Department of Meteorology

University of Reading

RADAER
AEROSOL-RADIATION INTERACTIONS

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UKCA Training Workshop, Cambridge, 11 January 2017

LECTURE SUMMARY

- **Why care about aerosol-radiation interactions?**
- **Theory of aerosol-radiation interactions**
  - **Mie scattering**
- **Description of RADAER**
  - **Methods**
  - **Diagnostics**
  - **Double-call simulations**

AEROSOL-RADIATION INTERACTIONS

VERY SHORT HISTORY

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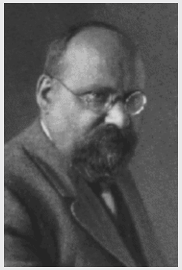
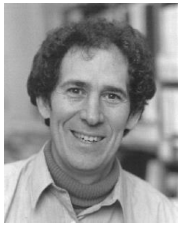
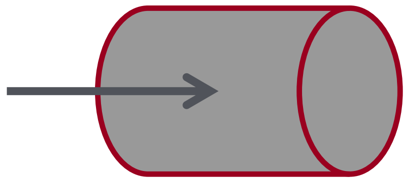
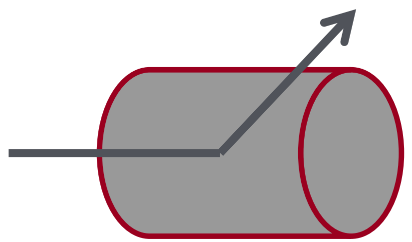
	**~1490**	**Leonardo da Vinci** notes that the side of a dust and smoke plume facing the Sun is far brighter than the other side.
	1908	**Gustav Mie** publishes in *Annalen der Physik* the solution to Maxwell equations for a homogeneous dielectric sphere.
	1971	**Stephen Schneider** and S.I. Rasool estimate in *Science* that anthropogenic aerosol cooling will dominate CO_2 warming.
	1980s	**Atsumu Ohmura** reports sizeable decreases in solar radiation reaching the surface, a phenomenon later coined “global dimming” and linked to aerosol-radiation interactions.

