
- r >> λ: Geometric optics
- r >> λ: Rayleigh scattering: particle acts as electric dipole, scattering intensity p(θ)=3/4(1+(cosθ)$^2$)




- Rayleigh **scattering efficiency** $Q_s \sim x^4$ measures scattering per particle area

# Mie scattering




Scattering intensity (, x)
Petty (2006)

r≈λ, spherical particles :

**Mie scattering**

- complex function of scattering angle

effects like rainbow,…

- Approximated by numerical algorithms

- Strong forward peak: treated together with non-scattered direct radiation in model (Delta-Eddington-scaling)

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# Radiation solver and cloud geometry

# Simplified two-stream equations (slide adapted from R. Hogan)

Gradient of flux with height

Loss of flux by scattering or absorption

Gain in flux by scattering from other direction

- Upwelling flux: $$\frac{\partial F^+}{\partial z} = -\beta_e\left(\gamma_1 F^+ - \gamma_2 F^-\right) + S^+$$

- Downwelling flux: $$-\frac{\partial F^-}{\partial z} = -\beta_e\left(\gamma_1 F^- - \gamma_2 F^+\right) + S^-$$

Source from scattering of the direct solar beam (shortwave) or emission (longwave)

with coefficients (with delta-Eddington scaling):

$$\gamma_1 = \frac{1}{\mu_1}\left[1 - \frac{\omega(1+g)}{2}\right] \quad \text{and}$$

$$\gamma_2 = \frac{1}{\mu_1}\left[\frac{\omega(1-g)}{2}\right],$$

# Radiation solvers and sub-grid cloud geometry

**Simplify** by treating **only vertical** dimension explicitly.

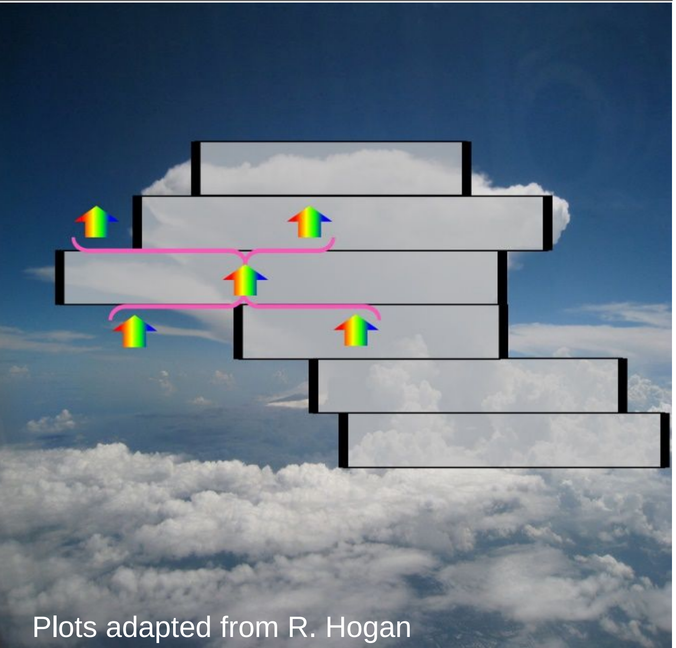
## Deterministic:

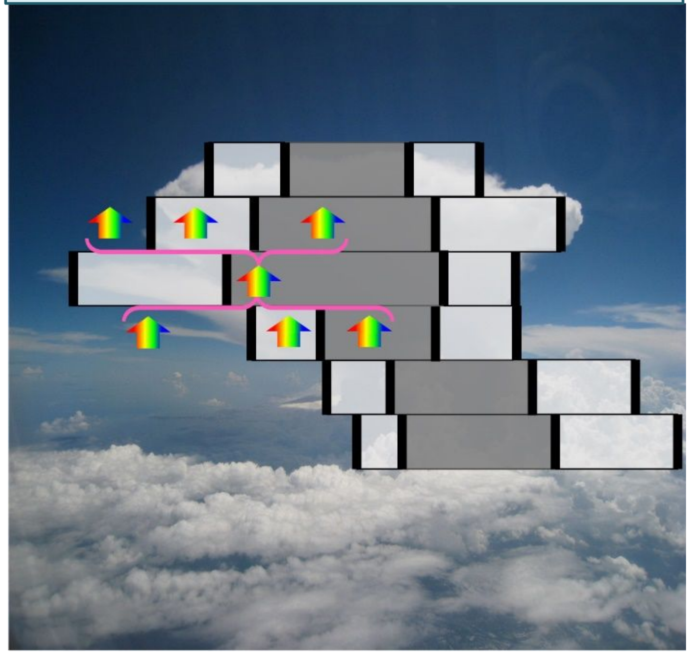
**Two-stream solver:** solve in **cloudy / clear regions**, partition at layer boundaries according to **overlap**

