Versatile GRASP algorithm: Application to POLDER/Parasol and MERIS/Envisat observations

"GRASP: Strength and weakness"

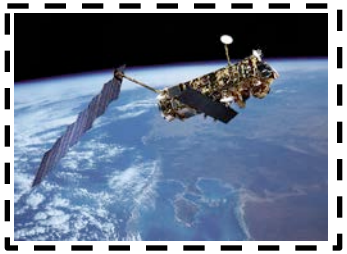
Oleg Dubovik[1], Pavel Litvinov[2], Tatyana Lapyonok[1], David Fuertes[2], Fabrice Ducos[1], Anton Lopatin[1], Xin Huang[1], Benjamin Torres[2], Georg Ogris[3], Michael Aspsetsberger[3] and Christian Federspiel[3]

1 - Laboratoire d'Optique Atmosphérique, CNRS – Université Lille 1, France;
2 - GRASP-SAS, LOA, Université Lille 1, Villeneuve d'Ascq, France
3 - Catalysts GmbH, High Performance Computing, Linz, Austria

AEROSAT, FMI, Helsinki, Finland, 12-13 October, 2017

GRASP: Generalized Retrieval of Aerosol and Surface Properties

MERIS



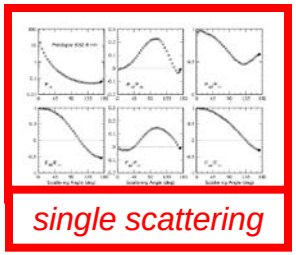
AERONET

POLDER

lidar AERONET

Sentinel - 4

laboratory

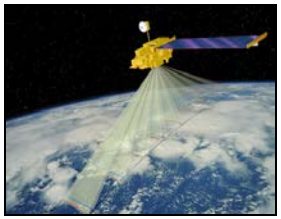


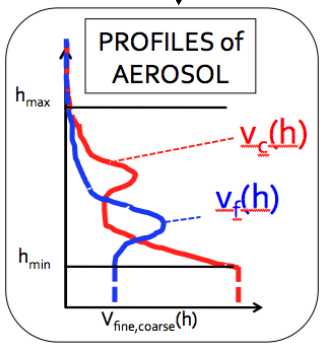
single scattering

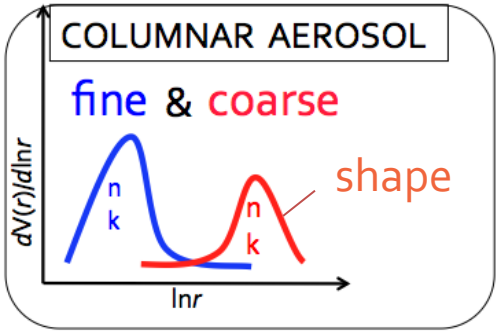
GRASP

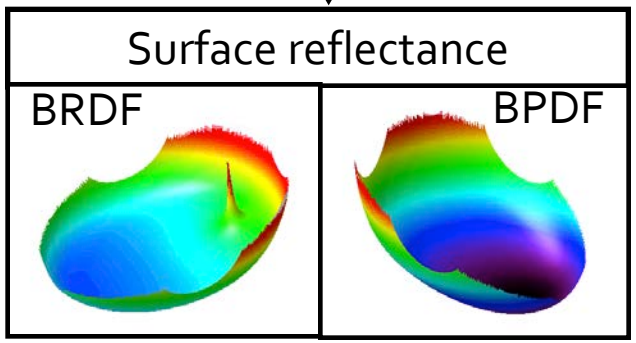
open source

MISR









Multi-Source LSM approach:

$$P_{1,2,3}=P_1P_2P_3\ldots \sim \exp\left(-\frac{1}{2\sigma_1^2}\sum_i \frac{\sigma_1^2}{\sigma_i^2}\left(\Delta f_i^T \Delta f_i\right)\right)=max \quad \rightarrow \quad \sum_i \frac{\sigma_1^2}{\sigma_i^2}\left(\Delta f_i^T \Delta f_i\right)=min$$

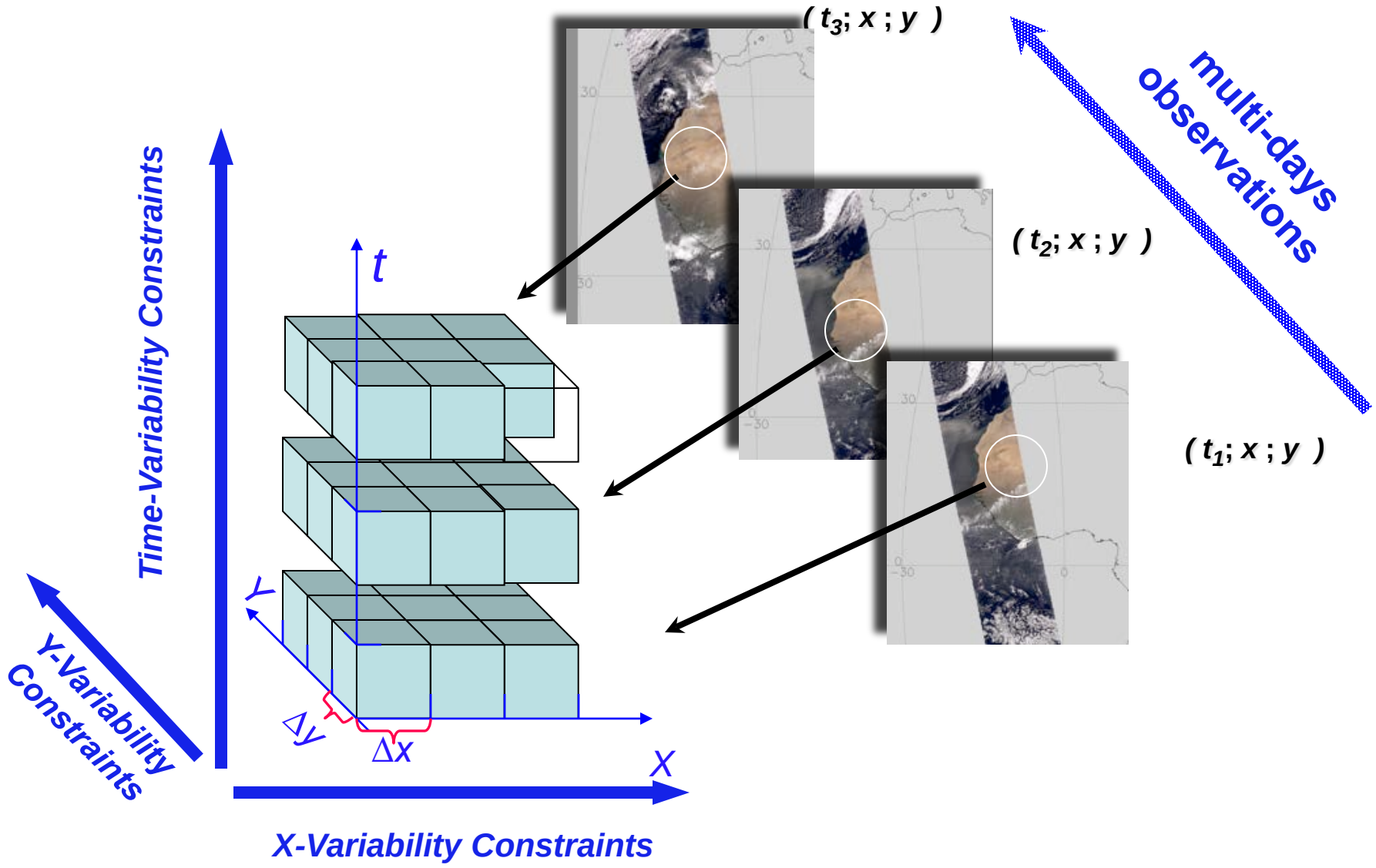
where $\Delta_i = f_i^* - f_i(a)$ and f_i^* - measurements or *a priori data*

P (...) - *Probability Density Function (**Likelihood**)*

- ***Optimum data combination***
- ***Optimum use of a priori information***
- ***Continuous solution space***
- ***Rigorous error estimations***
- ***Large number of retrieved parameters with less assumption***

- ***More "sophisticated"***
- ***Generally more time consuming***

The concept of multi-pixel retrieval



Multi-term LSM ***Multi-Pixel Solution:***

$$\begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} = \left[\begin{pmatrix} \mathbf{F}_1^T \mathbf{W}_1^{-1} \mathbf{F}_1 & 0 & 0 \\ 0 & \mathbf{F}_2^T \mathbf{W}_2^{-1} \mathbf{F}_2 & 0 \\ 0 & 0 & \mathbf{F}_3^T \mathbf{W}_3^{-1} \mathbf{F}_3 \end{pmatrix} + \begin{pmatrix} \gamma_1 \Omega_1 & 0 & 0 \\ 0 & \gamma_2 \Omega_2 & 0 \\ 0 & 0 & \gamma_3 \Omega_3 \end{pmatrix} + \gamma_x \Omega_x + \gamma_y \Omega_y + \gamma_t \Omega_t \right]^{-1} \begin{pmatrix} \mathbf{F}_1^T \mathbf{W}_1^{-1} \Delta \boldsymbol{f}_1^p \\ \mathbf{F}_2^T \mathbf{W}_2^{-1} \Delta \boldsymbol{f}_2^p \\ \mathbf{F}_3^T \mathbf{W}_3^{-1} \Delta \boldsymbol{f}_3^p \end{pmatrix}$$

$$\begin{pmatrix} a_v \\ a_n \\ a_n \\ a_h \\ a_{sph} \\ a_{Vc} \\ a_{brdf,1} \\ a_{brdf,2} \\ a_{brdf,3} \\ a_{bpdf} \end{pmatrix}$$

43 parameters

$$\gamma_\Delta \Omega = \begin{pmatrix} \gamma_{\Delta,1}\Omega_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \gamma_{\Delta,2}\Omega_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \gamma_{\Delta,3}\Omega_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \gamma_{\Delta,4}\Omega_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \gamma_{\Delta,5}\Omega_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \gamma_{\Delta,6}\Omega_6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \gamma_{\Delta,7}\Omega_7 \end{pmatrix}$$

$$\Omega_x = \mathbf{s}_x^T \mathbf{s}_x; \; \Omega_y = \mathbf{s}_y^T \mathbf{s}_y; \; \Omega_t = \mathbf{s}_t^T \mathbf{s}_t;$$

$$\mathbf{s}_y^T \mathbf{s}_y = \begin{pmatrix} \begin{pmatrix} I_{d_{11}} & I_{d_{12}} & I_{d_{13}} \\ I_{d_{21}} & I_{d_{22}} & I_{d_{23}} \\ I_{d_{31}} & I_{d_{32}} & I_{d_{33}} \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} I_{d_{11}} & I_{d_{12}} & I_{d_{13}} \\ I_{d_{21}} & I_{d_{22}} & I_{d_{23}} \\ I_{d_{31}} & I_{d_{32}} & I_{d_{33}} \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} I_{d_{11}} & I_{d_{12}} & I_{d_{13}} \\ I_{d_{21}} & I_{d_{22}} & I_{d_{23}} \\ I_{d_{31}} & I_{d_{32}} & I_{d_{33}} \end{pmatrix} \end{pmatrix};$$

$$\mathbf{s}_y^T \mathbf{s}_y = \begin{pmatrix} \begin{pmatrix} I_{d_{11}} & I_{d_{12}} & I_{d_{13}} \\ I_{d_{21}} & I_{d_{22}} & I_{d_{23}} \\ I_{d_{31}} & I_{d_{32}} & I_{d_{33}} \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} I_{d_{11}} & I_{d_{12}} & I_{d_{13}} \\ I_{d_{21}} & I_{d_{22}} & I_{d_{23}} \\ I_{d_{31}} & I_{d_{32}} & I_{d_{33}} \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} I_{d_{11}} & I_{d_{12}} & I_{d_{13}} \\ I_{d_{21}} & I_{d_{22}} & I_{d_{23}} \\ I_{d_{31}} & I_{d_{32}} & I_{d_{33}} \end{pmatrix} \end{pmatrix};$$

$$\mathbf{s}_t^T \mathbf{s}_t = \begin{pmatrix} \begin{pmatrix} I_{d_{11}} & 0 & 0 \\ 0 & I_{d_{11}} & 0 \\ 0 & 0 & I_{d_{11}} \end{pmatrix} & \begin{pmatrix} I_{d_{12}} & 0 & 0 \\ 0 & I_{d_{12}} & 0 \\ 0 & 0 & I_{d_{12}} \end{pmatrix} & \begin{pmatrix} I_{d_{13}} & 0 & 0 \\ 0 & I_{d_{13}} & 0 \\ 0 & 0 & I_{d_{13}} \end{pmatrix} \\ \begin{pmatrix} I_{d_{21}} & 0 & 0 \\ 0 & I_{d_{21}} & 0 \\ 0 & 0 & I_{d_{21}} \end{pmatrix} & \begin{pmatrix} I_{d_{22}} & 0 & 0 \\ 0 & I_{d_{22}} & 0 \\ 0 & 0 & I_{d_{22}} \end{pmatrix} & \begin{pmatrix} I_{d_{23}} & 0 & 0 \\ 0 & I_{d_{23}} & 0 \\ 0 & 0 & I_{d_{23}} \end{pmatrix} \\ \begin{pmatrix} I_{d_{31}} & 0 & 0 \\ 0 & I_{d_{31}} & 0 \\ 0 & 0 & I_{d_{31}} \end{pmatrix} & \begin{pmatrix} I_{d_{32}} & 0 & 0 \\ 0 & I_{d_{32}} & 0 \\ 0 & 0 & I_{d_{32}} \end{pmatrix} & \begin{pmatrix} I_{d_{33}} & 0 & 0 \\ 0 & I_{d_{33}} & 0 \\ 0 & 0 & I_{d_{33}} \end{pmatrix} \end{pmatrix}.$$

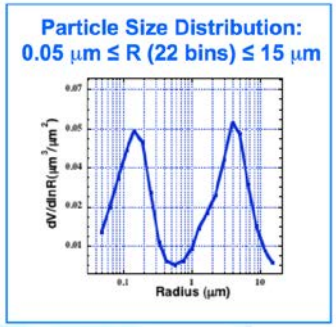
PARASOL:

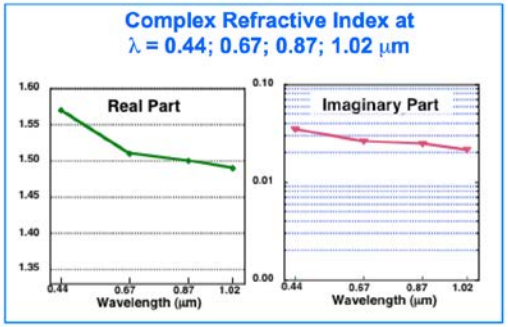
- radiances: *(443, 490, 560, 670, 870, 1020 nm)*
- polarization: *(490, 670, and, 870 nm)*
- up to 16 viewing directions

144 measurements

AEROSOL:

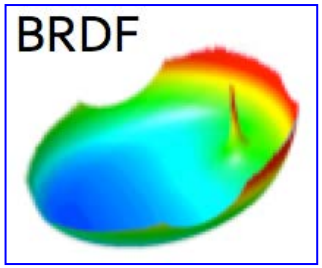
- size distribution (5 or more bins)
- spectral index of refraction (8 λ)
- sphericity fraction;
- aerosol height

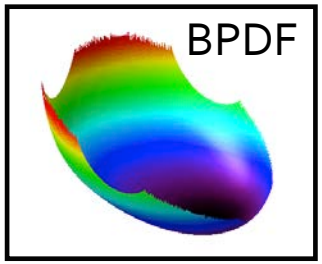




SURFACE:

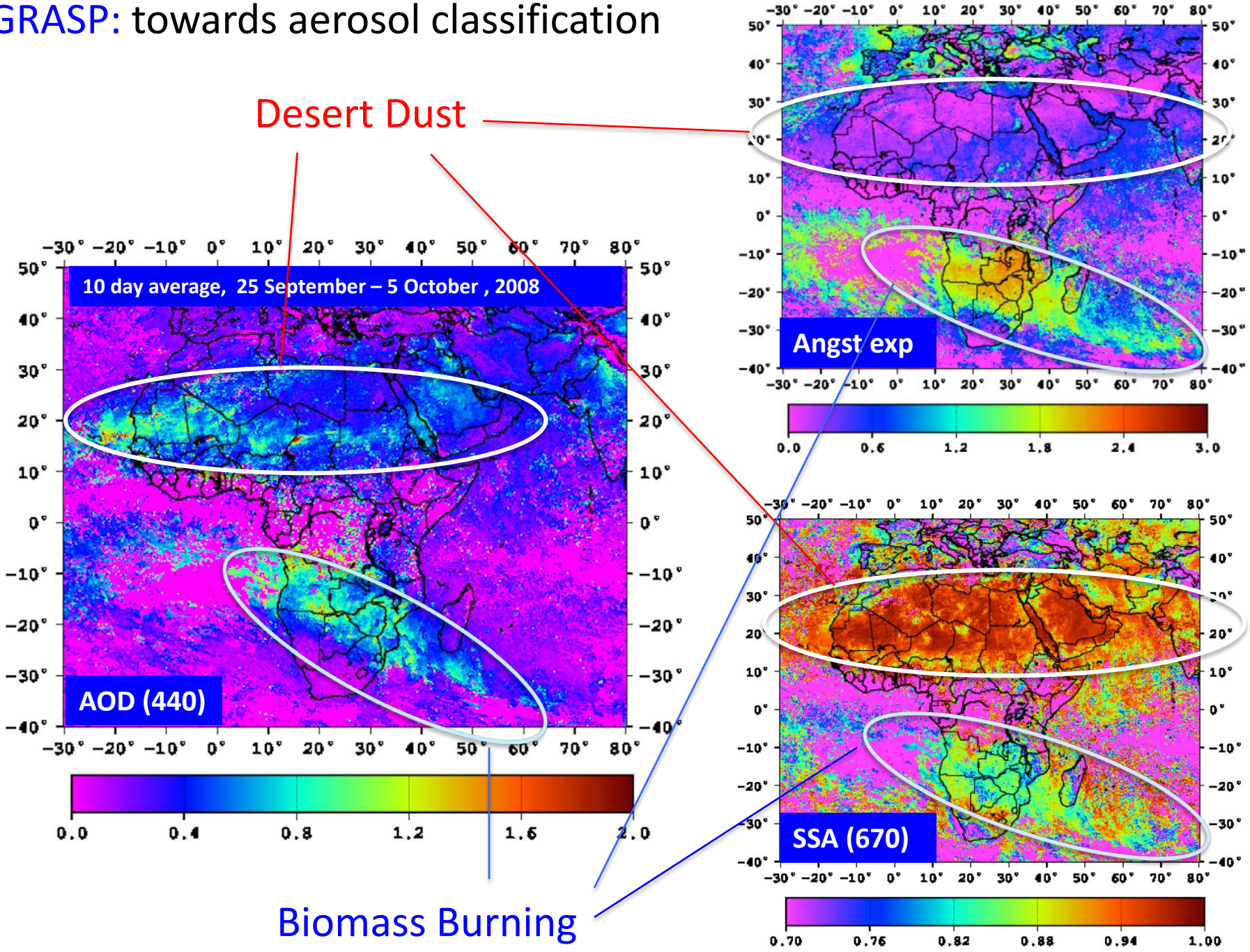
- BRDF (3 spectrally dependent parameters)
- BPDF (1 or 2 spectrally dependent parameters)





43 = (5 (SD) +12 (ref. ind.) + 1 (nonsp.) + 18 (BRDF) +6 (BPDF) + 1 (height)

GRASP: towards aerosol classification

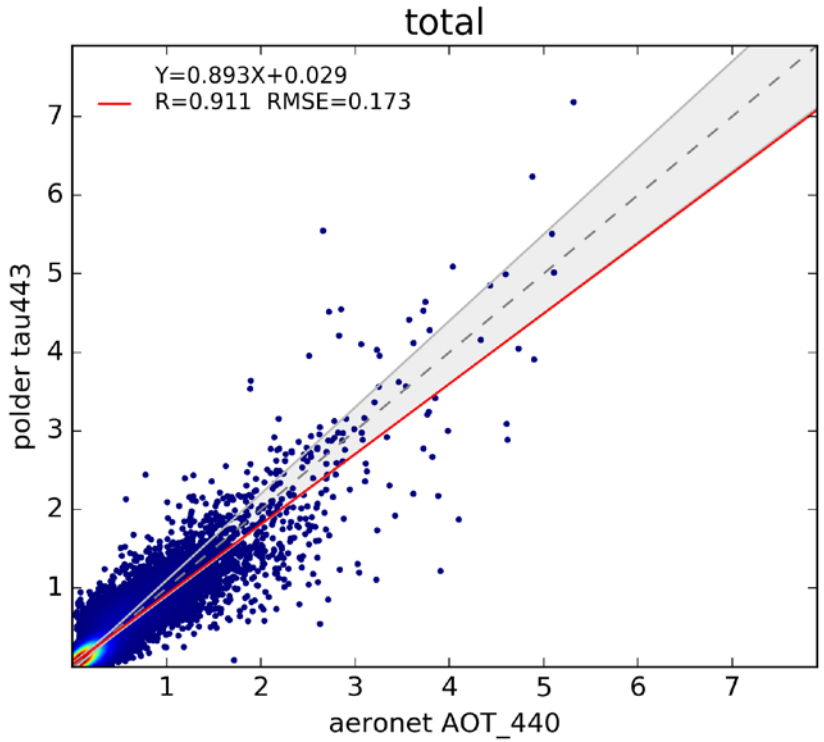


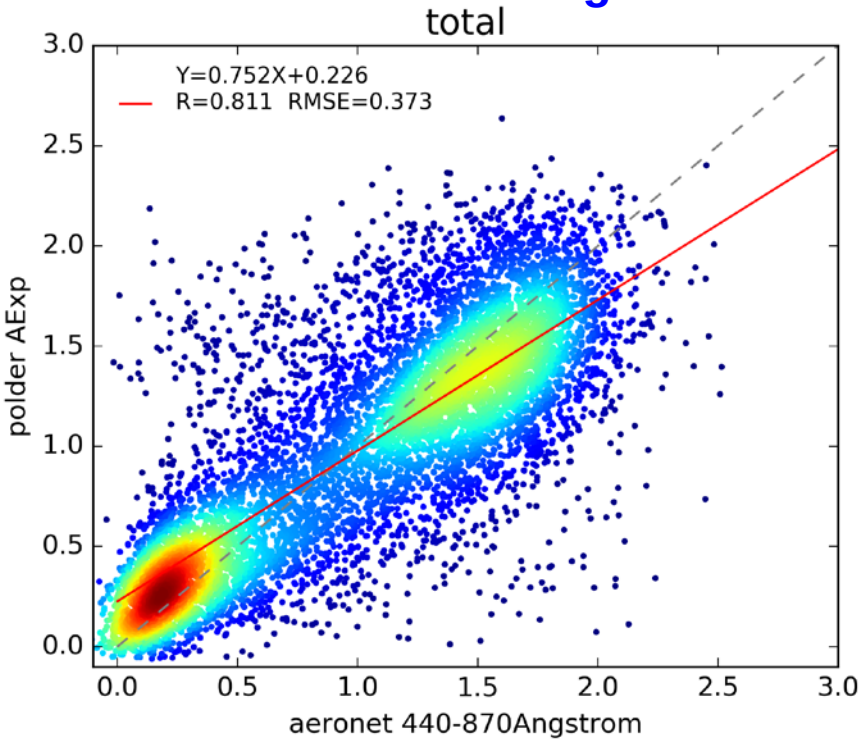
Validation vs AERONET 2004 - 2013

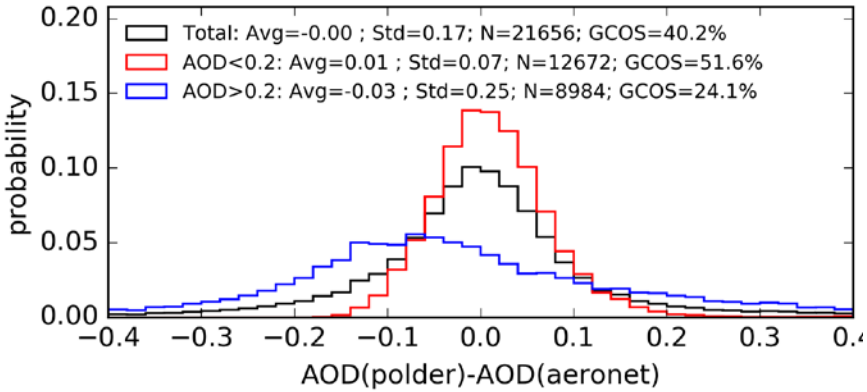
AOD

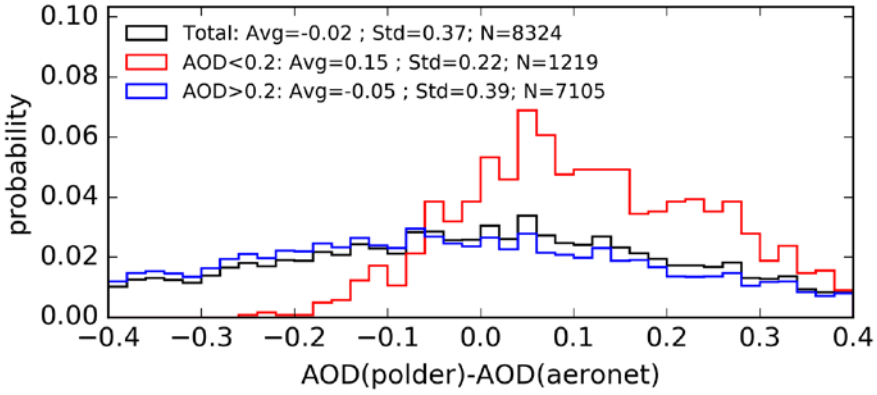
Land

Angstrom







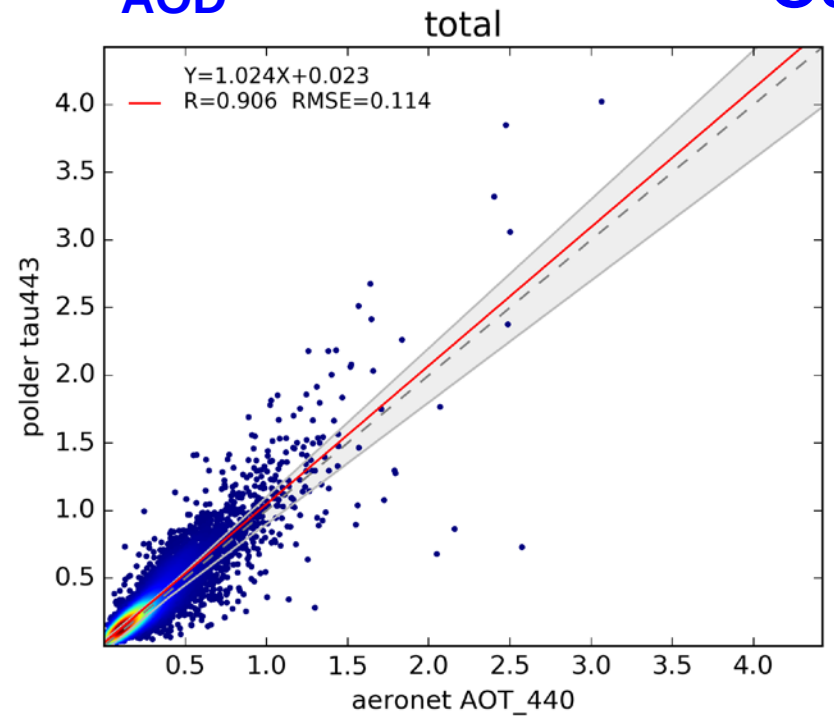


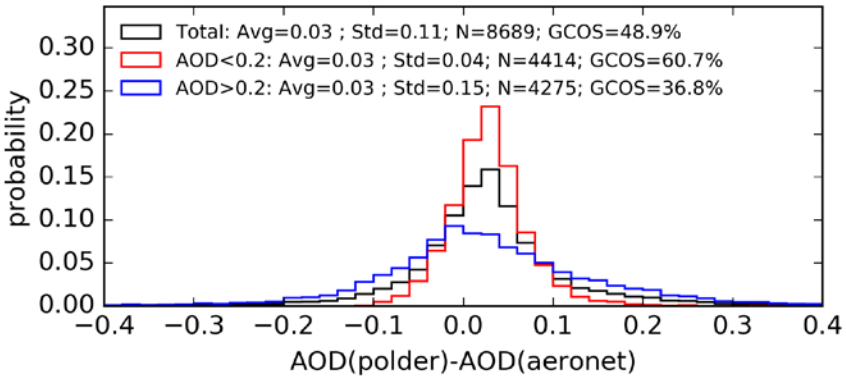
PARASOL Validation vs AERONET 2004 - 2013

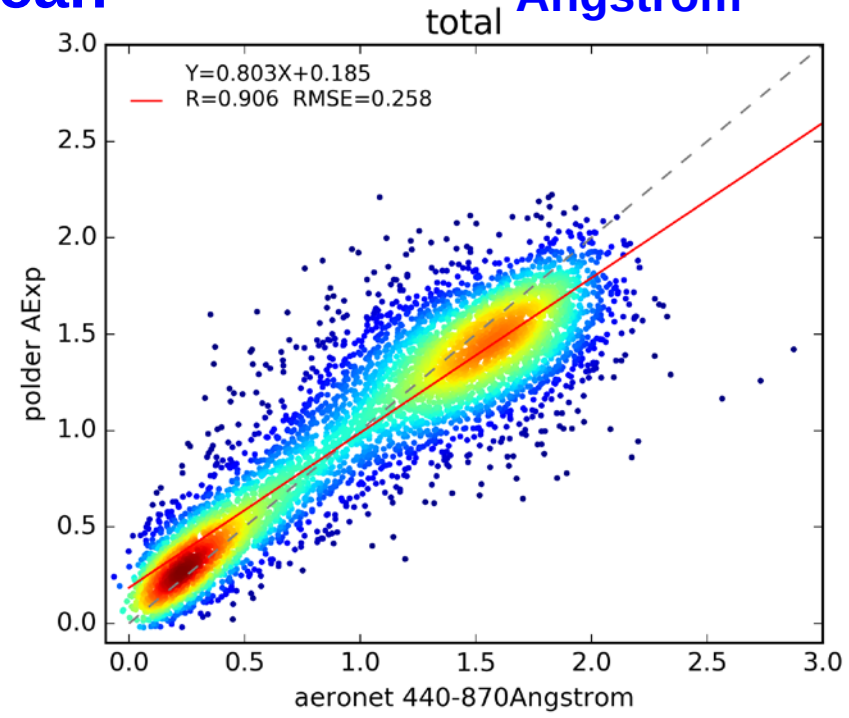
AOD

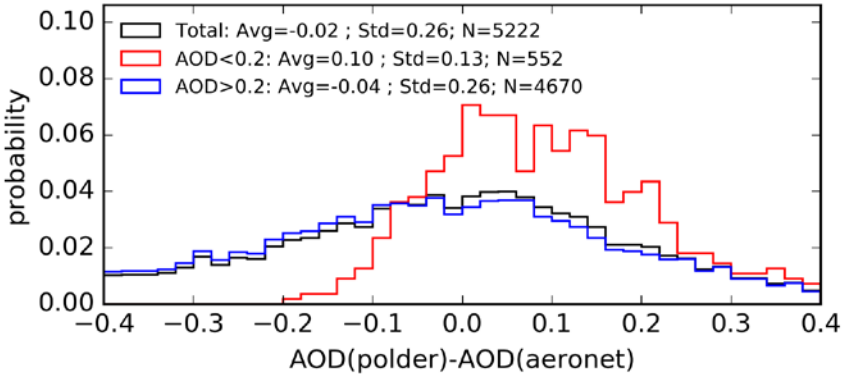
Ocean

Angstrom

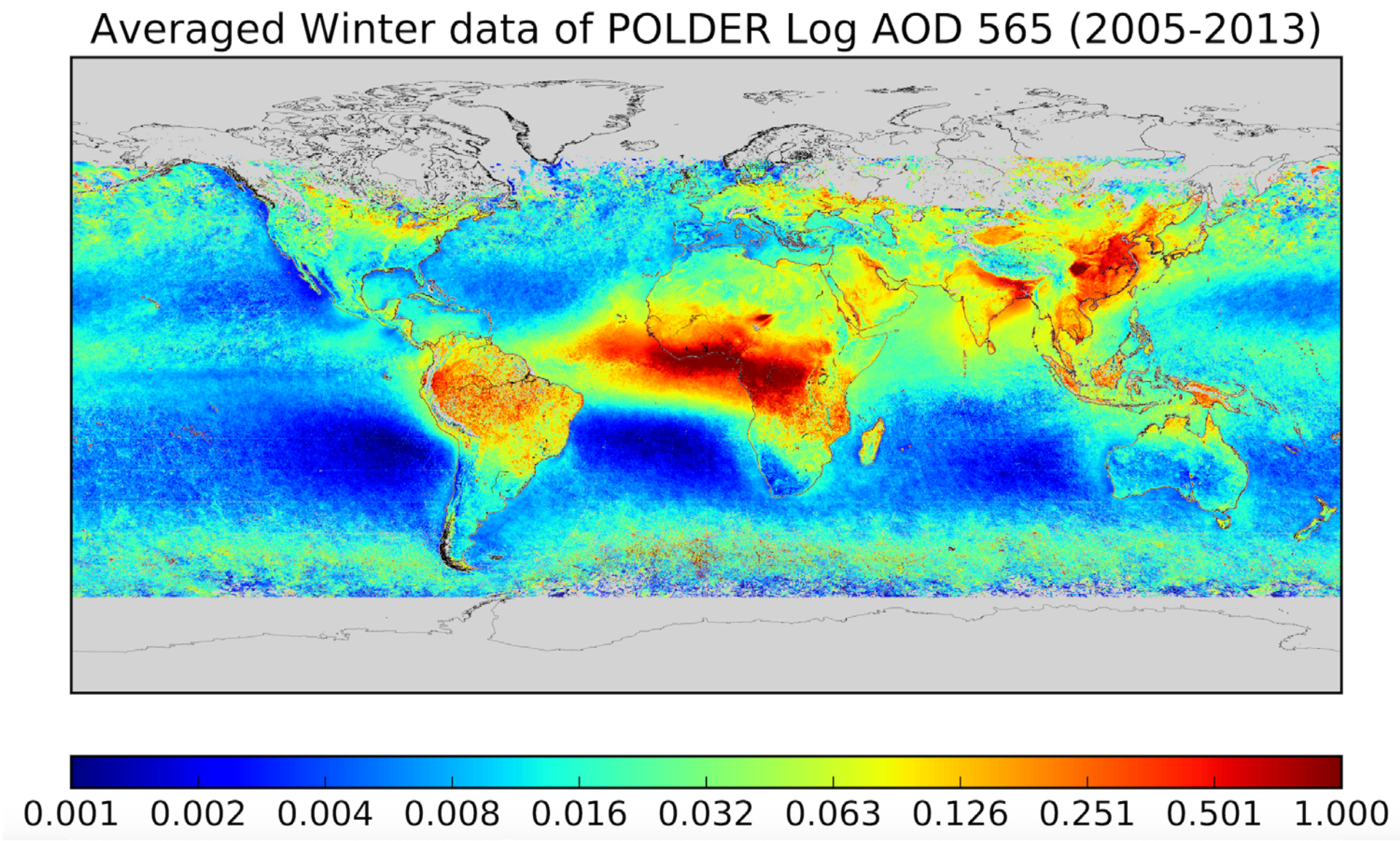




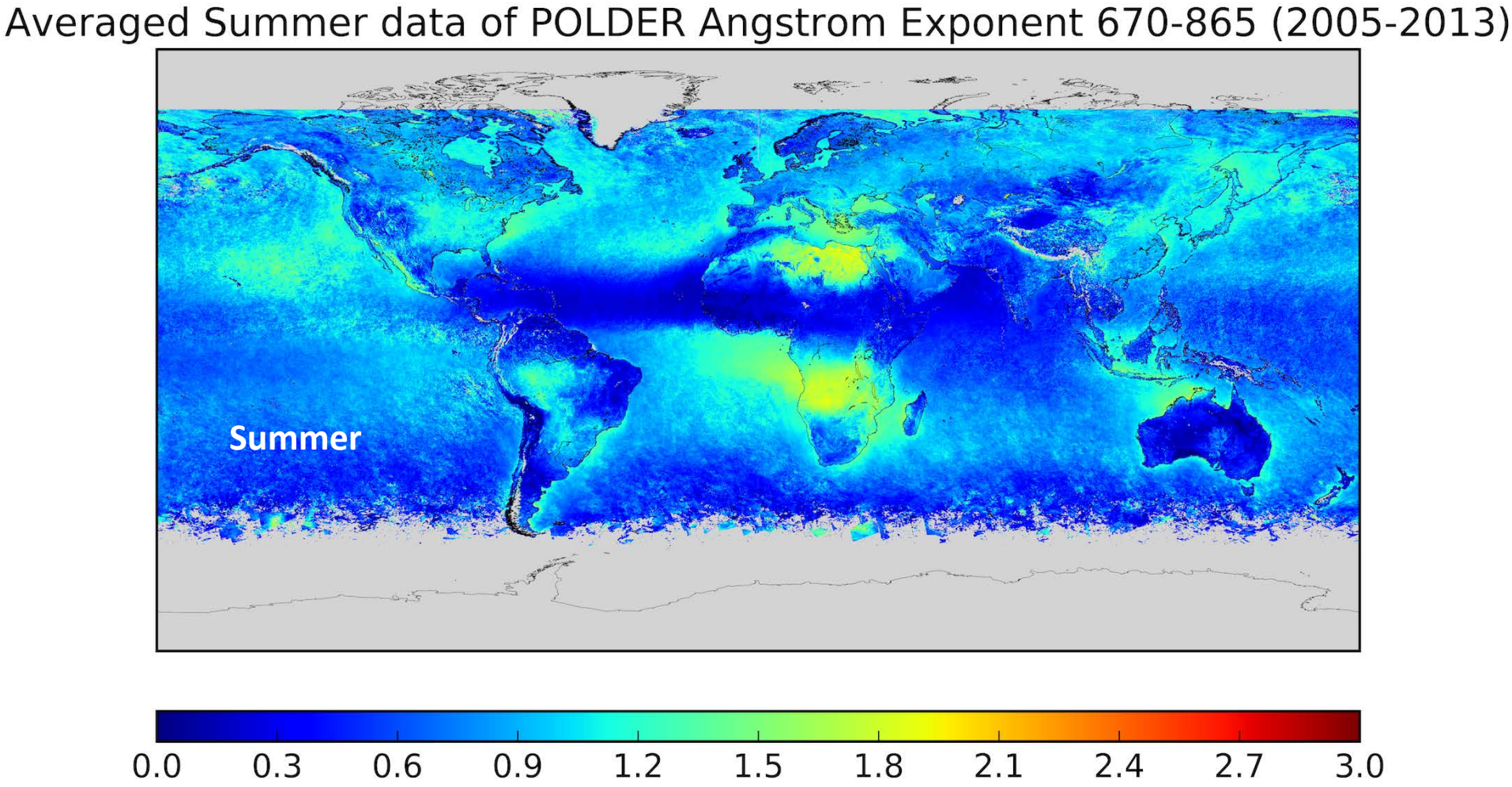




AOD (565), Winter (PARASOL archive average)