AEROSOL-RADIATION INTERACTIONS

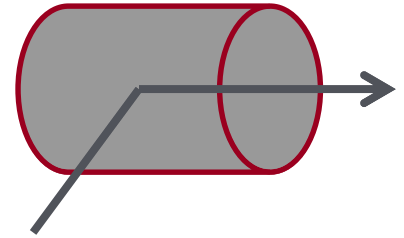
- Absorption



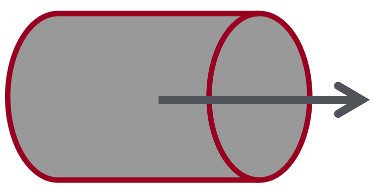
- Scattering out of viewing direction



- Scattering into viewing direction



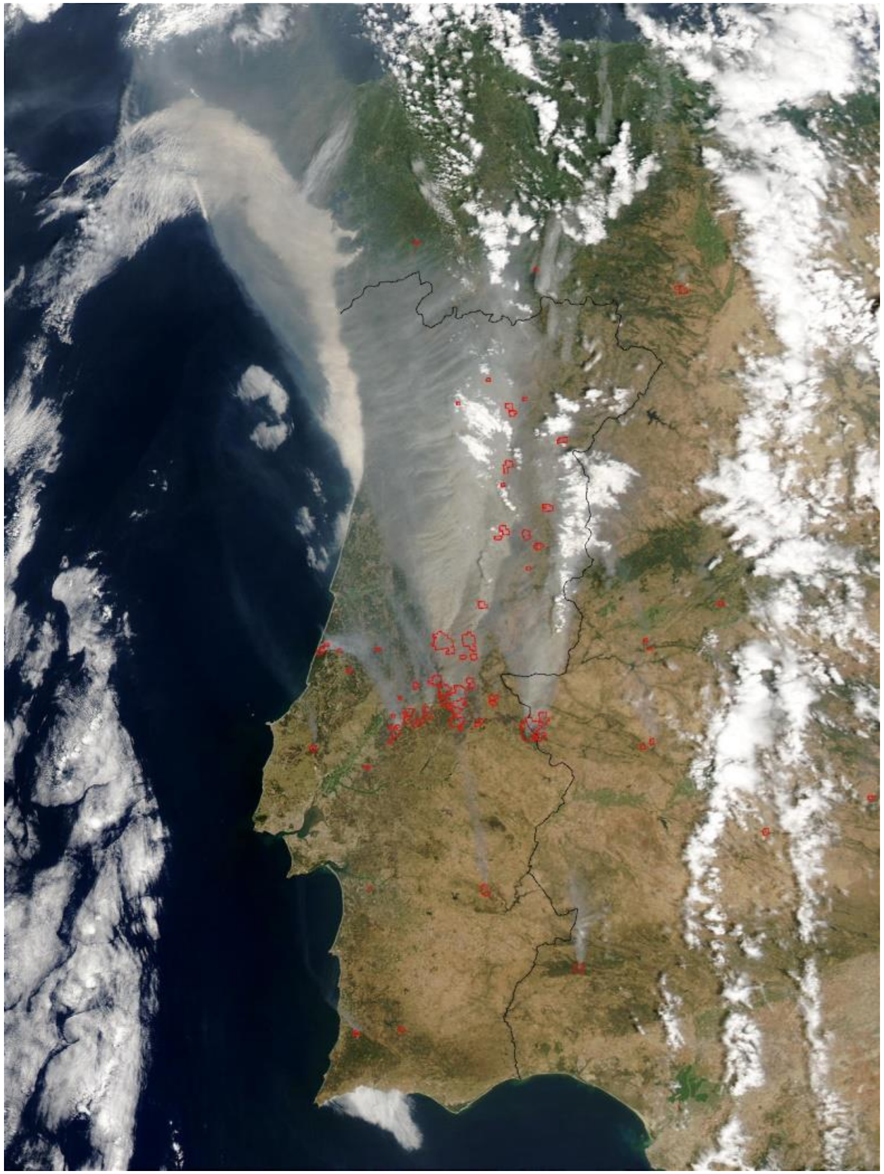
- Emission



WHY WE CARE ABOUT AEROSOL-RADIATION INTERACTIONS

- They are part of the energy budget of the Earth: “aerosol-radiation interactions” or “direct radiative effect”.
- They affect visibility.
- For anthropogenic aerosols, they represent a radiative forcing of the climate system: RFari or 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

