UKCA_RADAER
AEROSOL-RADIATION INTERACTIONS

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LIMITLESS **POTENTIAL** | LIMITLESS **OPPORTUNITIES** | LIMITLESS **IMPACT**

LECTURE SUMMARY

- **Why care about aerosol-radiation interactions?**

- **Theory of aerosol-radiation interactions**
  - **Mie scattering**

- **Description of UKCA_RADAER**
  - **Methods**
  - **Diagnostics**
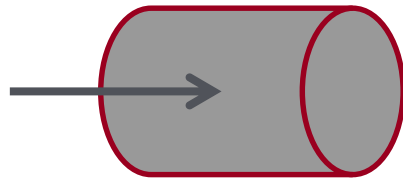 - **Double-call simulations**

AEROSOL-RADIATION INTERACTIONS

"This mixture of smoke and dust seems far brighter on the side from which sunlight comes than on the opposite side."
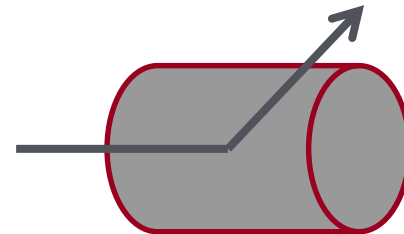
Leonardo da Vinci, Manuscript A (circa 1490)
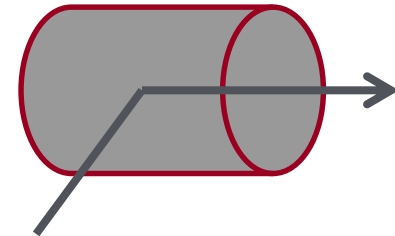
AEROSOL-RADIATION INTERACTIONS

