Radiation

M. Burba | Numerical Model Training | July 2025

Material: S. Schäfer, R. Hogan, M. Ahlgrimm

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

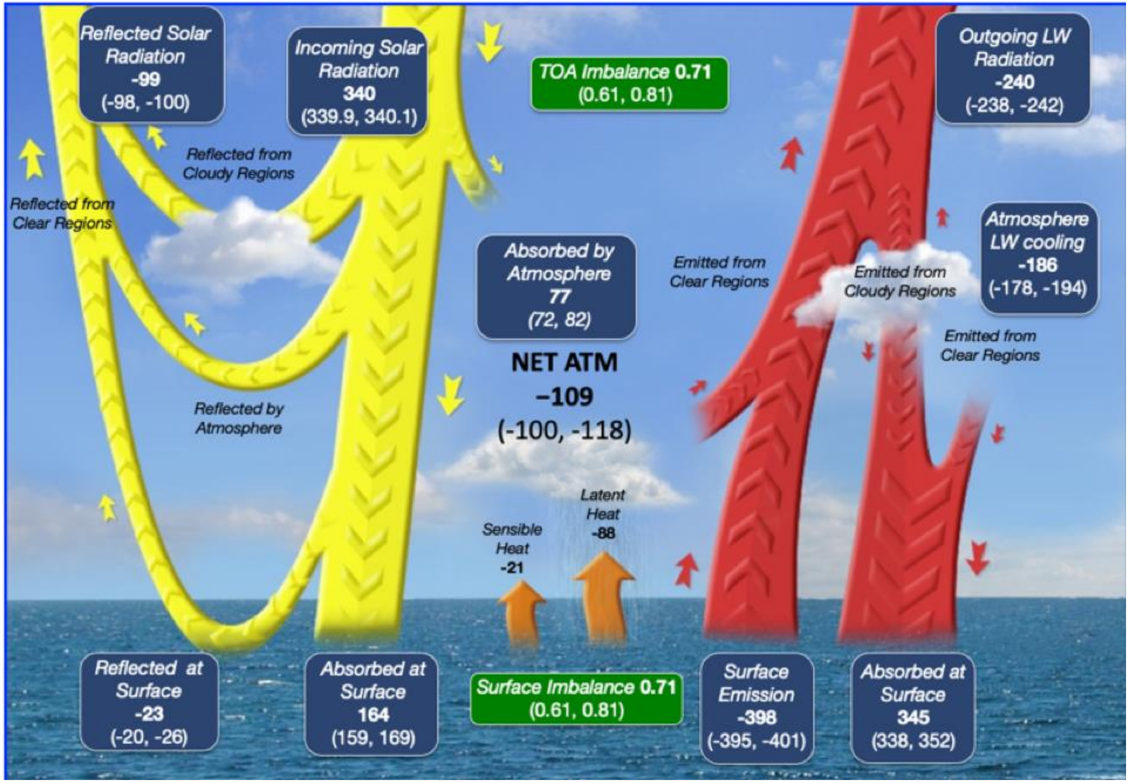
Overview: In this lecture

- Physics of radiation in the atmosphere
  - Motivation: why do we care?
  - Bulk radiation treatment
  - Spectra and atmospheric gases
  - Scattering by atmospheric particles
  - Aerosol and surface properties
- Radiation modelling (in ICON)
  - Specifically: ecRAD
- How to run radiation
  - Namelist settings
  - Uncertainties

Introduction

Radiation – why do we care?

The global radiation budget



"Average view"

Balance between SW heating and LW cooling ultimately determines average surface temperature

Source:
https://ceres.larc.nasa.gov/images/EnergyBudget.png

Differential heating drives circulations

- Differential heating at poles and equator drives large-scale dynamics
  - Pole: radiative cooling, heated by circulation
  - Equator: effective heating by the sun, cooled by circulation

- Heating (cooling) in low layers (high layers) drives convection

ICON Radiative transfer modeling

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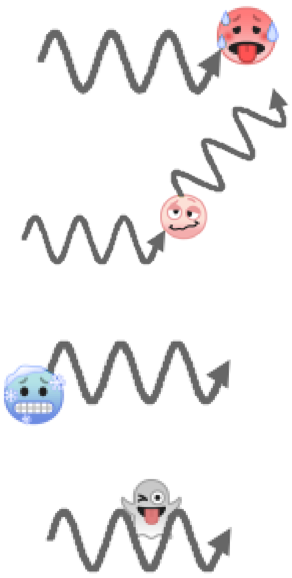
Extinction

- Absorption
- Scattering

Emission

Transmission



Physical Processes

Molecules
Aerosol
Hydrometeors

Components interacting with electromagnetic waves (concentration, properties)

Albedo,
Emissivity

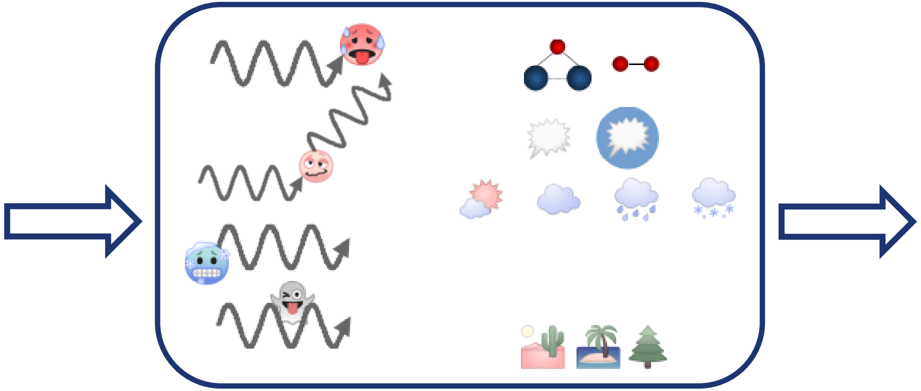
Surface properties

May vary according to assumptions:
lat, lon, season, time, height, …

Radiative transfer modeling: ecRad

Inputs for ecRad:

- Atmospheric fields: Temperature, Pressure, water vapor, hydrometeors, cloud cover
- Aerosol, surface albedo, surface emissivity, T_{skin}, land fraction, glacier fraction, effective radius
- Sun zenith angle
- GHG concentrations



ecRad

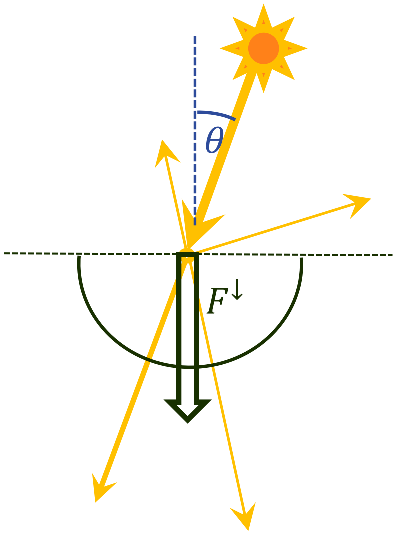
Outputs of ecRad:

- Fluxes, SW and LW
- VIS, NIR, PAR

Physics of radiation

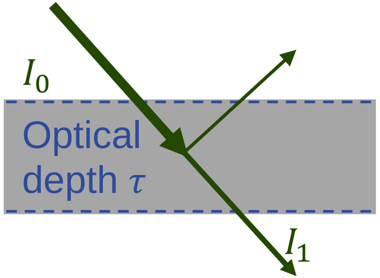
Bulk Radiation Treatment

Definitions: Radiance, flux and bulk approximation



- **Radiance** *R*: power per unit area and solid angle
- **Flux** *F*: power per area integrated over angles, e.g. total up- or downward flux
- $F^{\downarrow}(\lambda) = \int_{\Omega} R_{\lambda} d\Omega,$ λ wavelength

Bulk approximation:
Upwelling/downwelling flux only!



