Assimilation of radiances for Aerosol monitoring

The ARAS project

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Introduction

The “Aerosol Radiance Assimilation Study” – ARAS – is an relatively small project (18 months) to develop and test a radiance assimilation scheme for aerosol in ECMWF’s Integrated Forecast System (IFS).

- ECMWF has been assimilating MODIS AOD operationally for about ten years*. Provides a constraint on column aerosol mass.
- Radiance assimilation will also use MODIS, but will be a multi-wavelength assimilation, constraining both aerosol mass and size.
- By moving to radiance assimilation, the problem of inconsistency in aerosol properties between satellite product and model is avoided.
- The trade-off is that surface reflectance becomes a problem for the assimilation.

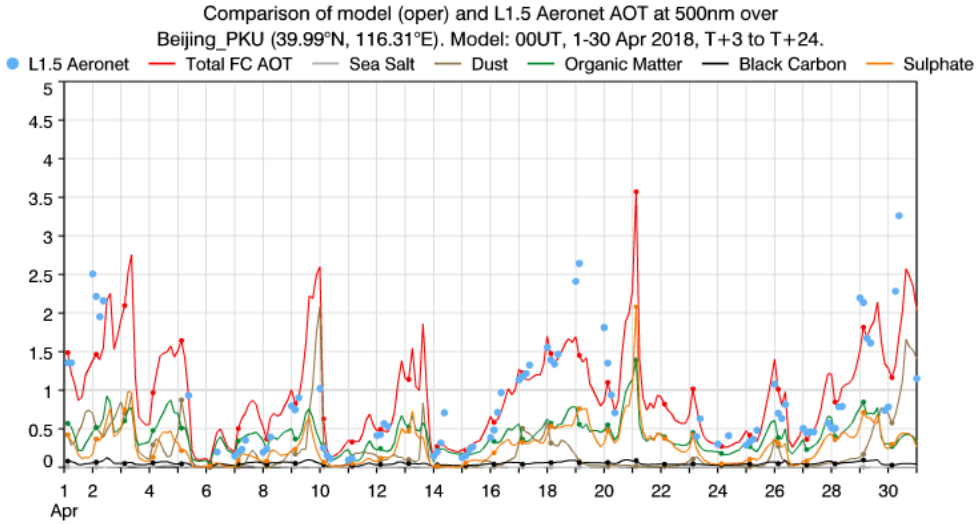
*Benedetti et al., J. Geophys. Res. Atmos. (2009)
DOI: 10.1029/2008JD011115

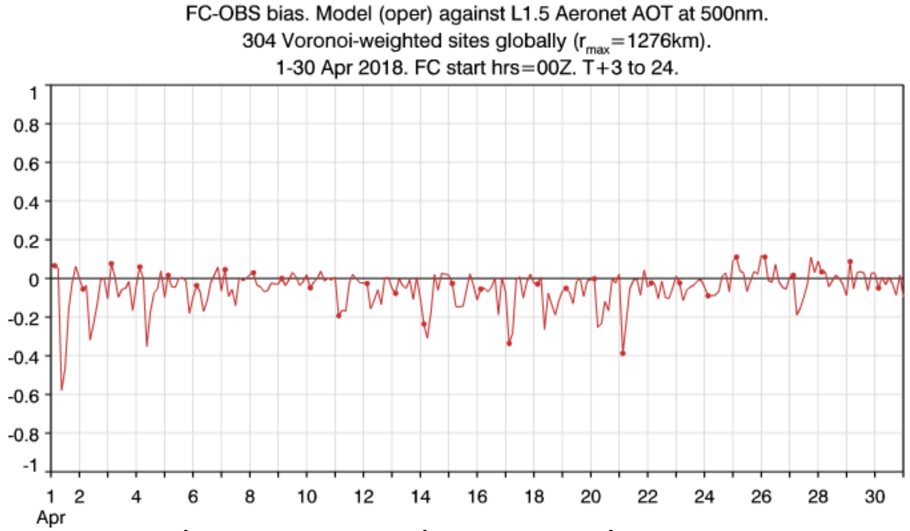
General approach

- The observation operator for the assimilation scheme is the forward model (FM) from the Optimal Retrieval of Aerosol and Cloud (ORAC) algorithm
  - This provides a fast multiple scattering radiative transfer model for IFS.
  - Also includes a pretty comprehensive ocean surface reflectance model.
  - Land surface will rely on MODIS BRDF.
- Three main pieces of development work are required:
  1. Modification of ORAC-FM two work with model description of aerosol.
  2. Generation of tangent linear and adjoint versions of the ORAC-FM.
  3. (Re)calculation of background and measurement covariances for the multi-variate assimilation state vector.

