Assimilating visible radiances to constrain aerosol properties in the ECMWF Integrated Forecast System: The ARAS project

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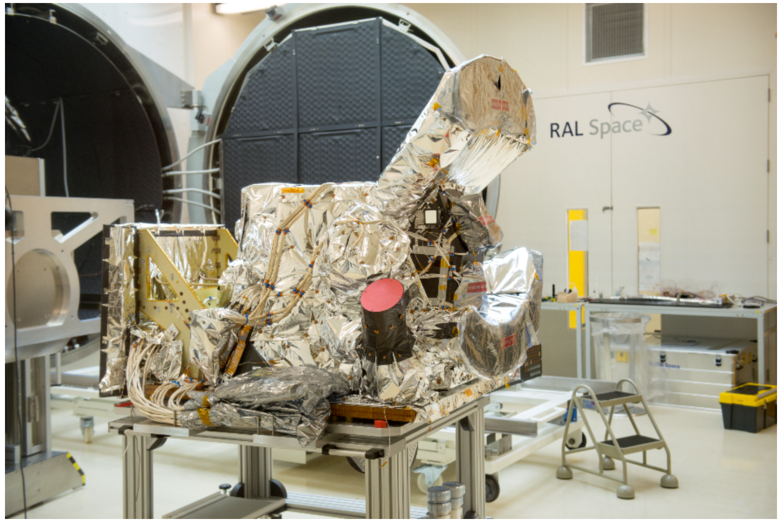
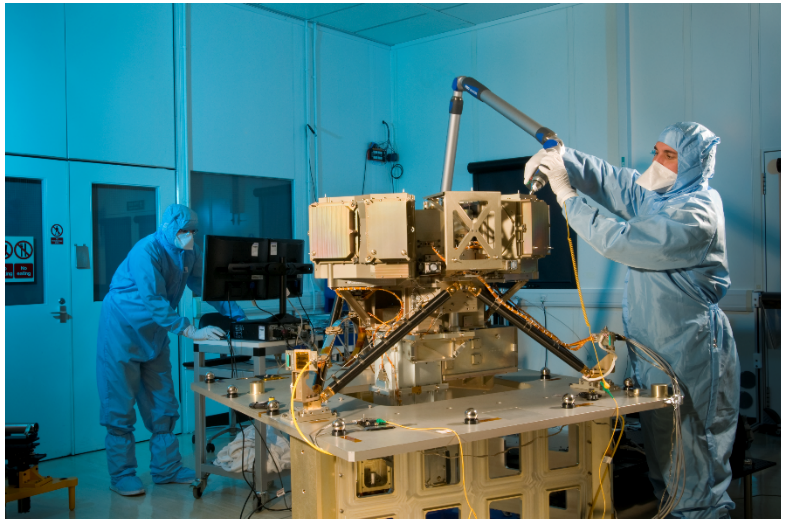




Introduction

- The Aerosol Radiance Assimilation Study was a ESA funded project to investigate the use of satellite radiances, rather than retrieved AOD, to constrain aerosol properties in the ECMWF's Integrated Forecast System (IFS).
- The IFS has been operationally assimilating AOD derived from MODIS (and also, more recently, the P-MAP product) for over a decade.
- ARAS introduced a fast forward-operator, derived from the Optimal Retrieval of Aerosol and Cloud (ORAC) retrieval scheme, into the IFS, which allows the model to estimate aerosol-affected top of atmospheric radiances from its state.
- This system was tested using the IFS 4D-Var assimilation system, and was shown provide similar performance to a 2-wavelength AOD assimilation.

Scientific motivation

AOD assimilation

vs

Radiance assimilation

- New satellites and retrievals continue to appear – difficult to characterize the relative uncertainties of AOD products. Using radiances could be more straightforward (once implemented).
- So far, only AOD has been assimilated, constraining column aerosol loading; adding constraint to other aerosol parameters should also be easier with radiances.
- The error characterization of radiances is easier than that of products and assimilation assumptions are all consistent (i.e. the same aerosol model is used from emissions to TOA radiances)

Technical challenges

Direct assimilation of aerosol-sensitive radiances in an **online 4D-Var system** has never before been successfully implemented

- For radiance assimilation, a radiative transfer model is needed to convert the model state into top-of-atmosphere radiance.
  - IFS uses RTTOV for thermal-IR radiance generation.
  - RTTOV is *not yet* capable of producing accurate visible radiances, including multiple scattering from aerosol or cloud, fast enough for operational assimilation.

For the IFS, ARAS represents the first time that:

… dual control variable is used for AOD

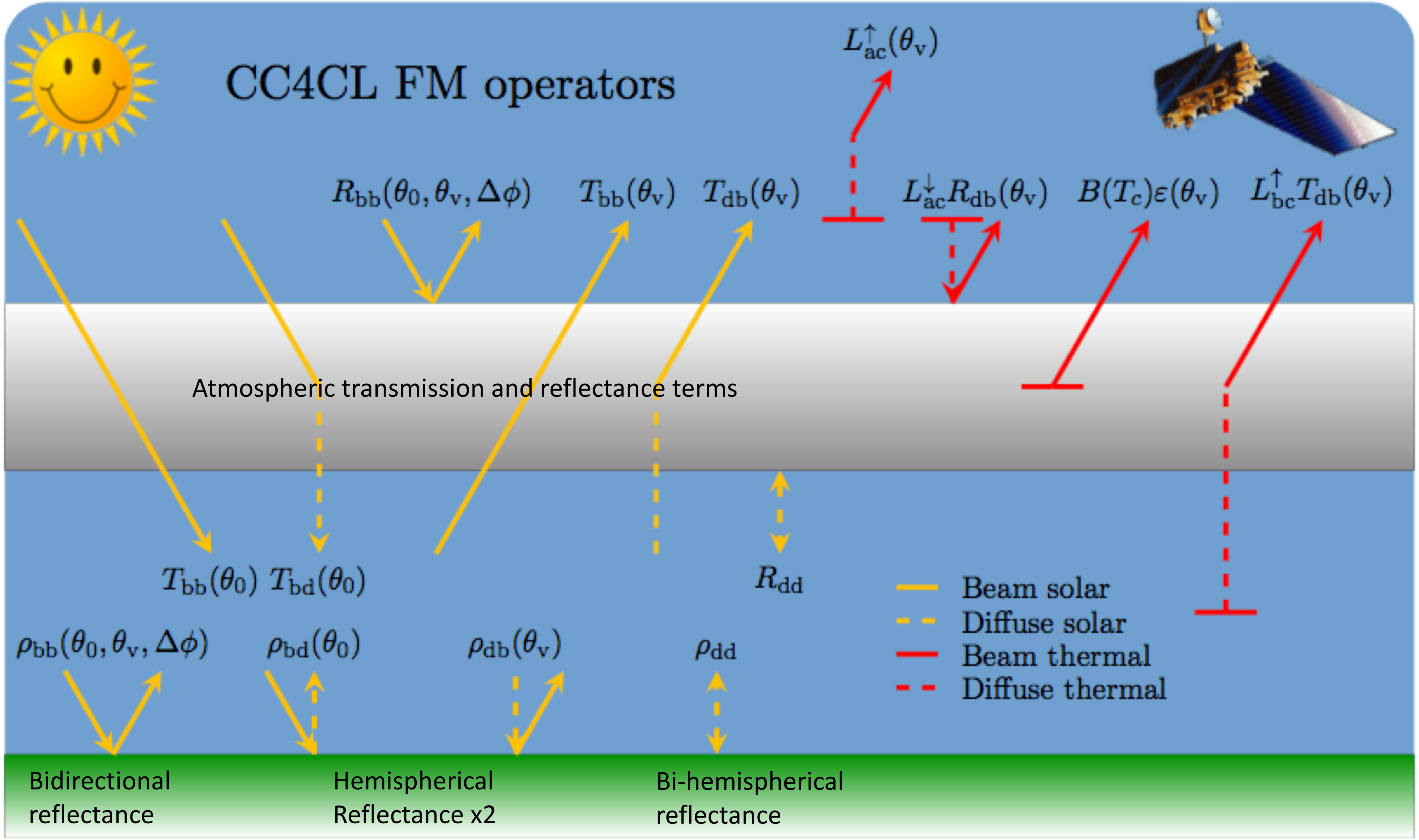
… visible wavelength radiances are assimilated

Radiative Transfer Model in the visible:
Observation operator
(Forward / Tangent-Linear / Adjoint)

