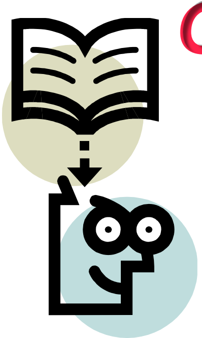
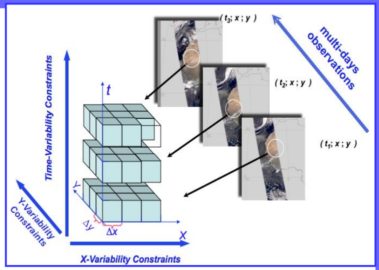


GRASP Algorithm:

Retrieval of the detailed properties of atmospheric aerosol from PARASOL and other sensors



Oleg Dubovik *(University of Lille-1, CNRS, France)*

GRASP team: P. Litvinov[1],T. Lapyonok[1], F. Ducos[1], D. Fuertes[1], X. Huang[1], A. Lopatin[1], B.Torres[1], Y. Derimian[1], L. Li[1], C. Chen[1] M. Aspetsberger[2], C. Federspiel[2], etc.

1 - University of Lille-1, CNRS, France

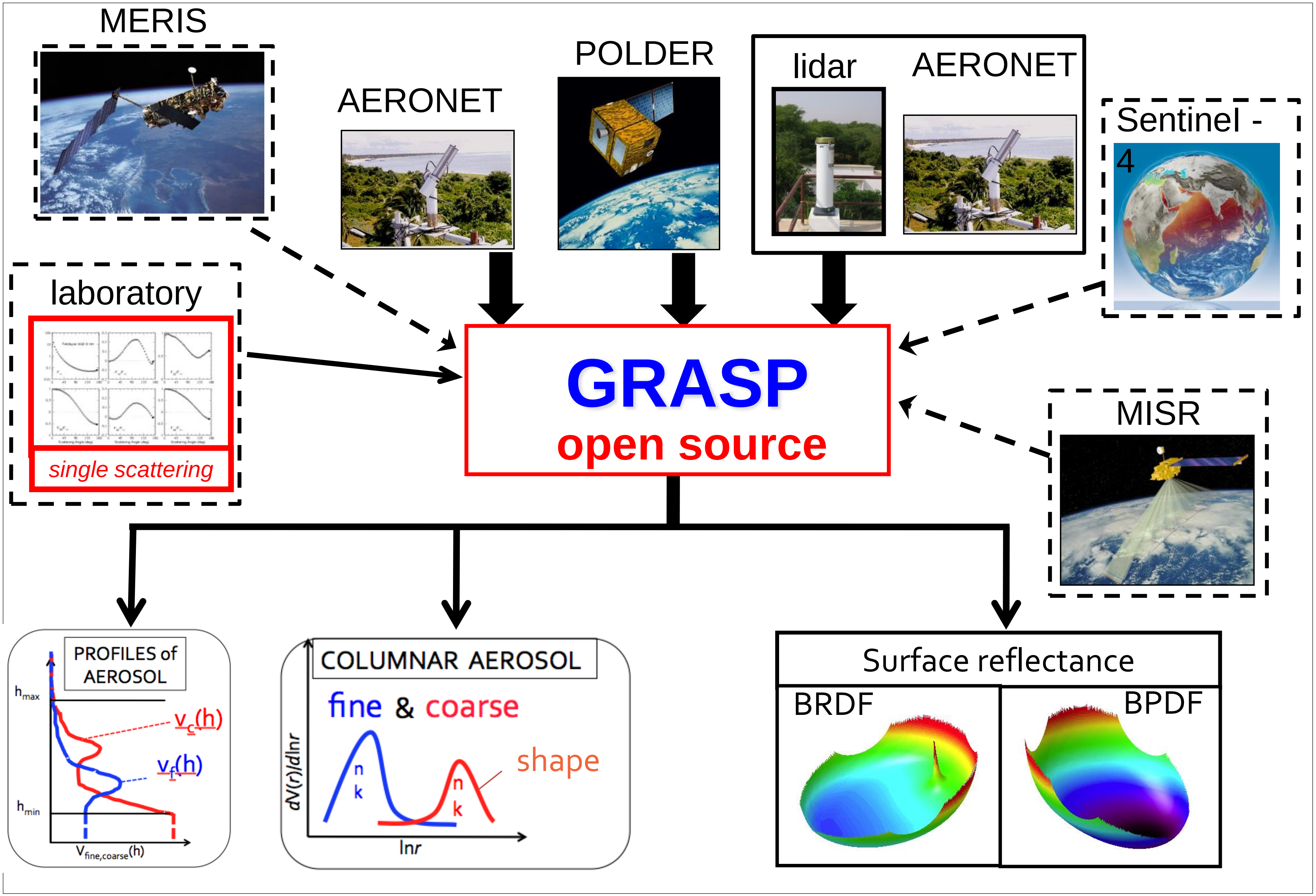
2- Catalysts GmbH, High Performance Computing, Linz, Austria






7th ICAP Meeting, Barcelona, Spain, June 16 - 19 , 2015

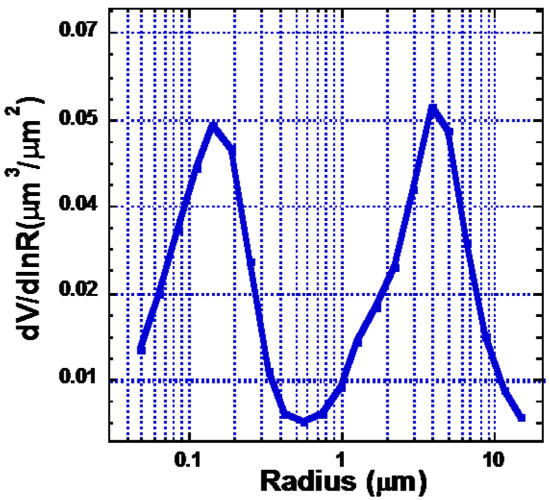
GRASP: Generalized Retrieval of Aerosol and Surface Properties



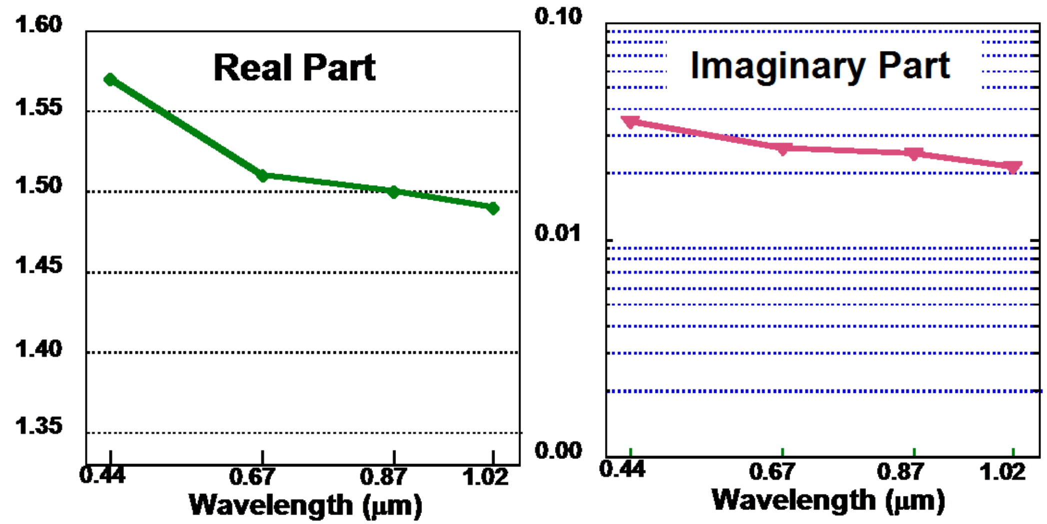
AERONET retrievals are driven by 31 variables :

dV/lnr - size distribution (22 values);
n(λ) and k(λ) - ref. index (4 +4 values)
C_{spher} (%) - spherical fraction (1 value)

Particle Size Distribution: 0.05 μm ≤ R (22 bins) ≤ 15 μm



Complex Refractive Index at λ = 0.44; 0.67; 0.87; 1.02 μm



Single - Pixel Retrieval:

RT calculation on fly !!!

f_j^* - *PARASOL data*:

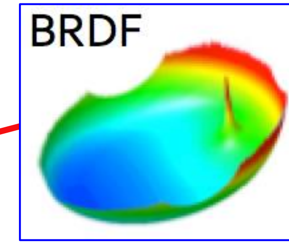
Angular measurements (~15 angles) of

- ***Intensity*** (λ = 0.49; 0.67; 0.87; 1.02 μm)
- ***Polarization*** (λ = 0.49; 0.67; 0.87 μm)

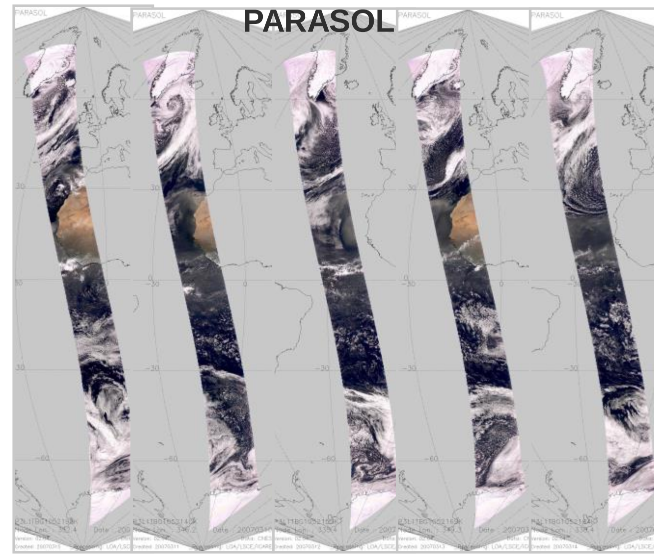
a_j - *Parameters to be retrieved*:

-***Aerosol*** propetries:
- size distribution; - real refractive index
- imaginary refractive index; - particle shape, - height

-***Surface*** properties (***over land***):
- BRF parameters; - BPRF parameters



$$\begin{cases} f_j^* \\ 0_j^* \end{cases} = \begin{pmatrix} F_j \\ S_j \end{pmatrix} a_j + \begin{pmatrix} \Delta_j^m \\ \Delta_j^a \end{pmatrix}$$



A Priori Constraints limiting derivatives (e.g. *Dubovik 2004*) of

- for aerosols (e.g. in AERONET, *Dubovik and King 2000)* **:**
- aerosol size distribution variability over size range;
- spectral variability of complex refractive index;

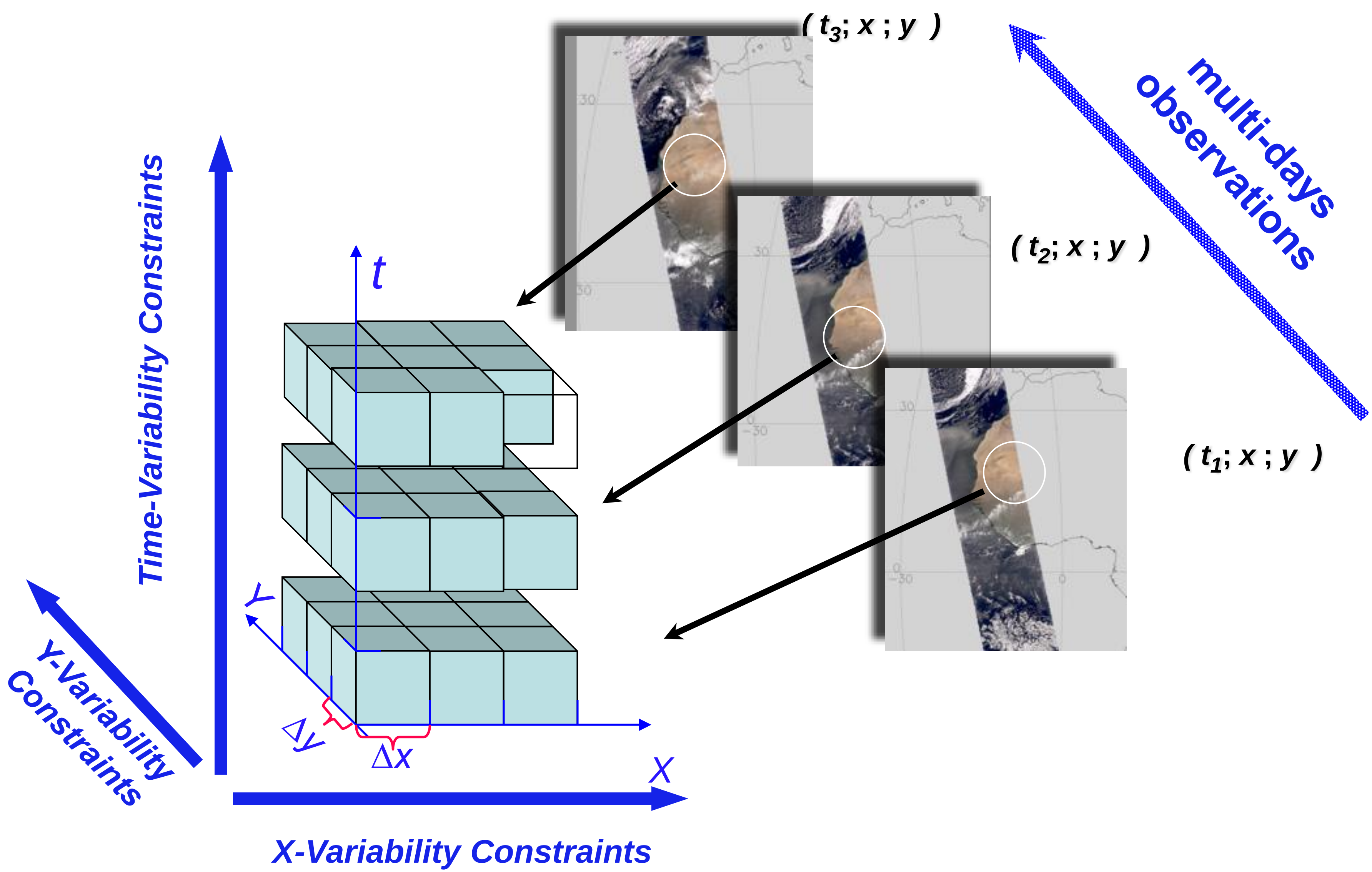
- for surface (e.g. in AERONET/satellite retrievals, *Sinuyk et al. 2007)* **:**
- spectral variability of BRF/ PBRF parameters.