General approach

- Validation/evaluation of the scheme will be done using existing ECMWF tools
  - Performance against AERONET AOD and surface PM measurements will be evaluated.
  - Radiance assimilation will be compared to current AOD assimilation and free running (no aerosol assimilation) control runs.



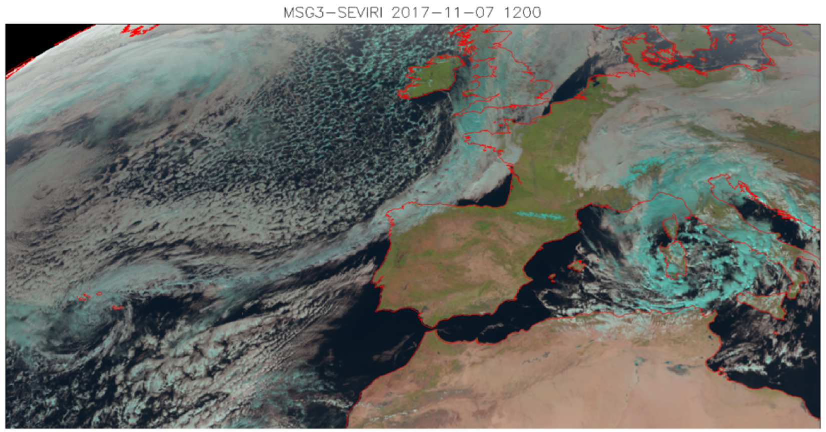


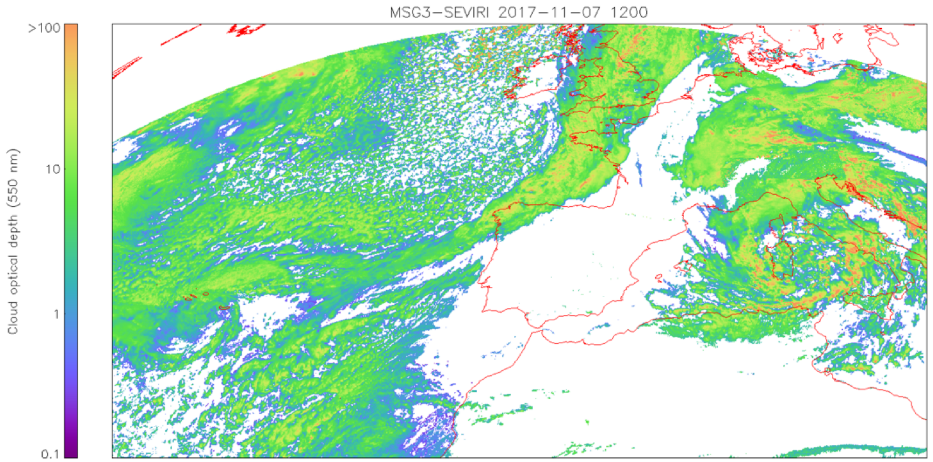
https://atmosphere.copernicus.eu/user-support/validation/verification-global-services

ORAC overview

ORAC (Optimal retrieval of aerosol and cloud) is an optimal estimation scheme for retrieving aerosol and cloud properties from visible-IR satellite imagers.

- Applied to a wide range of instruments.
- Used to produce a range of aerosol and cloud products.





ORAC overview

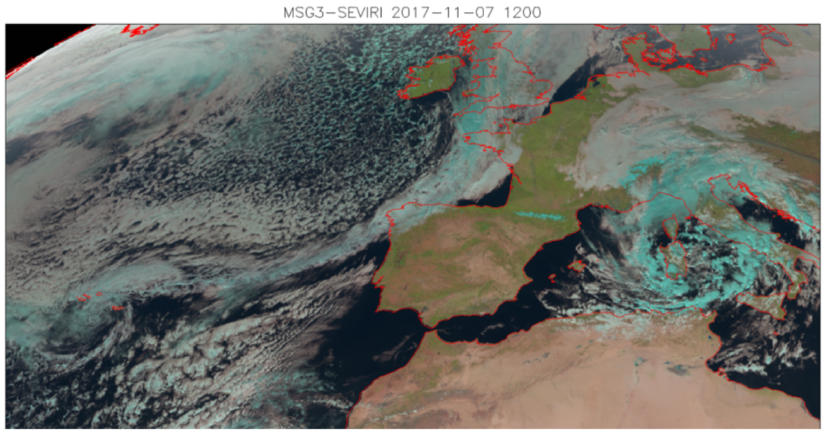
The algorithm is developed under a community code model, with a GPL license