- **Extinction coefficient** β: local extinction by absorption and scattering
- **Optical depth** $\tau = \beta\ s$ measures extinction along a path s
- **Transmission** $T = 1 - \exp(-\tau)$ amount of incoming radiation which is not scattered or absorbed by a layer

Radiative transfer equation: 2 stream eq.

$$\frac{dF^{\uparrow}_{diff}}{d\tau} = F^{\uparrow}_{diff} - F^{\downarrow}_{diff} - \text{sources}$$

$$\frac{dF^{\downarrow}_{diff}}{d\tau} = F^{\downarrow}_{diff} - F^{\uparrow}_{diff} + \text{sources}$$

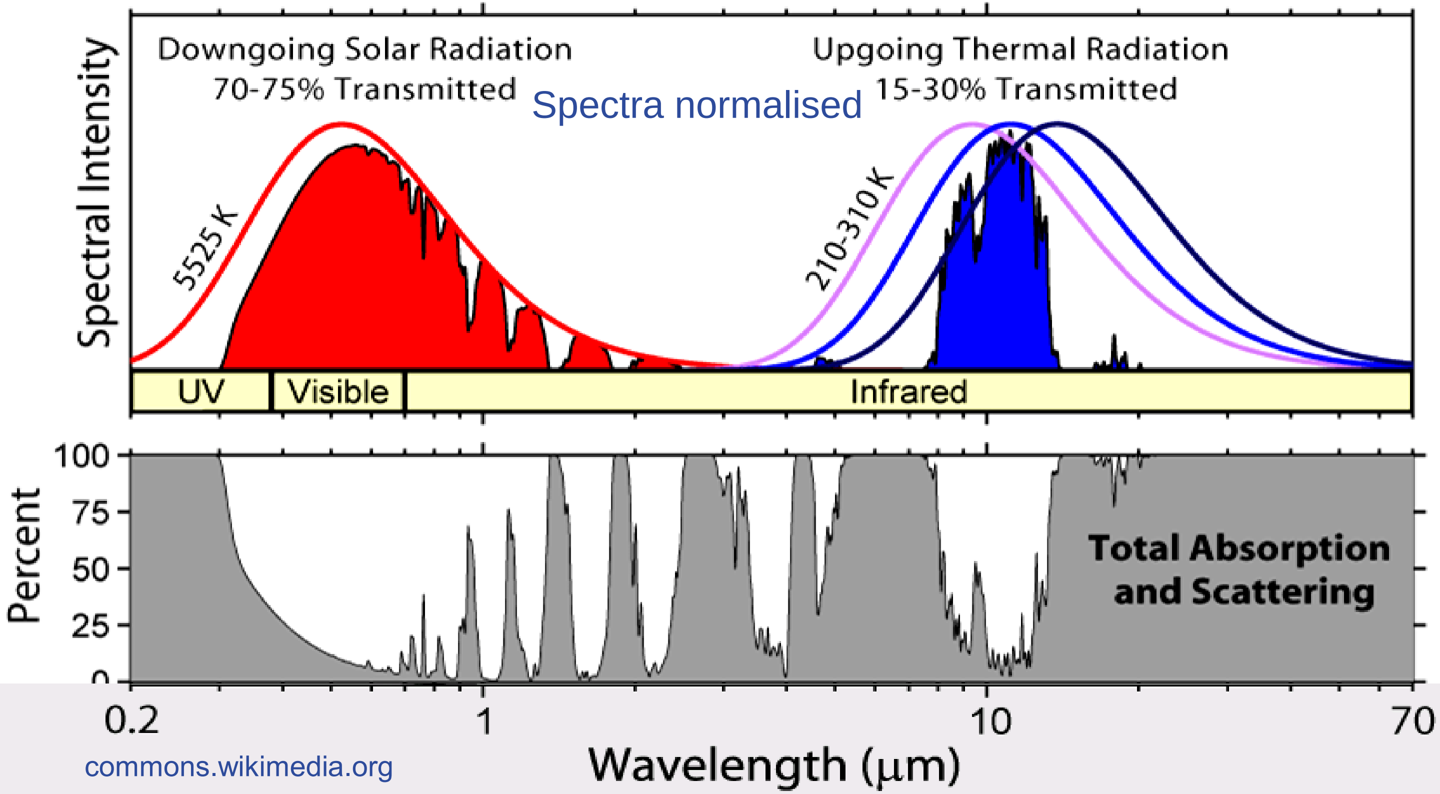
$$\frac{dF^{\downarrow}_{direct}}{d\tau} = -\text{sources}$$