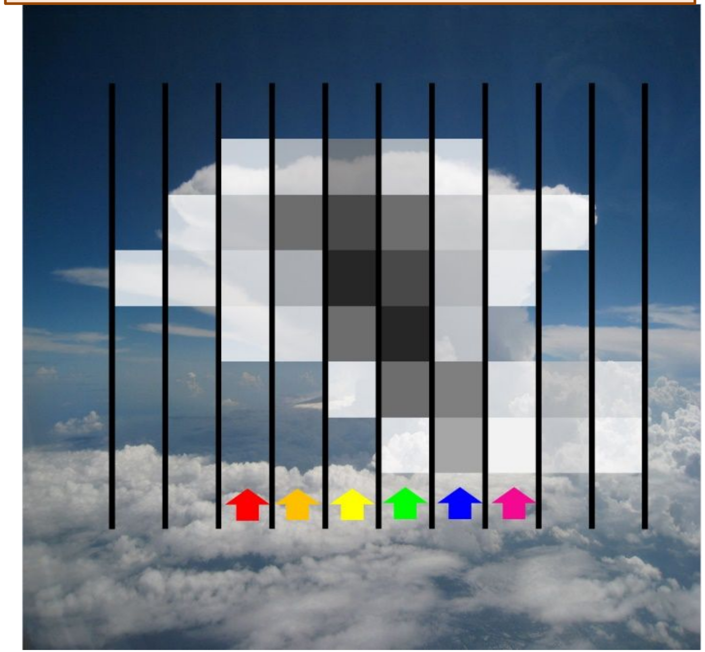
**Tripleclouds/SPARTACUS** (ecRad)**:** similar; 3 regions: **clear, thin cloud, thick cloud**  cloud **inhomogeneity**

## Stochastic:

**McICA** (ecRad)**:** draw **random clouds in sub-columns** for overlap + inhomogeneity; **distribute spectral intervals** in 1 sub-column each  **fast, random noise**