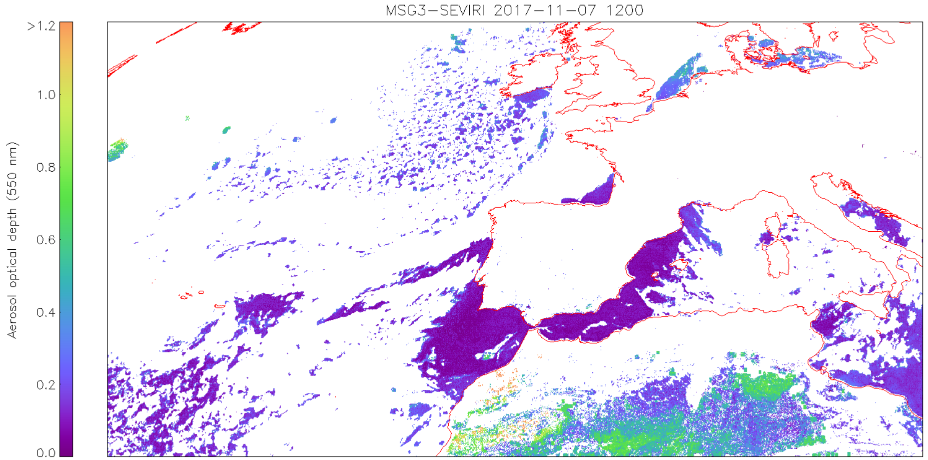
- Code is on GitHub:

https://github.com/ORAC-CC

- Code Wiki hosted by UK Centre for Environmental Data Archival (CEDA):

