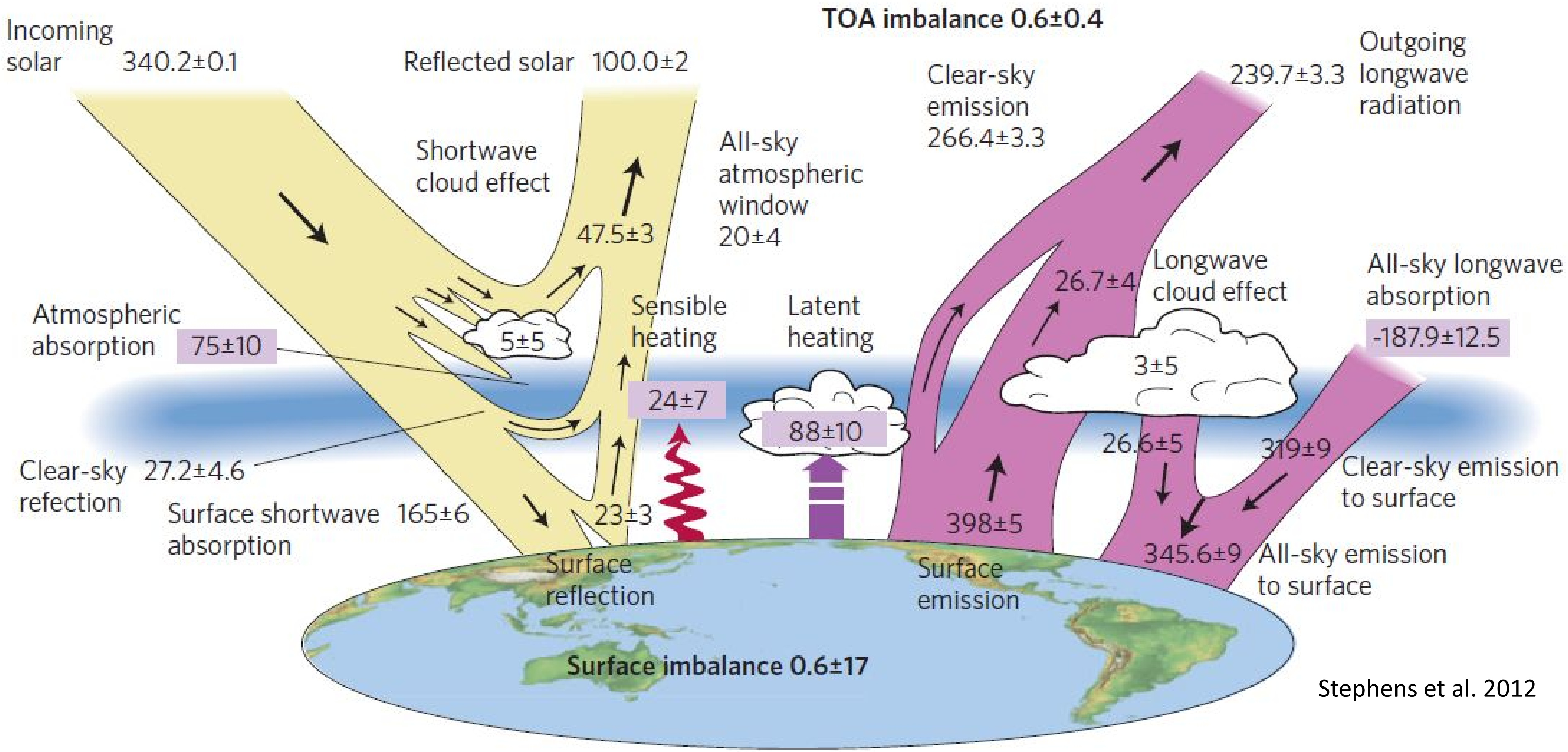
Radiation

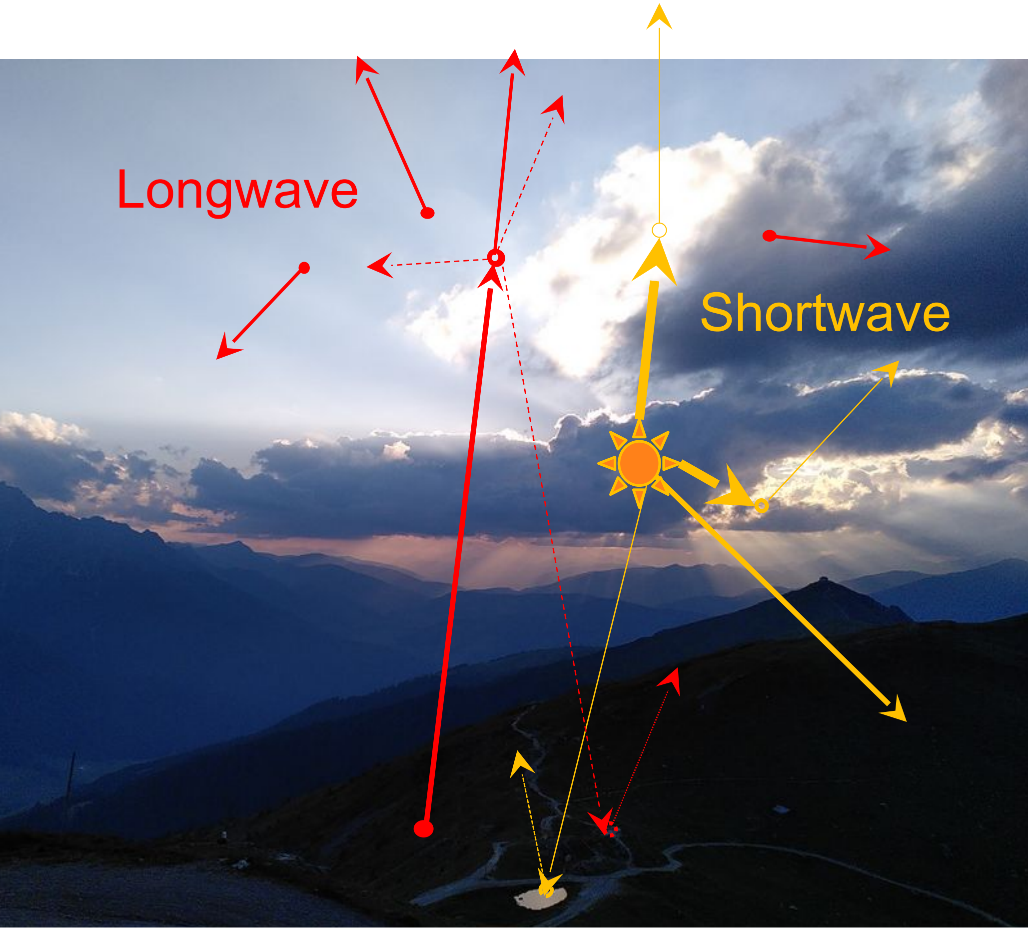
Radiation budget drives climate and weather



