Department of Meteorology

University of Reading

RADAER
AEROSOL-RADIATION INTERACTIONS

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UKCA Training Workshop, Cambridge, 9 January 2018

LECTURE SUMMARY

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

AEROSOL-RADIATION INTERACTIONS

A BRIEF HISTORY (1/2)

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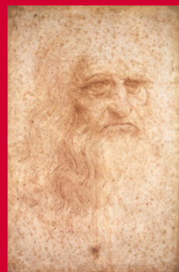
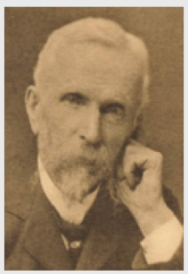
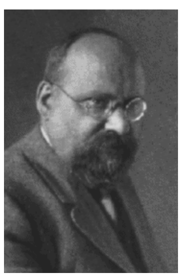


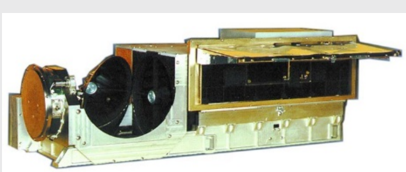
~1490 — **Leonardo da Vinci** notes that the side of a dust and smoke plume facing the Sun is far brighter than the other side.



1874 — **John Aitken** makes the first measurements of atmospheric aerosol number, discovers nucleation and the role of aerosols in liquid cloud formation.



1908 — **Gustav Mie** publishes in *Annalen der Physik* the solution to Maxwell equations for a homogeneous dielectric sphere.



1978 — Launch of the **Advanced Very High Resolution Radiometer** (AVHRR), which will provide the first daily views of aerosols over the global oceans.

A BRIEF HISTORY (2/2)

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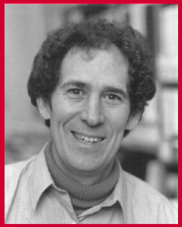	**1971**	**Stephen Schneider** and S.I. Rasool estimate in *Science* that anthropogenic aerosol cooling will dominate CO_2 warming.
	1980s	**Atsumu Ohmura** reports sizeable decreases in solar radiation reaching the surface, a phenomenon later coined “global dimming” and attributed to aerosol-radiation interactions.
	1991	**Bob Charlson** *et al.* estimate in *Science* that the radiative forcing of sulphate aerosols is −1 to −2 W m^{-2}, with about half contributed by aerosol-radiation interactions.
ipcc INTERGOVERNMENTAL PANEL ON climate change	2013	IPCC best estimate and uncertainty range for ERFari: –0.45 (–0.95 to +0.05) W m^{-2}

AEROSOL-RADIATION INTERACTIONS

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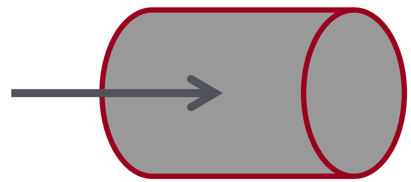
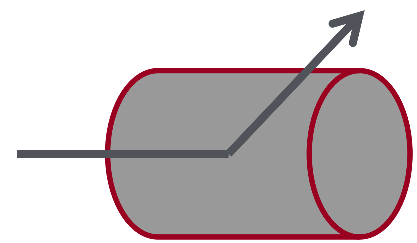
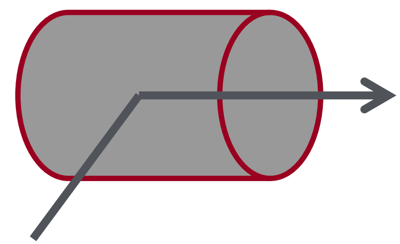
- Absorption



