ORAC
Bringing three threads together

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NATURAL ENVIRONMENT RESEARCH COUNCIL
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Overview

- Introduction/reminder of what ORAC is
- Current status of ORAC
  - Aerosol cci
  - Cloud cci
  - Volcanic ash cloud retrieval
- *A posteriori* scene identification in ORAC
  - What is it?
  - Does it work?

What is ORAC

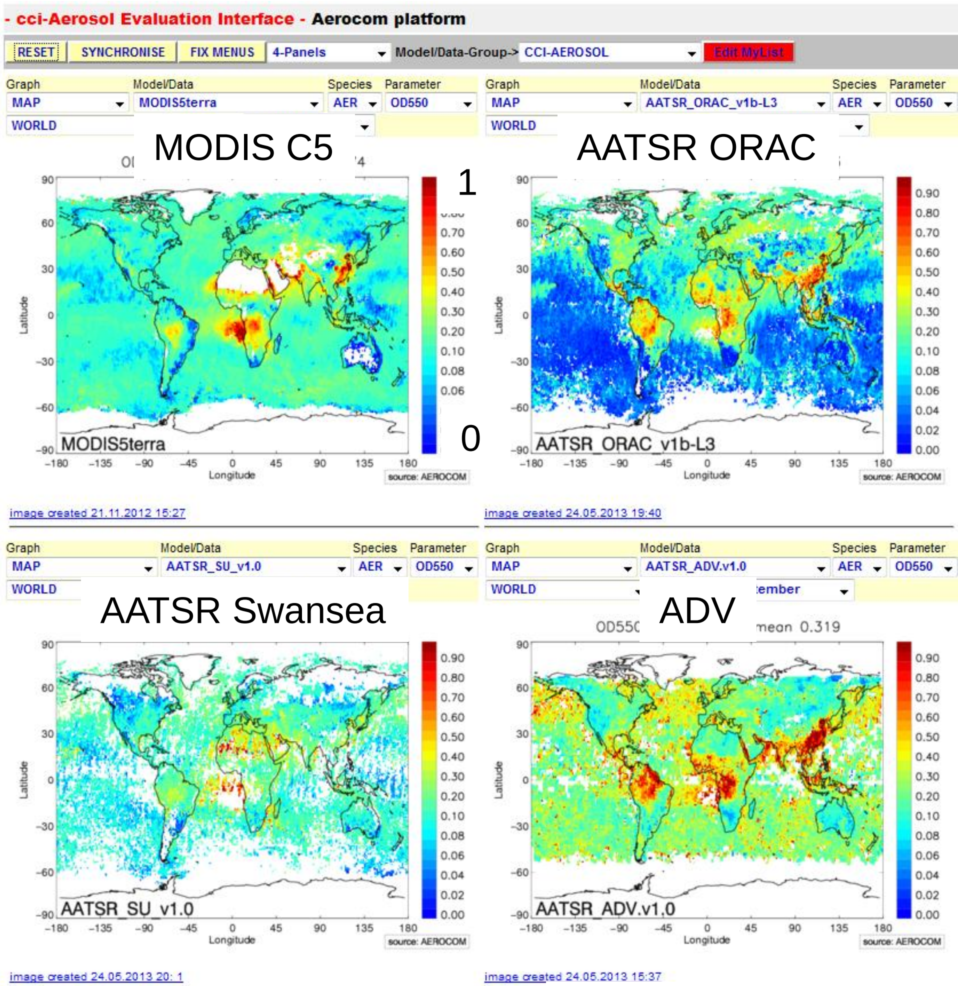
- "Optimal Retrieval of Aerosol & Cloud", or "Oxford-RAL Aerosol & Cloud".
  - Some in Cloud cci have also started calling it "CC4CL"
- Optimal estimation retrieval scheme for visible/IR imaging instruments
- There are aerosol, cloud and aerosol-SST variants in existence
- It has been applied to the (A)ATSR, SEVIRI, MODIS & AVHRR sensor families
- Is one of the four (A)ATSR algorithms in aerosol_cci and the "heritage channel" algorithm for cloud_cci

Aerosol cci

- Unusually, all the algorithms that entered Phase I of the project continuing into Phase II.
  - Main ECV products will be from (A)ATSR and POLDER
  - Three “competing” (A)ATSR algorithms
    - ORAC
    - Swansea dual-view
    - Advanced Dual View (ADV) from FMI
  - Swansea algorithm has been selected to provide the prototype ECV for the full ATSR-2/AATSR time-series
- Phase II will concentrate on
  - Improving uncertainty propagation
  - Improving validation and extending beyond AOD
  - Producing multiple long-term data sets

Public data sets *should be* here:
http://www.icare.univ-lille1.fr/archive/index.php?dir=CCI-Aerosols/

Baseline datasets (start of 2010): AOD September 2008



Plots: AEROCOM website

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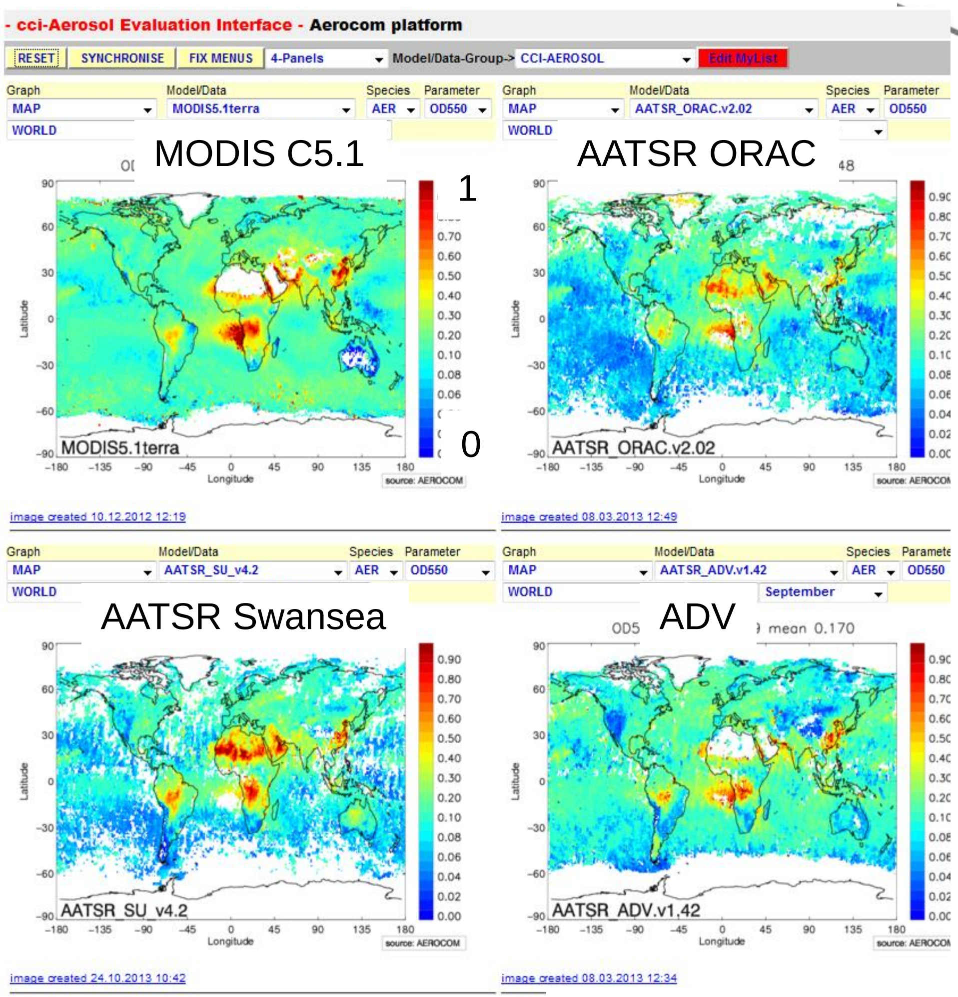
Final round-robin (end 2012): AOD September 2008



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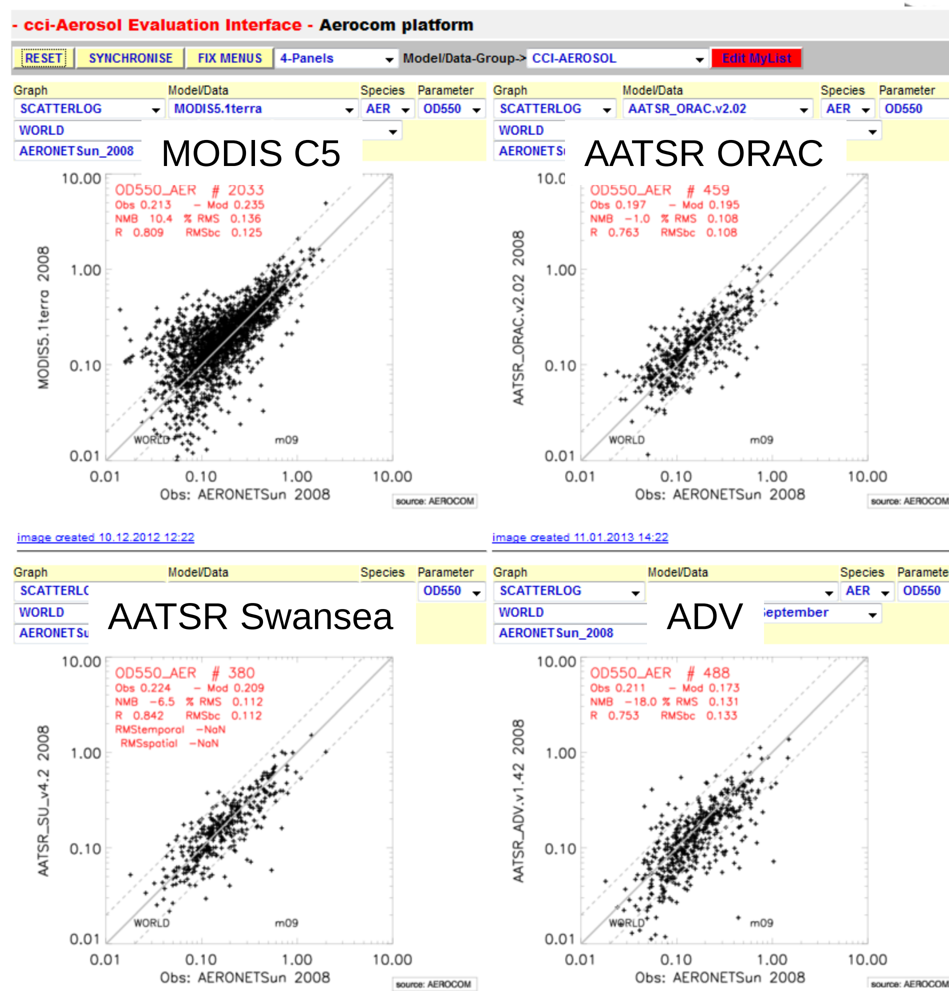

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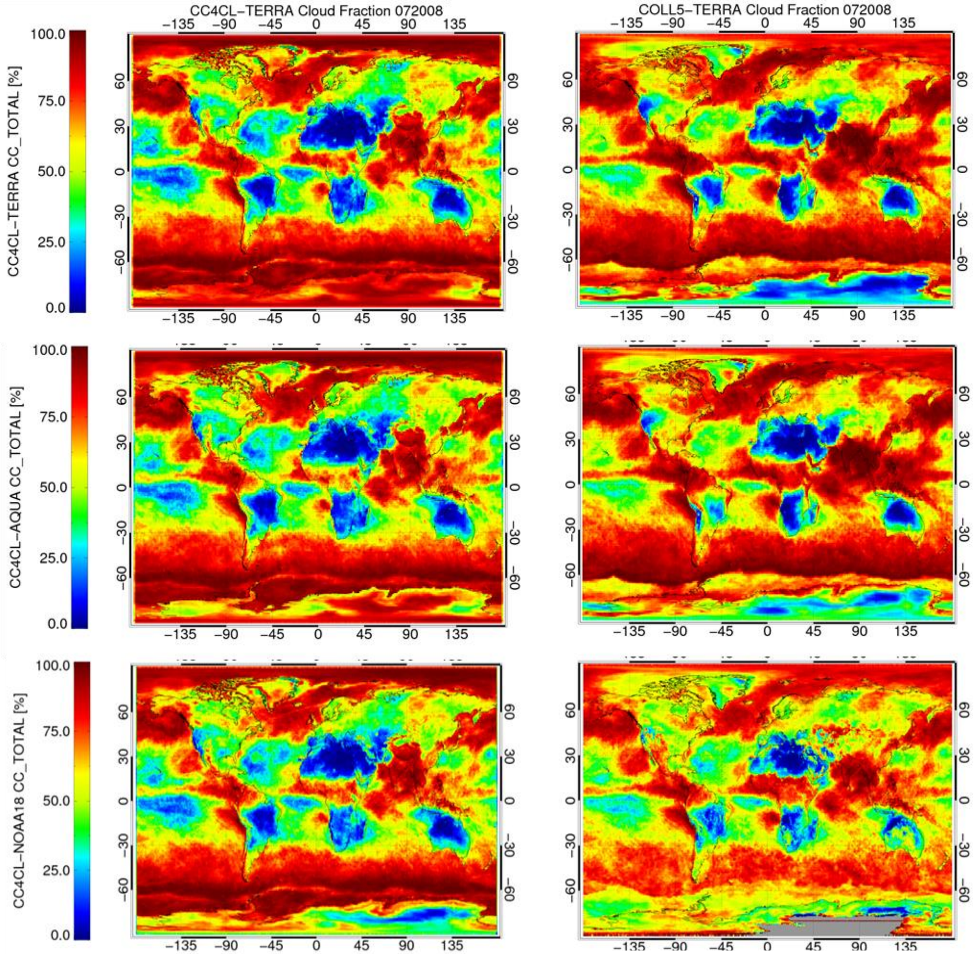
Cloud cci