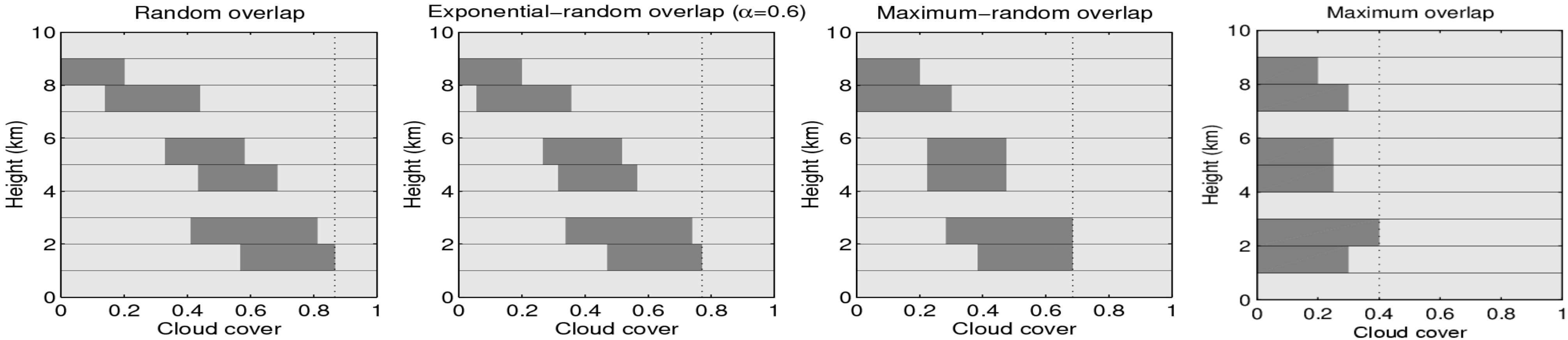






Plots adapted from R. Hogan

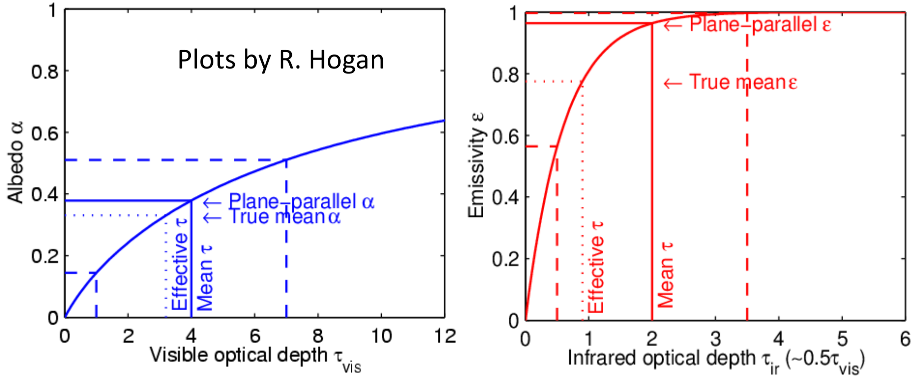
# Cloud geometry uncertainties




Adapted from Hogan & Illingworth 2000

- For given layer clouds, **cloud overlap** decides total cloud cover
- Observations: **exponential-random overlap,** decorrelation length **should depend** on cloud type

- Reflectivity and longwave emissivity **non-linear functions** of optical depth: need **horizontal cloud variability** (fractional standard deviation FSD = standard deviation / mean optical depth)
- Should also depend on cloud type, resolution

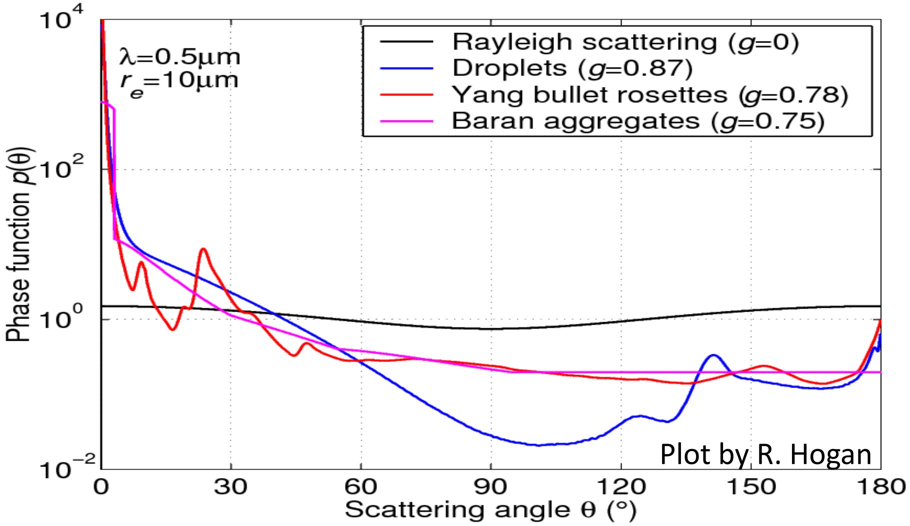


# Ice particle shape and effective radius

- **Ice particle shape** assumptions (liquid: spherical)
- Fu ice optics (Fu 1996, 1998, default): hexagonal columns



- Alternative ice optics in ecRad:  ice habit mixtures




- Mixture of particle sizes in clouds
- Parametrised **effective radius**

 = mean radius weighted by number, area, scattering efficiency of each particle size

- Definition needs to agree with optics
- Consistency with microphysics?