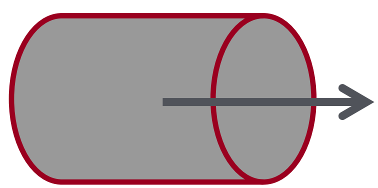
- Scattering out of viewing direction



- Scattering into viewing direction



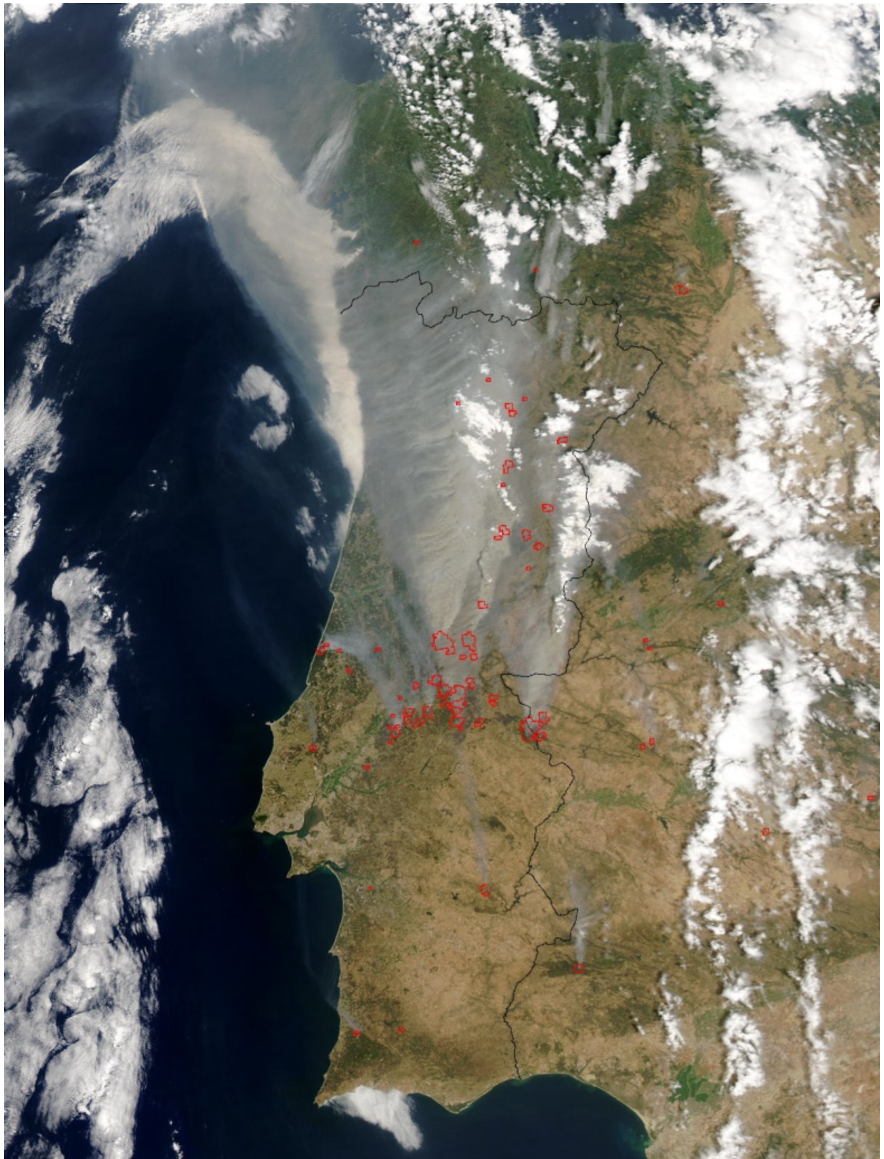
- Emission



WHY WE CARE ABOUT AEROSOL-RADIATION INTERACTIONS

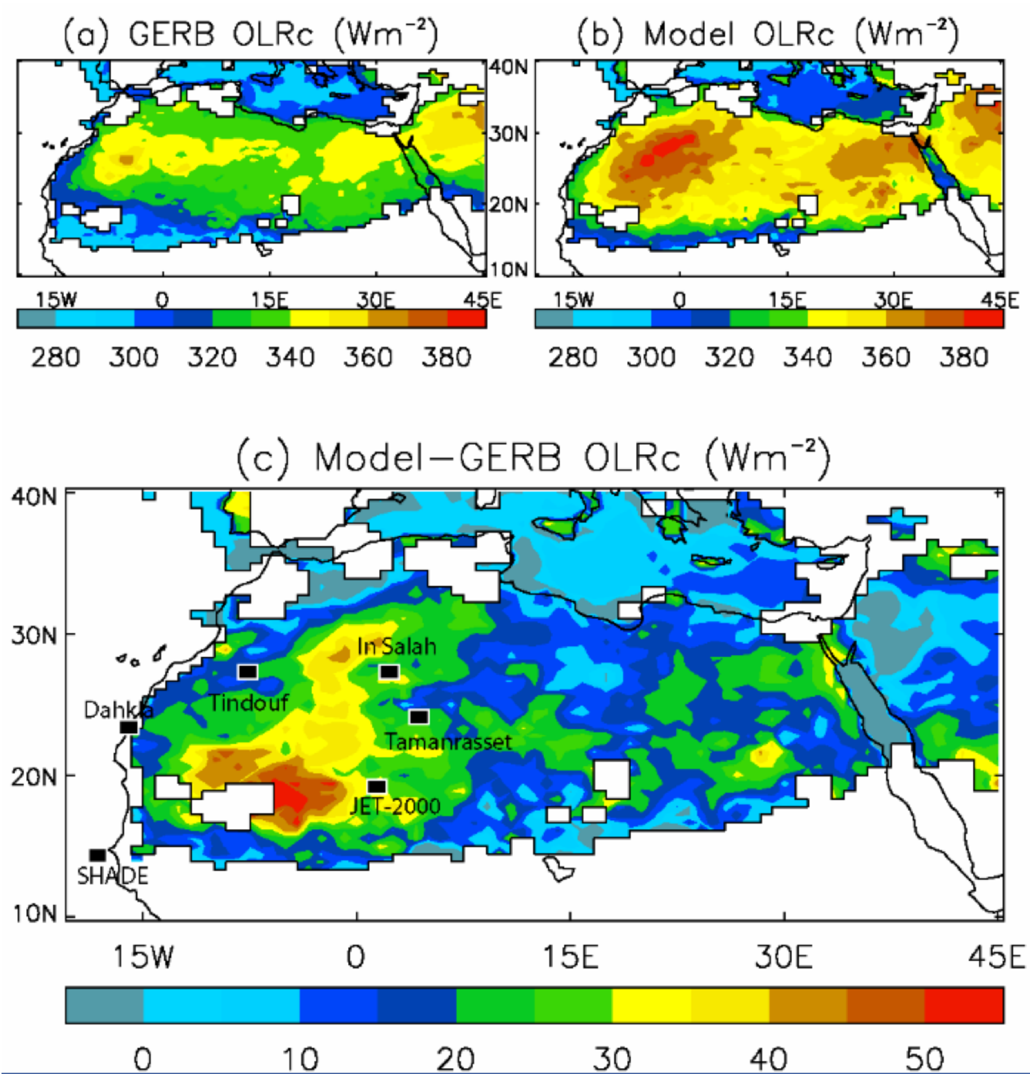
- They are part of the energy budget of the Earth: “aerosol-radiation interactions” or “direct radiative effect”.
- They affect visibility.
- For anthropogenic aerosols, they represent a radiative forcing of the climate system: (E)RFari or direct (effective) radiative forcing.
- They allow model evaluation against remote-sensing products.