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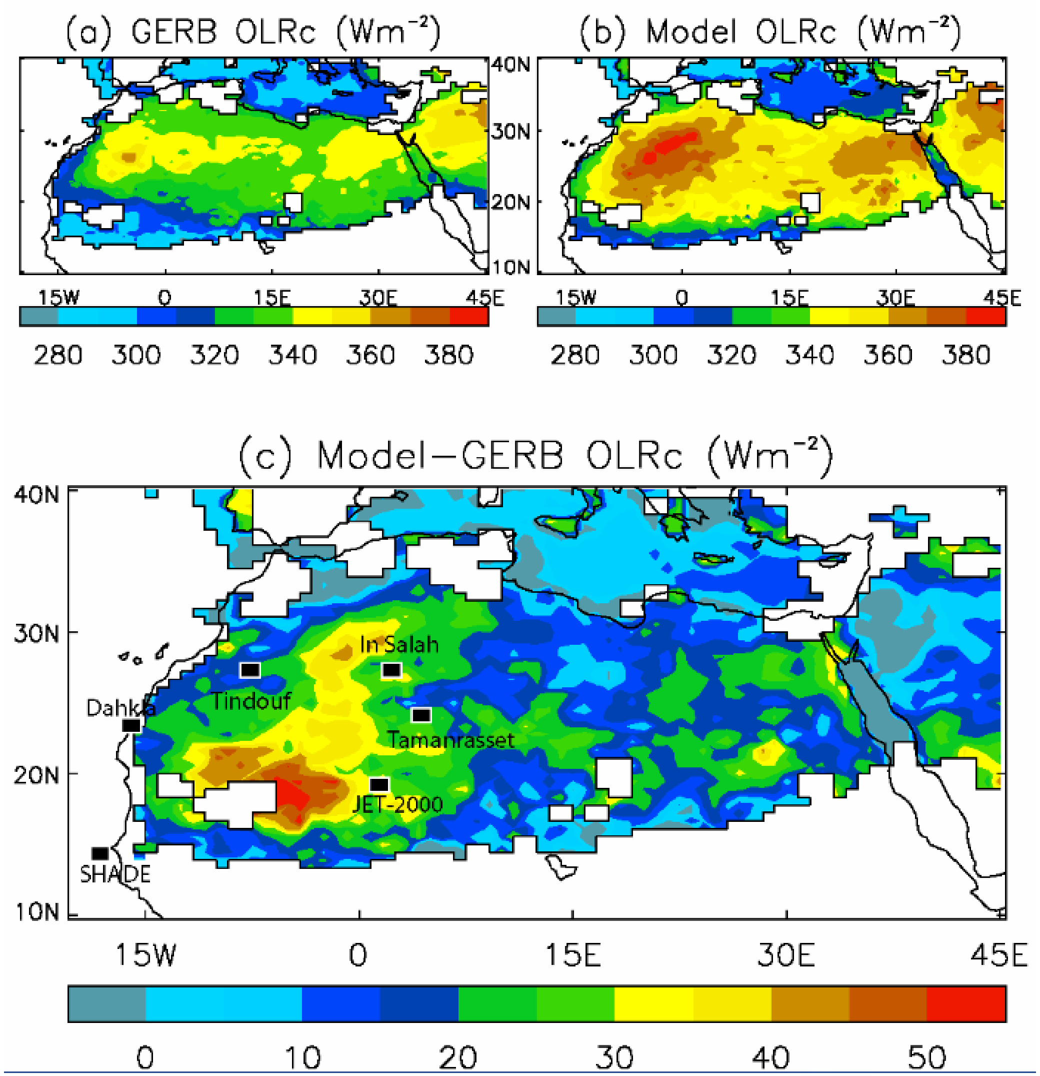

- Haywood et al. (2005) *Can desert dust explain the outgoing longwave radiation anomaly over the Sahara during July 2003?*