- **Further uncertainties:** surface coupling: albedo, emissivity;  cloud and aerosol input

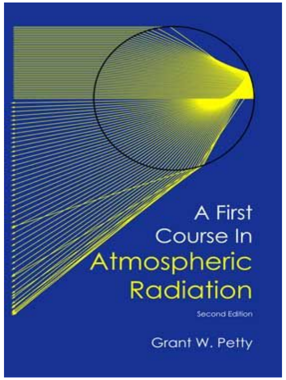
# Summary

- Radiation drives weather and climate, plant growth, human comfort,… at all scales
- Simplified description for weather / climate models: Two-stream equations for up-/downward flux, emission : Stefan-Bolzman-law; bulk optical properties
- Spectrum divided into bands to capture gas emission and absorption
- Clouds: Mie scattering, cloudy + clear region in each gridbox, some uncertainty
- Météo-France NWP / climate models: **ecRad** - fast and flexible radiation scheme Parametrisations can be changed individually

Thank you for your attention!

# Literature

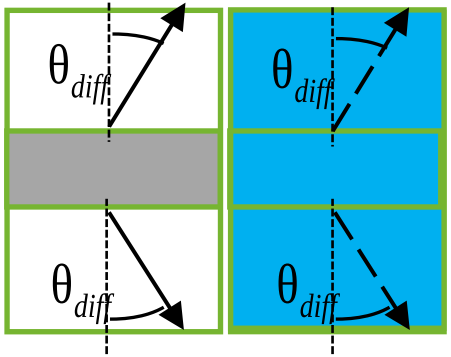
- Petty, Grant William, 2006. *A first course in atmospheric radiation*. Sundog Pub.
- Liou, K.-N., 1992: *Radiation and Cloud Processes in the Atmosphere*. Oxford University Press.




- ecRad radiation scheme: Hogan, R. J., Bozzo, A. (2018). *A flexible and efficient radiation scheme for the ECMWF model*. JAMES.
- RRTM gas optics: Mlawer, Eli J. et al., 1997. *Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave*. JGR.
- Cloud geometry: Shonk, Jonathan K.P. et al., 2010. *Effect of improving representation of horizontal and vertical cloud structure on the Earth's global radiation budget. Part I + Part II*. QJRMS.