WHY WE CARE



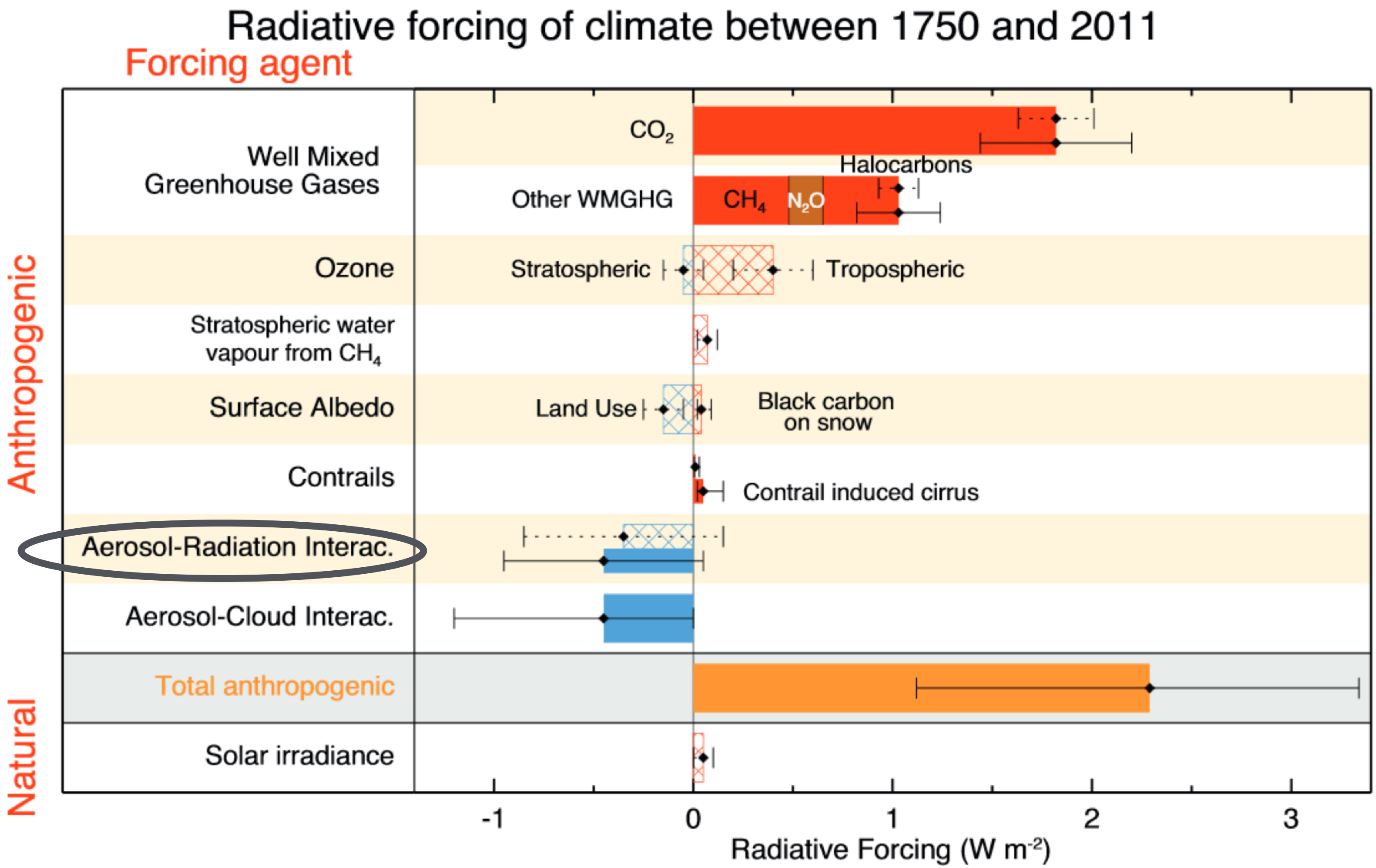
- Forest fires in Portugal, 3 August 2003
- Image by MODIS radiometer
- Above dark surfaces, scattering by aerosols increase shortwave planetary albedo: loss of energy at the top of atmosphere and surface
- Above bright surfaces, absorption by aerosols decrease shortwave planetary albedo: gain of energy at the top of atmosphere, loss of energy at surface.