Note: ignored factors…

Physics of Radiation

Radiation spectra and atmospheric gases

ICON Incoming SW and outgoing LW radiation spectra



commons.wikimedia.org

ICON Atmospheric gases

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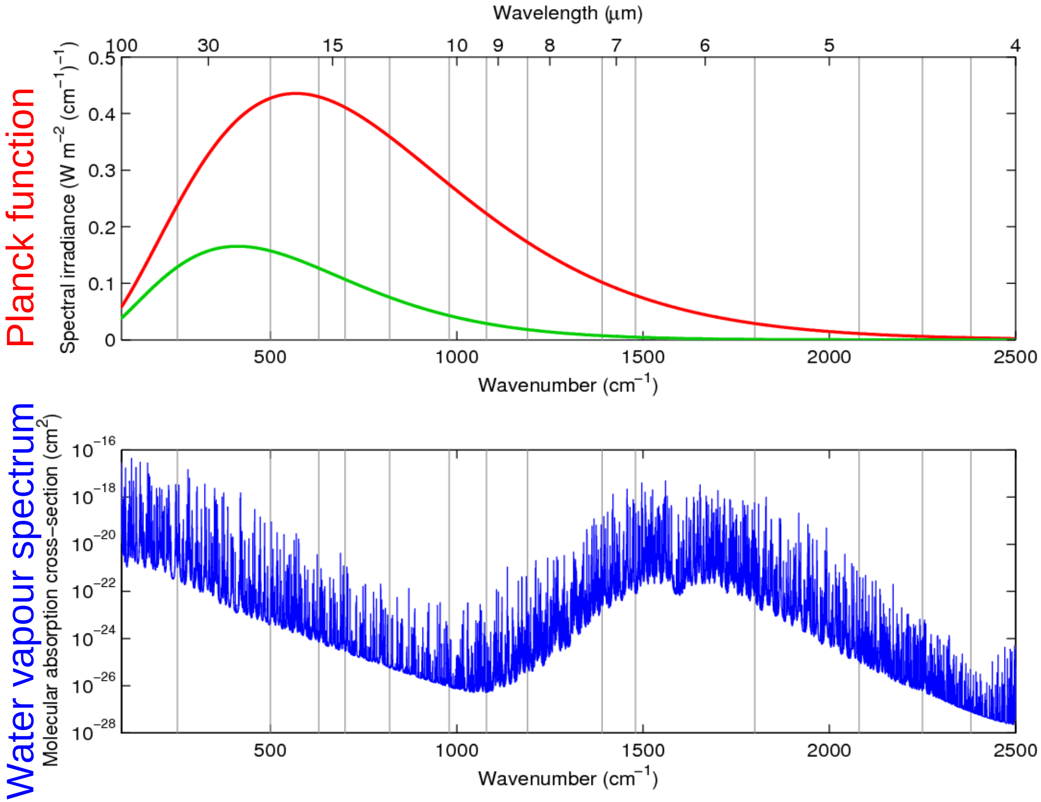
Gas	**Parts by volume** (per million)	**Interaction**
Nitrogen (N_2)	780,840 ppm (78.084%)	**sw (scat)**
Oxygen (O_2)	209,460 ppmv (20.946%)	**sw (scat, abs)**
Water vapour (H_2O)	~0.40% total, surface ~1%-4%	**lw**, **sw (abs)**
Argon (Ar)	9,340 ppmv (0.9340%)	
Carbon dioxide (CO_2)	390 ppmv (0.039%) **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)**

- 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 → GHG

Table by R. Hogan

Gas optics model – Example: RRTMG

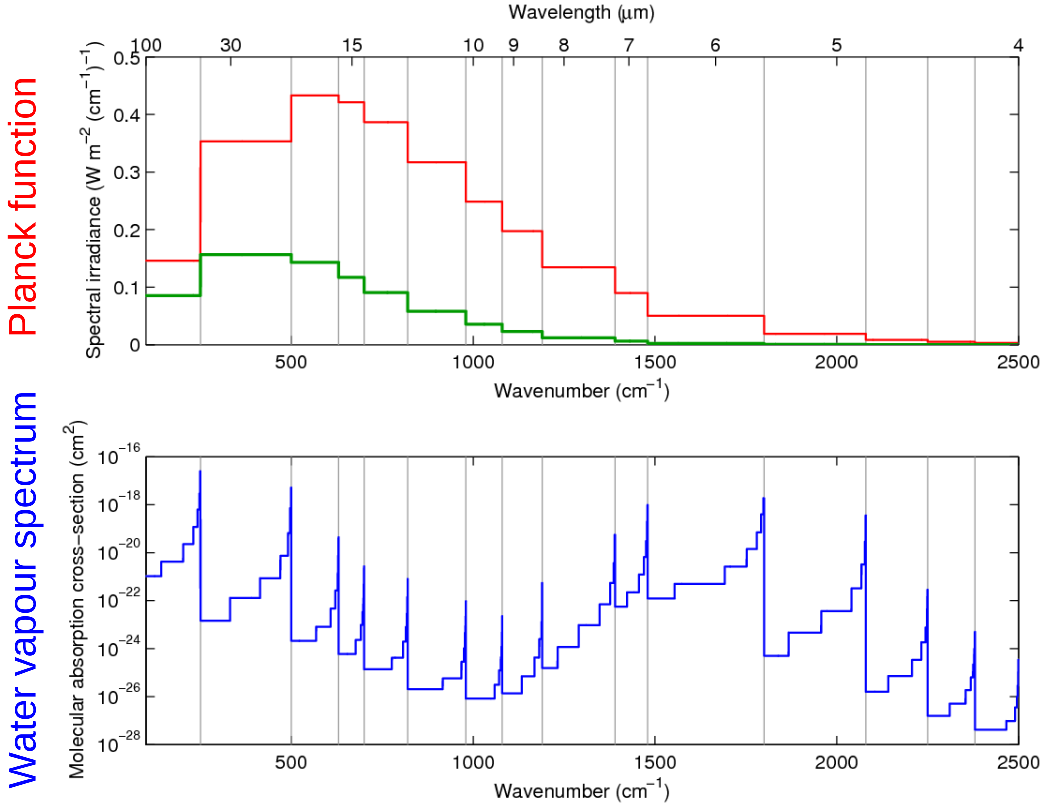
- "Rapid Radiative Transfer Model" gas-optics
- Divide spectrum into bands where Planck function is similar
- ICON uses RRTMG (Mlawer et al. 1997, Iacono et al. 2008): 14 bands in shortwave, 16 in longwave



Plot by R. Hogan

RRTMG: g-points / correlated-k-method

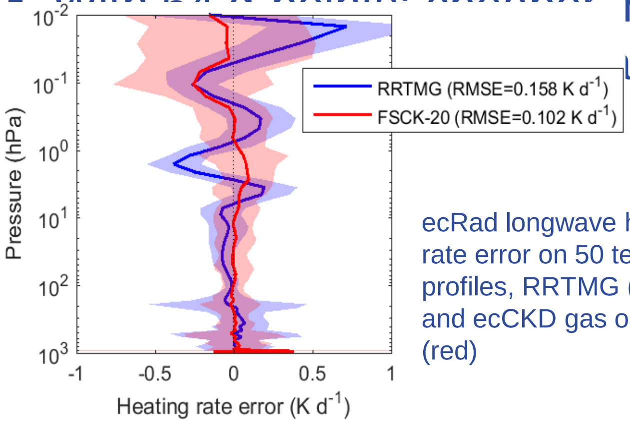
- In each **band**:
  - Approximate Planck function
  - Re-order by gas absorption, approximate in 6-21 **g-points** (Lacis, Oinas 1991)
- RRTMG: ~200 g-points
- Gas on g-points, particles/surface on bands
- Drawback: many repeated values in spectrum