Stephens et al. 2012

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

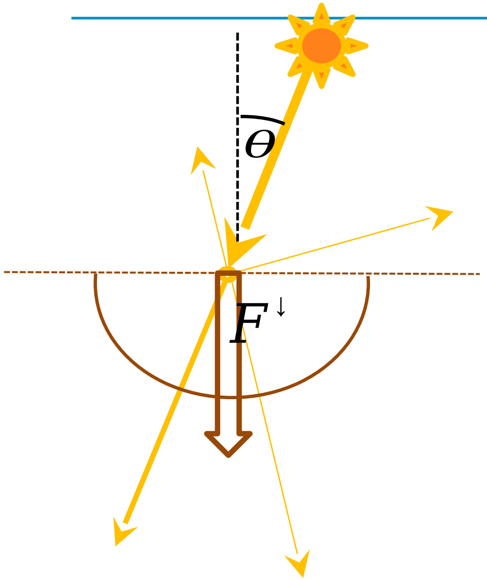
Radiation in reality

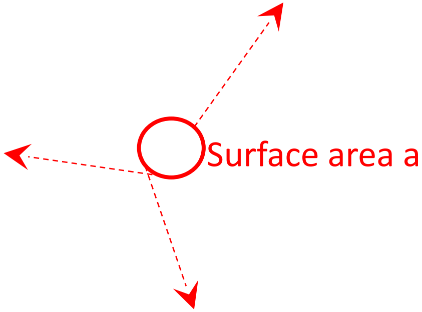


- Photons emitted by sun (**shortwave** / visible) and Earth system (**longwave** / infrared), absorbed or scattered by surface, atmospheric gases, aerosol, cloud water or ice particles

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

Radiation variables and thermal emission laws





- Zenith angle θ, azimuth angle ϕ

- **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,

  $F^{\downarrow}(\lambda) = \int_{\pi/2}^{\pi} \int_{0}^{2\pi} R(x, \lambda, \theta, \phi)\, d\phi\, d\theta,$ λ wavelength

- Thermal emitted power per area, (one wavelength): **Planck's law**;

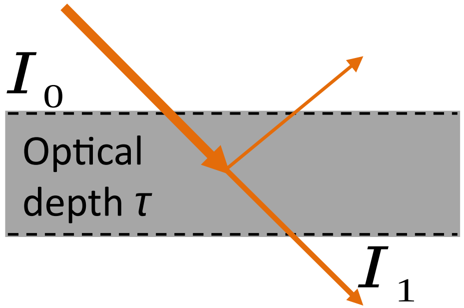
All wavelengths: **Stefan-Boltzmann law** $F = \sigma T^4$

σ Stefan-Boltzmann constant

Material bulk optical properties

- **Extinction coefficient** β 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**

  ω = 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)

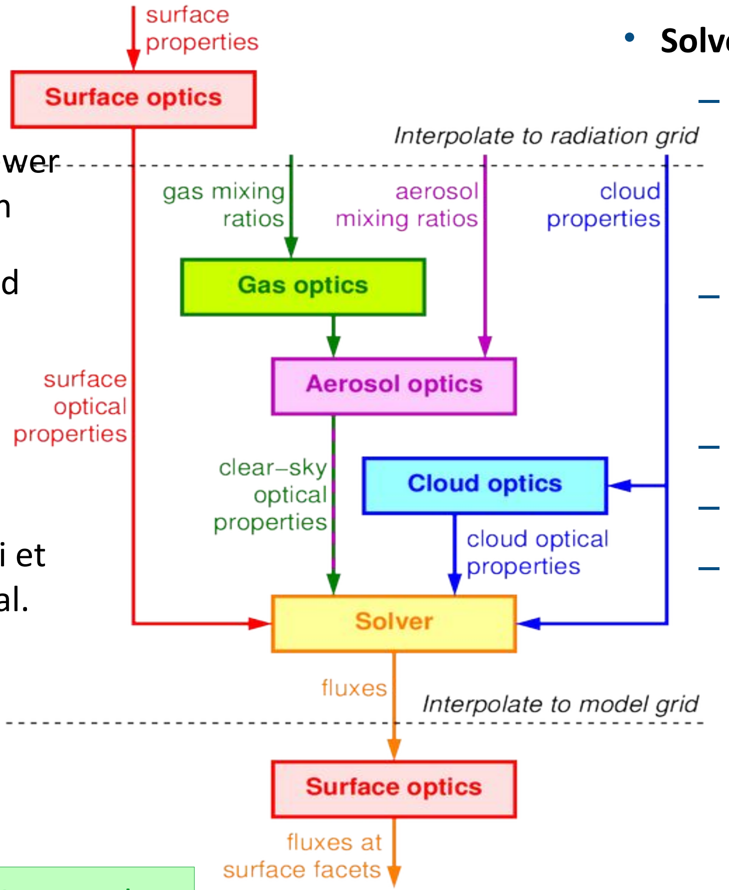
New modular radiation scheme ecRad (Hogan & Bozzo 2018)

- **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

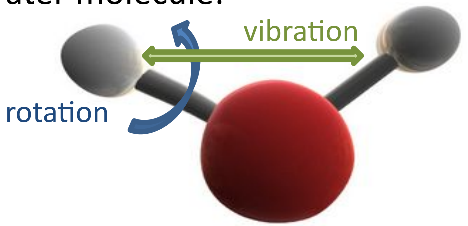
Info / documentation: https://confluence.ecmwf.int/display/ECRAD/ECMWF+Radiation+Scheme+Home

Radiation spectra and atmospheric gases

Atmospheric gases

- Molecules have different modes (vibration, rotation)

Water molecule:



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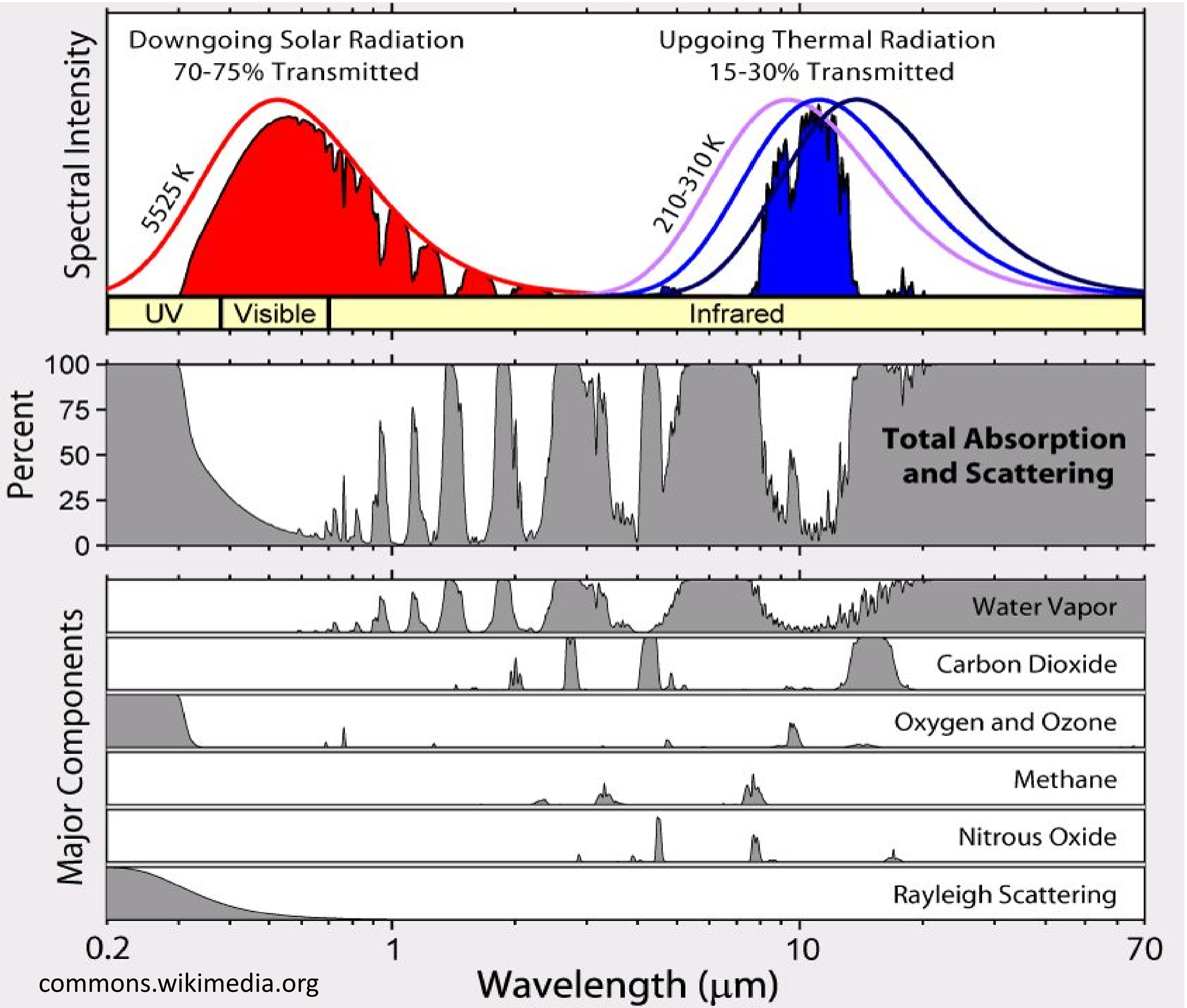
- Absorbing / emitting photons changes mode, photon wavelength corresponds to energy change