WHY WE CARE



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

WHY WE CARE



IPCC AR5, Figure 8.15 (2013)

MIE SCATTERING

AEROSOL SIZE DISTRIBUTION

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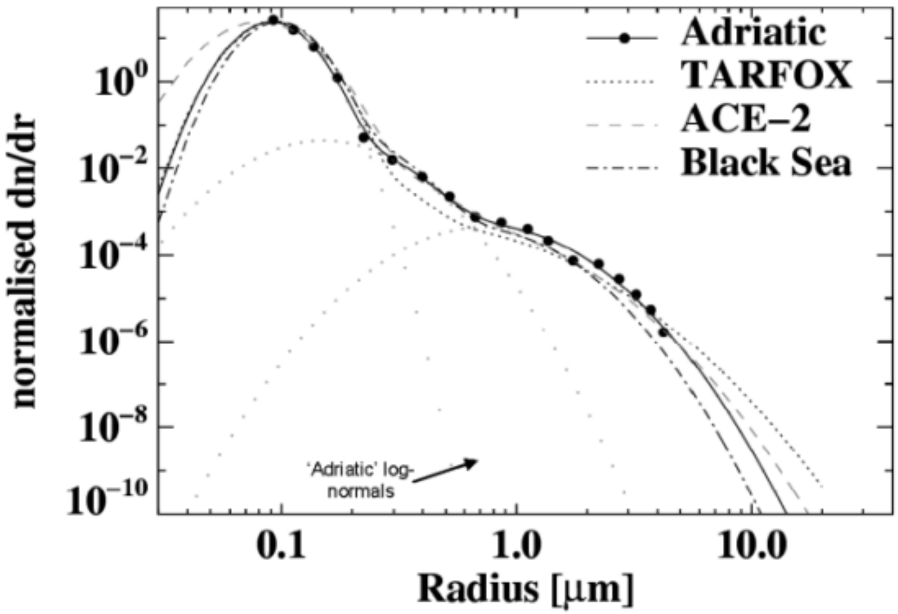

Aircraft measurements, Osborne *et al.* [2007]

- 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

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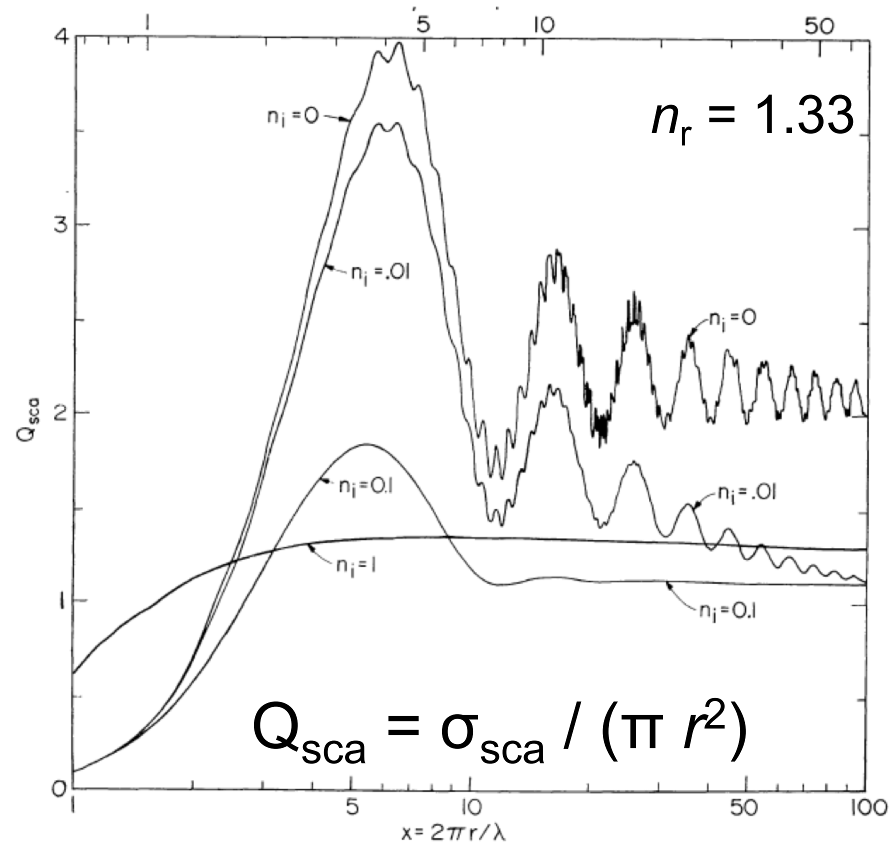
- Mie theory allows the calculation of the scattering and absorption cross sections σ_{sca} and σ_{abs} (in m^2).