- Absorption

- Scattering out of viewing direction

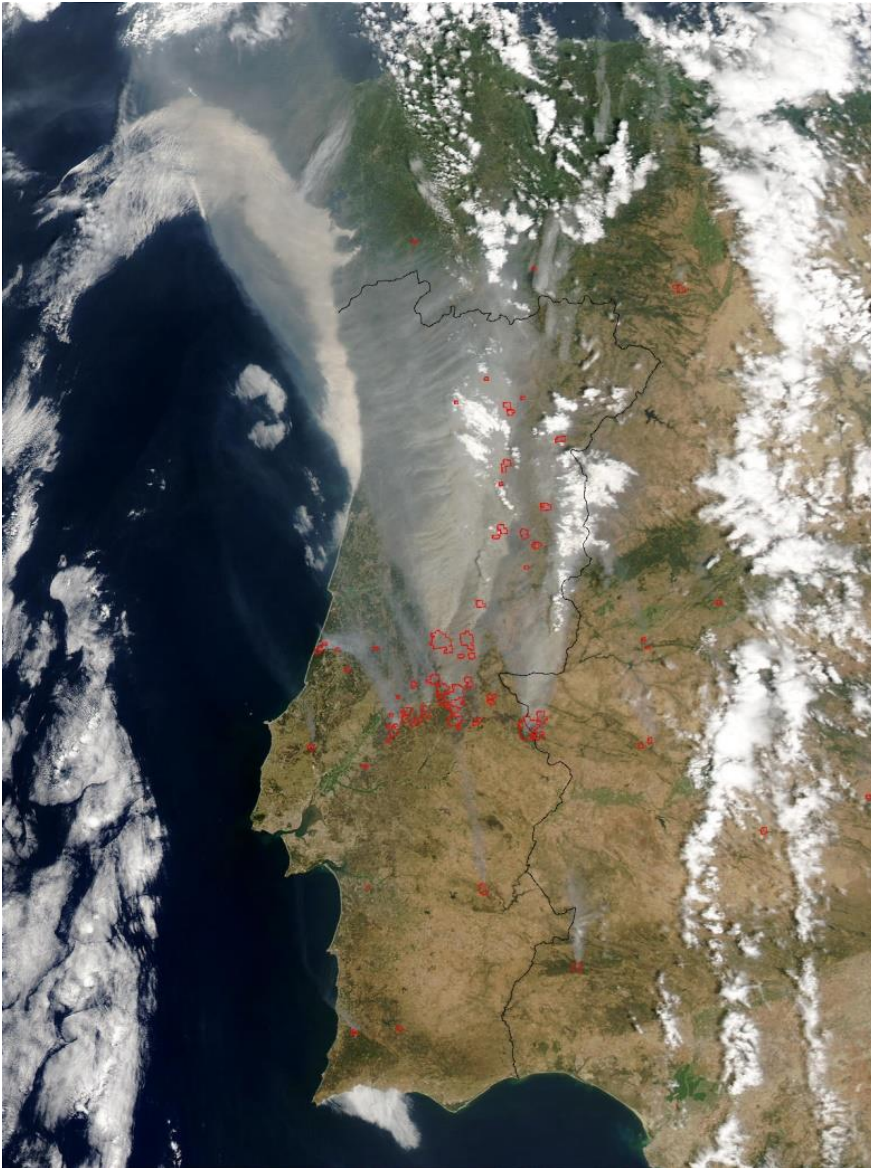- Scattering into viewing direction

- Emission

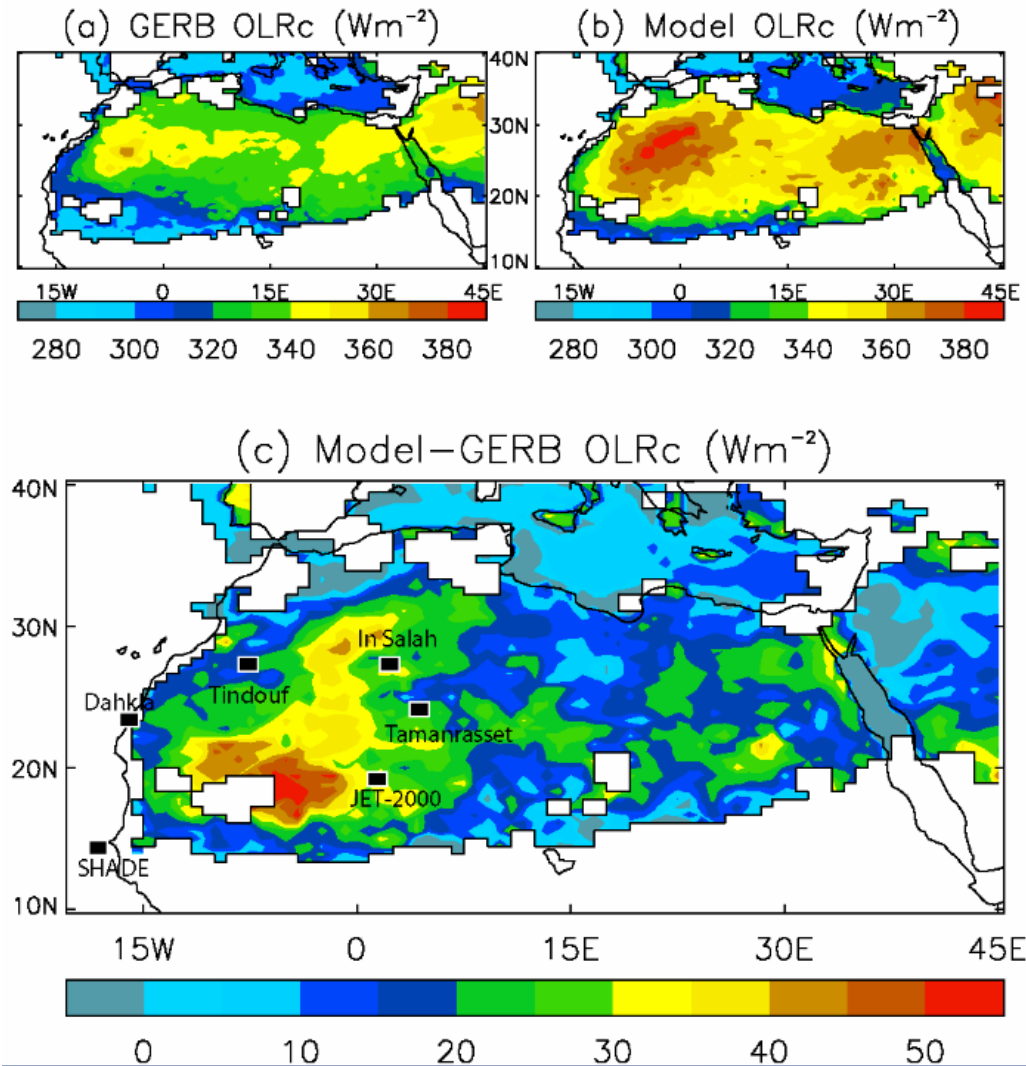# WHY WE CARE ABOUT AEROSOL-RADIATION INTERACTIONS

- They are part of the energy budget of the Earth: the direct radiative effect.