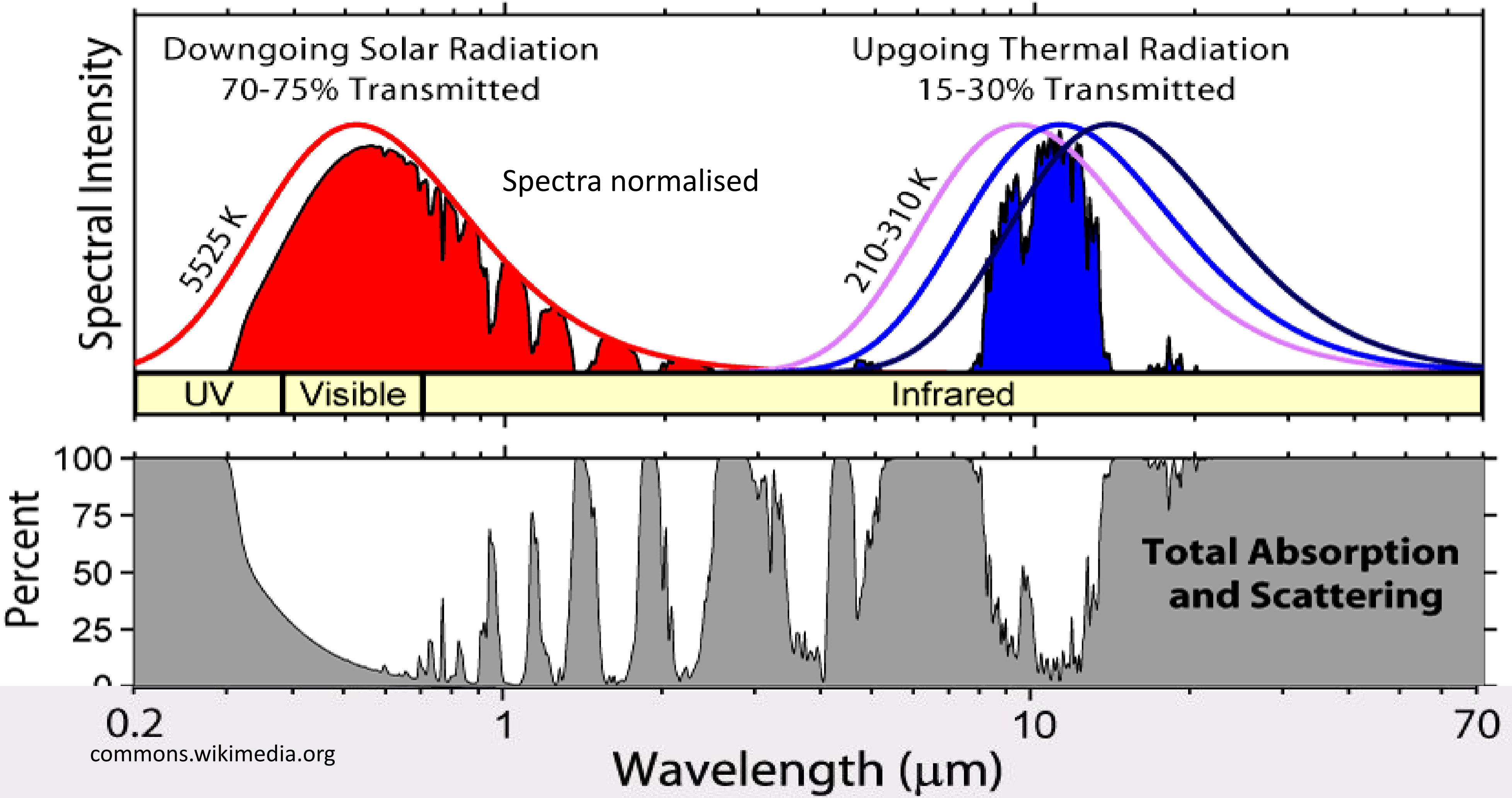
# Two-stream equations

- **Simplifications**:
  - ignore phase, polarisation
  - only treat up-/downward flux instead of radiances in all directions (2 streams)
  - scattering phase function described by one parameter: asymmetry factor g




- Treat cloudy / clear region of gridbox separately
- Treat direct solar radiation separately; Diffuse radiation: assume solar zenith angle to approximate integral over angles

# Emission spectra of sun and Earth

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# Atmospheric gases

| Gas | Parts by volume (per million) | Interaction |
|---|---|---|
| **Nitrogen** ($N_2$) | 780,840 ppm (78.084%) | sw (scat) |
| **Oxygen** ($O_2$) | 209,460 ppmv (20.946%) | sw (scat, abs) |
| **Water vapour** ($H_2O$) | ~0.40% total, surface ~1%-4% | lw, sw (abs) |
| Argon (Ar) | 9,340 ppmv (0.9340%) | |
| **Carbon dioxide** ($CO_2$) | 390 ppmv (0.039%) rising | lw, sw (abs) |
| Neon (Ne) | 18.18 ppmv (0.001818%) | |
| Helium (He) | 5.24 ppmv (0.000524%) | |
| **Methane** ($CH_4$) | 1.79 ppmv (0.000179%) rising | lw |
| 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 (0.000009%) | |
| **Ozone** ($O_3$) | 0.0 to 0.07 ppmv (0.000007%) | lw, sw (abs) |

Table by R. Hogan

- Gas-radiation interactions: shortwave (**sw**) absorption (**abs**) and scattering (**scat**), longwave (**lw**) absorption (greenhouse gases)
- Not all gases **radiatively active**, small concentrations can have strong effect