Data and tools

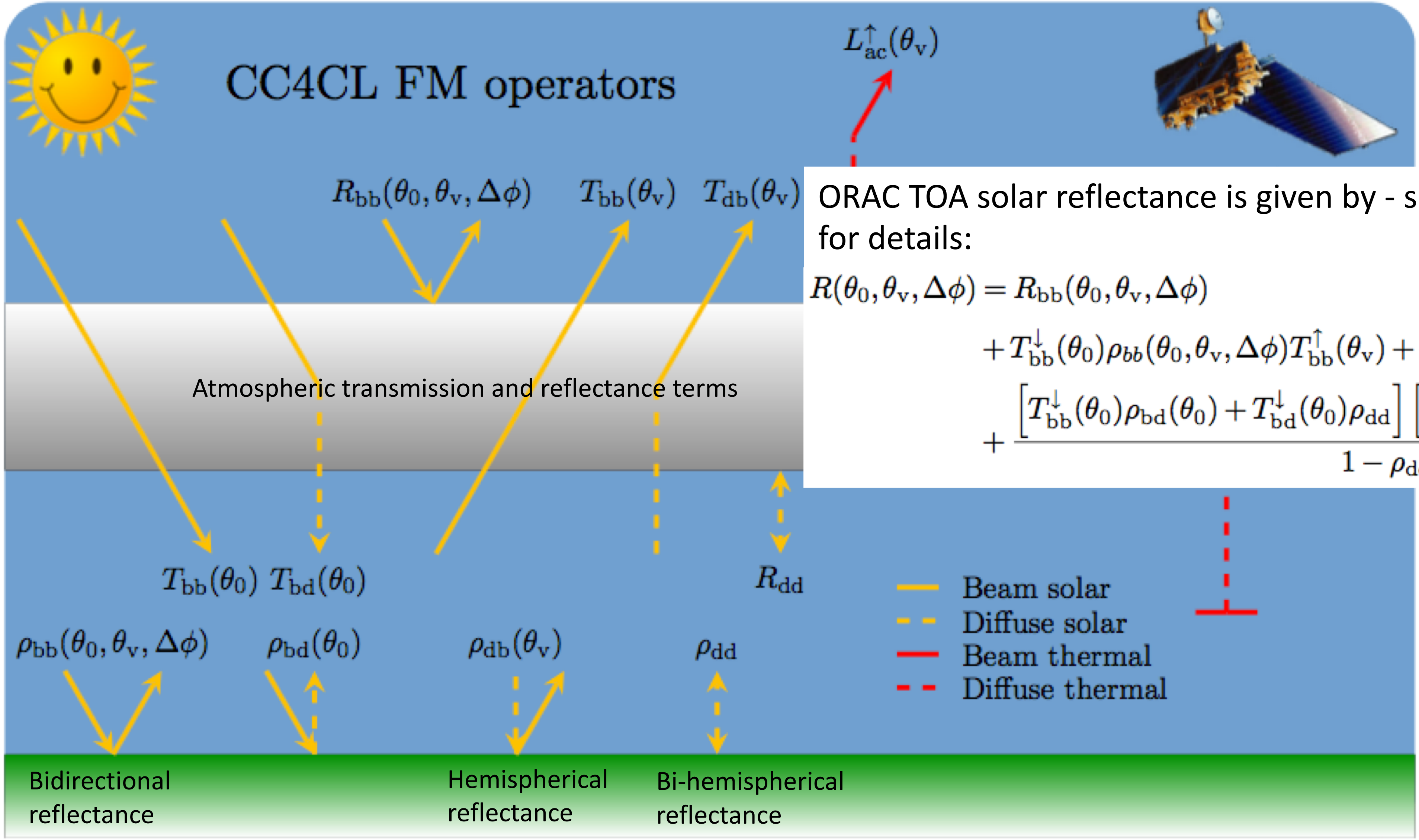
- The assimilation system is the ECMWF Integrated Forecast System 4D-Var in "composition configuration" (ie. Similar to the model used for Copernicus Atmospheric Monitoring Service, CAMS).
  - A dual control variable is used for AOD assimilation (CAMS using a single variable).
  - Dual control variable also used for reflectances, ocean surface reflectance model and land surface reflectance atlas.
- Aerosol data is MODIS Aqua and Terra collection 6 (Levy et al. 2013).
  - AODs at wavelengths of 670 and 866 nm.
  - Level-2 (regridded and cloud-cleared) radiances at 670 and 866 nm.
  - These data were already available in the ECMWF buffer system used for IFS assimilation.
- Radiative transfer model: Optimal Retrieval of Aerosol and Cloud (ORAC) forward model, developed at RAL and University of Oxford (McGarragh et al. 2018).
  - Lookup tables of atmospheric transmission and reflectance, produced from DISORT
  - BRDF surface reflectance treatment

The ORAC-RT scheme



- ORAC handles both reflected solar radiation and the thermal IR.
  Only solar radiation considered in ARAS.
- Surface BRDF is handled by 4 reflectance terms.
- For aerosol modelling, fixed pressure, temperature and gaseous composition profile is assumed.
- Aerosol has a fixed vertical distribution, aerosol column mixing ratio and composition are variable.

The ORAC-RT scheme



ORAC TOA solar reflectance is given by - see McGarragh et al. (2018) for details:

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

Adapting ORAC RT to IFS

Adapting the ORAC forward model to work as a observation operator in a model (like IFS) presents a few problems:

1. The model describes aerosol as mass concentrations of a number of aerosol components, rather than having a set of pre-defined “types”, as used by the ORAC retrieval scheme.
2. No simple parameterisation of the aerosol size distribution is carried around by the model, while ORAC characterises aerosol by optical depth and effective radius.
3. The model components (both aerosol and background atmospheric) vary vertically, as well as horizontally.

Adapting ORAC RT to IFS

- A simple approach was adopted to adapt the ORAC LUT approach to the IFS:
- LUTs are parameterised in terms of column averages of the bulk aerosol scattering properties carried around by the IFS:
  - Extinction coefficient
  - Single scattering albedo
  - Asymmetry parameter
- As with the retrieval forward-model, LUTs are calculated using a standard, fixed, background atmosphere:
  - The observation operator is decoupled from the background model atmosphere.
- This approach is computationally fast, relatively simple to implement (including tangent-linear and adjoint variants of the operator needed by IFS) and avoids any explicit dependence on aerosol composition in the LUTs.

Surface reflectance

- This could be said to be the “elephant in the room” for aerosol radiance assimilation.
  - TOA radiance is strongly dependent on the surface reflectance, especially over bright land surfaces.
  - Accurate modelling of, or correction for, the surface reflectance is one of the key elements to any aerosol retrieval.
- Over the ocean, ARAS used the wind-driven ocean surface reflectance model from RTTOV (bi-directional), with simple estimates of hemispheric reflectances (for speed).
  - Ocean colour not included.
- Over land, ARAS used the surface BRDF atlas provided by RTTOV.

Radiance data issues

- It was hoped that the level-2 MODIS reflectances used in the study would be “ready-to-go”:
  - They are already in the buffer system used by IFS to import observational data for assimilation.
  - They were expected to be cloud-cleared and consistent with the corresponding level-2 AOD data; essentially being the radiances feed into the AOD retrieval.
- However, two issues were encountered:
  1. Sun-glint was present in the level-2 radiances

     Dealt with by the implementation of a simple glint screening step.
  2. There was a significant positive bias in the radiance data compared to the model first guess – cloud contamination?

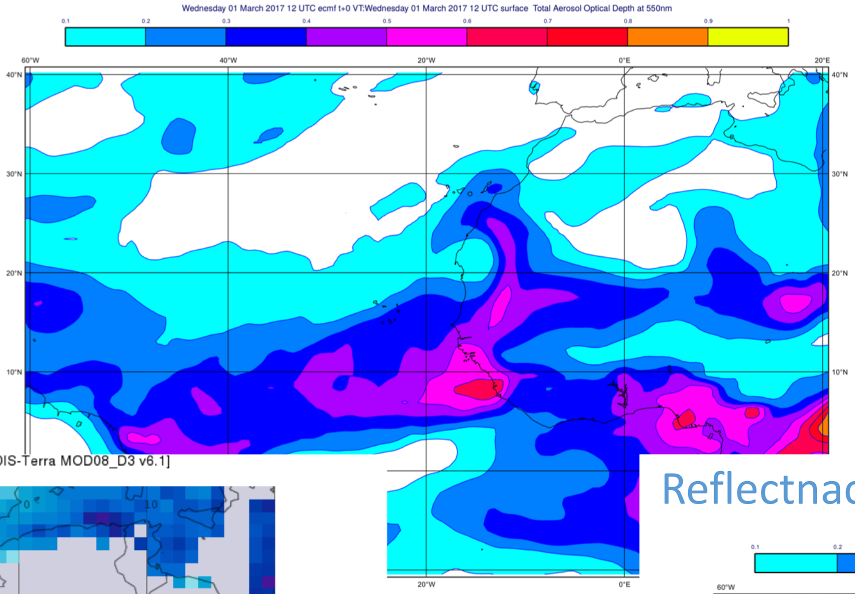
     IFS’s existing bias correction mechanisms were able to correct for this – not yet in an optimised way however!

Assimilation experiments

- A total of four separate model experiments were performed:
    1. Northern summer 2017 (16 May – 31 Aug) ocean only
    2. Northern summer 2017 (16 May – 31 Aug) ocean and land
    3. Northern autumn 2017 (16 Aug – 30 Nov) ocean only
    4. Northern autumn 2017 (16 Aug – 30 Nov) ocean and land
- For each experiment the model was run globally with a 16-day spin-up, in the following configurations:
    1. Control run - no aerosol assimilation
    2. Dual control variable AOD (at 670 and 866 nm) assimilation
    3. Dual control variable radiance (at 670 and 866 nm) assimilation

…for a total of 10 model runs.

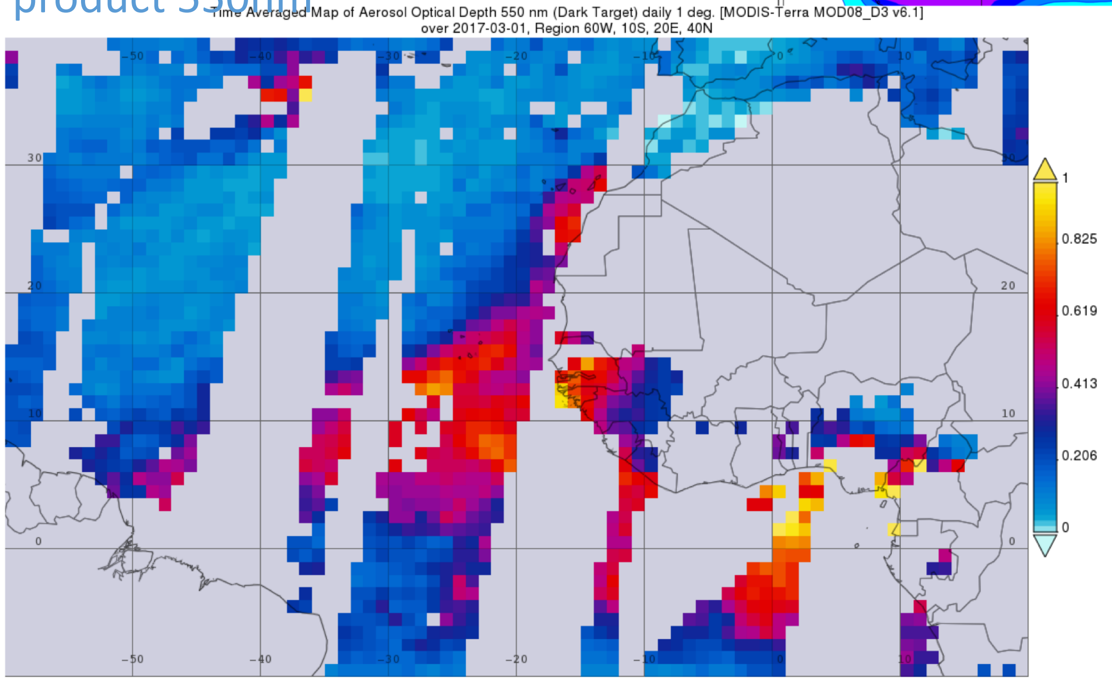
Reflectance analysis example after 1 cycle