- They affect visibility.

- For anthropogenic aerosols, they represent a radiative forcing of the climate system: the direct radiative forcing.

- They allow model evaluation against remote-sensing products.

WHY WE CARE

- Forest fires in Portugal, 3 August 2003

- Image by MODIS radiometer

- Above dark surfaces, scattering by aerosols increase shortwave planetary albedo: loss of energy at the top of atmosphere and surface

- Above bright surfaces, absorption by aerosols decrease shortwave planetary albedo: gain of energy at the top of atmosphere, loss of energy at surface.

WHY WE CARE

(a) GERB OLRc (Wm⁻²)

(b) Model OLRc (Wm⁻²)
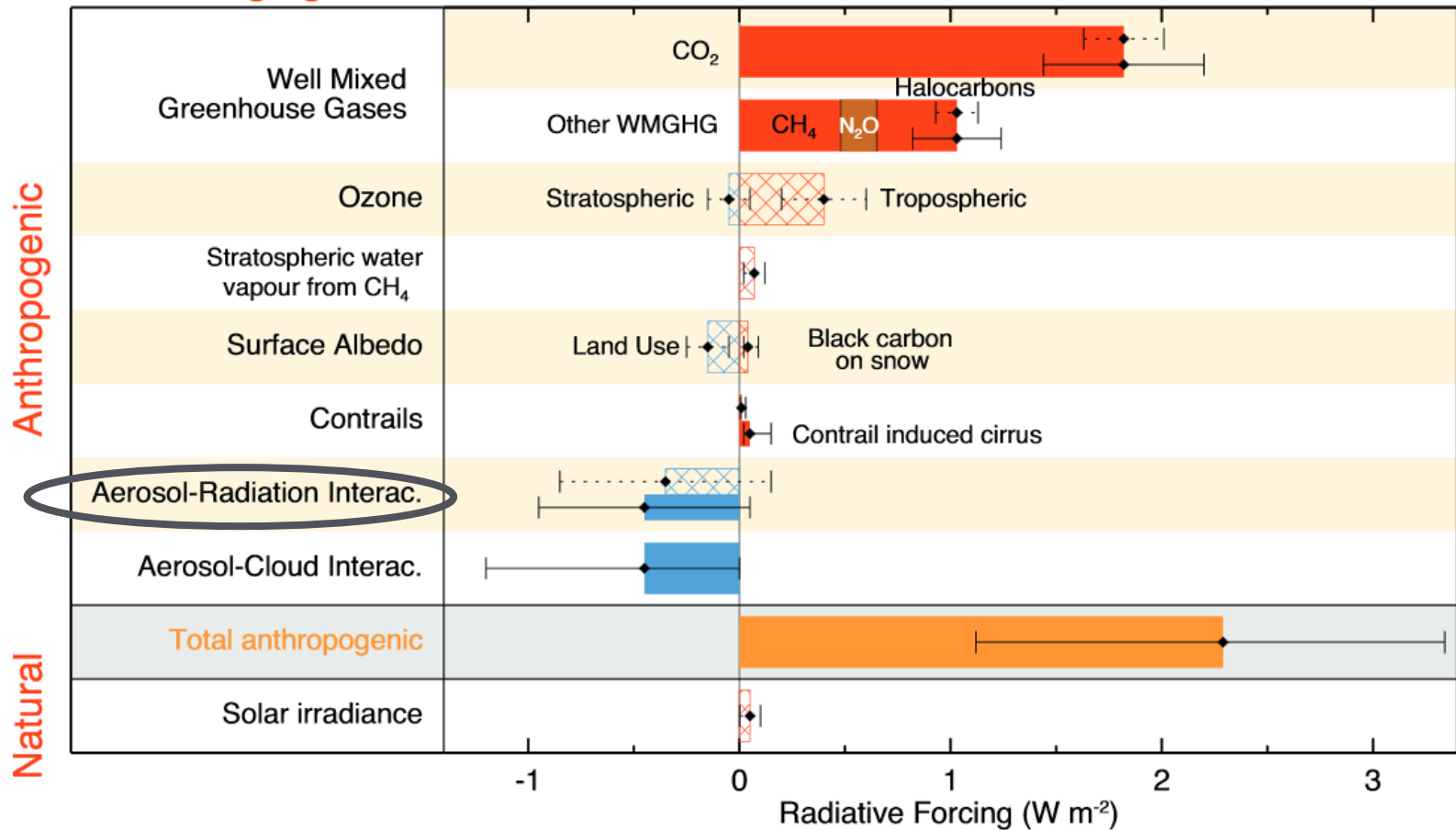
(c) Model−GERB OLRc (Wm⁻²)