Angstrom exponent, Summer (PARASOL archive average)



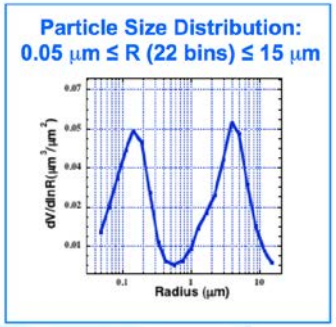
MERIS:

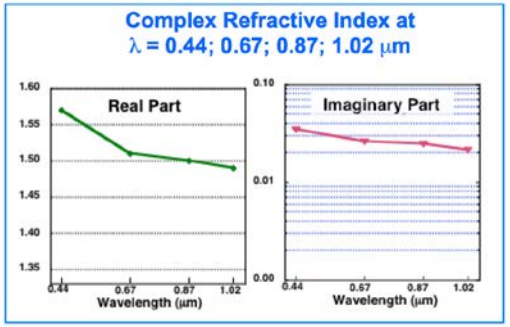
- radiances: *(413, 443, 490, 510, 560, 665, 755, 870)*
- 1 viewing direction

8 measurements

AEROSOL:

- size distribution (5 or more bins)
- spectral index of refraction (8 λ)
- sphericity fraction;



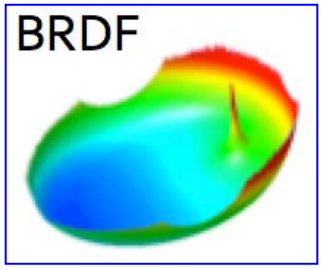


$$\tau^{aerosol}(\lambda) = C_i \sum_{i=1,\ldots,5} \int_{r_{min}}^{r_{max}} K_\tau^i(k_i;n_i;\varepsilon_i;r) V_i(r) dr$$

SURFACE:

- BRDF

(3 parameters)



43 = (5 (SD) +16 (r. ind.) + 1(nonsp.) + 21 (BRDF)) ⟶ 25 = (4 (aer. comp.) + 21 (BRDF))

GRASP/MERIS 2002- 2012 product has been generated

10 km resolution

GRASP/MERIS: year 2008 averages

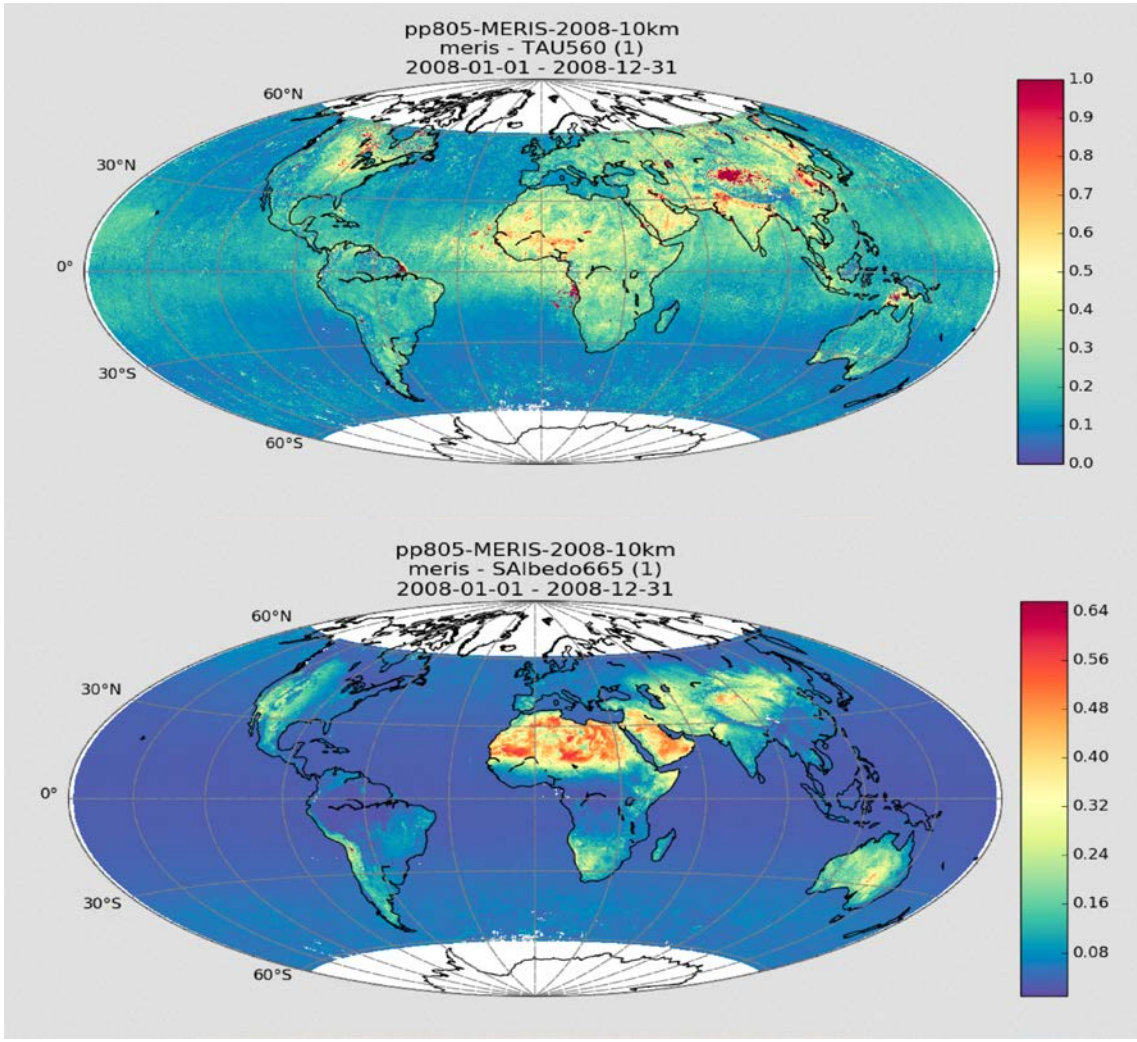
AOD(560 nm)

No location specific assumptions !!!

No climatologies!

Surface Albedo (670 nm)

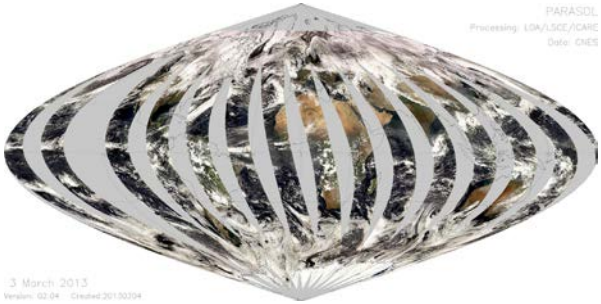
ESA CAWA project



PARASOL:

- radiances: *(443, 490, 560, 670, 870, 1020 nm)*
- polarization: *(490, 670, and, 870 nm)*
- up to 16 viewing directions

144 measurements



≠

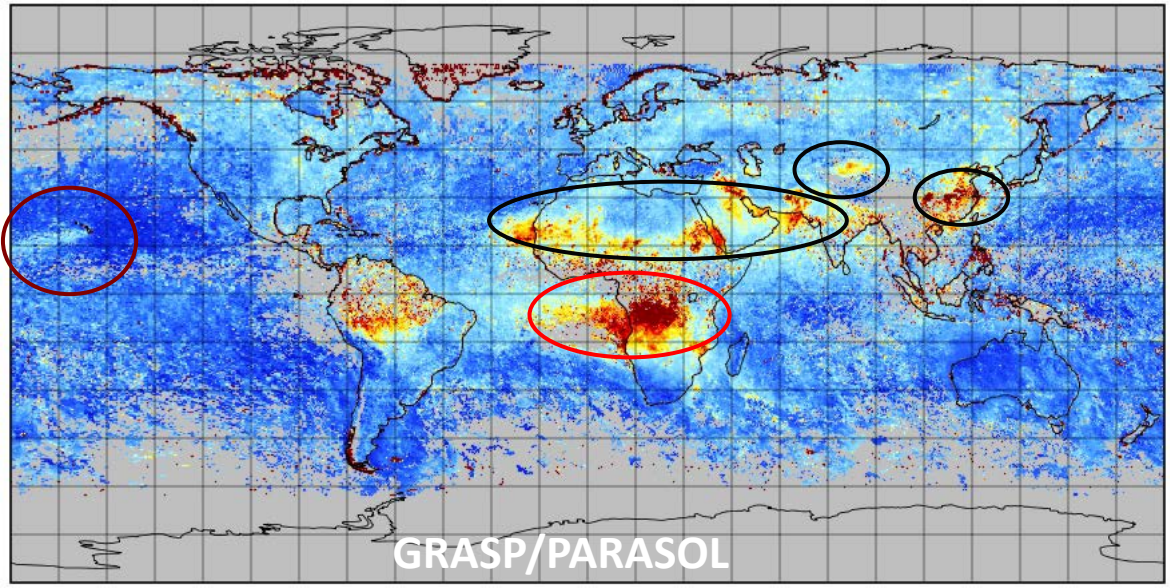
MERIS:

- radiances: *(413, 443, 490, 510, 560, 665, 755, 870)*
- 1 viewing direction

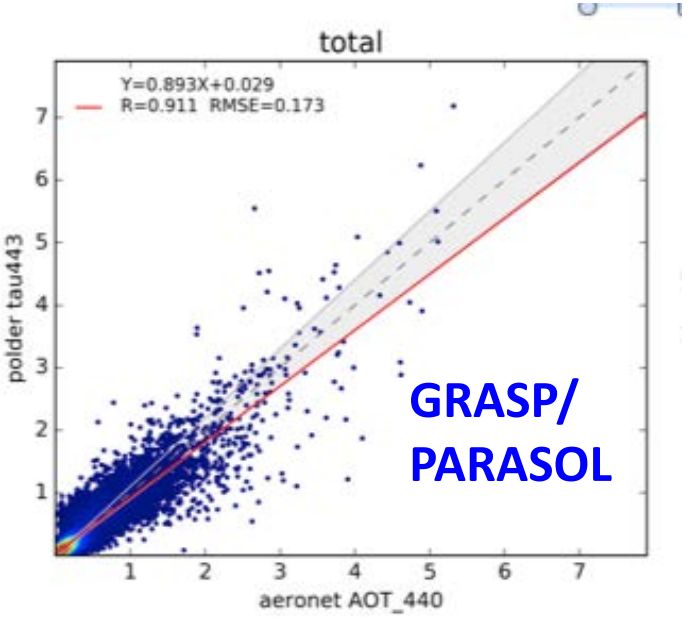
8 measurements

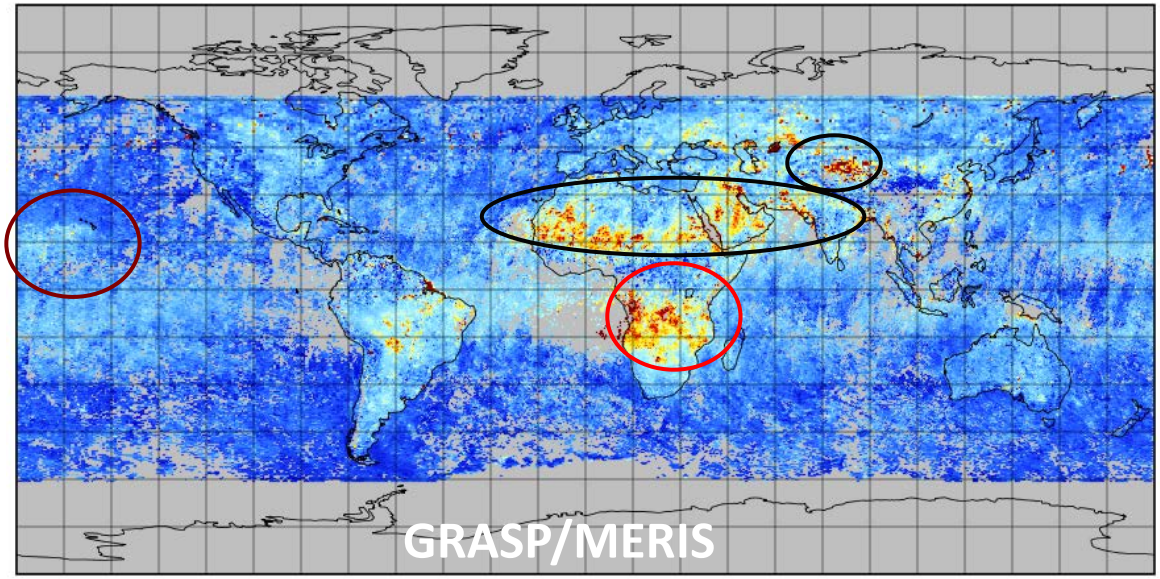
What are the differences in the results?

September, 2008



Total extinction for aerosol optical properties for 560 nm

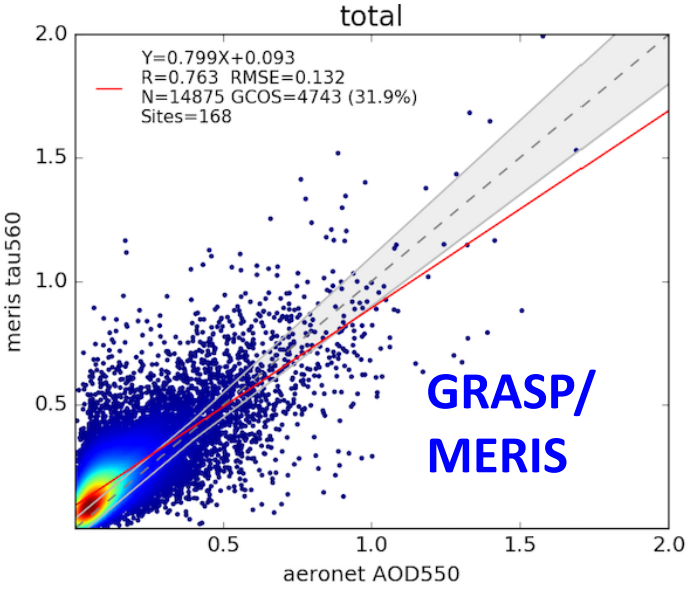




Total extinction for aerosol optical properties for 560 nm ()

0.0 0.2 0.4 0.6 0.8 1.0

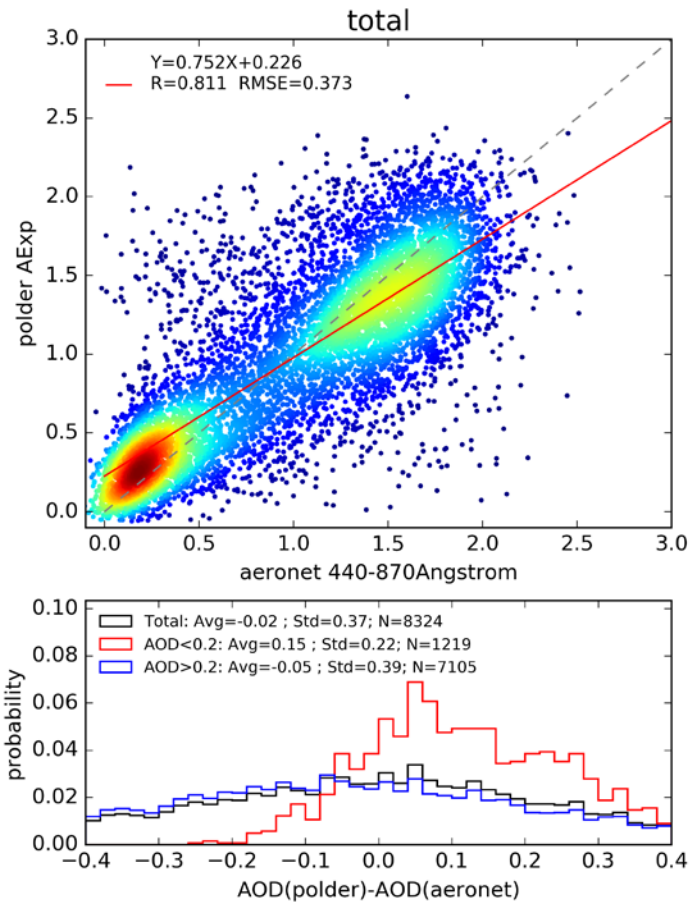
Data Min = 0.0, Max = 28.5, Mean = 0.2



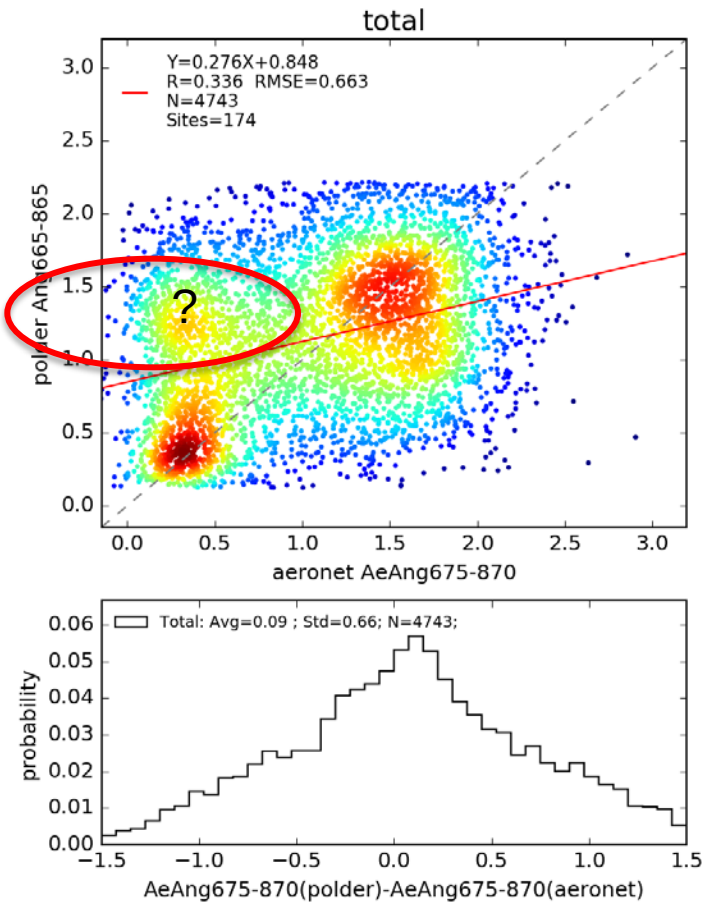
Validation vs AERONET over land

Angstrom

GRASP/PARASOL



GRASP/MERIS

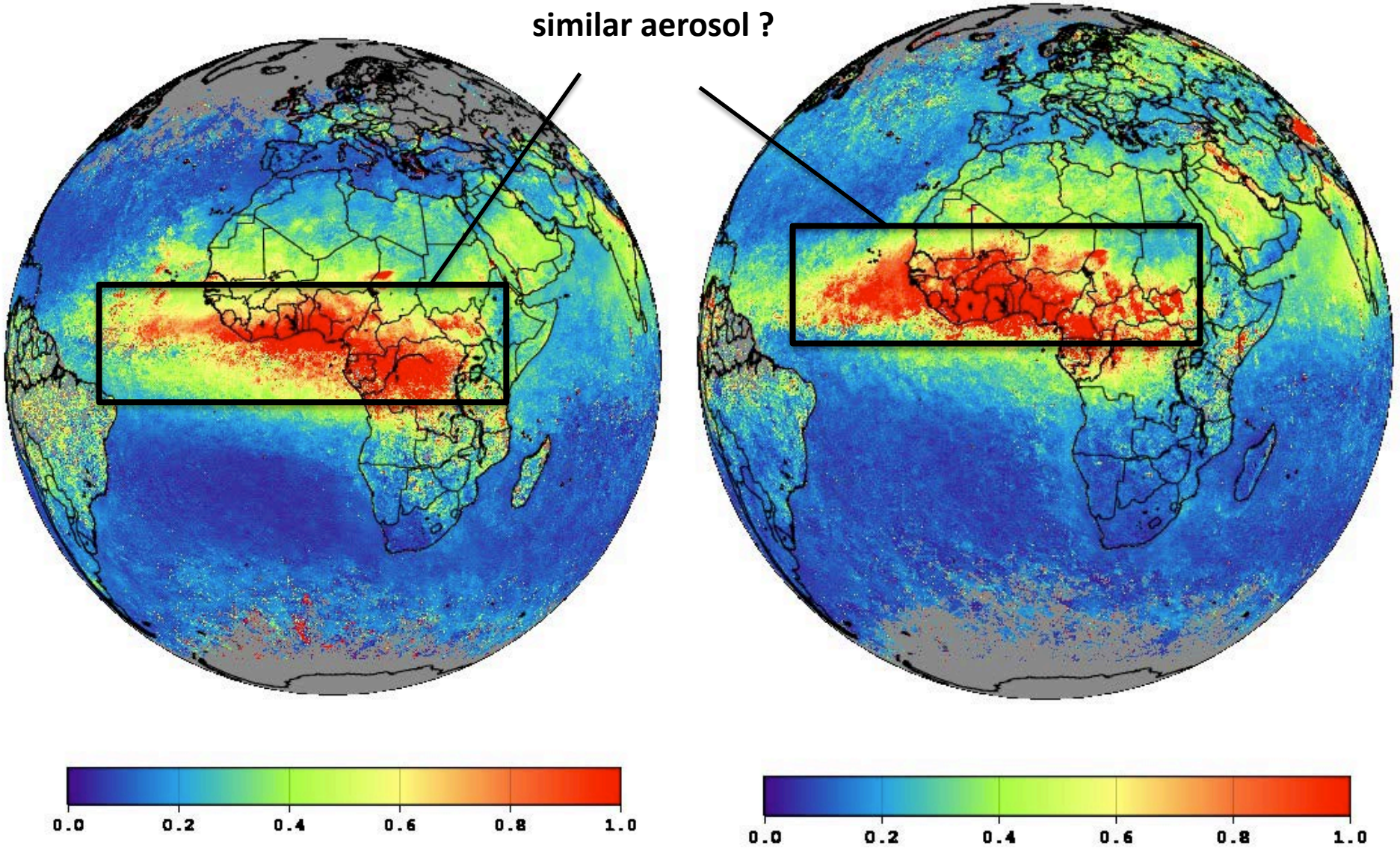


AOD(565) – aerosol loading

2012 Winter

2012 Spring

similar aerosol ?



Angstrom exponent

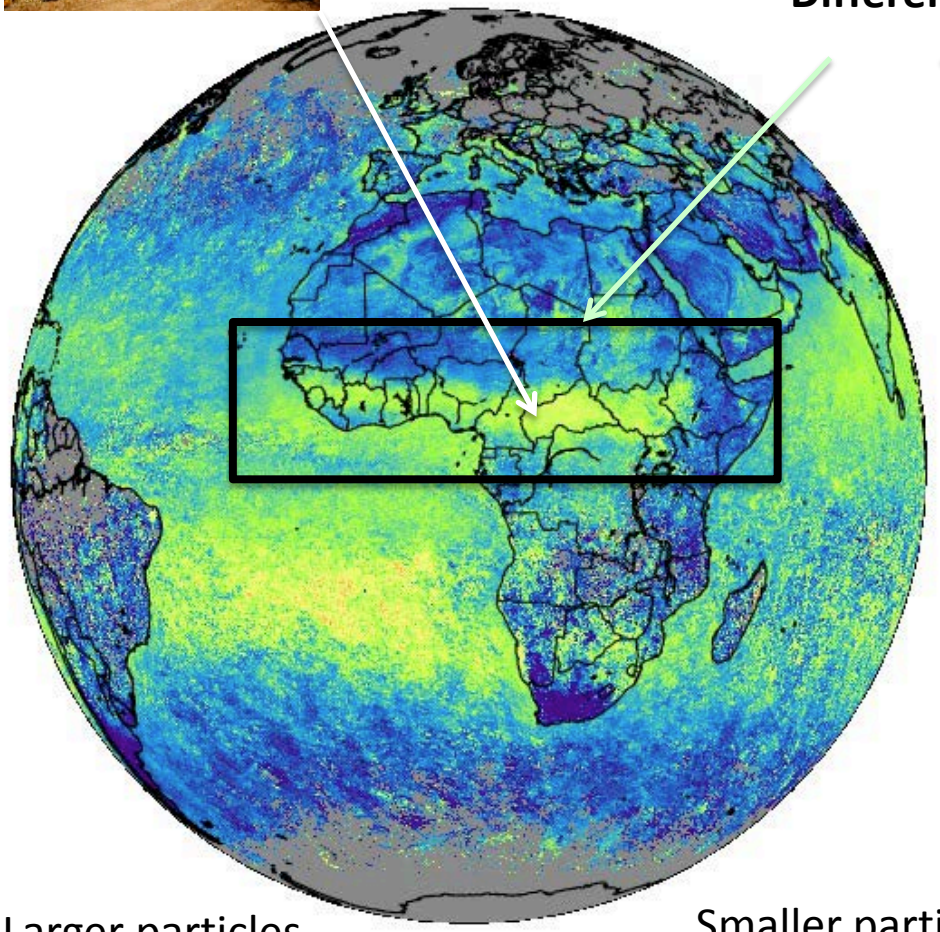
Biomass burning

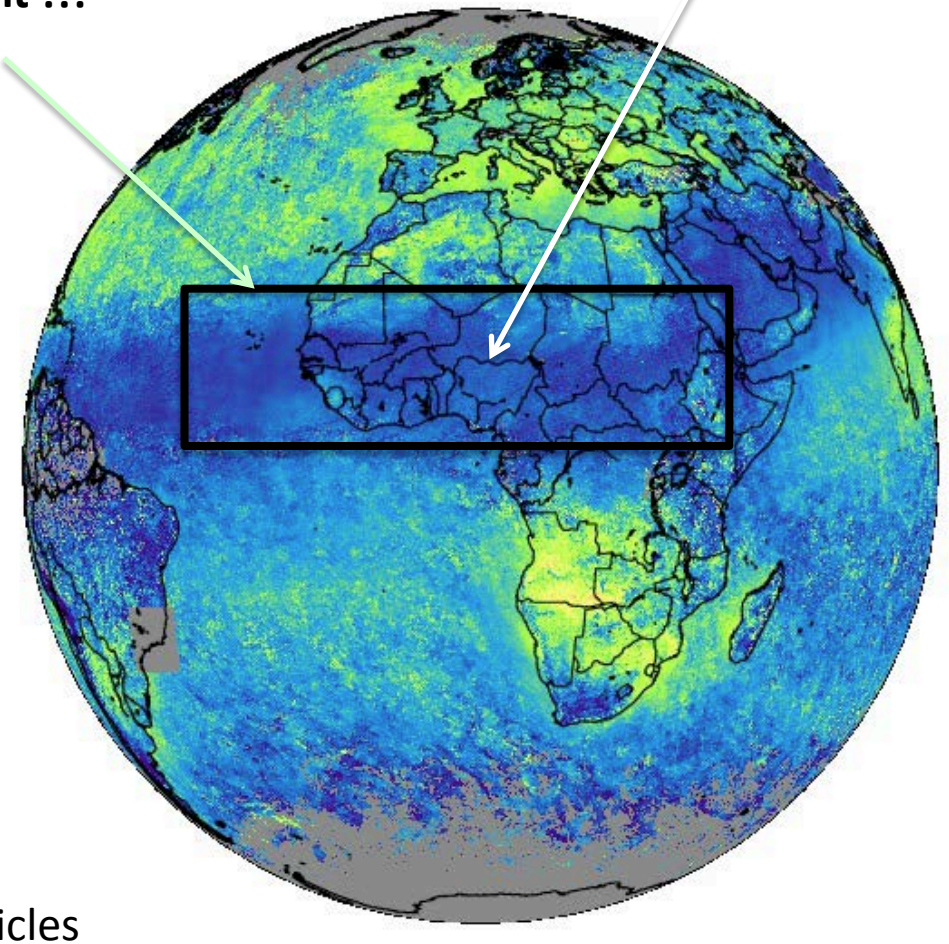
dust

2012 Winter

2012 Spring

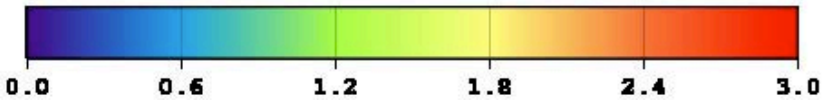
Different !!!





Larger particles

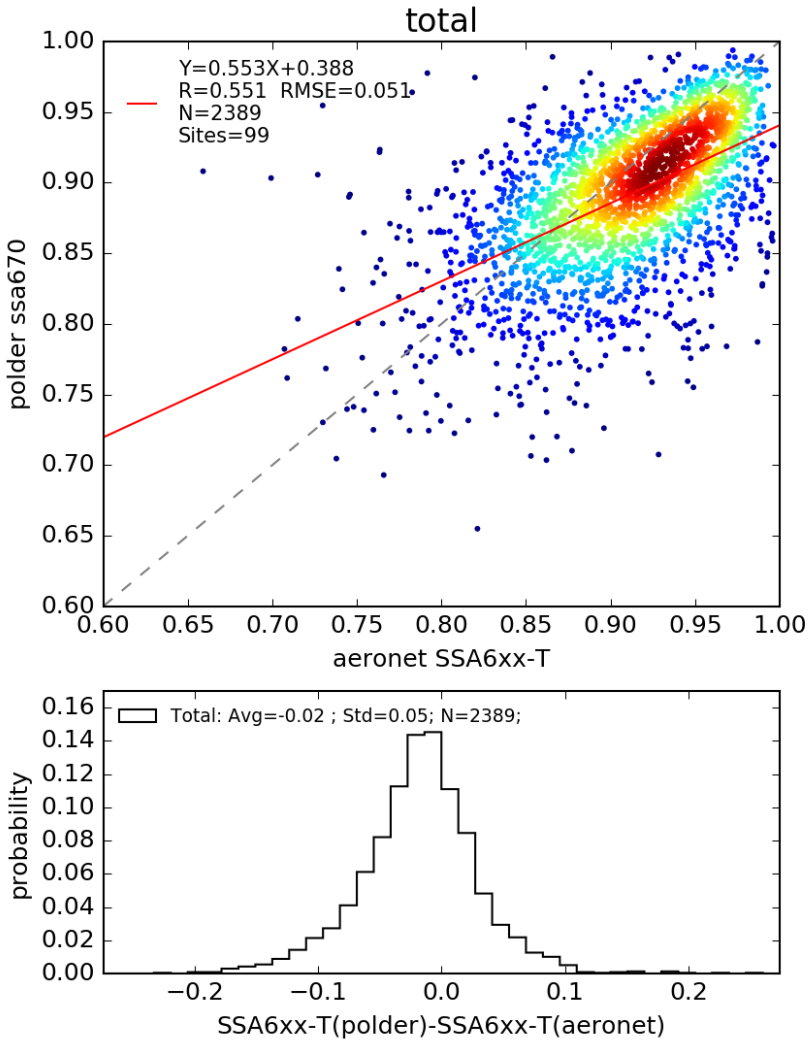
Smaller particles



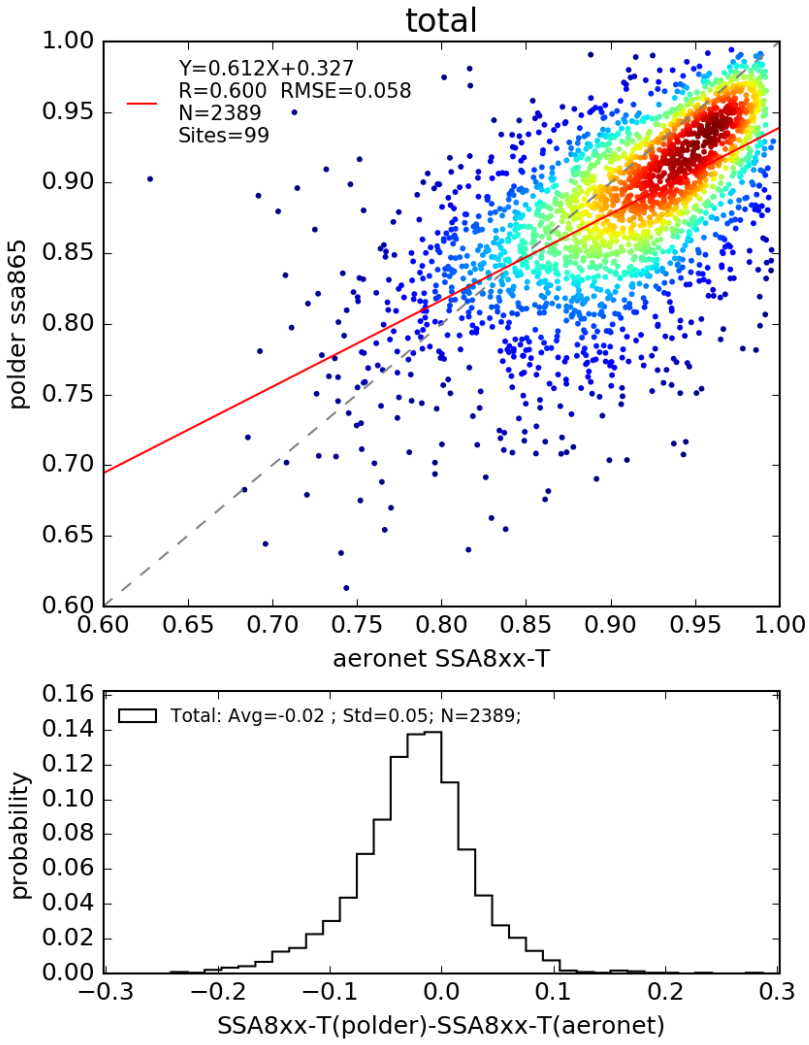
PARASOL Validation vs AERONET 2004 - 2013

Land + Ocean

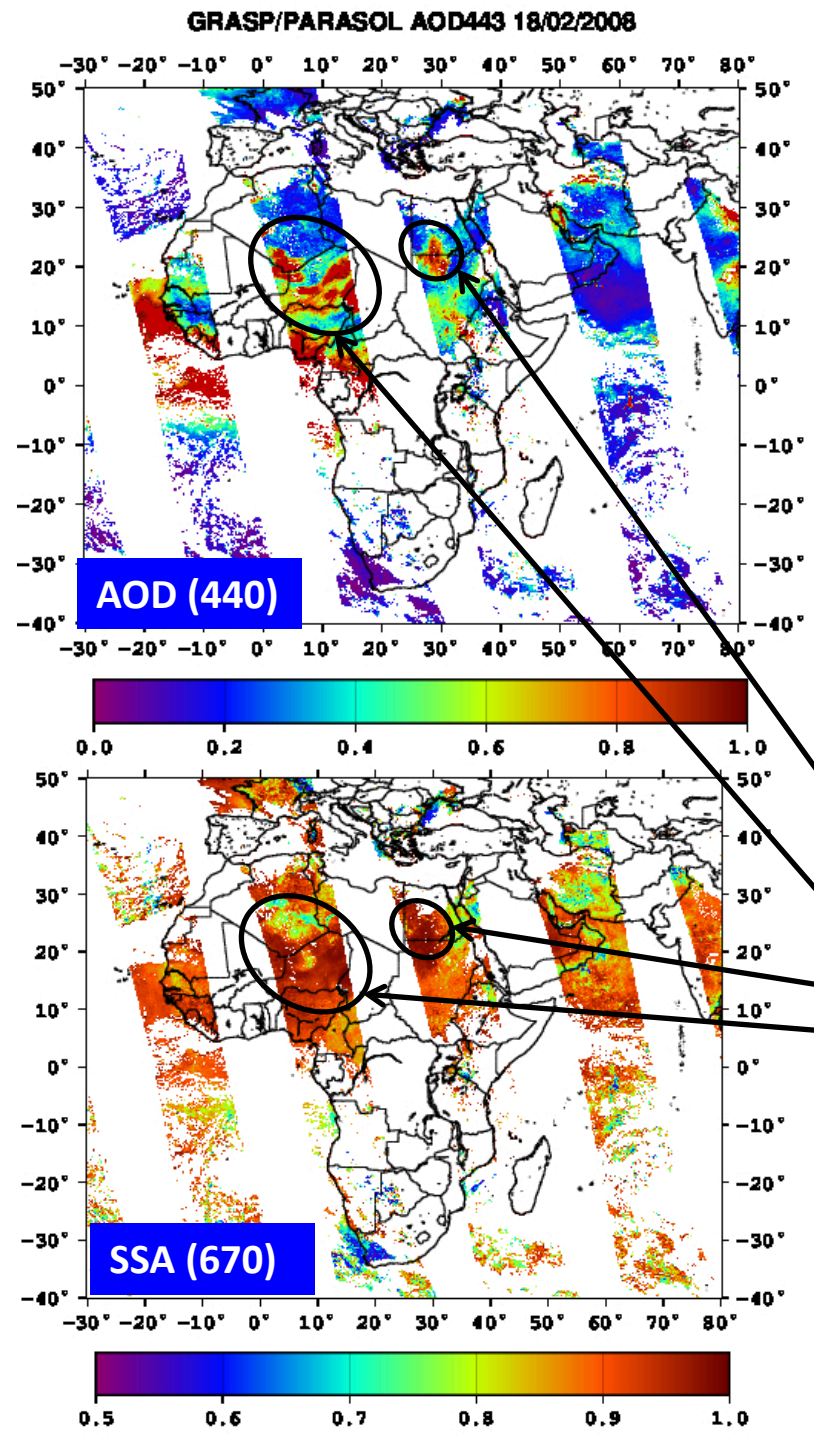
SSA(670) R=0.55

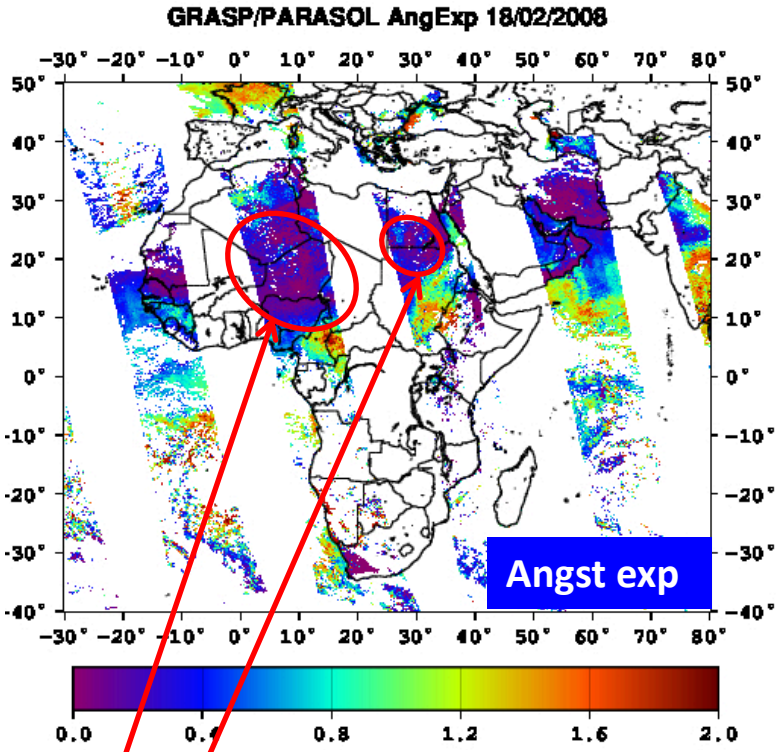


SSA(870) R=0.6



Dust detection with GRASP



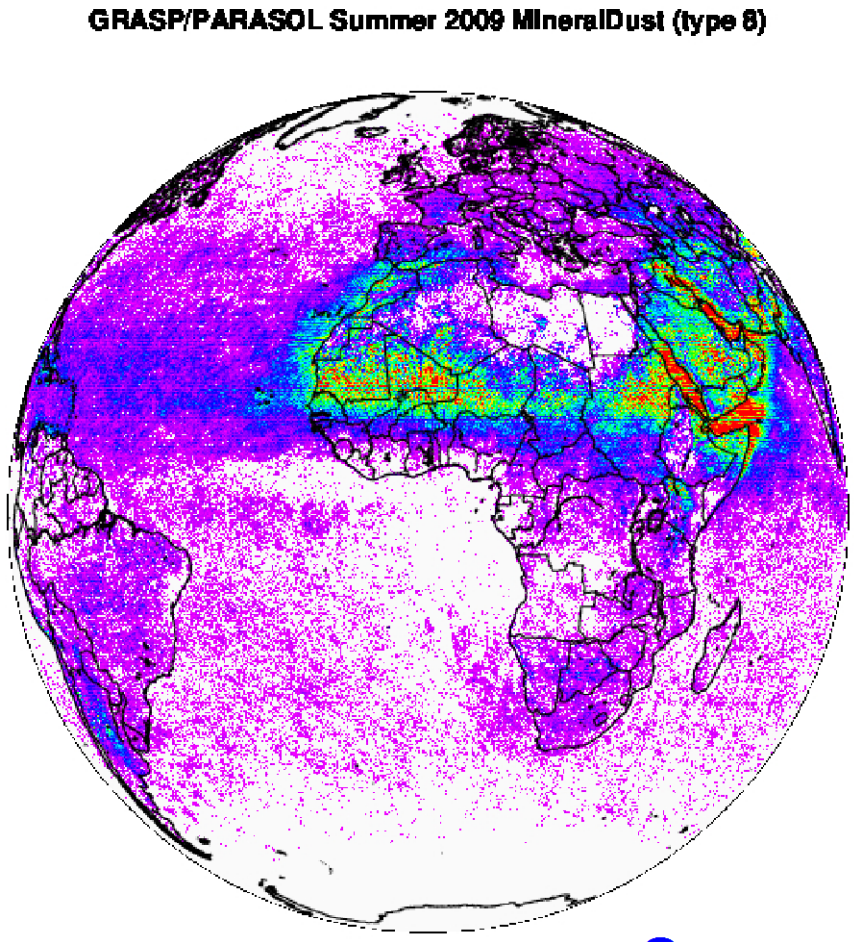


Dust events:

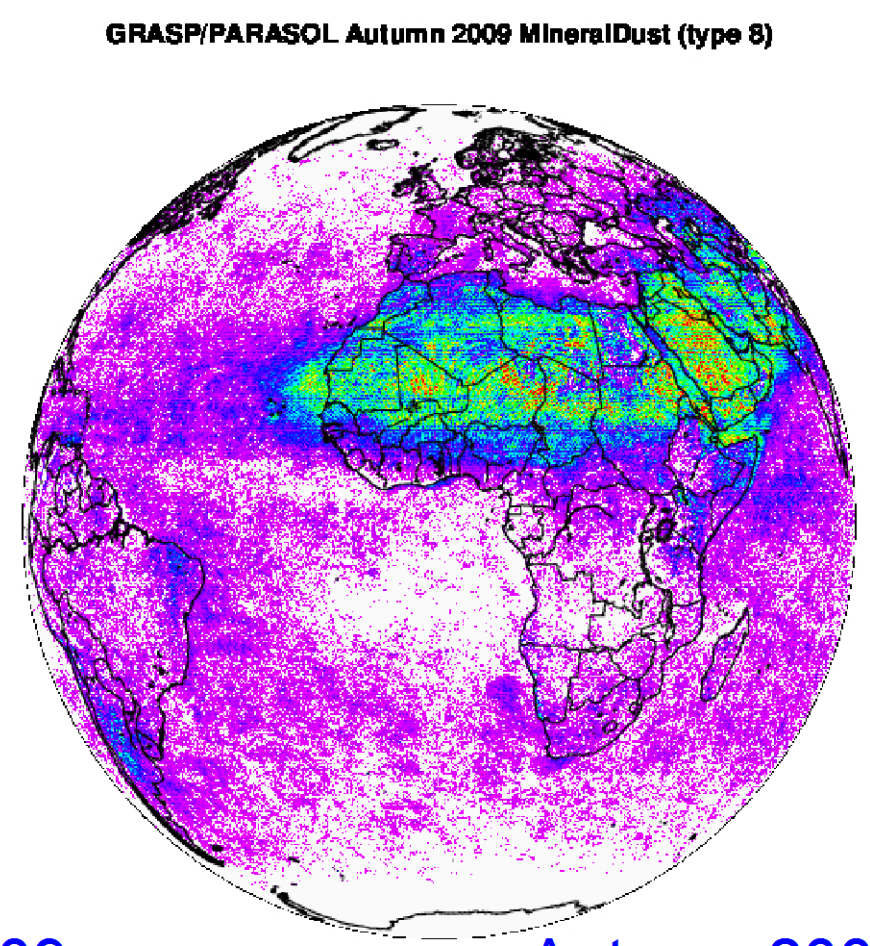
- ✓High AOD
- ✓Angstrom Exponent < 0.5
- ✓SSA (440 - 1020) > 0.9

Aerosol type detection with GRASP

Mineral dust frequency of occurrence



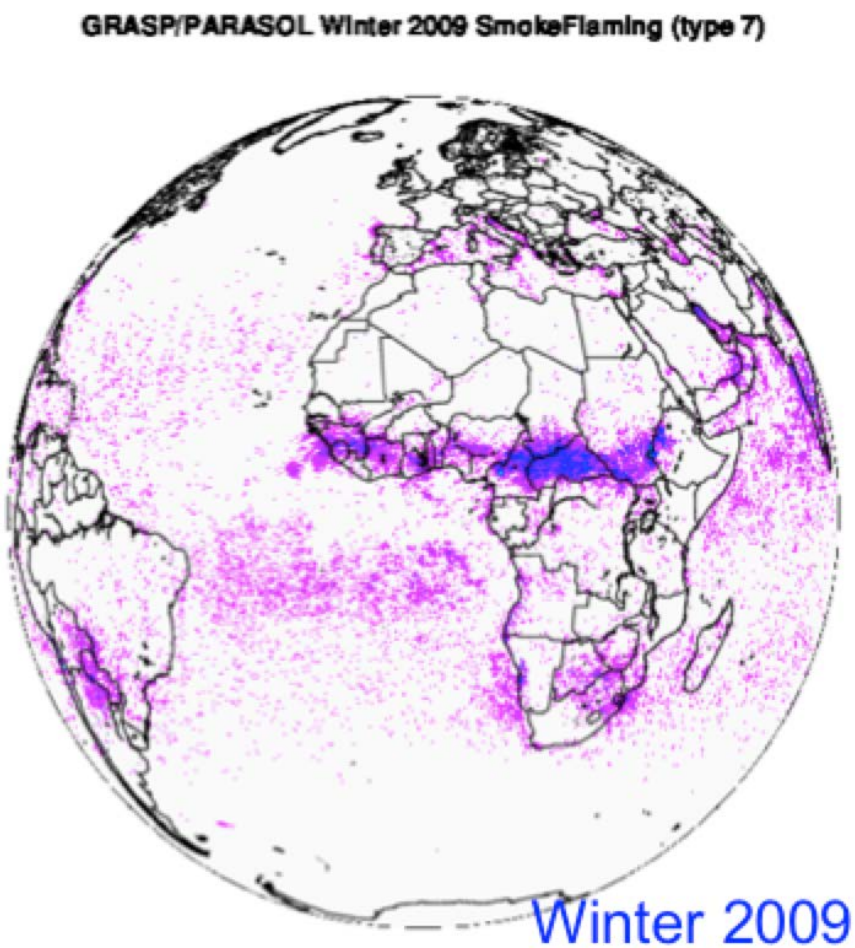
Summer 2009

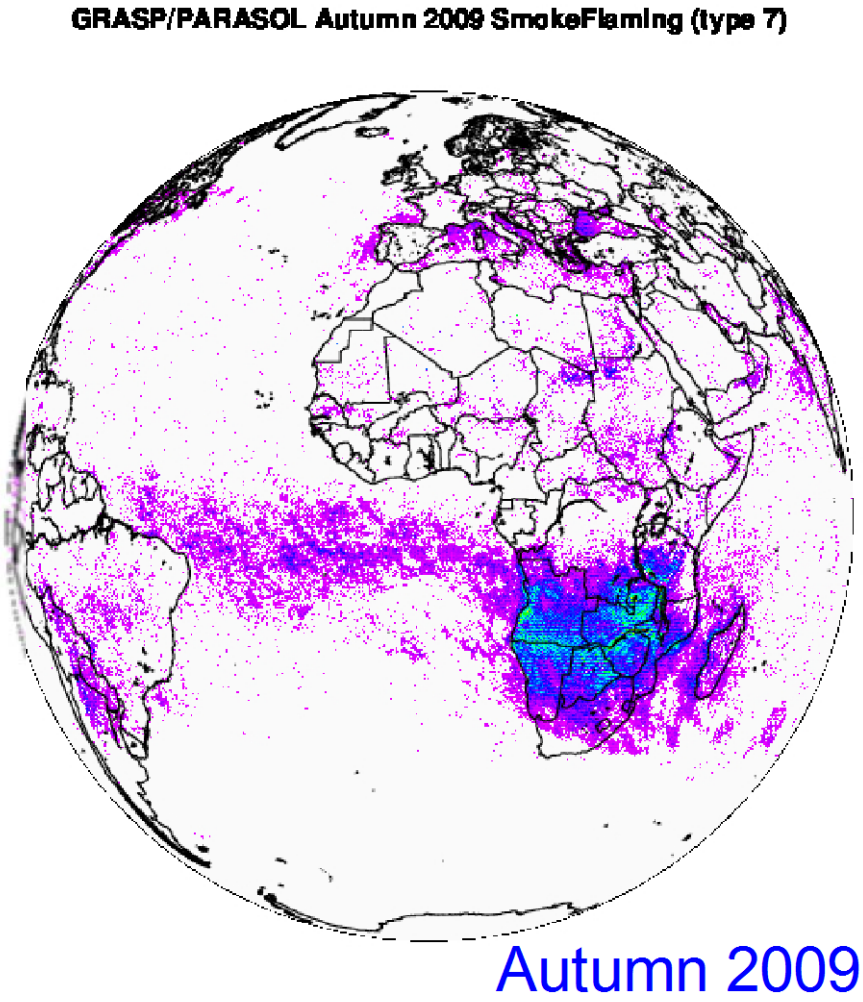


Autumn 2009

Aerosol type detection with GRASP

Smoke frequency of occurrence



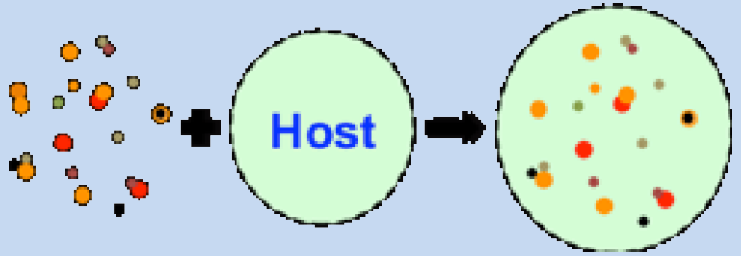


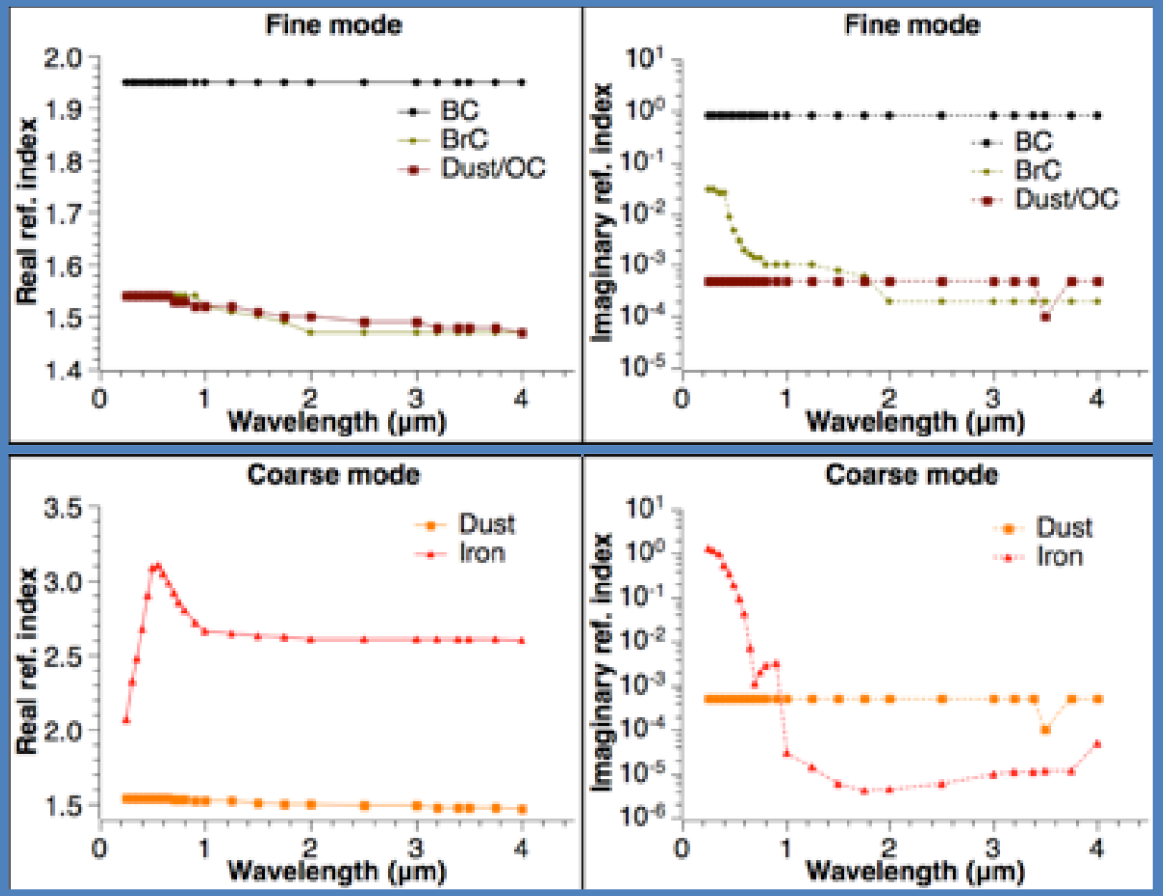
Chemical composition retrieval from POLDER and AERONET

Lei Li et al., *in preparation*

Schuster et al., 2005….

size-dependent Maxwell-Garnett mixture

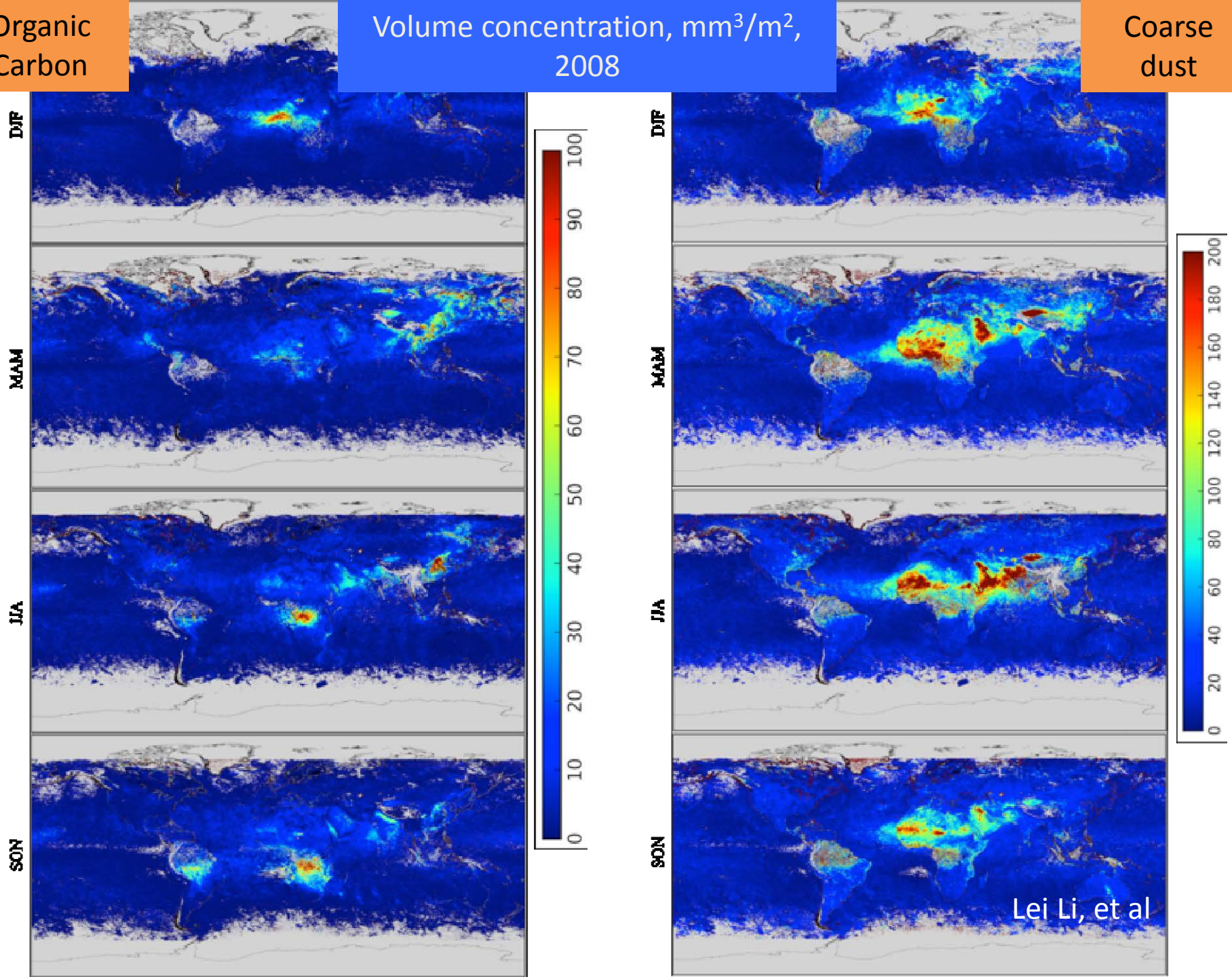




Organic Carbon

Volume concentration, mm^3/m^2, 2008

Coarse dust



GRASP
In principle, yes!

size distribution (spectral AOD)

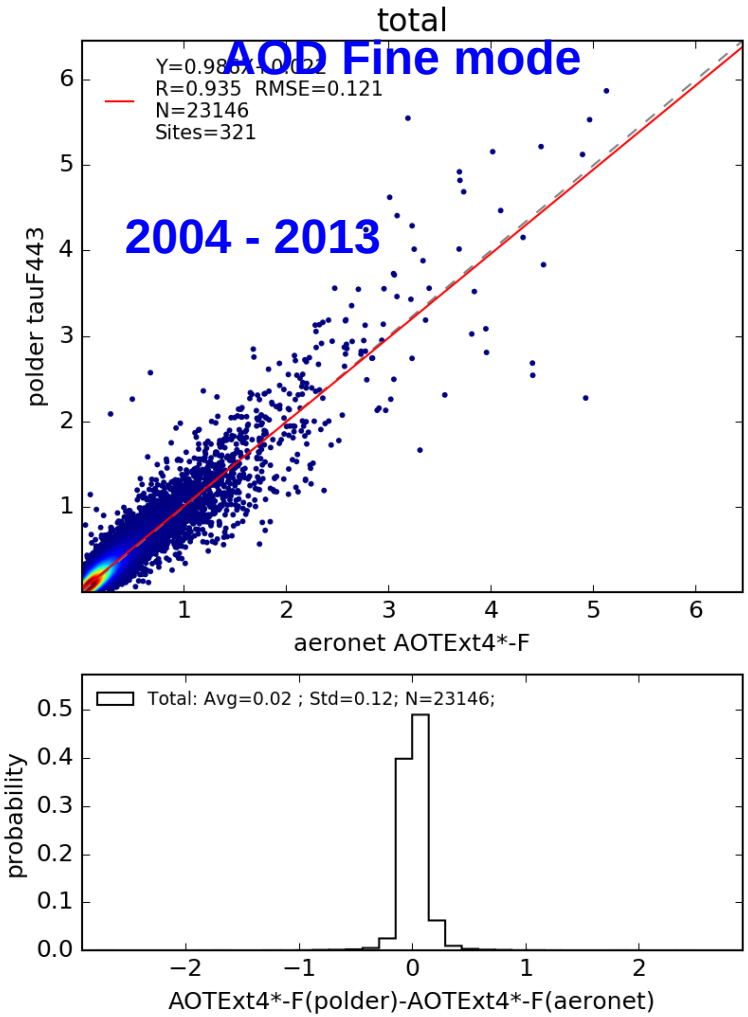
refractive index (~ water fraction)

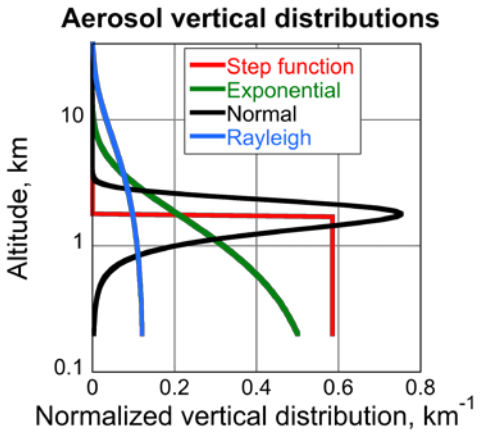
scale height

PM2.5 ?

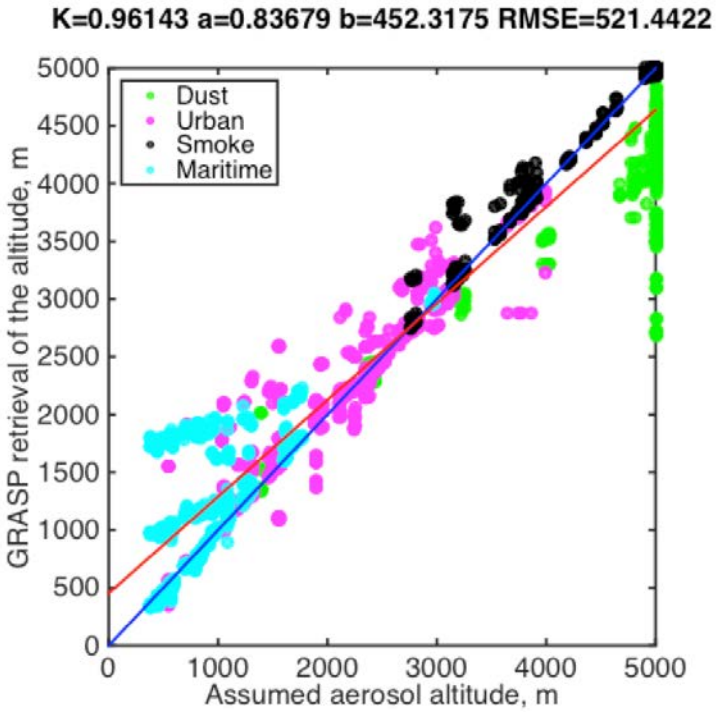
PM2.5 from polarimetry ?

PM 2.5 ~AOD(fine mode) + height

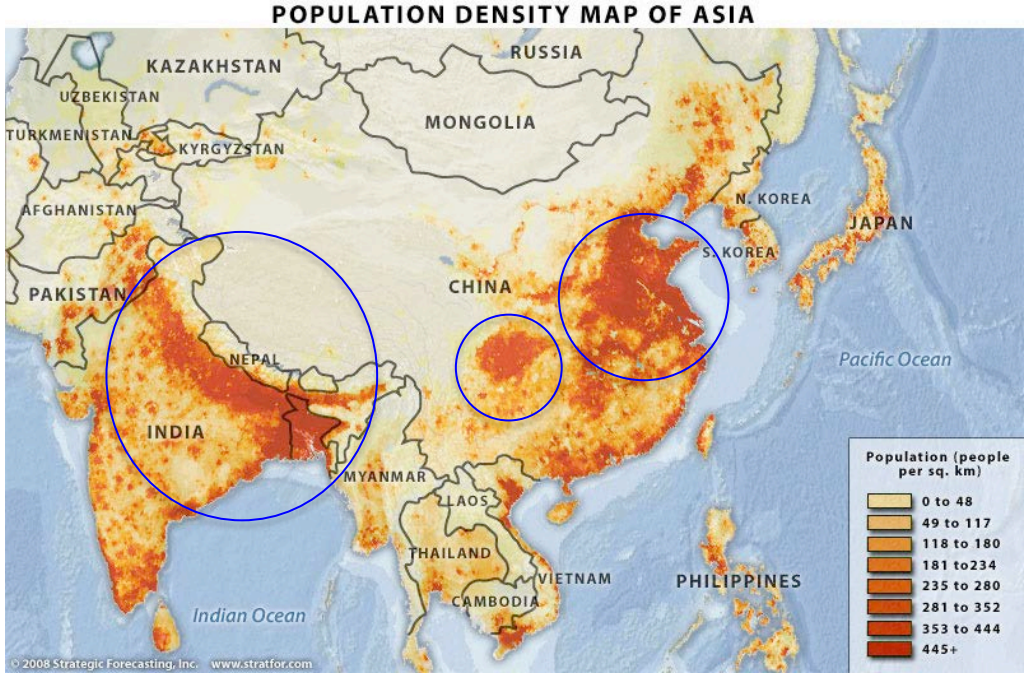




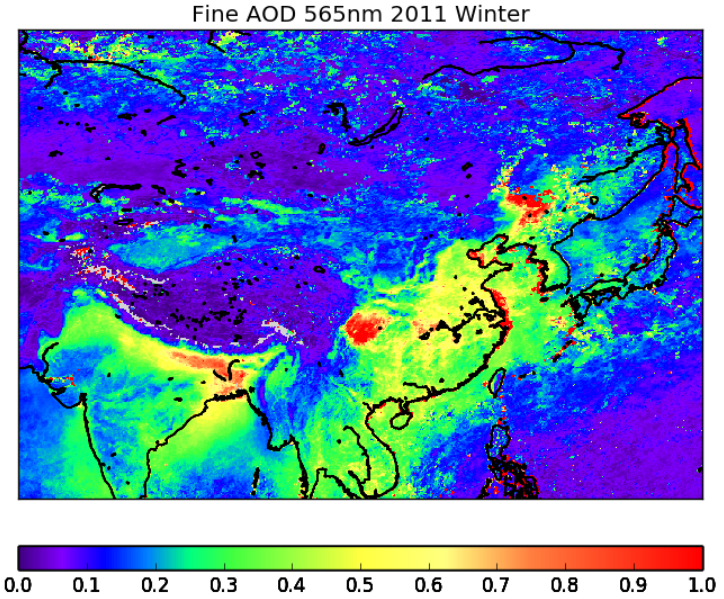
Scale height

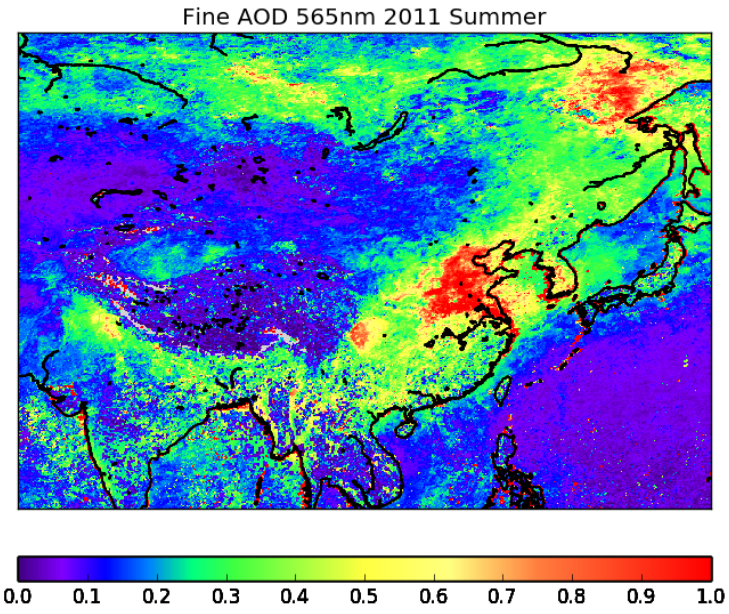


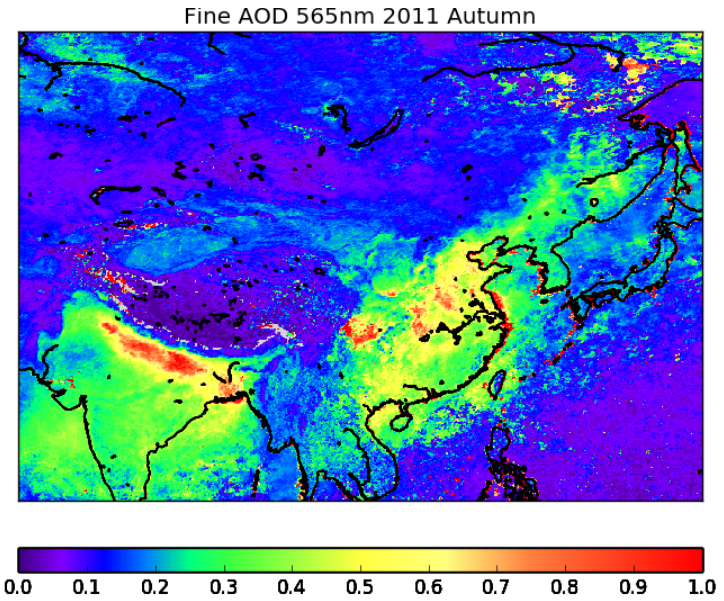
Correlation of population density and pollution



$AOD_{fine}(565)$



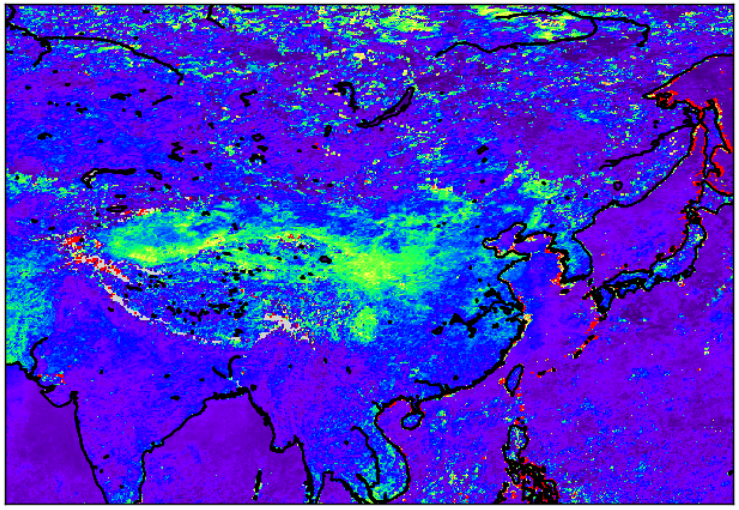


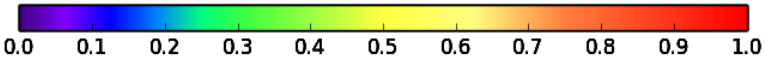


Distribution of coarse mode aerosol Asia

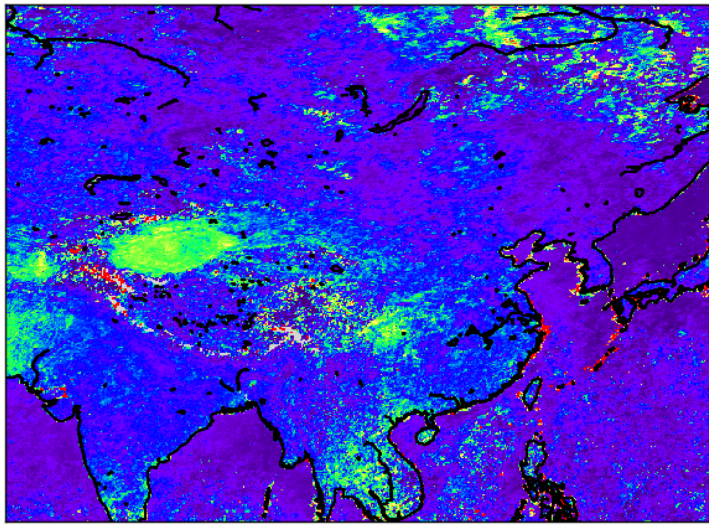
$AOD_{coarse}(565)$

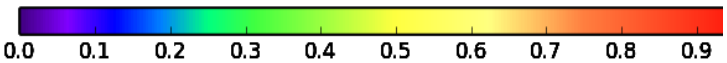
Coarse AOD 565nm 2011 Winter



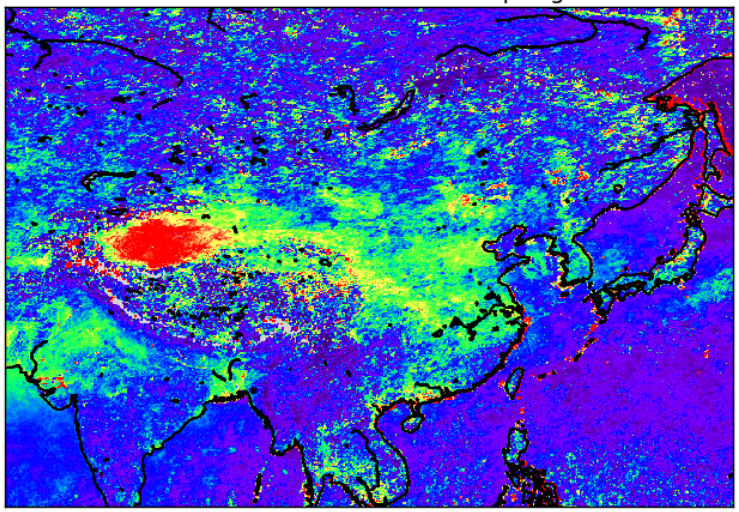


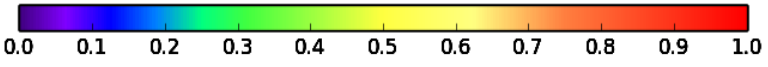
Coarse AOD 565nm 2011 Autumn



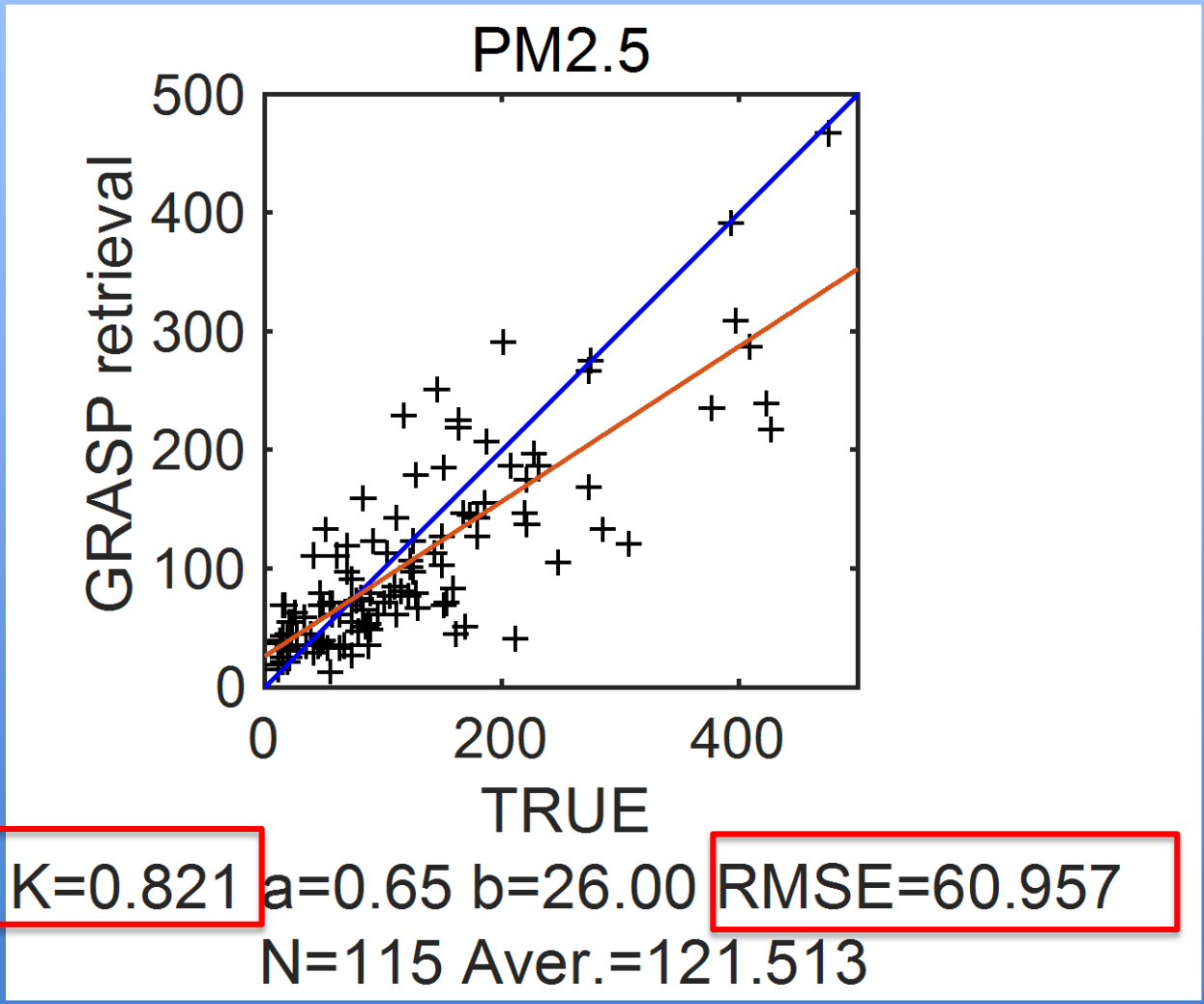


Coarse AOD 565nm 2011 Spring





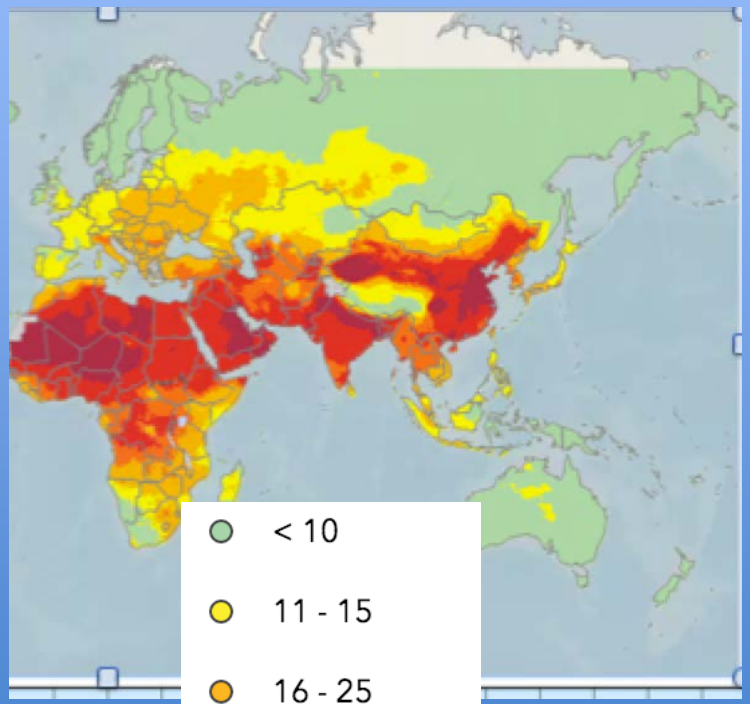
PARASOL/GRASP PM2.5 over Beijing 2009–2012