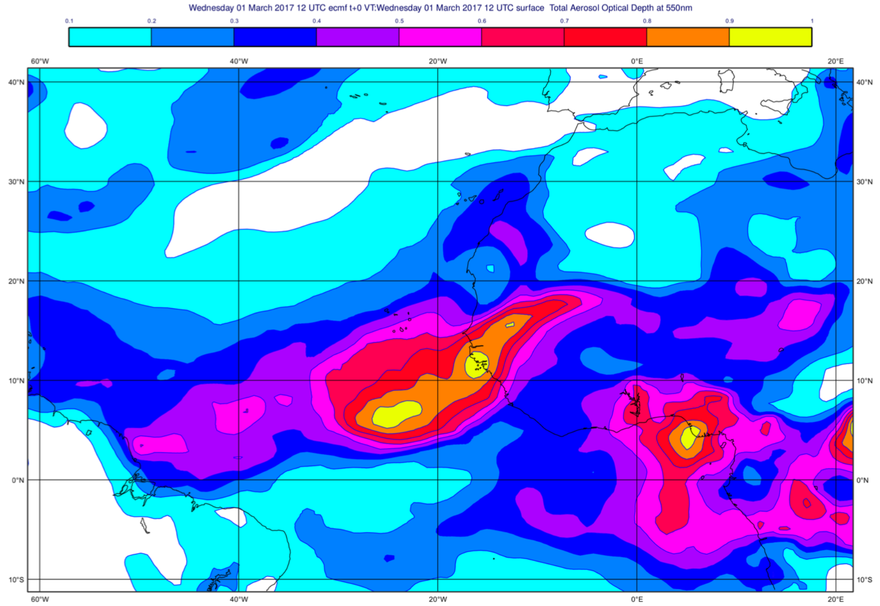
Model control run AOD

Reflectance assimilation certainly appears to improve model AOD estimate!

MODIS AOD product 550nm



Reflectnace assimilation AOD (after 1 cycle)

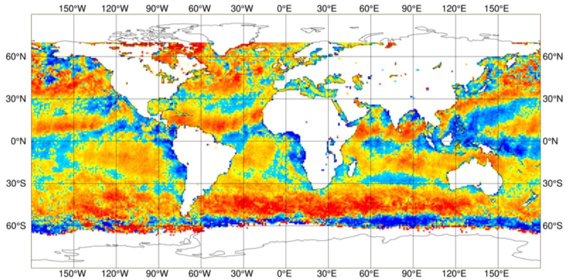


Model bias corrections

Bias corrections applied at 675nm

STATISTICS FOR ODA FROM TERRA/MODIS
MEAN BIAS CORRECTION (USED)
DATA PERIOD = 2017-05-15 21 - 2017-08-31 21
EXP = HAMI, LEVEL = 6.00 - 7.00 HPA
Min: 0.001 Max: 0.016 Mean: 0.011
GRID: 1.00x 1.00

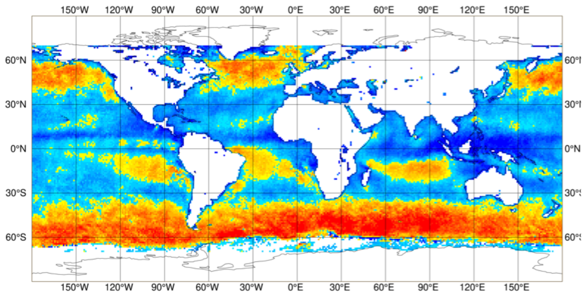
Summer



Colour-bar range: 0.0005-0.0163

STATISTICS FOR ODA FROM TERRA/MODIS
MEAN BIAS CORRECTION (USED)
DATA PERIOD = 2017-08-15 21 - 2017-11-30 21
EXP = HAZF, LEVEL = 6.00 - 7.00 HPA
Min: 0.001 Max: 0.021 Mean: 0.014
GRID: 1.00x 1.00

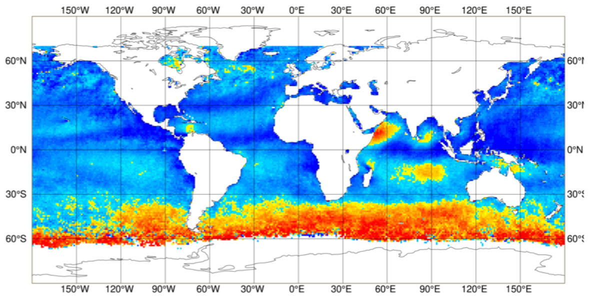
Autumn



Colour-bar range: 0.0010-0.0214

STATISTICS FOR RFA FROM TERRA/MODIS
MEAN BIAS CORRECTION (USED)
DATA PERIOD = 2017-05-15 21 - 2017-08-31 21
EXP = HB3K, LEVEL = 6.00 - 7.00 HPA
Min: 0.005 Max: 0.063 Mean: 0.029
GRID: 1.00x 1.00

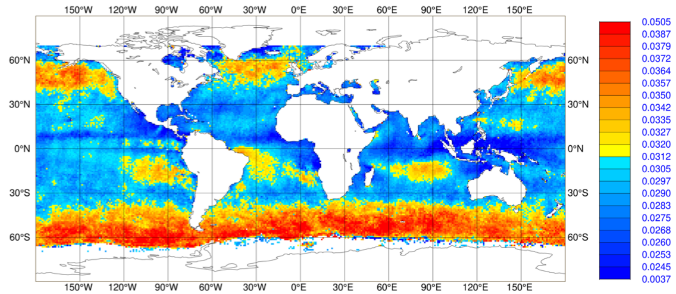
Summer



Colour-bar range: 0.0043-0.0637

STATISTICS FOR RFA FROM TERRA/MODIS
MEAN BIAS CORRECTION (USED)
DATA PERIOD = 2017-08-15 21 - 2017-11-30 21
EXP = HB3T, LEVEL = 6.00 - 7.00 HPA
Min: 0.004 Max: 0.050 Mean: 0.030
GRID: 1.00x 1.00

Autumn



Colour-bar range: 0.0037-0.0505

AOD run **Reflectance run**

- The bias corrections applied to observations in the radiance assimilation are larger than those for AOD.
- Largest corrections are needed at high latitudes
  - Cloud contamination in observations?
  - Modelled surface reflectance too low?

Validation metrics

- Mean Bias Error (BE or Bias): captures the average deviations between model, c, and observations, o. It has the units of the variable. Values near 0 are the optimal, negative values indicate underestimation and positive values indicate overestimation.

$$BE = \frac{1}{n}\sum_{i=1}^{n}(c_i - o_i)$$

- Root Mean Square Error (RMSE): is strongly dominated by the large values, due to the squaring operation.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(c_i - o_i)^2}$$

- Correlation coefficient (r): indicates the extent to which patterns in the model match those in the observations.

$$r = \frac{\sum_{i=1}^{n}(c_i - \bar{c})\cdot(o_i - \bar{o})}{\sqrt{\sum_{i=1}^{n}(c_i - \bar{c})^2}\cdot\sqrt{\sum_{i=1}^{N}(o_i - \bar{o})^2}}$$

- Fractional Gross Error (FGE): is a measure of model error, behaves symmetrically with respect to under- and overestimation, without over emphasizing outliers.

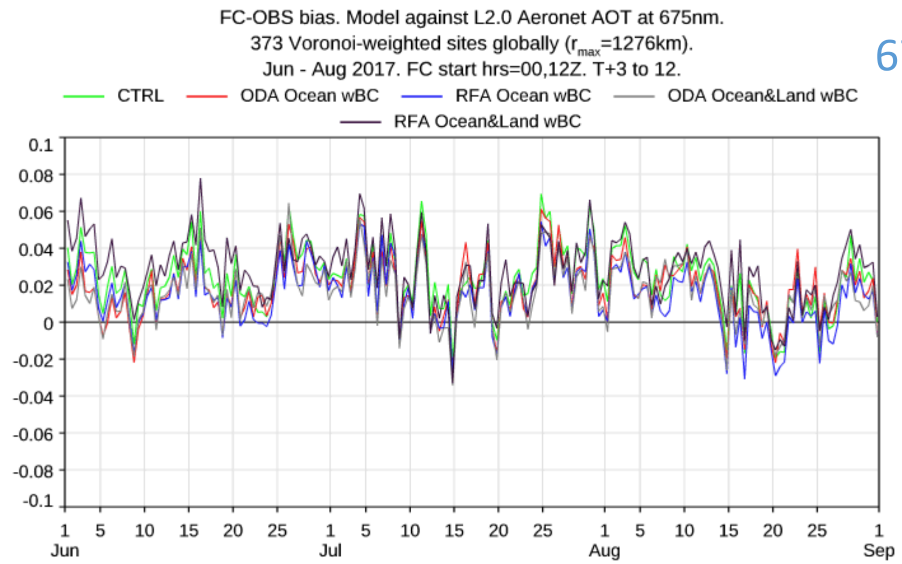
$$FGE = \frac{2}{n}\sum_{i=1}^{n}\left|\frac{c_i - o_i}{c_i + o_i}\right|$$

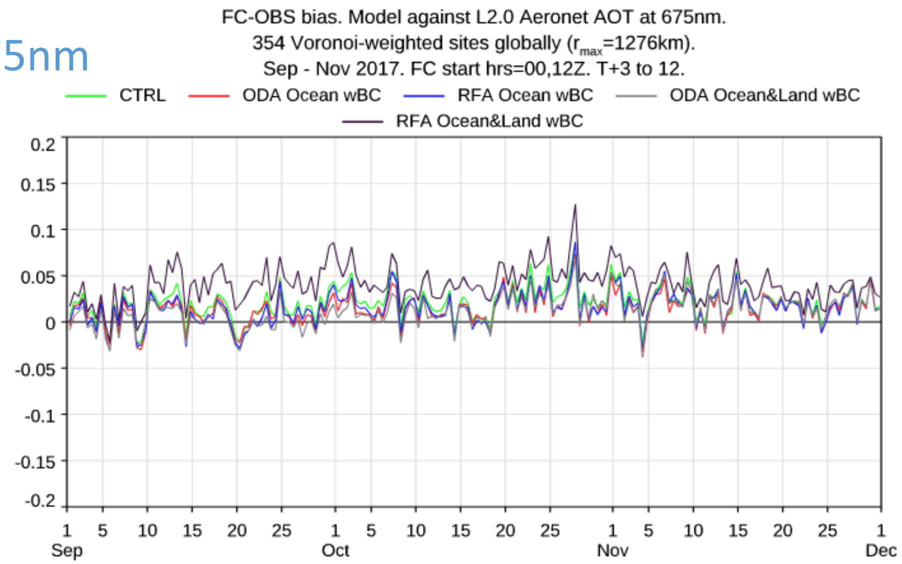
- Modified Normalized Mean Bias (MNMB): is normalized by the mean of the observed and modelled values.