Multi-term LSM statistically optimized ***Solution*** (*Dubovik and King 2000, Dubovik 2004*) **:**

$$a_j = \left(F_j^T W_j^{-1} F_j + \gamma_j \Omega_j\right)^{-1} \left(F_j^T W_j^{-1} f_j^*\right)$$

,where $W_j = S_j^T S_j$; $W_i = \frac{1}{\varepsilon_f^2} C_f$; $\gamma_j = \frac{\varepsilon_f^2}{\varepsilon_a^2}$

The concept of multi-pixel retrieval



Multi - Pixel Retrieval:

$$\left\{\begin{pmatrix} f_1^* \\ O_1^* \end{pmatrix}, \begin{pmatrix} f_2^* \\ O_2^* \end{pmatrix}, \begin{pmatrix} f_3^* \\ O_3^* \end{pmatrix}, \dots, O_t^*, O_x^*, O_y^* \right\} = \begin{pmatrix} \begin{pmatrix} \mathbf{F}_1 \\ \mathbf{S}_1 \end{pmatrix} & 0 & 0 \\ 0 & \begin{pmatrix} \mathbf{F}_2 \\ \mathbf{S}_2 \end{pmatrix} & 0 \\ 0 & 0 & \begin{pmatrix} \mathbf{F}_3 \\ \mathbf{S}_3 \end{pmatrix} \\ \dots & \dots & \dots \\ \mathbf{S}_{t,1} & \mathbf{S}_{t,2} & \mathbf{S}_{t,2} \\ \mathbf{S}_{x,1} & \mathbf{S}_{x,2} & \mathbf{S}_{x,3} \\ \mathbf{S}_{y,1} & \mathbf{S}_{y,2} & \mathbf{S}_{y,3} \end{pmatrix} \begin{pmatrix} \mathbf{a}_1 \\ \mathbf{a}_2 \\ \mathbf{a}_3 \end{pmatrix} + \begin{pmatrix} \begin{pmatrix} \Delta_1^m \\ \Delta_1^a \end{pmatrix} \\ \begin{pmatrix} \Delta_2^m \\ \Delta_2^a \end{pmatrix} \\ \begin{pmatrix} \Delta_3^m \\ \Delta_3^a \end{pmatrix} \\ \Delta_t^a \\ \Delta_x^a \\ \Delta_y^a \end{pmatrix}$$

Single-Pixel Data (PARASOL measurements and physical a priori constraints) ***are used by the same way as in Single-Pixel retrieval*.**

Multi-Pixel a priori constraints (*e.g.Dubovik et al. 2008):*

- limited ***spatial*** variability of each aerosol /surface parameter
- limited ***temporal*** variability of each aerosol /surface parameter

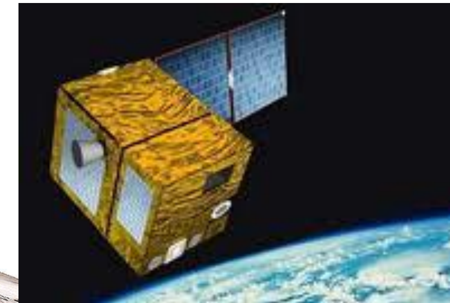
NOTE: *degree of variability constraints (smoothnes) can be different and adequately chosen for each parameter*

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

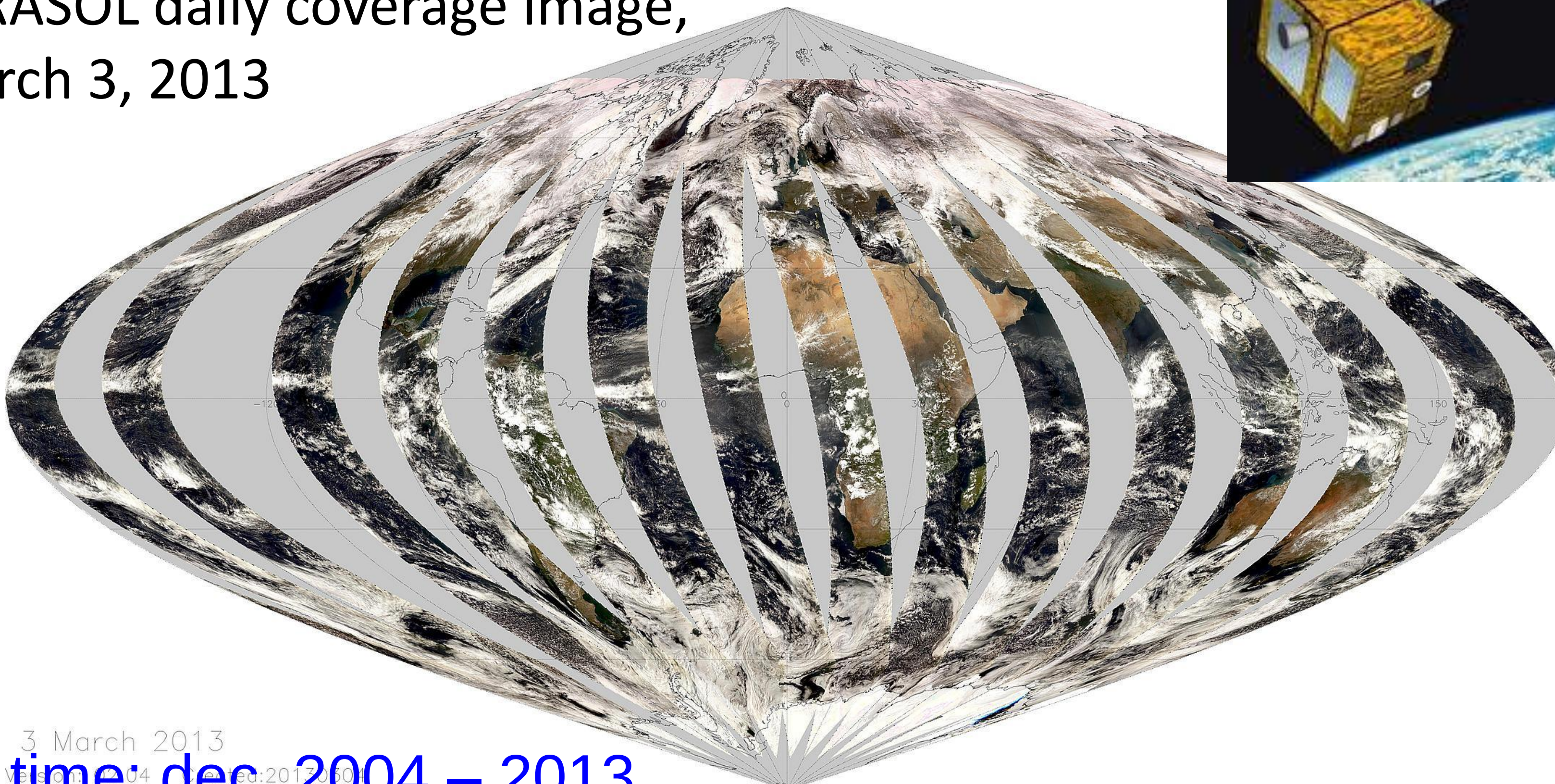
$$\begin{pmatrix} \mathbf{a}_1 \\ \mathbf{a}_2 \\ \mathbf{a}_3 \end{pmatrix} = \left[\begin{pmatrix} \mathbf{F}_1^T \mathbf{W}_1^{-1} \mathbf{F}_1 & 0 & 0 \\ 0 & \mathbf{F}_2^T \mathbf{W}_2^{-1} \mathbf{F}_2 & 0 \\ 0 & 0 & \mathbf{F}_3^T \mathbf{W}_3^{-1} \mathbf{F}_3 \end{pmatrix} + \begin{pmatrix}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

,where $\Omega_x = \mathbf{S}_x^T \mathbf{S}_x$; $\Omega_y = \mathbf{S}_y^T \mathbf{S}_y$; $\Omega_t = \mathbf{S}_t^T \mathbf{S}_t$; $\gamma_x = \frac{\varepsilon_f^2}{\varepsilon_x^2}$; $\gamma_y = \frac{\varepsilon_f^2}{\varepsilon_y^2}$; $\gamma_t = \frac{\varepsilon_f^2}{\varepsilon_t^2}$

PARASOL: the space–borne instrument most suitable for enhanced aerosol/surface characterization



PARASOL daily coverage image, March 3, 2013



life time: dec. 2004 – 2013

INTENSITY

for aerosol (0.44, 0.49, 0.56, 0.67, 0.865, 1.02 μm)

for gas absorption: (0.763, 0.765, 0.910 μm)

POLARIZATION (Q, U): (0.49, 0.67, 0.865 μm)

Swath: about 1600 km cross-track

Global coverage: every 2 days

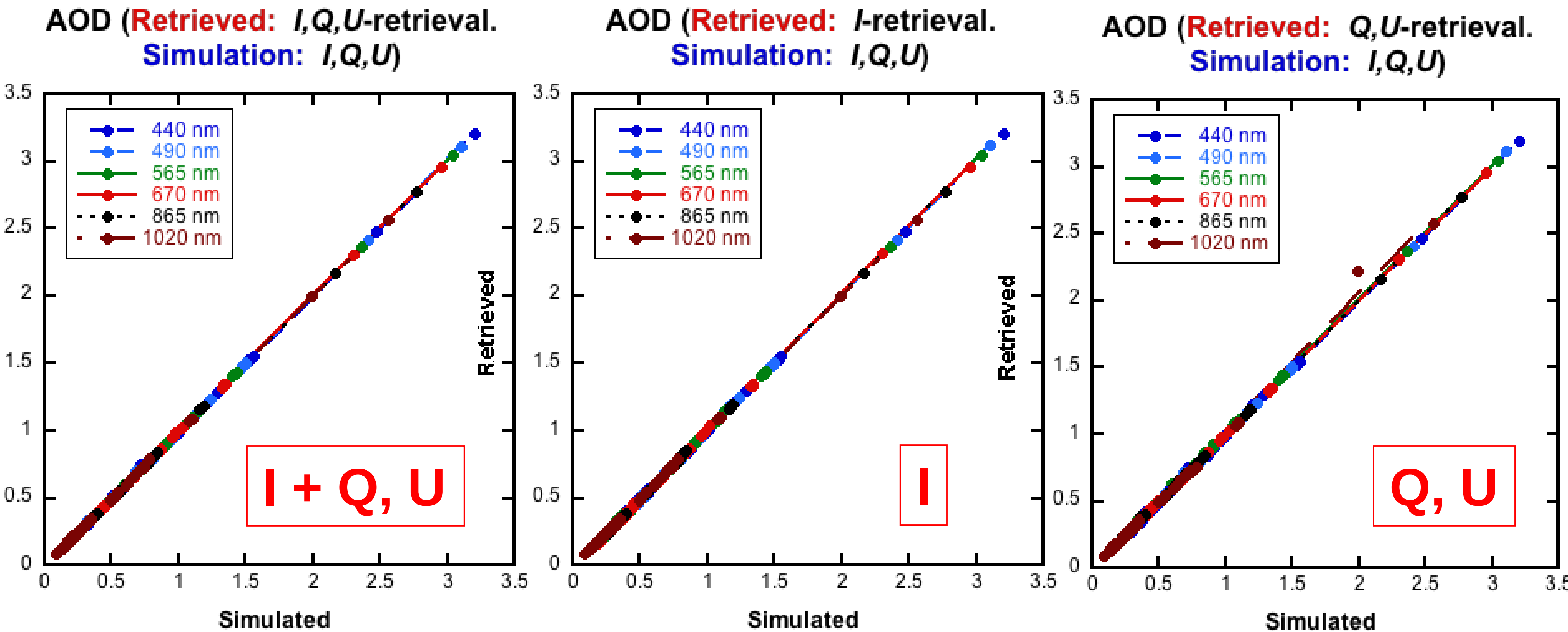
1 pixel spatial resolution: 5.3km × 6.2km

Viewing directions: 16: (80^0 – 180^0)

Test with synthetic measurements

Aerosol Optical Thickness

PARASOL over Banizoumbou in January, February 2008

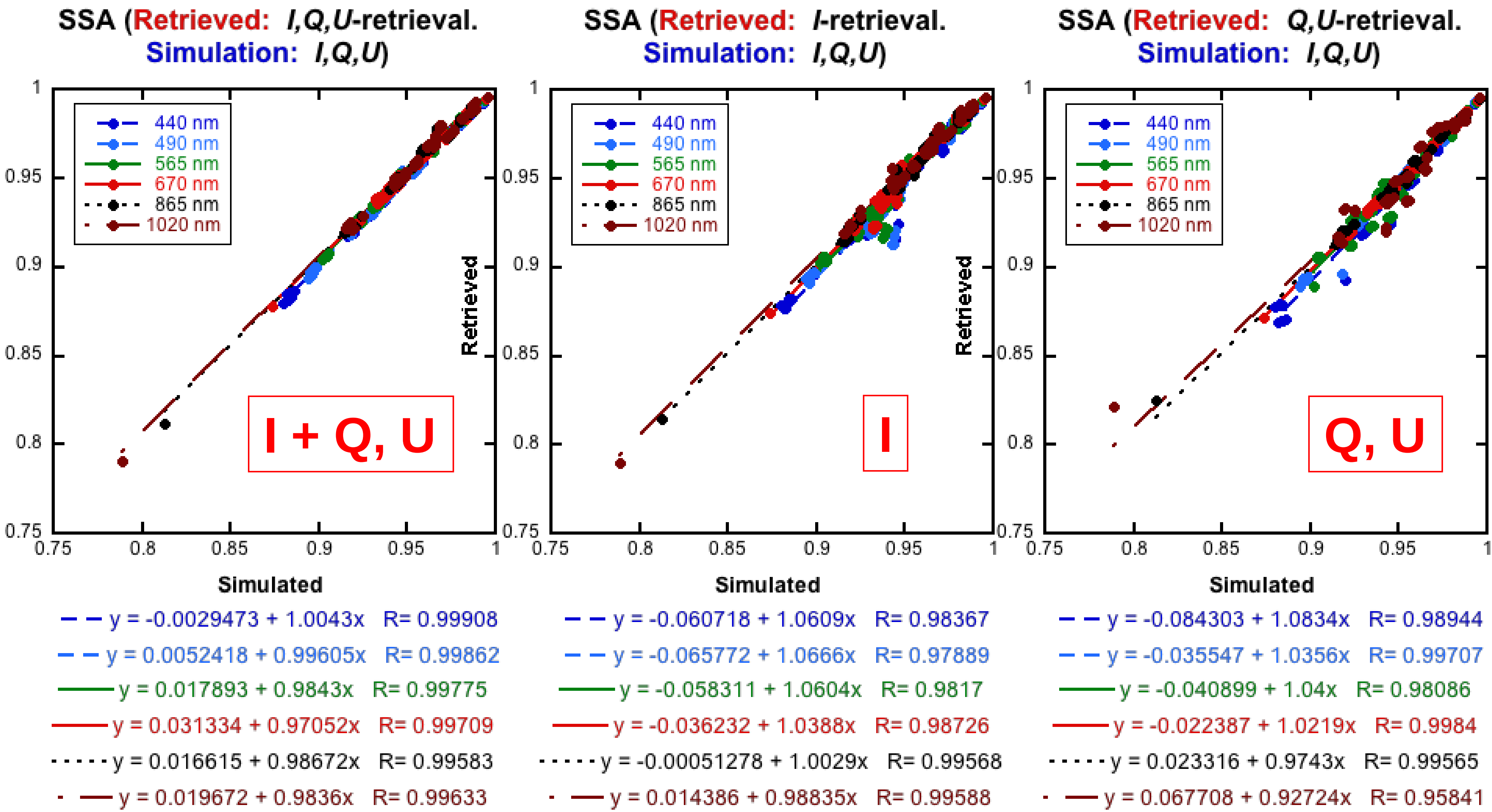


I + Q, U	I	Q, U
y = -0.0043839 + 1.0023x R= 0.99995	y = -0.0071561 + 1.008x R= 0.99987	y = -0.0052906 + 1.0007x R= 0.99986
y = -0.0045597 + 1.0029x R= 0.99996	y = -0.007389 + 1.0073x R= 0.99986	y = 0.0010661 + 1.0003x R= 0.99995
y = -0.0056832 + 1.0029x R= 0.99997	y = -0.0088212 + 1.0087x R= 0.99985	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