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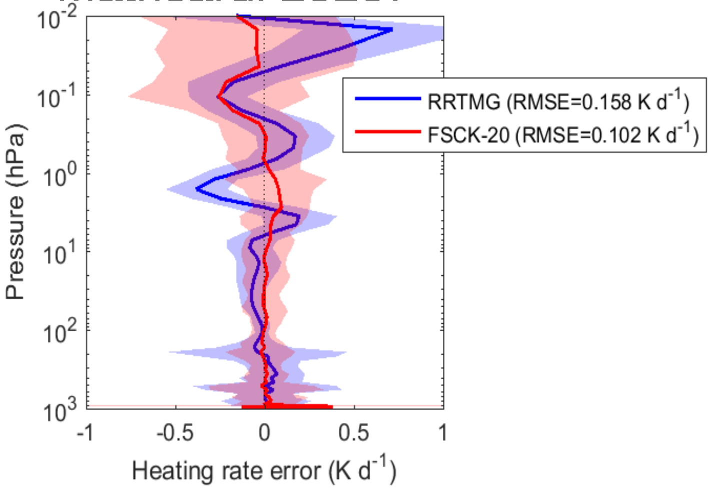
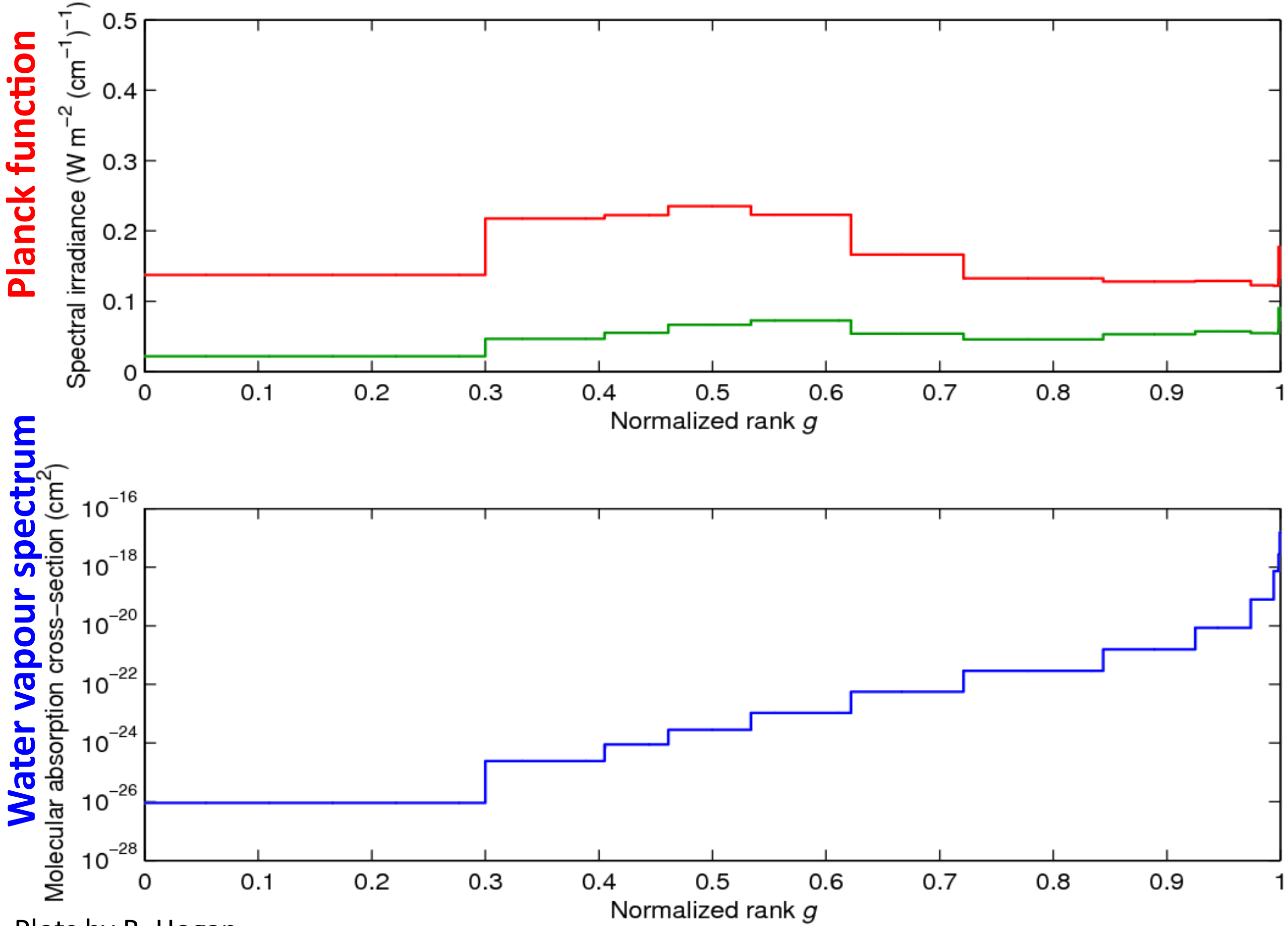
# ecCKD gas optics: full-spectrum correlated-k-method (Hogan 2010)