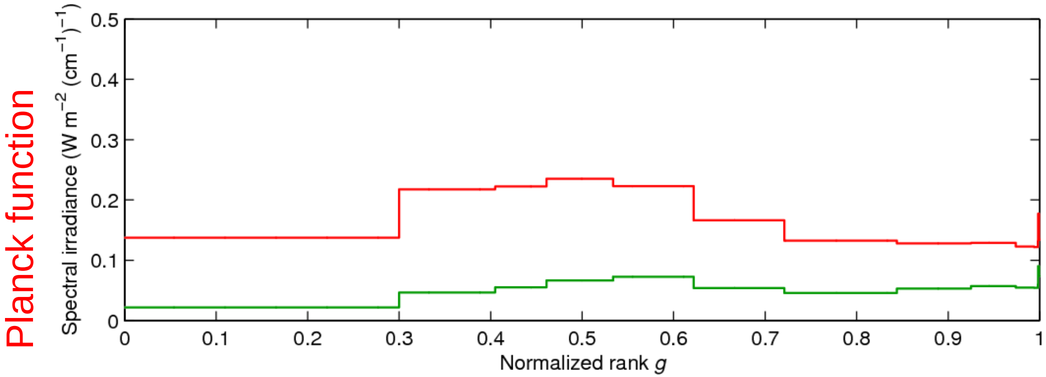
Plot by R. Hogan

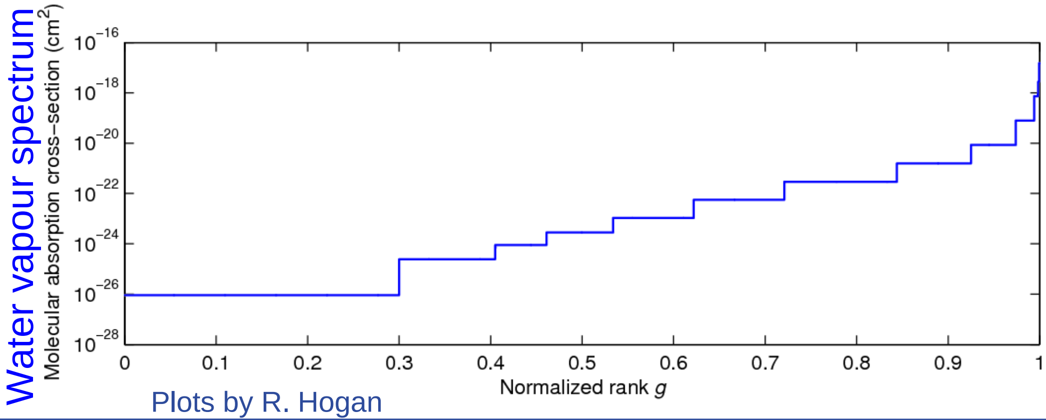
ecCKD gas optics: full-spectrum correlated-k-method

- Re-order whole spectrum, average Planck emission for wavelengths in each g-point, optics of cloud etc. can be per g-point or coarser band
- With 64 g-points: cheaper, more ... n and



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





Plots by R. Hogan

Summary: Gas optics

- Interaction of gases with radiation depends on the wavelength
- Full wavelength spectra must be simplified for computational efficiency
- Trade-off between accuracy and number of bands
- ecCKD: needs fewer bands to be more accurate than RRTMG
- DWD NEC vector machine: no immediate gain on computational time by reducing bands from ~200 down to 64
  - Efficiency depends on hardware architecture!

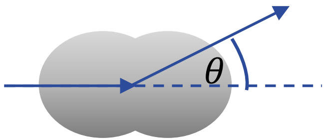
Physics of Radiation

Scattering by atmospheric particles

Scattering by particles: wavelength vs. size matters

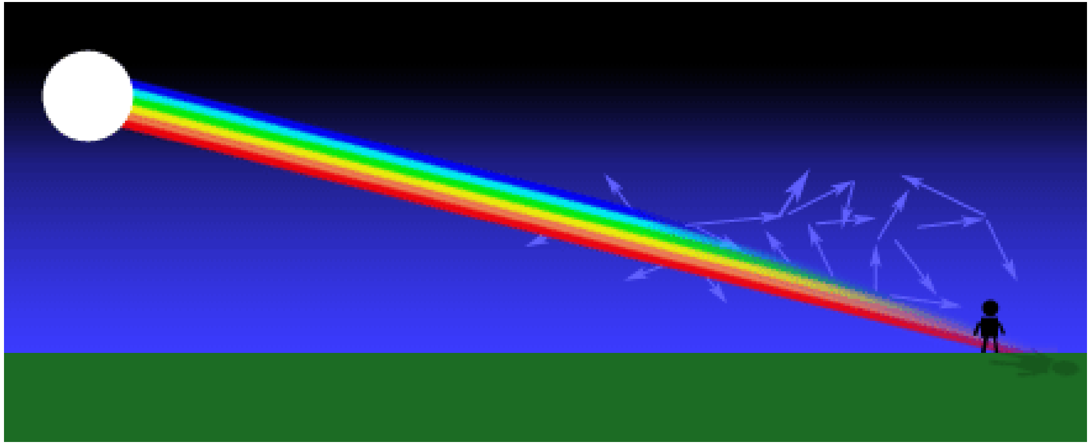
- Scattering intensity is a function of scattering angle θ and size parameter x (ratio of particle radius r and wavelength λ)

- $r \gg \lambda$: Geometric optics
- $r \ll \lambda$: Rayleigh scattering
  - Elastic scattering by spheres
  - Scattering intensity



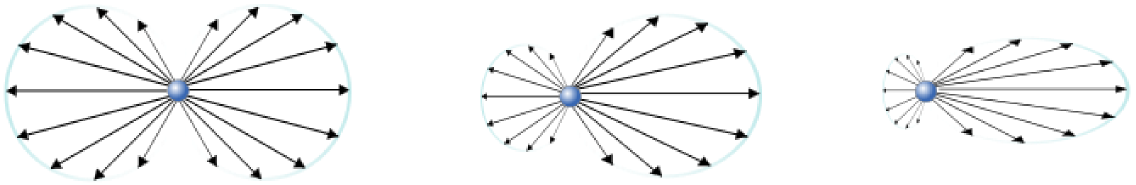
Rayleigh scattering: gases

- $p(\theta) = \frac{3}{4}(1 + (\cos\theta)^2)$
- Strong λ dependency: λ^{-4}
- Examples: blue sky during the day, red sunrise & sunset



Source: https://commons.wikimedia.org/wiki/File:RayleighScattering.gif

Mie scattering: wavelength approximately radius



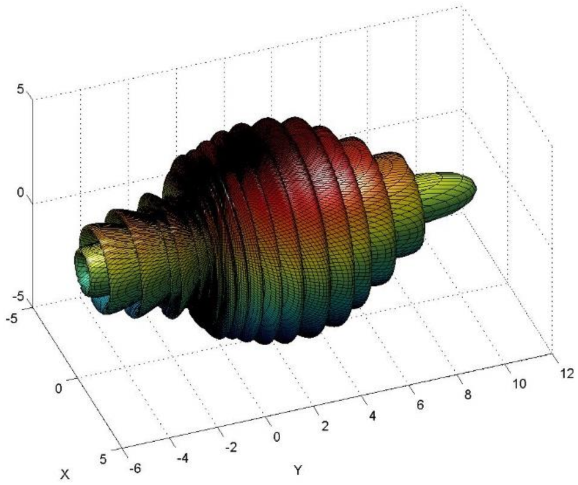
Scattering intensity (θ, x)