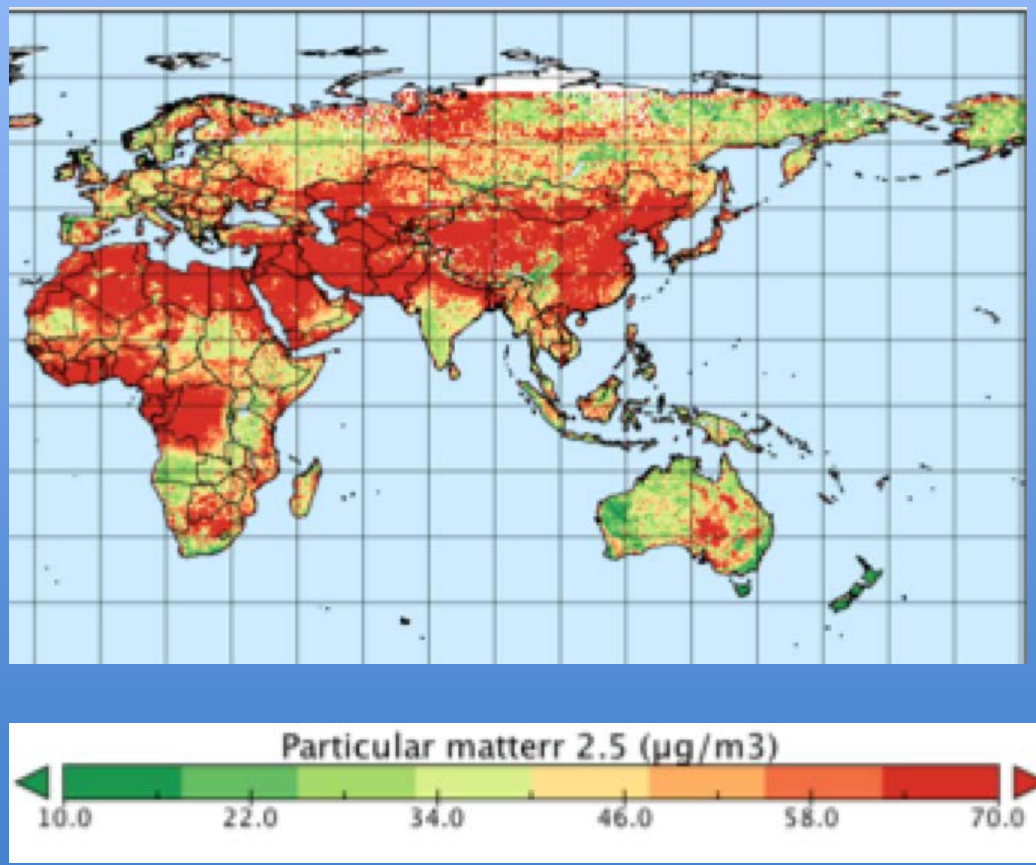
AOT>0.3, residual<3%

PM2.5 climatology

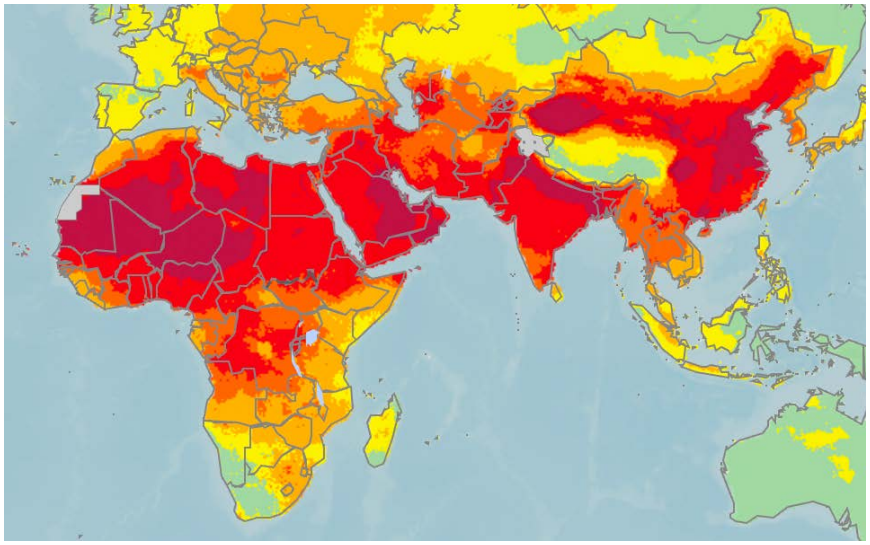
WHO Global Urban Ambient Air Pollution Database



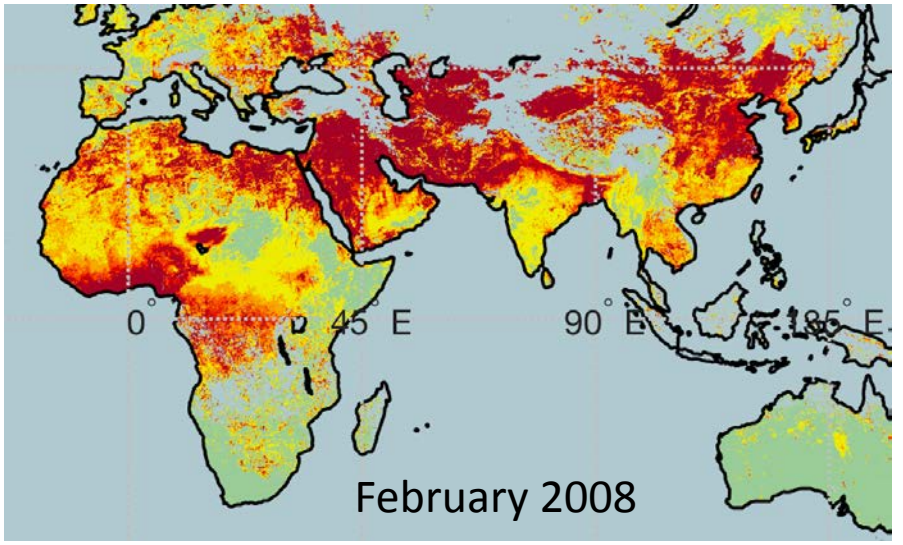
PARASOL/GRASP 2008

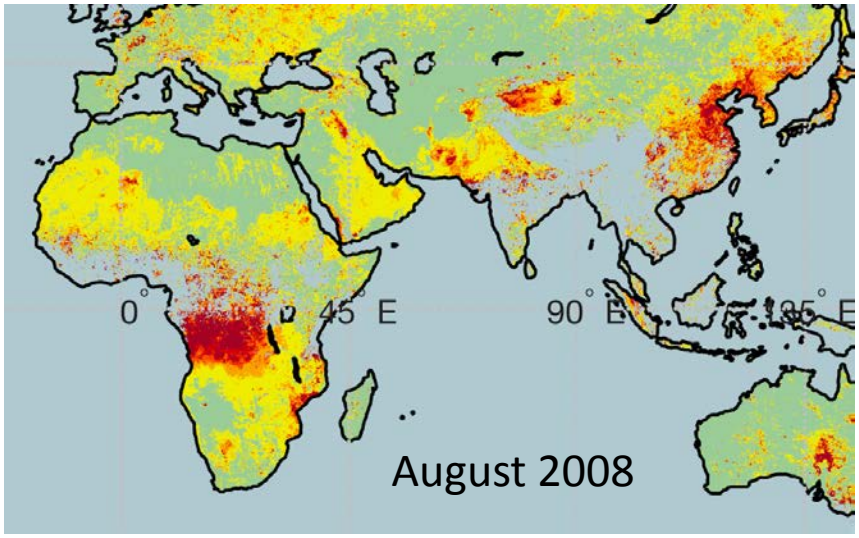


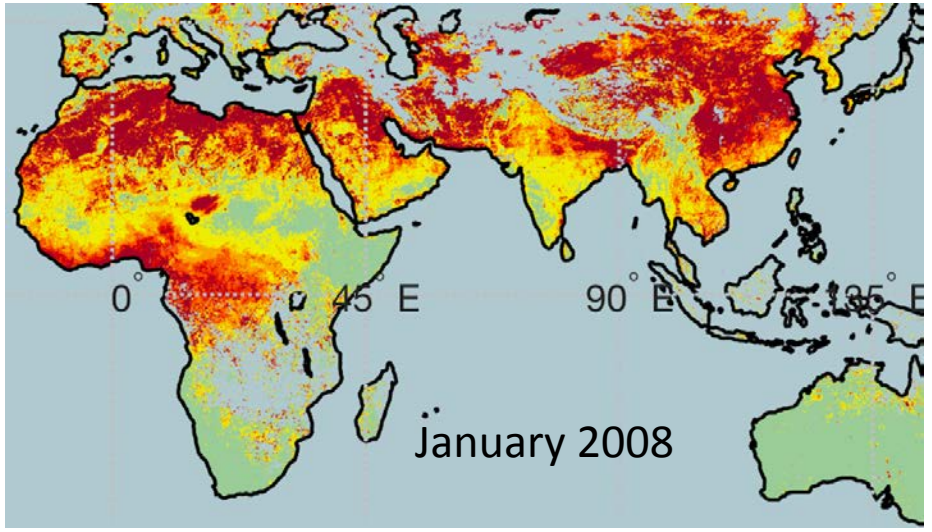
WHO Global Urban Ambient Air Pollution Database

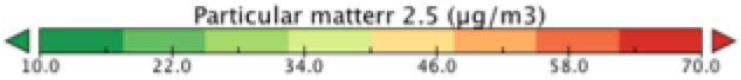


PARASOL/GRASP 2008

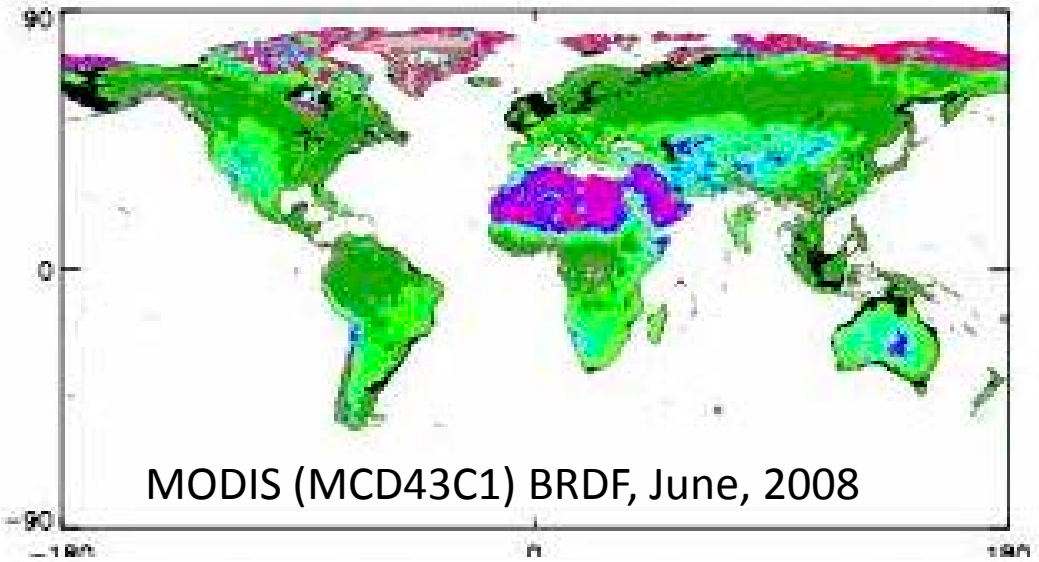


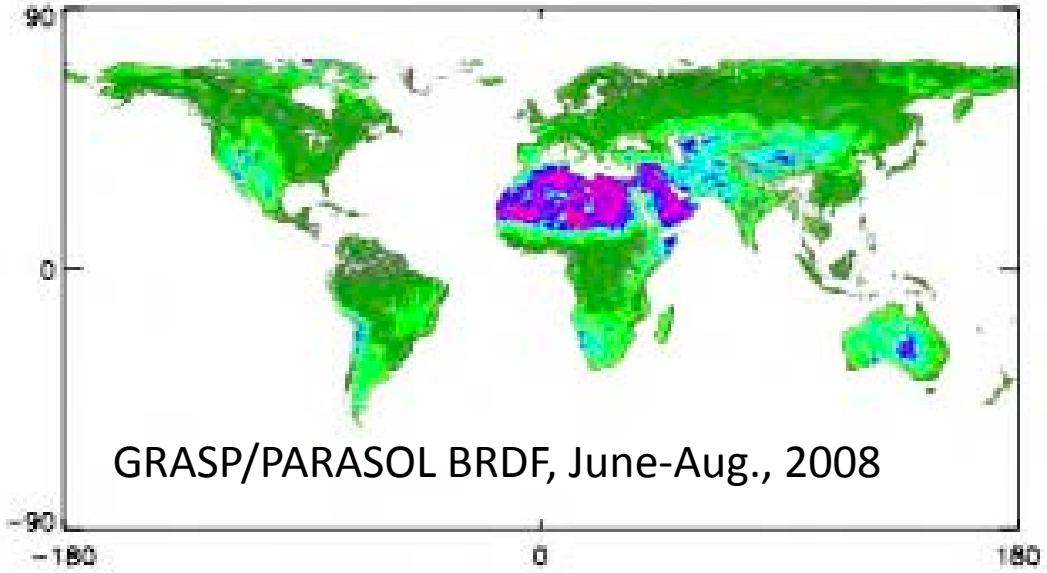


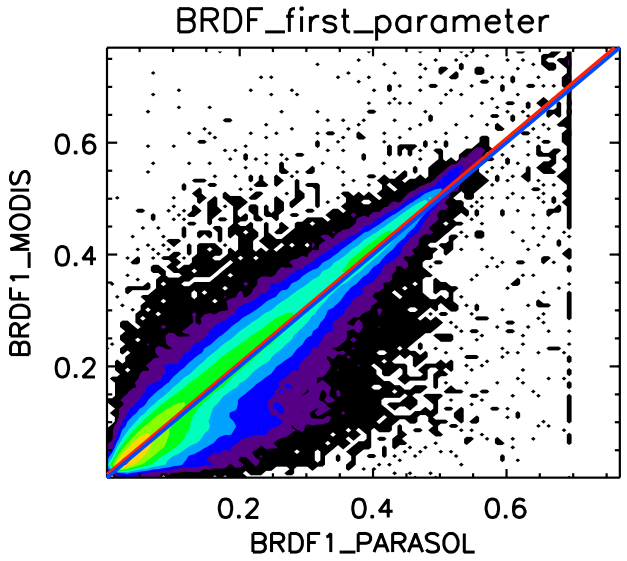


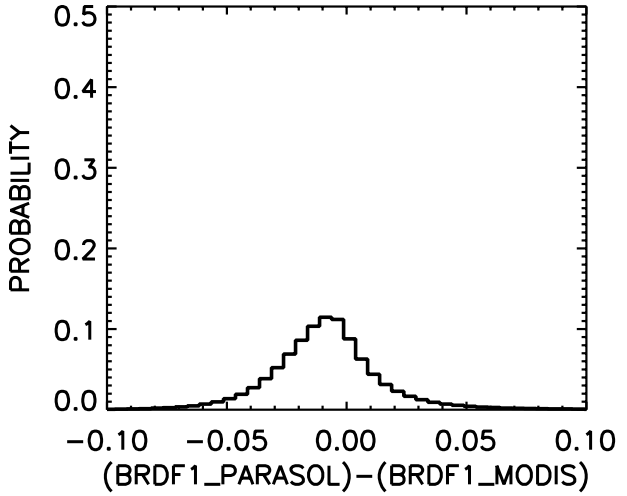


First parameter (670 nm) of Ross-Li BRDF, 2008



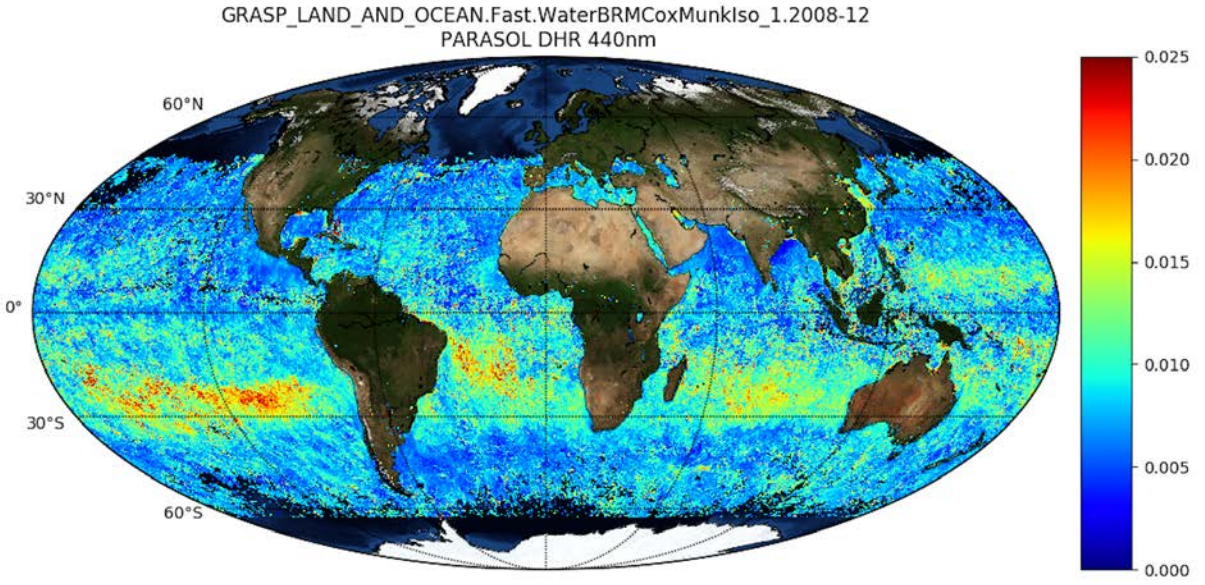






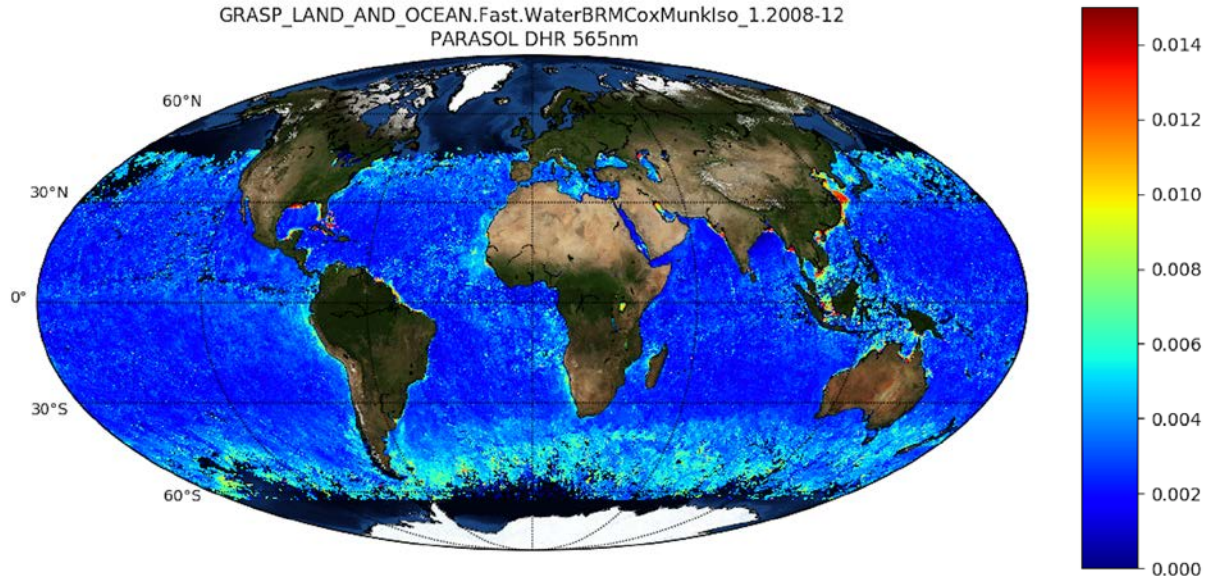
PARASOL water living radiance

December 2008,



« Blue » water

« clean »



« Green » water

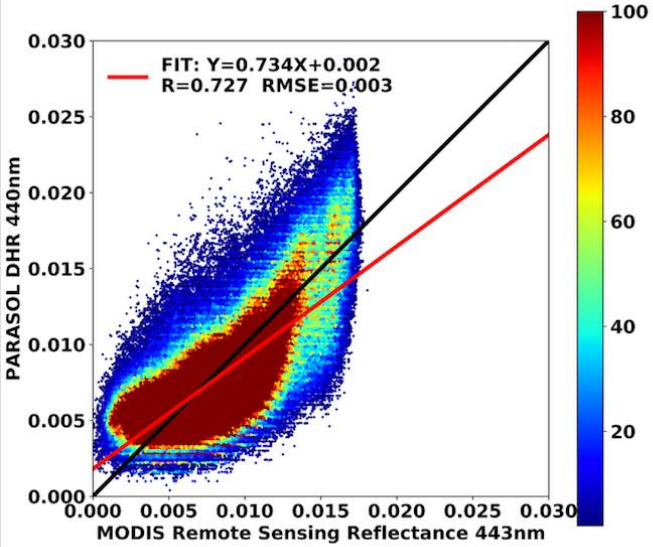
« bio active »,
bio-active (phytoplankton), etc.

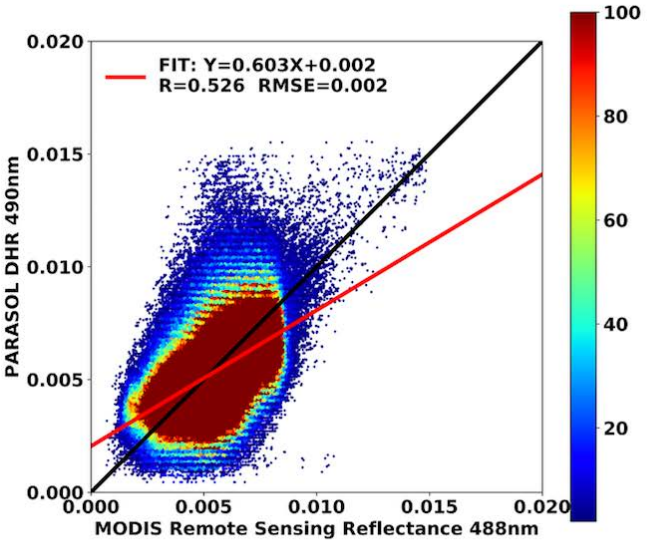
PARASOL 2008

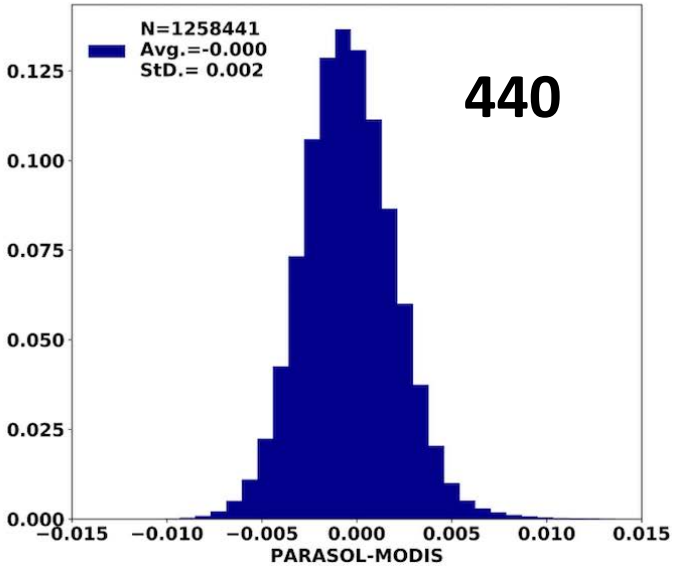
Water Leaving Radiances

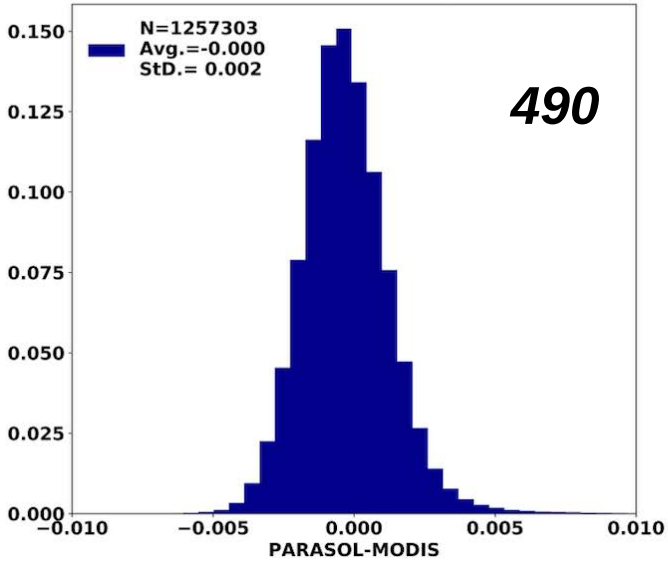
Preliminary result…

Correlation with MODIS



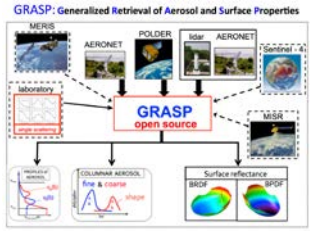






GRASP
In principle, yes!

"Strength and weaknesses: "



Concepts:

- ✓ Based on rigorous stat. optimization (can use multiple a priori constraints, e.g. multi-pixel, etc.);
- ✓ Uses direct RT calculations;
- ✓ Versatile (applicable to different sensors and retrieves different parameters);
- ✓ Designed for multi-sensor retrieval (satellite, polar and geostationary, ground-based, airborne, etc.);

Positive practical features:

- ✓ High accuracy (at least with synthetic data);
- ✓ Many parameters (e.g. retrieval of both aerosol and surface properties);
- ✓ High "transparency":
  - no location specific a priori constraints;
  - the constraints are the same globally;
  - generally retrieval is at original resolution;
  - no climatologies, the same initial guess (can be changed);
  - generally retrieval is at original resolution (for POLDER, and 3MI);
- ✓ Rigorous (allows error estimation – *to be demonstrated*);
- ✓ "Self evolving": (tested and improved in many applications, etc.);
  - tested and improved in many applications
  - the constraints are the same globally;
  - easily adaptable to new applications (synergies, etc.);

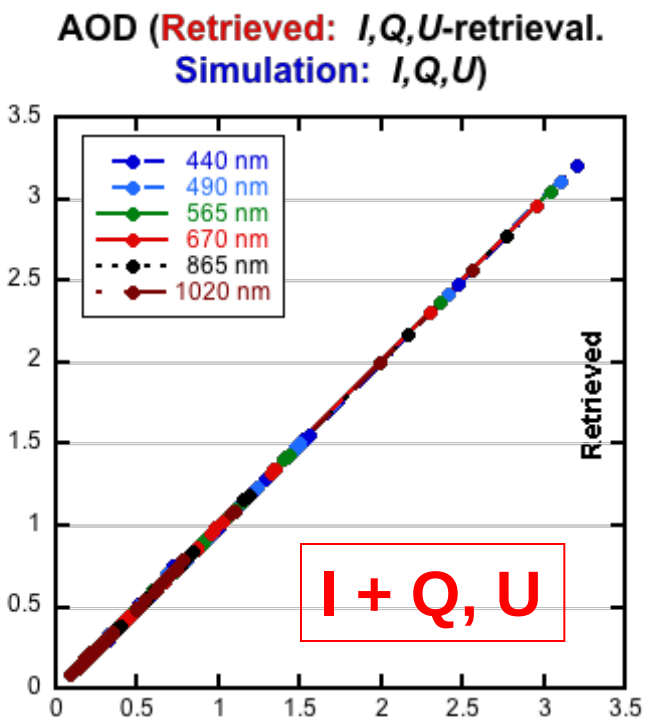
Weaknesses:

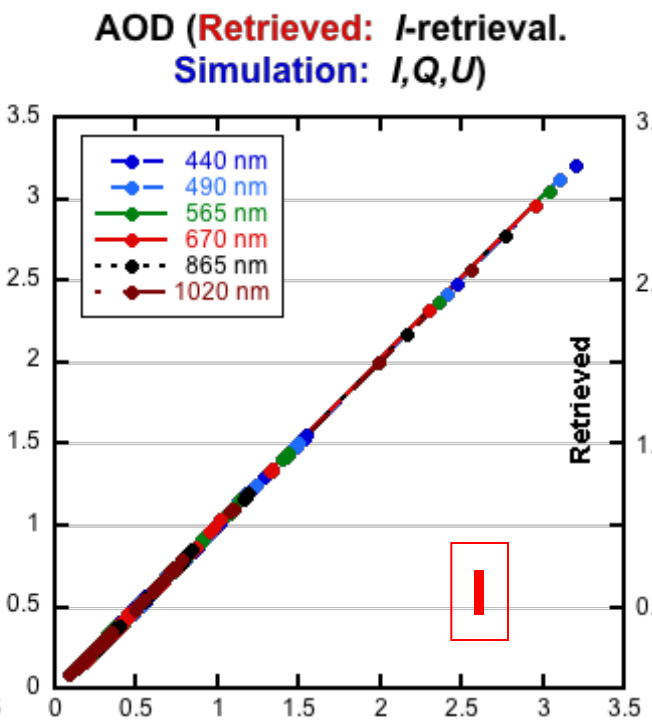
- ✓ Slower than LUT retrievals (was highly optimized, efforts are continuing).
- ✓ Vulnerable to cloud-screening and data preparation (to be addressed soon).
- ✓ Application requires knowledge for new users (many efforts are put on explanations/illustrations);
- ✓ etc.

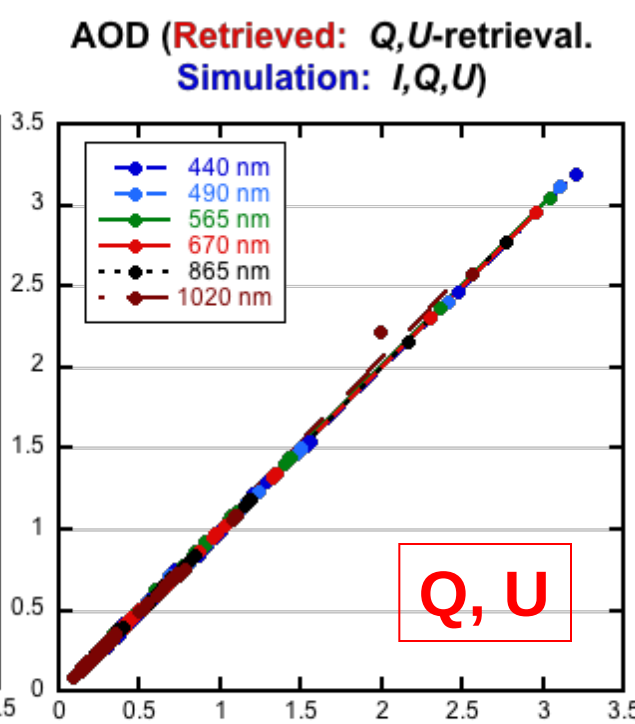
Test with synthetic measurements

Aerosol Optical Thickness

PARASOL over Banizoumbou in January, February 2008





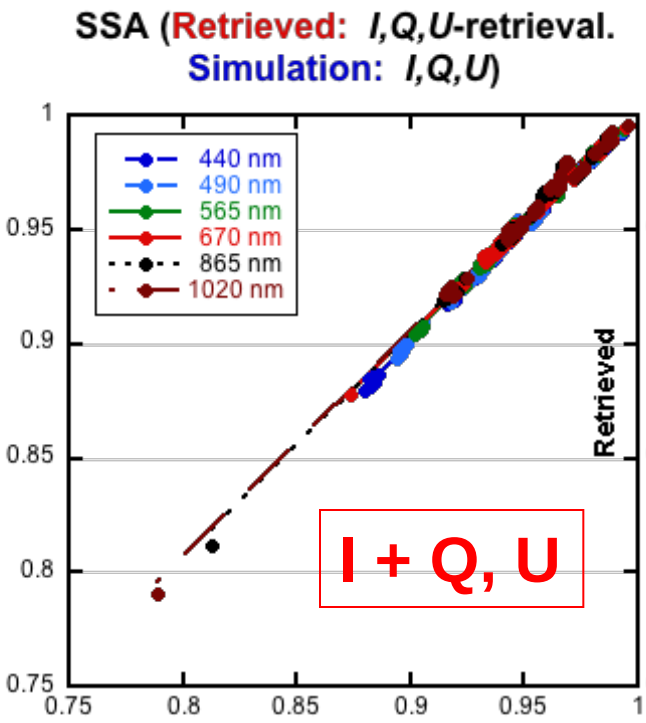


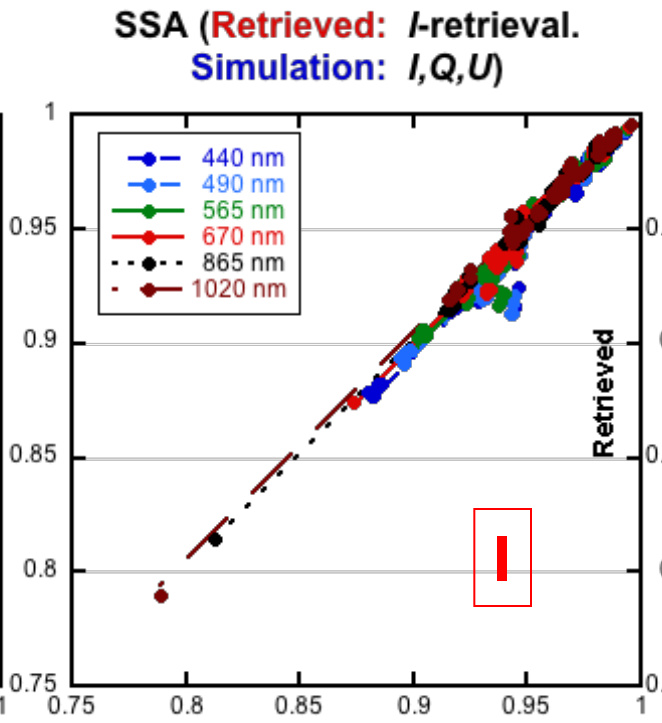
y = -0.0043839 + 1.0023x R= 0.99995	y = -0.0071561 + 1.008x R= 0.99987	y = -0.0052906 + 1.0007x R= 0.99986
y = -0.0045597 + 1.0029x R= 0.99996	y = -0.007389 + 1.0073x R= 0.99986	y = 0.0010661 + 1.0003x R= 0.99995
y = -0.0056832 + 1.0029x R= 0.99997	y = -0.0088212 + 1.0087x R= 0.99985	y = 0.00096879 + 1.0044x R= 0.99991
y = -0.0052555 + 1.0031x R= 0.99998	y = -0.0092578 + 1.0092x R= 0.99987	y = 0.0012797 + 0.99963x R= 0.99997
y = -0.0057708 + 1.0041x R= 0.99998	y = -0.0072864 + 1.0071x R= 0.99989	y = 0.0016497 + 0.99921x R= 0.99997
y = -0.0053979 + 1.0049x R= 0.99996	y = -0.005577 + 1.0055x R= 0.99989	y = -0.011559 + 1.0302x R= 0.99806