- Re-order whole spectrum, average Planck emission, cloud + aerosol optics interpolated onto chosen bands, more options available
- With 64 g-points: cheaper, more precise that RRTMG (Hogan and Matricardi 2020)

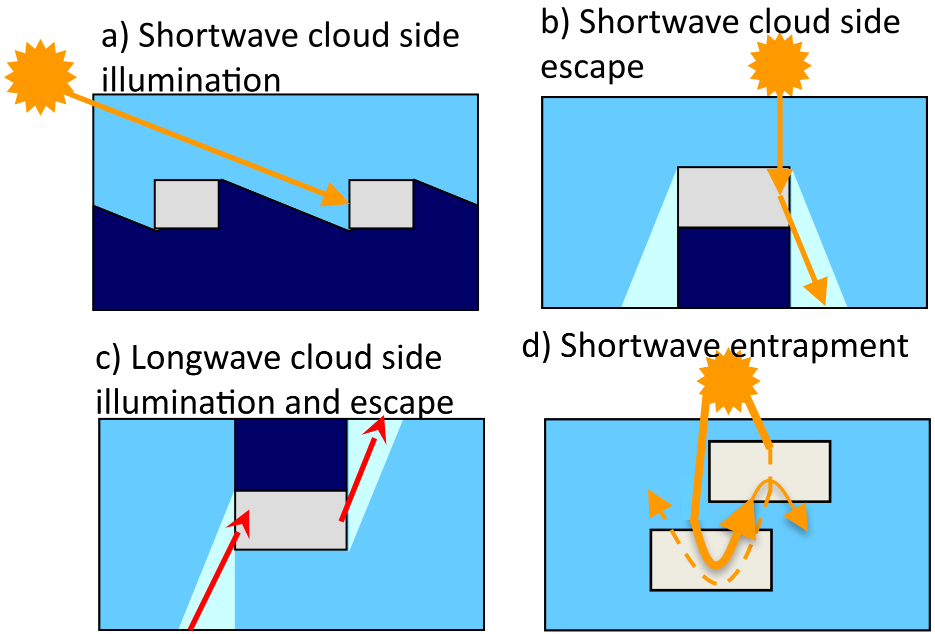



ecRad longwave heating rate error (50 test profiles), RRTMG (blue) and ecCKD gas optics (red)




Plots by R. Hogan

# 3D cloud effects




- **Shortwave cloud side illumination** increases cloud reflectivity, **cloud side escape** decreases cloud reflectivity
- **Longwave cloud side illumination and escape** increase cloud effect
- **Shortwave entrapment** decreases cloud reflectivity
- Similar effects at complex surfaces (trees / mountains / buildings)
- **Usually neglected, SPARTACUS** solver in ecRad can treat them (Schäfer et al. 2016, Hogan et al. 2016, 2019), cost x4

**Further uncertainties:** surface coupling: albedo, emissivity, one- or multi-level coupling
Cloud and aerosol input