- ORAC has been used to produce global cloud products for 2007-2009 from
  - MODIS (Aqua+Terra) [DWD]
  - AVHRR (NOAA-15, 16, 17) [DWD]
  - AATSR [RAL]
- Development of the retrieval system is still ongoing
  - Addressing bugs/problems revealed by first processing
  - Optimising the retrieval for speed



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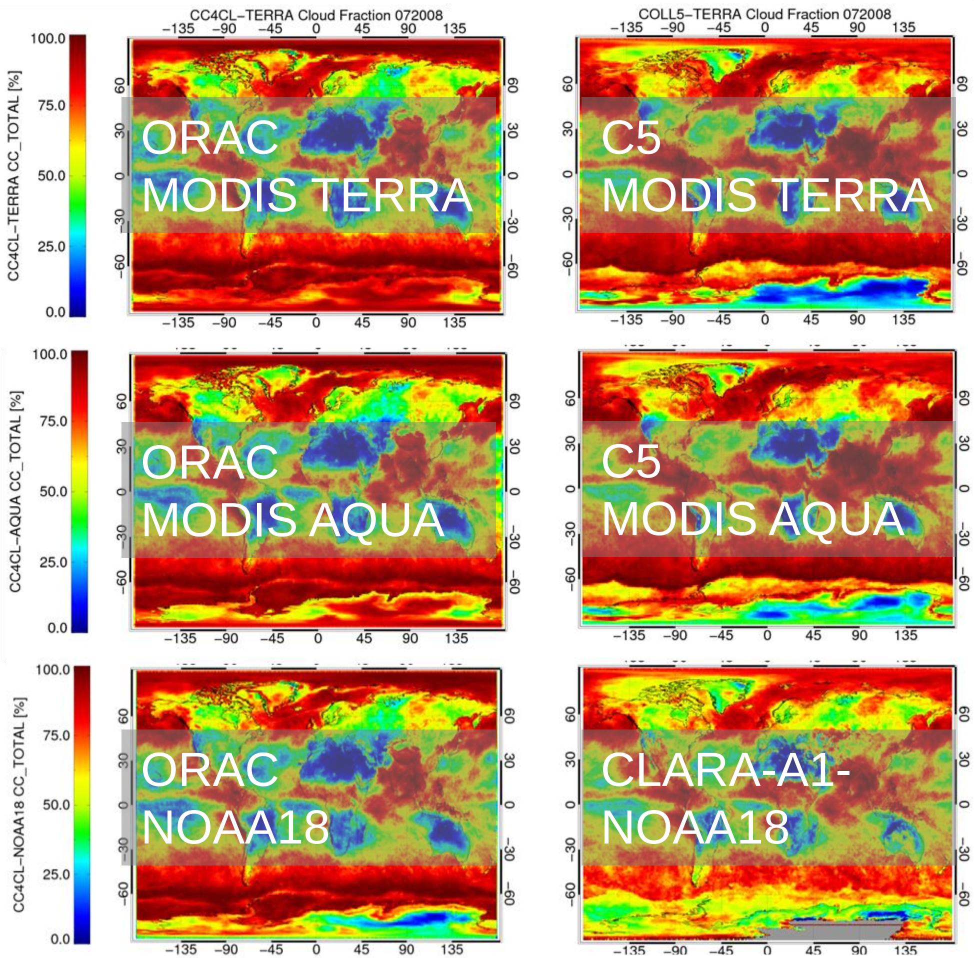

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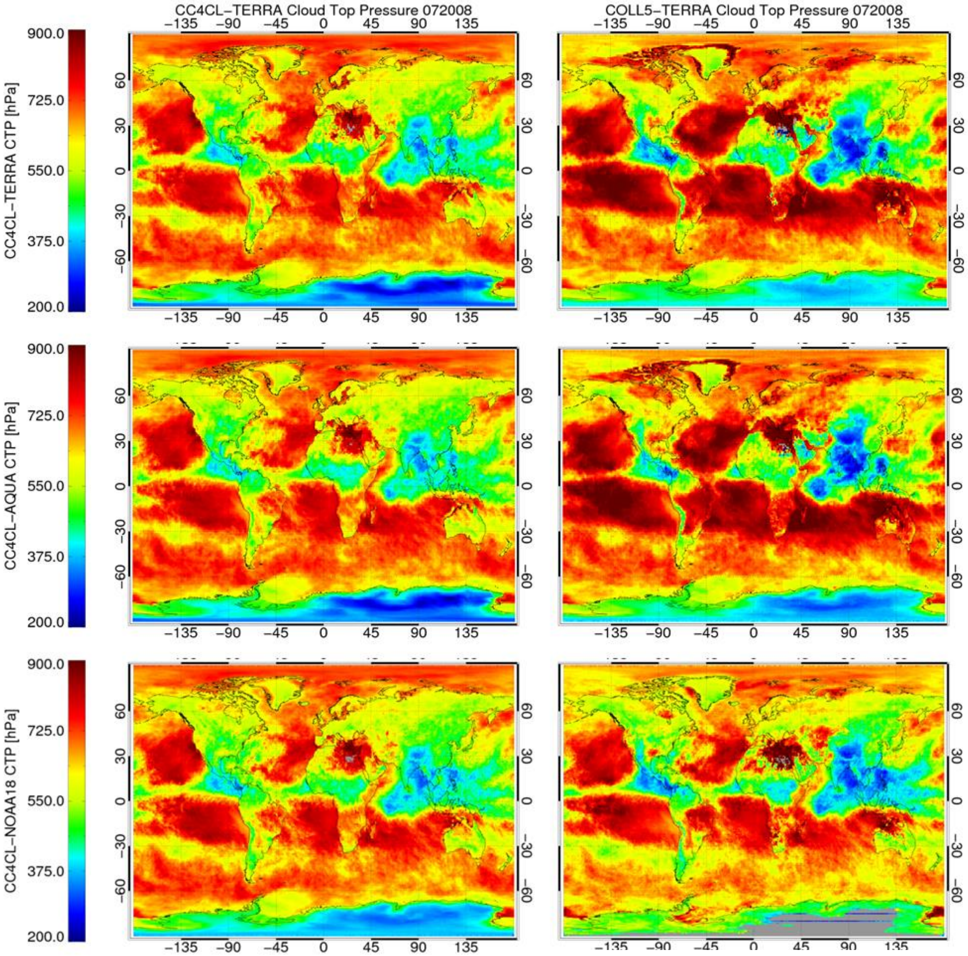
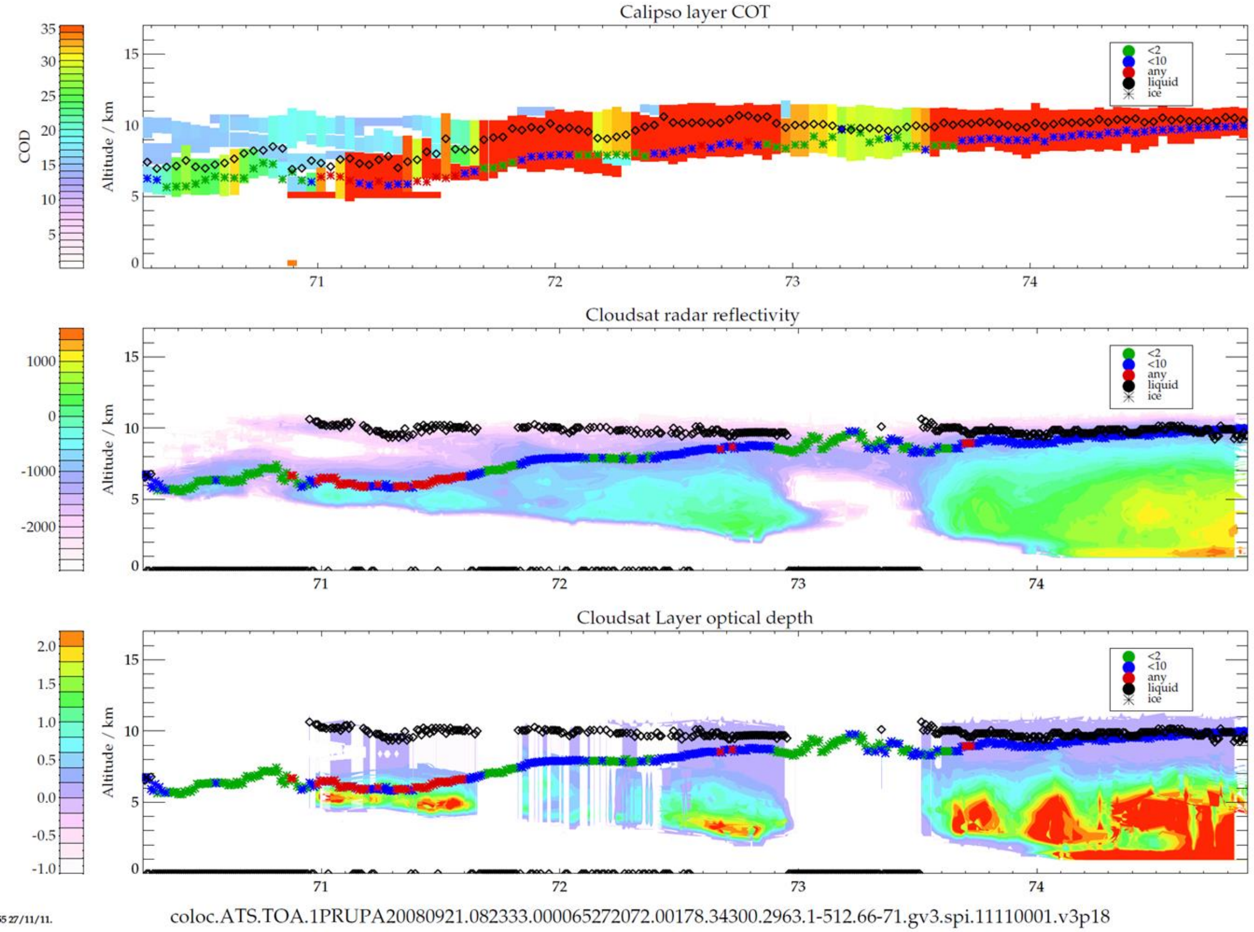
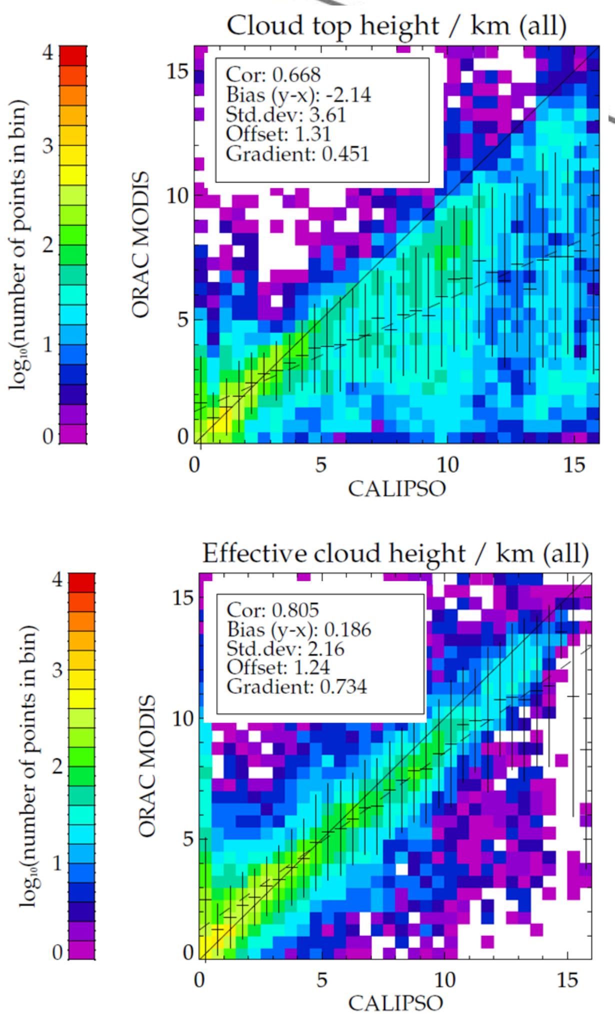