Source: https://upload.wikimedia.org/wikipedia/commons/thumb/6/67/Mie_scattering.svg/721px-Mie_scattering.svg.png?uselang=fr

- $r \sim \lambda$, spherical particles : **Mie scattering**
  - complex function of scattering angle
  - Approximated by numerical algorithms
  - Strong forward peak: treated together with non-scattered direct radiation in model
  - Model: Simplify by bulk **asymmetry parameter *g***

    $g > 0$: more forward scattering

    $g < 0$: more backward scattering



Source: 3D_Miestreuung_an_2um_Kugel.jpg (1201×900)

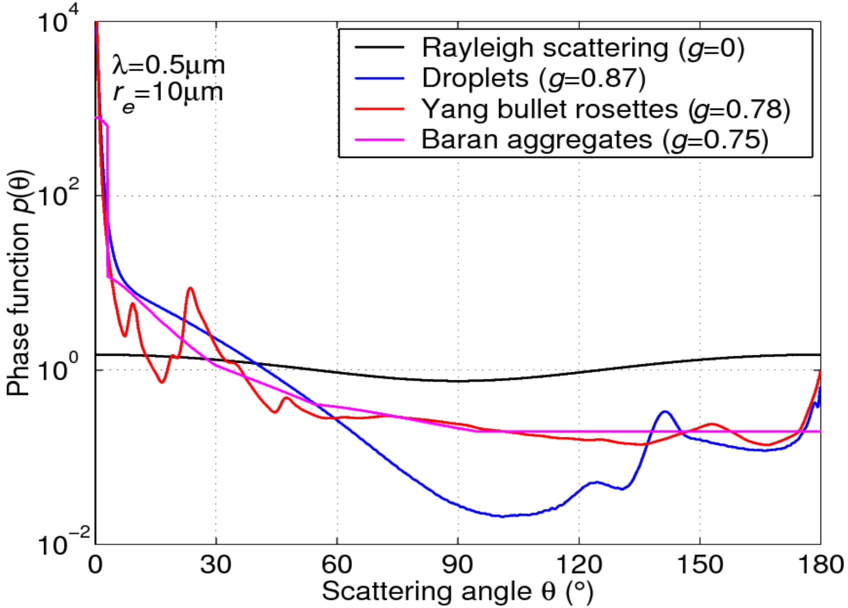
Particle shape, asymmetry parameter

- Particle shape adds more complexity
- Ice particle shapes are complex
  → use shape assumptions; default in ICON: hexagonal columns (Fu 1996, 1998)

- Simplify by bulk **asymmetry parameter**

$$g = \frac{1}{4\pi} \int_0^{\pi} \int_0^{2\pi} p(\theta) \cos(\theta) d\phi \, d\theta \, ,$$

  - $g > 0$: more forward scattering
  - $g < 0$: more backward scattering



Plot by R. Hogan

ICON Particle size distribution, effective radius

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- Clouds contain a mixture of particles of different sizes and shapes

- Distributions scatter like particles with one **effective radius**
  - $\boldsymbol{r_{eff}}$= average radius weighted by number, area and scattering efficiency of each particle size

- Model: parametrise r_{eff}

Summary: Particle scattering

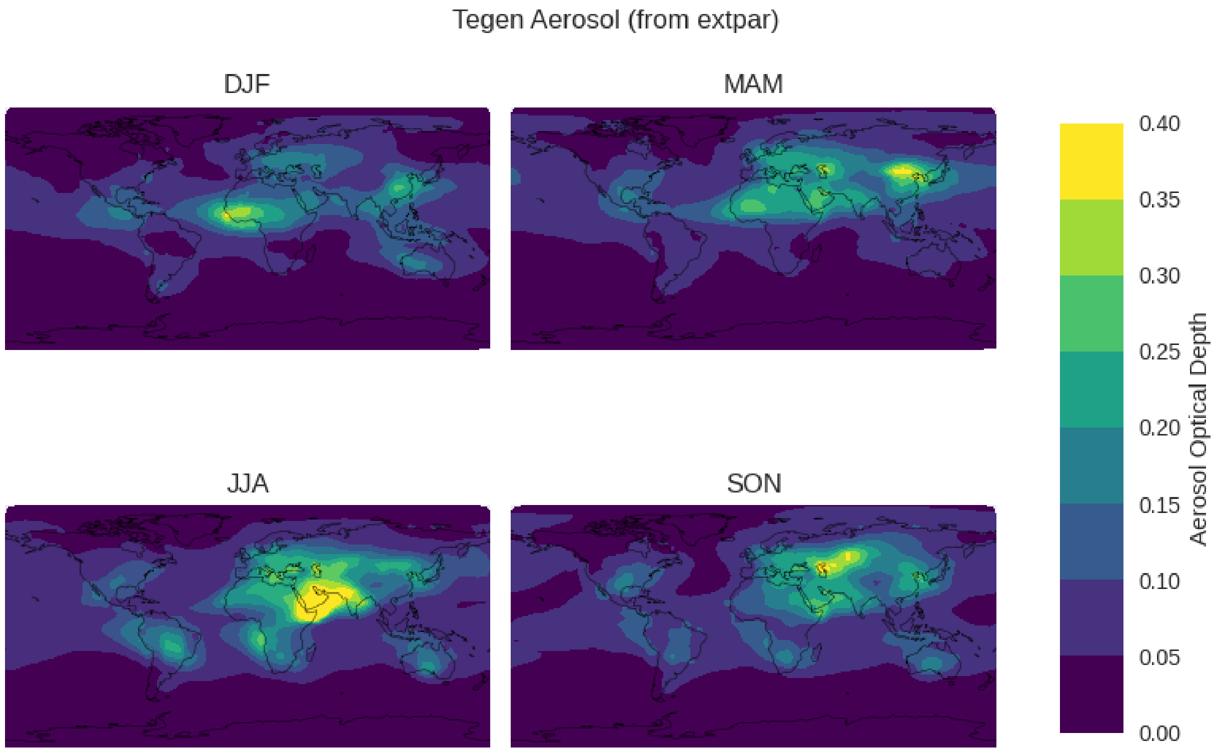
- Size- and shape-dependent
- Heavily simplified in the model – large uncertainty
  - Complex shapes (ice) more uncertain than simpler shapes (liquid drops)
  - Assumptions made for radiation not necessarily the same as those for microphysics

Physics of Radiation

Aerosol and surface properties

Aerosol: Tegen climatology is default

- Use aerosol climatology of optical properties e.g. Tegen et al 1997
- Tegen is operational NWP default
  - extpar file
  - *irad_aero = 6*