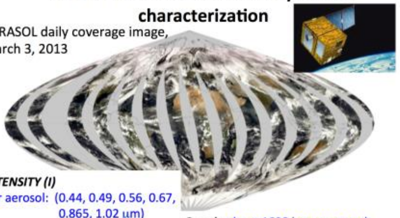
EXAMPLES of PARASOL/GRASP retrievals - 2008

NO ASSUMPTIONS on aerosol and surface

All calculation on the fly

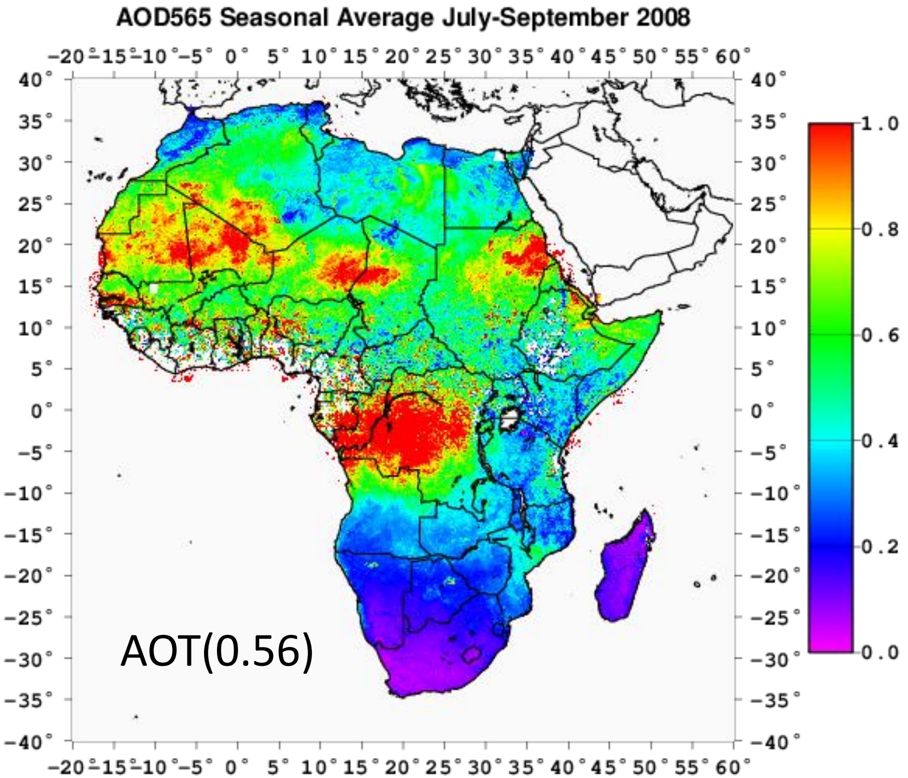
PARASOL: the space–borne instrument most suitable for enhanced aerosol/surface characterization

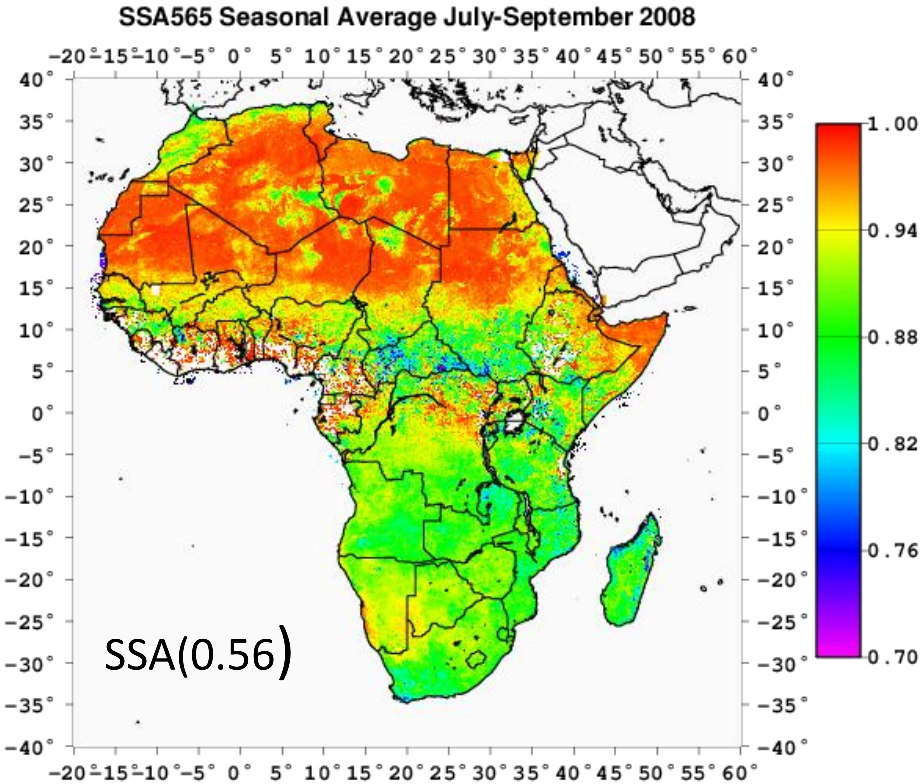
PARASOL daily coverage image, March 3, 2013



INTENSITY (I)
for aerosol: (0.44, 0.49, 0.56, 0.67, 0.865, 1.02 μm)
for gas absorption): (0.763, 0.765, 0.910 μm)
POLARIZATION (Q, U): (0.49, 0.67, 0.865 μm)

Swath: about 1600 km cross-track
Global coverage: every 2 days
1 pixel spatial resolution: 5.3km × 6.2km
Viewing directions: 16: (80^0 – 180^0)





AOT(0.56) - **loading**

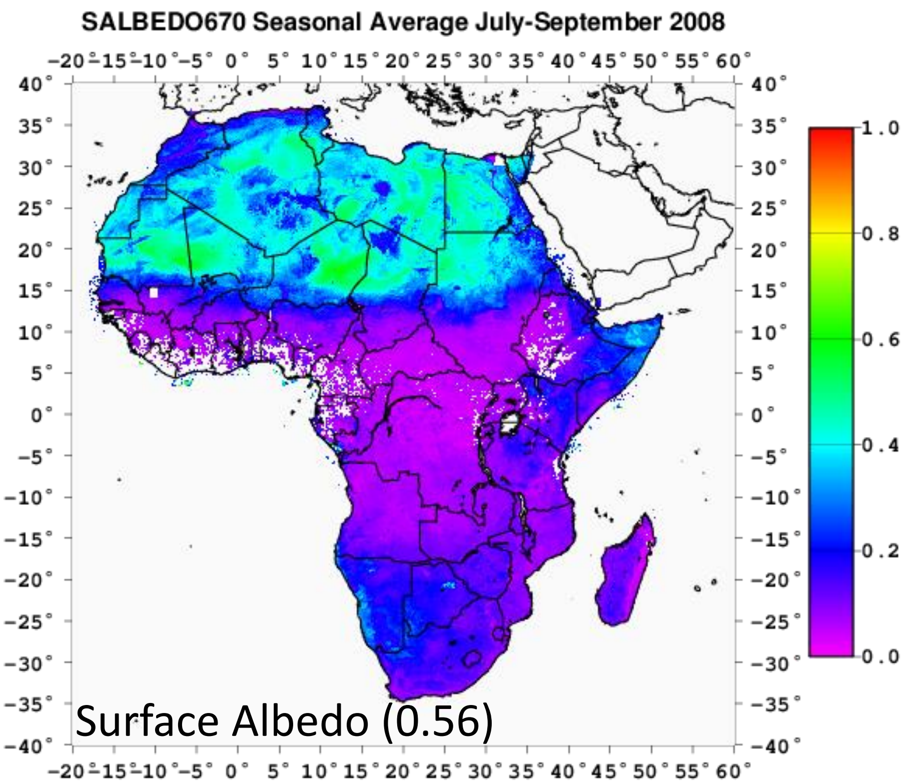
SSA(0.56) - **absorption**

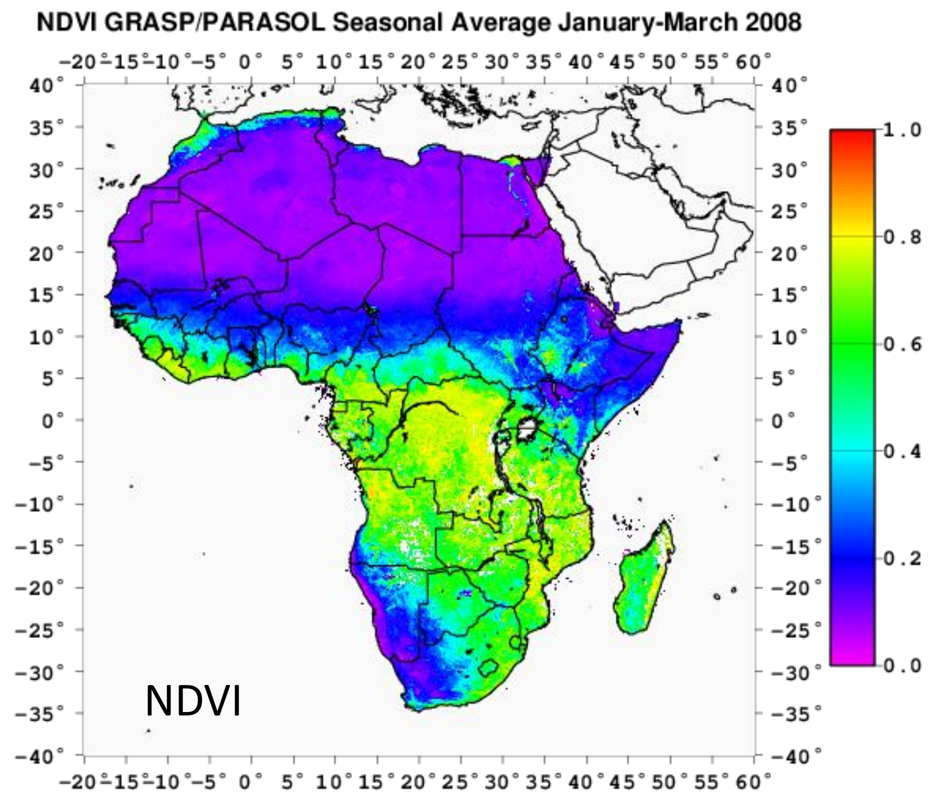
Processed at ICARE

EXAMPLES of PARASOL/GRASP retrievals - 2008

NO ASSUMPTIONS on aerosol and surface

All calculation on the fly



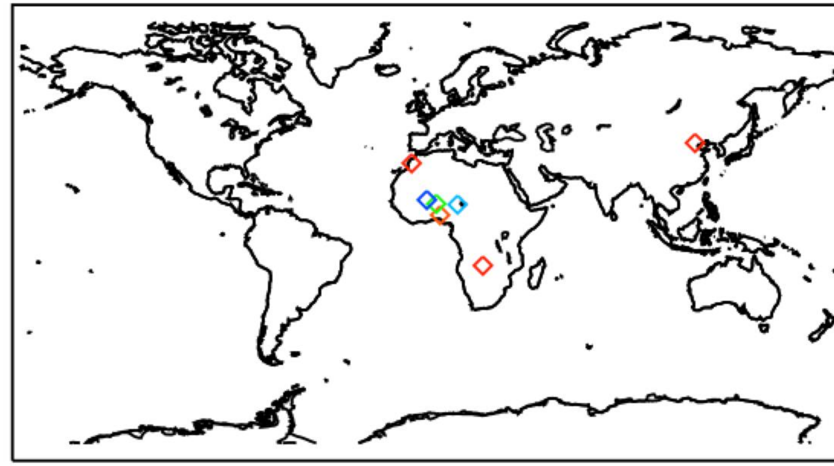


Albego(0.56) - **surface**

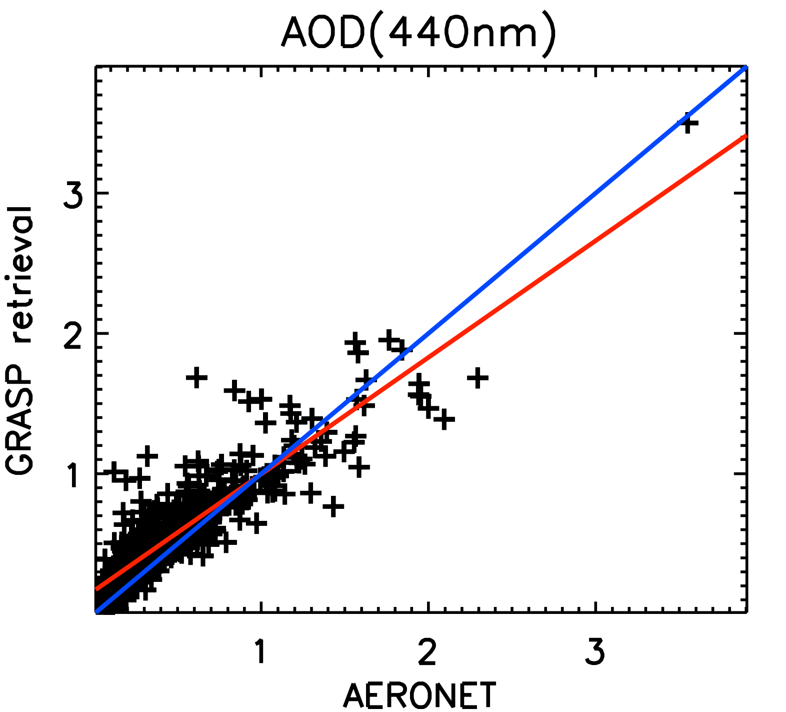
NDVI

Processed at ICARE

1 year of PARASOL data compared with AERONET over Africa at 6 sites:

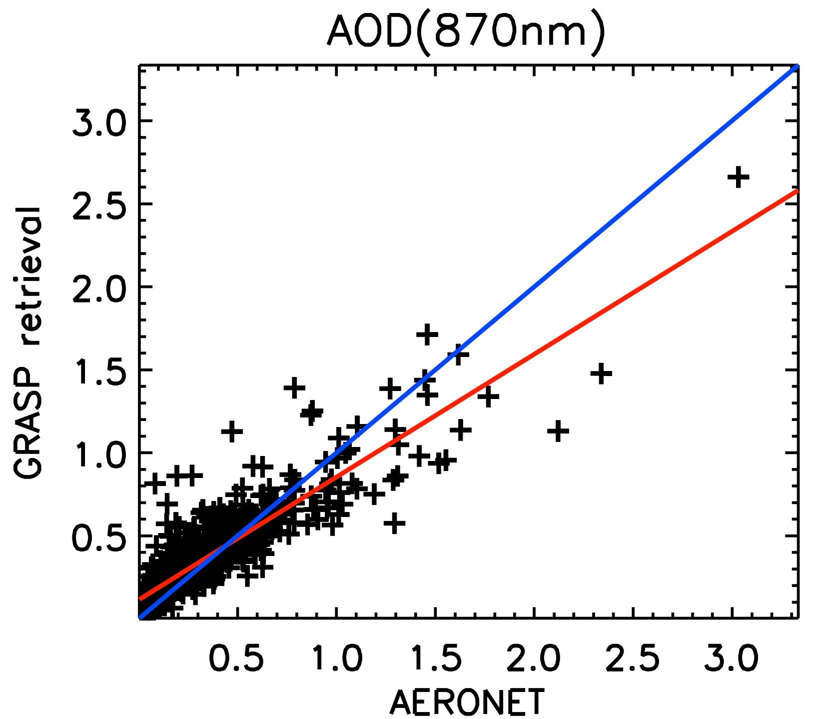


AOD (440)



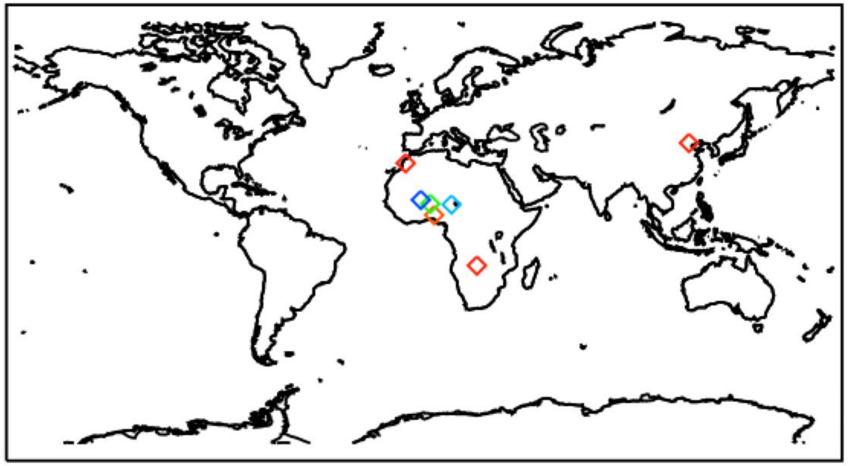
K=0.896 a= 0.83 b= 0.16 RMSE= 0.193

AOD (870)

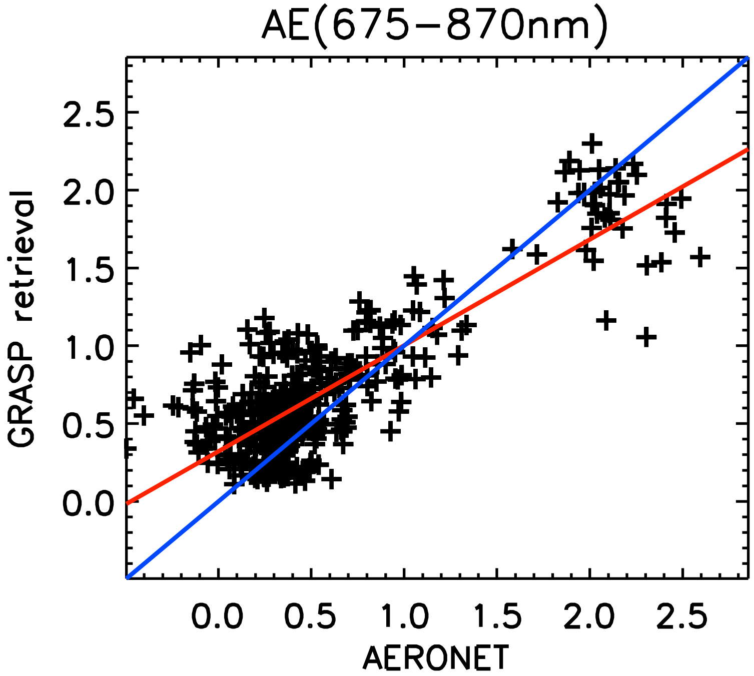


K=0.885 a= 0.74 b= 0.11 RMSE= 0.161

1 year of PARASOL data compared with AERONET over Africa at 6 sites:

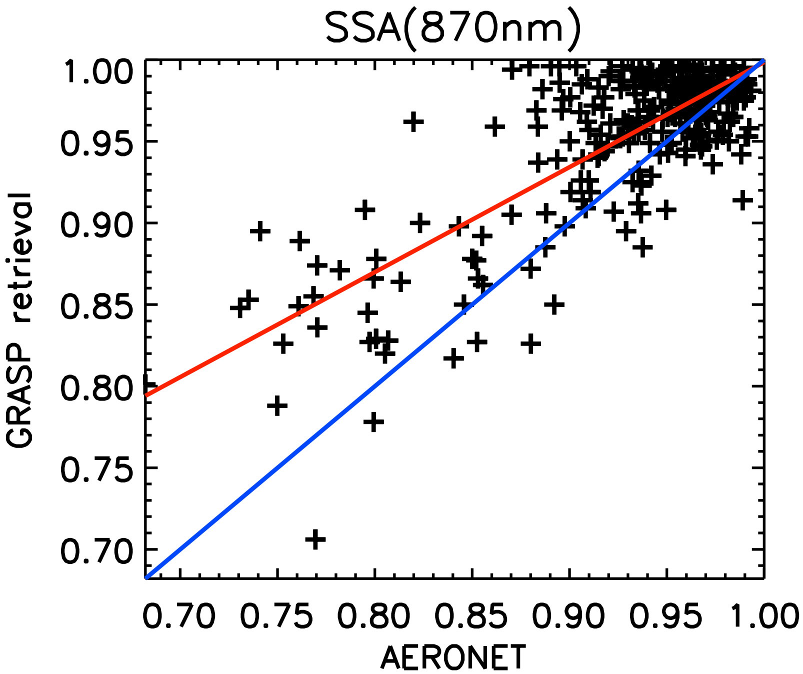


Angstrom Exponent



K=0.838 a= 0.68 b= 0.32 RMSE= 0.345

Aerosol SSA



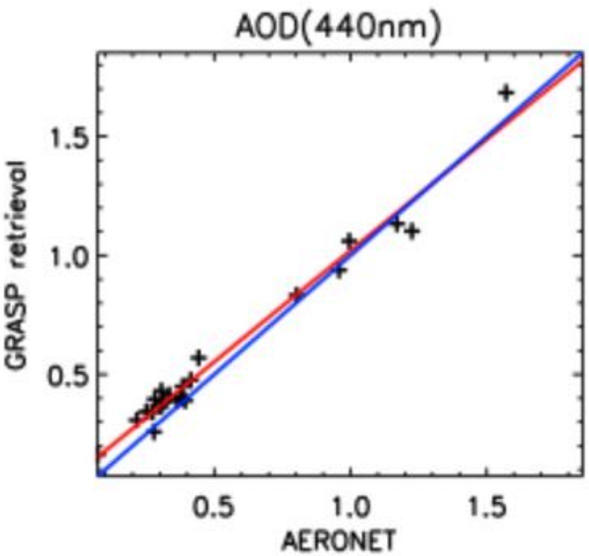
K=0.783 a= 0.64 b= 0.36 RMSE= 0.044

1 year of PARASOL data compared with AERONET

Ilorin –

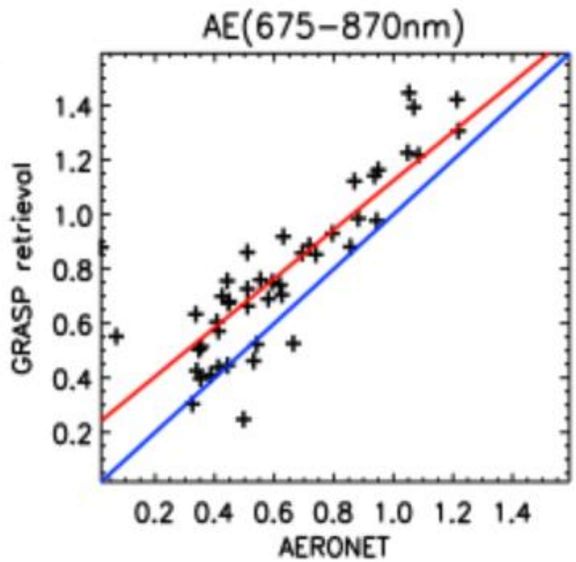
complex mixture of dust and biomass burning