$$B'_n = \frac{2}{N}\sum_{i}\left(\frac{f_i - o_i}{f_i + o_i}\right)$$

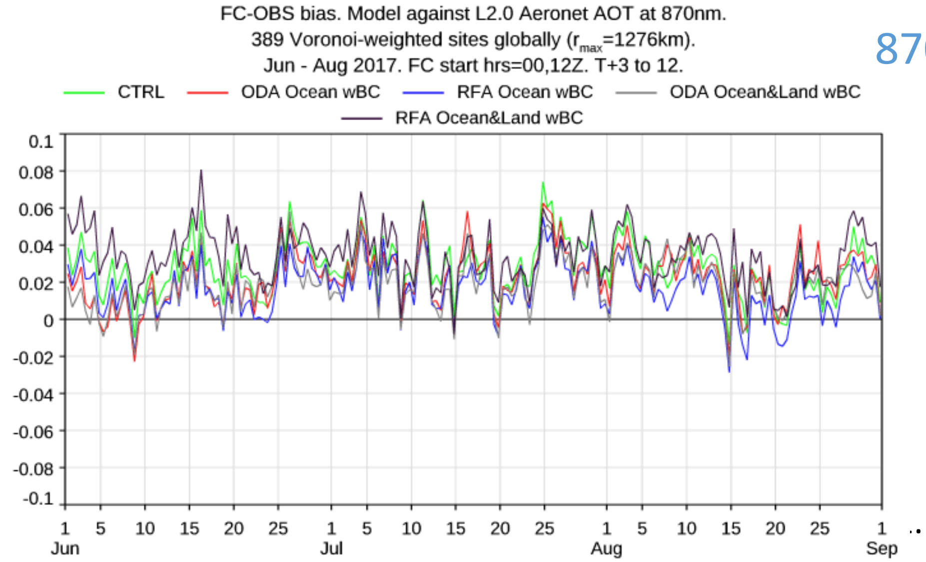
Analyses vs AERONET AOD - BIAS

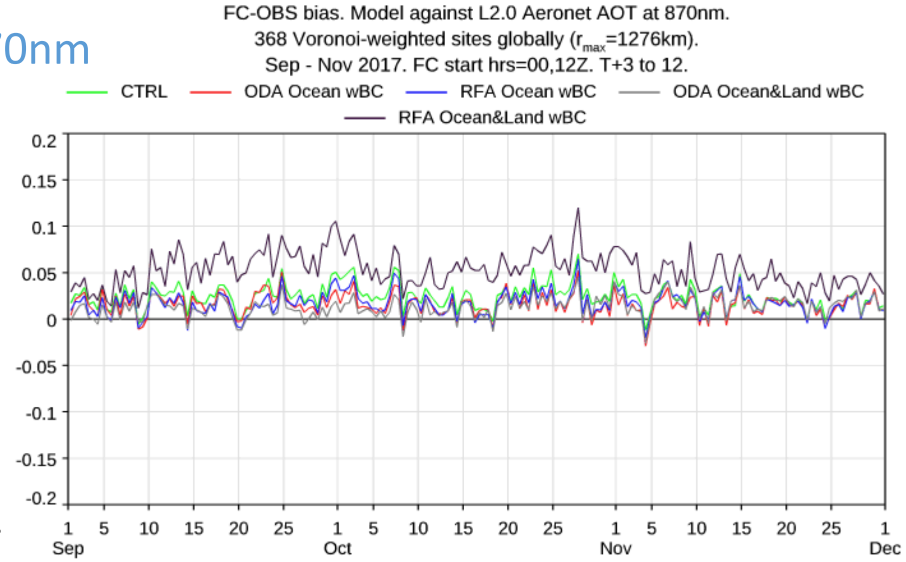
675nm





870nm

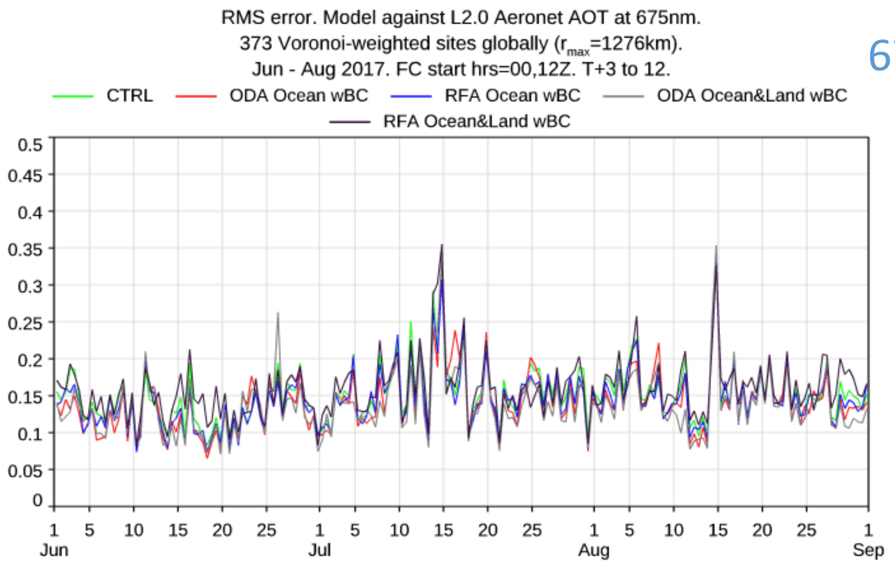


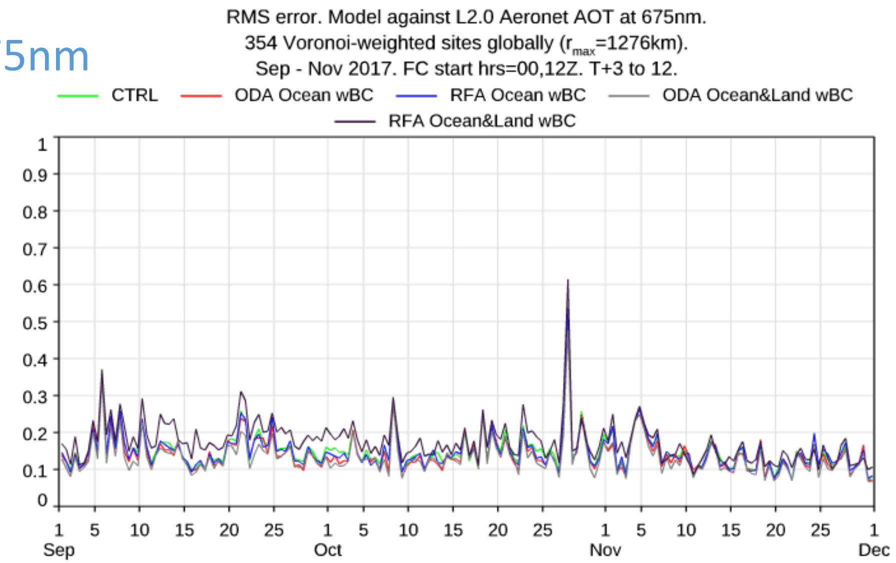


The assimilation of reflectance (RFA) over ocean is comparable to that of AOD in terms of bias.
RFA over Ocean & Land performs clearly the worst.