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

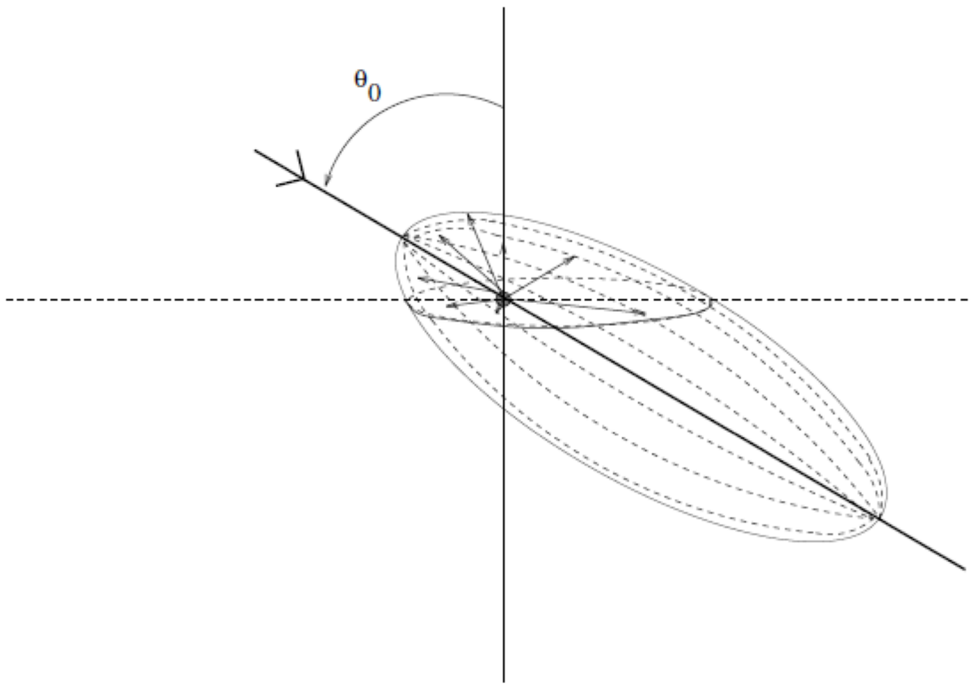
- For hygroscopic aerosols, the impact of water uptake on *x* and *m* needs to be included.