AOD



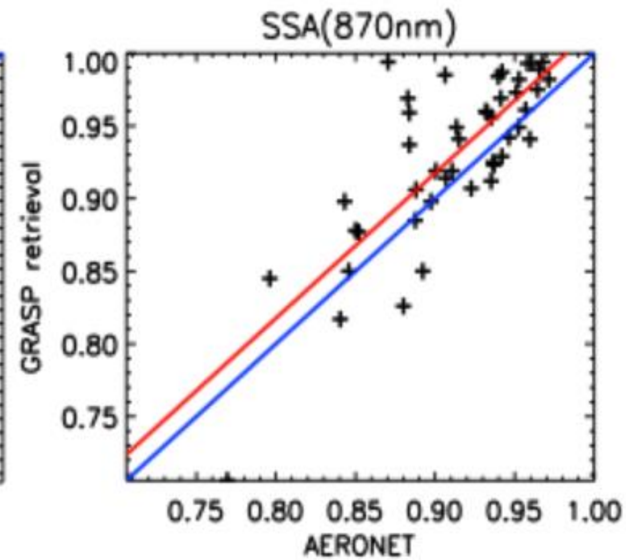
K=0.989 a= 0.93 b= 0.09 RMSE= 0.079

Angstrom Exponent



K=0.832 a= 0.90 b= 0.23 RMSE= 0.235

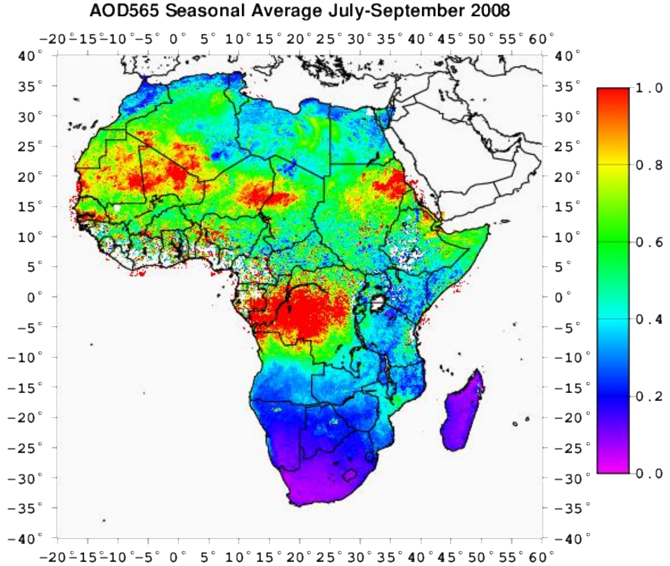
SSA



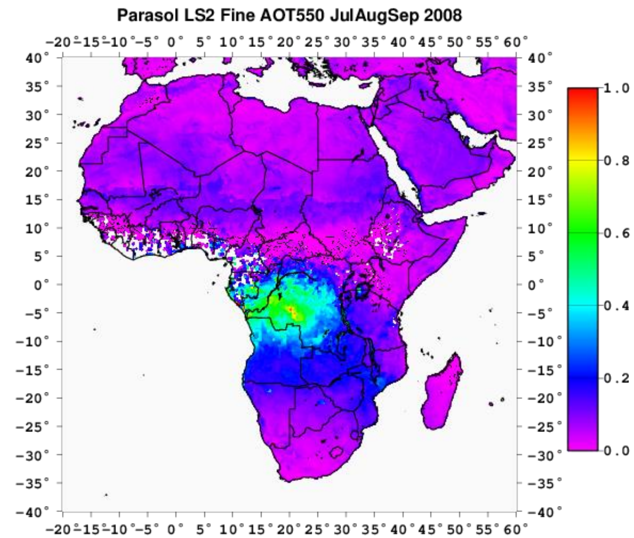
K=0.795 a= 1.00 b= 0.02 RMSE= 0.039

Comparison with other aerosol products

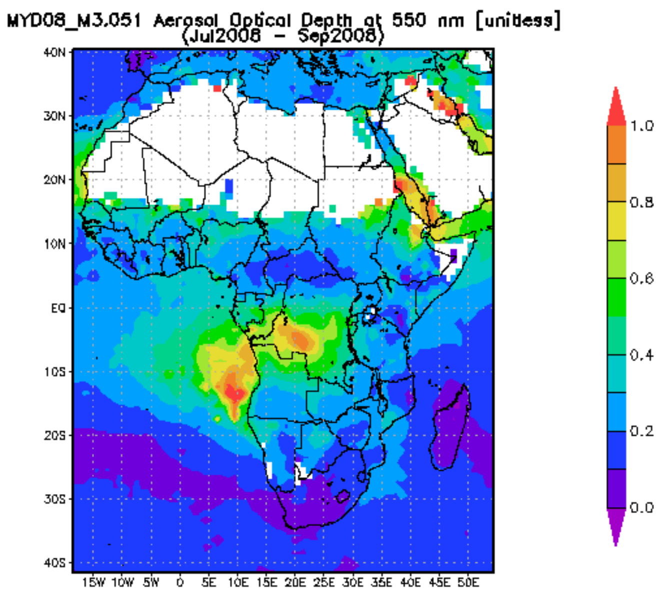
PARASOL /GRASP



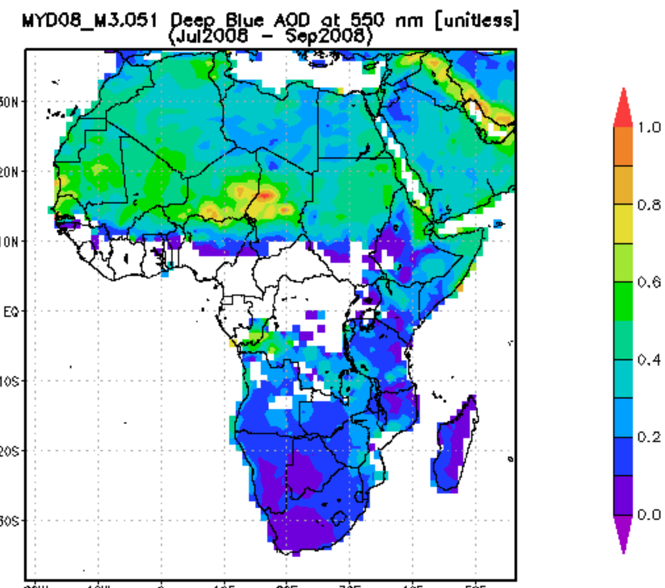
PARASOL /fine mode operational

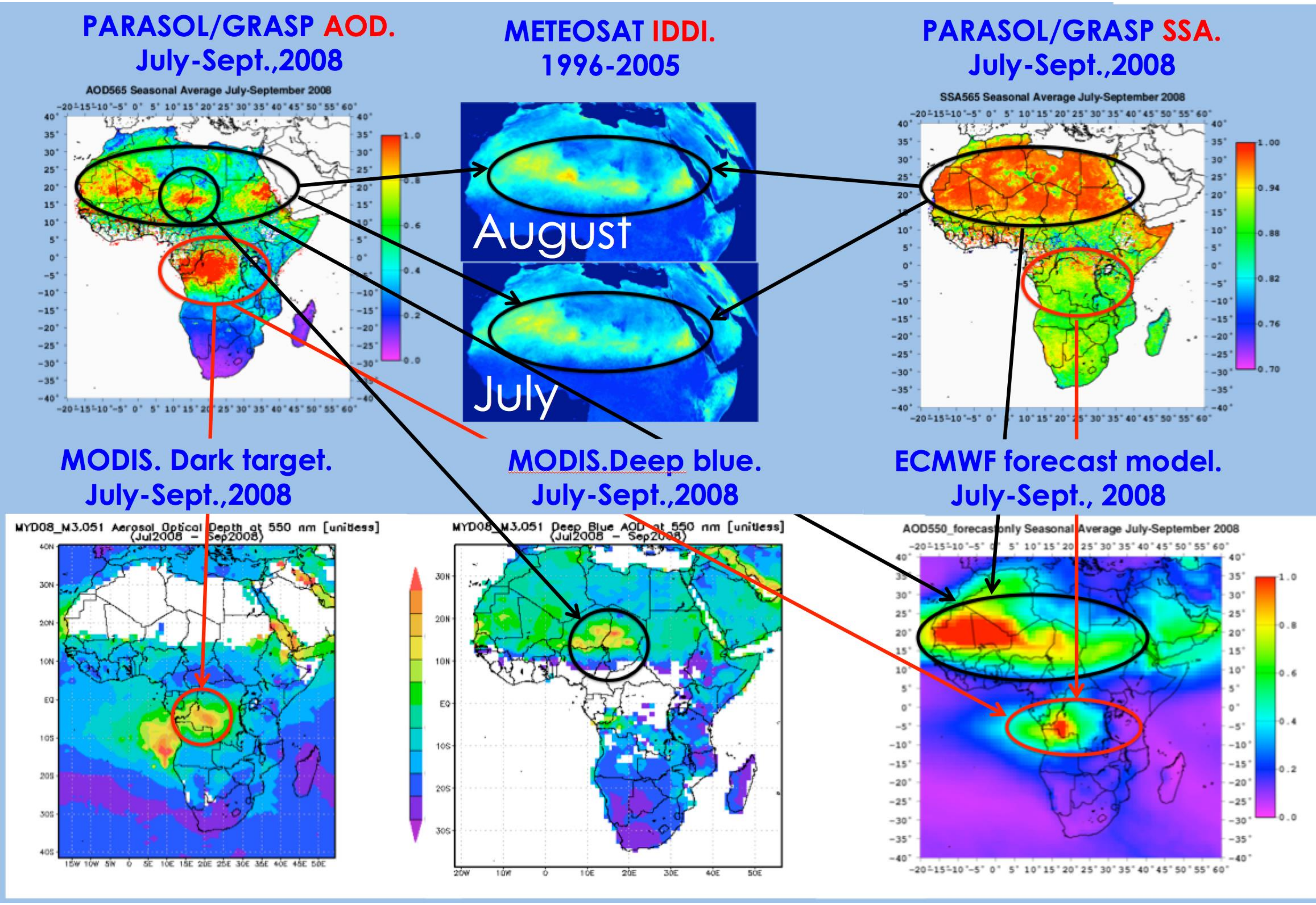


MODIS /Dark Target

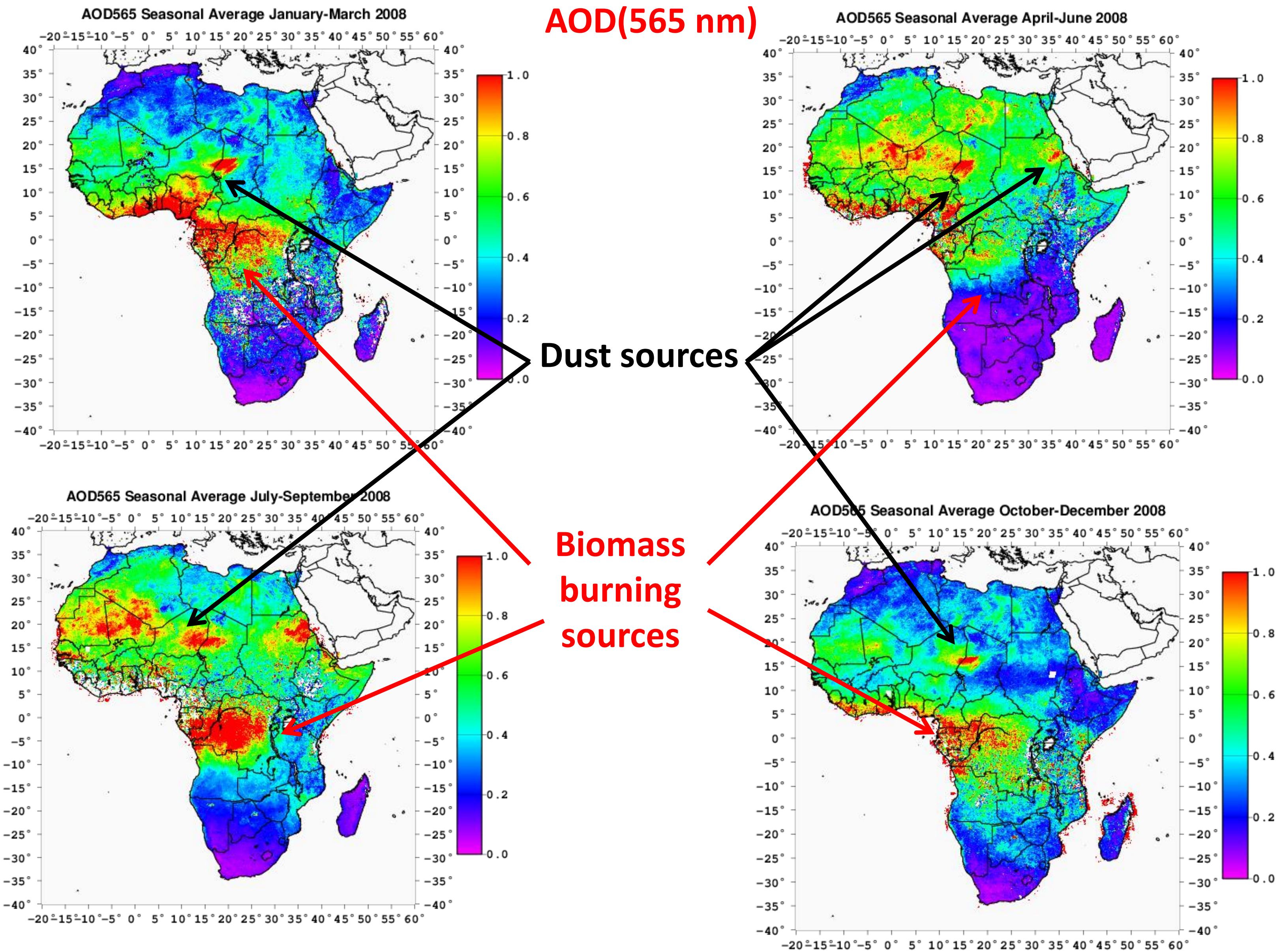


MODIS /Deep Blue

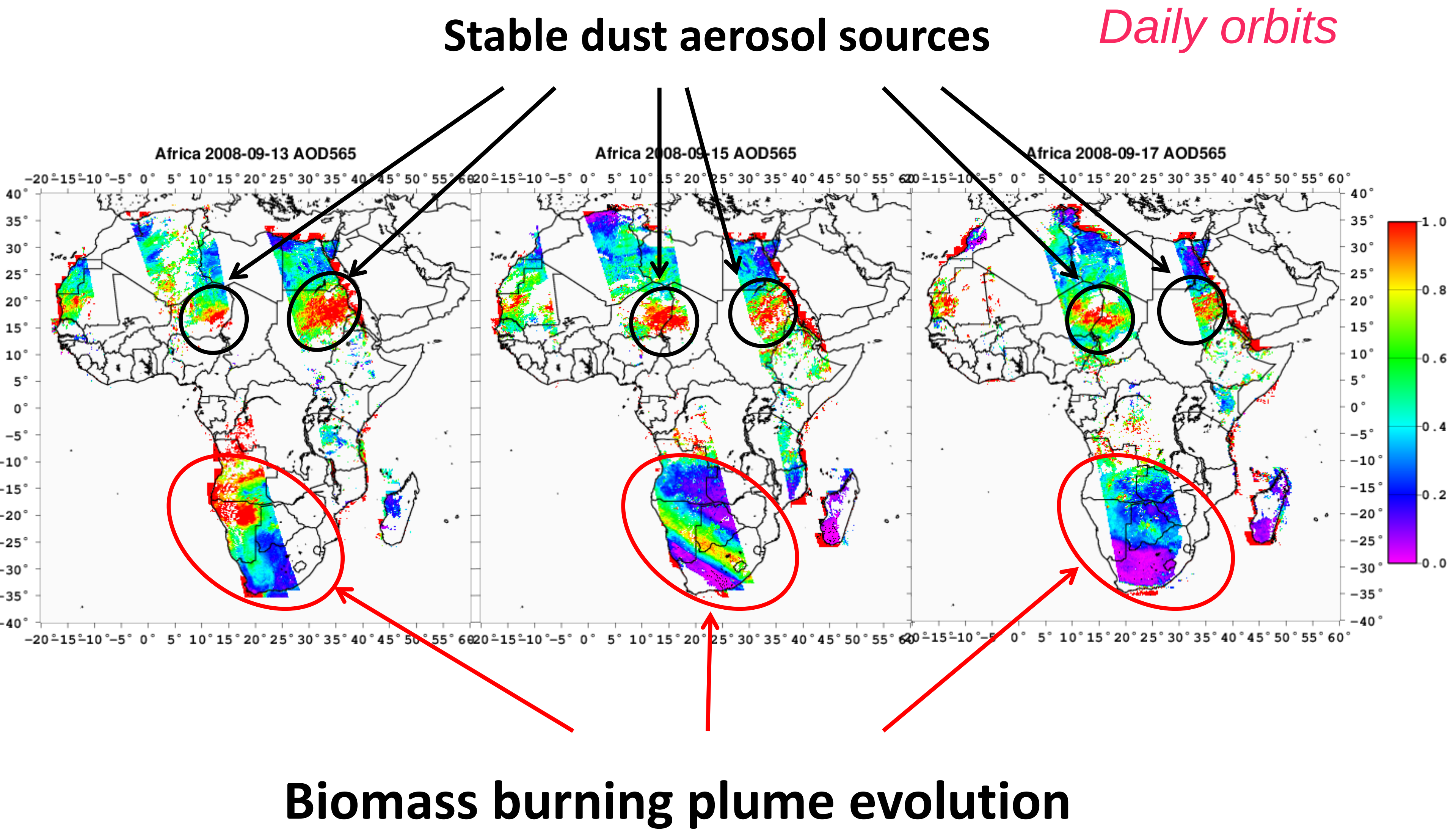



PARASOL/GRASP AOD.
July-Sept.,2008
AOD565 Seasonal Average July-September 2008
METEOSAT IDDI.
1996-2005
August
July
PARASOL/GRASP SSA.
July-Sept.,2008
SSA565 Seasonal Average July-September 2008
MODIS. Dark target.
July-Sept.,2008
MYD08_M3.051 Aerosol Optical Depth at 550 nm [unitless]
(Jul2008 – Sep2008)
MODIS.Deep blue.
July-Sept.,2008
MYD08_M3.051 Deep Blue AOD at 550 nm [unitless]
(Jul2008 – Sep2008)
ECMWF forecast model.
July-Sept., 2008
AOD550_forecastonly Seasonal Average July-September 2008

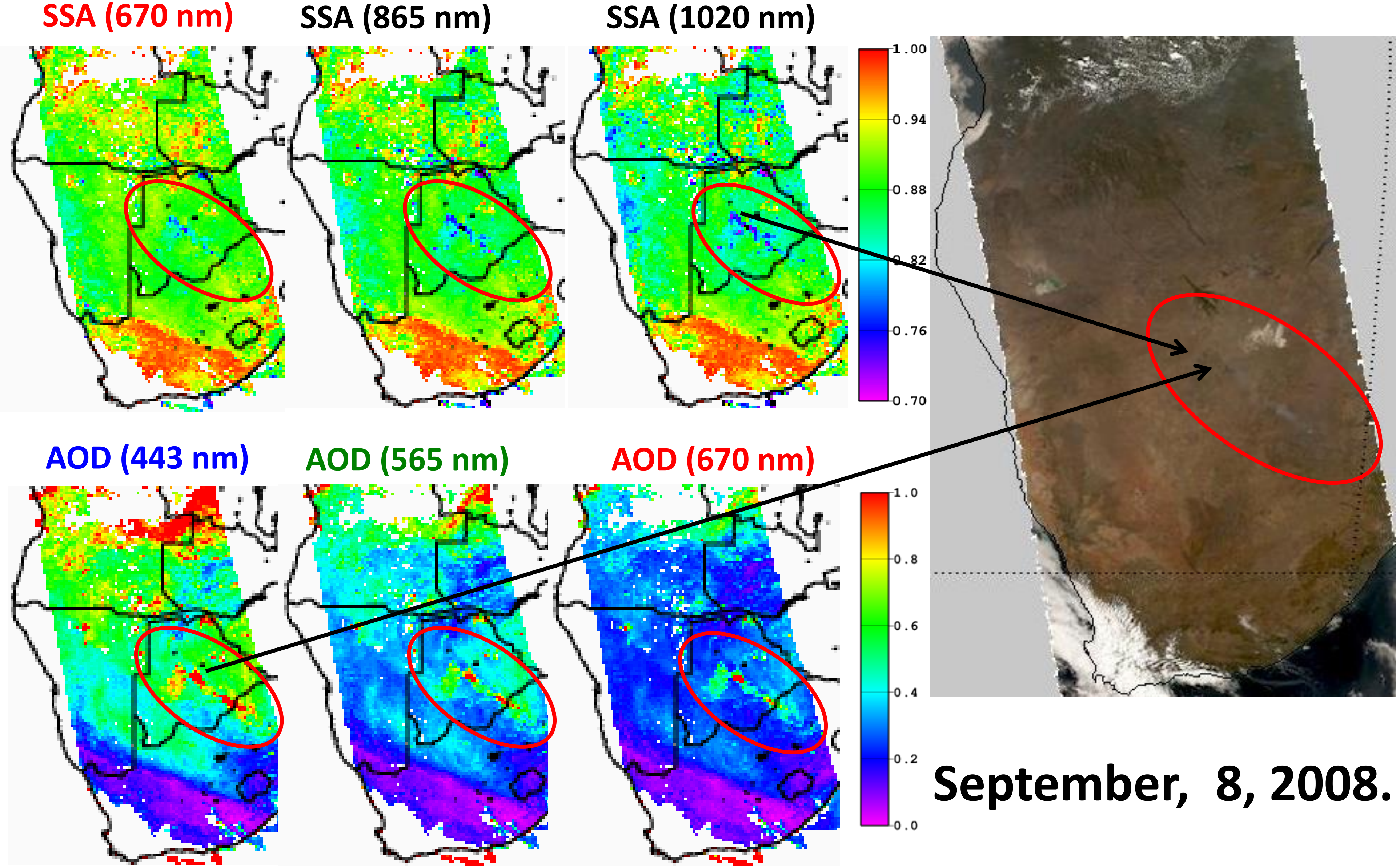
Retrieved seasonal variability of aerosol AOD - 2008