ICON Aerosol: other options (*irad_aero*)

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- Currently dynamic area of development!
- ICON-ART aerosol (irad_aero=9)
  - Uses Tegen for aerosols not computed by ART
- CAMS climatology
  - irad_aero=7, cams_aero_filename
  - Create climatology on your grid: scripts/preprocessing/make_camsclim_onICONgrid.sh
- Kinne, stratospheric volcanic, simple plumes. Powerful in combination
  - Kinne: constant or time series data
  - Volcanic stratospheric aerosol for CMIP6
  - Simple plumes: possible emissions
  - Useful for climate application
- CAMS 3D forecasted aerosol
  - irad_aero =8, cams_aero_filename

ICON CAMS vs Tegen climatology

CAMS climatology	Tegen Climatology
3D climatology of mixing ratios	2D climatology of AOD
5 species of aerosols used (of 9)	5 species of aerosols
Vertical profile based on dynamics	Fixed vertical profile
Optical properties calculated for each RRTM/ecRad WL intervals	Optical properties calculated at 550 nm and corrections made for other WL
Optical properties of hydrophilic aerosols are RH-dependent	Optical properties are RH-independent
Longwave scattering included	longwave scattering not included

Kindly provided by H. Muskatel, IMS

ICON Surface emissivity & albedo

- climatology in external parameter file (“extpar”)
- depends on soil type, month, wavelength range, modified for soil moisture, snow, sea ice

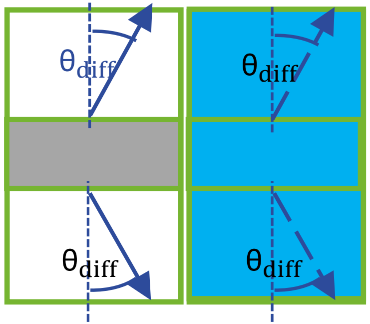
Modelling Radiation

Solver and cloud geometry

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
- cloudy and clear region of gridbox

- Direct solar radiation is handled separately;
- Diffuse radiation: assume solar zenith angle θ_{diff} to approximate integral over angles



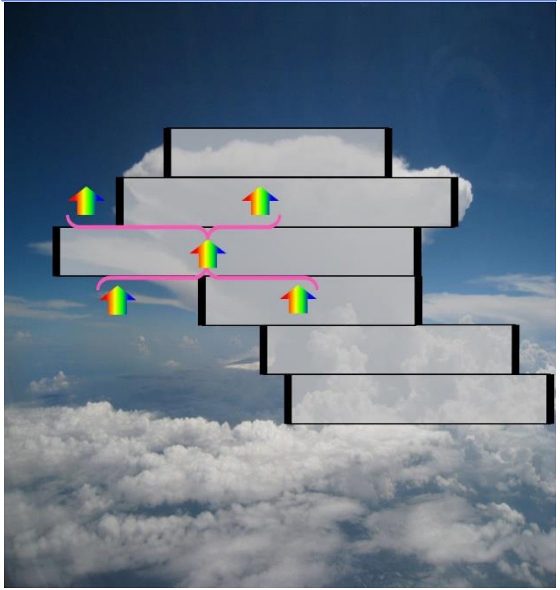
In every layer, for clear and cloudy, compute:

- Extinction (loss)
- Scattering (loss and gain)
- Internal source (gain)

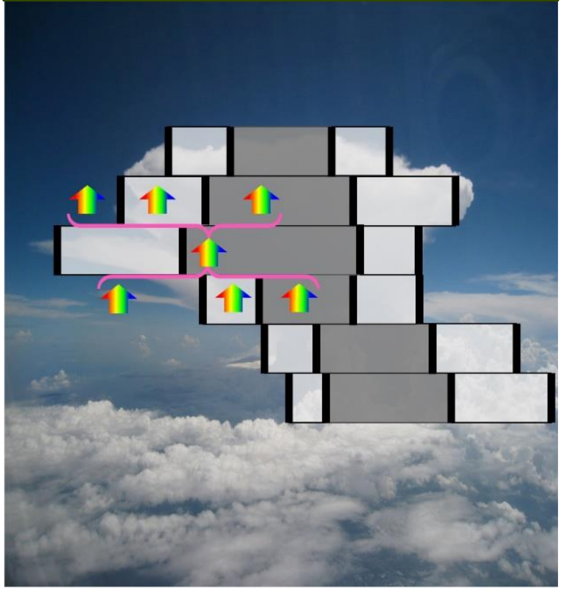
Clouds in radiation solvers

All solvers for global models **simplify** by treating **only vertical** dimension explicitly.

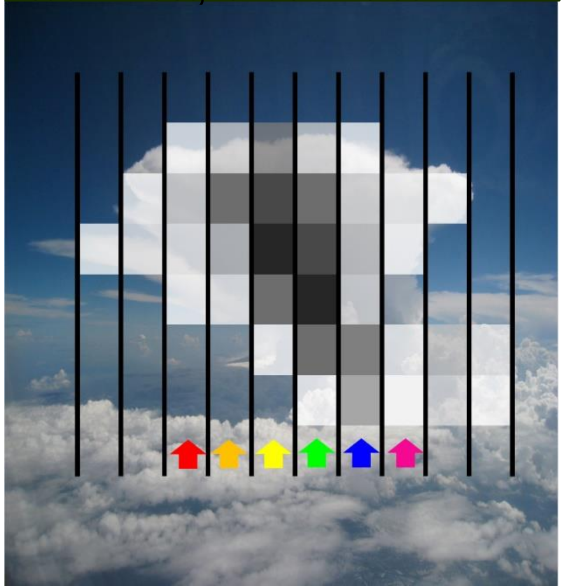
Two-stream solver (e.g. RRTM in ICON)**:** solve in **cloudy / clear regions**, partition at layer boundaries according to **overlap**