Hansen and Travis (1974), Figure 9

PHASE FUNCTION

- 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

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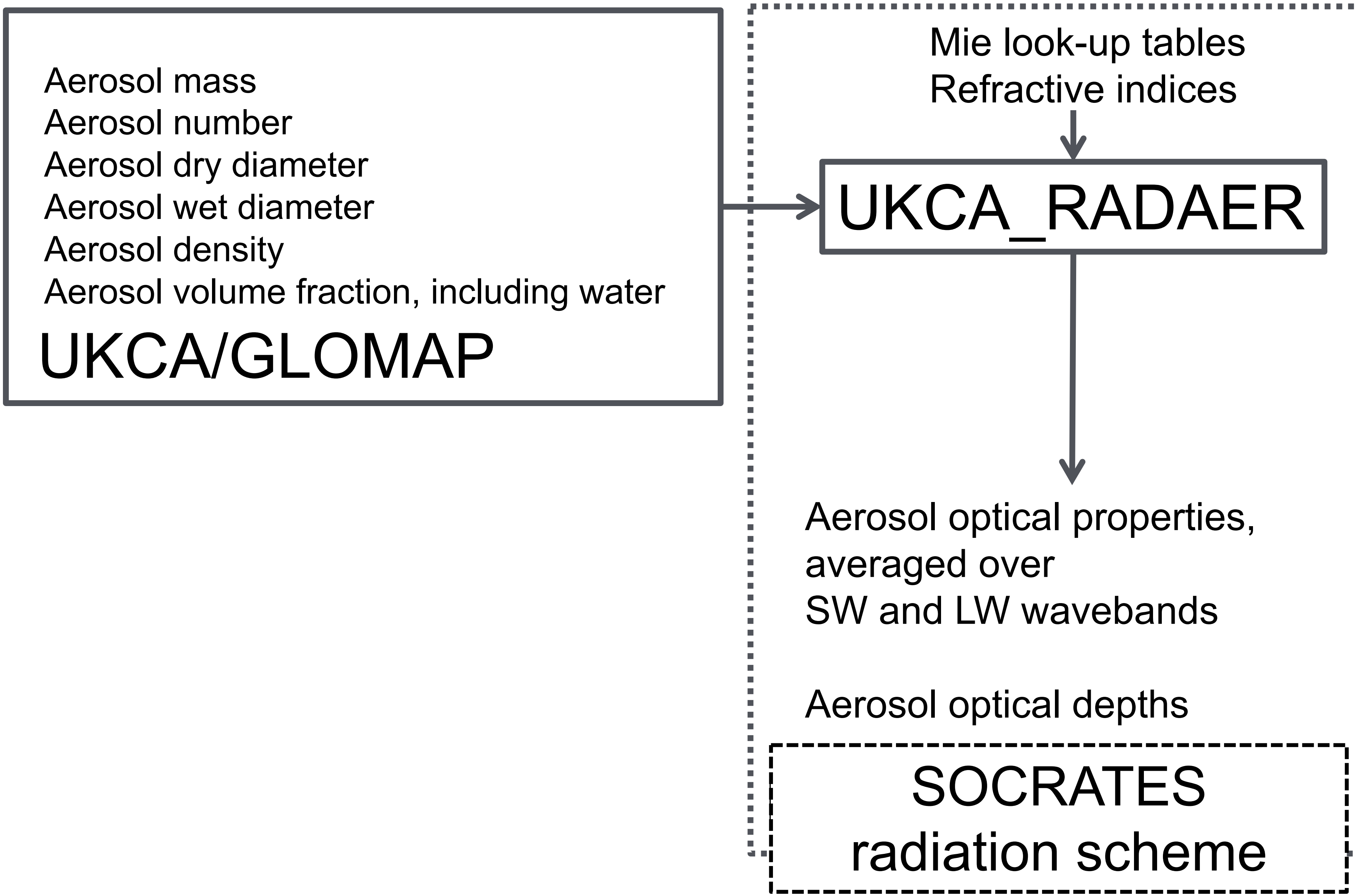
Aerosol mass
Aerosol number
Aerosol dry diameter
Aerosol wet diameter
Aerosol density
Aerosol volume fraction, including water
UKCA/GLOMAP
Mie look-up tables
Refractive indices
UKCA_RADAER
Aerosol optical properties,
averaged over
SW and LW wavebands
Aerosol optical depths
SOCRATES
radiation scheme

RADAER: LOOK-UP TABLES

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- 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