WHY WE CARE

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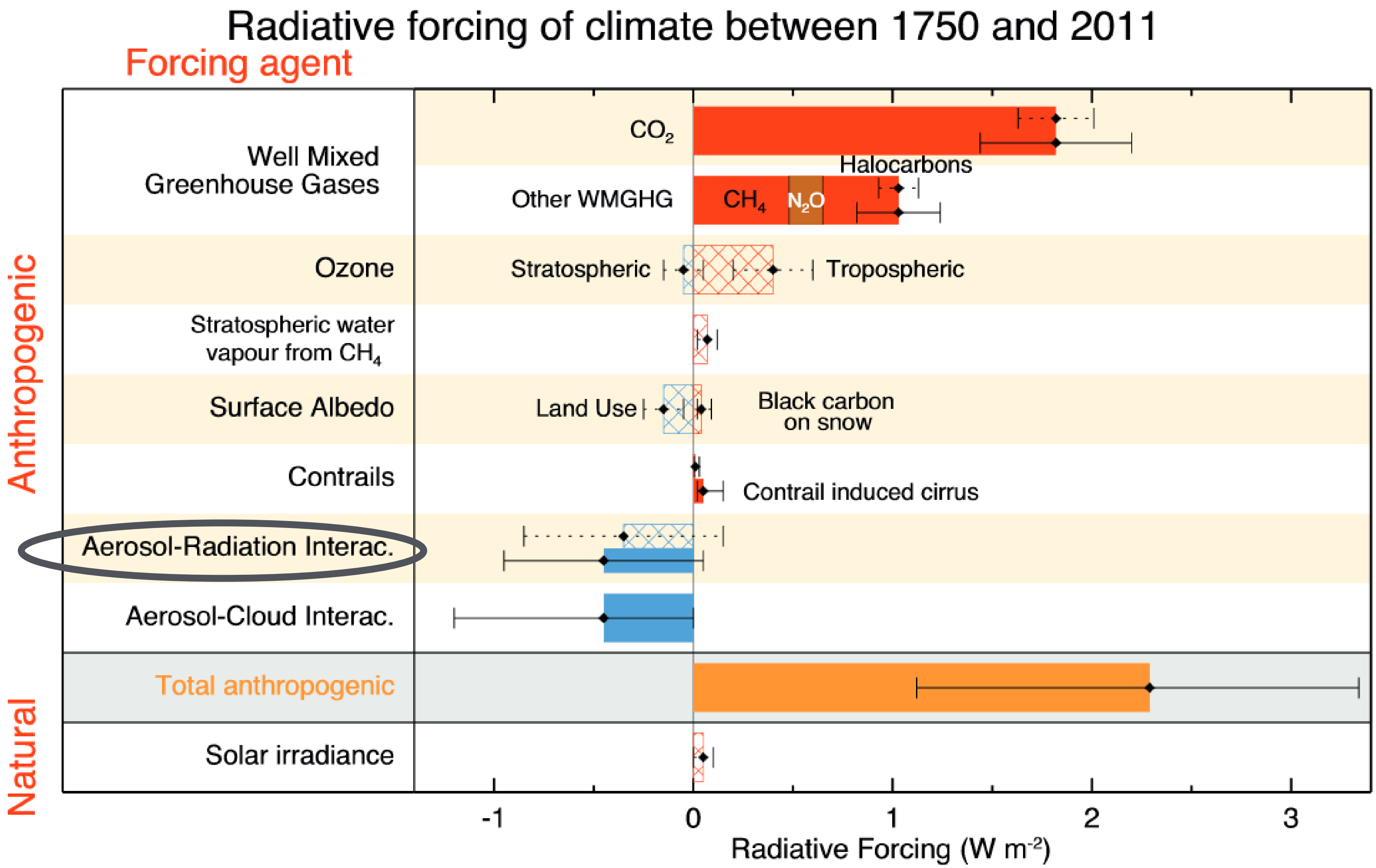
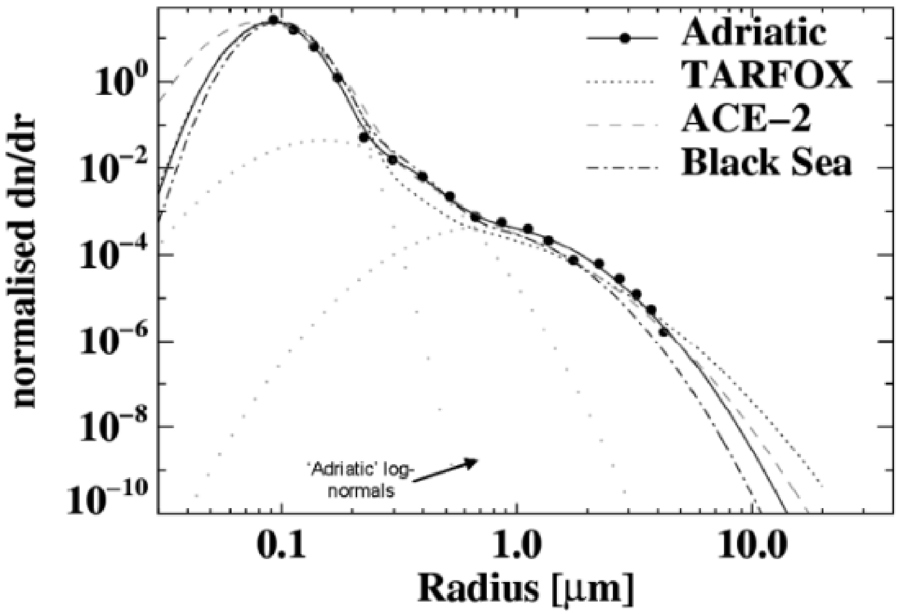