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



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

ICON Cloud vertical overlap

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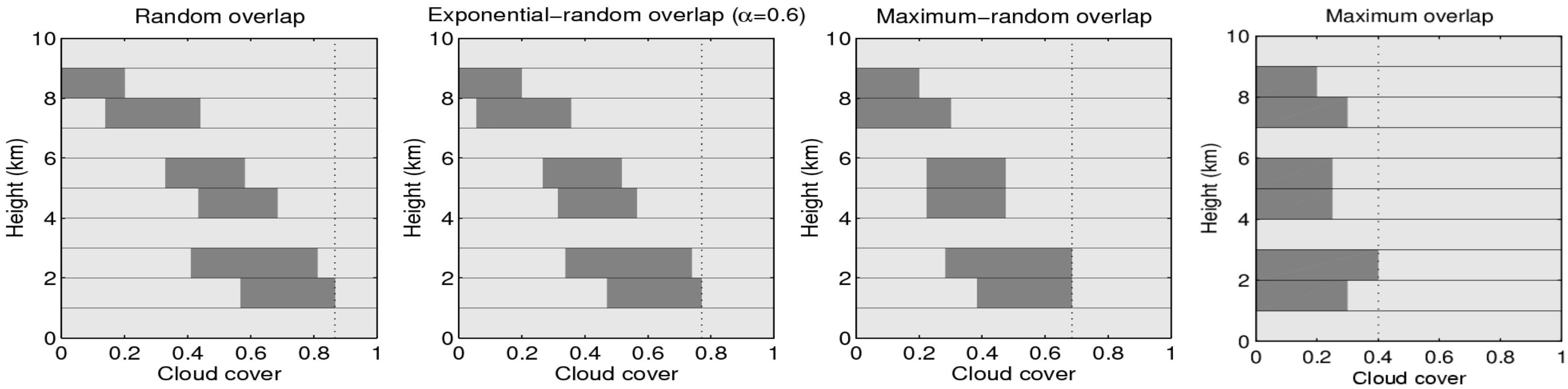
- For given cloud fraction in each layer, **cloud overlap** determines total cloud cover

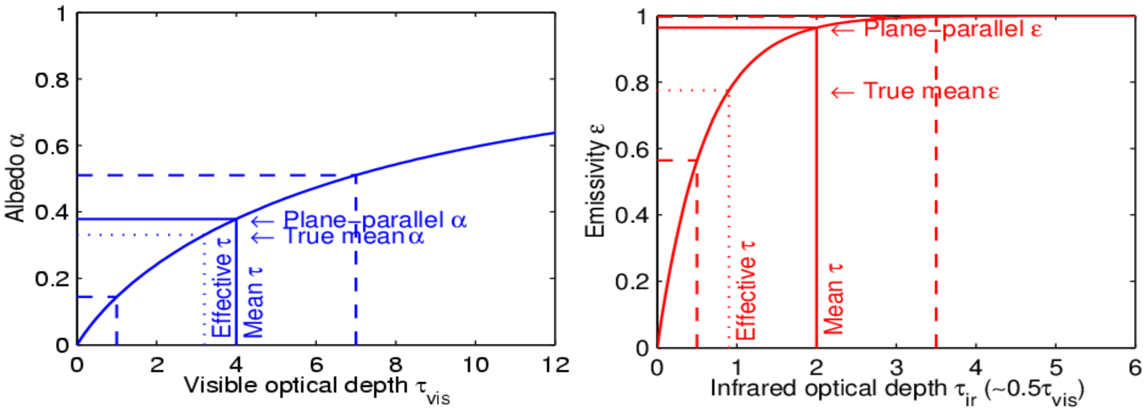


Adapted from Hogan & Illingworth 2000, QJRMS

- Based on observations (Hogan & Illingworth 2000): **exponential-random overlap,** decorrelation length ca. 2km, or dependent on cloud type
- Development: latitude-dependent decorrelation length-scale

Cloud inhomogeneity

Reflectivity and longwave emissivity are **non-linear** functions of optical depth / cloud water
→ mean optical properties ≠ optical properties of mean optical depth τ
Using reflectivity and emissivity of mean optical depth overestimates cloud effect.



Plot by R. Hogan

- ecRad: sub-divide cloud into two or more sub-regions with different optical depth (Pincus et al. 2003; Shonk & Hogan 2008)
- Assumed distribution (Gamma/log-normal), inhomogeneity parameter FSD= σ/mean = 1

ICON Summary: Radiation solvers

- All solvers simplify by mainly considering up/down flux within the model column
- Greatest uncertainty stems from interaction with cloud!
  - How to partition clear/cloudy areas in grid box
  - How to arrange clear/cloudy areas vertically (overlap)
  - How to represent subgrid-variability more generally
  - Cloud microphysics also uncertain

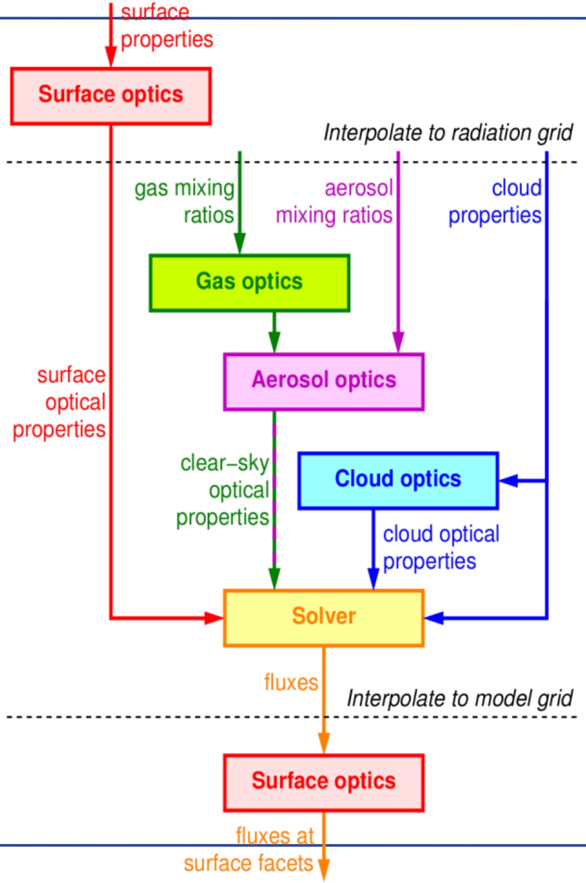
- Note: RRTM is a solver (old, two-stream), RRTMG is a gas-optics package!

ICON Radiation Scheme

ecRAD, and how to run it

ecRad: A modular radiation scheme

- Aerosol optics: variable species number and properties (set at run-time)
- Gas optics
  - RRTMG (Iacono 2008)
  - ecCKD (Hogan 2010): fewer spectral intervals needed for similar precision
- Cloud optics:
  - liquid: SOCRATES (MetOffice), Slingo (1989)
  - ice: Fu 1996, 1998 (default) , Yi et al. 2013 or Baran et al. 2014
- Surface (under development) Consistent treatment of urban and forest canopies



- Solvers for radiative transfer equations:
  - McICA (Pincus et al. 2005), Tripleclouds (Shonk & Hogan, 2008) or SPARTACUS (Schäfer et al. 2016, Hogan et al. 2016)
  - Longwave scattering optional
  - Can configure cloud overlap
  - Cloud inhomogeneity: can configure width and shape of PDF

(Hogan & Bozzo, 2018)

ICON ecRad in ICON

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Physics interface
mo_nh_interface_nwp.f90

Radiation interface:
mo_nwp_rad_interface_nwp.f90
Radiation config?
Full/reduced grid?