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



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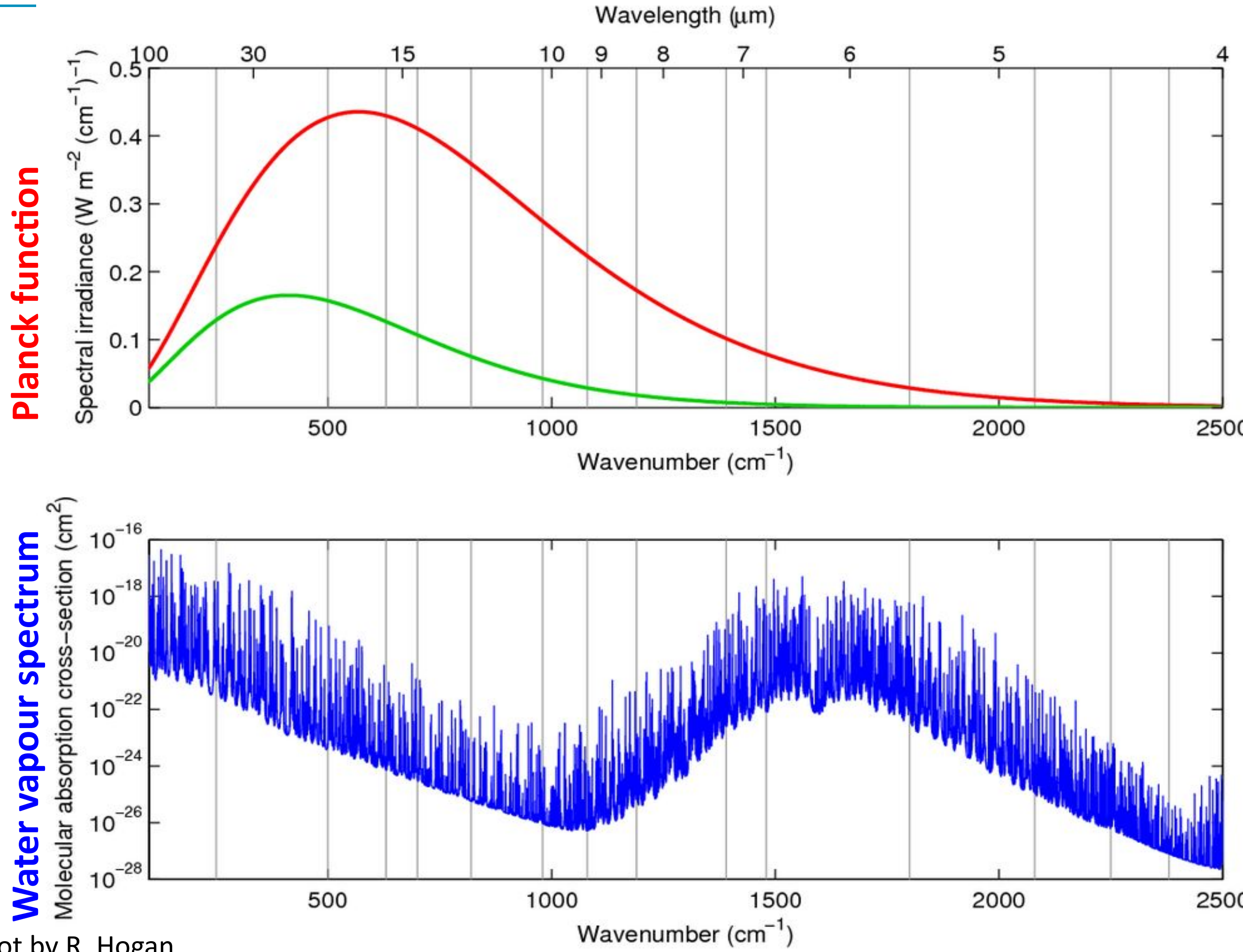
Gas optics: bands (RRTMG)

- Divide spectrum into bands with similar Planck function

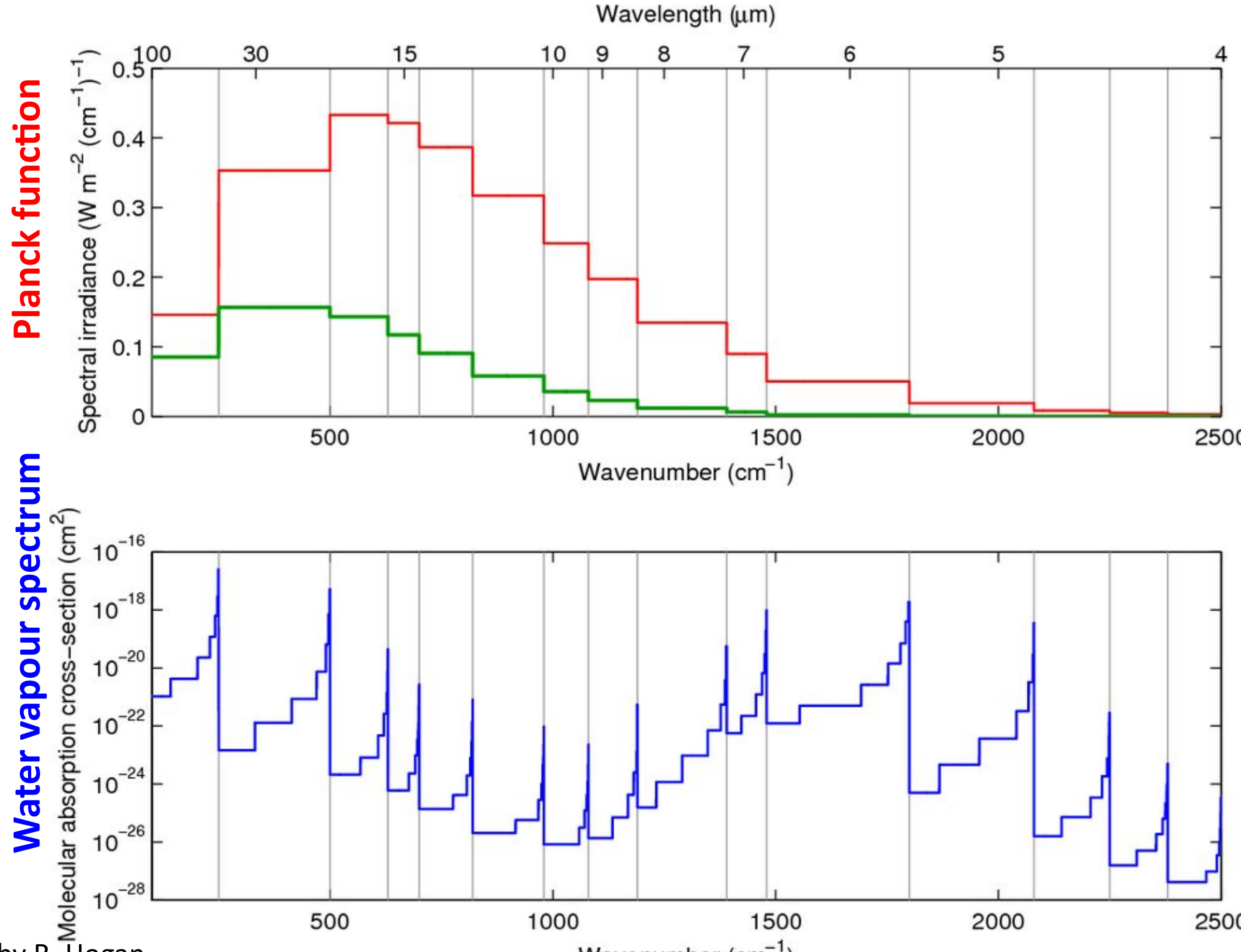
- In each band:
  - approximate Planck function
  - Gas absorption function still varies strongly