Plots: Stefan Stapelberg (DWD)

The cloud-top-height problem

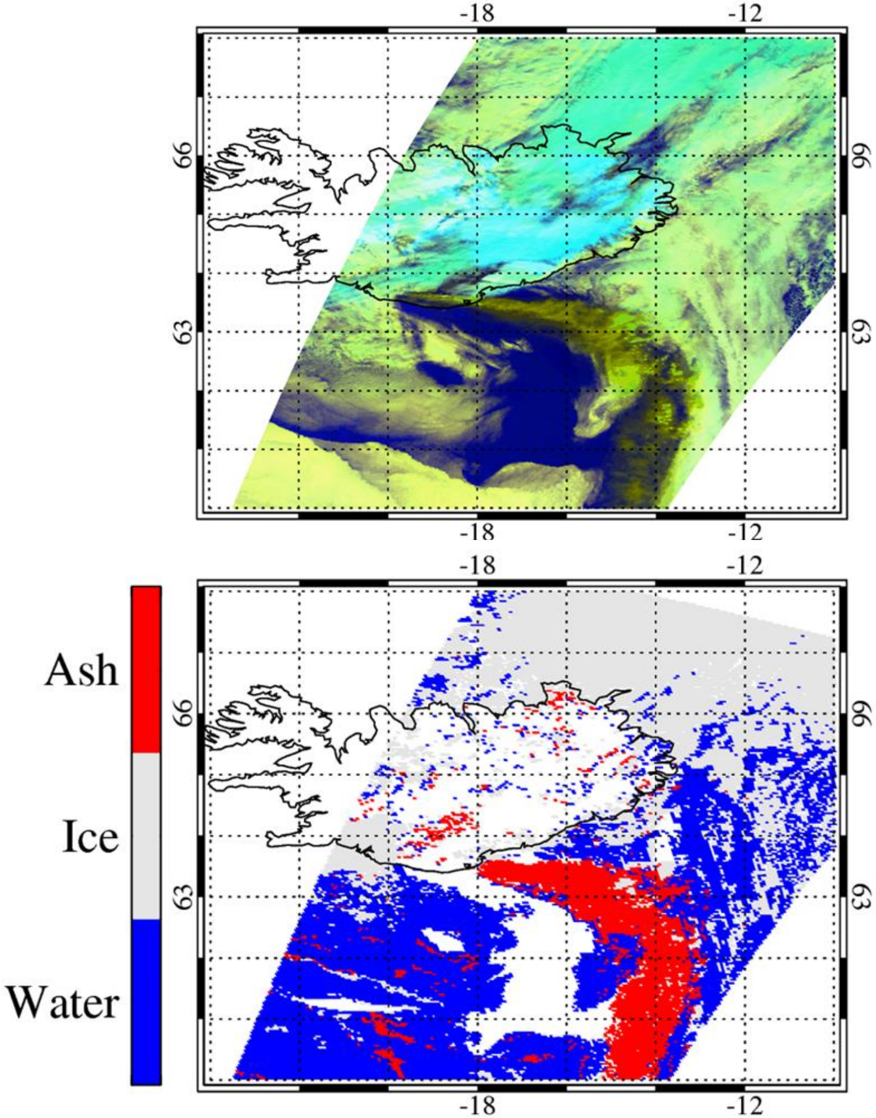




Plots: Caroline Pouslen (RAL)

Volcanic ash

- ORAC has now been extensively applied to the retrieval of volcanic ash properties
- The OE method is well suited to this problem, as ash is generally easily distinguished from cloud
- Two main problems remain:
  - Ash optical properties
  - The multi-layer issue



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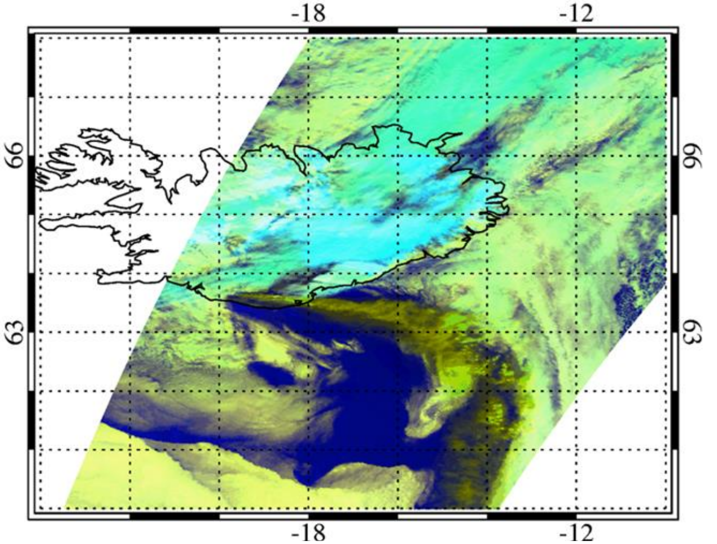

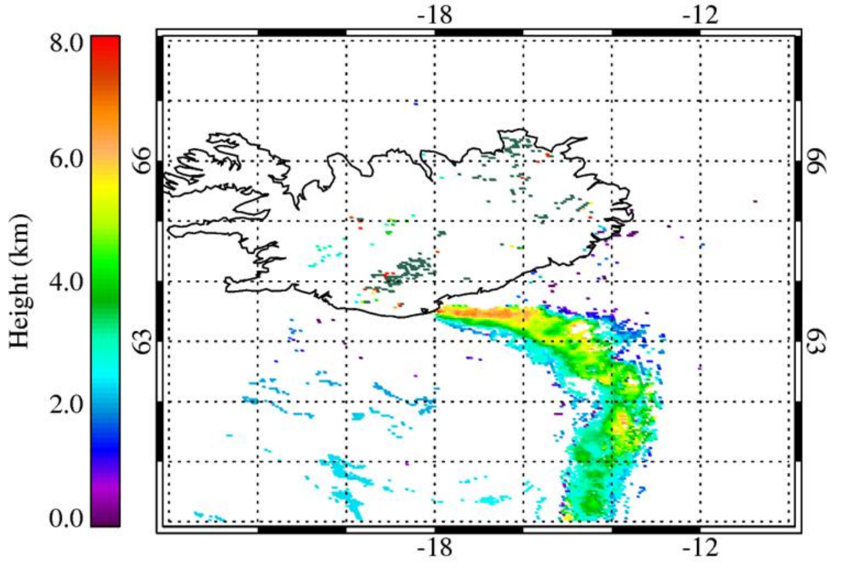

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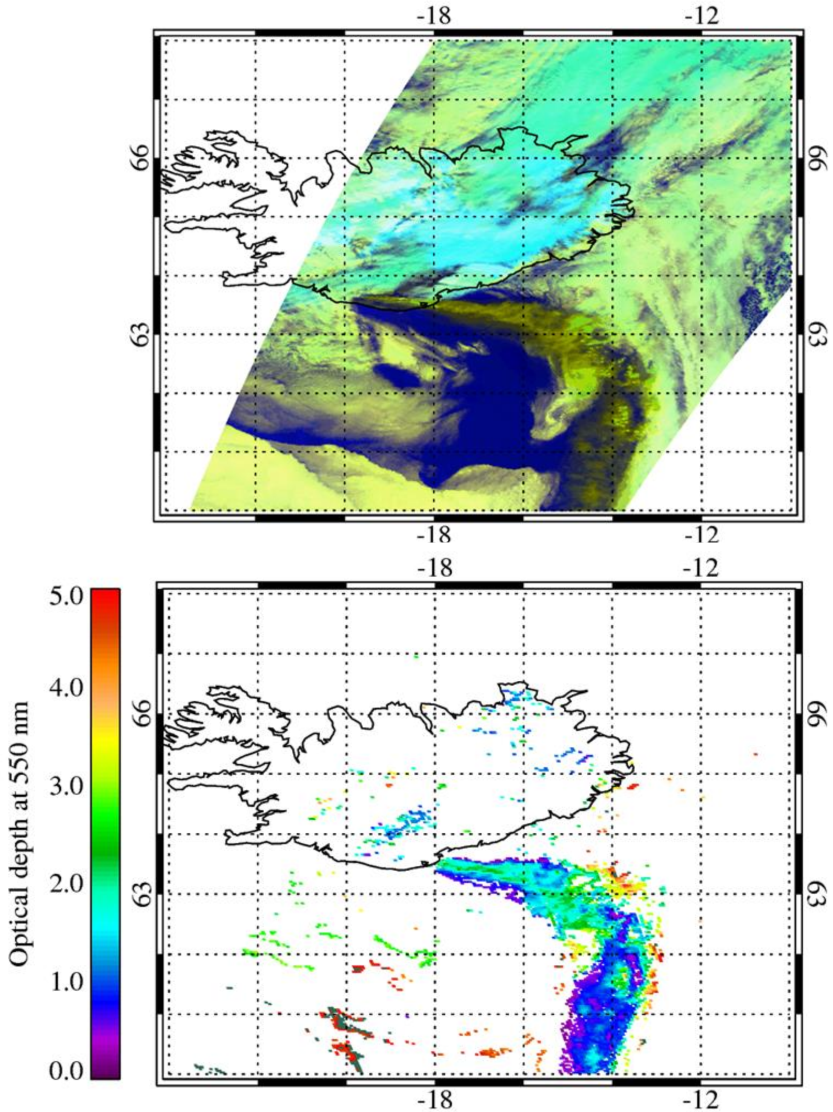

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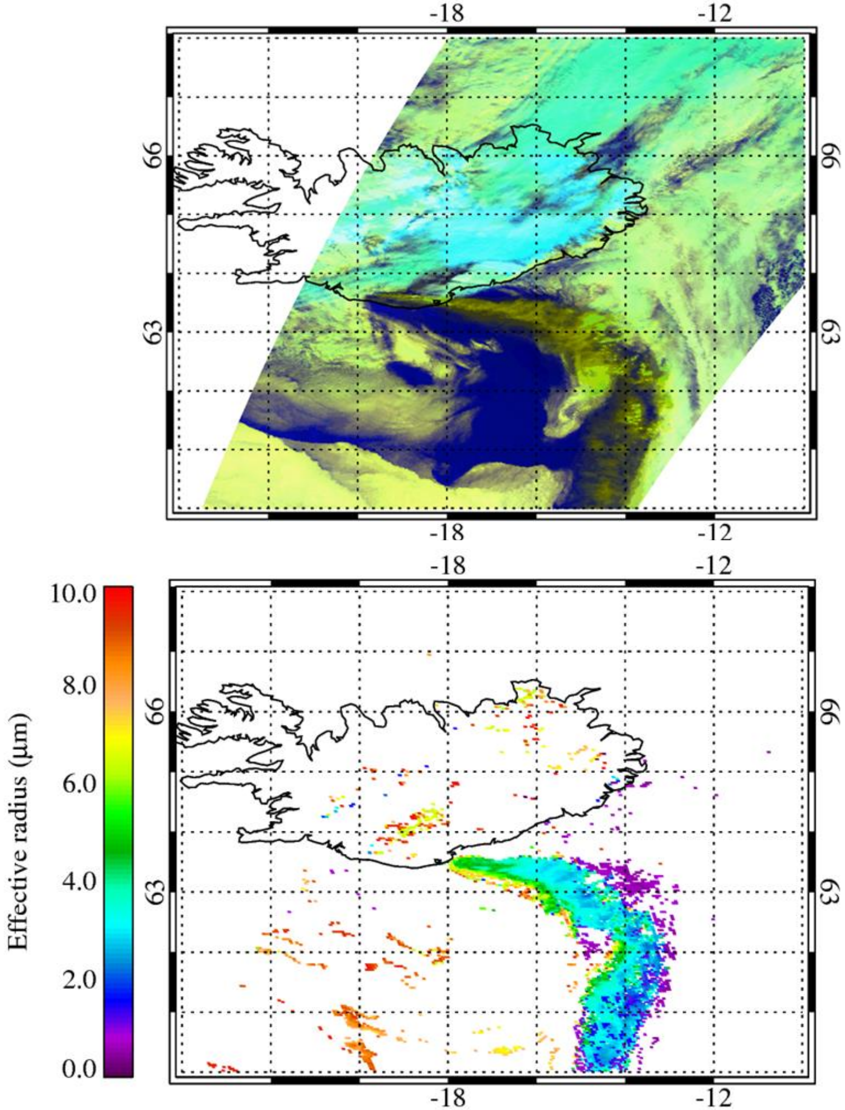