IPCC AR5, Figure 8.15 (2013)

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

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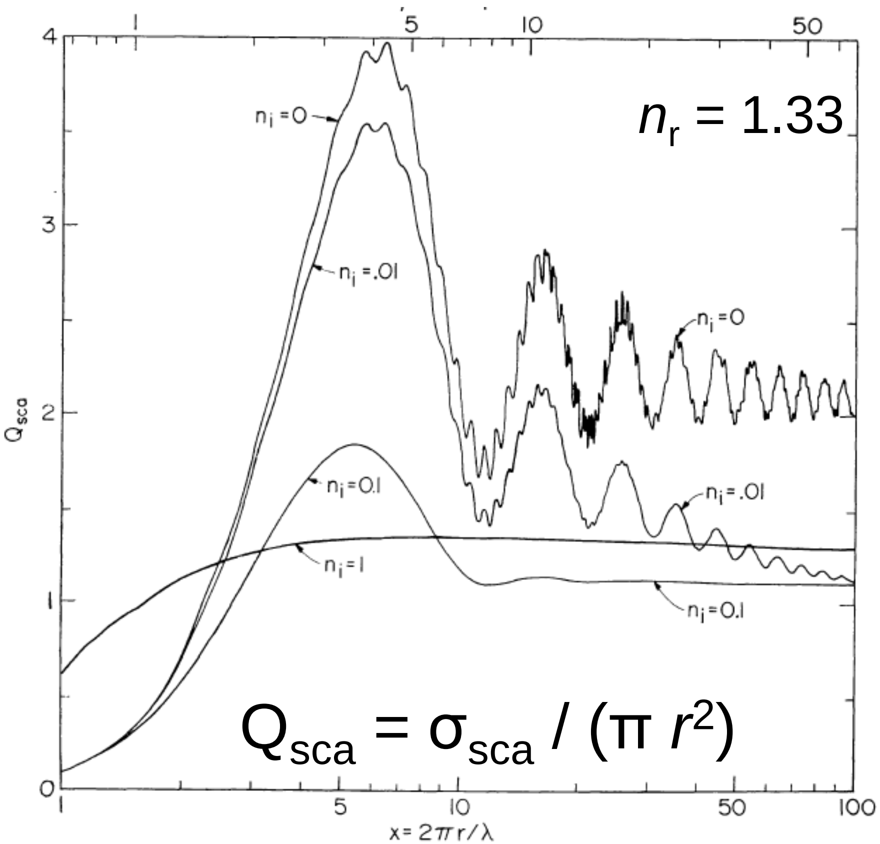
- Aerosol radii *r* (0.1 to 10 μm) are of similar magnitude to the wavelength λ of shortwave and longwave radiation
  - Shortwave (or solar) spectrum: 0.25 to 5 μm
  - Longwave (or terrestrial) spectrum: 3 to 50 μm
- When *r* ~ λ, this is the domain of **Mie** scattering.
- Mie theory (1908) applies to homogeneous spheres, which is generally a good approximation for aerosols.
  - With the notable exception of mineral dust 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.