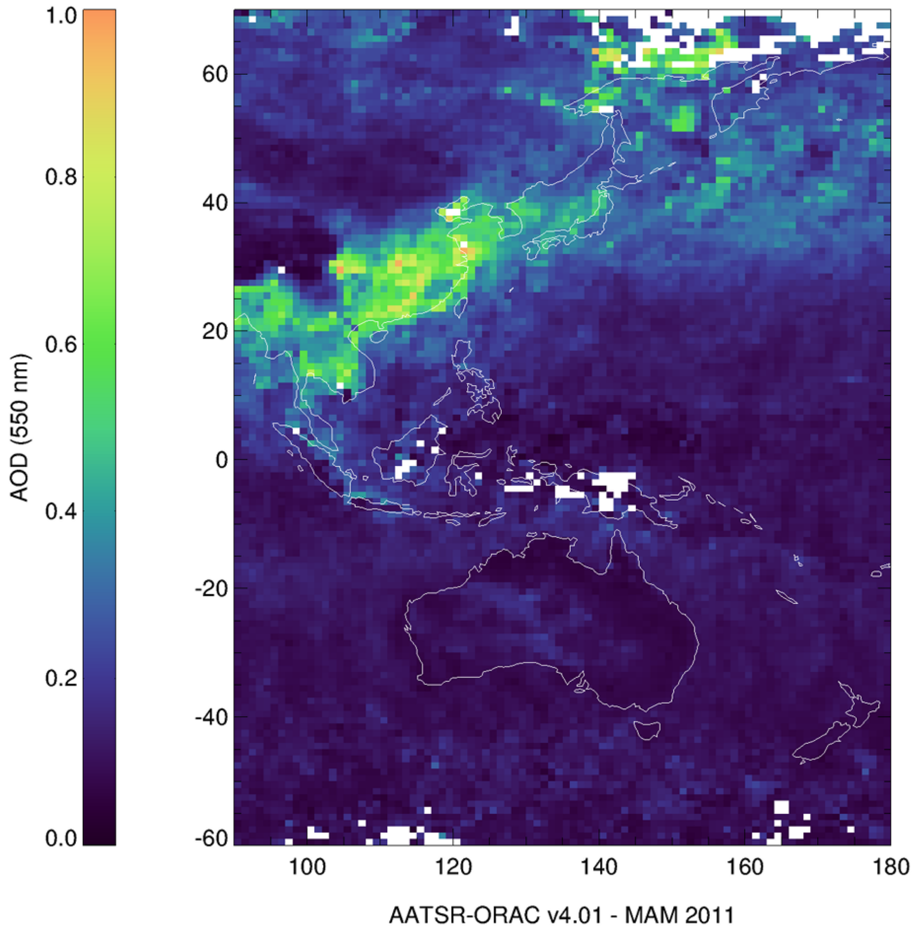
http://proj.badc.rl.ac.uk/orac



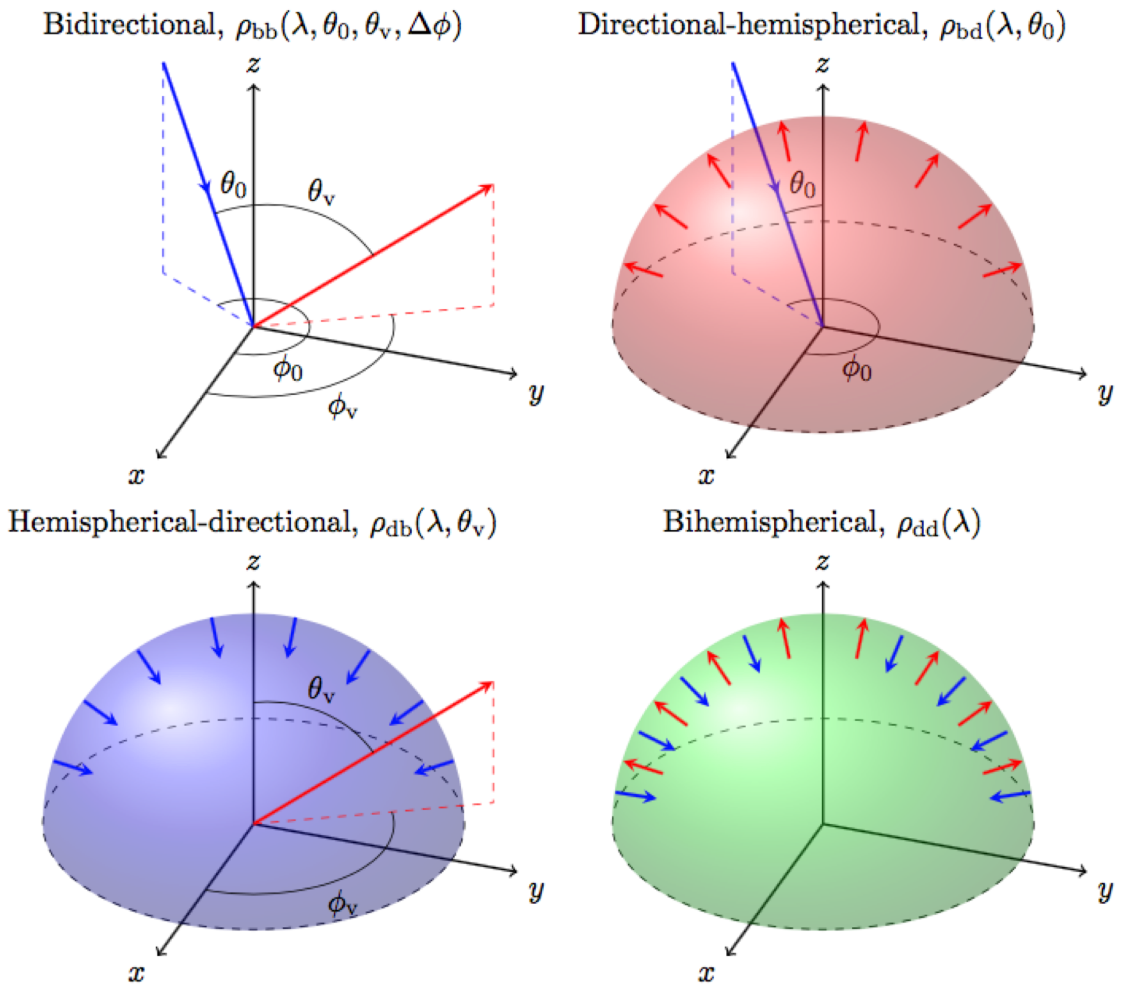


ORAC overview

- ORAC operates using a fast-forward model which uses lookup tables (LUTs) of cloud / atmospheric reflectance and transmission.
- The LUTs are generated off-line using a full-up radiative transfer code (currently DISORT).
- In "cloud-mode", clear-sky radiative transfer is done online using RTTOV.