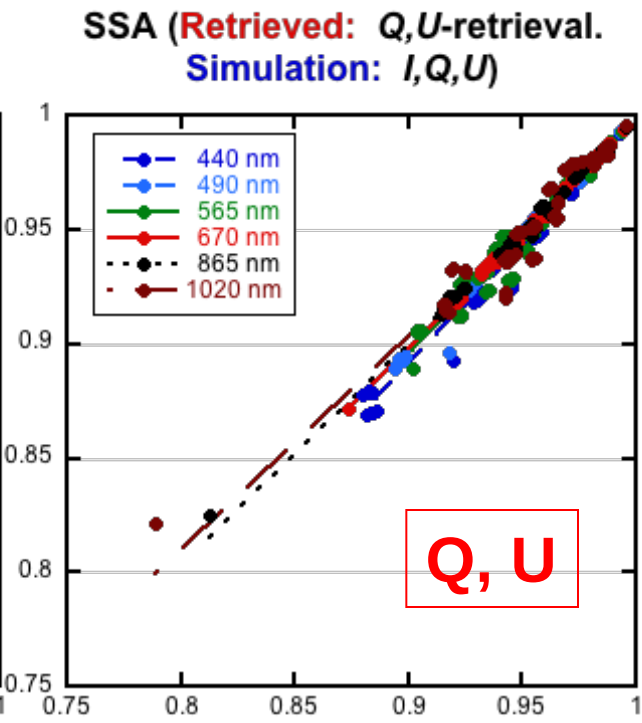
Test with synthetic measurements

Single Scattering Albedo

PARASOL over Banizoumbou in January, February 2008



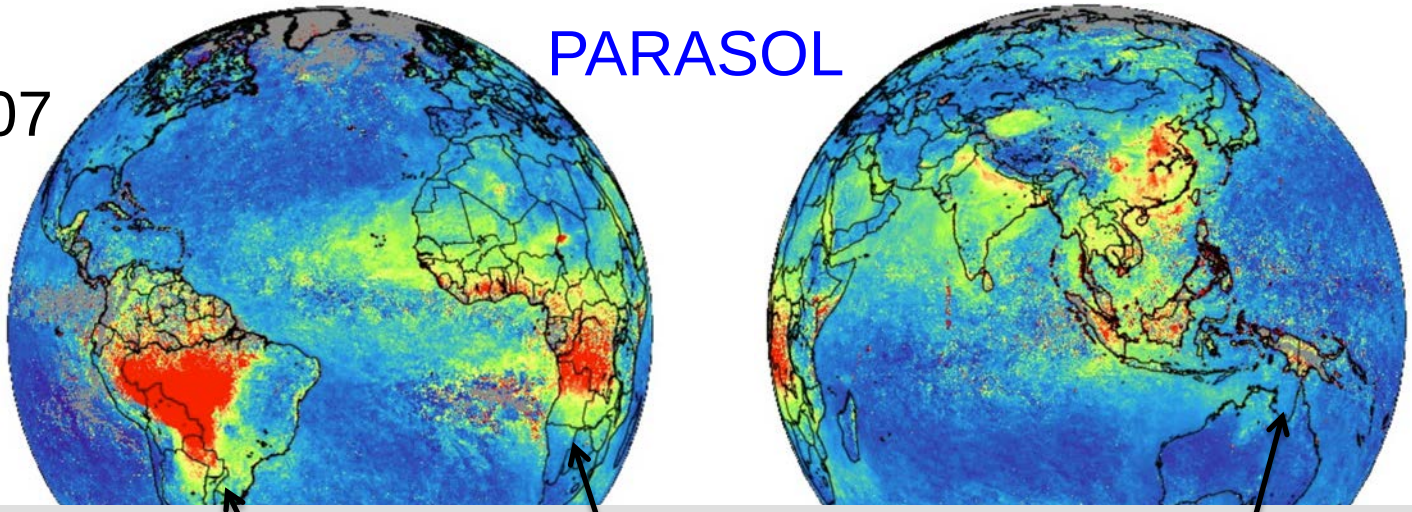


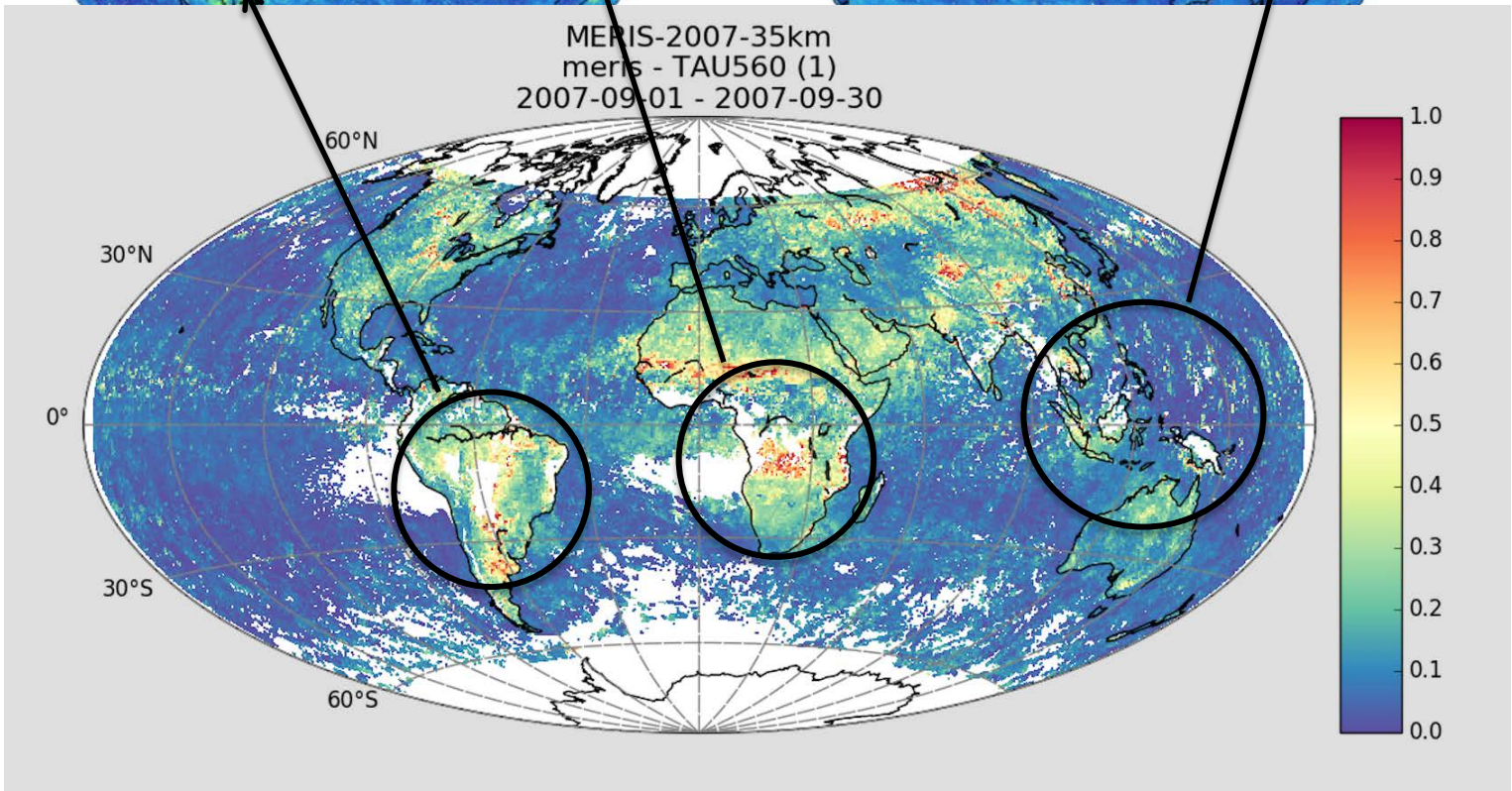


I + Q, U	I	Q, U
y = -0.0029473 + 1.0043x R= 0.99908	y = -0.060718 + 1.0609x R= 0.98367	y = -0.084303 + 1.0834x R= 0.98944
y = 0.0052418 + 0.99605x R= 0.99862	y = -0.065772 + 1.0666x R= 0.97889	y = -0.035547 + 1.0356x R= 0.99707
y = 0.017893 + 0.9843x R= 0.99775	y = -0.058311 + 1.0604x R= 0.9817	y = -0.040899 + 1.04x R= 0.98086
y = 0.031334 + 0.97052x R= 0.99709	y = -0.036232 + 1.0388x R= 0.98726	y = -0.022387 + 1.0219x R= 0.9984
y = 0.016615 + 0.98672x R= 0.99583	y = -0.00051278 + 1.0029x R= 0.99568	y = 0.023316 + 0.9743x R= 0.99565
y = 0.019672 + 0.9836x R= 0.99633	y = 0.014386 + 0.98835x R= 0.99588	y = 0.067708 + 0.92724x R= 0.95841

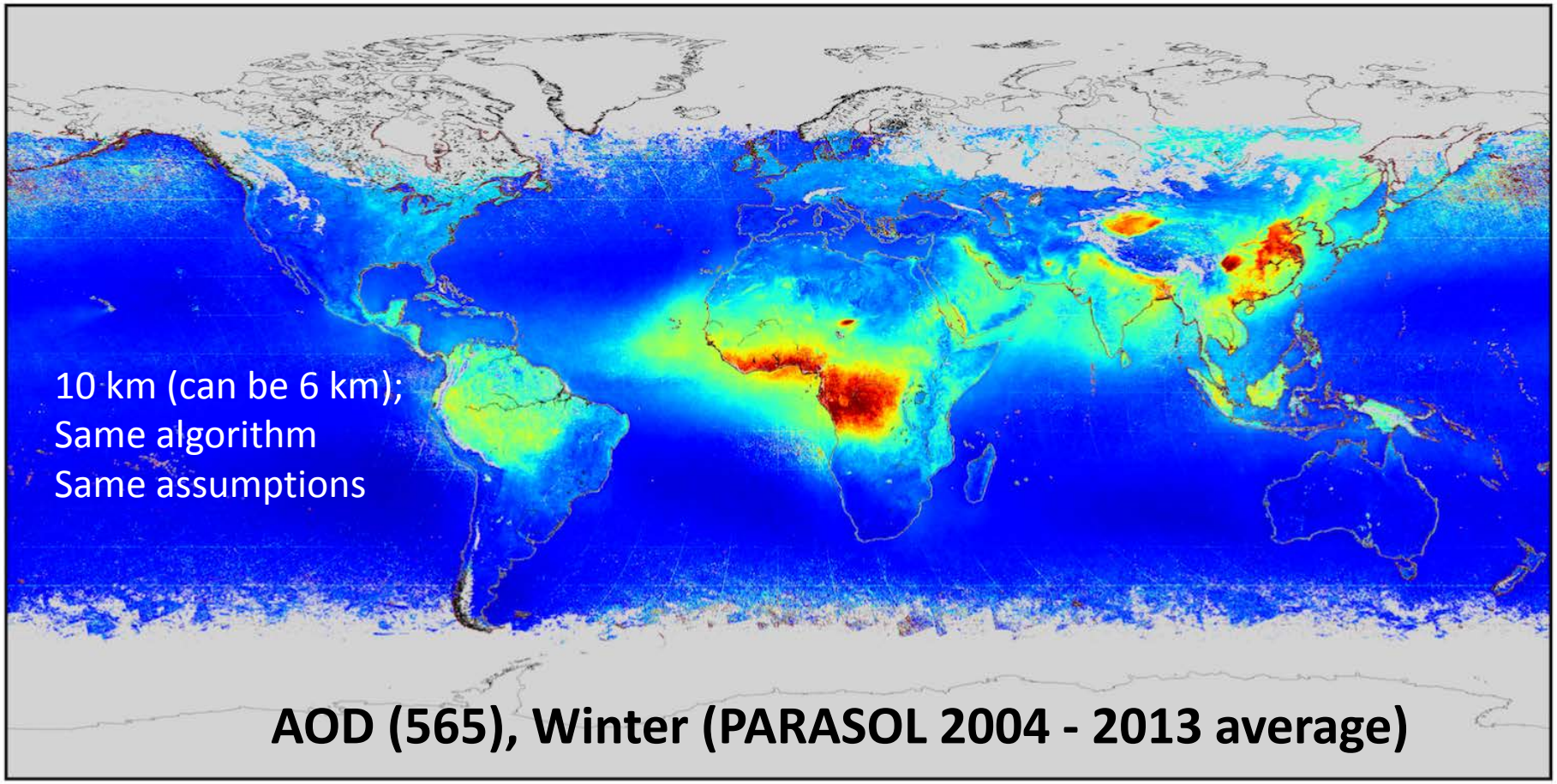
Fall, 2007

PARASOL

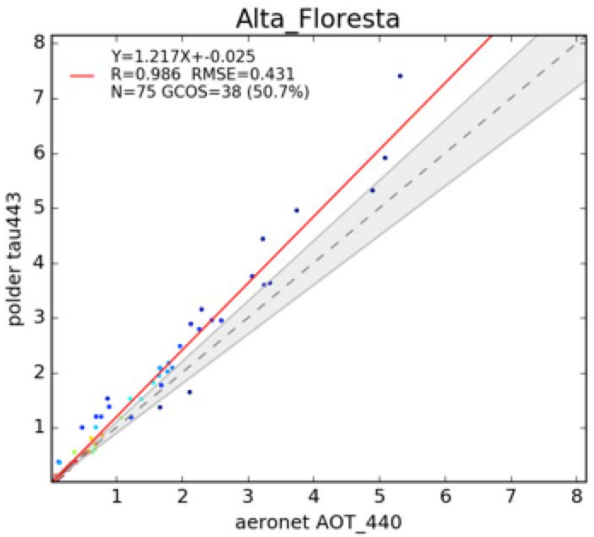


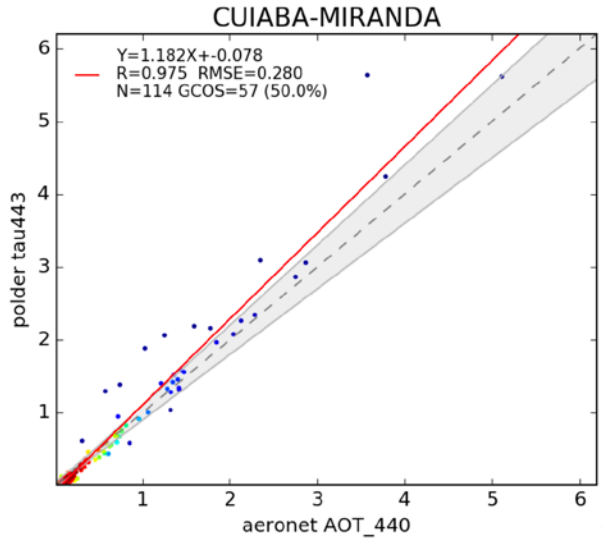


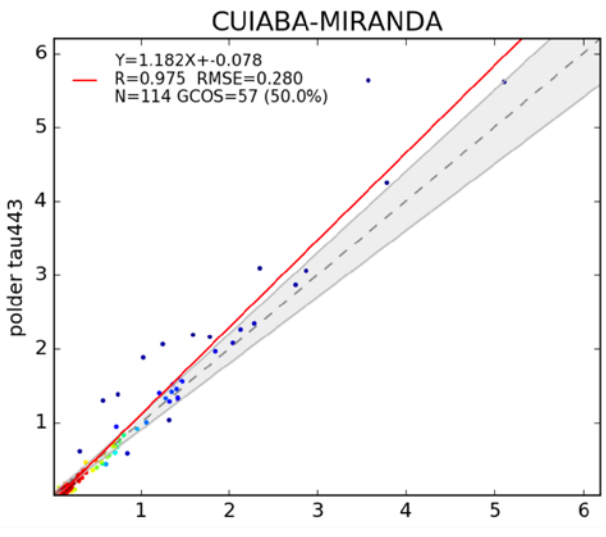
PARASOL/GRASP 2004- 2013 product has been generated

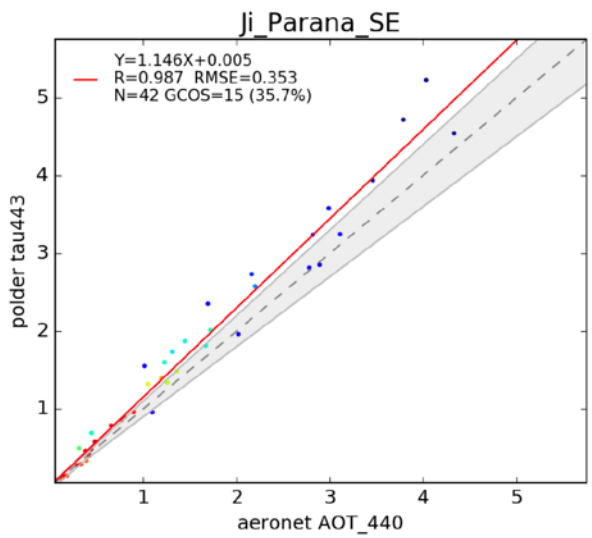


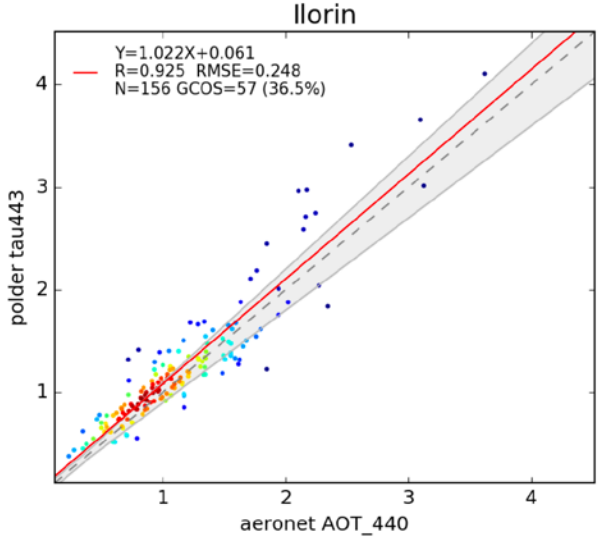
Validation against AERONET for high AOD biomass cases

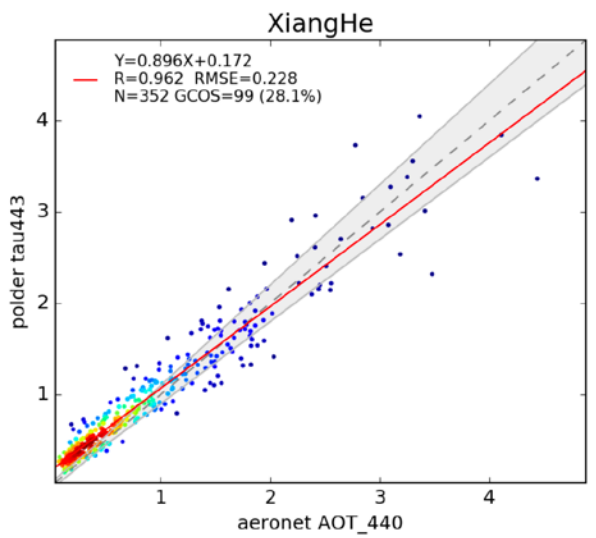




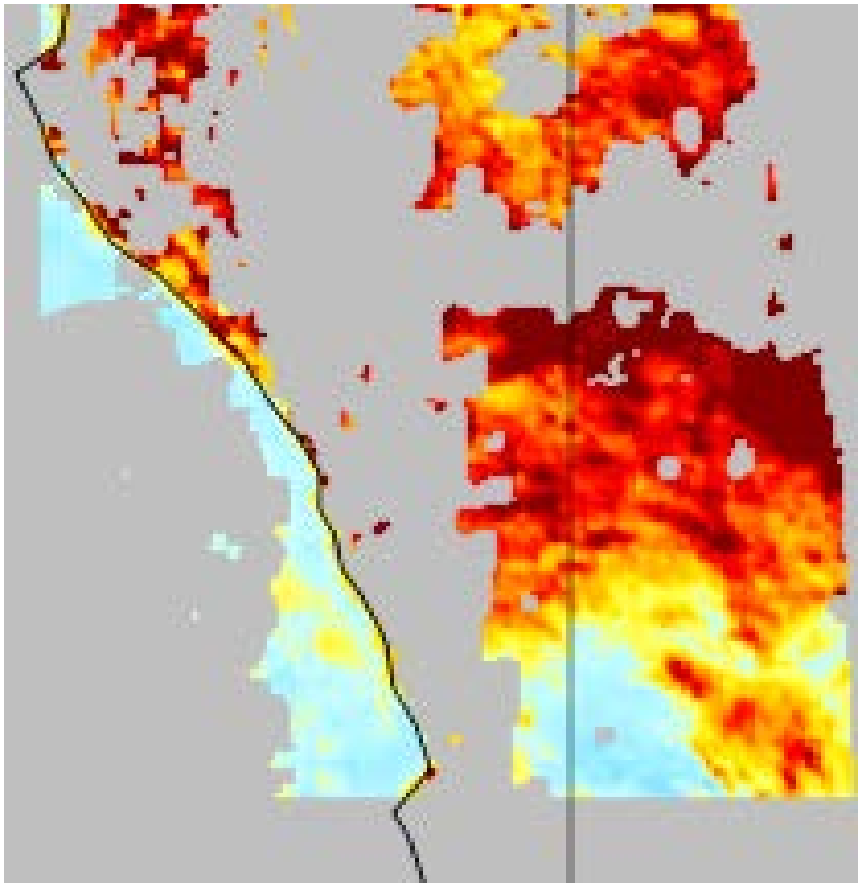


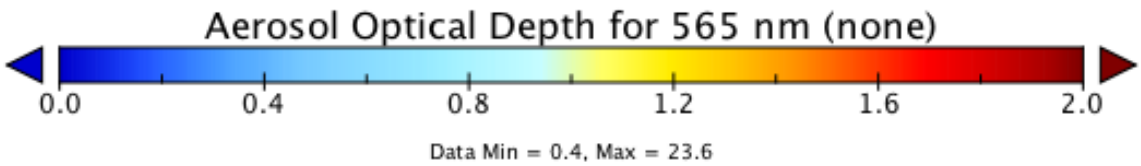






Biomass burning. Mongu region, August, 3, 2013

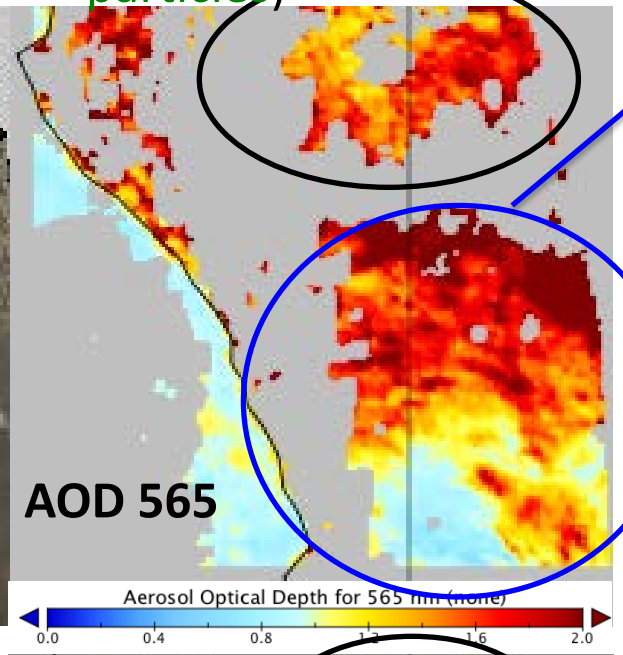


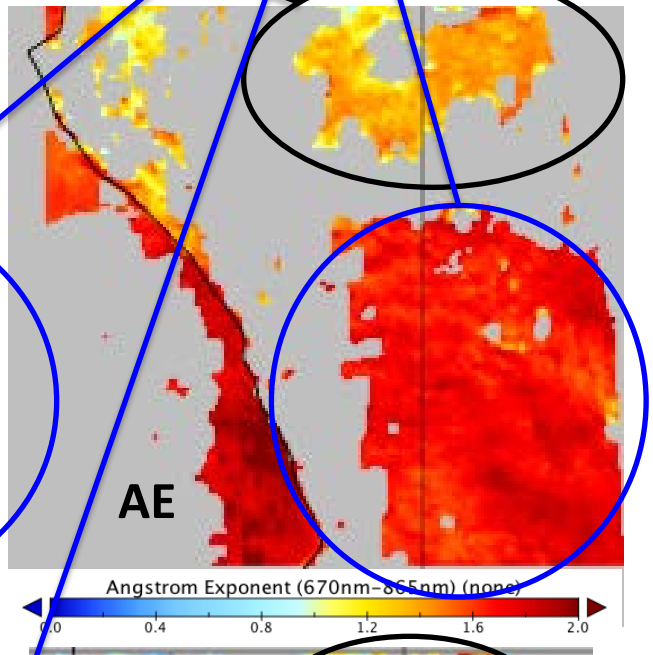


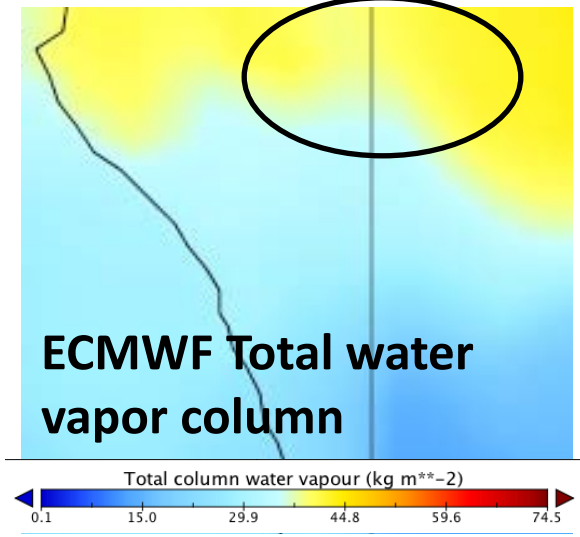
Biomass burning. Africa, August, 3, 2013

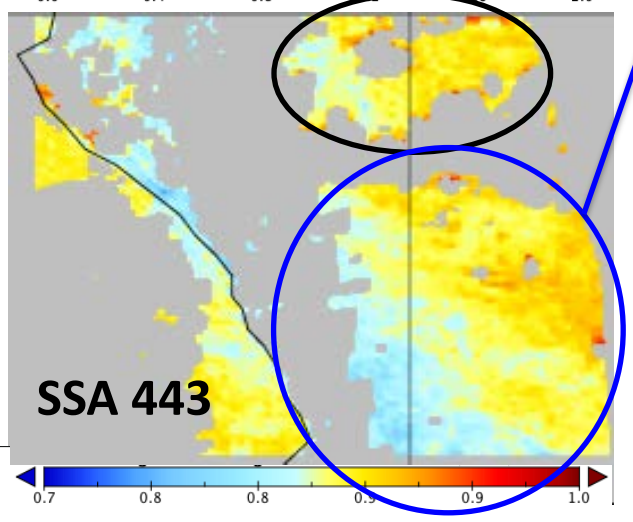
Aged soot-containing Particles (less absorbing, bigger particles)

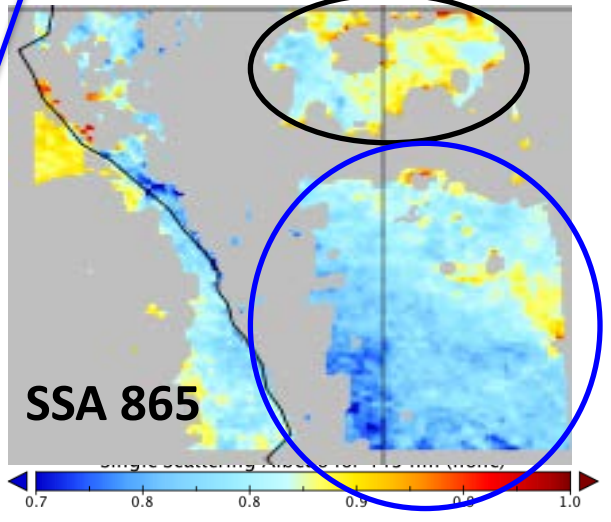
Absorbing smoke







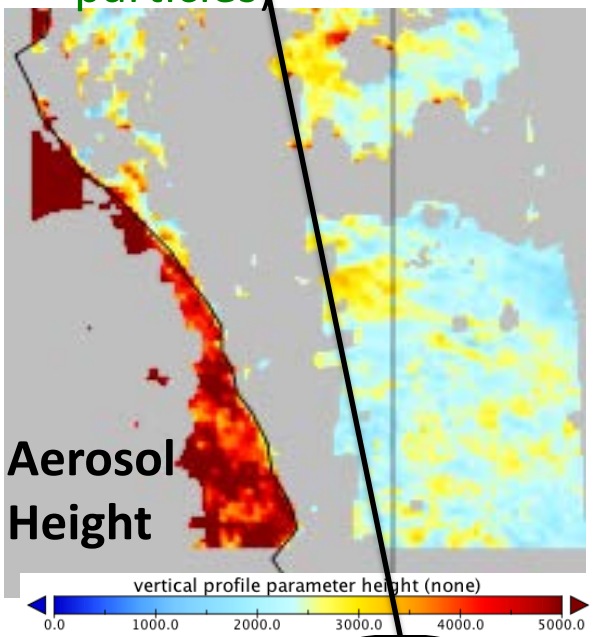


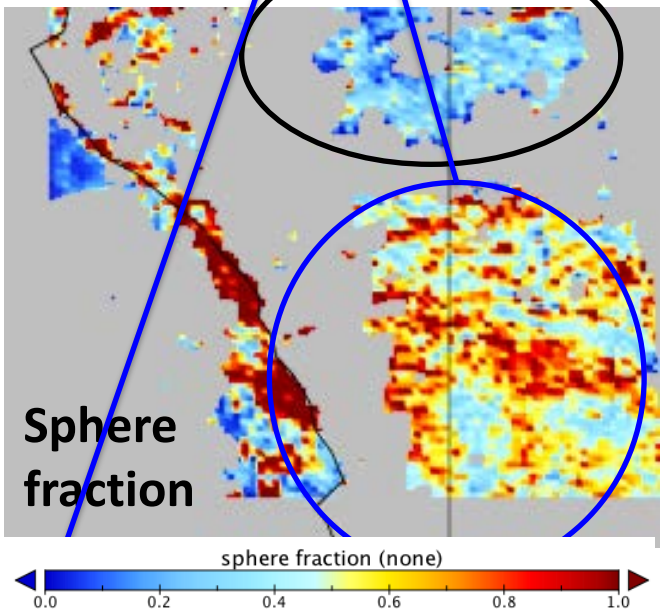


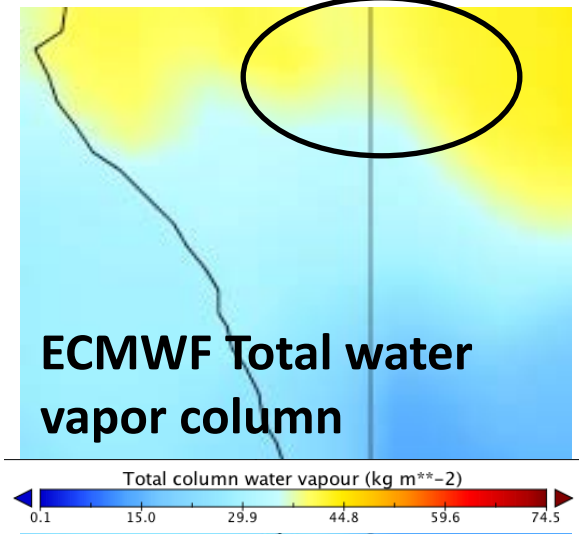
Biomass burning. Africa, August, 3, 2013

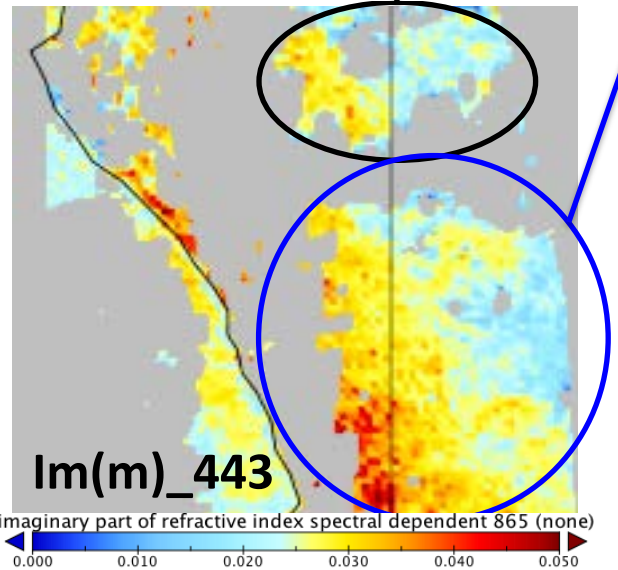
Aged soot-containing Particles (less absorbing, bigger particles)