Hansen and Travis (1974), Figure 9

PHASE FUNCTION

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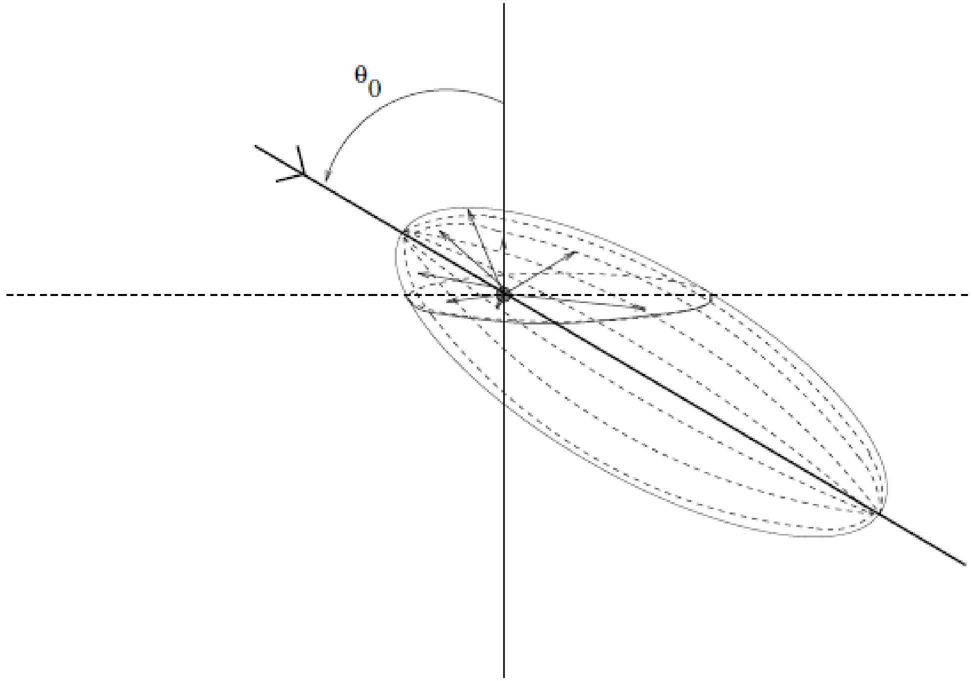
- Also calculated by Mie theory, the phase function gives the probability of being scattered in a given direction.