Aerosol transport tracking with GRASP



Aerosol types identification with GRASP (AOD, SSA, AE)

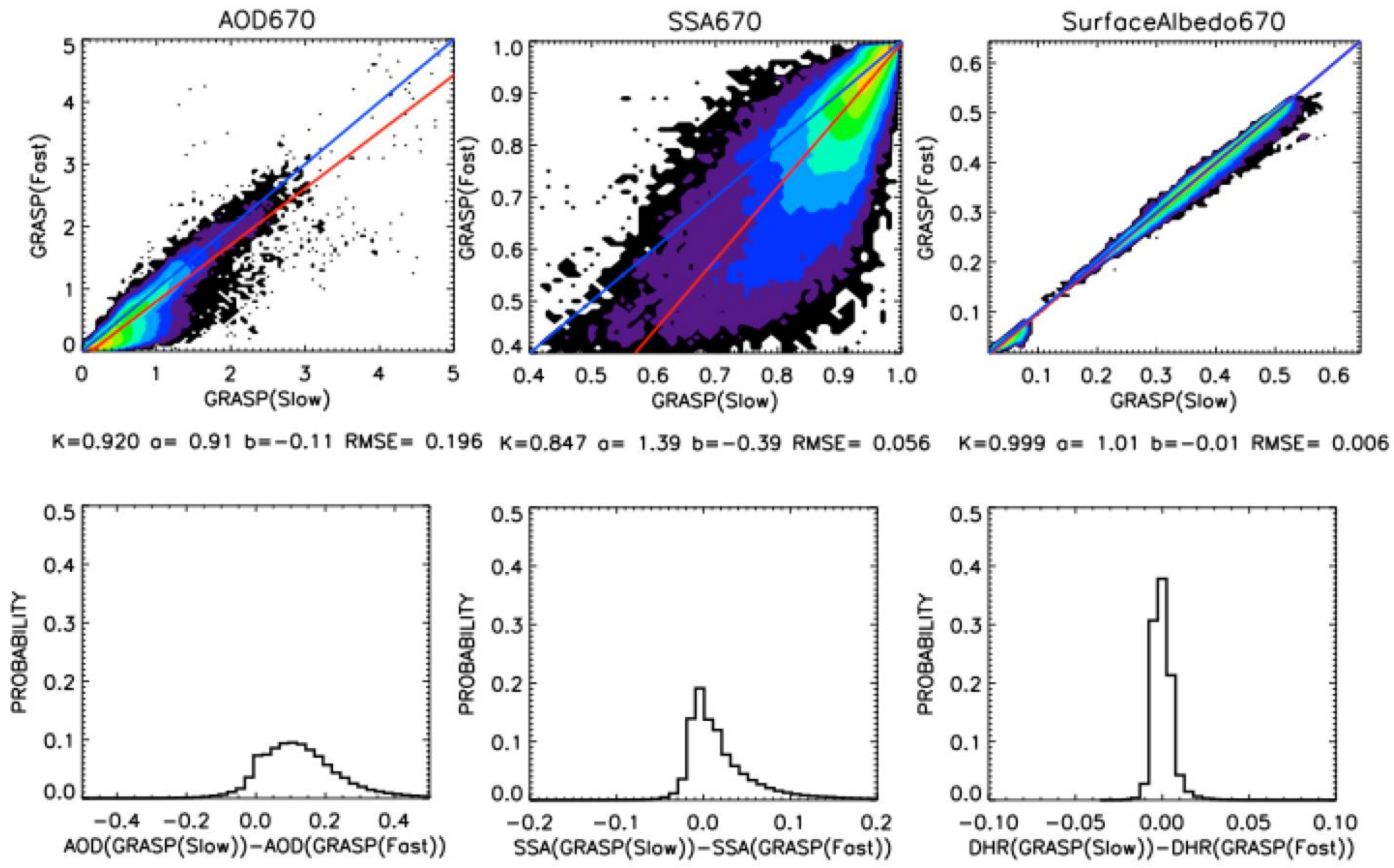


September, 8, 2008.

Is GRASP is fast enough for operational processing?

Accurate, 3 sec per pixel, accelerated is ~ 0.3 or less per pixel

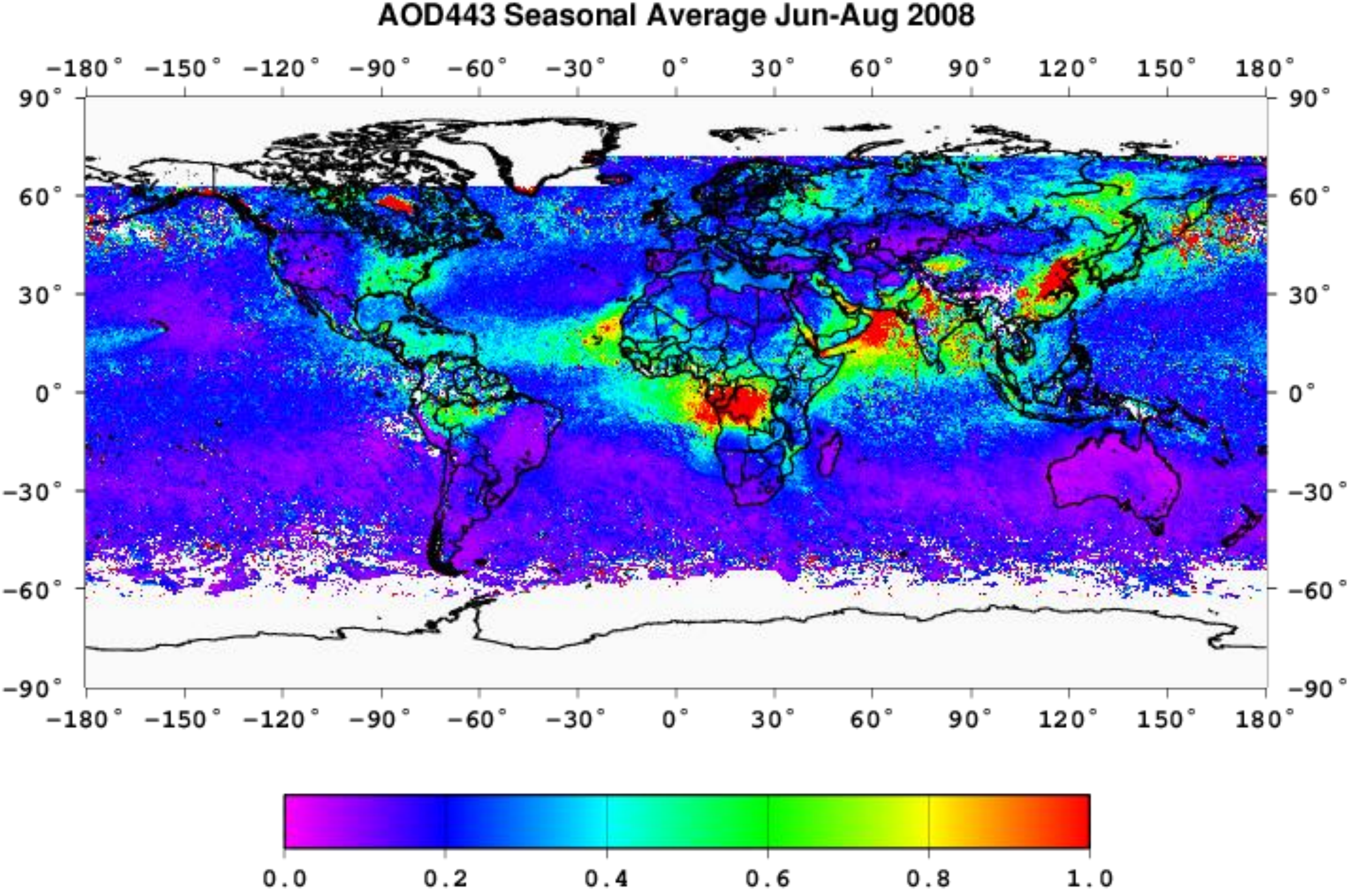
GRASP "accelerated" vs. GRASP "accurate"



AOD (440 nm): June – August, 2008

PARASOL/GRASP

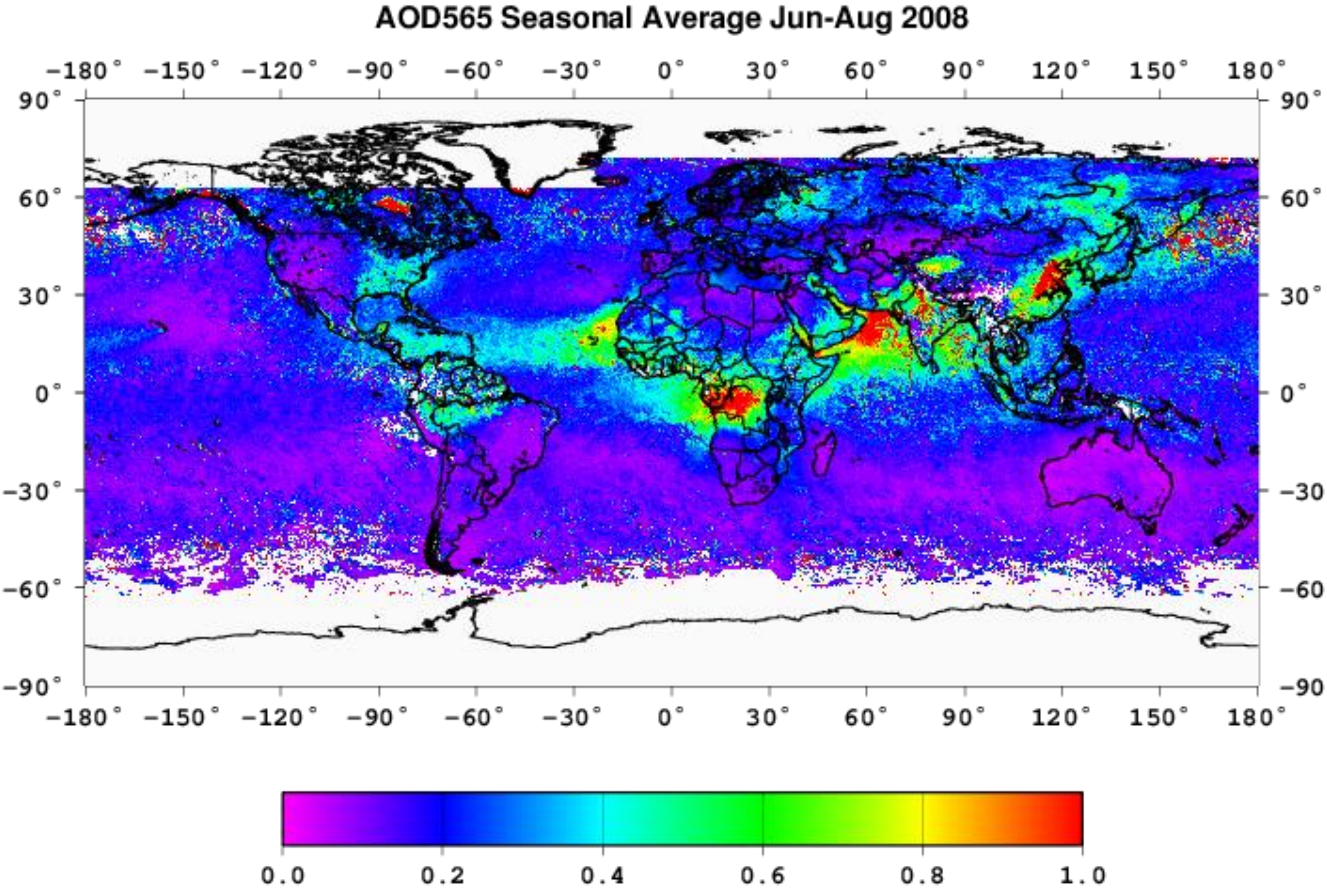
No assumptions!!!



AOD (560 nm): June – August, 2008

PARASOL/GRASP

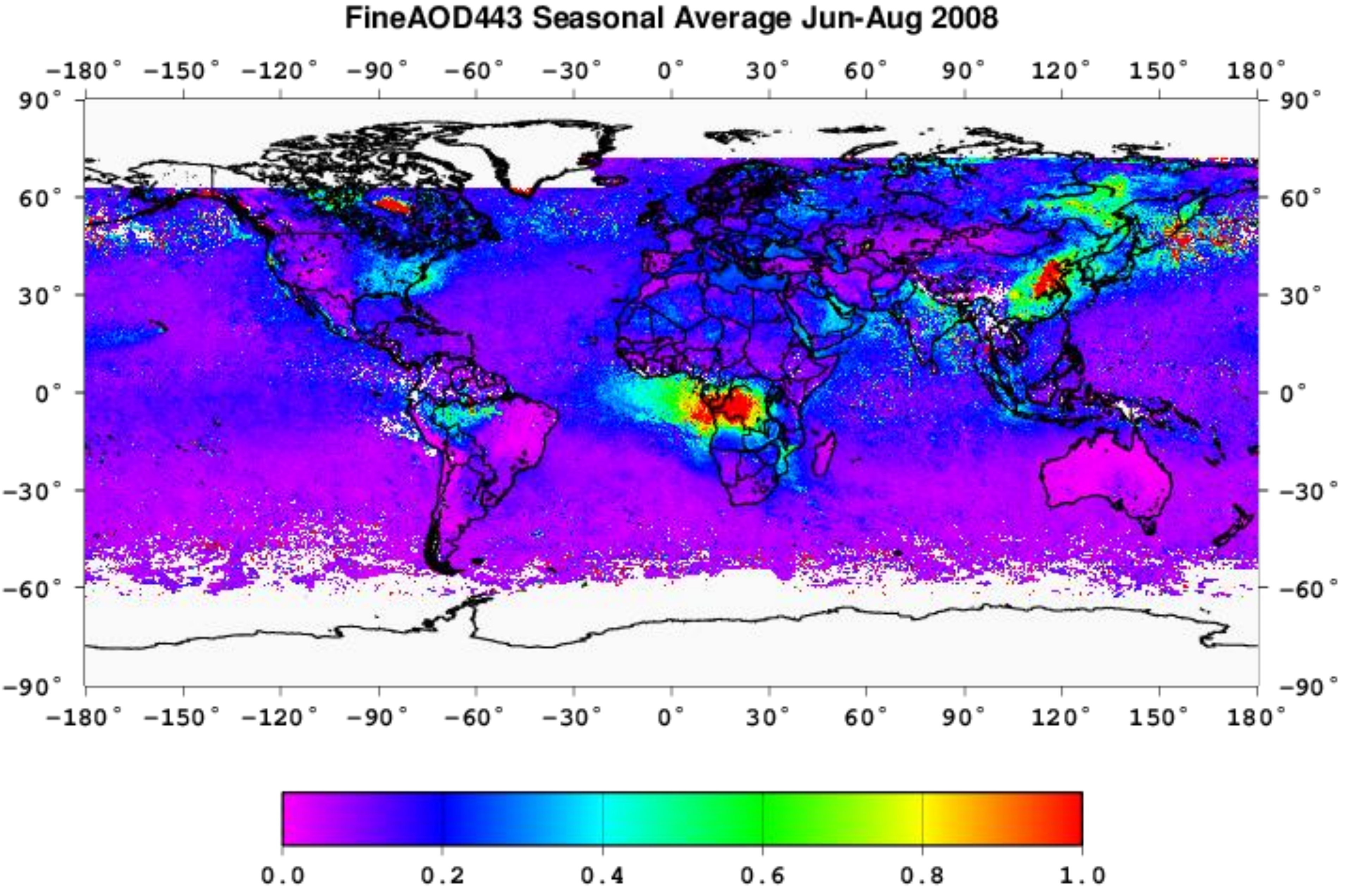
No assumptions!!!