Observation Operator: Surface reflectance

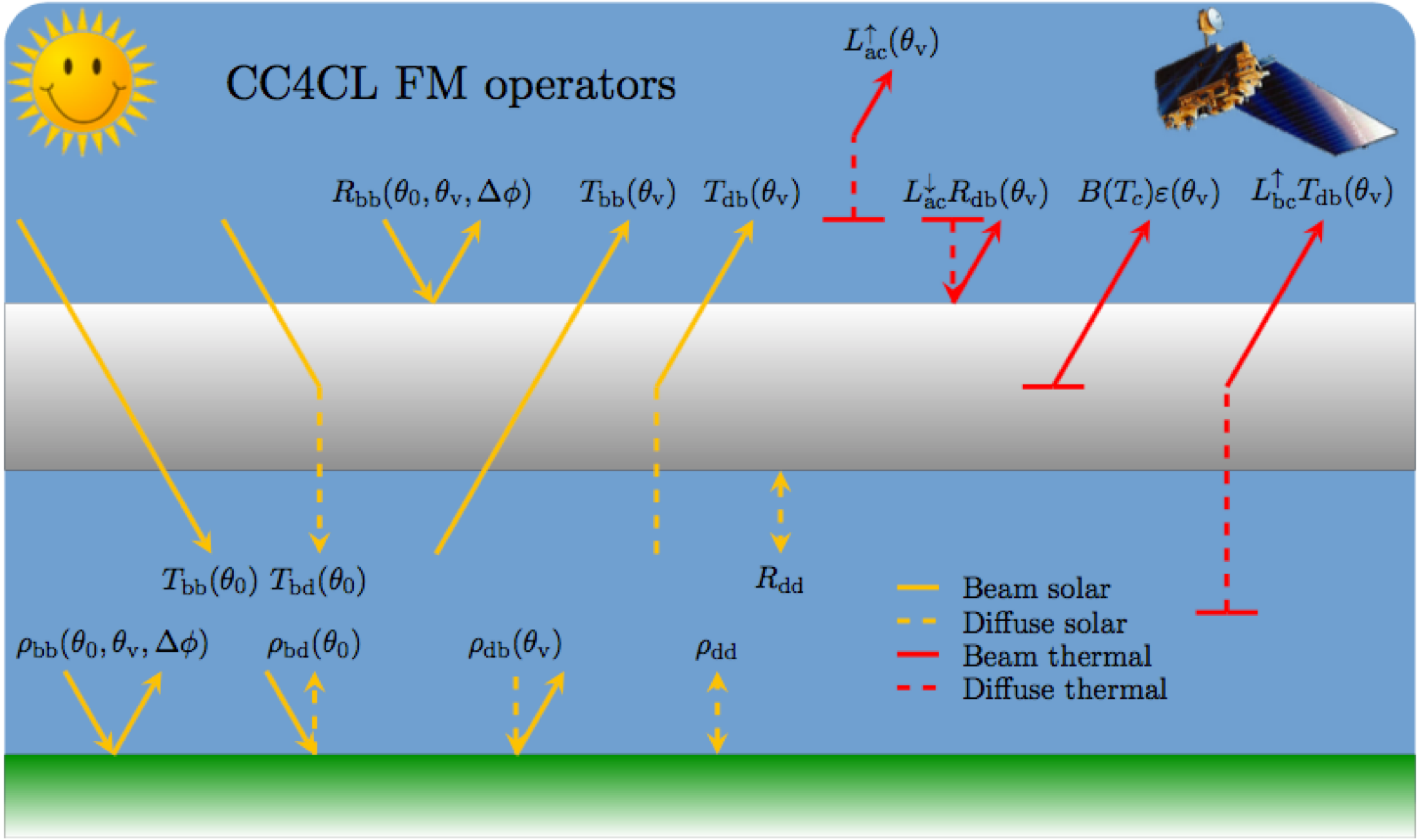


ORAC utilises a more rigorous and complex FFM than most similar cloud or aerosol retrievals:

- Diffuse and direct components treated separately.
- Better description of surface
- A sea surface reflectance model* provides the BRDF over the ocean.
- MODIS BRDF (MCD43b) is used over the land.