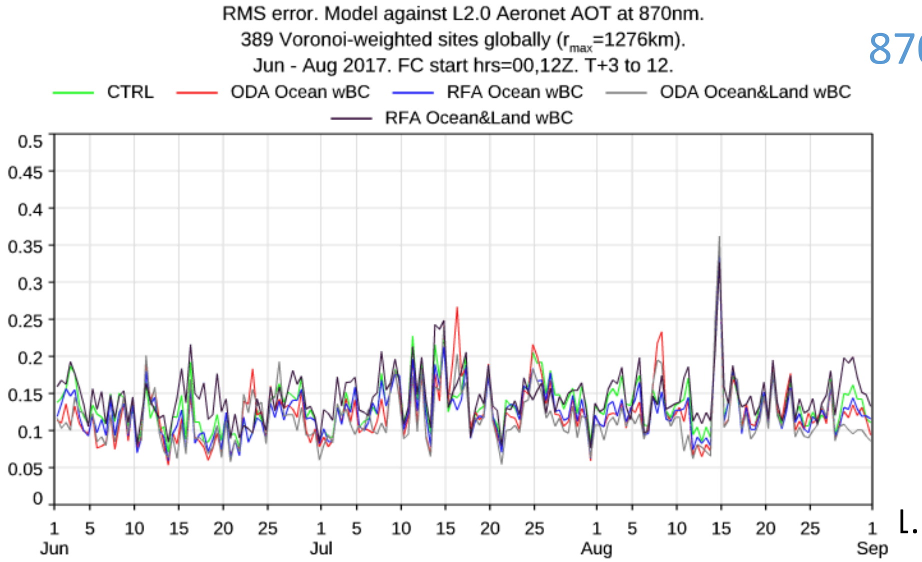
Analyses vs AERONET AOD - RMSE

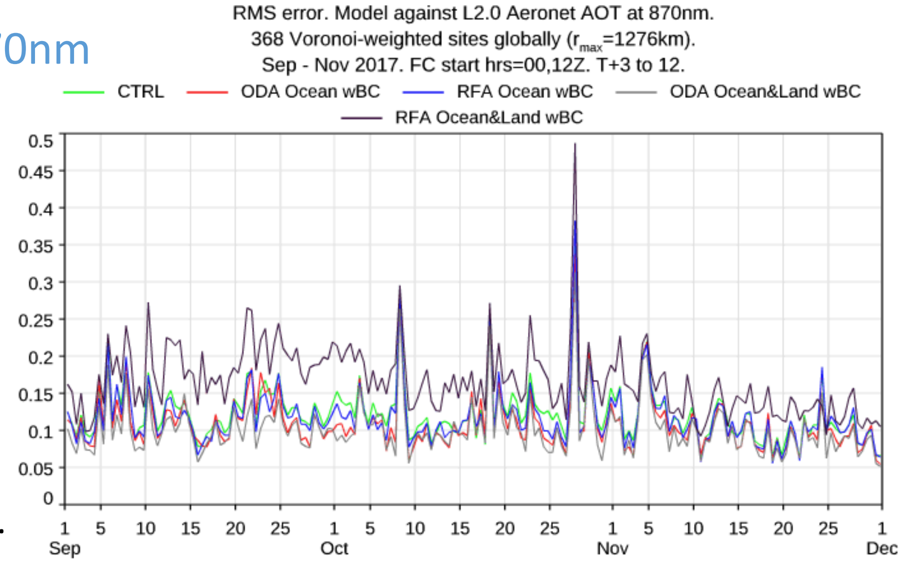
675nm





870nm

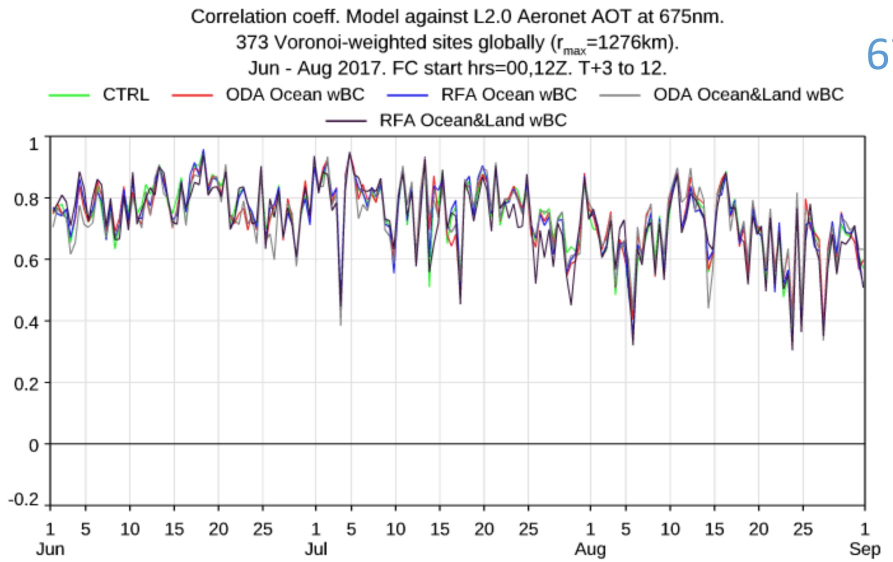


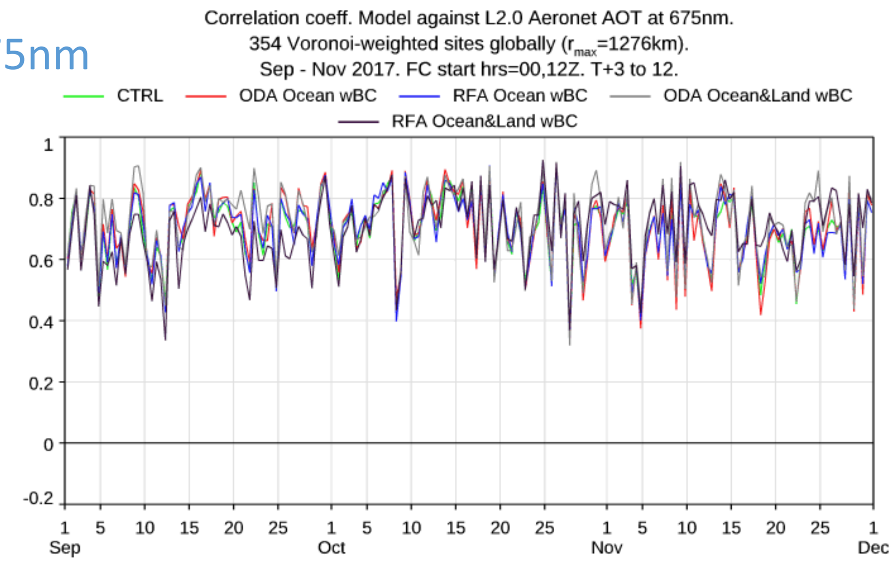


Mixed behaviour with slight advantage for AOD in terms of RMSE. Biggest error corresponds to RFA Ocean & Land.

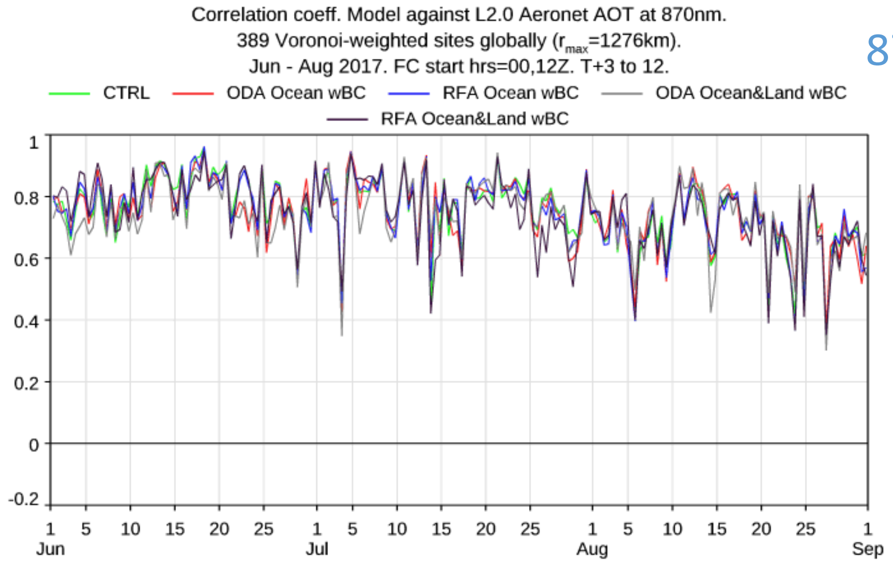
Analyses vs AERONET AOD - Correlation

675nm





870nm



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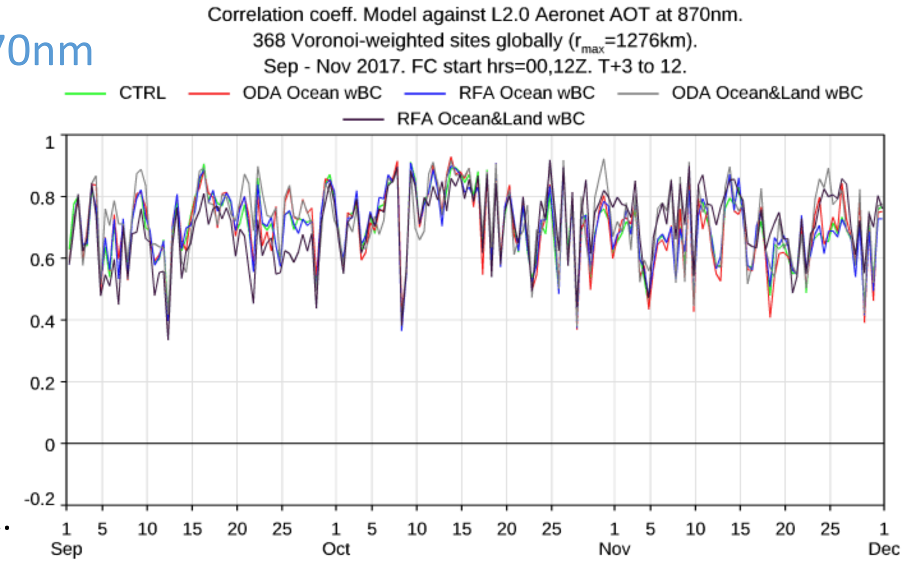
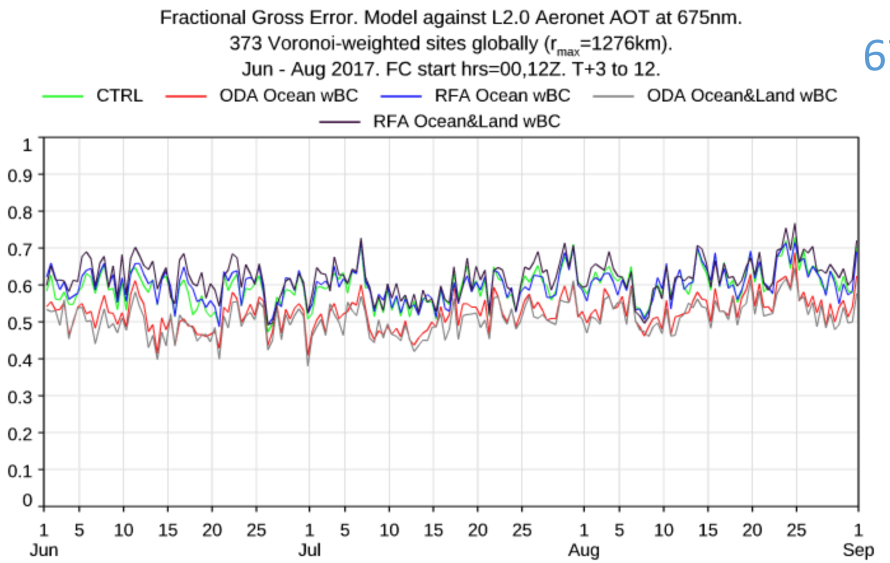
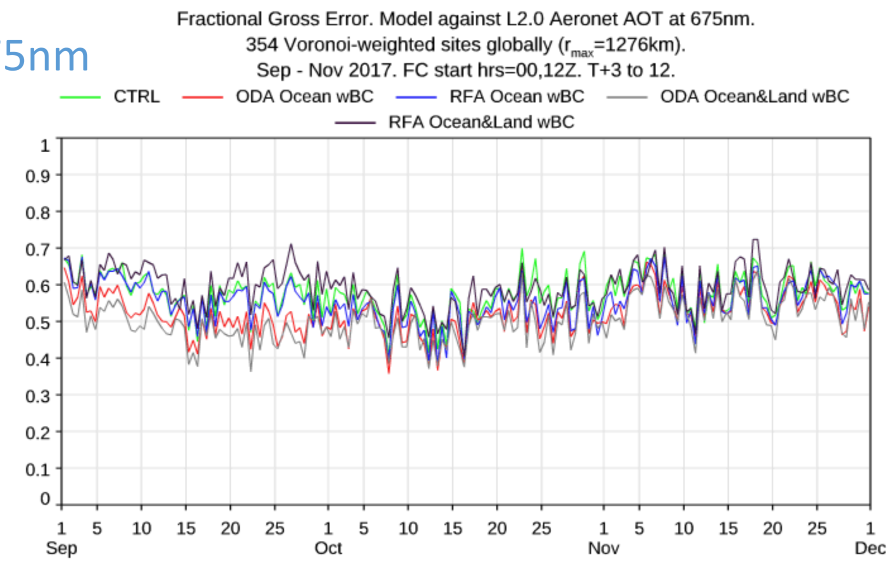


No significant differences in terms of correlation.