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

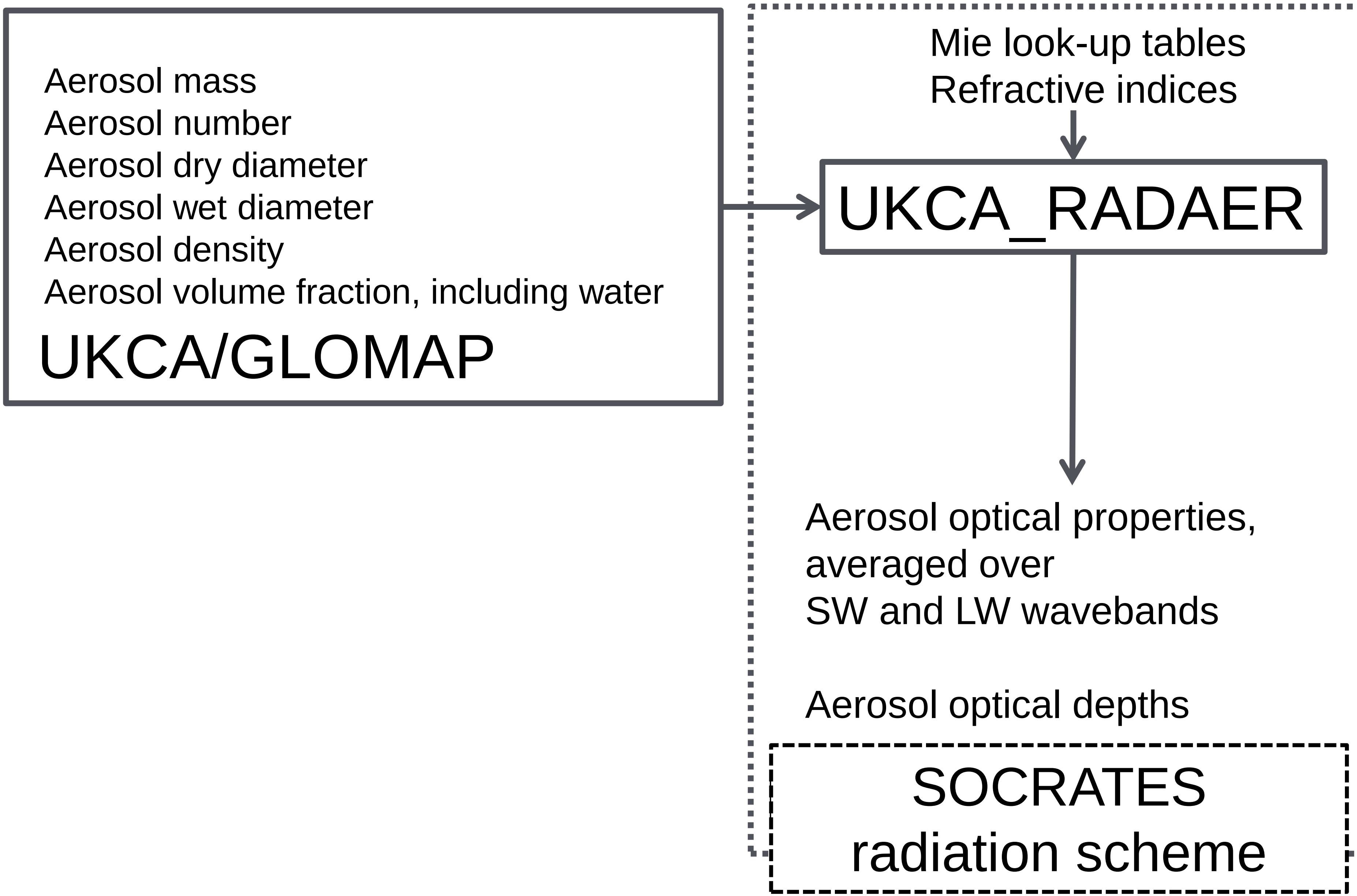
- The quantities valid for a given particle radius need to be integrated over the size distribution *n*(*r*)

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

- This is done for the three optical properties required:
- σ_{sca}, σ_{abs}, and g

RADAER

RADAER


Aerosol mass
Aerosol number
Aerosol dry diameter
Aerosol wet diameter
Aerosol density
Aerosol volume fraction, including water
UKCA/GLOMAP
Mie look-up tables
Refractive indices
UKCA_RADAER
Aerosol optical properties,
averaged over
SW and LW wavebands
Aerosol optical depths
SOCRATES
radiation scheme

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.

RADAER: LOOK-UP TABLES

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- 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

RADAER: LOOK-UP TABLES

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- RADAER is set in the run_ukca namelist
- Rose: um > namelist > UM Science Settings > Section 34 UKCA

l_ukca_radaer	Direct effect of MODE aerosols in radiation scheme	true
l_ukca_aie1	1st Indirect Effect of MODE aerosols (on radiation)	true
ukcaprec	File of pre-computed values	'$UMDIR/vn$VN/ctldata/spectral/ga7/RADAER_pcalc.ukca'
l_ukca_aie2	2nd Indirect Effect of MODE aerosols (on precip.)	true
ukcaaclw	LW file: aitken and insol acc modes	'$UMDIR/vn$VN/ctldata/UKCA/radaer/nml_ac_lw'
ukcaacsw	SW file: aitken and insol acc mode	'$UMDIR/vn$VN/ctldata/UKCA/radaer/nml_ac_sw'
ukcaanlw	LW file: soluble accumulation mode	'$UMDIR/vn$VN/ctldata/UKCA/radaer/nml_an_lw'
ukcaansw	SW file: soluble accumulation mode	'$UMDIR/vn$VN/ctldata/UKCA/radaer/nml_an_sw'
ukcacrlw	LW file: coarse-mode	'$UMDIR/vn$VN/ctldata/UKCA/radaer/nml_cr_lw'
ukcacrsw	SW file: coarse-mode	'$UMDIR/vn$VN/ctldata/UKCA/radaer/nml_cr_sw'
l_ukca_radaer_sustrat	Sulphuric acid aerosol in stratosphere	true

Here, vn10.4.