In each gridbox

ecRad radiation scheme

Collect optical properties (surface, gas, aerosol, cloud)

shortwave solver

longwave solver

Radiative fluxes/transmissivities

Radiative heating
radheat in mo_radiation.f90

Heating rates

Implementation in ICON:
D. Rieger, M. Köhler,
R. J. Hogan, S. A. K. Schäfer,
A. Seifert, A. de Lozar and
G.Zängl (2019): *ecRad in ICON – Implementation Overview*, Reports on ICON

Reduced radiation grid

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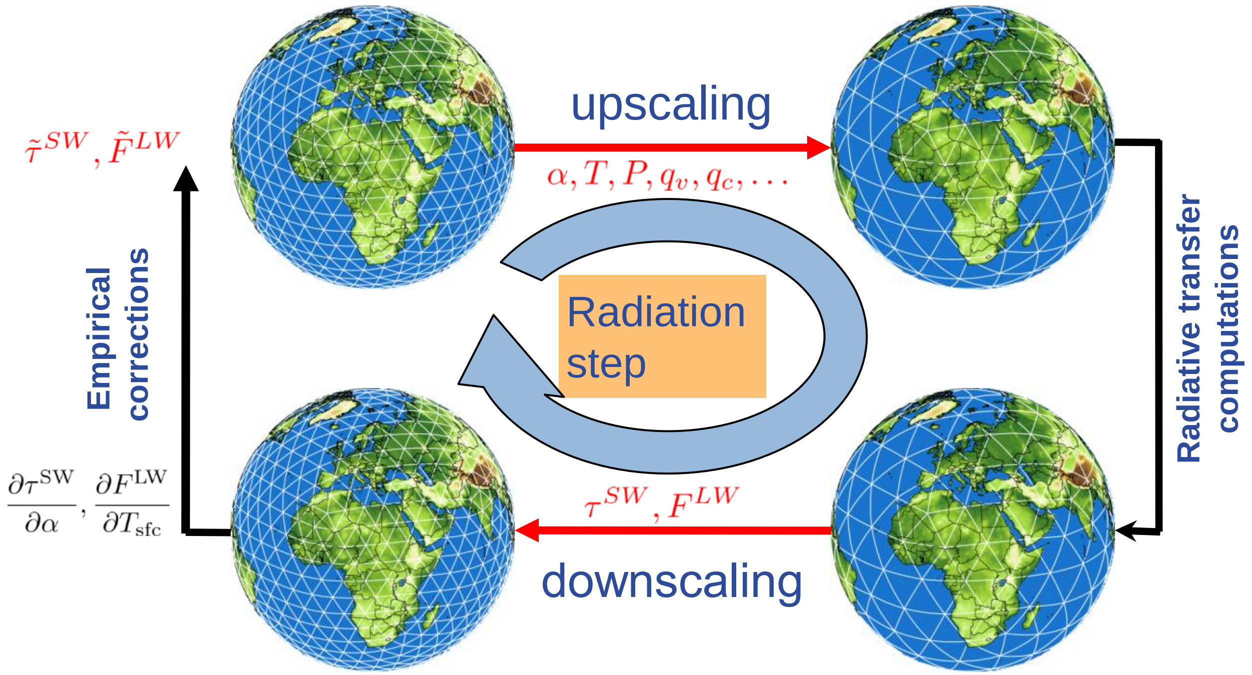
Hierarchical structure of triangular mesh: calculate physical processes (e.g. radiative transfer) with different spatial resolution compared to dynamics.




```
&grid_nml
 lredgrid_phys              = .TRUE.
 radiation_grid_filename    = <name>
/
```

Default for NWP at DWD

Reduced Radiation Grid

- Advantages of the reduced radiation grid
  - Fully supported
    - &nwp_phy_nml: *latm_above_top*
      → reduce TOA bias by adding an extra layer
    - Scores better than with full grid
  - Accurate
  - Interpolation quicker than running radiation on full grid
  - Load balancing available: mix day and night time columns on every processor
  - Radiation time step larger than physics time step, so reducing spatial resolution is reasonable

Use the reduced radiation grid!

ICON Radiation Namelist Options in ICON

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configure: *./configure --enable-ecrad* (default)

&nwp_phy_nml

inwp_radiation = 4 ! 0: no radiation, 1: RRTM, 4: ecRad
dt_rad = ? ! Radiation time step. Use multiple of convection time step!

&radiation_nml

ecRad_data_path = <ICON-directory>/externals/ecrad/data
icld_overlap = 2 ! 1: maximum-random, 2: exponential-random, 3: maximum, 4: random
irad_aero = 6 ! Aerosols; 0: no aerosol, 2: constant, 6: Tegen climatology, 9: ART
ecrad_isolver = 0 ! Radiation solver; 0: McICA, 1: Tripleclouds (Hogan and Shonk 2008)
ecrad_igas_model = 0 ! Gas model and spectral bands; 0: RRTMG, 1: ecckd (Hogan and Matricardi 2020)
ecrad_iliquid_scat = 0 ! Liquid optics scheme: 0: SOCRATES, 1: Slingo (1989)
ecrad_iice_scat = 0 ! Ice optics scheme: 0: Fu et al. (1996), 1: Baran et al. (2016)
ecrad_llw_cloud_scat = .false. ! Do longwave cloud scattering?

ICON configuration cont.

Not all combinations possible. ecRad documentation at https://confluence.ecmwf.int/display/ECRAD

Current operational: RRTMG gas optics + McICA solver
Alternative: ecCKD gas optics + TripleClouds solver → faster on other architectures

McICA solver with ecCKD is noisy with only 64 g-points. Not recommended.

DO NOT USE RRTM RADIATION!
Buggy, outdated, no longer supported.

Summary

- Radiation drives weather and climate
- Described fully by Maxwell equations + gas emission / absorption
- **Simplification** in global models: **two-stream equations** for up-/downward flux
- Cloudy + clear region in gridbox, bulk optical properties
- Spectrum divided into bands to capture variable emission and absorption
- Some uncertainties, especially in clouds (particle size, geometry,…)
- **ICON:** modular **ecRad:** fast and flexible radiation scheme, parametrisations can be changed individually.
    - Treats cloud inhomogeneity and can treat 3D cloud effects

Thank you for your attention!

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FE14, Physical Processes
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Questions?

ICON References

- Radiation textbooks
  - Petty G. W., 2006. *A first course in atmospheric radiation*. Sundog Pub.
  - Liou, K.-N., 1992: *Radiation and Cloud Processes in the Atmosphere*. Oxford University Press.
- ecRad: Hogan, R. J., Bozzo, A. (2018). *A flexible and efficient radiation scheme for the ECMWF model*. JAMES.
- ecRad in ICON: Rieger, D., M. Köhler, R. J. Hogan, S. A. K. Schäfer, A. Seifert, A. de Lozar and G. Zängl (2019). *ecRad in ICON - Implementation Overview*, Reports on ICON.
- RRTM gas optics: Mlawer, E. J. et al., 1997. *Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave*. JGR.
- Cloud geometry: Shonk, J. 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.