*Sayer et al., Atmos. Meas. Tech. (2010)
DOI: 10.5194/amt-3-813-2010

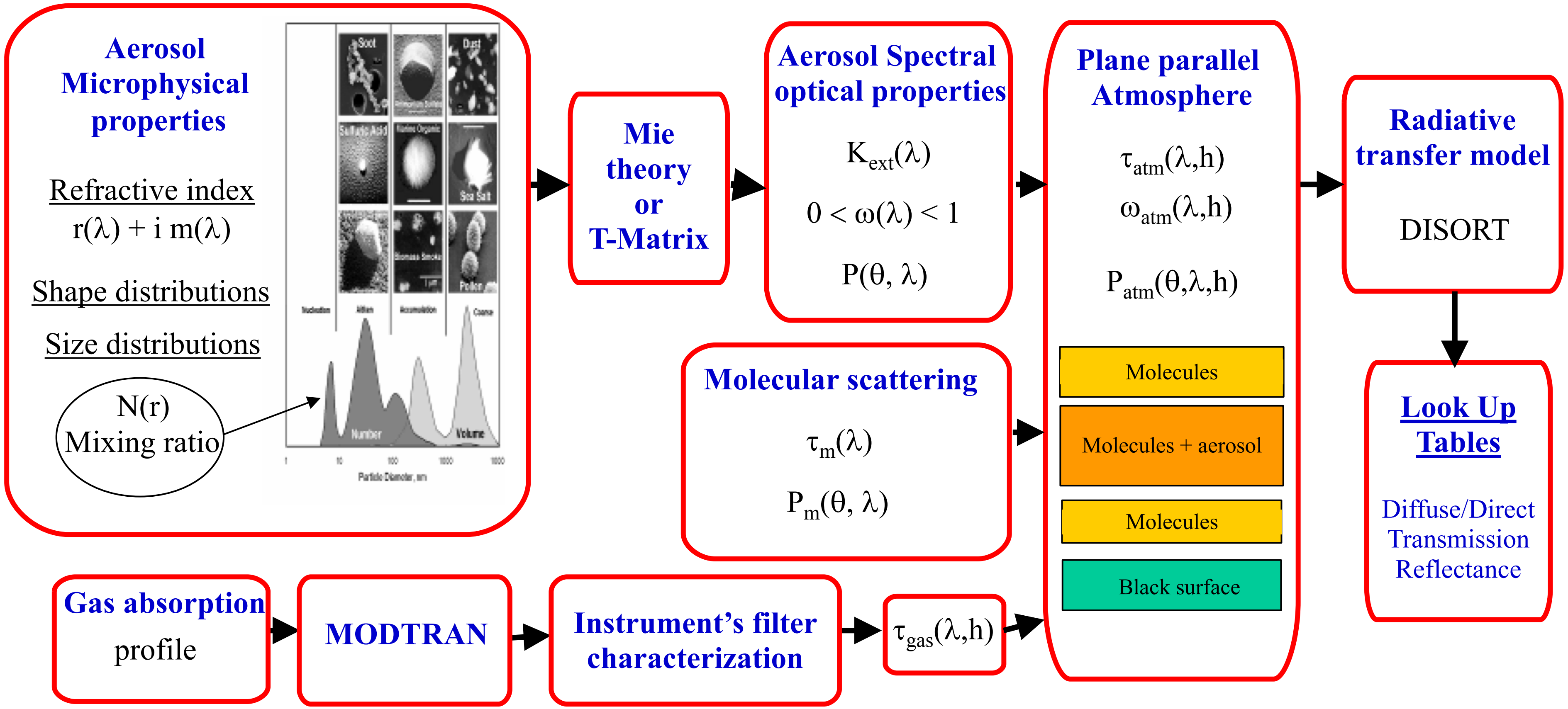
Observation operator: Atmosphere



CC4CL is the name given to ORAC in the cloud_cci project

McGarragh et al., Atmos. Meas. Tech. Discuss. (2017)
DOI: 10.5194/amt-2017-333

Calculation of atmospheric parameters



Observational Operator: Fast-FM

$$R(\theta_0,\theta_\mathrm{v},\Delta\phi) = R_\mathrm{bb}(\theta_0,\theta_\mathrm{v},\Delta\phi)$$