- Haywood et al. (2005) *Can desert dust explain the outgoing longwave radiation anomaly over the Sahara during July 2003?*

WHY WE CARE

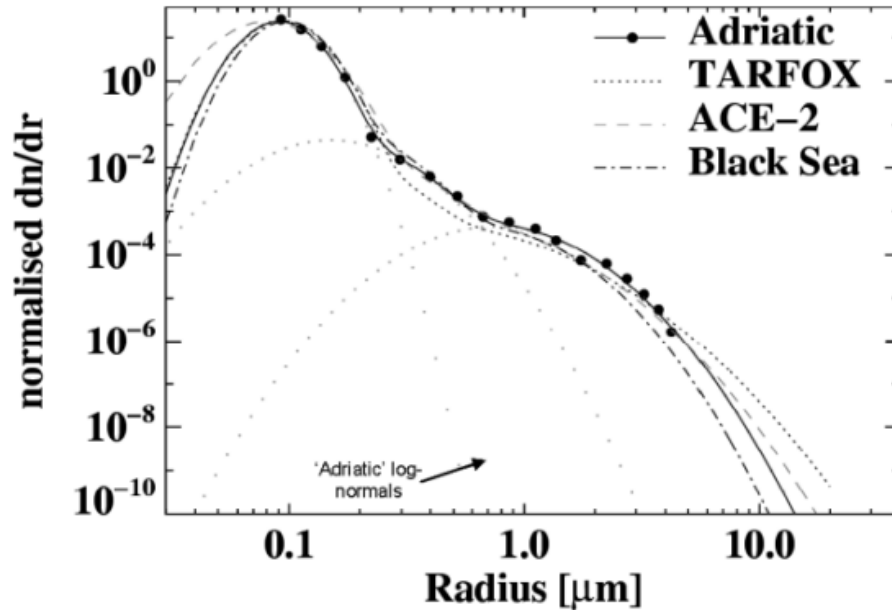Radiative forcing of climate between 1750 and 2011

IPCC AR5, Figure 8.15 (2013)

MIE SCATTERING

AEROSOL SIZE DISTRIBUTION

Aircraft measurements, Osborne *et al.* [2007]

- The distribution of particle number (or surface, or volume) as a function of particle radius shows local maxima, called modes.