Plot by R. Hogan

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

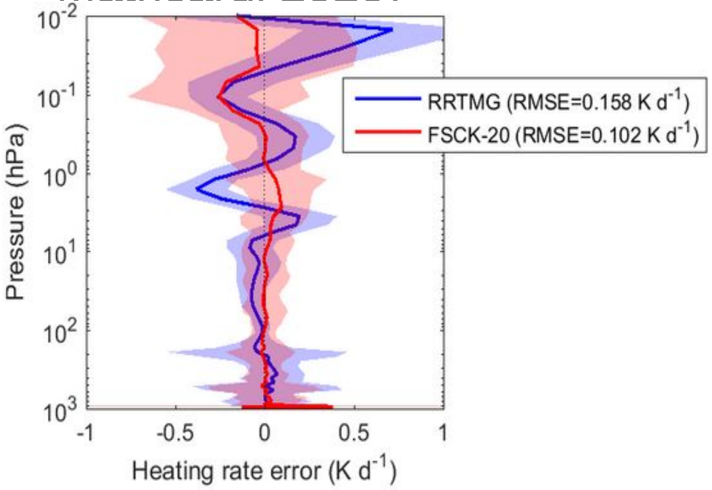
- In each band: Approximate Planck function, cloud+aerosol optics on bands: in RRTMG 14 SW + 16 LW
- Re-order in band by gas absorption, approximate on g-points
  → > 200 g-points
- Determines spectral dimension and code structure of most radiation schemes (incl. older ecRad versions)
- New more precise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



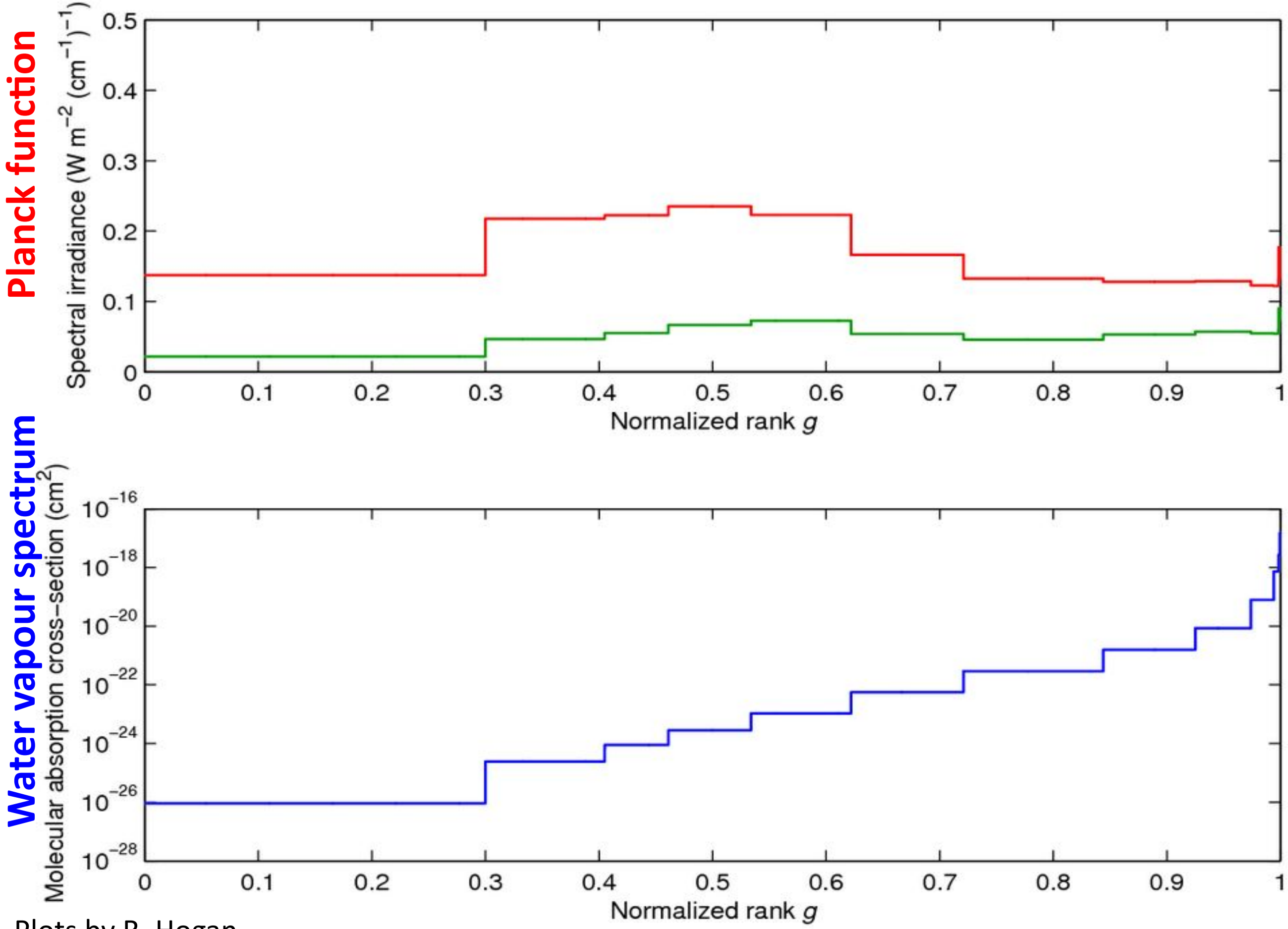
Plot by R. Hogan

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)