RADAER METHODS

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 ($kg\ m^{-3}$).

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)

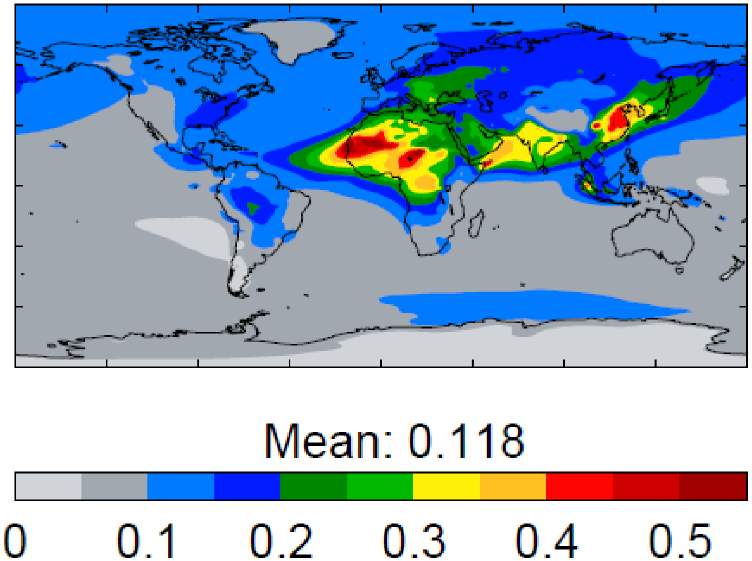
- ukca_radaer_compute_aod()
  - Optical properties remain monochromatic (6 wavelengths)
  - Integration over the column

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



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

RADAER: DIAGNOSTICS

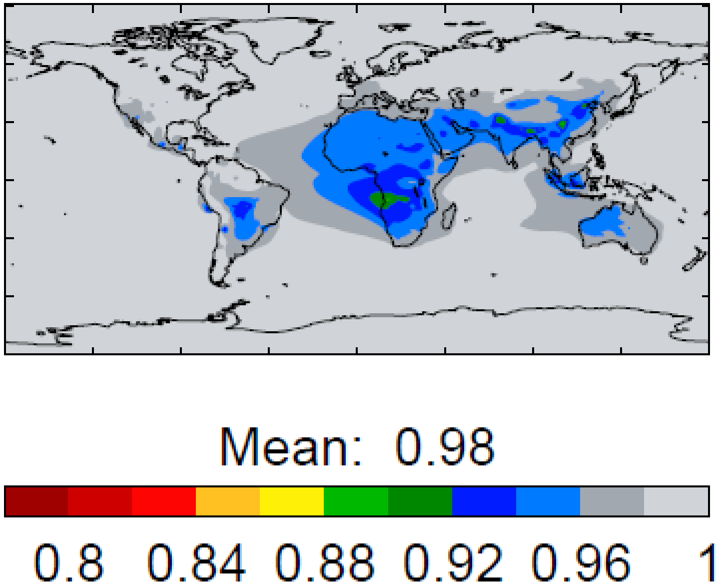
- Aerosol absorption optical depth (AAOD)
  - 1 per aerosol mode
  - Section 2 diagnostics, *require a branch*.
  - Same 6 wavelengths (pseudo-levels) as AOD

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

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

- Characterises absorption.

GLOMAP-mode SSA



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

RADAER: DIAGNOSTICS

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- 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.

SUMMARY

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- RADAER is a piece of code within the Unified Model's SOCRATES 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]
- n.bellouin@reading.ac.uk

UKCA_RADAER: DOUBLE-CALL SIMULATIONS

- 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*. ”