- The size distribution is critical for interactions with radiation.
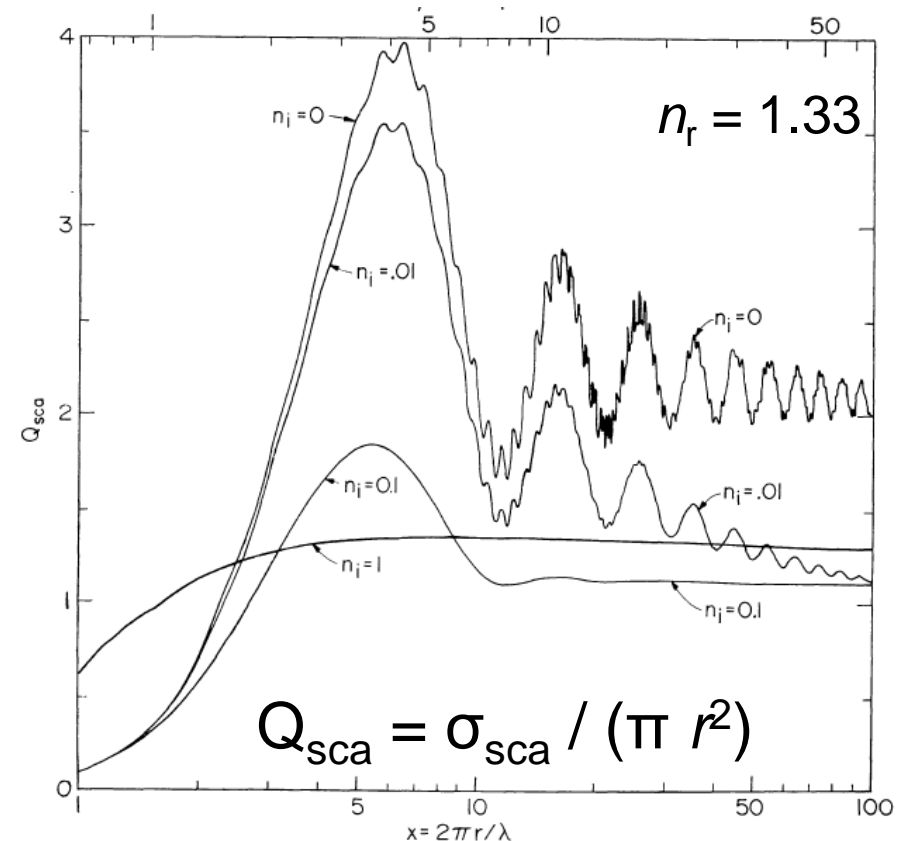
Radius range	r < 0.05 µm	r < 0.5 µm	r > 0.5 µm
Mode	Nucleation, Aitken	Accumulation	Coarse
Typical origin	Gas-to-particle conversion	Coagulation, combustion	Friction

MIE SCATTERING

- Aerosol radii r (0.1 to 10 µm) are of similar magnitude to the wavelength λ of shortwave and longwave radiation
  - Shortwave (or solar) spectrum: 0.25 to 5 µm
  - Longwave (or terrestrial) spectrum: 3 to 50 µm

- When $r \sim$ λ, this is the domain of **Mie** scattering.

- Mie theory (1908) applies to homogeneous spheres, which is generally a good approximation for aerosols.
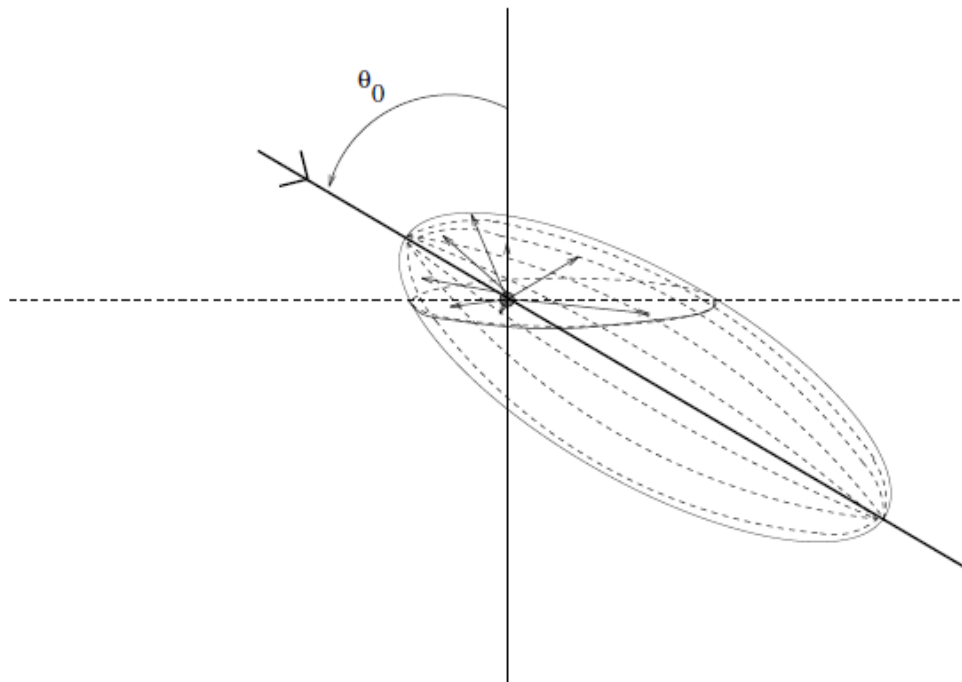
MIE SCATTERING

- Mie theory allows the calculation of the scattering and absorption cross sections σ_{sca} and σ_{abs} (in m^2).