- 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

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

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

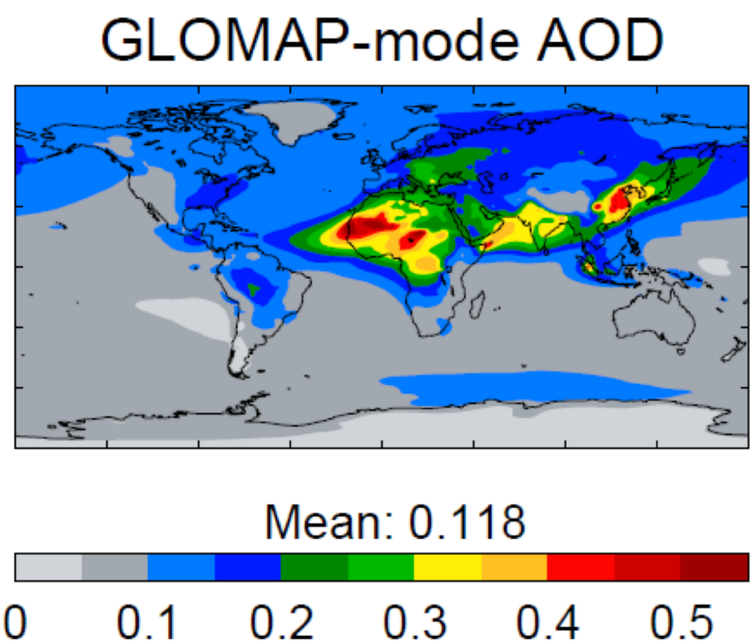
RADAER
KEY FUNCTIONS

- 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.



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

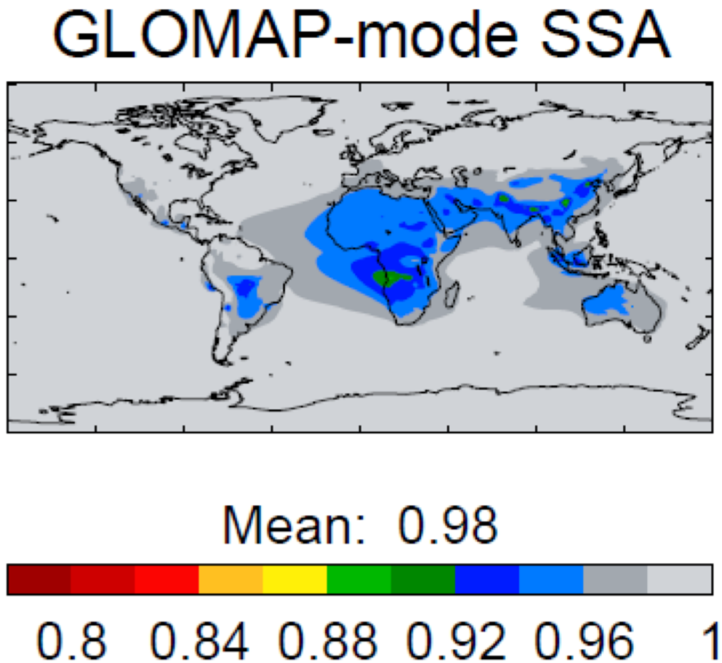
RADAER: DIAGNOSTICS

- 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):

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

- Characterises absorption.



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

RADAER: DIAGNOSTICS

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- Other diagnostics available (with branches before vn10.8):
  - 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
    - In recent UM version, those diagnostics are in m^{-1}.
    - In older versions they were either layer AODs or specific coefficients in $m^2\ kg^{-1}$, so check the help text.
    - Useful to compare against lidars.

RADAER: EVOLUTION

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- The code is fairly mature so no sizeable internal changes are planned at this stage.
  - Performance improvements are likely to be implemented in the coming years.
  - Could implement core-shell calculations of modal refractive index, but not seen as a priority.

- Coupling of RADAER with calculation of photolysis rates being developed by Michael Holloway at the University of Lancaster.

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]
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