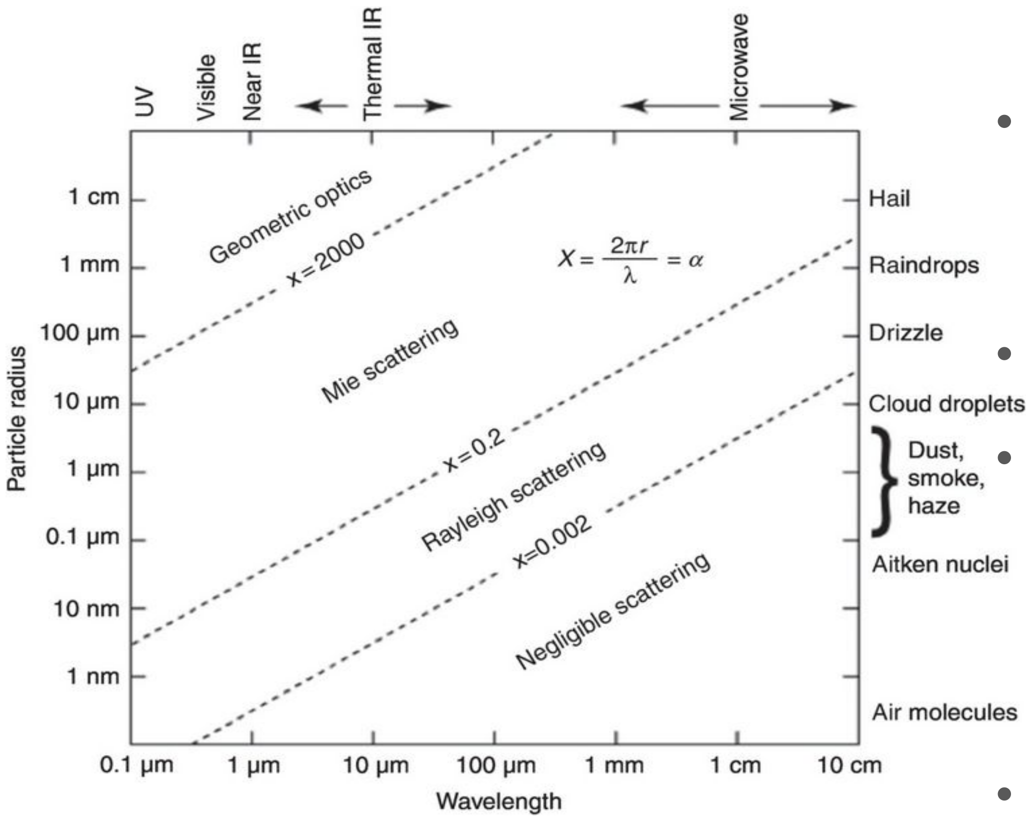
ecRad longwave heating rate error (50 test profiles), RRTMG (blue) and ecCKD gas optics (red)



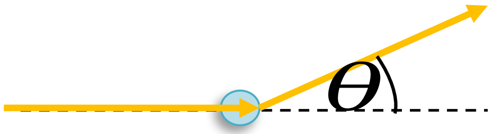
Plots by R. Hogan

Cloud particles

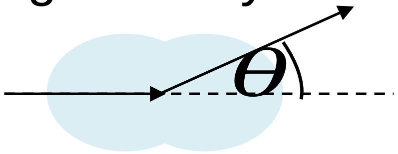
Scattering by particles clouds, aerosol, air molecules



Petty (2006)

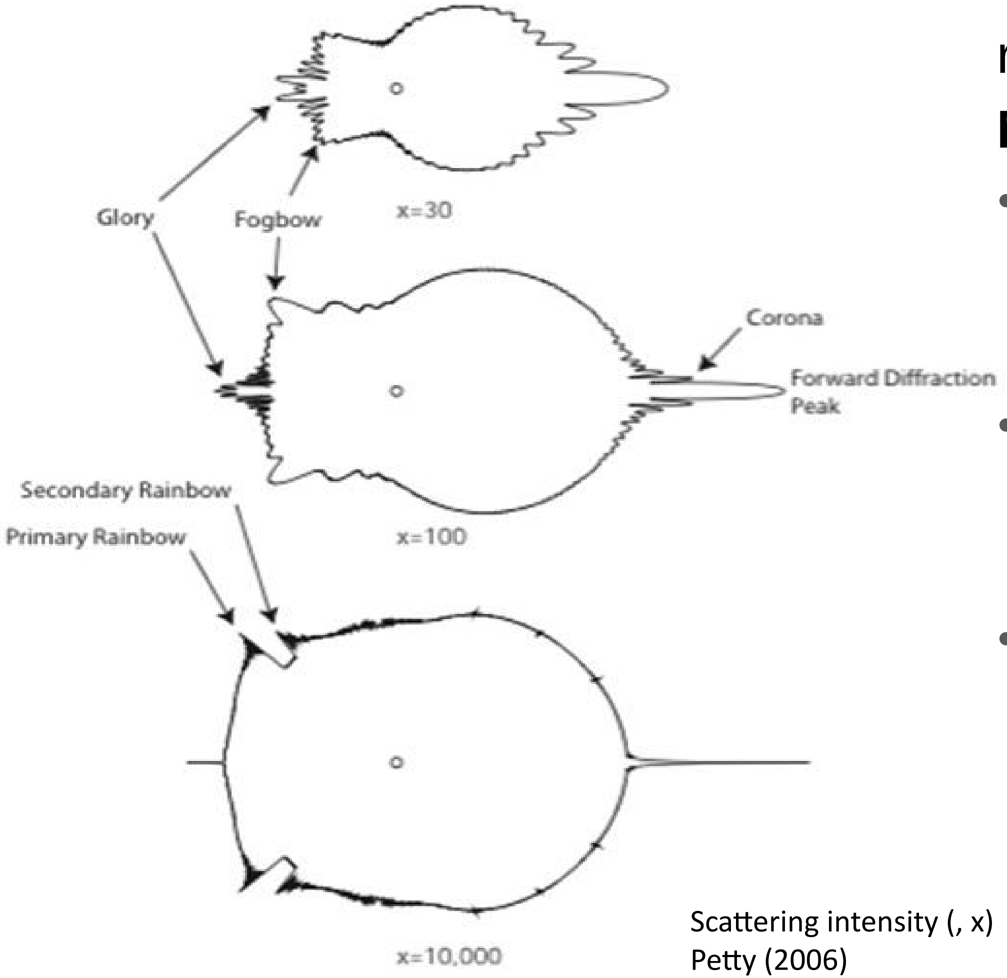


- Scattering intensity at scattering angle θ depends on size parameter x=2πr/λ: ratio of particle radius r and wavelength λ
- r >> λ: Geometric optics
- r >> λ: Rayleigh scattering: particle acts as electric dipole, scattering intensity $p(\theta)=3/4(1+(\cos\theta)^2)$



- 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,…

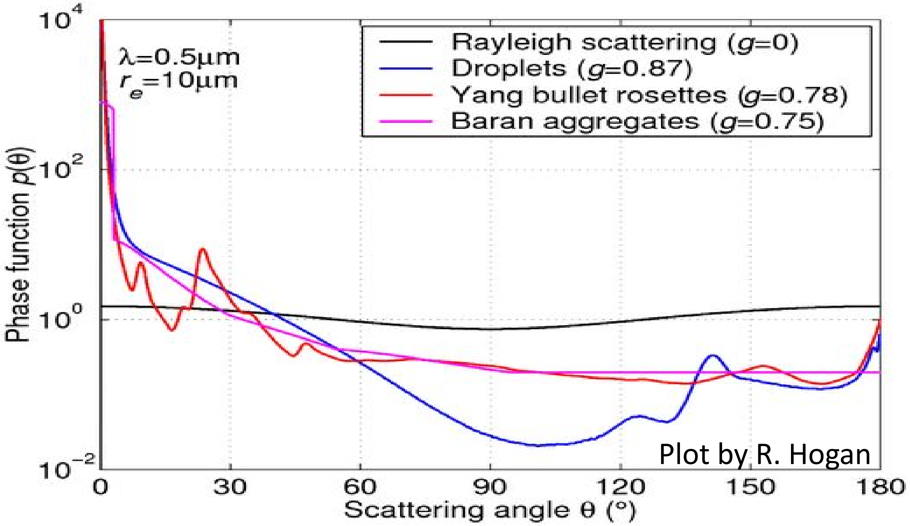
- Approximated by numerical algorithms

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

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

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

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

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

with coefficients (with delta-Eddington scaling):