- According to Mie theory, σ_{sca} and σ_{abs} depend *only* on:
  - The size parameter
    - $x = 2\pi\, r\, /\, \lambda$
  - The complex refractive index
    - $m = n_r - n_i$

- For hygroscopic aerosols, the impact of water uptake on x and m needs to be included.

$n_r = 1.33$

$Q_{sca} = \sigma_{sca}\, /\, (\pi\, r^2)$

Hansen and Travis (1974), Figure 9

PHASE FUNCTION

- Also calculated by Mie theory, the phase function gives the probability of being scattered in a given direction.

θ_0

Boucher (2012)
Aérosols Atmosphériques
Figure 7.12

- In most climate models, phase function is represented by its average, the dimensionless asymmetry parameter *g.*

MIE SCATTERING FOR AN AEROSOL DISTRIBUTION

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- The quantities valid for a given particle radius need to be integrated over the size distribution $n(r)$

$$\sigma_{sca}(r, \lambda, n_r, n_i) = \int Q_{sca}(r, \lambda, n_r, n_i)\, n(r) r^2\, dr$$

- This is done for the three optical properties required:

- σ_{sca}, σ_{abs}, and g

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UKCA/GLOMAP

Aerosol mass
Aerosol number
Aerosol dry diameter
Aerosol wet diameter
Aerosol density
Aerosol volume fraction, including water

Mie look-up tables
Refractive indices

UKCA_RADAER

Aerosol optical properties, averaged over
SW and LW wavebands

Aerosol optical depths

ES radiation scheme

UKCA_RADAER: LOOK-UP TABLES

- Mie scattering calculations are too expensive to be done at runtime.

- However GLOMAP size distributions are interactive, so aerosol optical properties cannot be prescribed offline.

- Solution: look-up tables containing optical properties for all realistic combinations of x and m.

- Aerosol size distributions are assumed lognormal, with fixed standard deviations depending on mode.

UKCA_RADAER: LOOK-UP TABLES

- The look-up tables contain:
  - $\sigma_{sca}(x, n_r, n_i)$ and $\sigma_{abs}(x, n_r, n_i)$, in m^{-1} (normalised per unit volume)
  - g
  - aerosol volume fraction $V(x) = \frac{4}{3} \pi \int x^3 \, n(x) \, dx$ (norm. per unit vol.)
- 51 values of x, 51 values of n_r, 51 to 801 values of n_i
- Realistic ranges depend on the aerosol mode and the range of wavelength considered:

Mode	Spectrum	x	n_r	n_i
Accumulation	SW	$4 \; 10^{-3}$ to 32	1.25 to 2	0 to 0.6
	LW	$4 \; 10^{-6}$ to 2	0.50 to 3	10^{-9} to 1
Coarse	SW	0.3 to 48	1.25 to 2	0 to 0.6
	LW	$3 \; 10^{-4}$ to 3	0.5 to 3	10^{-9} to 1

UKCA_RADAER: LOOK-UP TABLES

- UMUI: Section 34 UKCA > COUPL > RADAER

Here, vn8.6.

UKCA_RADAER METHODS

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1. Compute x from GLOMAP's modal wet diameter and current wavelength.