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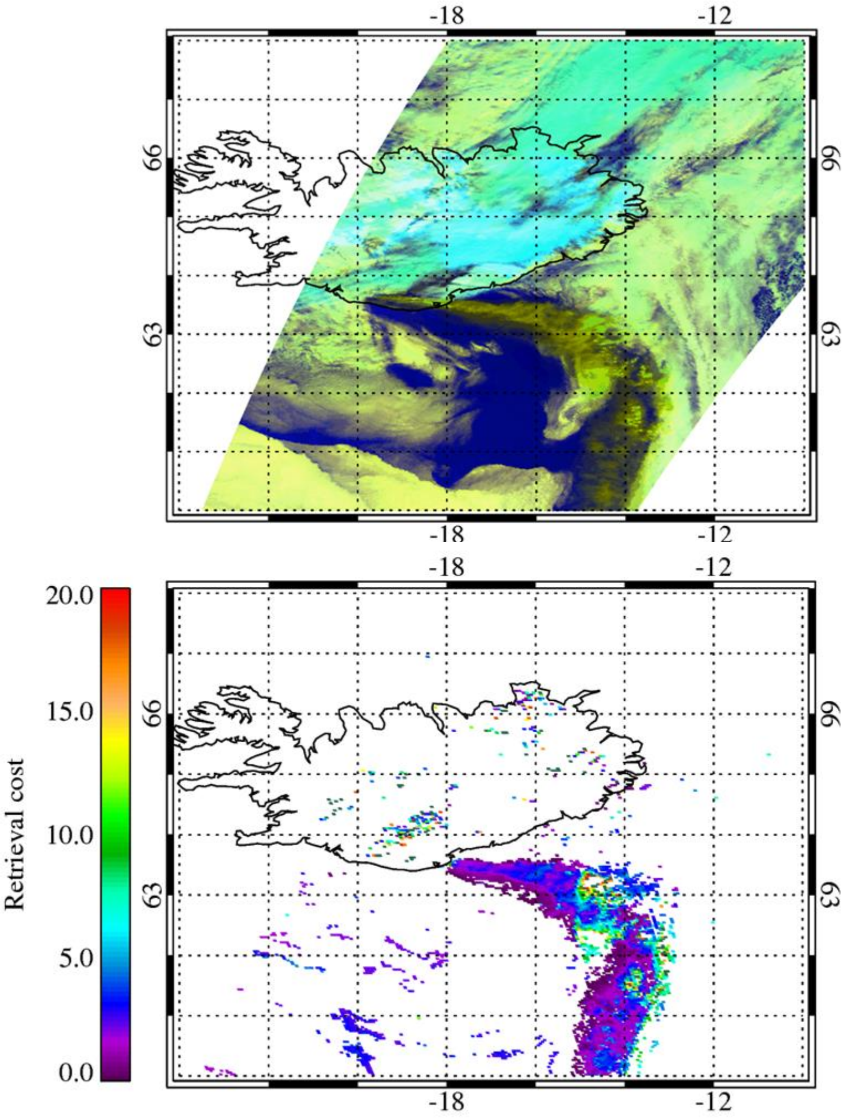
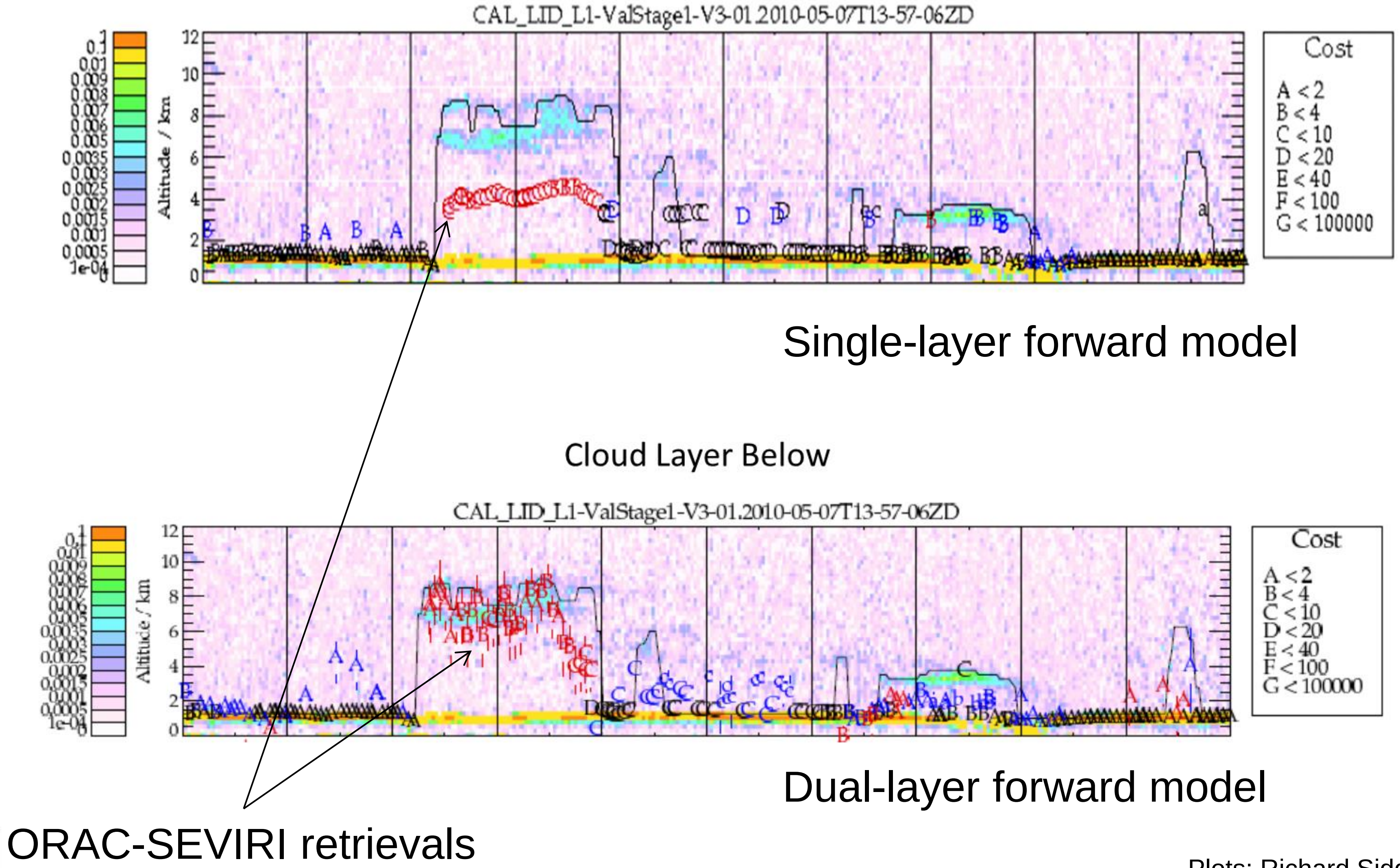


Multi-layer retrieval



Plots: Richard Siddans (RAL)

What's next for ORAC

NOW

ORAC cloud
- Community algorithm
- Fully version controlled
- Single-view, Lambertian surface with thermal-IR
- All Fortran

ORAC aerosol
- Stand alone, no version control
- BRDF surface, multi-view, but no thermal-IR
- Fortran retrieval + IDL pre/post processing

ORAC SST
- Stand alone, no version control
- BRDF surface, multi-view, with thermal-IR
- Fortran retrieval + IDL pre/post processing

"ORAC IDL"
- Full IDL implementation
- More versatile
  - More instruments
  - Sounding channels
  - Online RTM
- Much slower

12 MONTHS

"Community ORAC"
- Community algorithm
- BRDF surface + multi-view
- Thermal IR
- Both aerosol/SST (IDL) and cloud (fortran) pre/post processing

Specific improvements

"ORAC IDL"
- Full IDL implementation

A posteriori scene identification

- OE retrieval provides statistics on the quality of the fit
  - In particular the retrieval cost is directly related to the conditional probability of the retrieved state given the measurement (for a particular set of assumptions):

$$J = -2 \ln P(\mathbf{x}|\mathbf{y})$$

- Can we use this information to distinguish between cloud and aerosol (and different cloud/aerosol types)?

χ^2 test

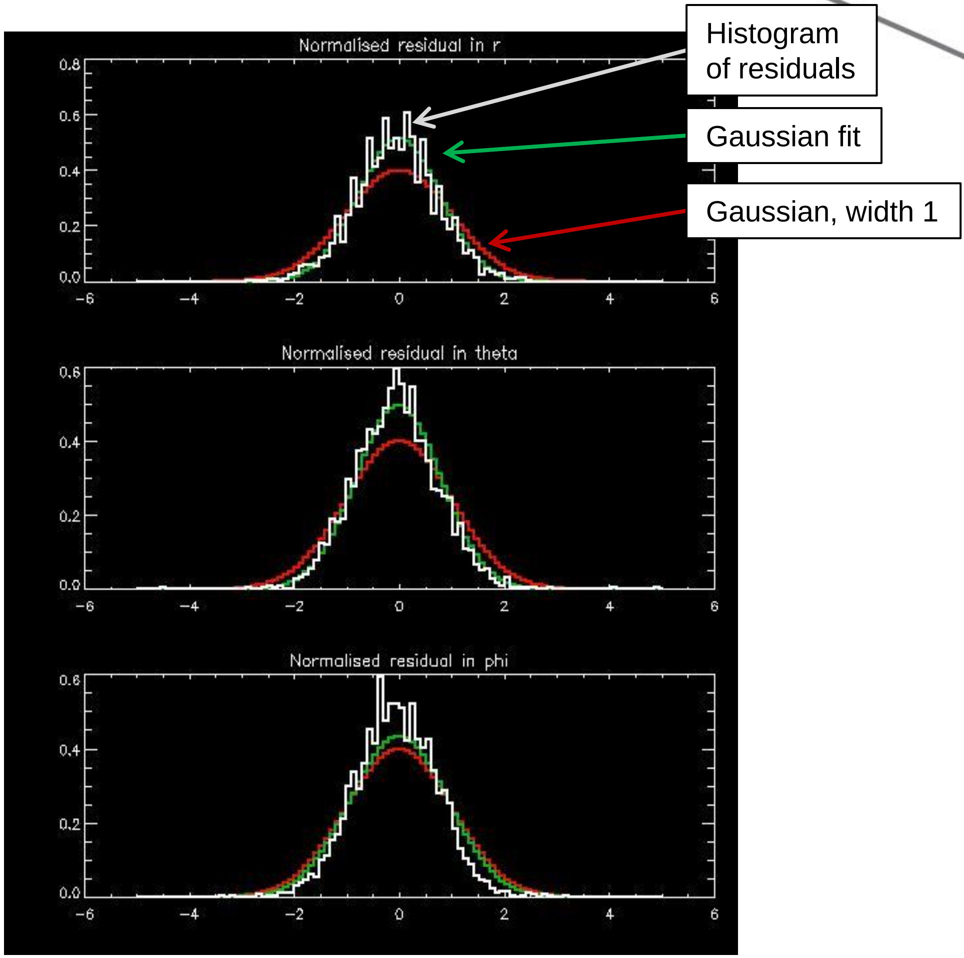
- Measurement cost function:

$$J_m = [\mathbf{y} - \mathbf{f}(\mathbf{x})]\ \mathbf{S}_y^{-1}\ [\mathbf{y} - \mathbf{f}(\mathbf{x})]$$

  will be a random sample from a normal distribution with a standard deviation of 1, with degrees of freedom equal to the number of measurements, *m*.
- Thus, it should follow a χ^2 distribution with *m* degrees of freedom and each J_m value can thus provide a probability that the retrieval is consistent with the measurement
- *Assumes that the covariance matrix,* $\mathbf{S}_y$*, is an accurate representation of the uncertainty in the system and that the forward model,* $\mathbf{f}(\mathbf{x})$*, is a good representation of the physics of the measurement.*
- Similar argument can be applied to the a priori cost.