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

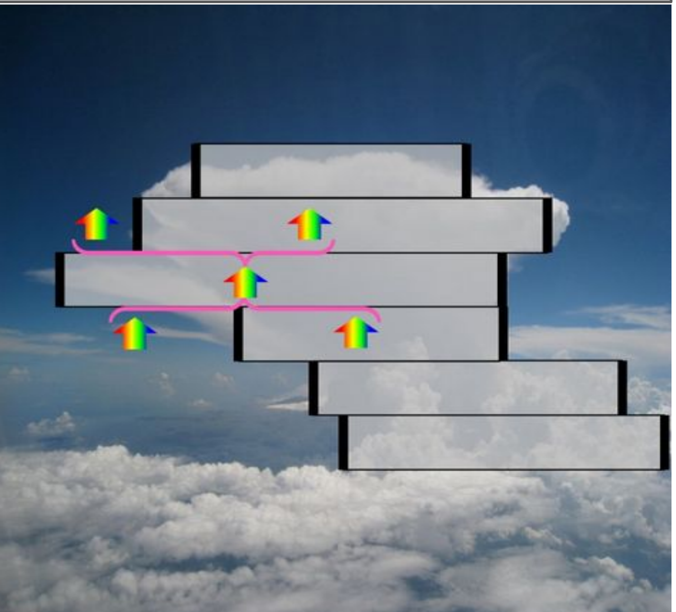
$$\gamma_2 = \frac{1}{\mu_1}\left[\frac{\omega(1-g)}{2}\right],$$

Radiation solvers and sub-grid cloud geometry

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

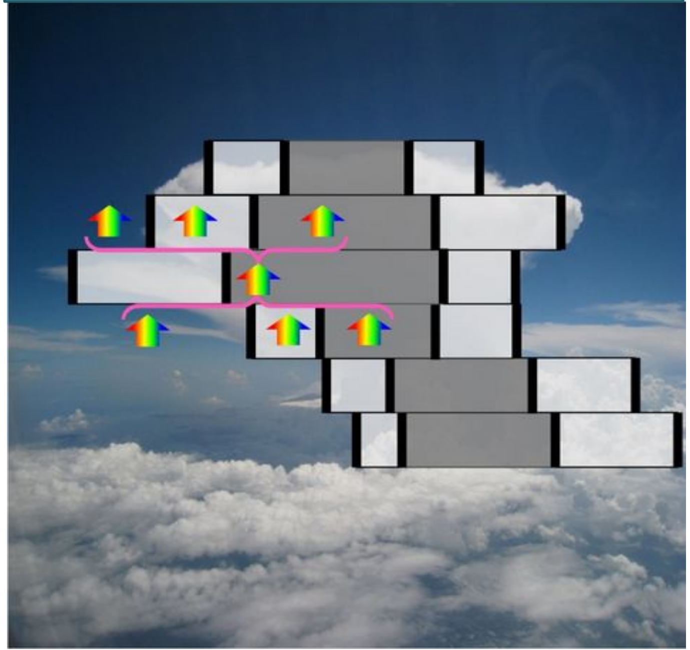
Deterministic:

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



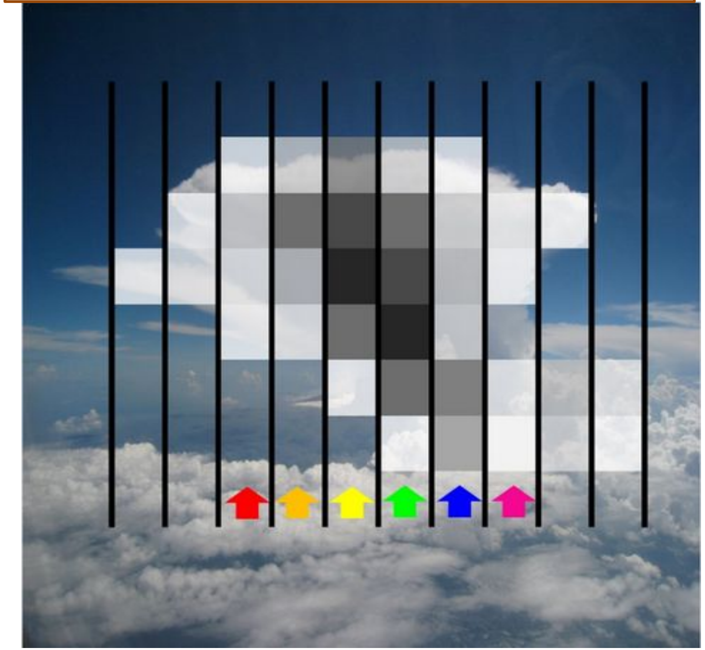
Plots adapted from R. Hogan

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

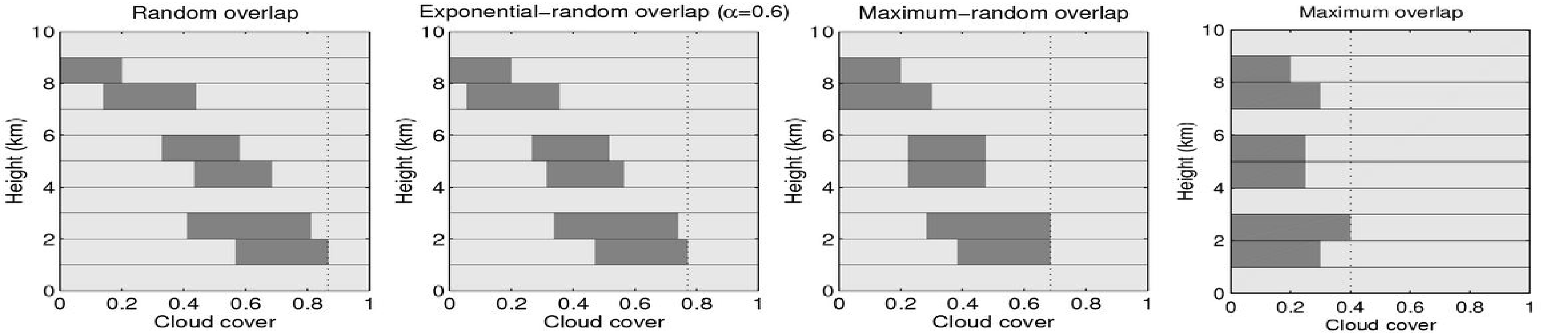


Stochastic:

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



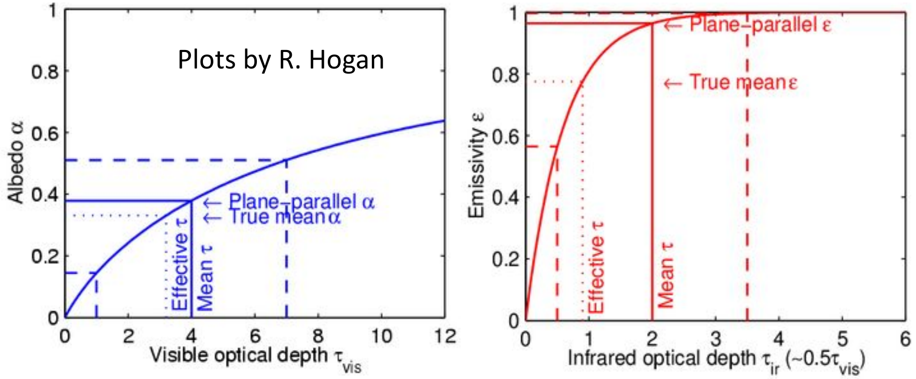
Cloud geometry uncertainties



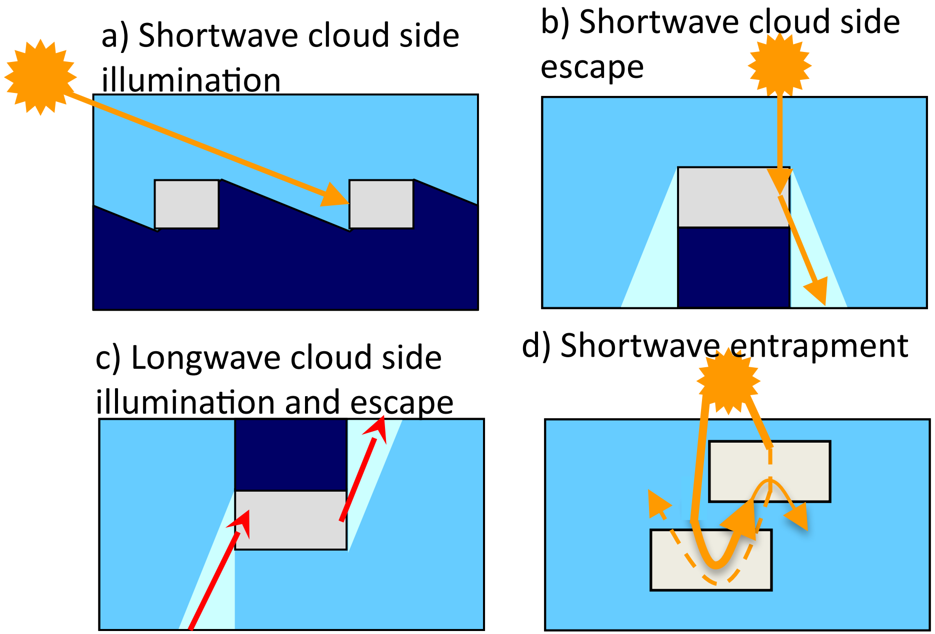
Adapted from Hogan & Illingworth 2000

- 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



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

Namelist: From MesoNH 6.0, all ecRad namelist parameters will all be available in MesoNH (see src/MNH/modn_param_ecradn.F90, https://confluence.ecmwf.int/download/attachments/70945505/ecrad_documentation.pdf?version=4&modificationDate=1584914933898&api=v2)

NAMELIST/NAM_PARAM_ECRADn/

IVERBOSESETUP, IVERBOSE, & # How much is written in output?

output fluxes, solver

LDO_SW, LDO_LW, LDO_SW_DIRECT, LDO_CLEAR, LDO_SURFACE_SW_SPECTRAL_FLUX, LDO_CANOPY_FLUXES_SW, LDO_CANOPY_FLUXES_LW & #which fluxes?

LDO_SAVE_SPECTRAL_FLUX, LDO_SAVE_GPOINT_FLUX, LDO_LW_DERIVATIVES, LDO_SAVE_RADIATIVE_PROPERTIES, &# save intermediate properties?

CSW_SOLVER_NAME, CLW_SOLVER_NAME, LDO_LW_CLOUD_SCATTERING, LDO_LW_AEROSOL_SCATTERING, & # Radiation solver, Do LW cloud / aerosol scattering?

gas / cloud optics

CGAS_MODEL_NAME, NRADLP, NRADIP, **CLIQUID_MODEL_NAME, CICE_MODEL_NAME**, LDO_FU_LW_ICE_OPTICS_BUG, & # gas, liquid, ice optics, do IFS ice bug?

CGAS_OPTICS_SW_OVERRIDE_FILE_NAME, CGAS_OPTICS_LW_OVERRIDE_FILE_NAME& # use gas optics from specified file ?

LDO_SW_DELTA_SCALING_WITH_GASES, LUSE_THICK_CLOUD_SPECTRAL_AVERAGING & # Do Delta-Eddington scaling with gases/ thick cloud spectral averaging?

XMAX_GAS_OD_3D, XMAX_CLOUD_OD, **LUSE_GENERAL_CLOUD_OPTICS**, & # max. gas / cloud optical depth, General cloud types method?

CCLOUD_TYPE_NAME, CCLIQ_OPTICS_OVERRIDE_FILE_NAME, CICE_OPTICS_OVERRIDE_FILE_NAME, & # Vector of cloud types, liquid / ice optics from specified file?

aerosols

LUSE_AEROSOLS, LUSE_GENERAL_AEROSOL_OPTICS, & # Do aerosols? Use general aerosol method?

LDO_CLOUD_AEROSOL_PER_SW_G_POINT, LDO_CLOUD_AEROSOL_PER_LW_G_POINT, & # do aerosols per band or per g-point?

NAEROSOL_TYPES , NI_AEROSOL_TYPE_MAP, CAEROSOL_OPTICS_OVERRIDE_FILE_NAME, & number + type of aerosols, use aerosol optics from file?

Surface

SURF_TYPE, LDO_WEIGHTED_SURFACE_MAPPING, & # Surface type / mapping

LSPEC_ALB, LSPEC_EMISS, LDO_NEAREST_SPECTRAL_SW_ALBEDO, LDO_NEAREST_SPECTRAL_LW_EMISS, & # spectral albedo / emissivity / mapping method

ISW_ALBEDO_INDEX, ILW_EMISS_INDEX, XSW_ALBEDO_WAVELENGTH_BOUND, XLW_EMISS_WAVELENGTH_BOUND, & # Albedo / emissivity index / bands

cloud geometry

XCLOUD_FRACTION_THRESHOLD, XCLOUD_MIXING_RATIO_THRESHOLD, & minimum thresholds for cloud

OVERLAP_SCHEME_NAME, LUSE_BETA_OVERLAP, NREG, **XCLOUD_FRAC_STD**, & # vertical overlap scheme, beta overlap? number of regions, fractional stand. dev.

XCLOUD_INHOM_DECORR_SCALING, XCLEAR_TO_THICK_FRACTION & # cloud inhomogeneity overlap compared to region overlap, ratio of thick cloud next to clear

CCLOUD_PDF_SHAPE_NAME, CCLOUD_PDF_OVERRIDE_FILE_NAME, & # name of horizontal cloud distribution PDF / Use PDF from file?

SPARTACUS solver: 3D effects

LDO_3D_EFFECTS, LDO_LW_SIDE_EMISSIVITY, LDO_3D_LW_MULTILAYER_EFFECTS, XMAX_3D_TRANSFER_RATE, & #Do 3D effects? / Which ones? Maximum 3D flux

CSW_ENTRAPMENT_NAME, LUSE_EXPM_EVERYWHERE, XOVERHANG_FACTOR, XOVERHEAD_SUN_FACTOR, & # method entrapment, matrix exponential, min SZA 3D

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

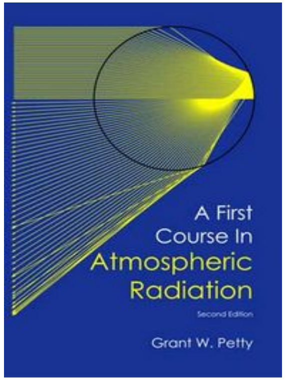
Thank you for your attention!

Contact: sophia.schaefer@meteo.fr

RÉPUBLIQUE FRANÇAISE

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.

Namelist parameters for ecRad in AROME

All ecRad parameters are explained in the user guide:
https://confluence.ecmwf.int/download/attachments/70945505/ecrad_documentation.pdf?version=4&modificationDate=1584914933898&api=v2

&NAERAD #radiation parameters for all schemes

Needed for ecRad:

LAER3D=.TRUE., # => using 3D or real-time aerosols? Might be important?