AOD-fine (440 nm): June – August, 2008

PARASOL/GRASP

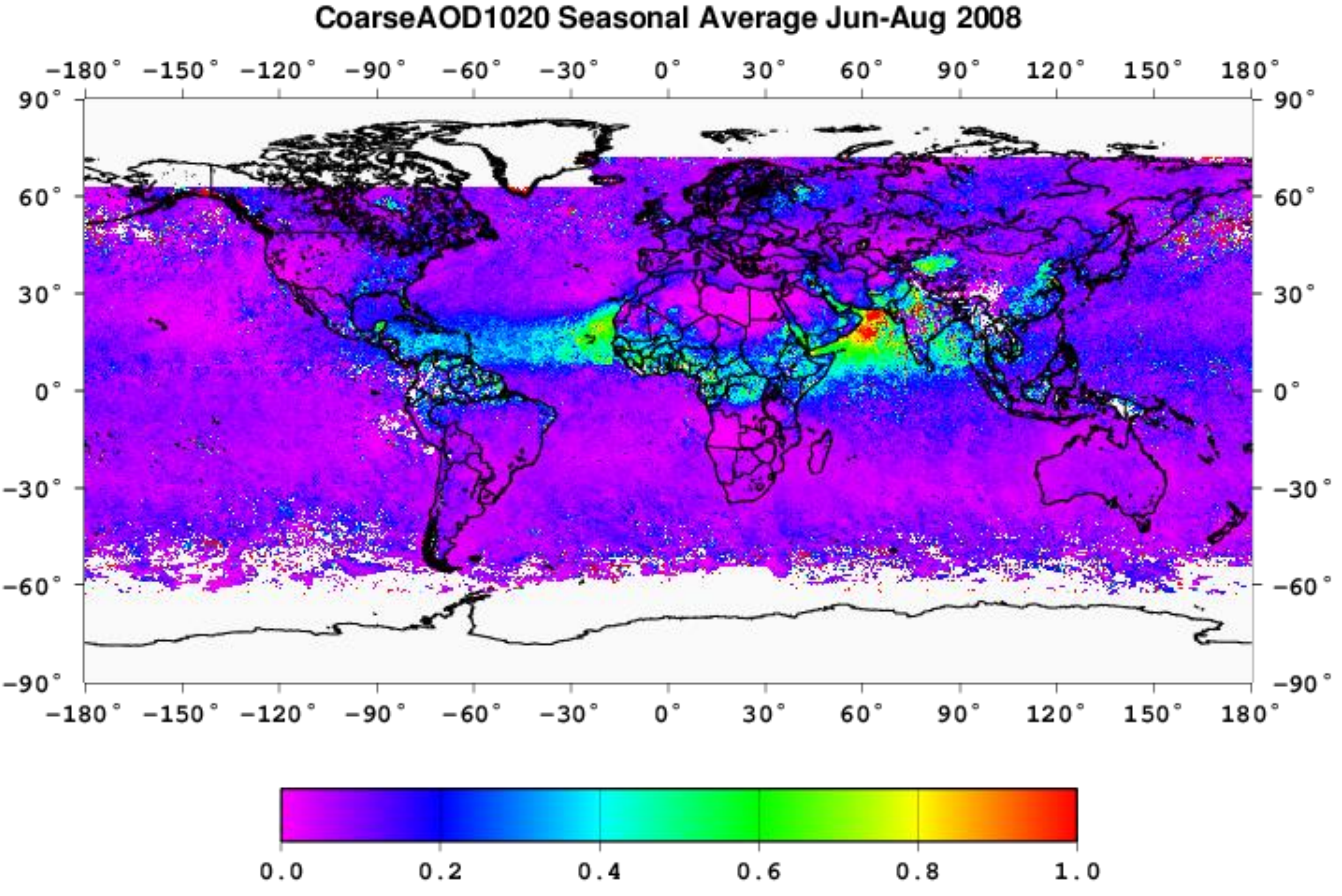
No assumptions!!!



AOD-coarse (1020nm): June – August, 2008

PARASOL/GRASP

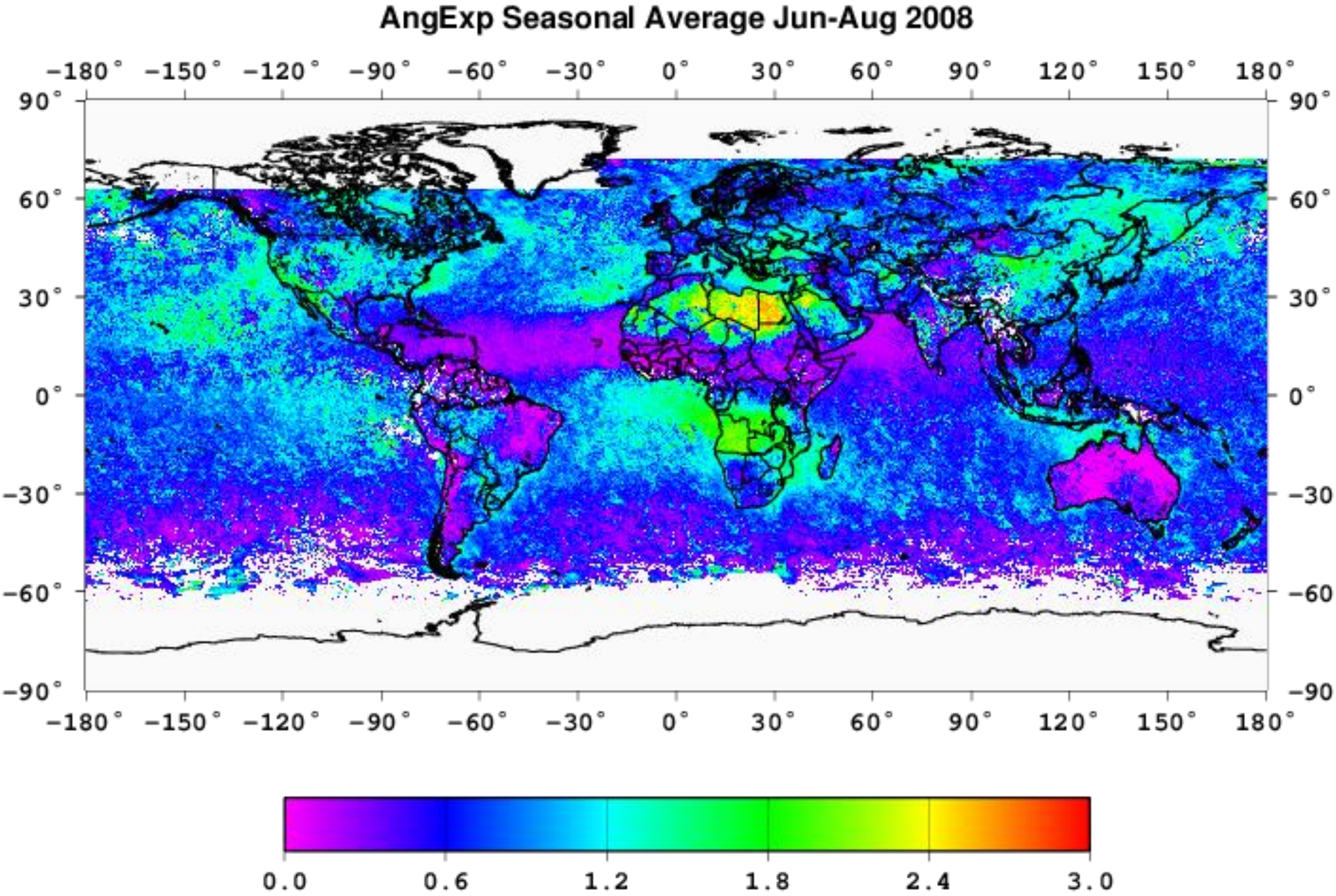
No assumptions!!!



Angstrom Exponent: June – August, 2008

PARASOL/GRASP

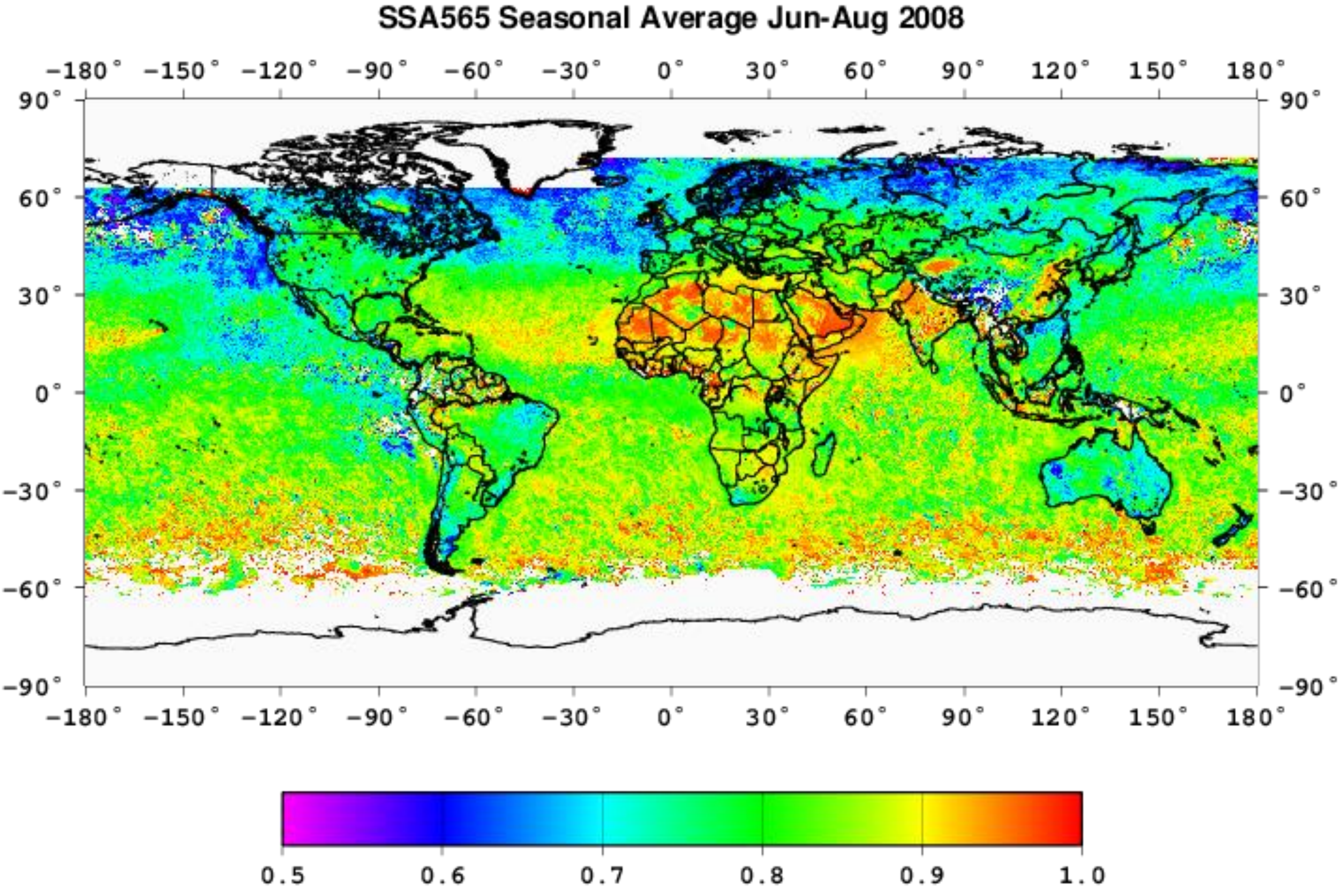
No assumptions!!!



SSA (560 nm): June – August, 2008

PARASOL/GRASP

No assumptions!!!