A test case

- Simple numerical retrieval of three parameters from 3 measurements
  - Forward model is transform from Cartesian to polar coordinates
- Gaussian noise with standard deviation of 0.01 added to forward model

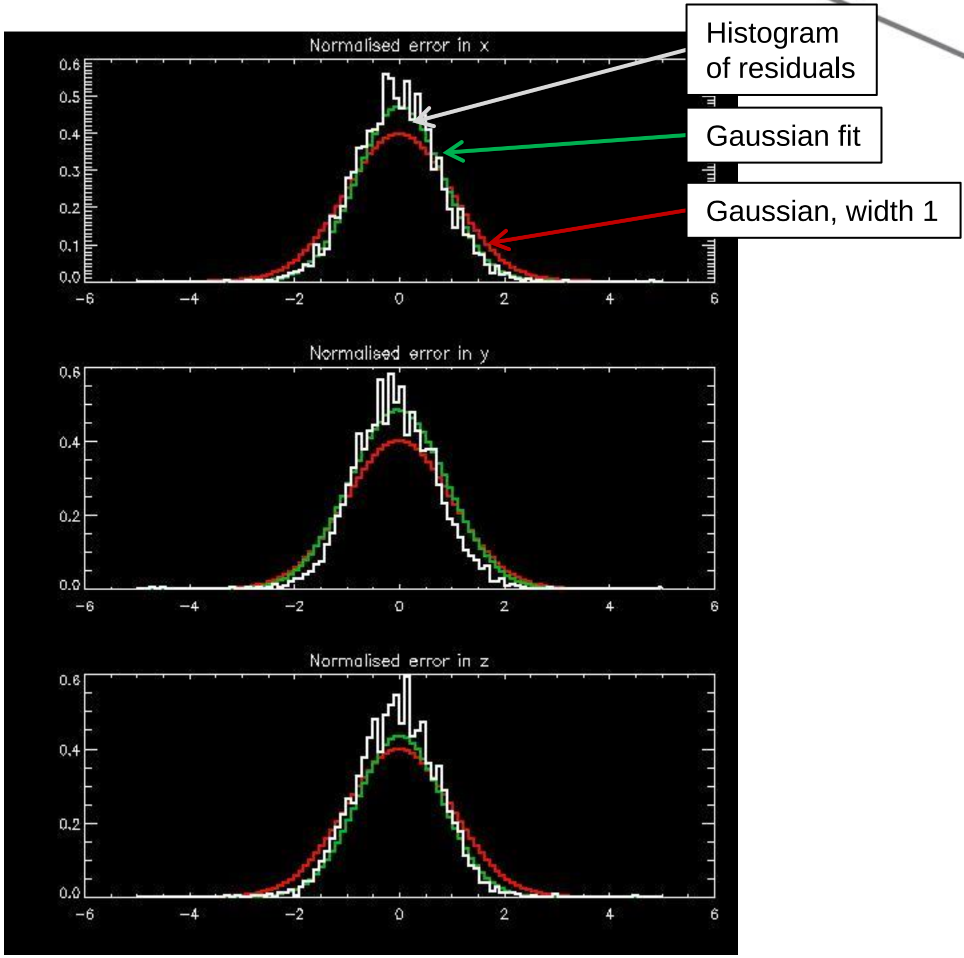


Distribution of measurement residuals, normalised by uncertainty

A test case

- Retrieved state and measurement both agree very well with theoretical distribution

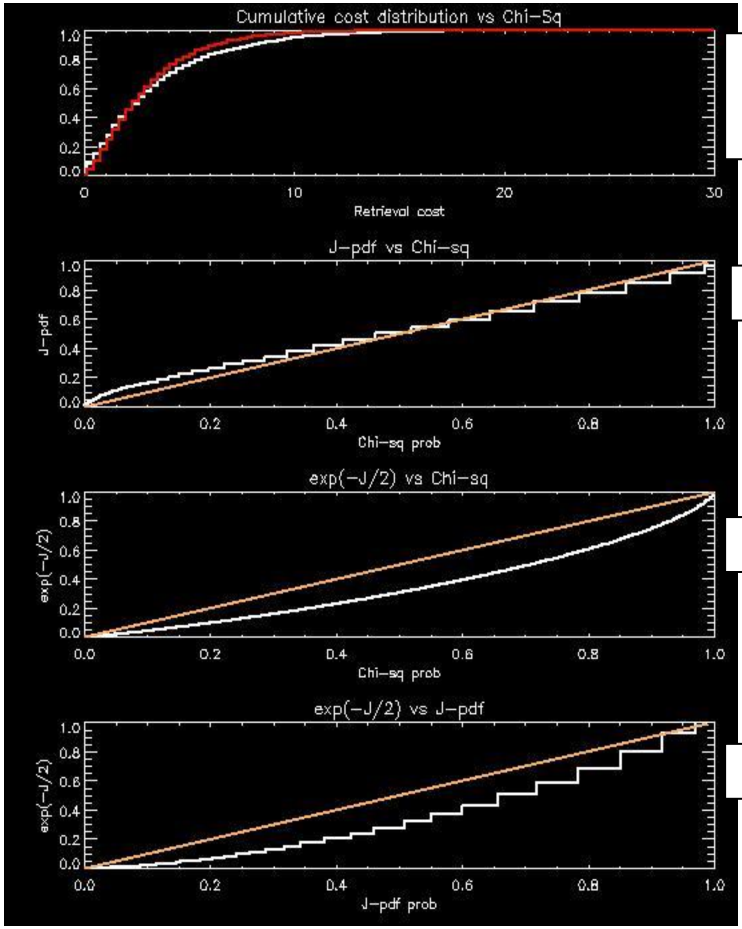
- Retrieval works!



Distribution of state vector residuals, normalised by retrieved uncertainty

A test case

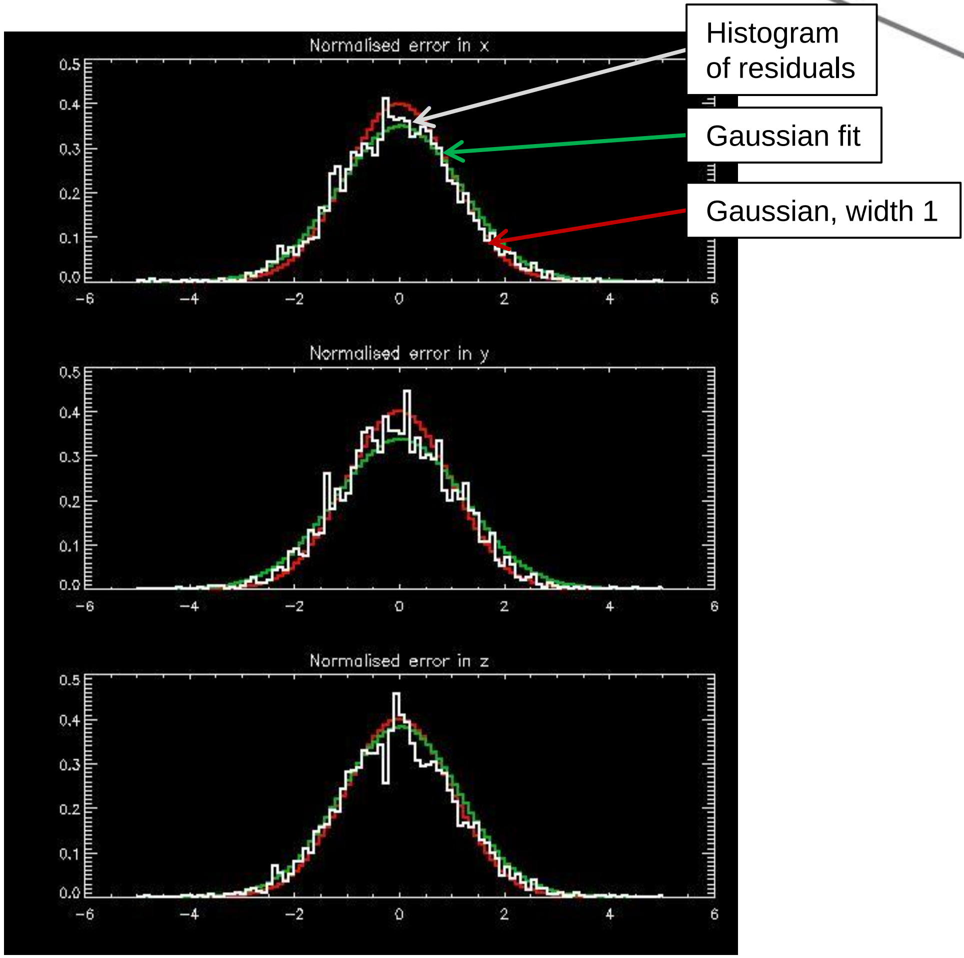
- Cumulative distribution of cost is very close to expected χ^2 distribution
- Note that the conditonal probability P(**x**|**y**) is pretty close to the χ^2 probabilty, but they are not the same



A test case

Assumed uncertainty 50% too small….

- Retrieval still works
- Even retrieved uncertainty is acceptable…

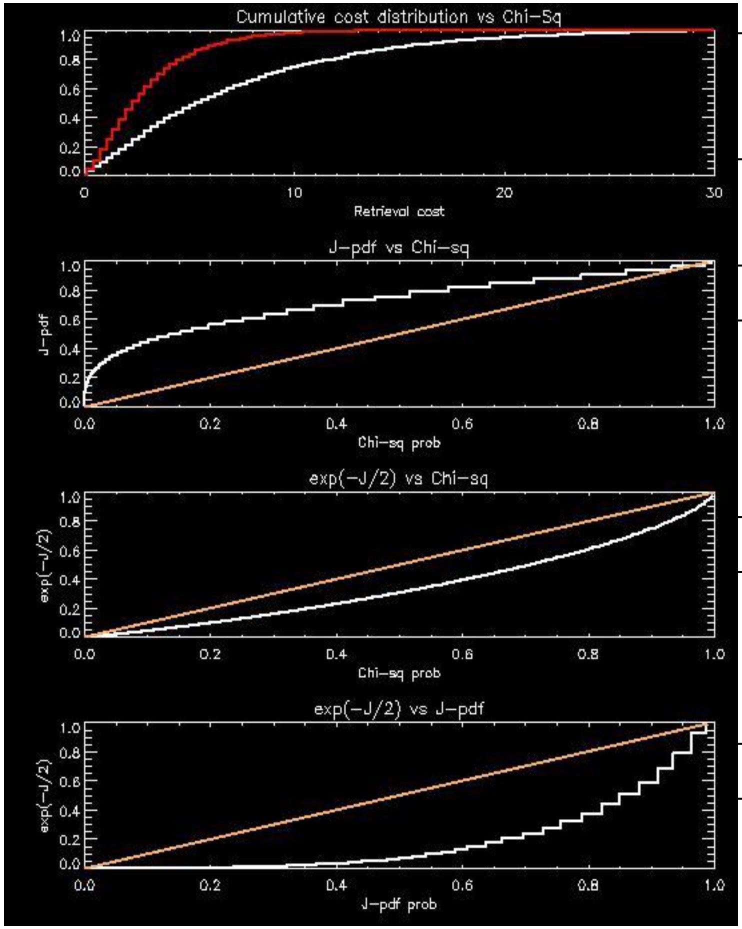


Distribution of state vector residuals, normalised by retrieved uncertainty

A test case

Assumed uncertainty 50% too small….