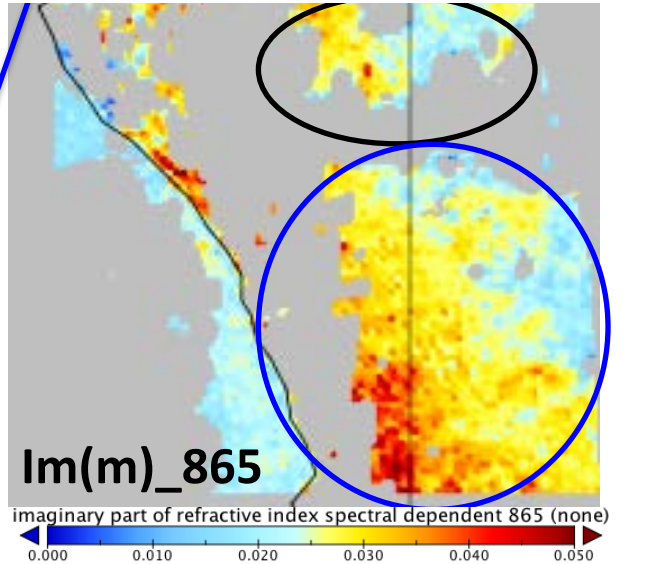
Absorbing smoke



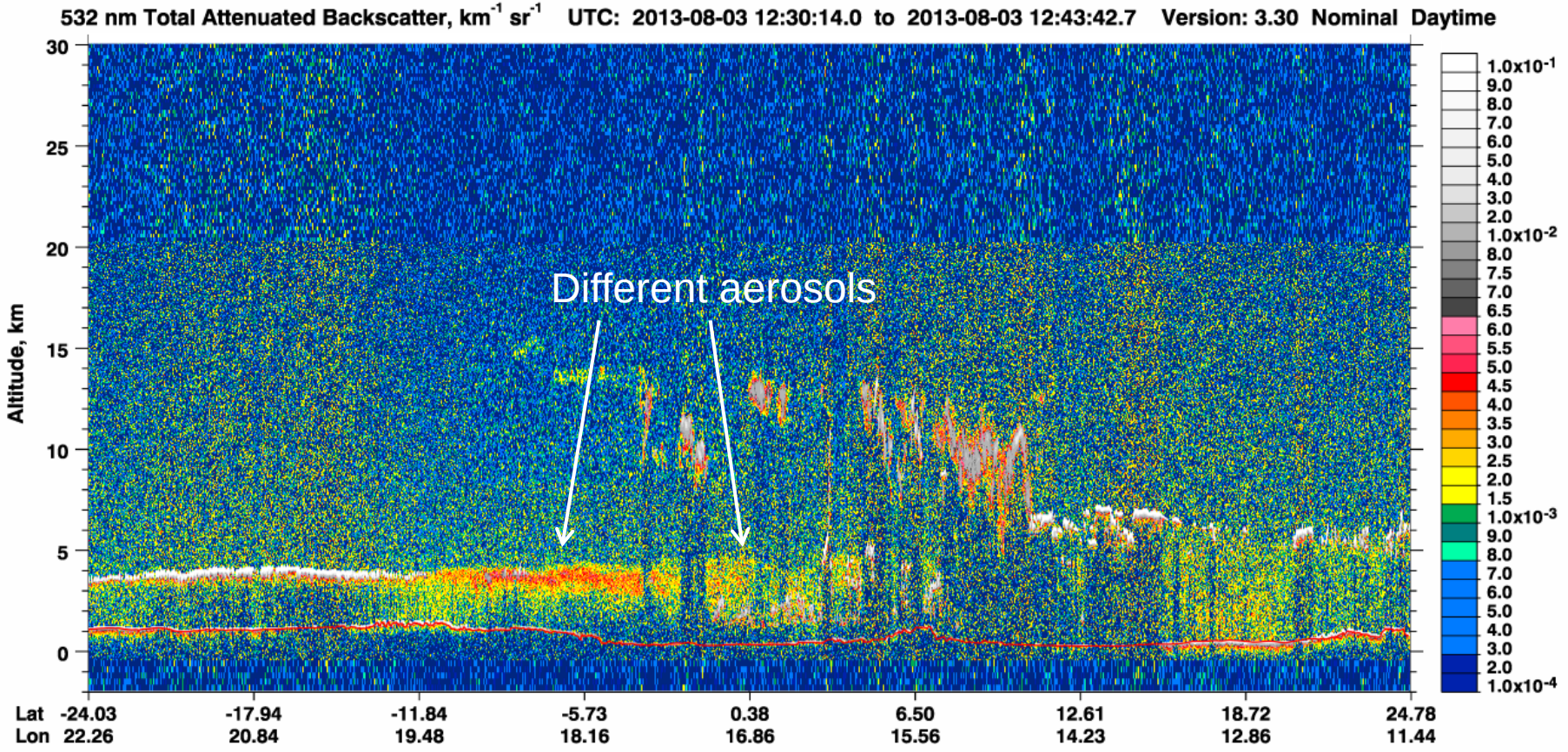




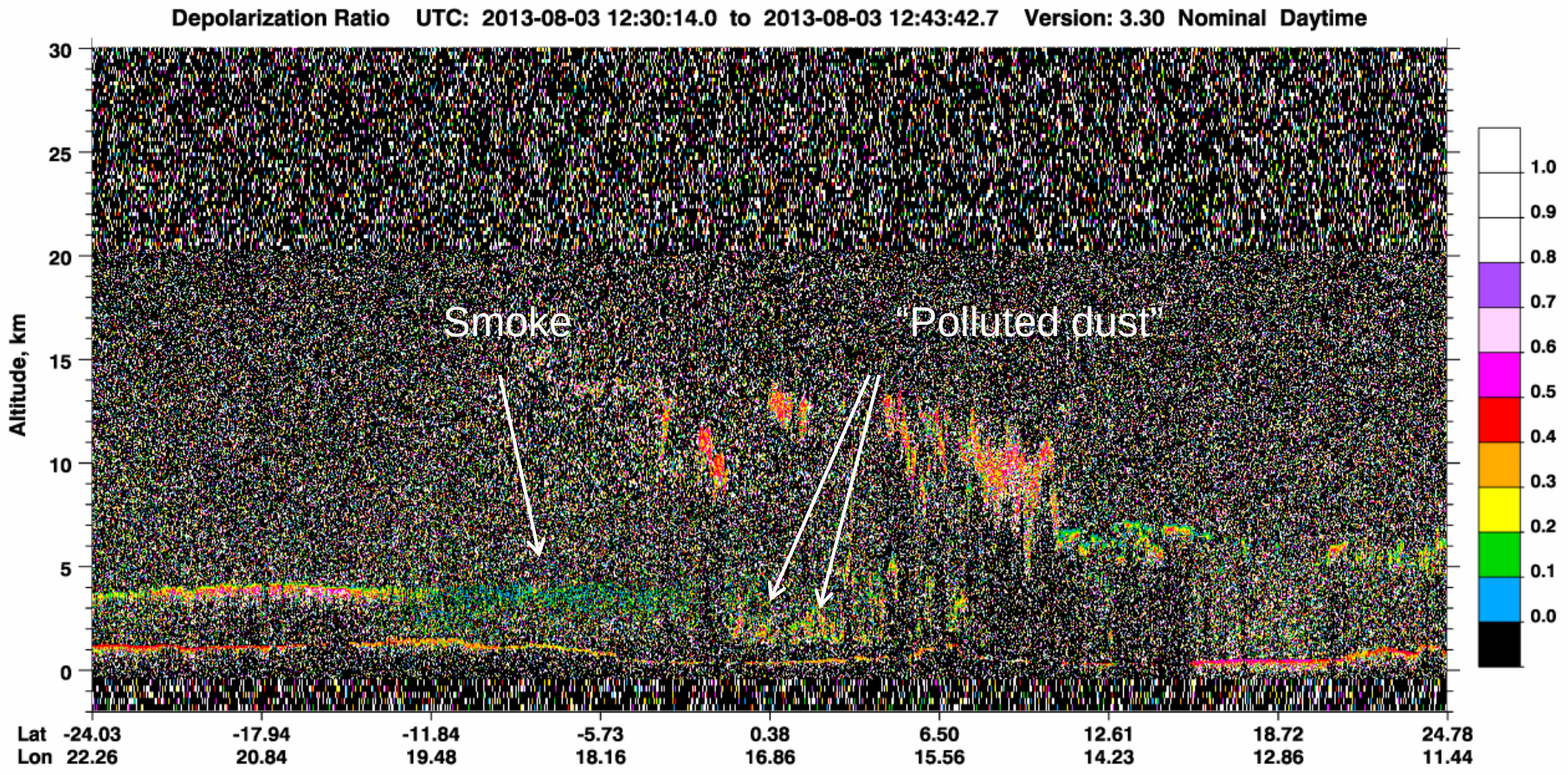




CALIPSO backscattering



CALIPSO depolarization

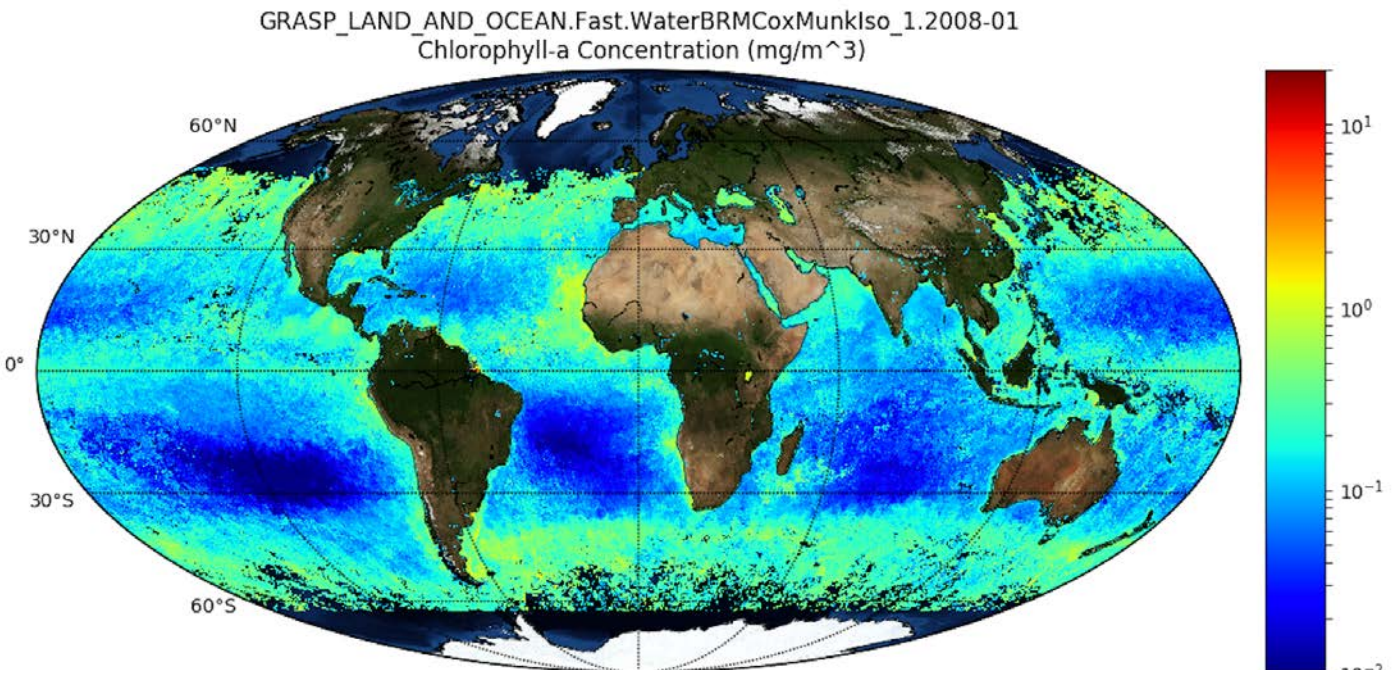


PARASOL 2008

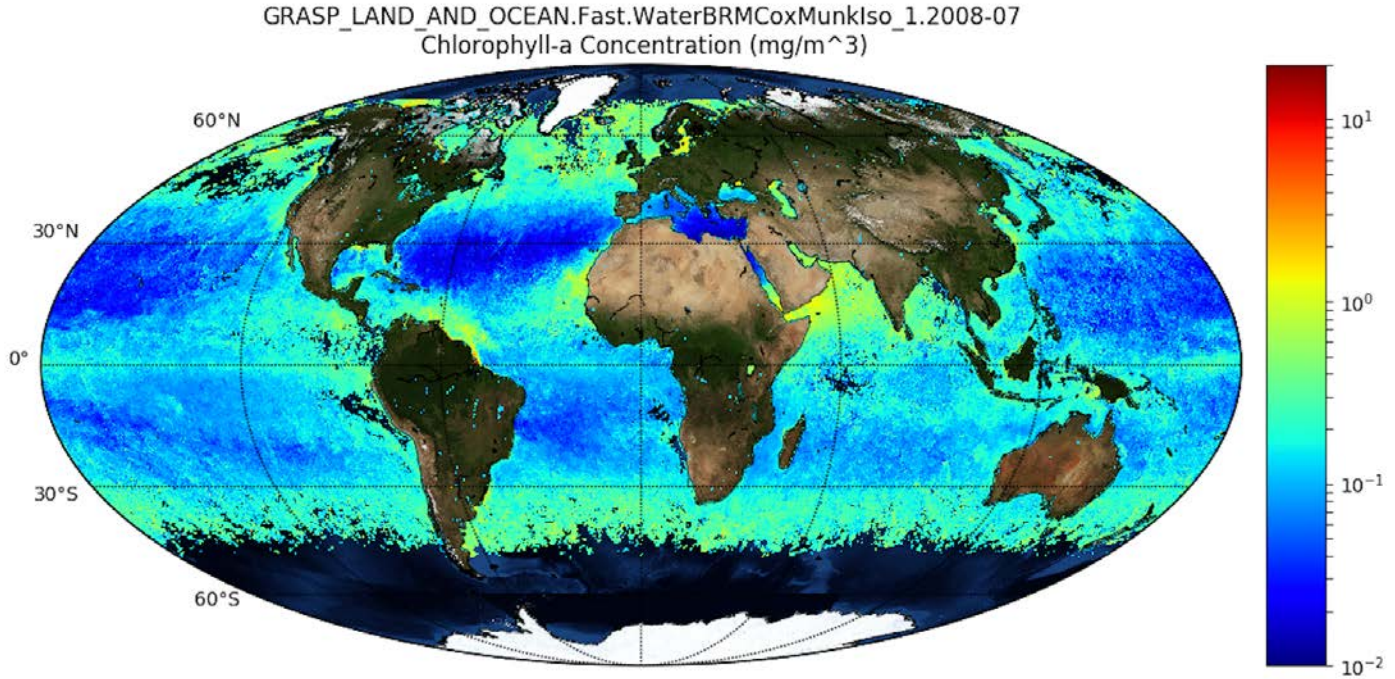
Chlorophyll

Preliminary result…

January



July



PARASOL 2008

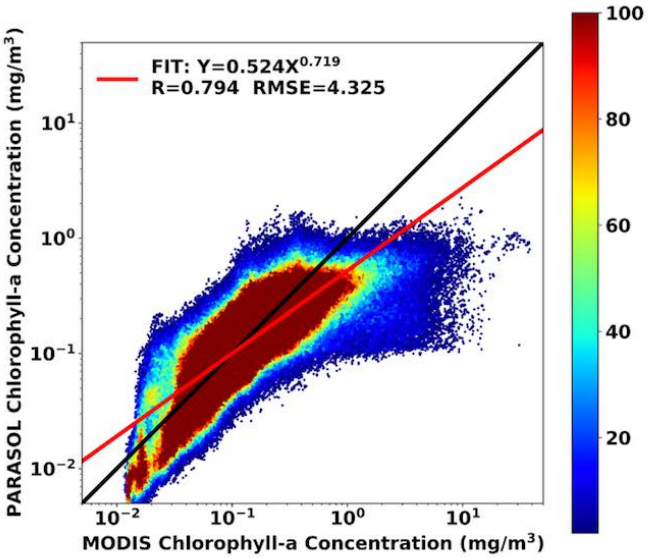
Chlorophyll

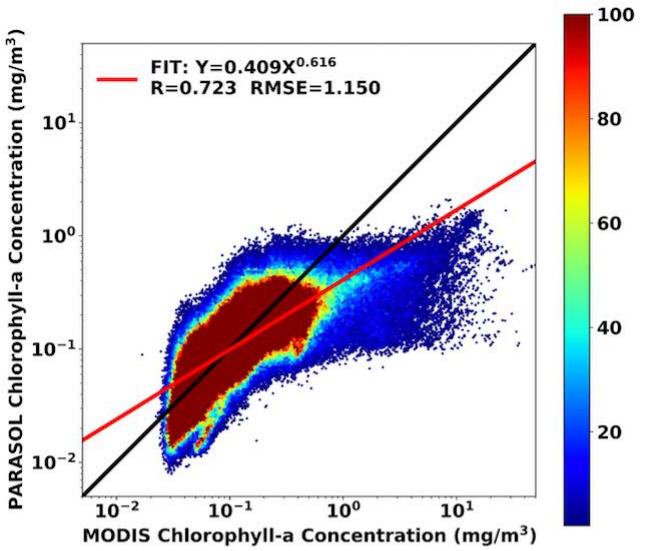
Preliminary result…

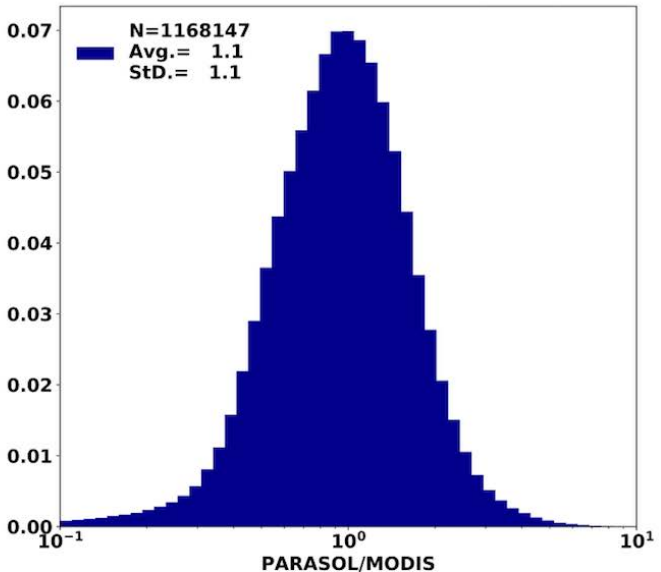
Correlation with MODIS

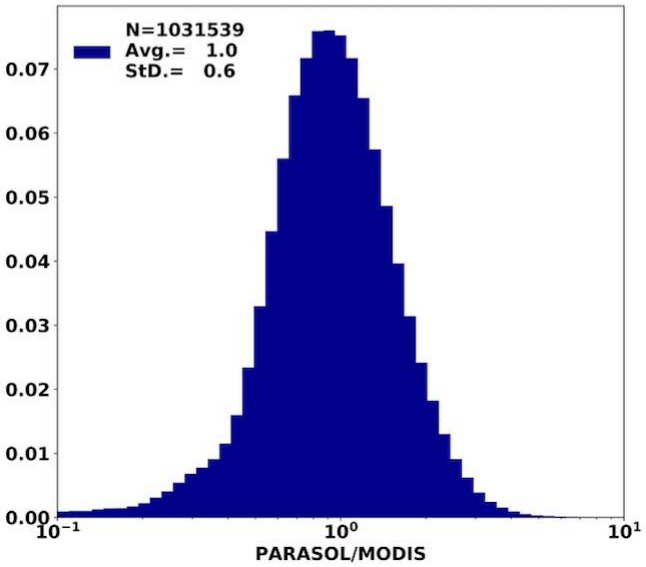
July

January





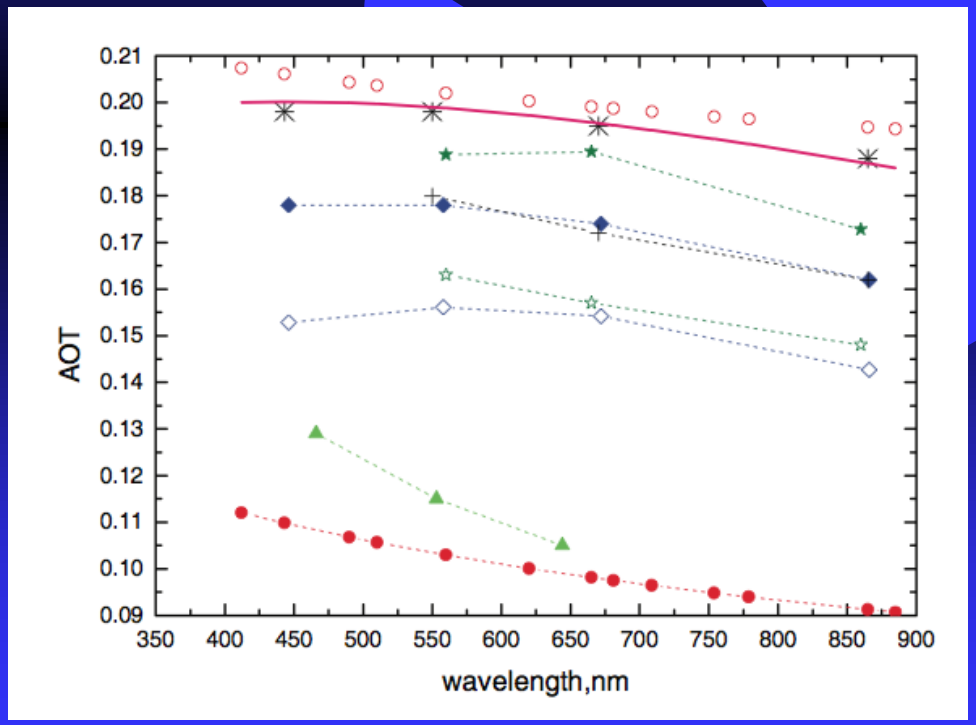


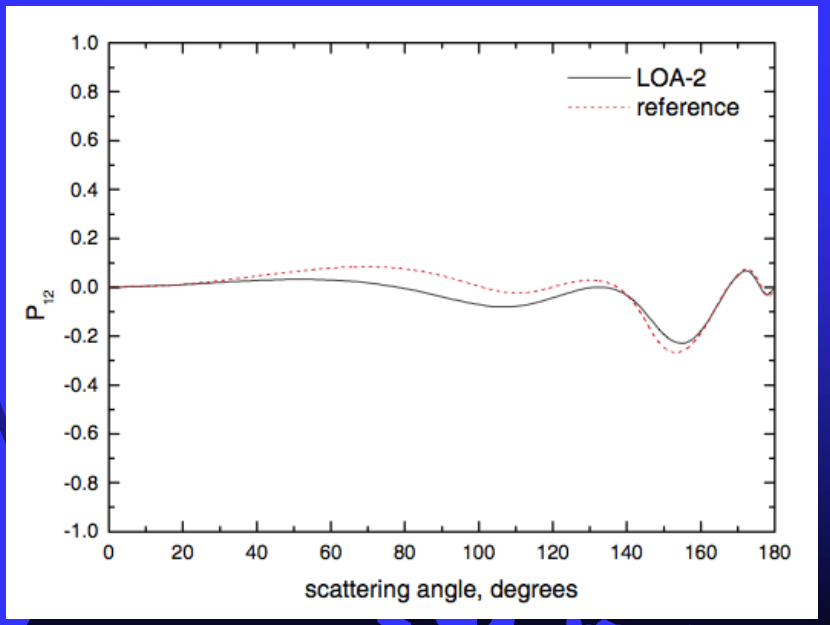


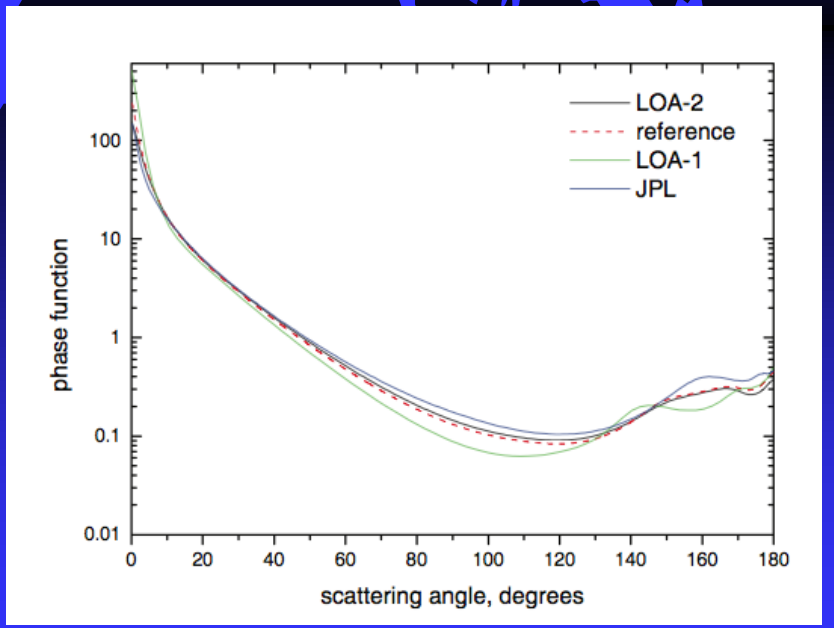
Tests over dark surface (« *Blind* » *Test*)

Kokhanovsky, et al, The inter-comparison of major satellite aerosol retrieval …., Atmos. Meas. Tech., 3, 909–932, 2010.

MERIS/NASB-1
MERIS/NASB-2
MODIS/NASA
MISR/PSI
MISR/JPL
POLDER/LOA-1
POLDER/LOA-2
AATSR/SU
AATSR/OU



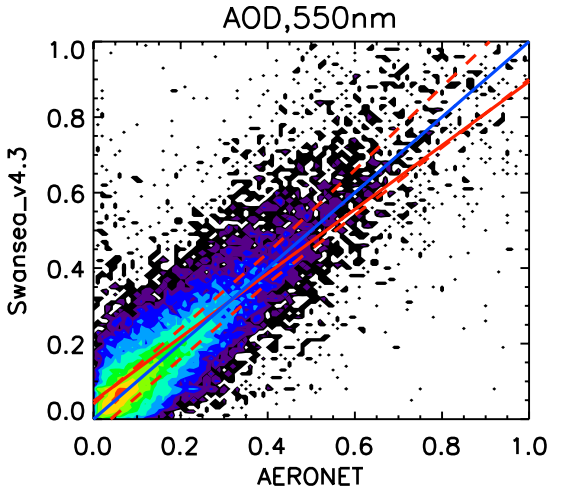




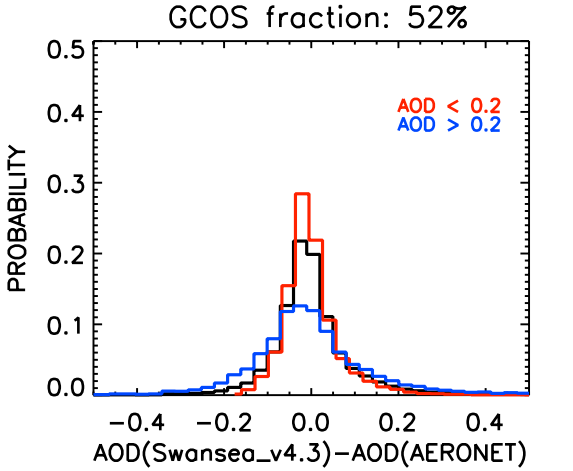
Validation vs AERONET, Angstrom over land

AATSR/Swansea, 2002-2012

AOD, R=0.80

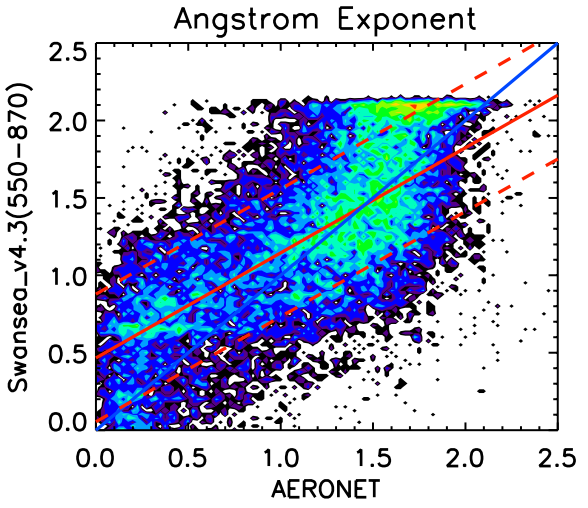


K=0.798 a= 0.85 b= 0.05 RMSE= 0.155

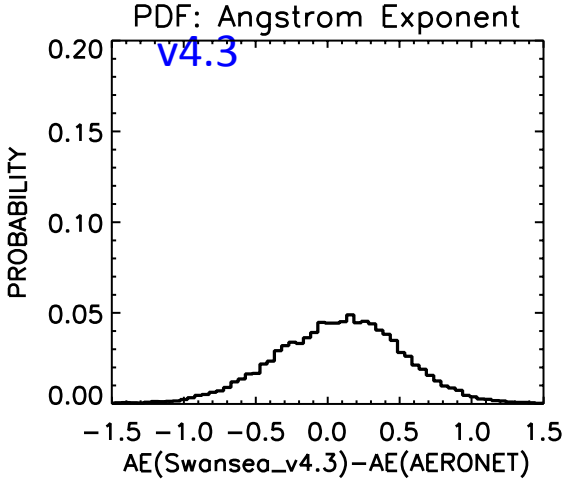


Aver. Value= 0.015 St.D.= 0.155 N=26586
Aver. Value= 0.018 St.D.= 0.077 N=17455
Aver. Value= 0.010 St.D.= 0.242 N=9131

Angstrom, R=0.67

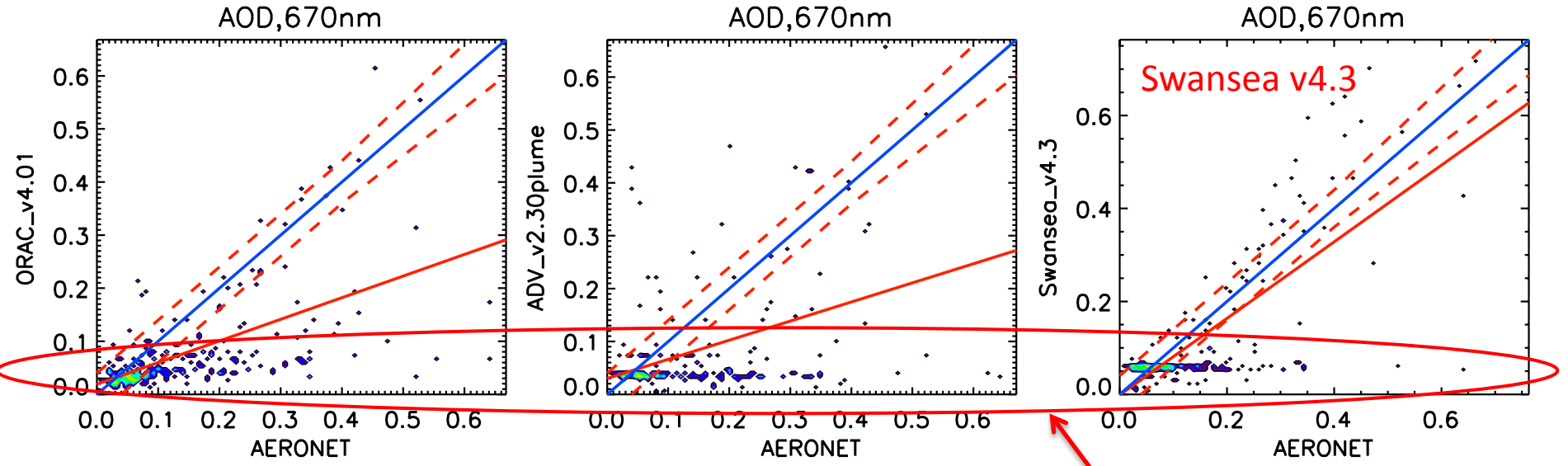


K=0.674 a= 0.68 b= 0.47 RMSE= 0.460

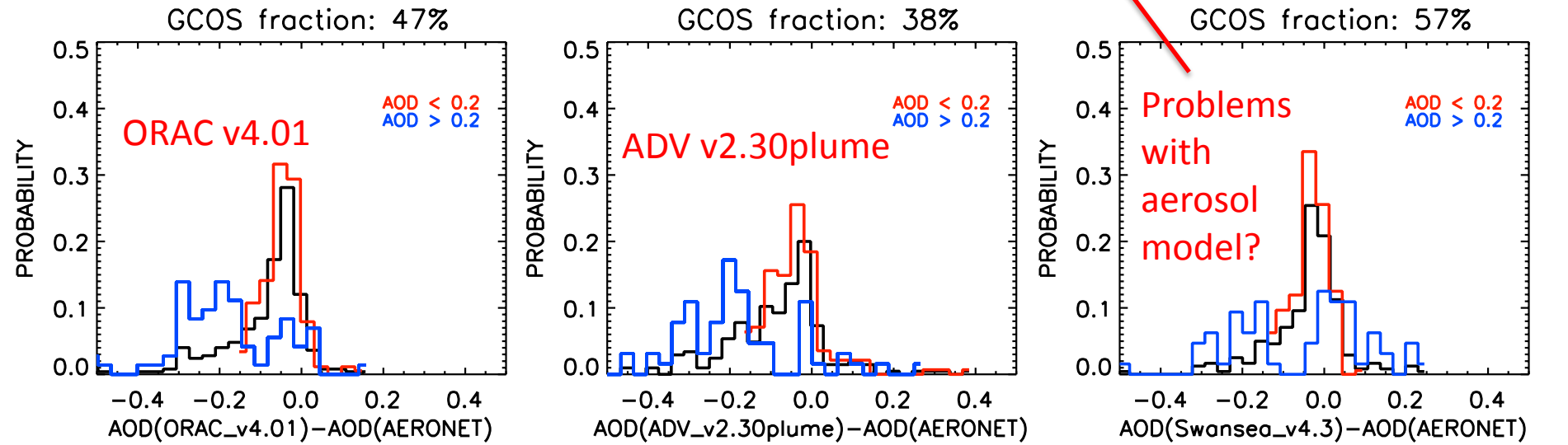


Aver. Value= 0.100 St.D.= 0.449 N=16939

Mongu 1200x 1200 zone. 2002-2012. **AATSR.**



K=0.595 a= 0.41 b= 0.02 RMSE= 0.128 K=0.410 a= 0.36 b= 0.03 RMSE= 0.151 K=0.760 a= 0.82 b=−0.00 RMSE= 0.101



Aver. Value=−0.073 St.D.= 0.105 N=249
Aver. Value=−0.033 St.D.= 0.047 N=177
Aver. Value=−0.171 St.D.= 0.139 N= 72

Aver. Value=−0.073 St.D.= 0.133 N=205
Aver. Value=−0.026 St.D.= 0.083 N=141
Aver. Value=−0.177 St.D.= 0.159 N= 64

Aver. Value=−0.028 St.D.= 0.097 N=240
Aver. Value=−0.020 St.D.= 0.045 N=176
Aver. Value=−0.052 St.D.= 0.170 N= 64

Mongu, 1200x 1200 zone.

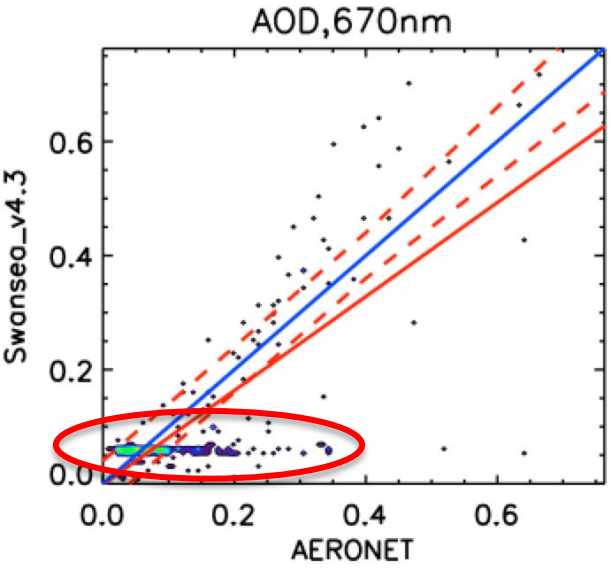
2002-2012

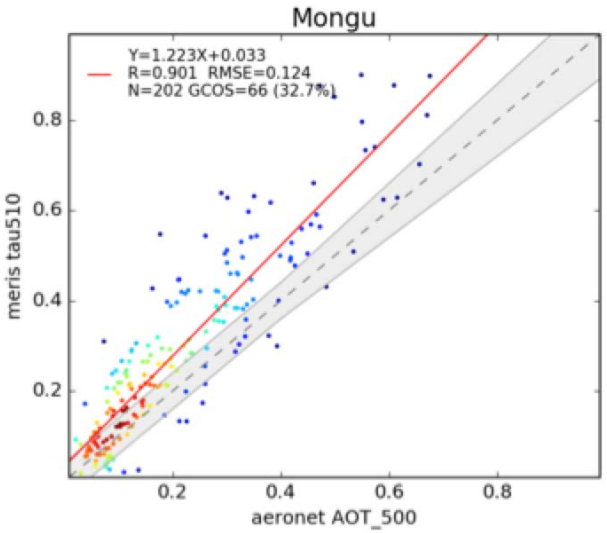
AATSR / SU, R=0.76

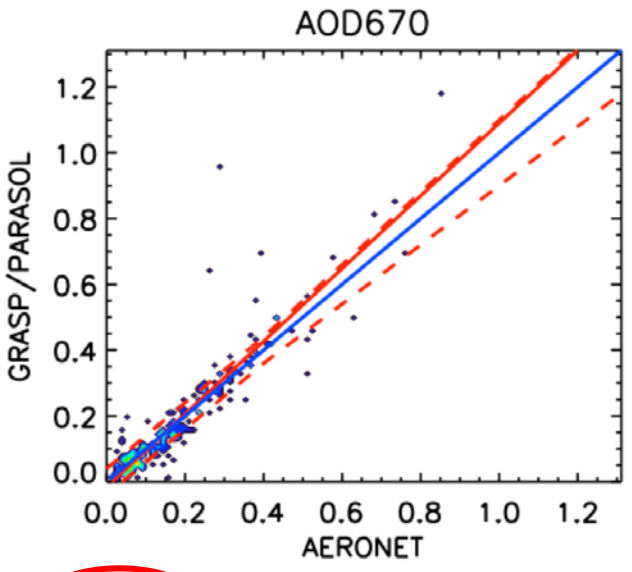
MERIS / GRASP, R=0.91

2004-2013

PARASOL / GRASP, R=0.91







K=0.760 a= 0.82 b=−0.00 RMSE= 0.101

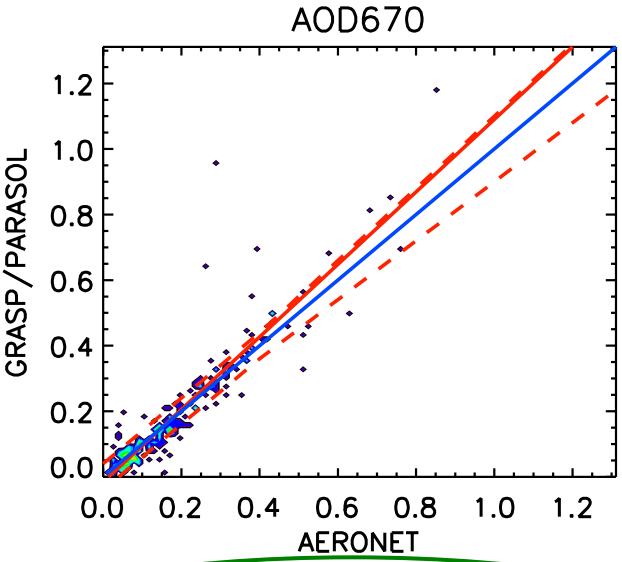
K=0.914 a= 1.11 b=−0.02 RMSE= 0.076

AATSR - fails with aerosol model ???

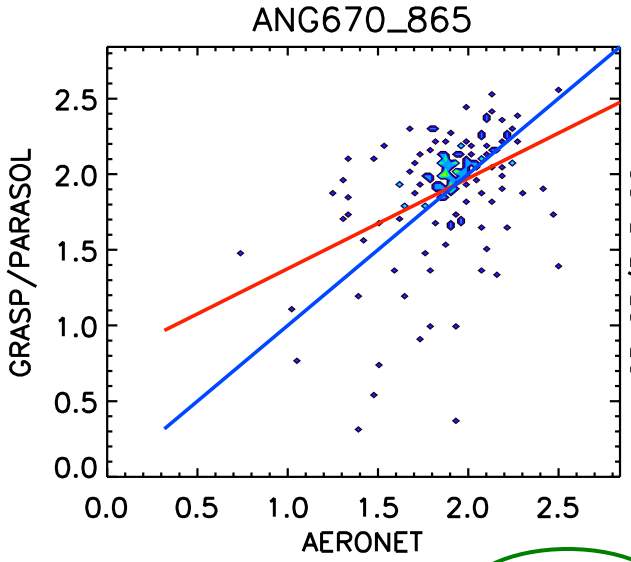
MERIS is surprisingly good with R, but slope is wrong ???

PARASOL could be better???

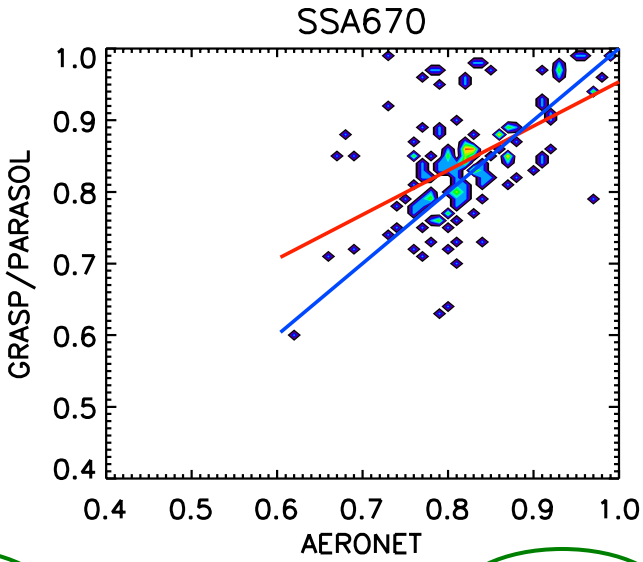
Mongu, 1200x 1200 zone. 2005-2013. 2 sites. **GRASP**



K=0.914 a= 1.11 b=−0.02 RMSE= 0.076

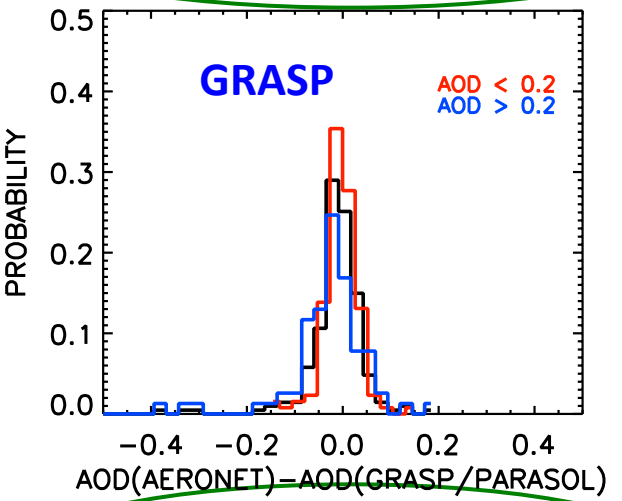


K=0.423 a= 0.60 b= 0.78 RMSE= 0.366



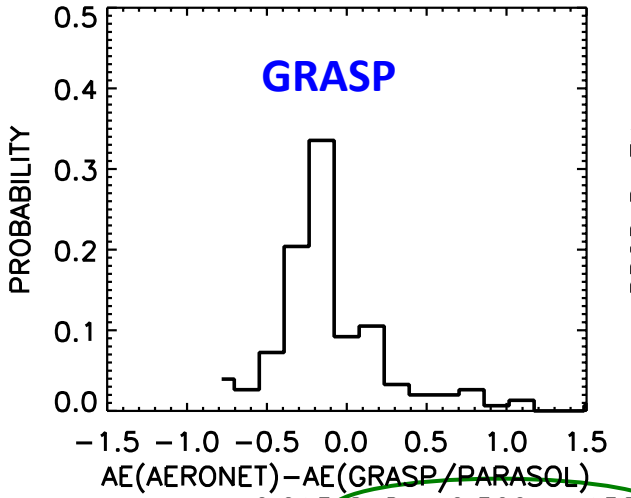
K=0.523 a= 0.62 b= 0.34 RMSE= 0.075

GCOS fraction:72%



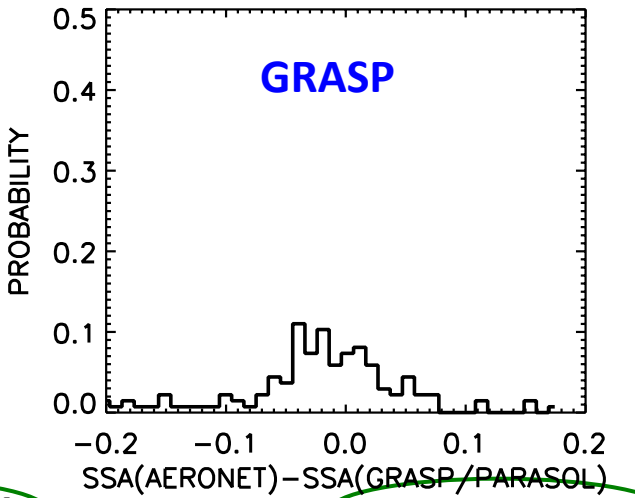
Aver. Value=−0.005 St.D.= 0.076 N=207
Aver. Value= 0.007 St.D.= 0.037 N=130
Aver. Value=−0.026 St.D.= 0.112 N= 77

PDF: AE



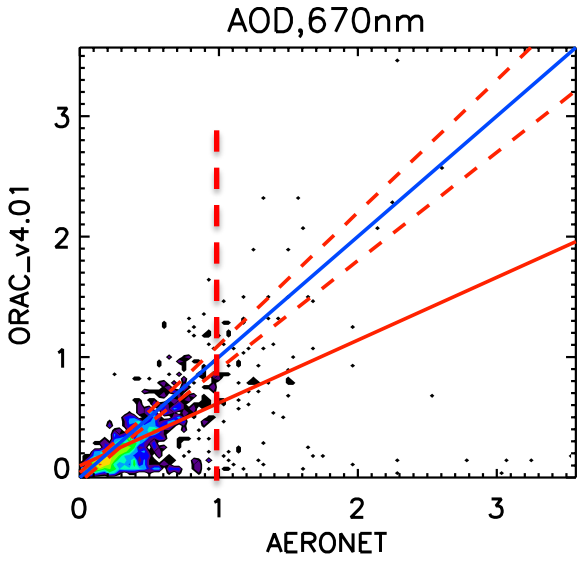
Aver. Value=−0.013 St.D.= 0.366 N=152

PDF: SSA

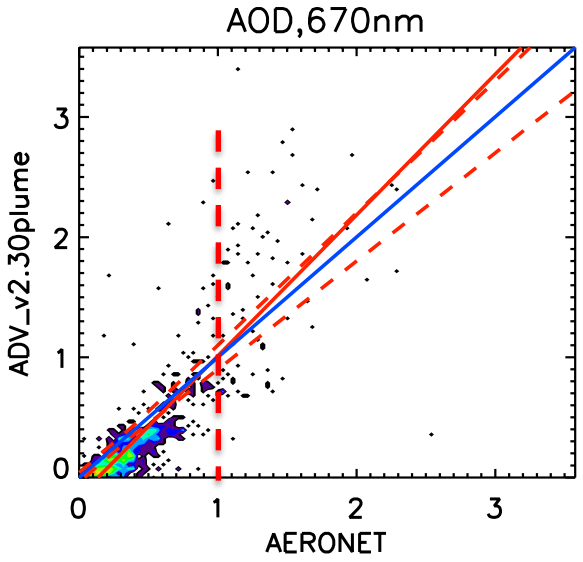


Aver. Value=−0.020 St.D.= 0.072 N=136

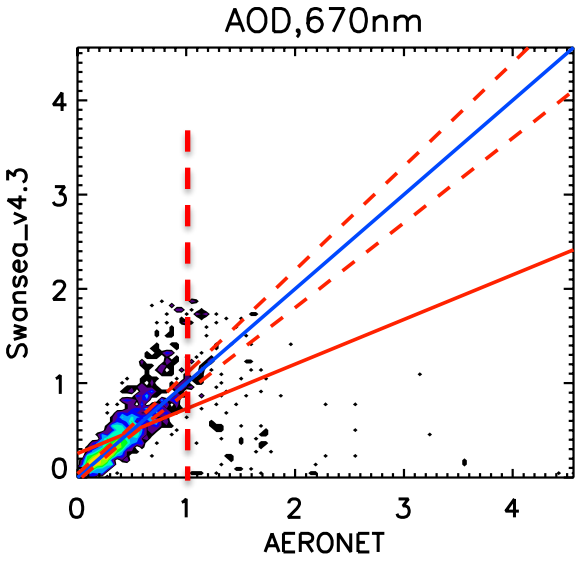
Banizoumbou 1200x 1200 zone. 2002-2012. **AATSR**.