LUSEPRE2017RAD=.FALSE., # => To use ecRad

LRRTM=.TRUE., # => To use ecRad

LSRTM=.TRUE.,# => To use ecRad

NAER=0, # Aerosol option, used, 1 by default, 0=no aerosols

NRADFR=18, # Variable for intermittent

NAERMACC=1, # CAMS aerosol, needed

NOZOCL=4, # Ozon climatology choice

NSW=6, # No. of shortwave bands, somethingg funny happening...

RRE2DE=0.64952, # Geometrical factor for hexagonal particles, not sure if needed

Not used in ecRad?:

NDUMPBADINPUTS=0, ??

NICEOPT=3, # Ice option, Internal for old scheme

NLIQOPT=2, # Liquid option, Internal for old scheme

NMCICA=1, # old scheme, hopefully

NOVLP=1, # Overlap - not needed

NRADIP=3, # effective radius size ice particle, probl. not used

NRADLP=2, # effective radius size liquid particle, prob. not used

RLWINHF=1, # Longwave inhomogenity, old scheme, spp-patterns ensemble

RSWINHF=1, # Shortwave inhomogenity, old scheme, spp-patterns ensemble

&RADIATION # ecRad parameters

Iverbose=1, # from 1 to 5

Iverbosesetup=3, # highest is 5

directory_name=".", # can change

do_clear=.TRUE., # clear sky and all sky calculations if TRUE

do_save_radiative_properties =.FALSE., # default FALSE

do_save_spectral_flux =.FALSE., # goes into seperate file, for debugging...

do_save_gpoint_flux=.FALSE., # as above, a lot of data

do_surface_sw_spectral_flux =.TRUE., # for spectral coupling to the surface

use_aerosols=.TRUE., # FALSE: all aerosol input ignored, should always be TRUE?!

do_lw_derivatives=.TRUE., # Diagnostic, set to FALSE?

gas_model_name='RRTMG-IFS', # Other options in user guide, only in offline ecRad

cloud_mixing_ratio_threshold=.100E-08, # less water than this then considered no cloud

cloud_inhom_decorr_scaling= 1.00, # same vertical decorrelation scale for cloud edges and cloud internal inhomogenity

cloud_fraction_threshold= .100E-05, # if less than this then no cloud

use_beta_overlap= .FALSE., # not using beta -> then using alpha overlap, default

liquid_model_name='Nielsen', #needs the .nc file provided in data folder

ice_model_name='Fu-IFS', # Operational option, other might be better

do_fu_lw_ice_optics_bug=.FALSE., # There was a bug in the IFS, can be reproduced if you want

overlap_scheme_name='Exp-Ran', # Most sensible choice, IFS used a different one

sw_solver_name='McICA', # Shortwave solver , McICA is the operational one

lw_solver_name='McICA', # Longwave solver, possible to use different from SW but need a reason

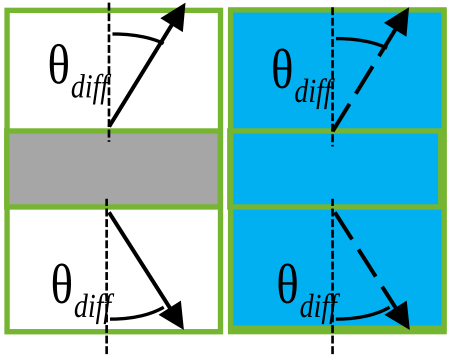
do_sw_delta_scaling_with_gases=.FALSE., # FALSE: only cloud particles, TRUE: also with gases

do_lw_cloud_scattering=.FALSE., # TRUE: more expensive, better, but more cost for small benefit

do_lw_aerosol_scattering=.FALSE., # benefit of TRUE is even smaller than for the cloud scattering

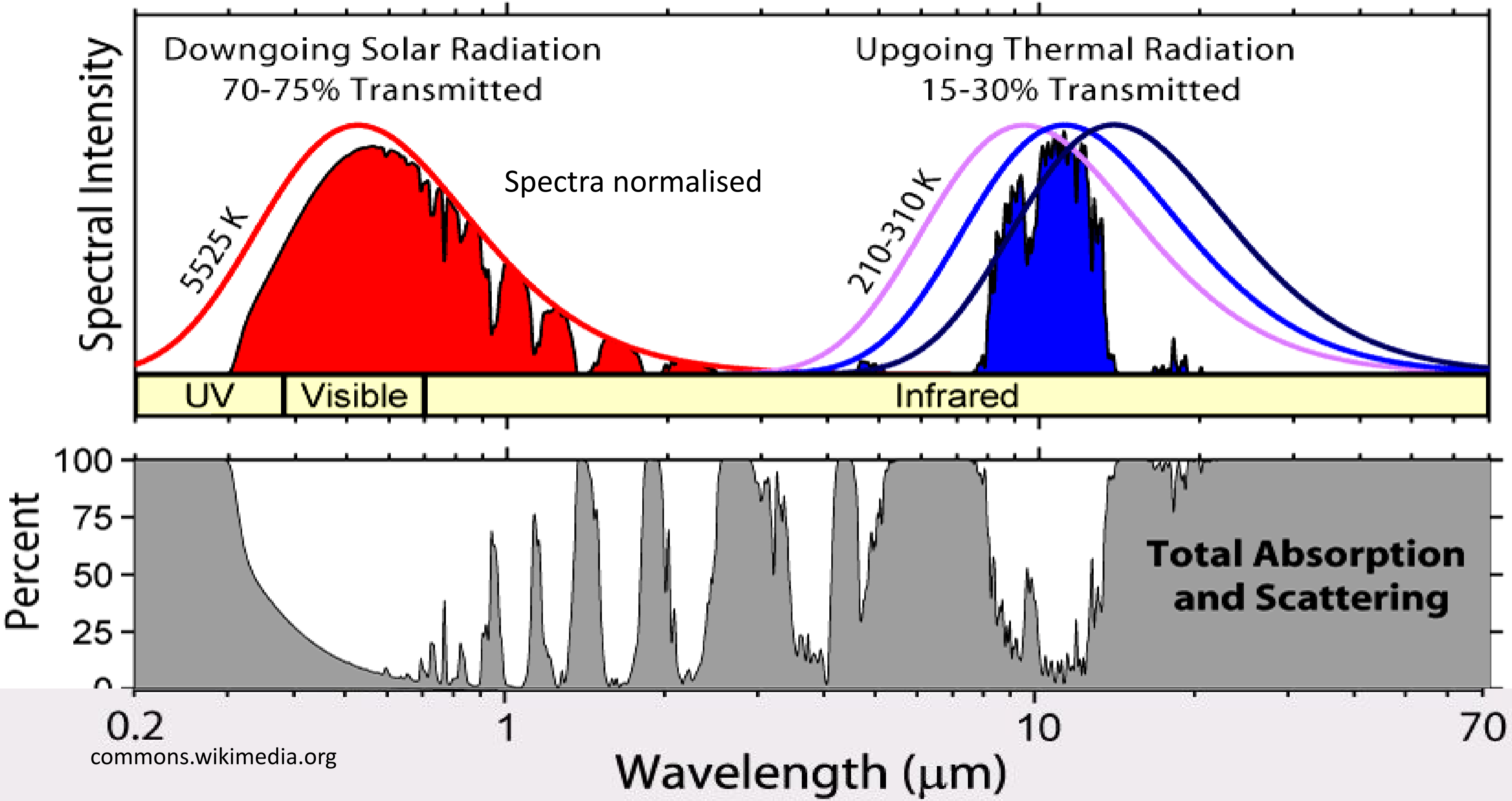
Two-stream equations

- **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