- χ^2 comparison breaks down
  - Too many high-cost retrievals
- However, the results are still qualitatively useful
  - Better states still provide higher χ^2 probabilities



Cumulative distribution of J_m and χ^2

J_m vs. χ^2

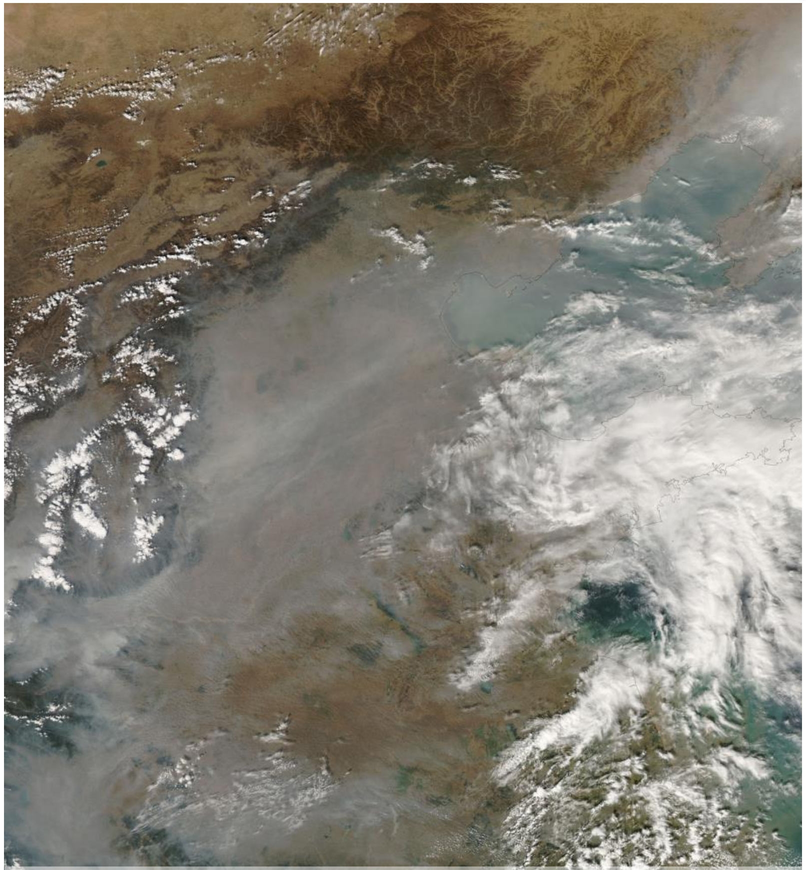
P(**x**|**y**) vs. χ^2

P(**x**|**y**) vs. J_m

Application to ORAC processor

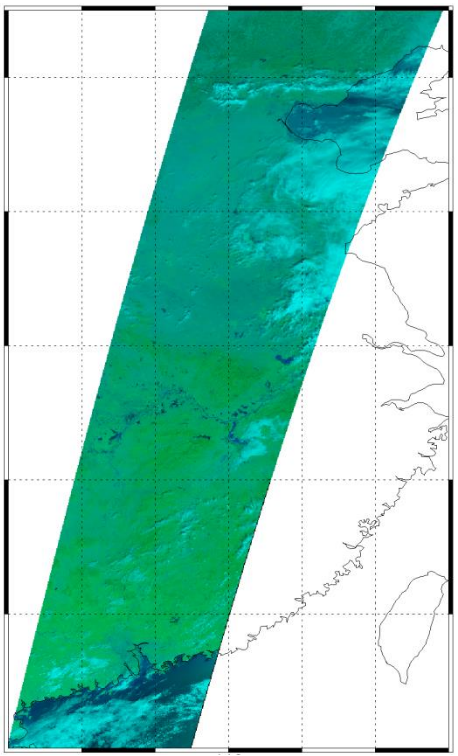
- Chinese haze event on 16-Oct-2008
- A good example of where traditional cloud flagging might struggle!

- AATSR processed:
  - Cloud_cci product
  - Aerosol_cci
  - “Bayesian” retrieval using cloud_cci processor

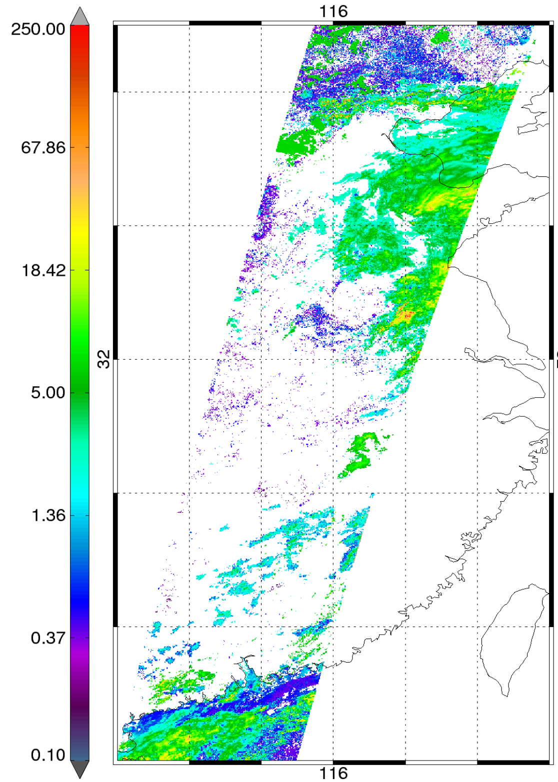


NASA Earth Observatory – from MODIS-Aqua
http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=35502&eocn=image&eoci=related_image

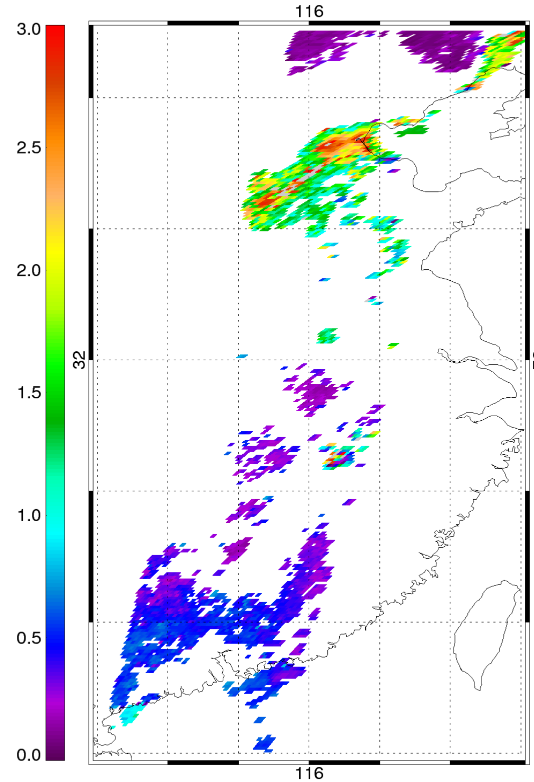
Cloud and Aerosol cci consistency



AATSR false colour

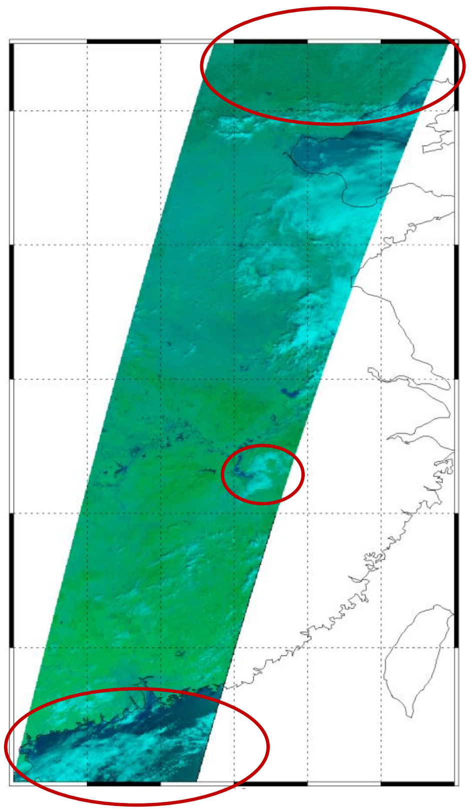


Cloud_cci L2 (ORAC) cloud optical depth



Aerosol_cci L2 (ORAC) aerosol optical depth

Cloud and Aerosol cci consistency



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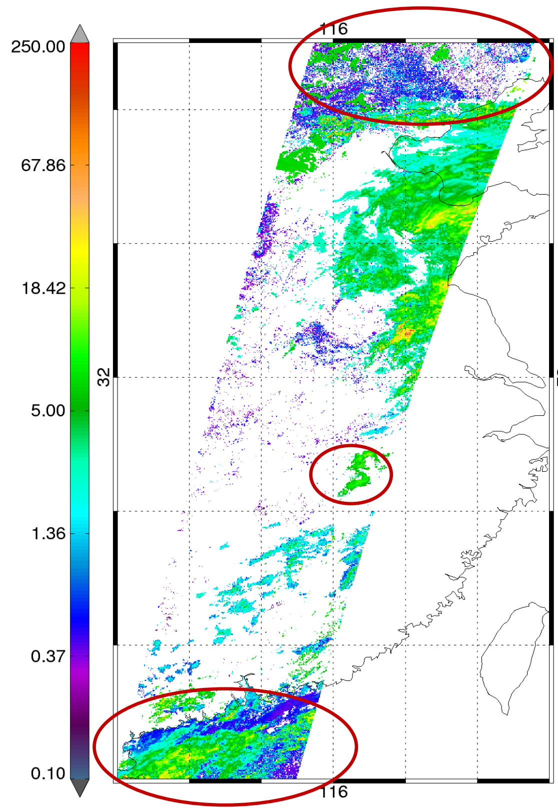

Cloud_cci L2 (ORAC)
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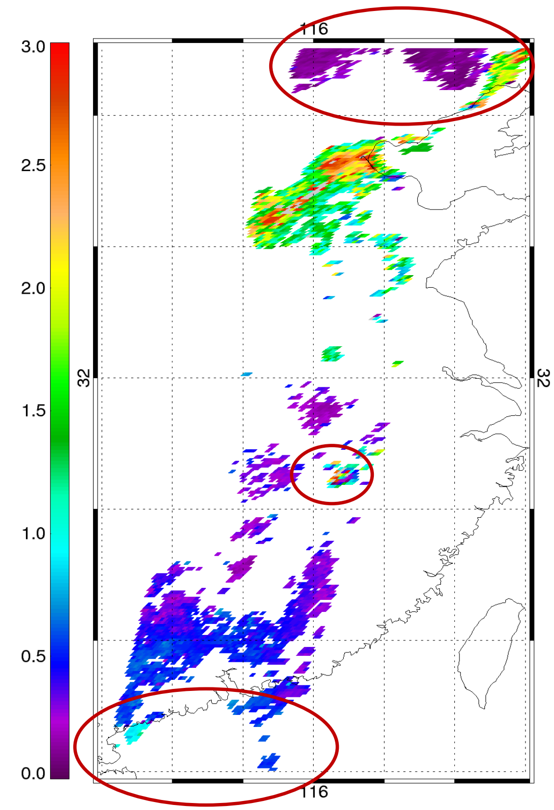
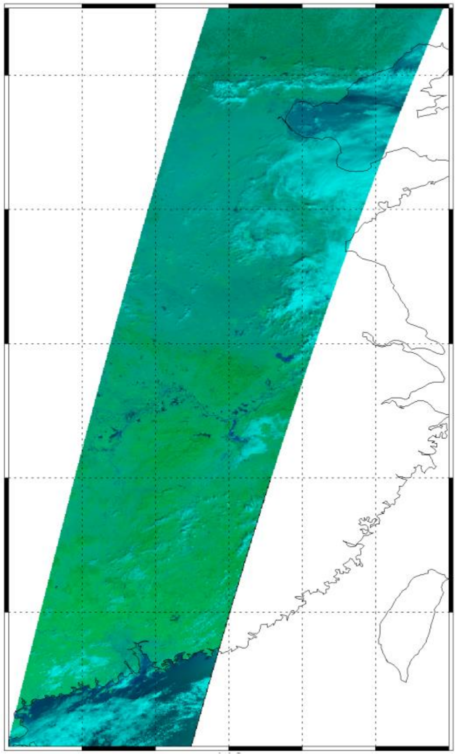