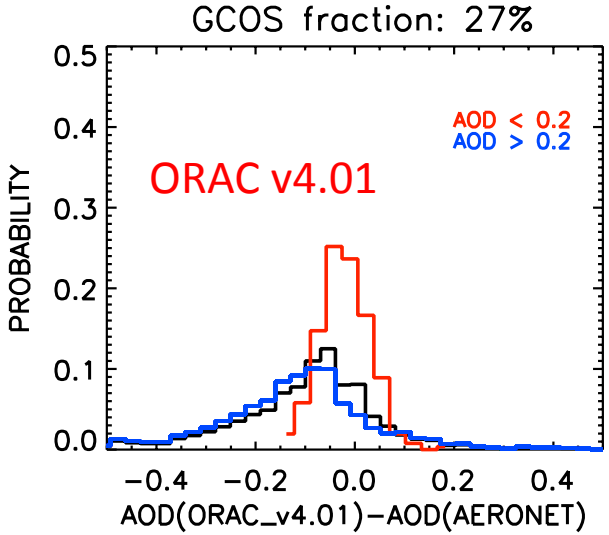
K=0.620 a= 0.52 b= 0.10 RMSE= 0.333



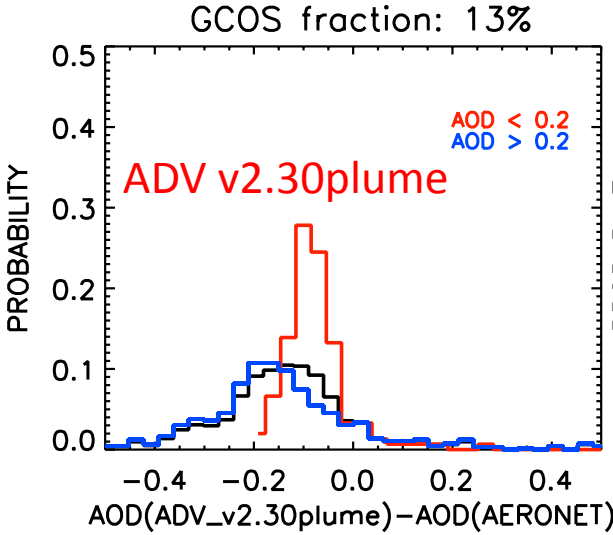
K=0.837 a= 1.17 b=−0.16 RMSE= 0.302



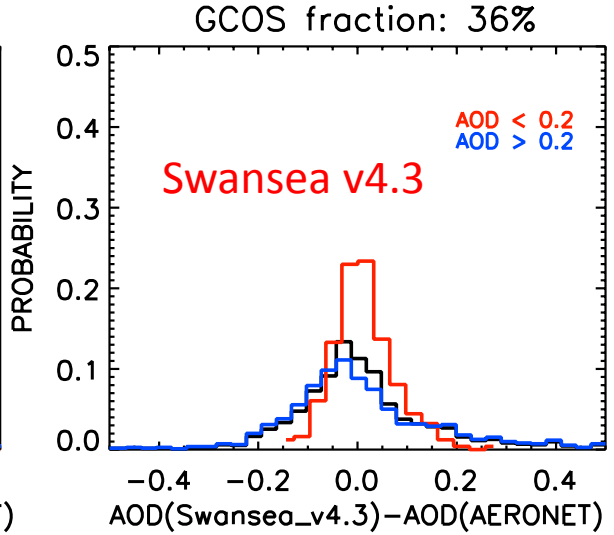
K=0.540 a= 0.47 b= 0.25 RMSE= 0.392



Aver. Value=−0.126 St.D.= 0.309 N=1310
Aver. Value=−0.006 St.D.= 0.051 N=258
Aver. Value=−0.156 St.D.= 0.337 N=1052



Aver. Value=−0.077 St.D.= 0.292 N=812
Aver. Value=−0.055 St.D.= 0.108 N=151
Aver. Value=−0.082 St.D.= 0.319 N=661

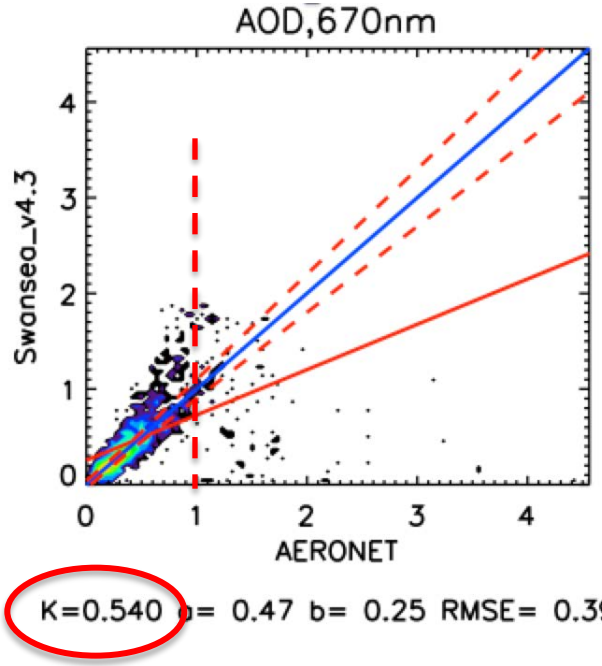


Aver. Value=−0.011 St.D.= 0.392 N=1345
Aver. Value= 0.028 St.D.= 0.063 N=248
Aver. Value=−0.020 St.D.= 0.432 N=1097

Banizoumbou 1200x 1200 zone

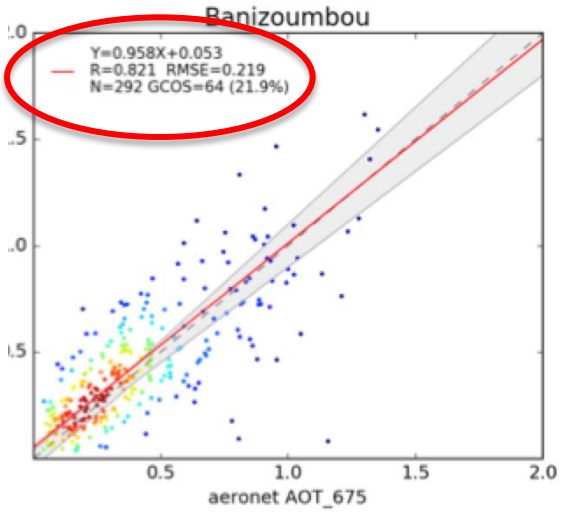
2002-2012

AATSR / SU, R=0.54



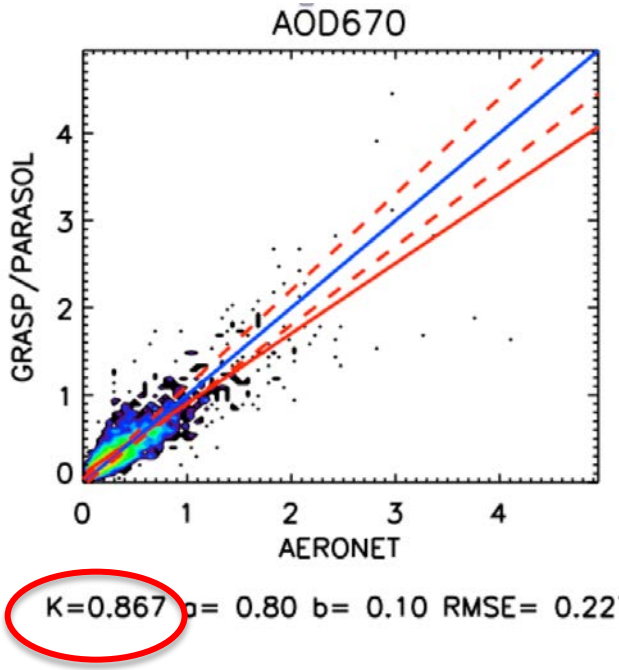
K=0.540 a= 0.47 b= 0.25 RMSE= 0.392

MERIS / GRASP, R=0.82



2004-2013

PARASOL / GRASP, R=0.87



K=0.867 a= 0.80 b= 0.10 RMSE= 0.227

AATSR- fails for AOD > 1.0 ???

PARASOL fails with the slope ???

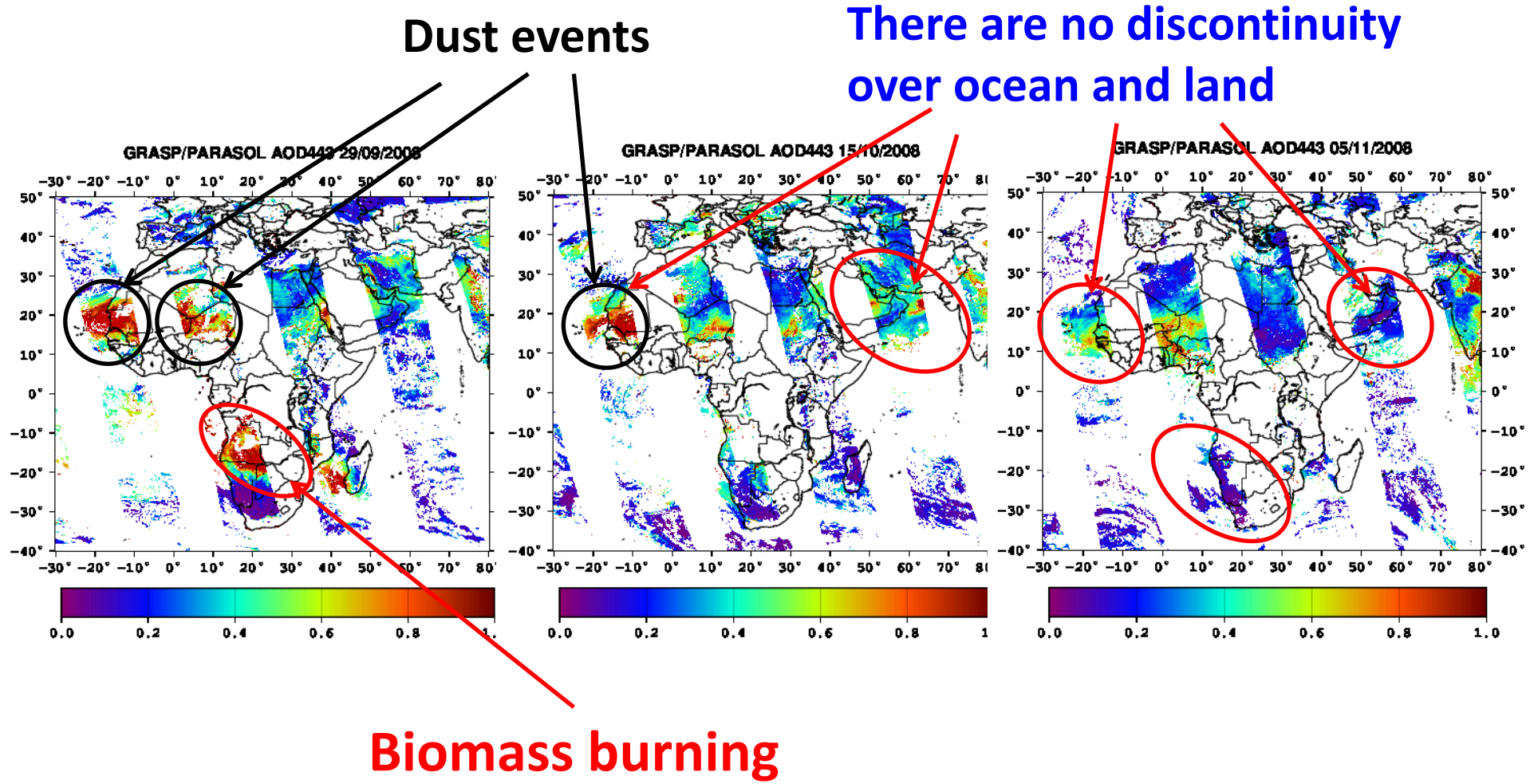
MERIS is surprisingly good ???

CONCLUSIONS:

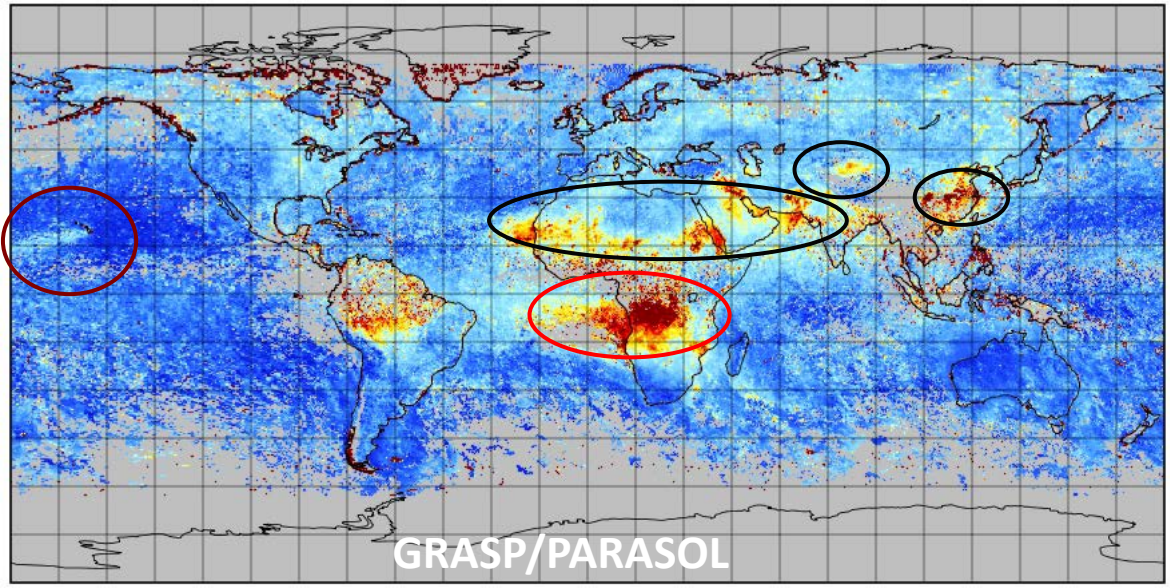
GRASP as it is now:

- ✓ Provides accurate solutions for both aerosol and surface:
  - no location specific a priori constraints;
  - used constraints are the same globally;
  - retrieval is original resolution (e.g.6 km – POLDER, 10 km – MERIS);
- ✓ It was highly accelerated:
  - entire Parasol/POLDER archive processed (on 100 CP cluster);
  - entire Envisat/MERIS archive processed
- ✓ It is practically versatile: applied to polar (PARASOL, MERIS, OLCI) and geostationary satellite (GOCI, S-4) observations and to ground-based and airborne measurements, passive and active (ACTRIS, ARONET/EURORE);
- ✓ Provides new interesting results about aerosol and surface that need to be evaluated and verified .

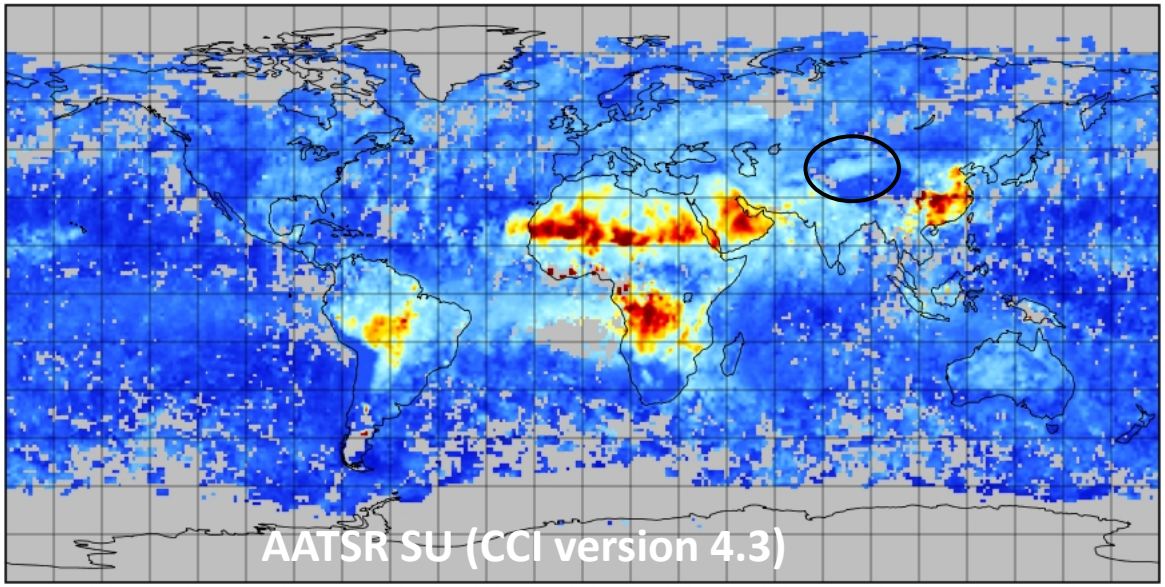
GRASP over land and ocean

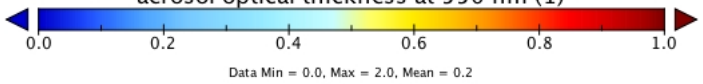


September, 2008

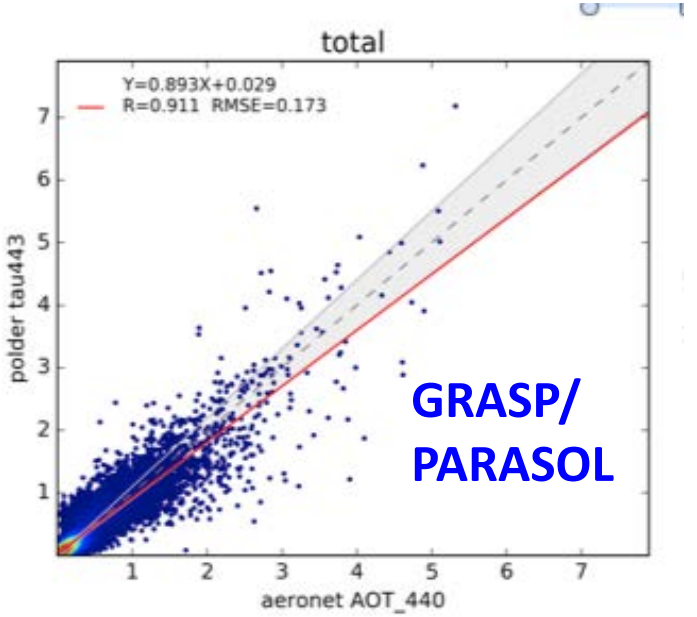


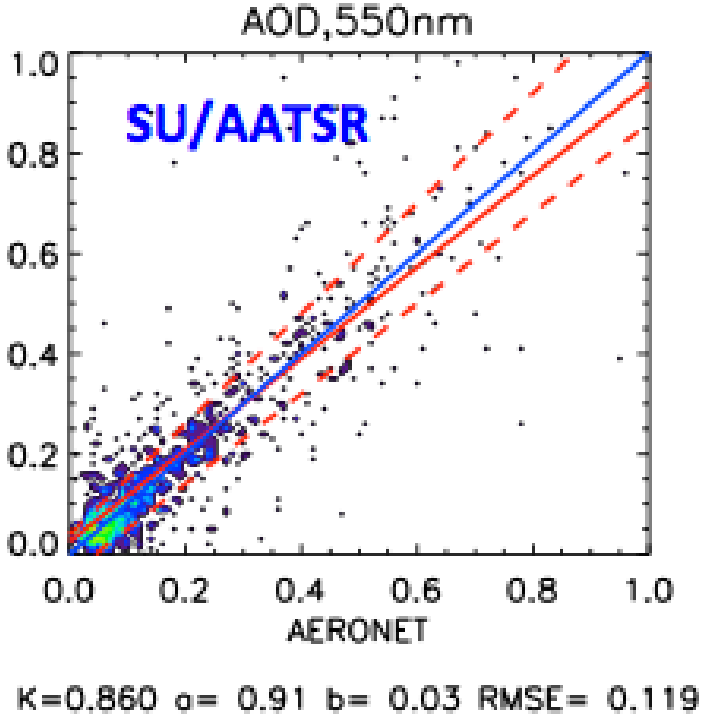
aerosol optical thickness at 550 nm





September, 2008

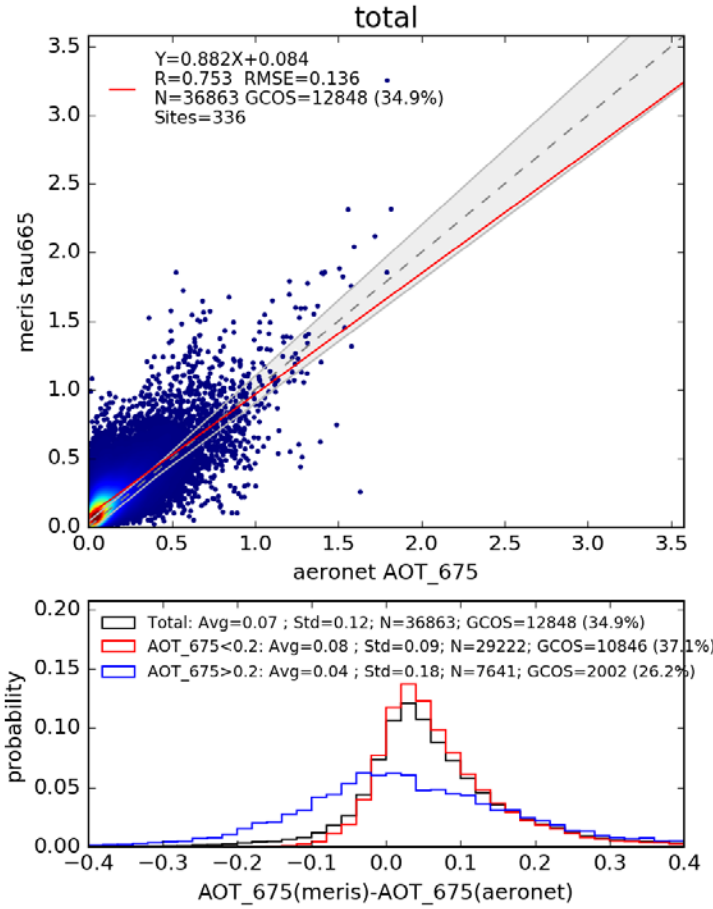




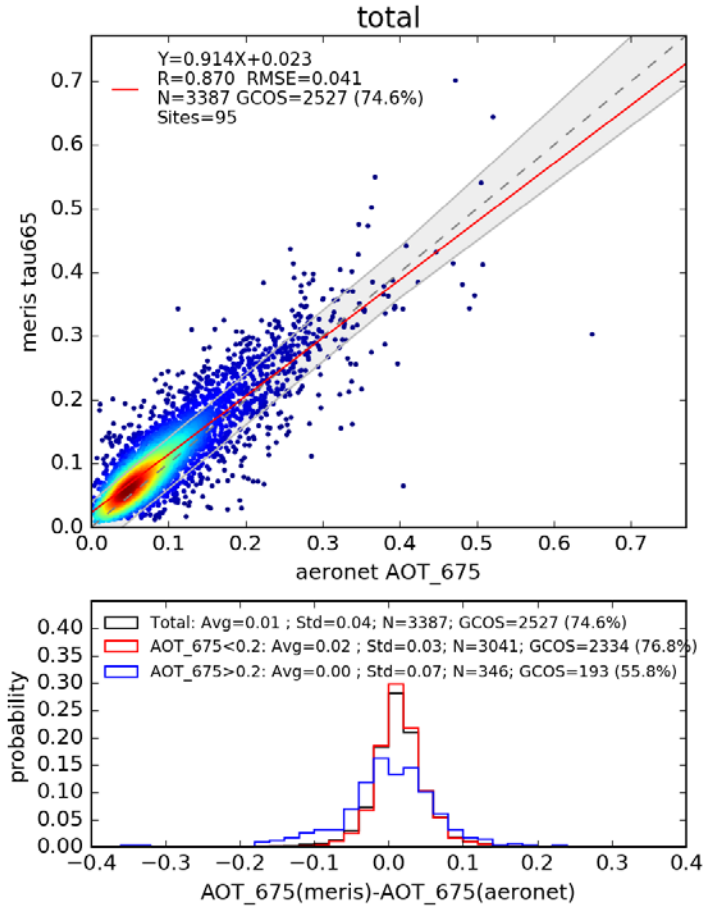
Validation vs AERONET 2002 - 2012

MERIS/GRASP - AOD

Land



Ocean



Multi-Term LSM

Other possibilities of a priori constraining

sensor

a priori

smoothness

$$\begin{cases} \boldsymbol{f}^* = \mathbf{F}\,\boldsymbol{a} + \Delta_f \\ \boldsymbol{a}^* = \boldsymbol{a} + \Delta_a \\ \boldsymbol{f}_2^{\bullet} = \boldsymbol{0}^* = \mathbf{S}\boldsymbol{a} + \Delta(\Delta\boldsymbol{a}) \end{cases}$$

$$\widehat{\boldsymbol{a}} = \left(\mathbf{F}^T\mathbf{C}_f^{-1}\mathbf{F} + \mathbf{S}^T\mathbf{C}_{0^*}^{-1}\mathbf{S} + \mathbf{C}_a^{-1}\right)^{-1}\left(\mathbf{F}^T\mathbf{C}_f^{-1}\boldsymbol{f}^* + \mathbf{C}_a^{-1}\,\boldsymbol{a}^*\right)$$

Identity ???

???

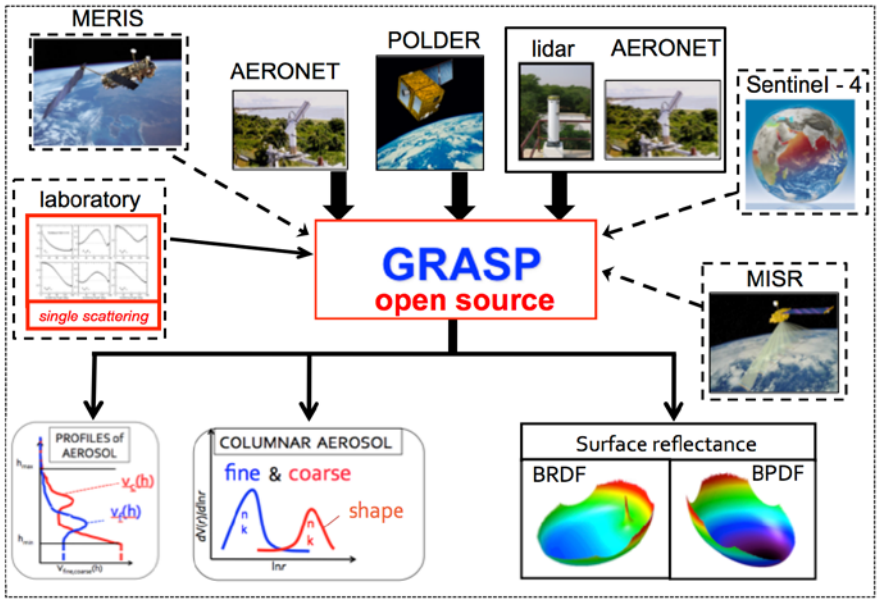
$$\widehat{\boldsymbol{a}} = \left(\mathbf{F}^T\mathbf{C}_f^{-1}\mathbf{F} + \mathbf{C}_a^{-1}\right)^{-1}\left(\mathbf{F}^T\mathbf{C}_f^{-1}\boldsymbol{f}^* + \mathbf{C}_a^{-1}\,\boldsymbol{a}^*\right)$$

"Optimum estimation"

$$\widehat{\boldsymbol{a}} = \left(\mathbf{F}^T\mathbf{C}_f^{-1}\mathbf{F} + \mathbf{S}^T\mathbf{C}_f^{-1}\mathbf{S}\right)^{-1}\left(\mathbf{F}^T\mathbf{C}_f^{-1}\boldsymbol{f}^*\right)$$

Phillips-Tikhonov-Twomey

GRASP: Generalized Retrieval of Aerosol and Surface Properties



Strength of GRASP algorithm concept:

- ✓ Based on accurate rigorous physics and math;
- ✓ Versatile (applicable to different sensors and retrieval of different parameters);
- ✓ Designed for multi-sensor retrieval (satellite, ground-based, airborne; polar and geostationary,);

- ✓ Provides accurate solutions:
  - for both aerosol and surface:
  - no location specific a priori constraints;
  - the constraints are the same globally;
  - retrieval is original resolution

Current and potential applications:

Satellite instruments:

polar: POLDER/PARASOL, 3MI/MetOp-SG, MERIS/Envisat, Sentinel-3 (OLCI, SLSTR), etc.

geostationary: Sentinel-4, FCI, GOCO, Himawari-8, etc.

Ground-based, airborne and laboratory instruments:

passive: AERONET radiometers, sun/luna/star-photometers, etc.

active: multi-wavelength elastic and non-elastic lidars; *airborne and laboratory: polar nephelometers,*

Multi-instrument synergy:

ground-based: lidar + radiometers + photometers , sun/luna/star-photometers, etc.

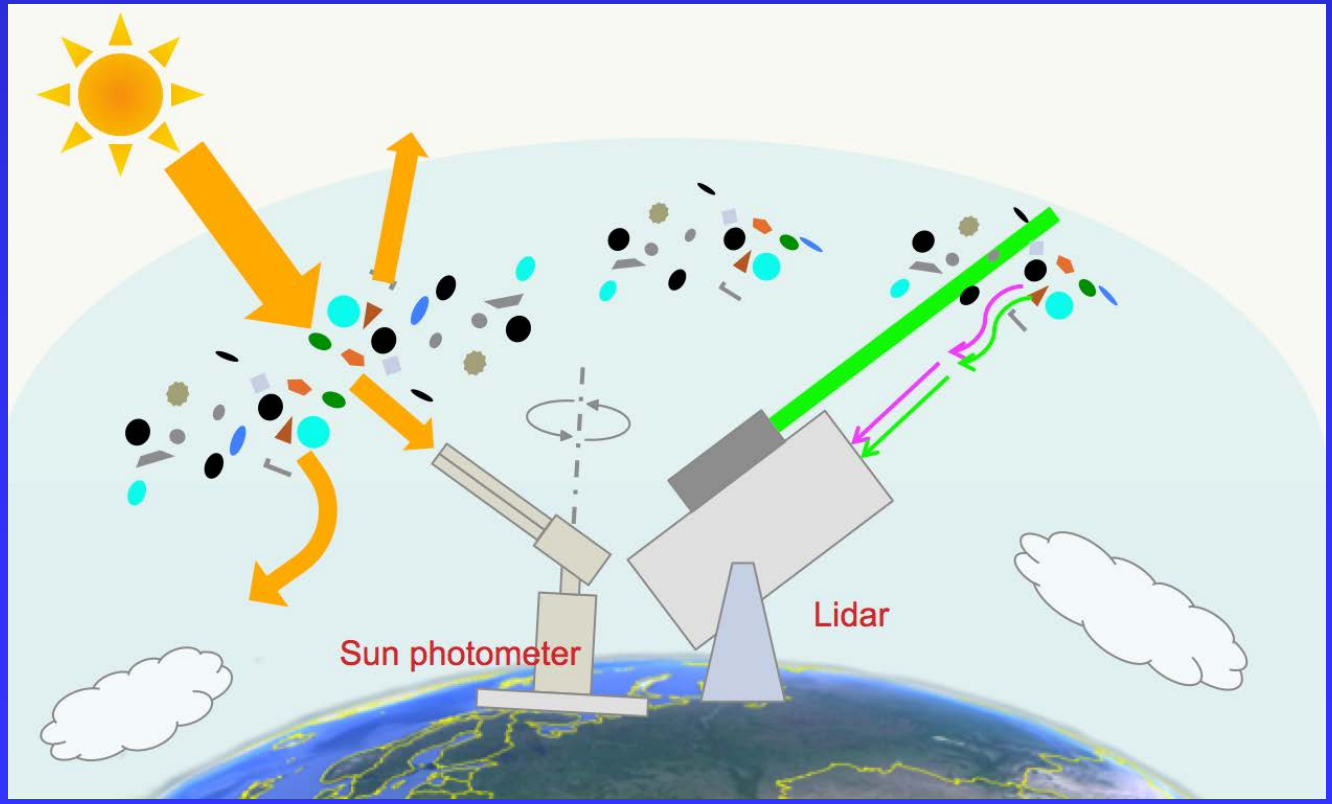
satellite: OLCI + SLSTR, polarimeter + lidar (e.g. PARASOL + CALIPSO)

Support: **CNES** (TOSCA, RD), **ANR** (CaPPA), **ESA** (S-4, MERIS/S-3, GPGPU, CCI, CCI-2,CC+); **EUMETSAT** (3MI NRT), **FP6-7** (ACTRIS 1-2), Catalysts GmbH, etc.

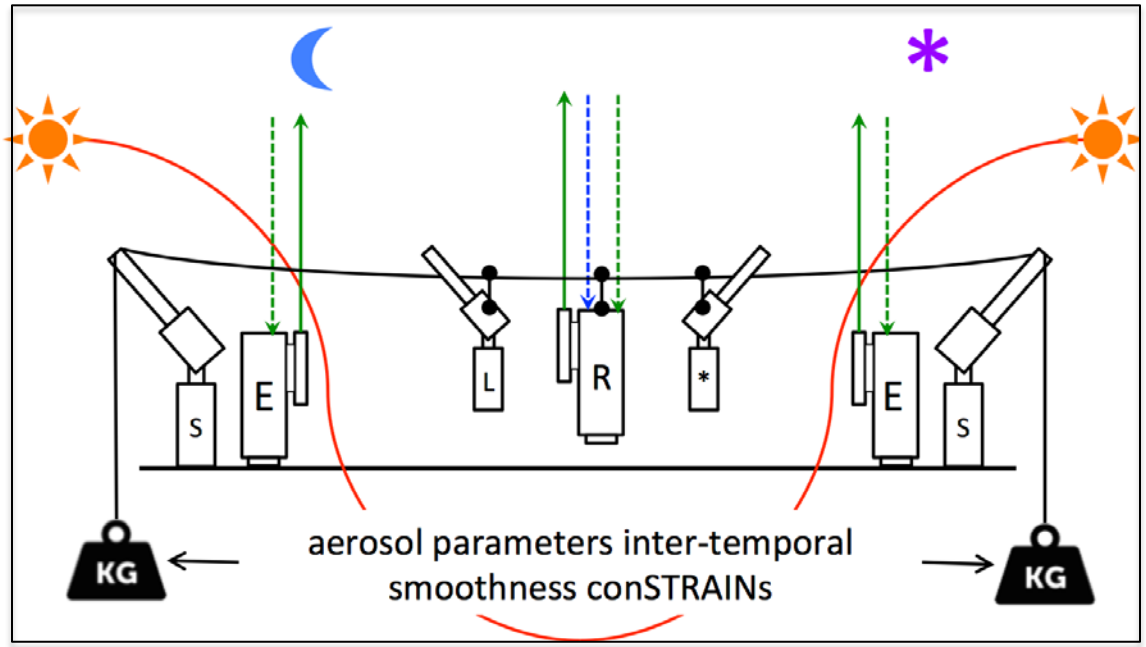
Collaborations: NASA/JPL, NASA/GSFC, NASA/GISS, NASA/Langley KNMI, JAXA, Catalysts GmbH (Austria), Chinese Academy of Science and Space Agency, Belarus, Ukraine, etc.