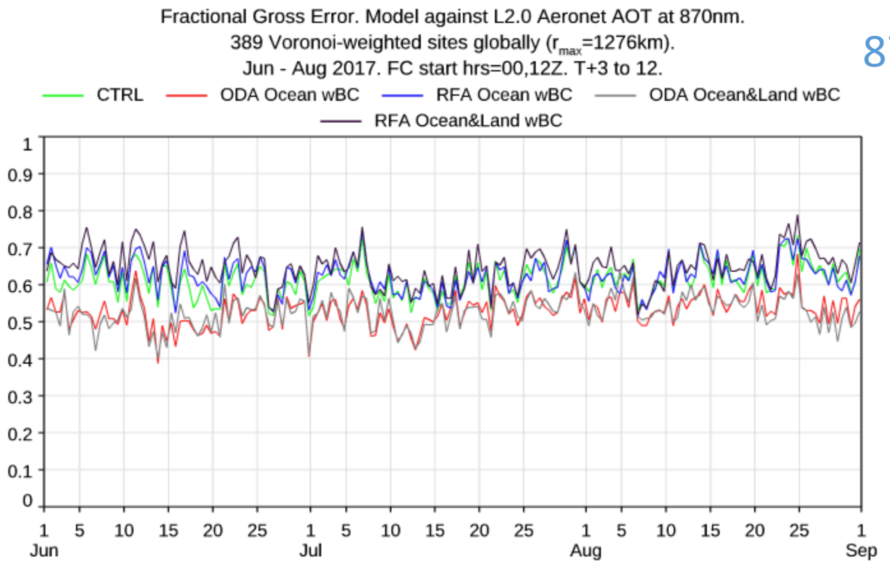
Analyses vs AERONET AOD - FGE

675nm





870nm



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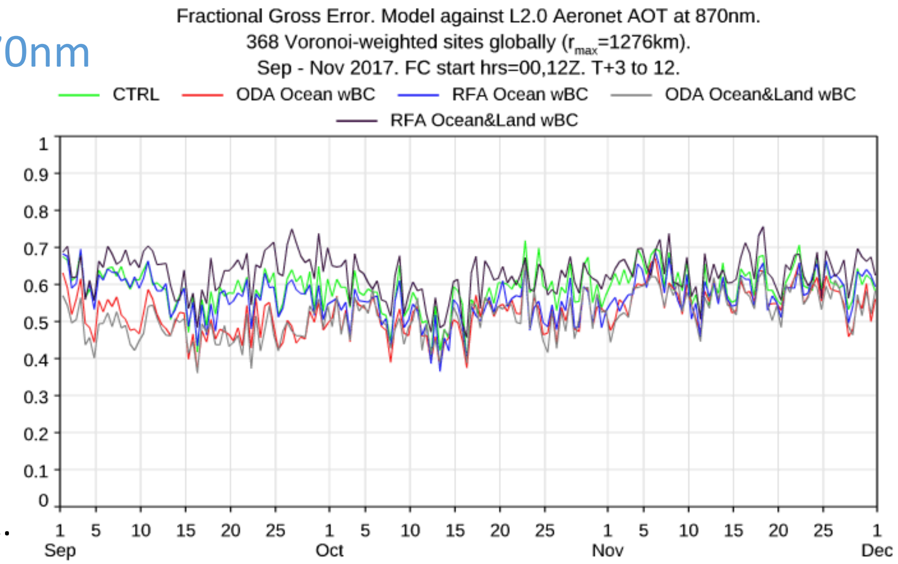
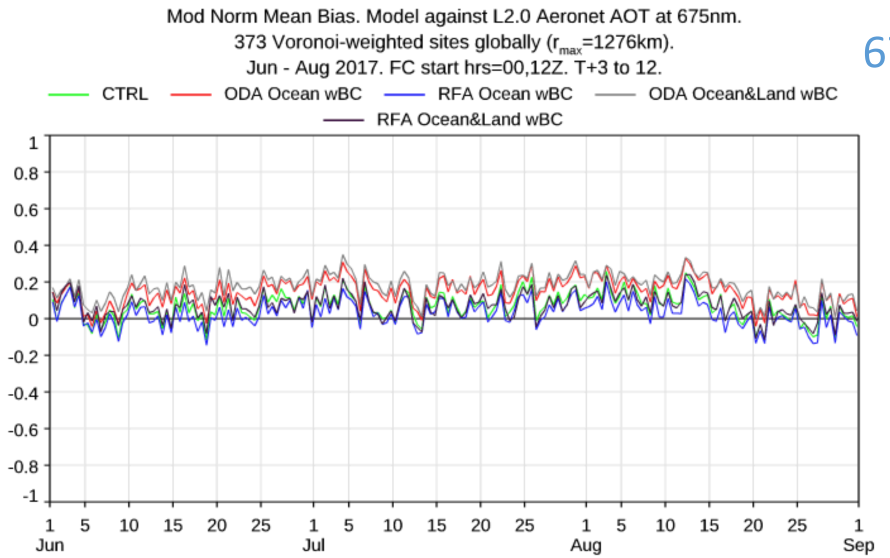
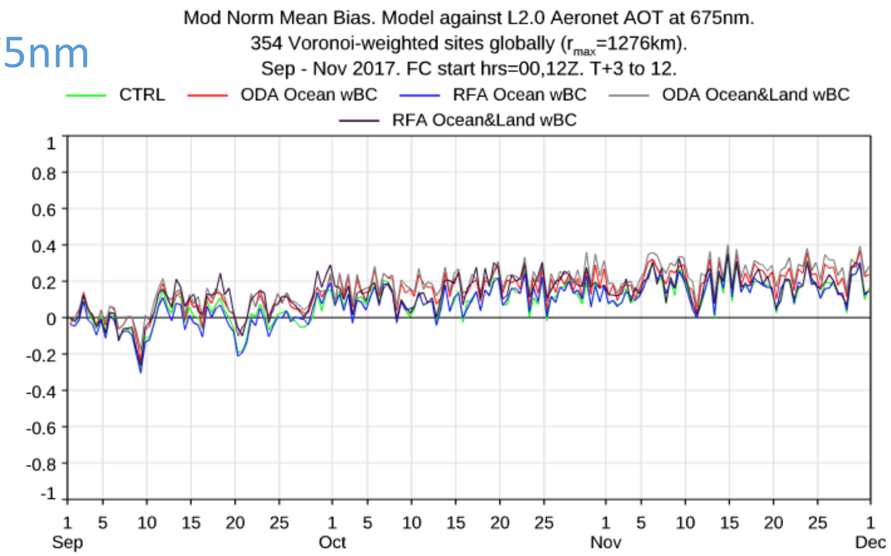


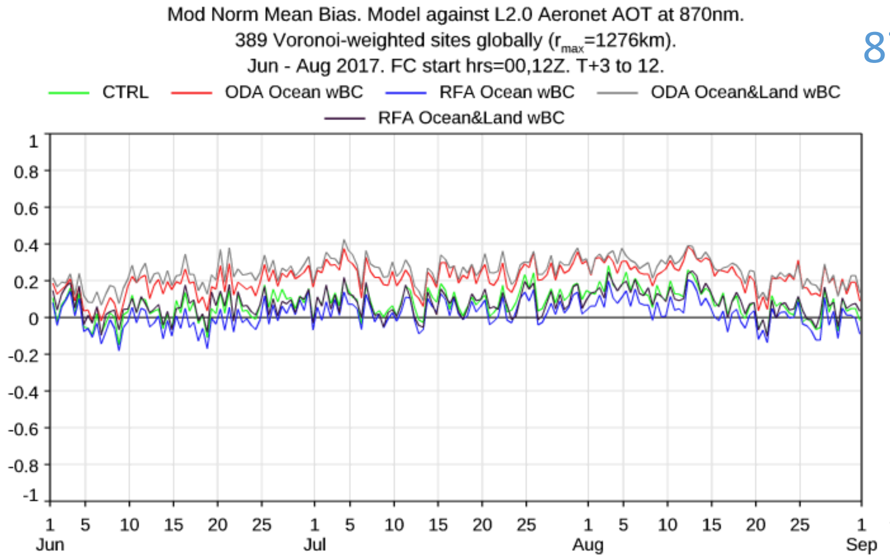
AOD exps perform the best in terms of FGE. RFA Ocean & Land sometimes perfoms worse than control.