Aerosol_cci L2 (ORAC)
aerosol optical depth

Bayesian approach…

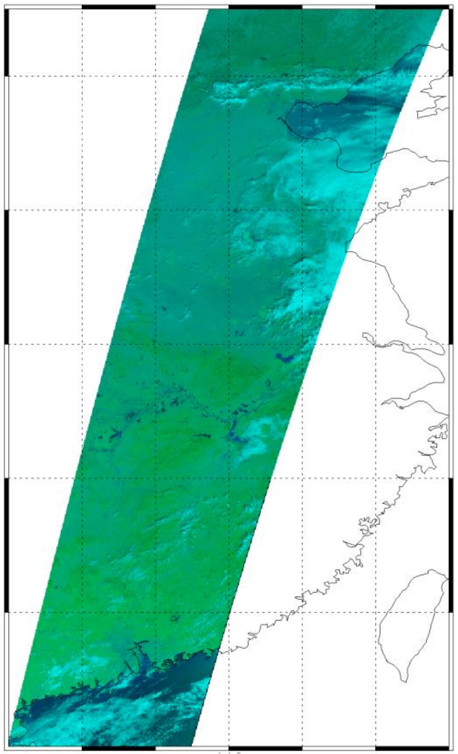


AATSR false colour

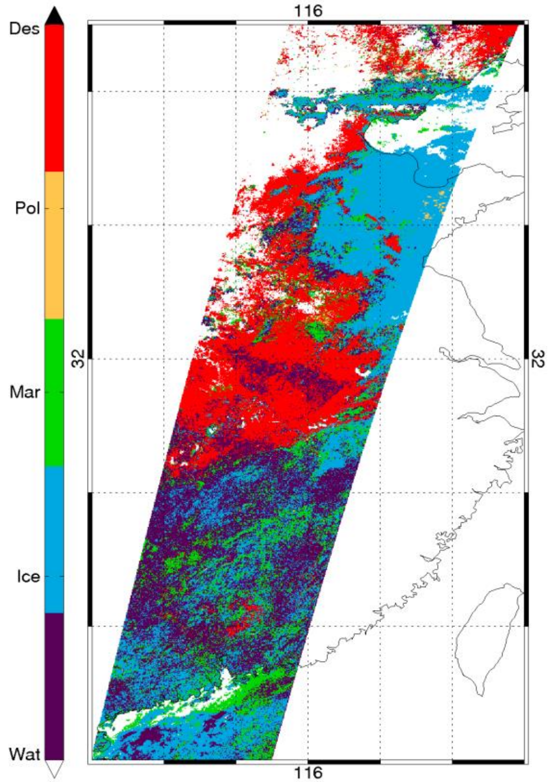
ORAC cloud_cci processor re-run on the scene shown:

- Run with:
  - Water & ice cloud
  - Desert dust (OPAC with a non-spherical coarse mode)
  - Maritime class (OPAC at 80%RH)
  - Polution (OPAC polluted continental)
- Used OPAC rather than aerosol_cci classes because the thermal IR properties needed

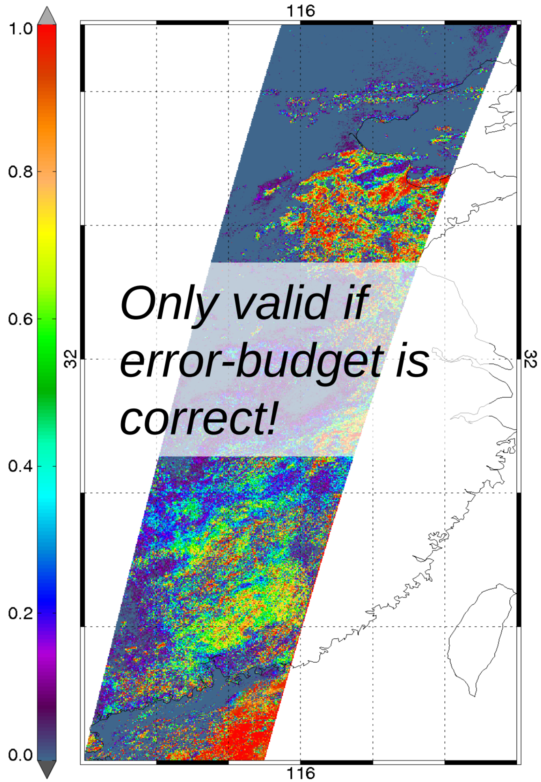
χ^2 results



AATSR false colour

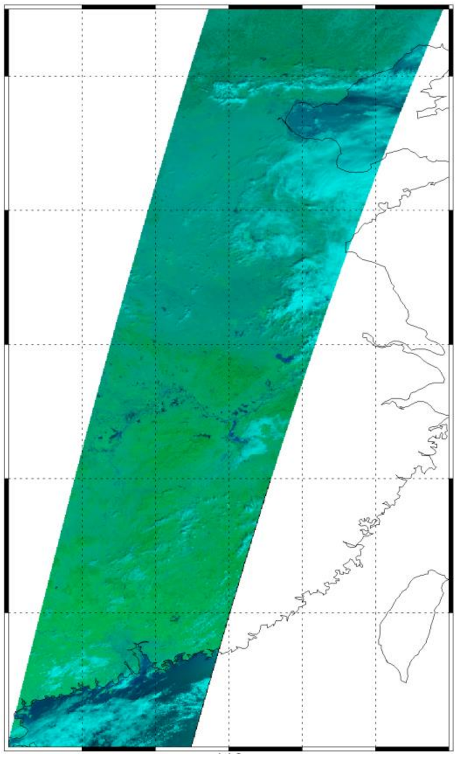


Best-type according to χ^2 test.



χ^2 probability of best-type.

Interpreting the results



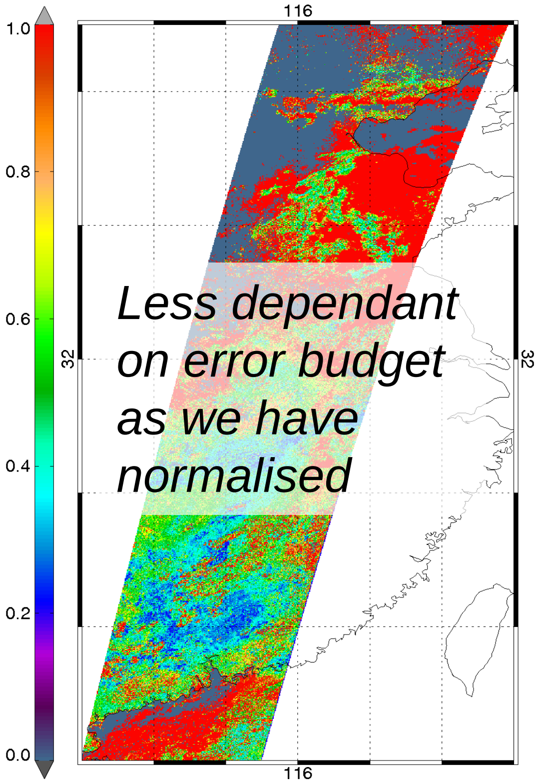
AATSR false colour

Of the available types, how certain are we of the best fitting?

- Normalise the probability:

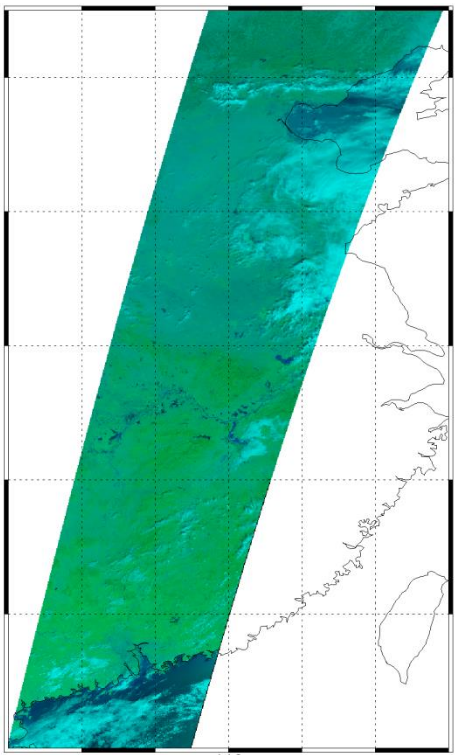
  $P_n = P_b / [\Sigma_i P_i]$

- This can be used as a "cloud mask"

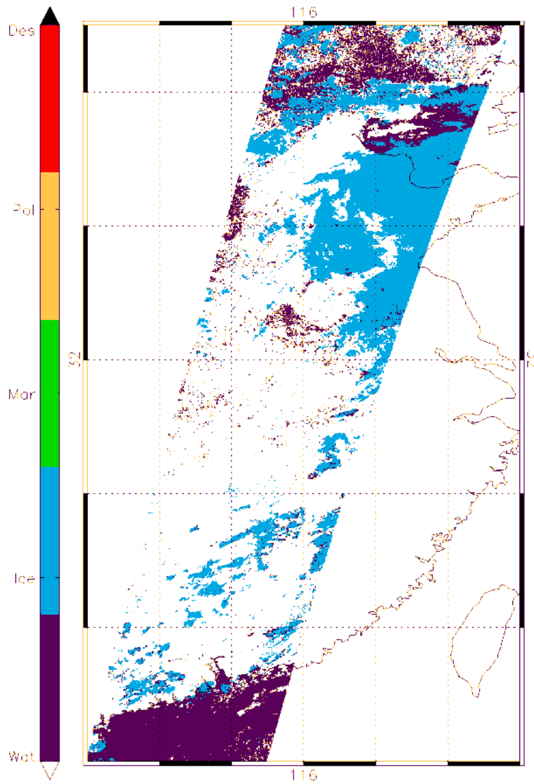


Normalised χ^2 probability of best-type.

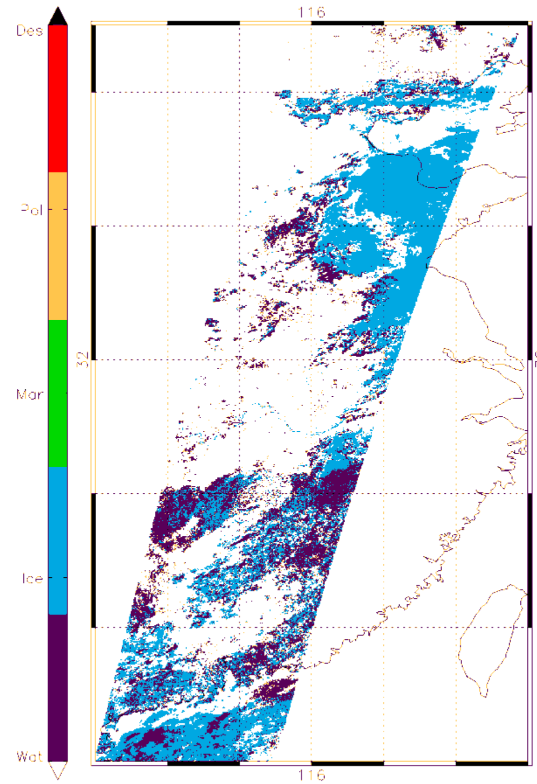
Does it work?



AATSR false colour



Cloud_cci cloud phase



χ^2 cloud phase. Either:

- Pn > 0.75 of water or ice
- Sum of Pn > 0.85 for water and ice

Concluding remarks

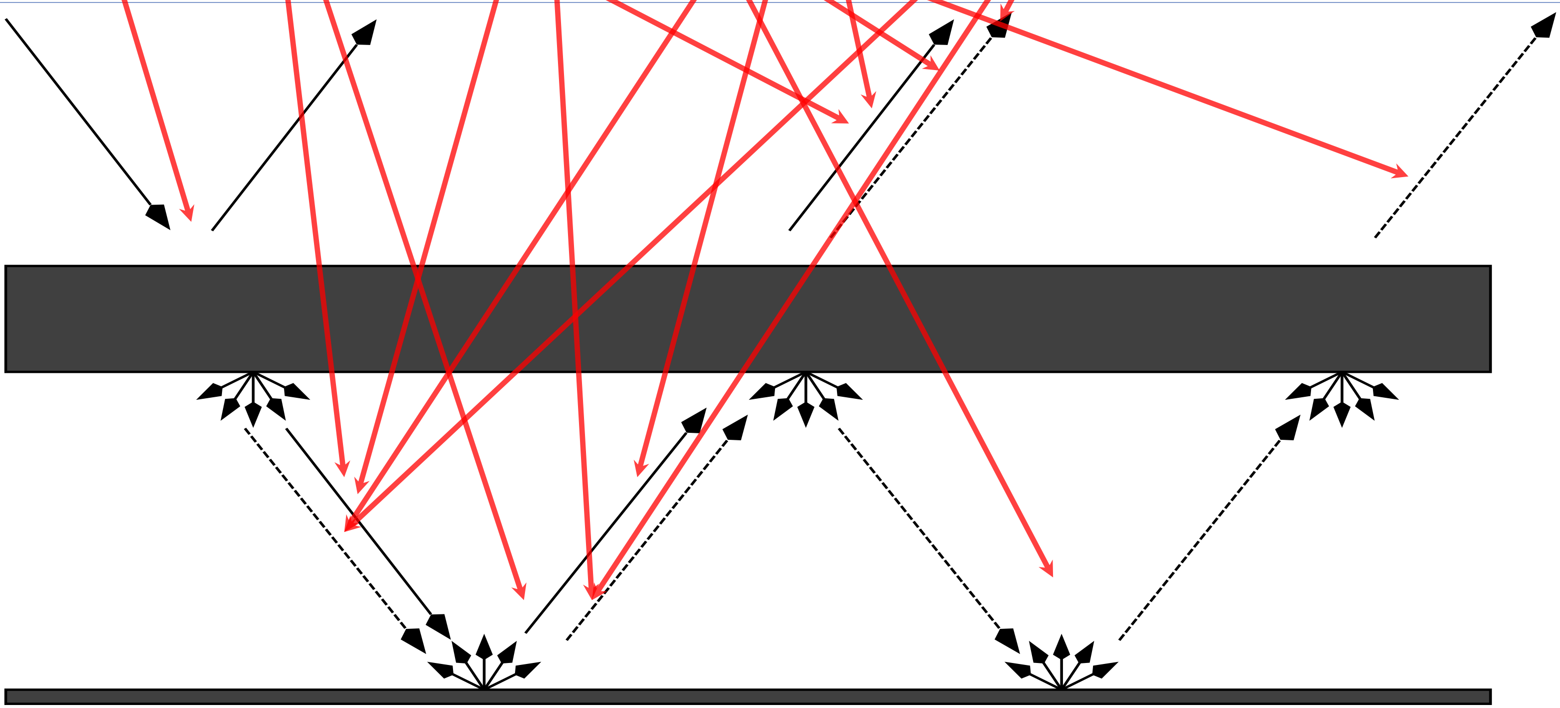
- A lot more work is to be done with the Bayesian scene identification
- The method shows both promise and potential problems. In this case:
  - Is not “tricked” by Chinese haze or sediment laden coastal waters.
    - The latter in particular seems to be a problem with the neural net mask.
  - Can fit very thin water cloud to (what appear to be) some clear sky pixels.
  - We don’t really get a cloud mask.
    - The question we are asking is “is our forward model consistent with observations”?

Extra slides

ORAC surface BRDF treatment

The approach taken is to treat direct and diffuse transmission separately:

$$R_{TOA} = R_{bb} + T_{bb}^{\downarrow}\rho_{bb}T_{bb}^{\uparrow} + T_{bb}^{\downarrow}\rho_{bd}T_{db}^{\uparrow} + T_{bd}^{\downarrow}\rho_{db}T_{bb}^{\uparrow} + T_{bd}^{\downarrow}\rho_{dd}T_{db}^{\uparrow} +$$
$$T_{bb}^{\downarrow}\rho_{bd}R_{dd}\rho_{db}T_{bb}^{\uparrow} + T_{bb}^{\downarrow}\rho_{bd}R_{dd}\rho_{dd}T_{db}^{\uparrow} + T_{bd}^{\downarrow}\rho_{dd}R_{dd}\rho_{db}T_{bb}^{\uparrow} + T_{bd}^{\downarrow}\rho_{dd}R_{dd}\rho_{dd}T_{db}^{\uparrow} +$$
$$\ldots$$



ORAC surface BRDF treatment

- The forward model currently used in ORAC results from making the approximation:

$$T_{bd}{\downarrow}\rho_{db}T_{bb}{\uparrow} + T_{bd}{\downarrow}\rho_{dd}T_{db}{\uparrow} \approx T_{bd}{\downarrow}\rho_{dd}T_{tb}{\uparrow}$$

where $T_{tb}{\uparrow} = T_{bb}{\uparrow} + T_{db}{\uparrow}$ is the total transmission of the atmosphere in the viewing direction.

- Applying this approximation, collecting terms and applying a series limit, results in:

$$R_{TOA} = Rbb + T_{bb}{\downarrow}(\rho_{bb}-\rho_{dd})T_{bb}{\uparrow} + \frac{(T_{bb}{\downarrow}\rho_{bd} + T_{bd}{\downarrow}\rho_{dd})\, T_{db}{\uparrow}}{1-\rho_{dd}R_{dd}}$$

ORAC surface BRDF treatment

- The constraints required to define the different surface reflectance terms (and the wavelength variation in surface reflectance, for single view retrievals) come from the a priori value
- Thus, we need a way of setting an a priori surface reflectance that includes an accurate representation of the BRDF
- LAND: MODIS BRDF (MCD43B)
- OCEAN: An sea surface reflectance model, incorporating:
  - reflectance off wave slopes from Cox and Munk statisitics + ECMWF 10m wind components
  - whitecap reflectance (again as a function of 10m wind)
  - volumetric scattering, using chlorophyll-a and CDOM products from GlobCOLOUR
  - Sayer et al., Atmos. Meas. Tech., 3, 813-838, 2010.

The Swansea-style forward model

- The Swansea forward model consists of two parts:
  - An equation for the surface reflectance, as a function of 6 model parameters (for AATSR) and the diffuse fraction of downwelling radiance:

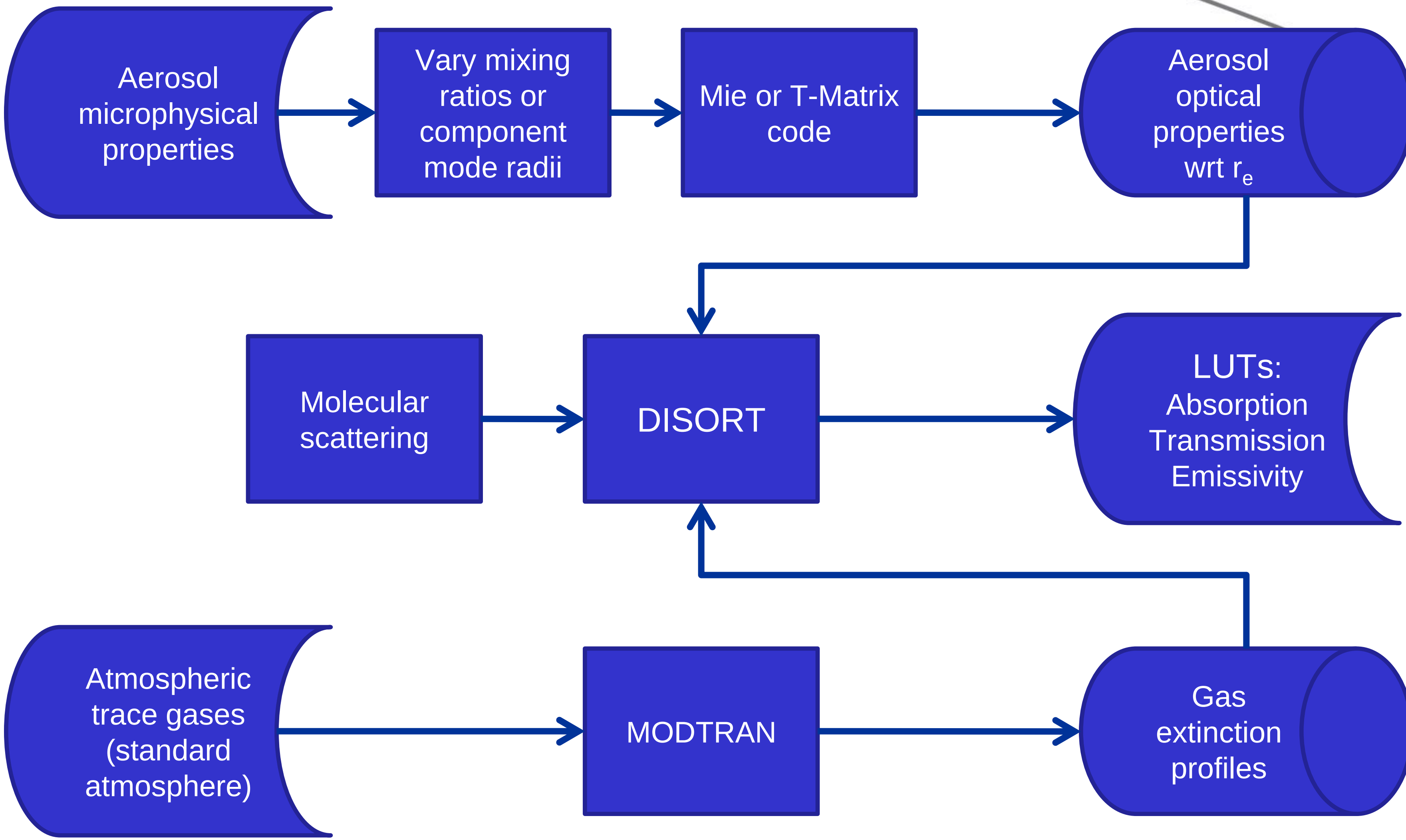
$$
\begin{aligned}
R_{\mathrm{surf}}(\lambda, \boldsymbol{\omega}) &= (1 - D(\lambda))\left[P(\boldsymbol{\omega})s(\lambda) + \frac{g\gamma s(\lambda)}{1-g}\right] + D(\lambda)\frac{\gamma s(\lambda)}{1-g} \\
g &= (1-\gamma)s(\lambda)
\end{aligned}
$$

  - The standard equation for TOA radiance widely used in aerosol and cloud retrieval algorithms:

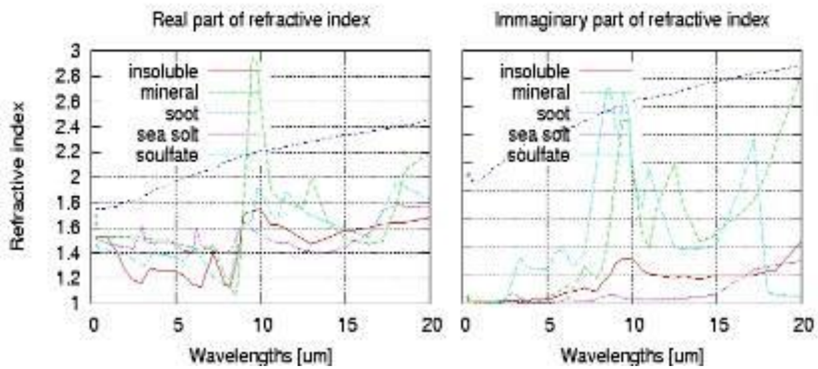
$$
R_{\mathrm{toa}} = R_{\mathrm{atm}}(\tau, r_e, \boldsymbol{\omega}_{\mathrm{s}}, \boldsymbol{\omega}_{\mathrm{v}}) + \tilde{T}(\tau, r_e, \boldsymbol{\omega}_{\mathrm{s}}, 2\pi)\frac{R_{\mathrm{surf}}}{1 - R_{\mathrm{surf}} R_{\mathrm{atm}}(\tau, r_e, 2\pi, 2\pi)}\tilde{T}(\tau, r_e, 2\pi, \boldsymbol{\omega}_{\mathrm{v}})
$$

Grey, W.M.F., P.R.J. North, S.O. Los: Appl. Opt., 45(12) 2786-2795, 2012

Aerosol models



Aerosol models



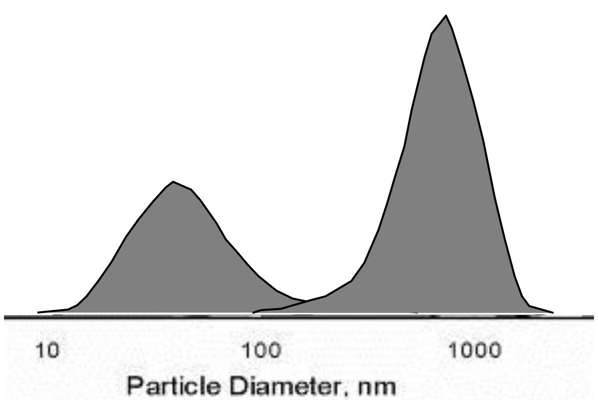
$$N(r) = \frac{C}{ln(\sigma) r \sqrt{2\pi}} exp\left\{ -\frac{[log(r/r_m)]^2}{2ln^2(\sigma)} \right\}$$

Every component is characterized by:

Spectral refractive index
$n(\lambda) + i\,k(\lambda)$

Mode radius r_m and spread σ log normal size distribution by number

Aspect ratio distribution



Changing the mixing ratio between components we obtain the optical properties corresponding to different effective radii

$$r_e = \frac{\int_0^\infty r^3 n(r) dr}{\int_0^\infty r^2 n(r) dr}$$

$K_{ext}(\lambda)$

$0 < \omega(\lambda) < 1$

$P(\theta,\lambda)$