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.

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 multivariate 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.
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.

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Observation operator: Atmosphere

CC4CL is the name given to ORAC in the cloud_cci project

Calculation of atmospheric parameters

Aerosol Microphysical properties
- Refractive index \( r(\lambda) + i \, m(\lambda) \)
- Shape distributions
- Size distributions
- Mixing ratio \( N(r) \)

Gas absorption profile

MODTRAN

Instrument’s filter characterization

Mie theory or T-Matrix

Aerosol Spectral optical properties
- Mie theory
- T-Matrix
- Extinction coefficient \( K_{\text{ext}}(\lambda) \)
- \( 0 < \omega(\lambda) < 1 \)
- \( P(\theta, \lambda) \)

Plane parallel Atmosphere
- \( \tau_{\text{atm}}(\lambda, h) \)
- \( \omega_{\text{atm}}(\lambda, h) \)
- \( P_{\text{atm}}(\theta, \lambda, h) \)

Radiative transfer model
- DISORT

Look Up Tables
- Diffuse/Direct Transmission Reflectance

Molecules
- Molecules + aerosol
- Black surface

\( \tau_{\text{gas}}(\lambda, h) \)
Observational Operator: Fast-FM

\[ R(\theta_0, \theta_v, \Delta \phi) = R_{bb}(\theta_0, \theta_v, \Delta \phi) \]

**Single surface reflection**

\[ + T_{bb}^\dagger(\theta_0) \rho_{bb}(\theta_0, \theta_v, \Delta \phi) T_{bb}(\theta_v) \]

\[ + T_{bb}^\dagger(\theta_0) \rho_{bd}(\theta_0) T_{db}(\theta_v) \]

\[ + T_{bd}^\dagger(\theta_0) \rho_{ab}(\theta_v) T_{db}(\theta_v) \]

\[ + T_{bd}^\dagger(\theta_0) \rho_{dd} T_{db}(\theta_v) \]

**Double surface reflection**

\[ + T_{bb}^\dagger(\theta_0) \rho_{bd}(\theta_0) R_{dd} \rho_{dd} T_{db}(\theta_v) \]

\[ + T_{bb}^\dagger(\theta_0) \rho_{dd}(\theta_0) R_{dd} \rho_{dd} T_{db}(\theta_v) \]

\[ + T_{bd}^\dagger(\theta_0) \rho_{dd} R_{dd} \rho_{dd} T_{db}(\theta_v) \]

\[ + T_{bd}^\dagger(\theta_0) \rho_{dd} R_{dd} \rho_{dd} T_{db}(\theta_v) \]

**Triple surface reflection**

\[ + T_{bb}^\dagger(\theta_0) \rho_{bd}(\theta_0) R_{dd} \rho_{dd} R_{dd} \rho_{dd} T_{bb}(\theta_v) \]

\[ + T_{bb}^\dagger(\theta_0) \rho_{bd}(\theta_0) R_{dd} \rho_{dd} R_{dd} \rho_{dd} T_{bb}(\theta_v) \]

\[ + T_{bd}^\dagger(\theta_0) \rho_{dd} R_{dd} \rho_{dd} R_{dd} \rho_{dd} T_{bb}(\theta_v) \]

\[ + T_{bd}^\dagger(\theta_0) \rho_{dd} R_{dd} \rho_{dd} R_{dd} \rho_{dd} T_{db}(\theta_v) \]

\[ + \ldots \]

**Gather terms**

**Apply series limit**

\[ R(\theta_0, \theta_v, \Delta \phi) = R_{bb}(\theta_0, \theta_v, \Delta \phi) \]

\[ + T_{bb}^\dagger(\theta_0) \rho_{bb}(\theta_0, \theta_v, \Delta \phi) T_{bb}(\theta_v) + T_{bd}^\dagger(\theta_0) \rho_{ab}(\theta_v) T_{db}(\theta_v) \]

\[ + \left[ T_{bb}^\dagger(\theta_0) \rho_{bd}(\theta_0) + T_{bd}^\dagger(\theta_0) \rho_{dd} \right] \frac{T_{db}(\theta_v) + R_{dd} \rho_{dd}(\theta_v) T_{bb}(\theta_v)}{1 - \rho_{dd} R_{dd}} \]

Compare with Lambertian approximation forward model (typically used):

\[ R_{TOA} = R_{bb} + \frac{T_{bb}^\dagger \rho_{tt} T_{bb}^\dagger}{1 - \rho_{tt} R_{dd}} \]
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:

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