Analyses vs AERONET AOD - MNMB



675nm





870nm

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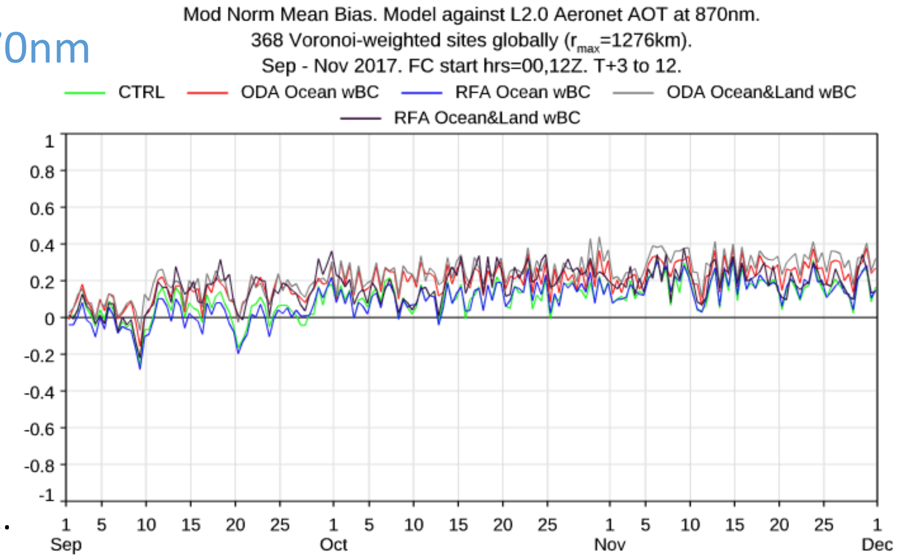
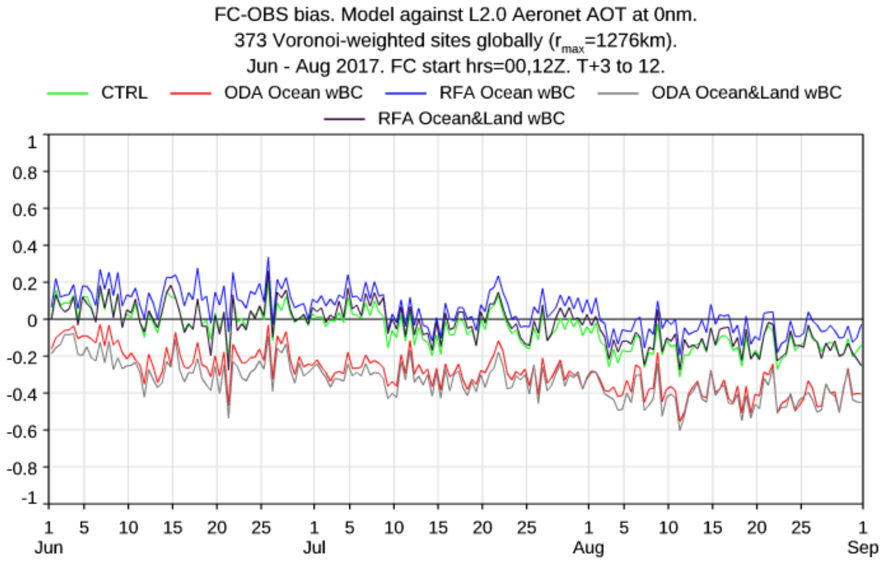
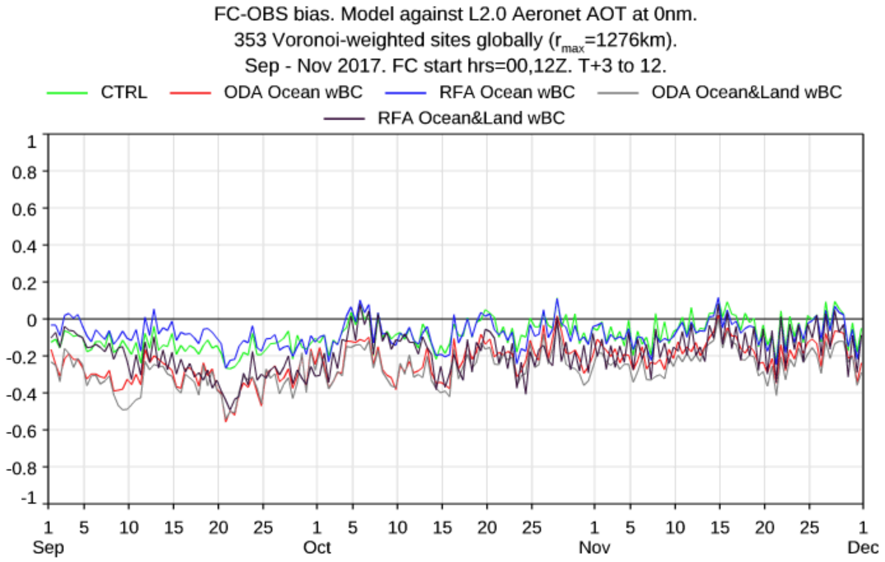


AOD assimilation performs worse than RFA in terms of MNMB. RFA Ocean performs the best.

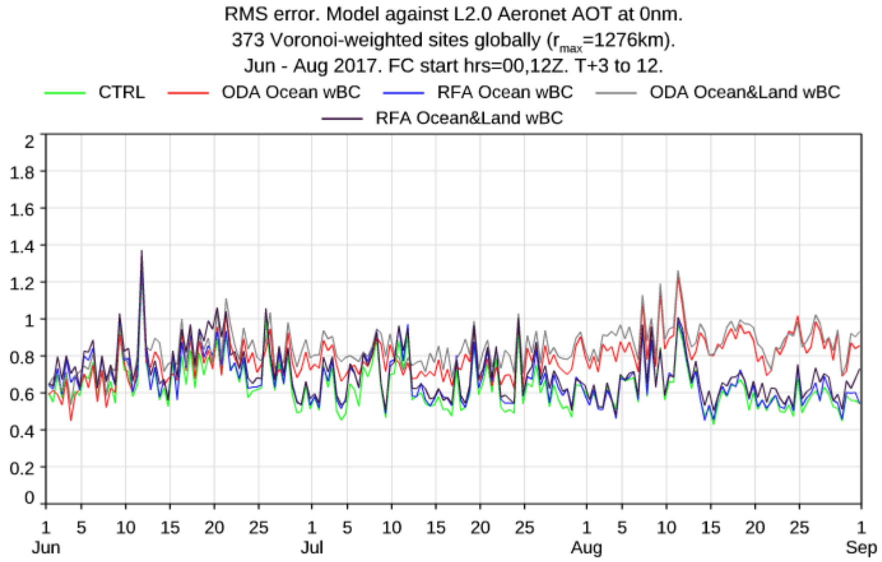
Analyses vs AERONET Angstrom - Bias

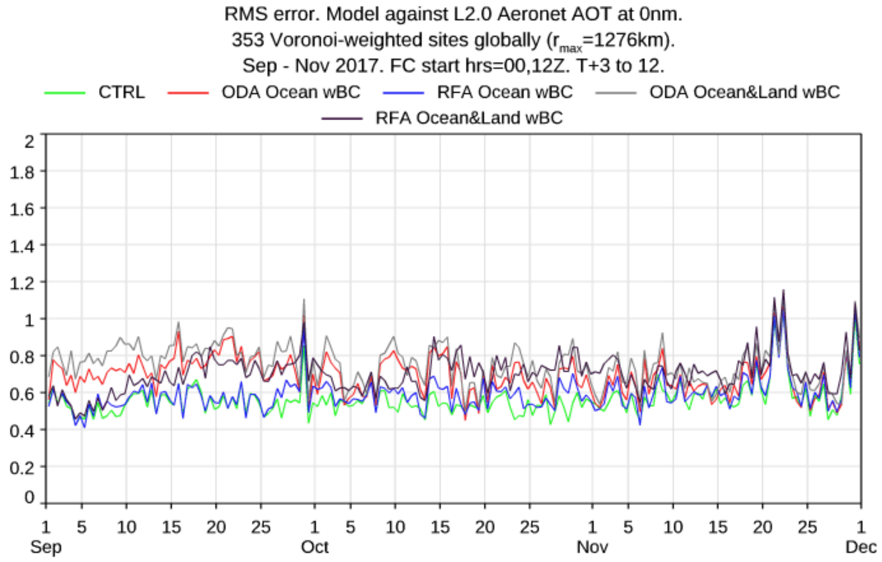




AOD assimilation performs worse than RFA and control in terms of Bias.

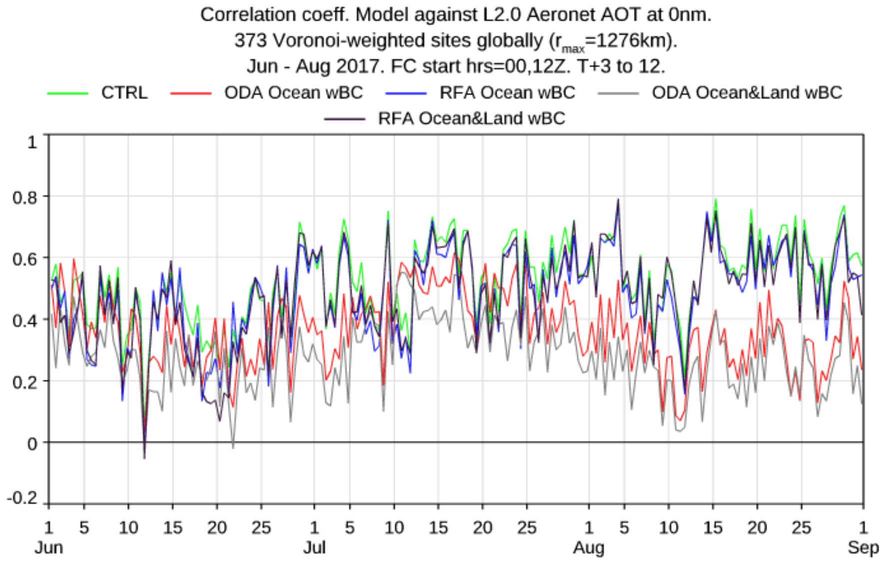
Analyses vs AERONET Angstrom - RMSE

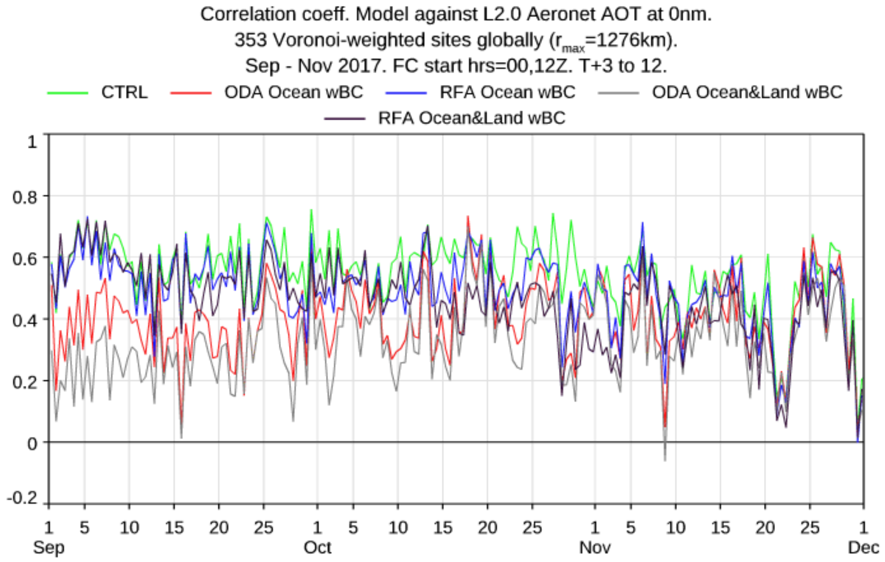




AOD assimilation performs worse than RFA and control in terms of RMSE.