2. Compute m of internal mixture as volume-weighted average of component m (including water)
   - $[NH_4]SO_4$ or H_2SO_4, BC, OC, SOA, sea-salt, mineral dust, NH_4NO_3

3. Now that x and m are known, access the right σ_{sca}, σ_{abs}, g, and V in the relevant look-up table.

4. Convert to specific scattering and absorption (m^2 kg^{-1}) to comply with radiation code requirements: $k_{sca} = \frac{\sigma_{sca}}{\rho\,V}$, where ρ is the modal density ($kg\ m^{-3}$).
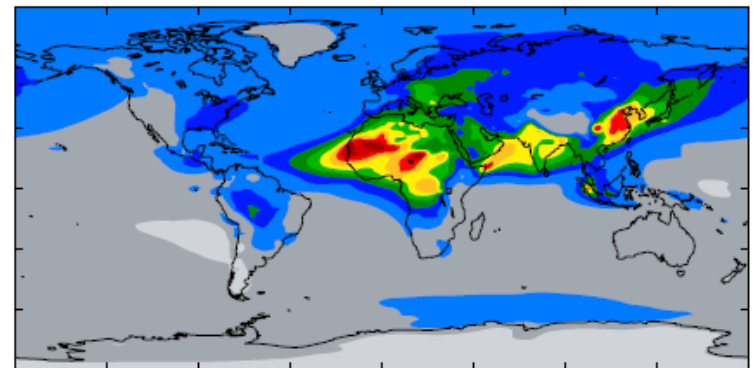
UKCA_RADAER KEY FUNCTIONS

- ukca_radaer_band_average()
  - Integrates aerosol optical properties across Unified Model spectral wavebands
  - 6 integration wavelengths per waveband
  - Weighted by solar irradiance (SW) or Planck's blackbody function (LW)

- ukca_radaer_compute_aod()
  - Optical properties remain monochromatic (6 wavelengths)
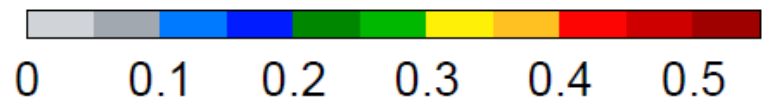 - Integration over the column

UKCA_RADAER: DIAGNOSTICS

- Aerosol optical depths (AOD)
  - 1 per aerosol mode
  - Section 2 diagnostics (2–300+), with 6 pseudo-levels representing wavelength: 0.38, 0.44, 0.55, 0.67, 0.87, and 1.02 μm

- Allow comparison against satellite retrievals (MODIS, MISR, POLDER, …) and ground-based measurements (AERONET)
- Angstrom exponent can be computed from AODs at two different wavelengths.

GLOMAP-mode AOD

Mean: 0.118

0 0.1 0.2 0.3 0.4 0.5

0.55 μm, vn7.3, Bellouin *et al.*, 2013.

UKCA_RADAER: DIAGNOSTICS
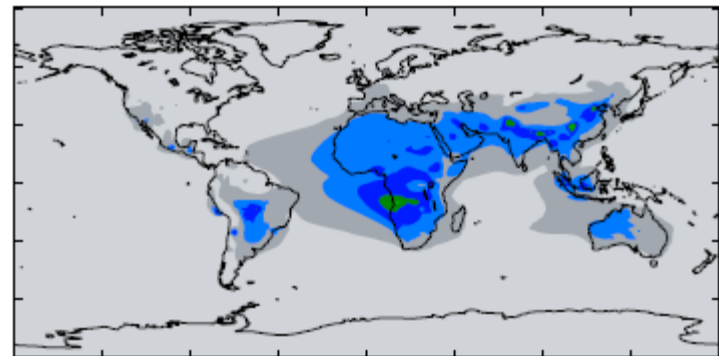
- Aerosol absorption optical depth (AAOD)

  - 1 per aerosol mode

  - Section 2 diagnostics, *require a branch*.

  - Same 6 wavelengths (pseudo-levels) as AOD

- Allow calculation of single-scattering albedo (SSA):

$$\varpi_0 = \frac{1 - AAOD}{AOD}$$

- Characterises absorption.