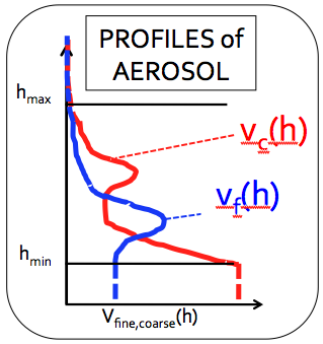
Priorities in GRASP development for ground-based and in situ observations:

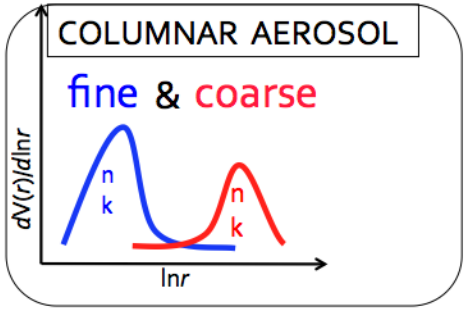
- *multi-instrument combination,*
- *diversity of observations,*
- *consistency of observations*



Multi-temporal multi-instrumental retrievals concept







ACTRIS Project

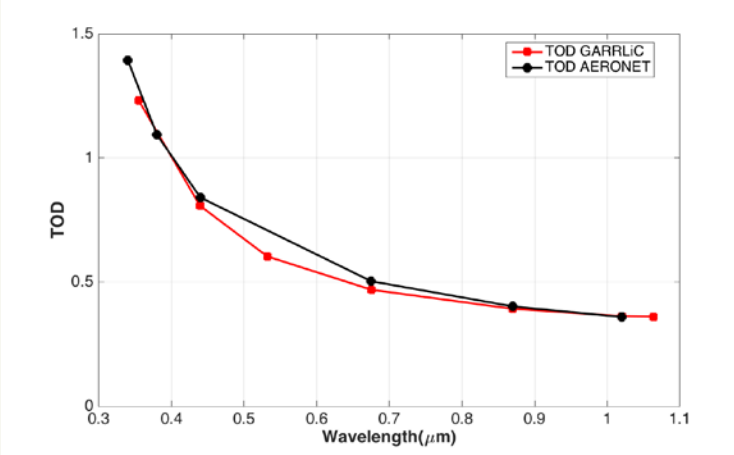
Advanced processing of ground-based observations using GRASP:

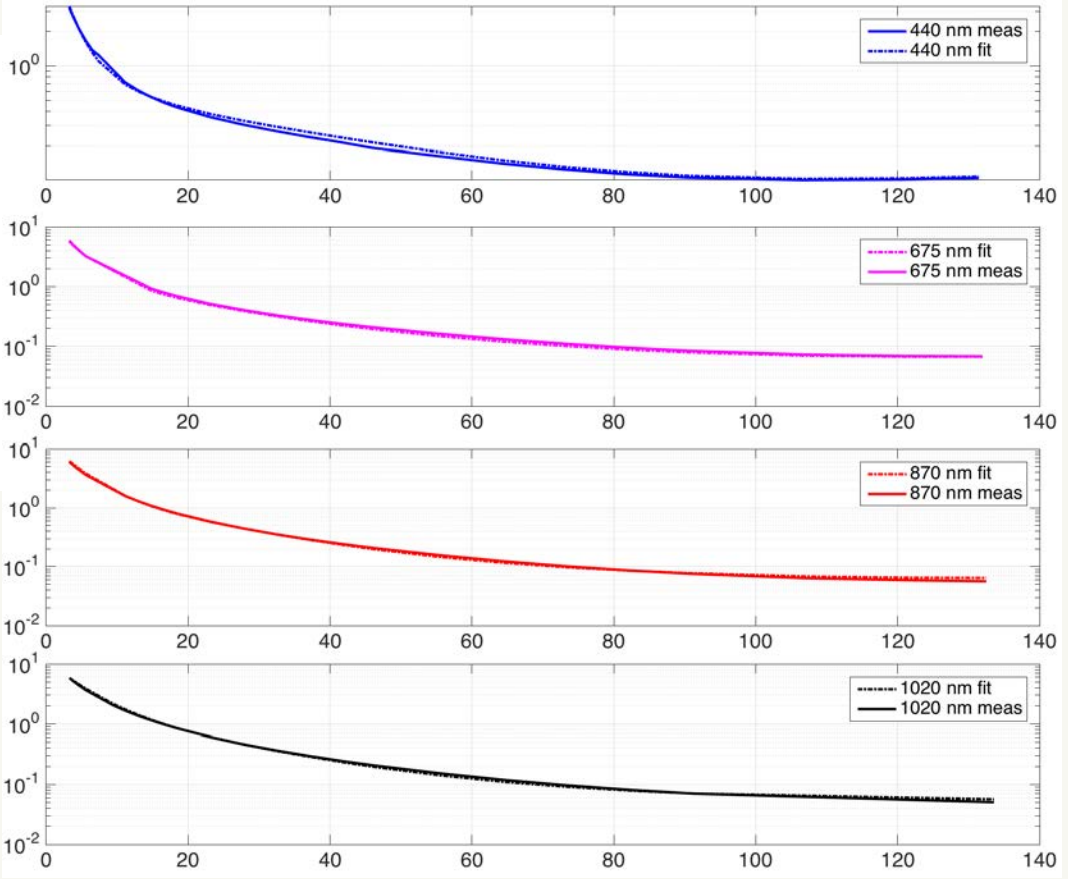
- combining observation during **several days**;
- combining **day and night** observations;
- combining **passive** (photometric) **and active** (lidar);
- combining **ground-based and satellite** observations;
- retrieving as many parameters as possible;

Expectations: more accurate and more complete validation data set

LIDAR + AERONET

Fitting AERONET by AERONET/lidar GRASP retrieval



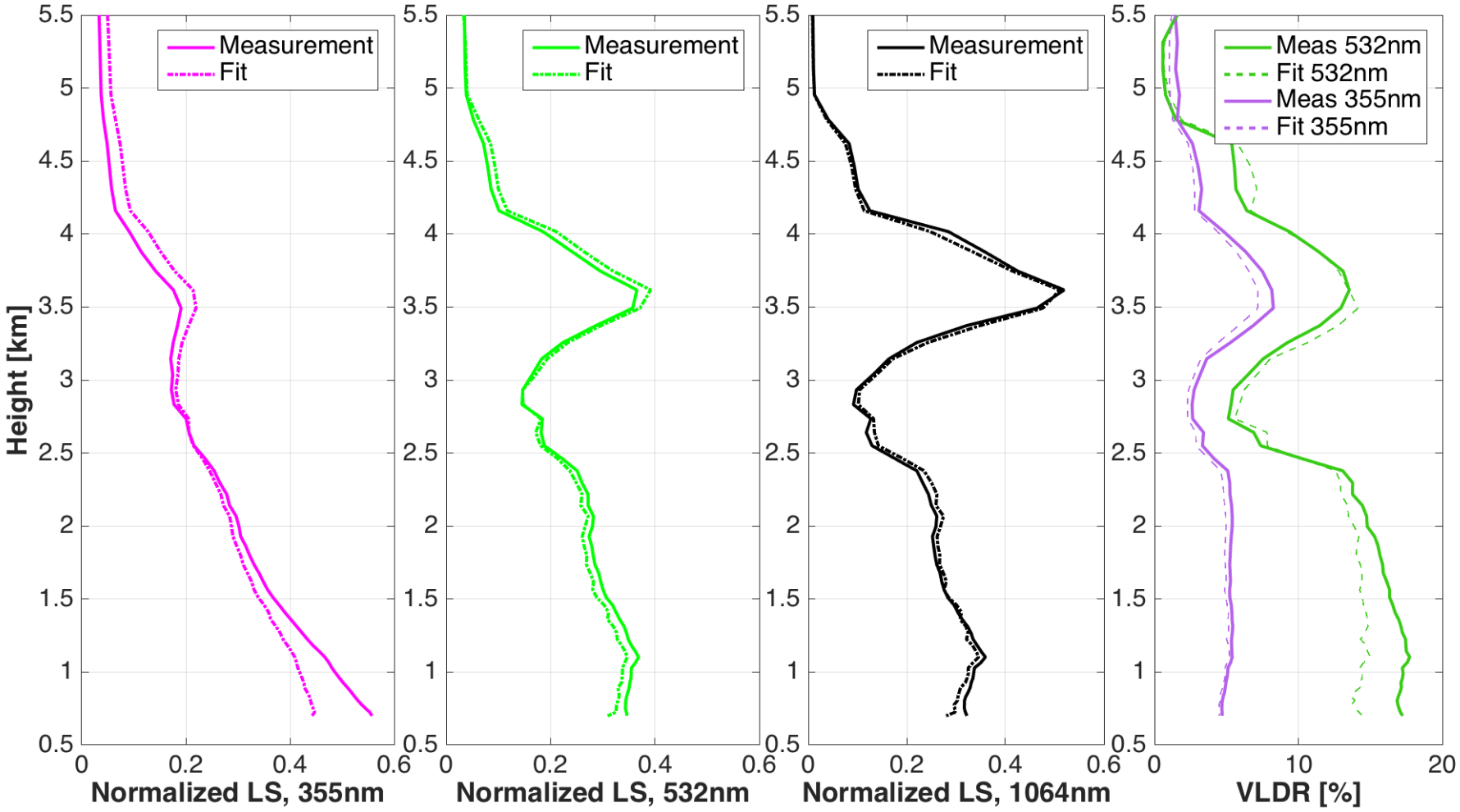


20 Jan 2016, M'bour

Qiaoyun HU, Anton Lopatin, etc.

LIDAR + AERONET

Fitting lidar observations by AERONET/lidar GRASP retrieval

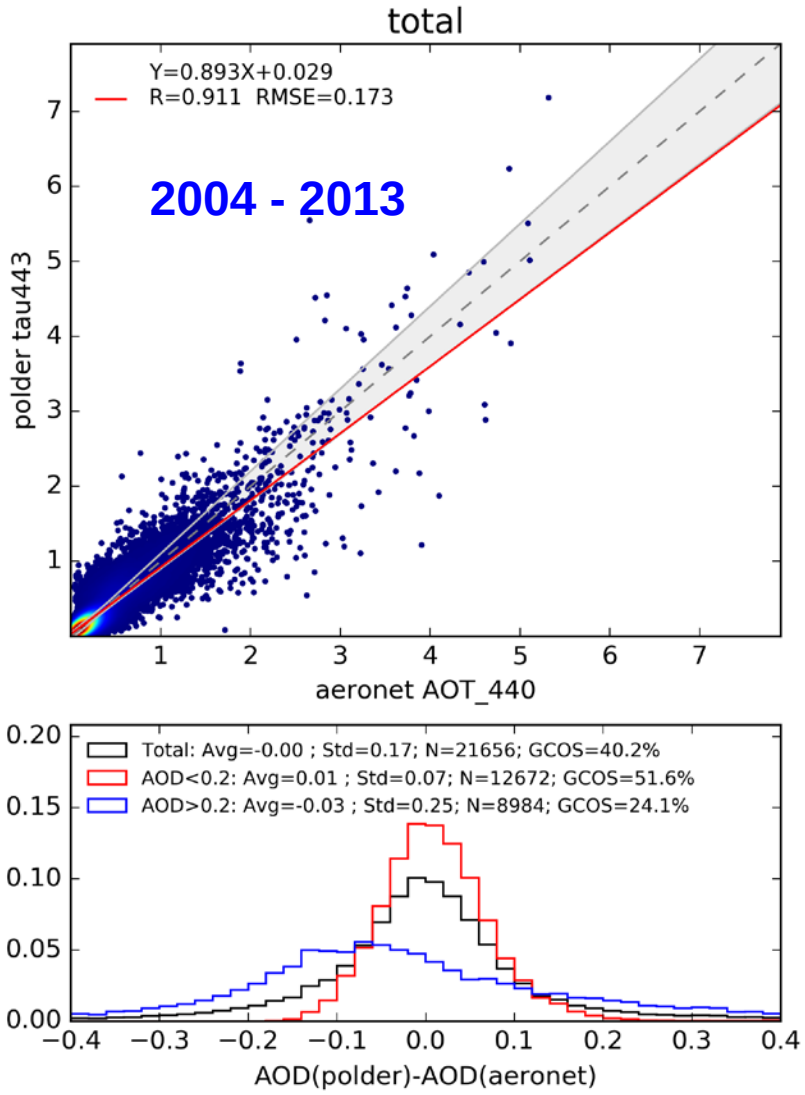


3 Backscattering + 2 Depolarizations

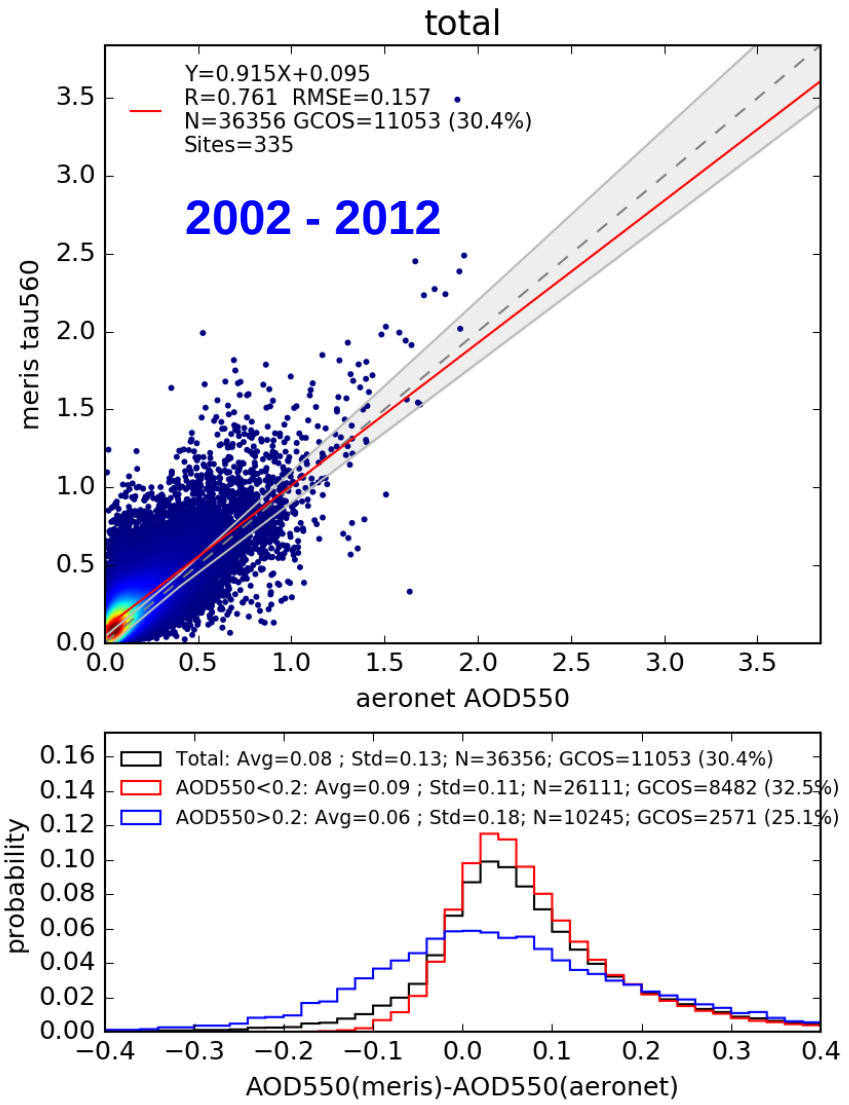
Qiaoyun HU, Anton Lopatin, etc.

Validation vs AERONET, AOD over land

PARASOL/GRASP, R=0.91

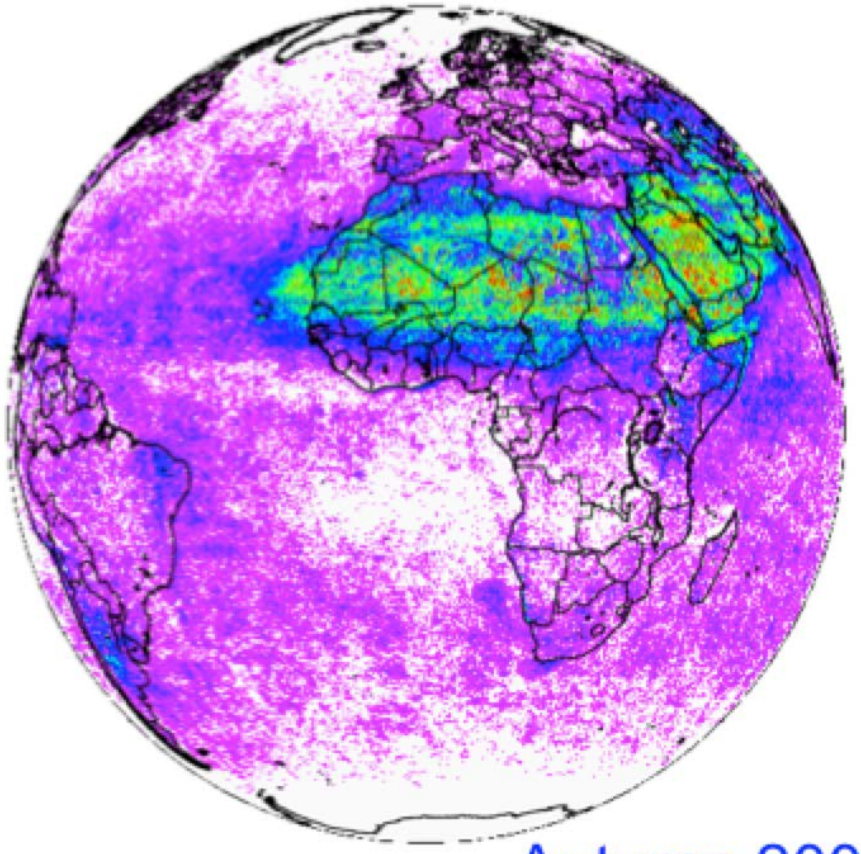


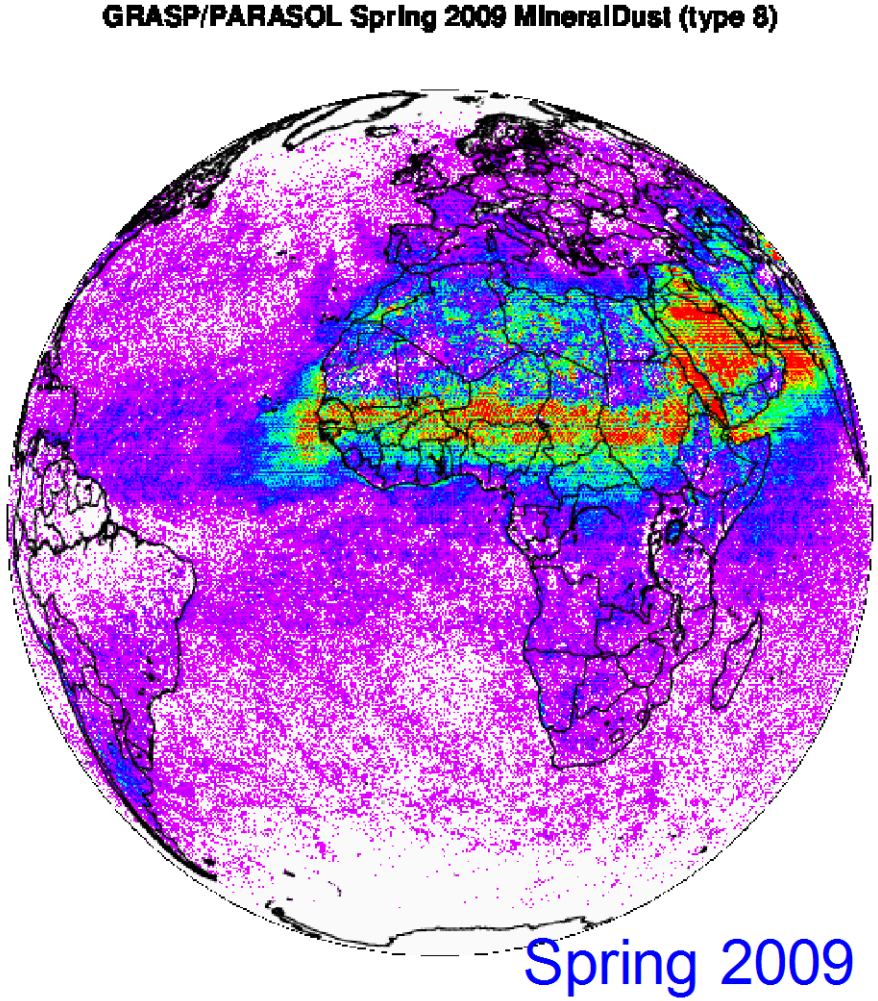
MERIS/GRASP, R=0.76



Aerosol type detection with GRASP

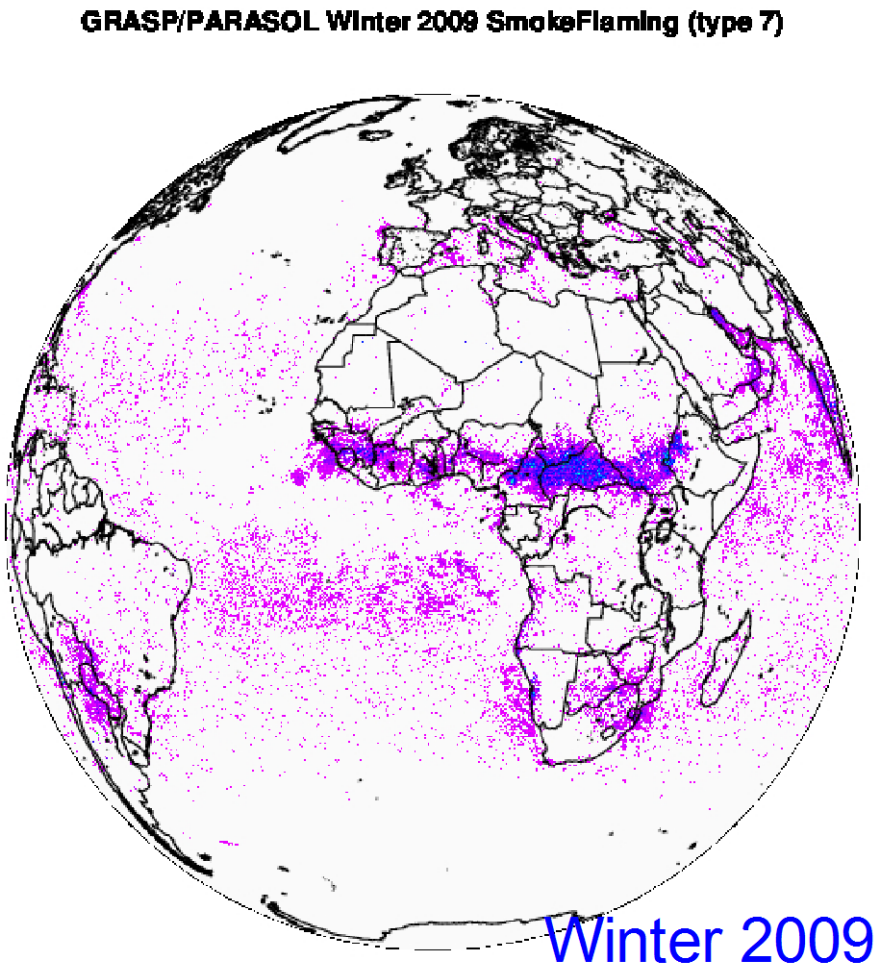
Mineral dust frequency of occurrence

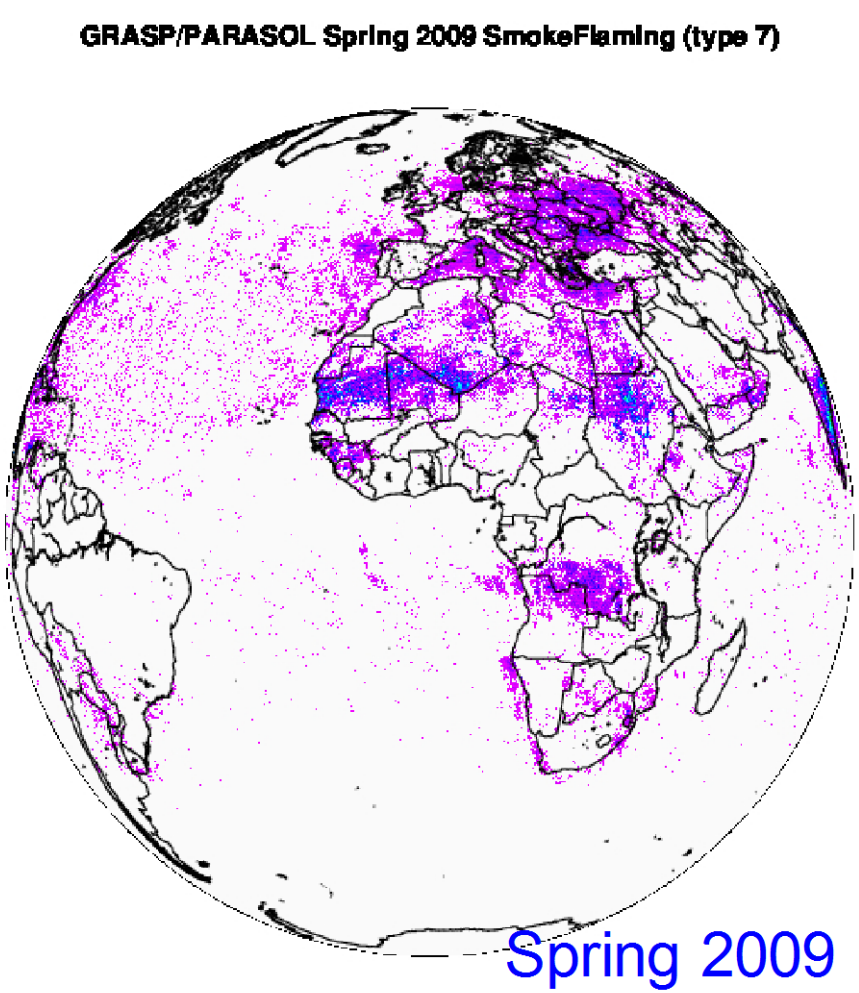




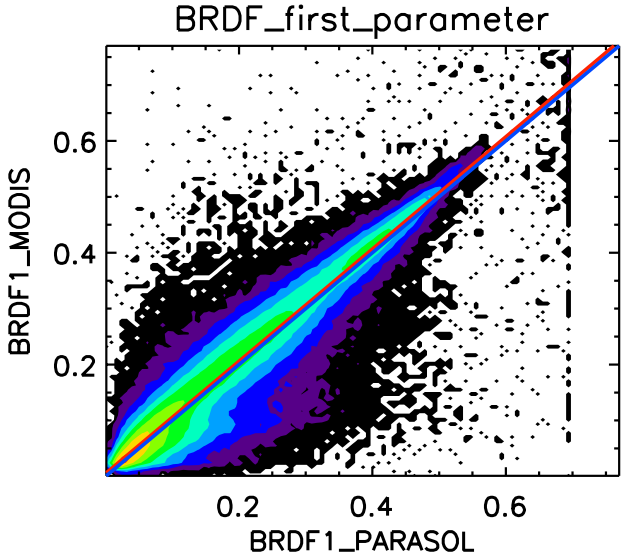
Aerosol type detection with GRASP

Smoke frequency of occurrence

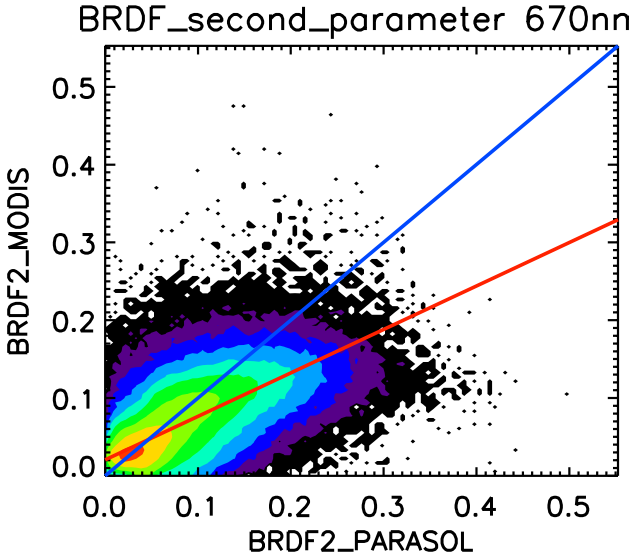




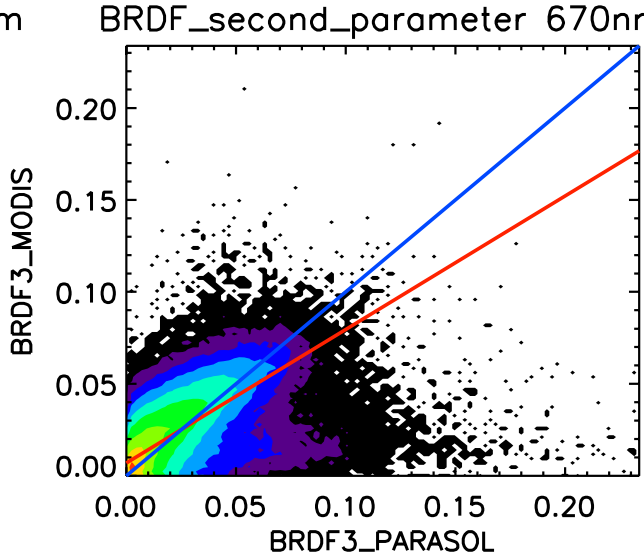
GRASP/PARASOL BRDF vs MODIS



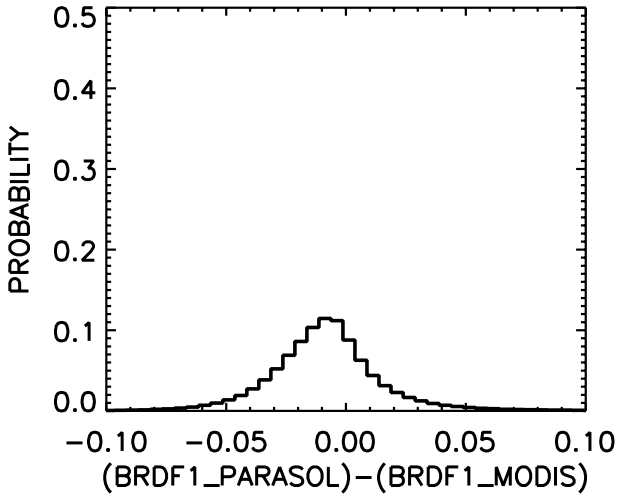
K=0.965 a= 1.00 b= 0.01 RMSE= 0.030



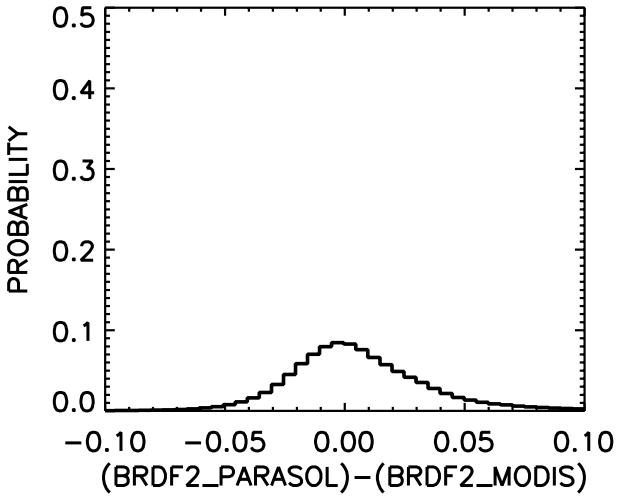
K=0.709 a= 0.56 b= 0.02 RMSE= 0.032



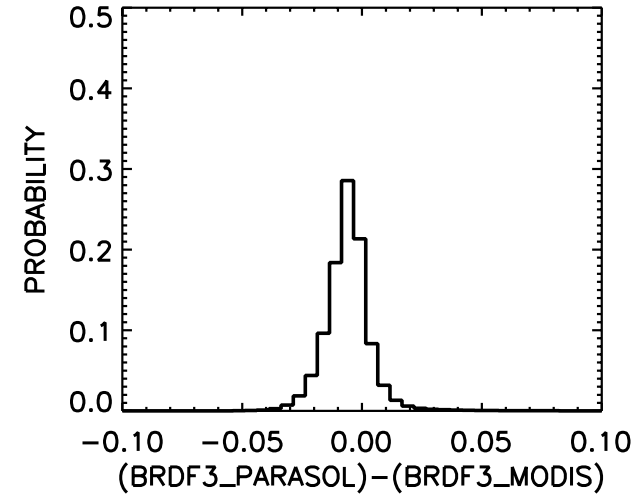
K=0.710 a= 0.73 b= 0.01 RMSE= 0.011



Aver. Value=−0.006 St.D.= 0.030 N=122295



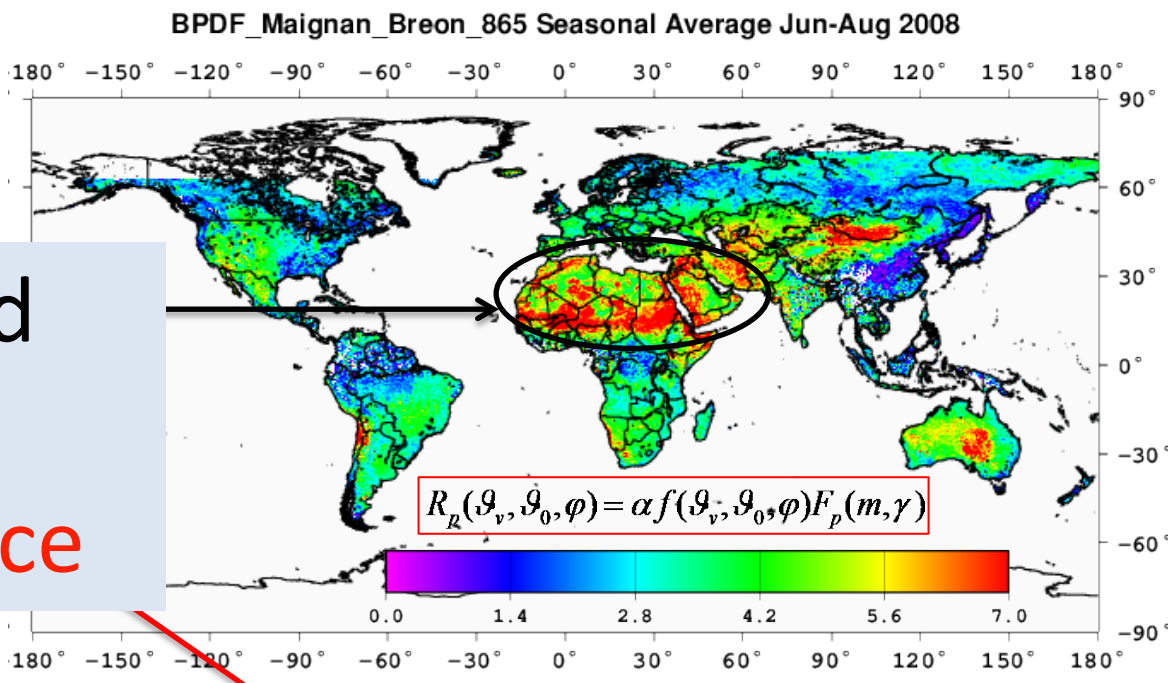
Aver. Value= 0.008 St.D.= 0.031 N=102997

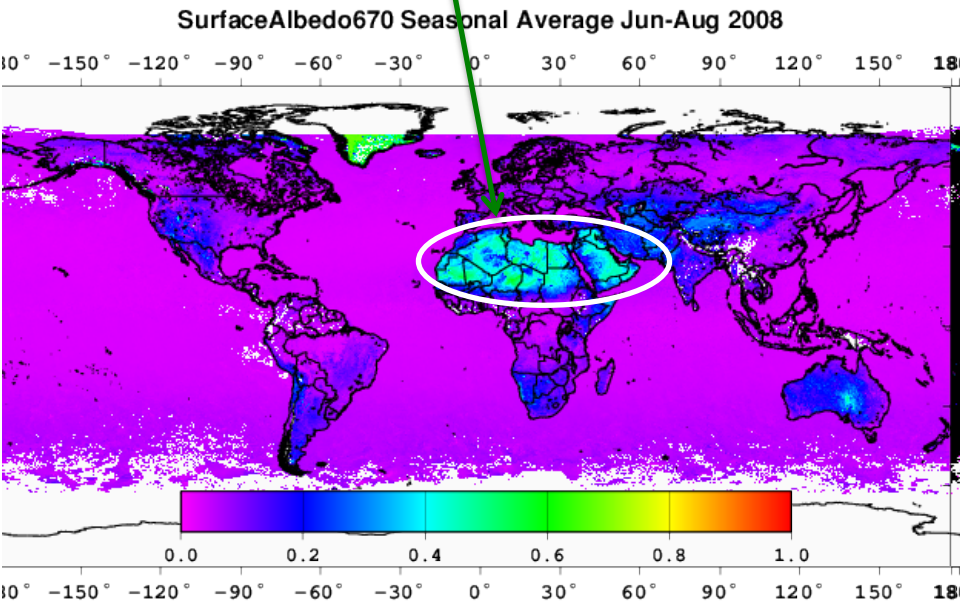


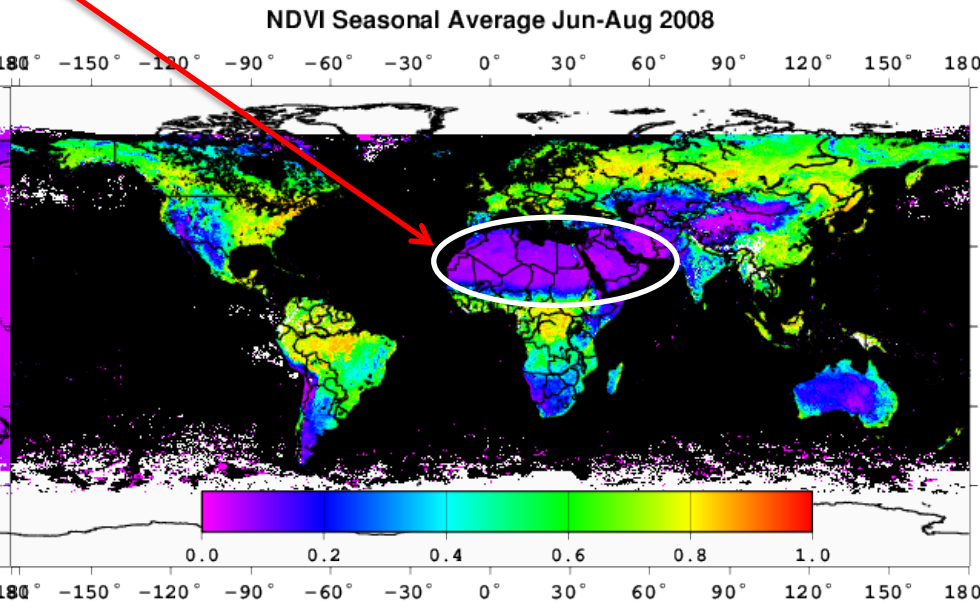
Aver. Value=−0.003 St.D.= 0.010 N=12229

Advanced surface retrieval with GRASP

The same NDVI and DHR but different Polarized reflectance

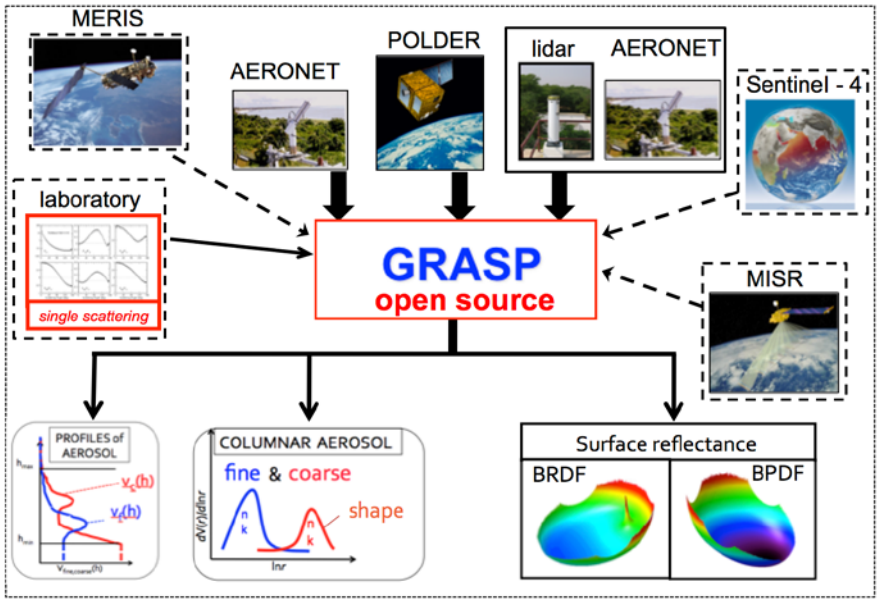






Polarized reflectance provides new information about surface type!

GRASP: Generalized Retrieval of Aerosol and Surface Properties



Strength of GRASP algorithm concept:

- ✓ Based on accurate rigorous physics and math;
- ✓ Versatile (applicable to different sensors and retrieval of different parameters);
- ✓ Designed for multi-sensor retrieval (satellite, ground-based, airborne; polar and geostationary,);

- ✓ Provides accurate solutions:
  - for both aerosol and surface:
  - no location specific a priori constraints;
  - the constraints are the same globally;
  - generally retrieval is at original resolution

Current and potential applications:

Satellite instruments:

polar: POLDER/PARASOL, 3MI/MetOp-SG, MERIS/Envisat, Sentinel-3 (OLCI, SLSTR), etc.

geostationary: Sentinel-4, FCI, GOCO, Himawari-8, etc.

Ground-based, airborne and laboratory instruments:

passive: AERONET radiometers, sun/luna/star-photometers, etc.

active: multi-wavelength elastic and non-elastic lidars; *airborne and laboratory: polar nephelometers,*

Multi-instrument synergy:

ground-based: lidar + radiometers + photometers , sun/luna/star-photometers, etc.

satellite: OLCI + SLSTR, polarimeter + lidar (e.g. PARASOL + CALIPSO)

Support: **CNES** (TOSCA, RD), **ANR** (CaPPA), **ESA** (S-4, MERIS/S-3, GPGPU, CCI, CCI-2,CC+); **EUMETSAT** (3MI NRT), **FP6-7** (ACTRIS 1-2), Catalysts GmbH, etc.

Collaborations: NASA/JPL, NASA/GSFC, NASA/GISS, NASA/Langley KNMI, JAXA, Catalysts GmbH (Austria), Chinese Academy of Science and Space Agency, Belarus, Ukraine, etc.