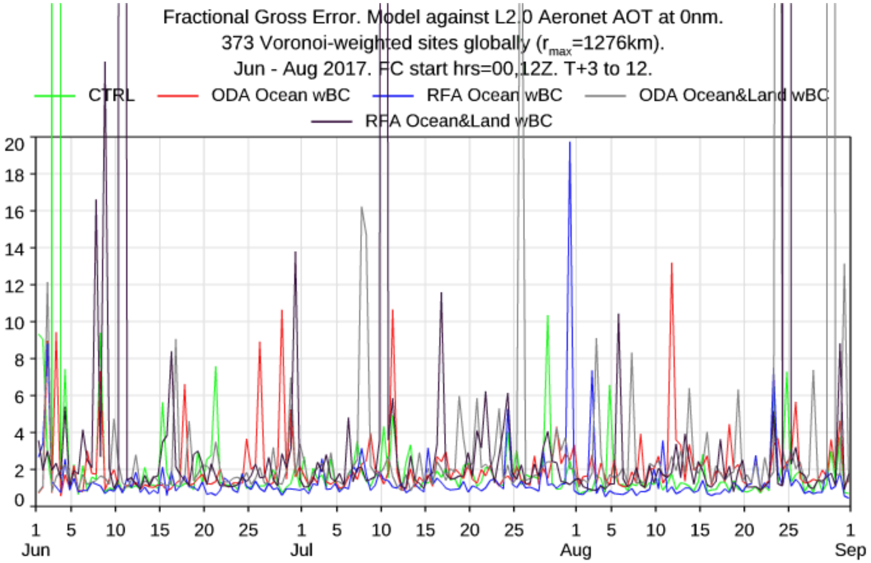
Analyses vs AERONET Angstrom - Corr.

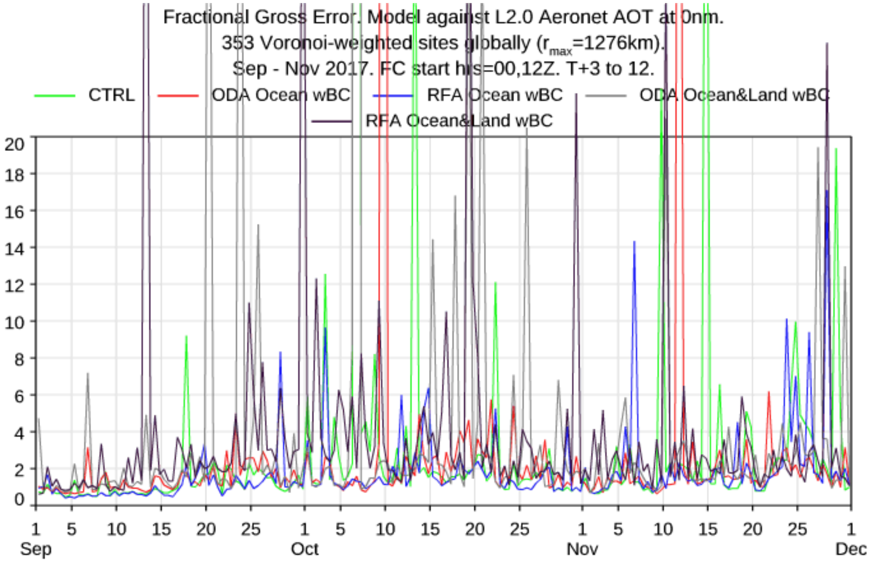




AOD assimilation performs worse than RFA and control in terms of correlation.

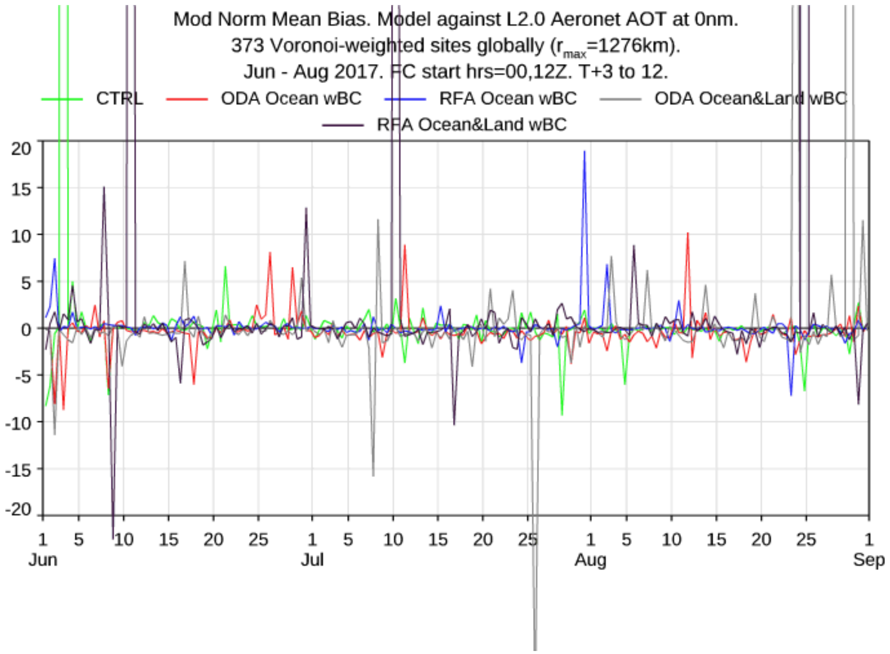
Analyses vs AERONET Angstrom - FGE

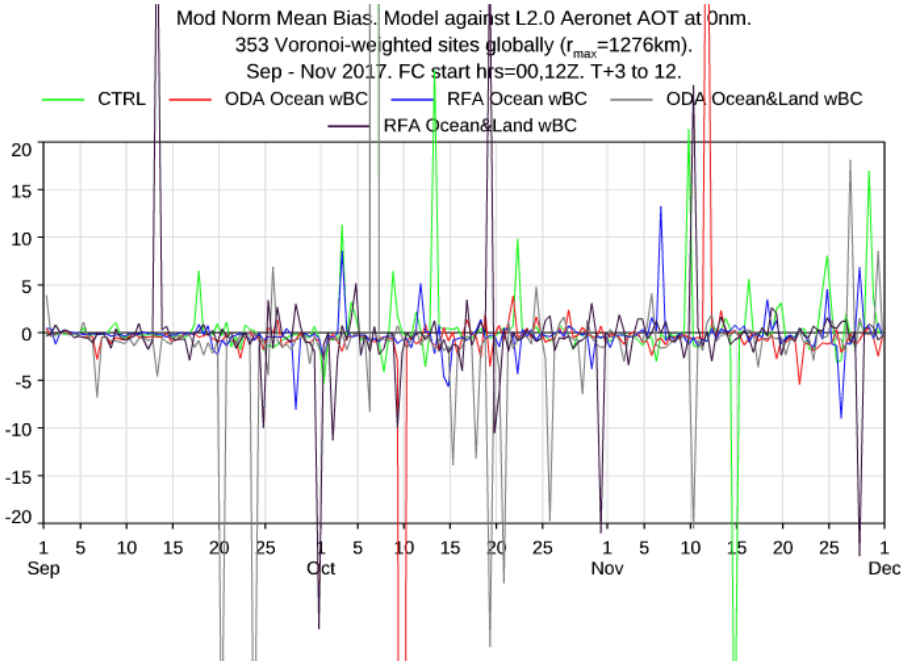




No clear best performer in terms of FGE.

Analyses vs AERONET Angstrom - MNMB





No clear best performer in terms of MNMB.

Validation conclusions

- The **bias correction** worked well in the sense that it addressed the biases in the RFA experiments and allowed the RFA assimilation to perform comparably, if not better, to the AOD assimilation. *It is important to stress that no tuning was made for bias correction.*
- In terms of **AERONET AOD** observations, AOD assimilation performed better than the RFA assimilation according to certain statistics and worse than RFA according to others, but no clear conclusions could be drawn.
- In terms of **Angstrom exponent** derived from AERONET observations, however, it appeared that the RFA assimilation performed better than, or equal to, the AOD assimilation in all statistics.
- Results from ocean and land experiments have been only recently obtained and a more thorough investigation than that allowed within the scope of the project is needed to understand the behaviour of the observation operator as well as the characteristics of the observations over land.
  - It is likely that the lower performance of the radiance ocean and land experiments, compared to those over ocean alone, are due to the simplistic approach taken to land surface reflectance in this work.

Project conclusions

- ARAS has been an extremely successful project that has lead to the assimilation of aerosol reflectances in the visible for the first time in a global 4D-Var assimilation system.
- It is gratifying to see that the assimilation of reflectances has proven to be very successful; exhibiting a remarkable performance for what is essentially a new development rolled out over the course of the last two years.
- More development is still necessary to bring the assimilation of reflectance at the same level (or possibly higher) of the assimilation of AODs.
  - Improvement of surface reflectance handling, particularly over land.
  - Tuning and optimisation of the bias correction and radiance quality control.

Glossary and references

- 4D-Var: 4-dimensional variational (data assimilation)
- AOD: Aerosol Optical Depth
- ARAS: Aerosol Radiance Assimilation Study
- BE: mean Bias Error
- BRDF: Bidirectional Reflectance Distribution Function
- CAMS: Copernicus Atmospheric Monitoring Service
- CC4CL: Community Cloud for Climate (Aka ORAC)
- ECMWF: European Centre for Medium Range Weather Forecasting
- FGE: Fractional Gross Error
- IFS: Integrated Forecasting System
- IR: Infrared
- LUT: Look-Up Table
- MNMB: Modified Normalised Mean Bias
- MODIS: Moderate-resolution Imaging Spectroradiometer
- ORAC: Optimal Retrieval of Aerosol and Cloud
- PMAp: Polar Multi-Sensor Aerosol Product
- RAL: Rutherford Appleton Laboratory
- RFA: Reflectance Assimilation
- RMSE: Root Mean Square Error
- RTTOV: Radiative Transfer for TOVS
- STFC: (UK) Science and Technology Facilities Council
- TOA: Top-Of-Atmosphere

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