Single surface reflection

$$+T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_\mathrm{bb}(\theta_0,\theta_\mathrm{v},\Delta\phi)T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_\mathrm{bd}(\theta_0)T^{\uparrow}_\mathrm{db}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{db}(\theta_\mathrm{v})T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{dd}T^{\uparrow}_\mathrm{db}(\theta_\mathrm{v})$$

Double surface reflection

$$+T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_\mathrm{bd}(\theta_0)R_\mathrm{dd}\rho_\mathrm{db}T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_\mathrm{bd}(\theta_0)R_\mathrm{dd}\rho_\mathrm{dd}T^{\uparrow}_\mathrm{db}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{db}T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{dd}T^{\uparrow}_\mathrm{db}(\theta_\mathrm{v})$$

Triple surface reflection

$$+T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_\mathrm{bd}(\theta_0)R_\mathrm{dd}\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{db}T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_\mathrm{bd}(\theta_0)R_\mathrm{dd}\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{dd}T^{\uparrow}_\mathrm{db}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{db}T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v})$$
$$+T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{dd}R_\mathrm{dd}\rho_\mathrm{dd}T^{\uparrow}_\mathrm{db}(\theta_\mathrm{v})$$
$$+\dots$$

Gather terms

Apply series limit

$$R(\theta_0,\theta_\mathrm{v},\Delta\phi) = R_\mathrm{bb}(\theta_0,\theta_\mathrm{v},\Delta\phi) + T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_{bb}(\theta_0,\theta_\mathrm{v},\Delta\phi)T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v}) + T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{db}(\theta_\mathrm{v})T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v}) + \frac{\left[T^{\downarrow}_\mathrm{bb}(\theta_0)\rho_\mathrm{bd}(\theta_0) + T^{\downarrow}_\mathrm{bd}(\theta_0)\rho_\mathrm{dd}\right]\left[T^{\uparrow}_\mathrm{db}(\theta_\mathrm{v}) + R_\mathrm{dd}\rho_\mathrm{db}(\theta_\mathrm{v})T^{\uparrow}_\mathrm{bb}(\theta_\mathrm{v})\right]}{1-\rho_\mathrm{dd}R_\mathrm{dd}}$$

Compare with Lambertian approximation forward model (typically used):

$$R_\mathrm{TOA} = R_\mathrm{bb} + \frac{T^{\downarrow}_\mathrm{bt}\rho_\mathrm{tt}T^{\uparrow}_\mathrm{tb}}{1-\rho_\mathrm{tt}R_\mathrm{dd}}$$

Adaption from Retrieval to Model use

There are some key differences between how the ORAC retrieval and the model characterise aerosol which need to be dealt with:

Retrieval	Model
Aerosol modelled as pre-defined mixtures of ”components” of fixed composition (eg. dust or fine-mode absorbing aerosol), providing a set of aerosol-types.	Aerosol described as mass of different chemical components in different size bins.
Each component has a defined log-normal size distribution.	Model doesn’t carry around a simple description of aerosol size distribution.
Atmospheric transmissions and reflectances are calculated using an assumed height distribution of aerosol, with composition and size invariant with height.	Aerosol varies vertically as well as horizontally.

Adaption from Retrieval to Model use

The common ground between the two aerosol descriptions is column bulk scattering properties:

- The observation operator LUTs will be parameterised in terms of the bulk scattering properties currently carried around in the model:

  Extinction coefficient

  Single scattering albedo

  Asymmetry parameter

- The operator will calculate column averages of each of these parameters.
- Tangent-linear and adjoint functions relating the bulk properties back to mass mixing ratios already exist.

Current status and next steps

- Project officially kicked off at the end of March, but preparatory work has been underway since the start of the year:
  - Forward model adaption approach has been finalised.
  - Coding of the observation operator has begun, and look-up tables as a function of the bulk scattering properties have been created.
  - New ECMWF employee to work on the assimilation and model evaluation side of the project will be starting in the next couple of weeks.
- Next steps:
  - Sea surface reflectance model needs to be interfaced with IFS sea-state model.
  - LUT I/O and interpolation routines need to be coded.
  - Tangent linear and adjoint coding.
  - Assessment of the assimilation scheme using runs of a few months.