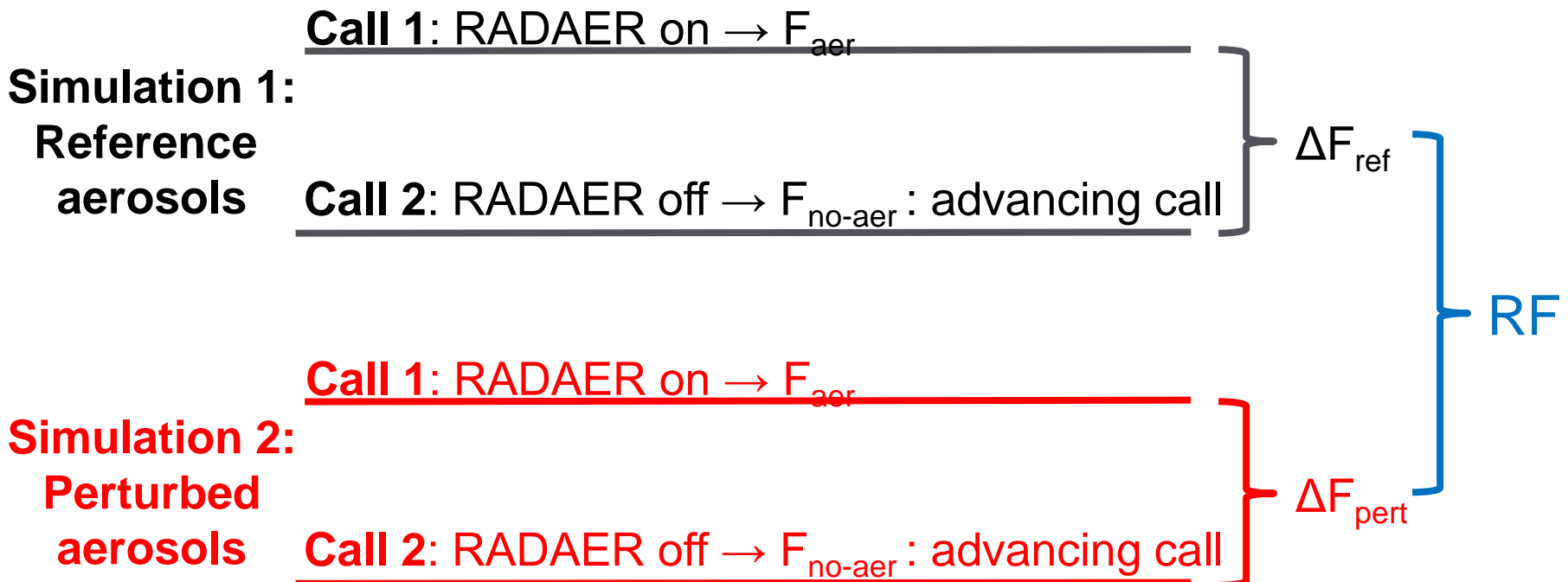GLOMAP-mode SSA

Mean: 0.98

0.8 0.84 0.88 0.92 0.96 1

0.55 μm, vn7.3, Bellouin *et al.*, 2013.

UKCA_RADAER: DIAGNOSTICS

- Other diagnostics available with branches:
  - Stratospheric aerosol optical depths
    - Same as AODs, but computed over stratospheric levels only.
    - Useful for volcanic eruption or geo-engineering studies.

  - Vertical profile of scattering or absorption coefficients
    - Essentially, 3D profiles of AOD at fixed wavelengths (0.55 or 1.02 µm).
    - When divided by geometric thickness of model levels, give σ_{sca} or σ_{abs}, in m^{-1}.
    - Useful to compare against lidars.

UKCA_RADAER: DOUBLE-CALL SIMULATIONS

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- Typically used to compute **radiative forcing** following the IPCC AR4 definition: "the change in net irradiance at the tropopause […] with surface and tropospheric temperatures and state *held fixed at the unperturbed values.*"

Simulation 1: Reference aerosols

Call 1: RADAER on $\rightarrow F_{aer}$

Call 2: RADAER off $\rightarrow F_{no\text{-}aer}$: advancing call

ΔF_{ref}

Simulation 2: Perturbed aerosols

Call 1: RADAER on $\rightarrow F_{aer}$

Call 2: RADAER off $\rightarrow F_{no\text{-}aer}$: advancing call

ΔF_{pert}

RF

SUMMARY

- UKCA_RADAER is a piece of code within the Unified Model's Edwards-Slingo Radiation Scheme.

- It allows interaction between radiation and UKCA/GLOMAP aerosols.

- It offers important diagnostics, e.g. aerosol optical depths.

- More details: Unified Model Documentation Paper 84, section 13.2

- Reference: Bellouin *et al., Atmos. Chem. Phys.,* doi:10.5194/acp-13-3027-2013, 2013. [Section 5]

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