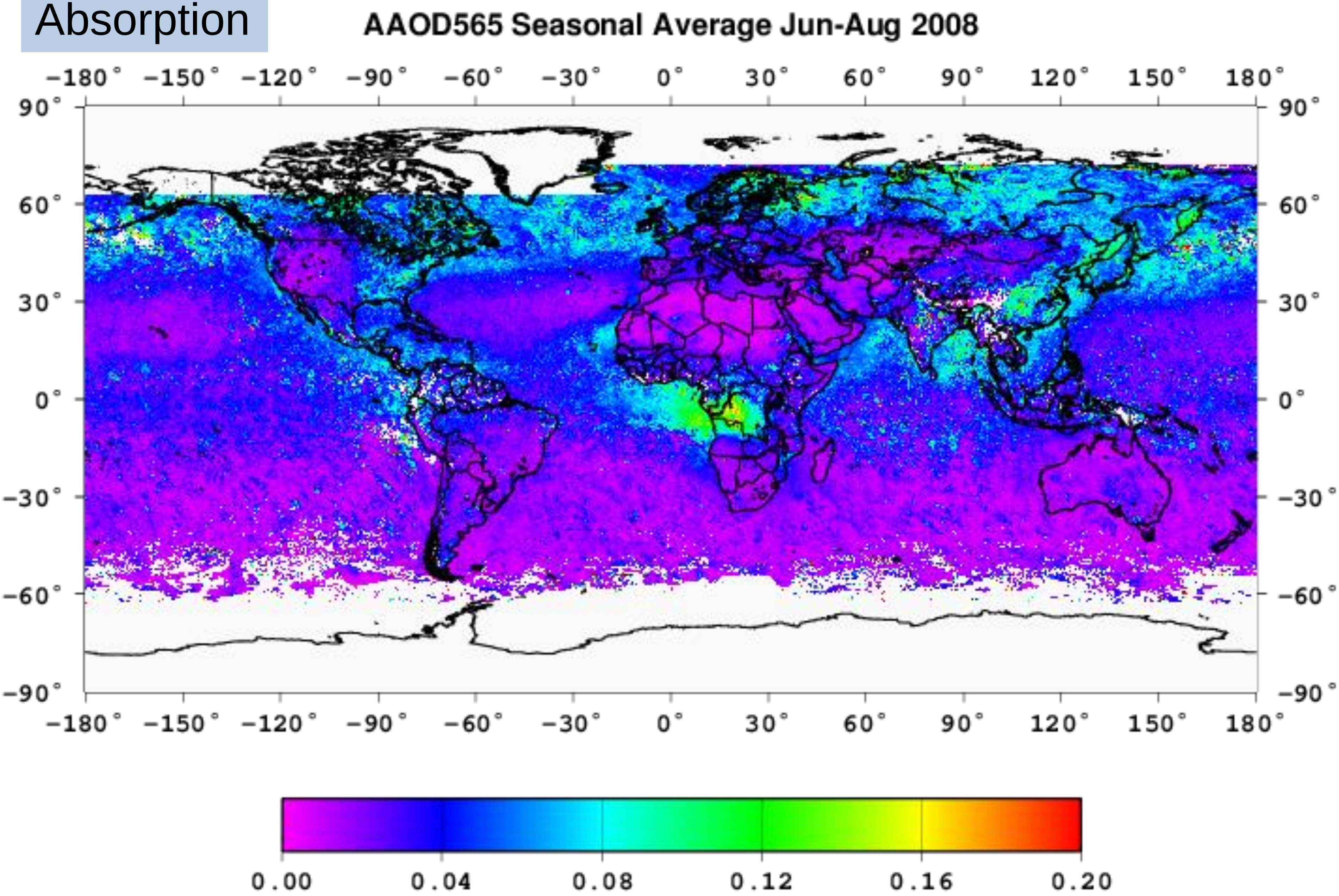


AAOD (560 nm): June – August, 2008

PARASOL/GRASP

No assumptions!!!

Absorption

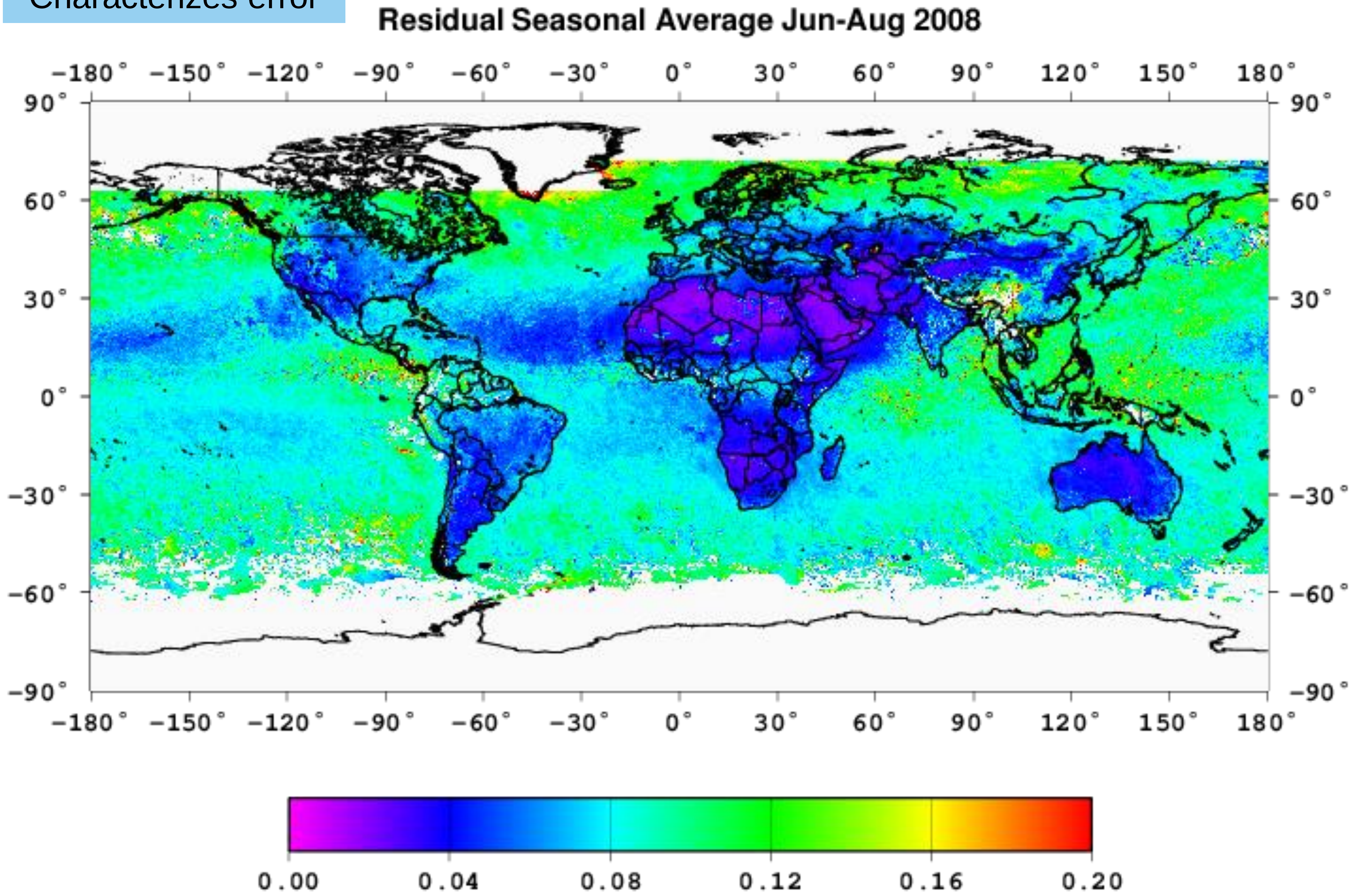


Residual : June – August, 2008

PARASOL/GRASP

No assumptions!!!

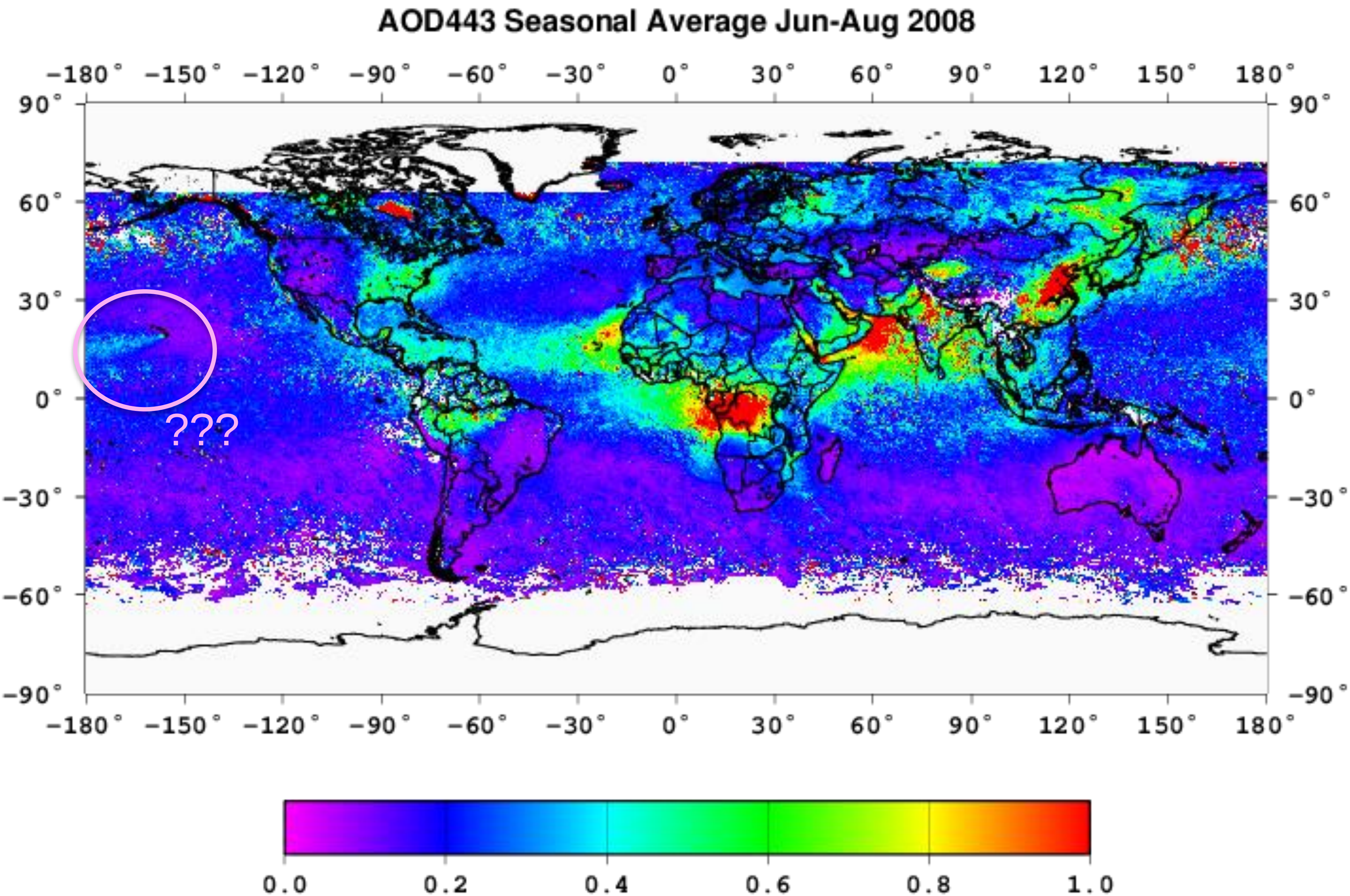
Characterizes error



AOD (440 nm): June – August, 2008

PARASOL/GRASP

No assumptions!!!



July 11, 2008

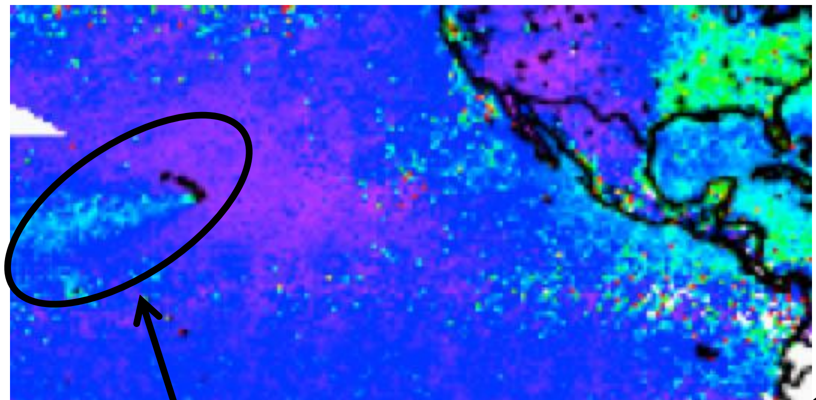
Kilauea volcano ash plume
(Hawaii, Halemaumau Crater, 2008)

July, 2008

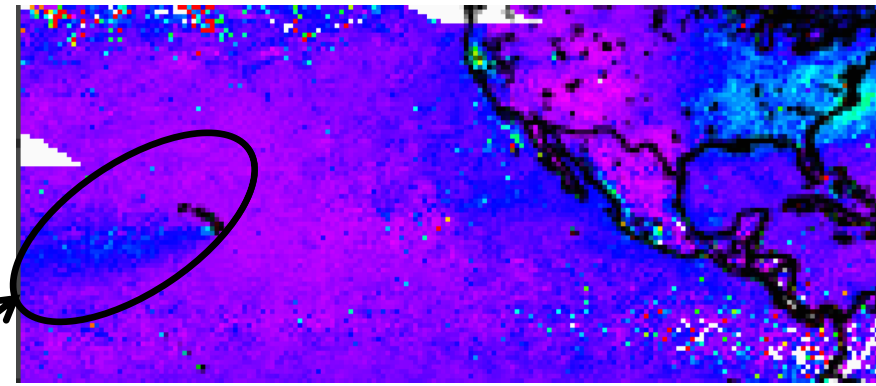
Kilauea volcano ash plume
(Hawaii, Halemaumau Crater, 2008)

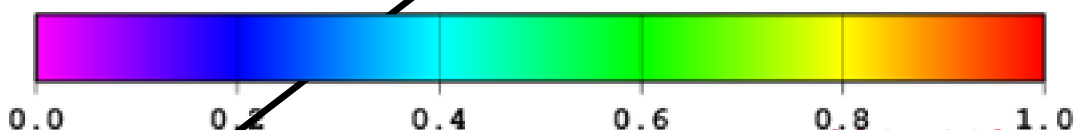
GRASP retrieval: Kilauea volcano (Hawaii, Halemaumau Crater, June-August, 2008)

AOD, 443 nm

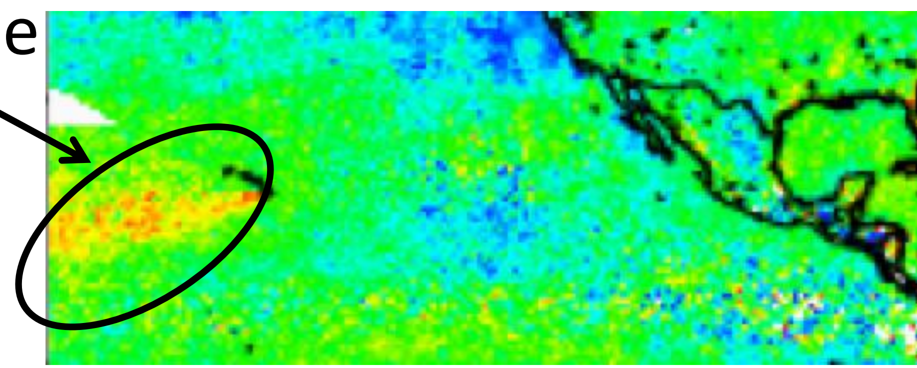


Fine mode AOD, 443 nm

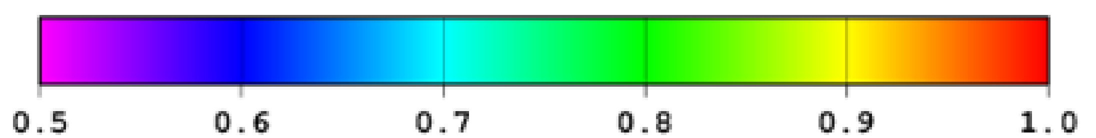




SSA, 443 nm



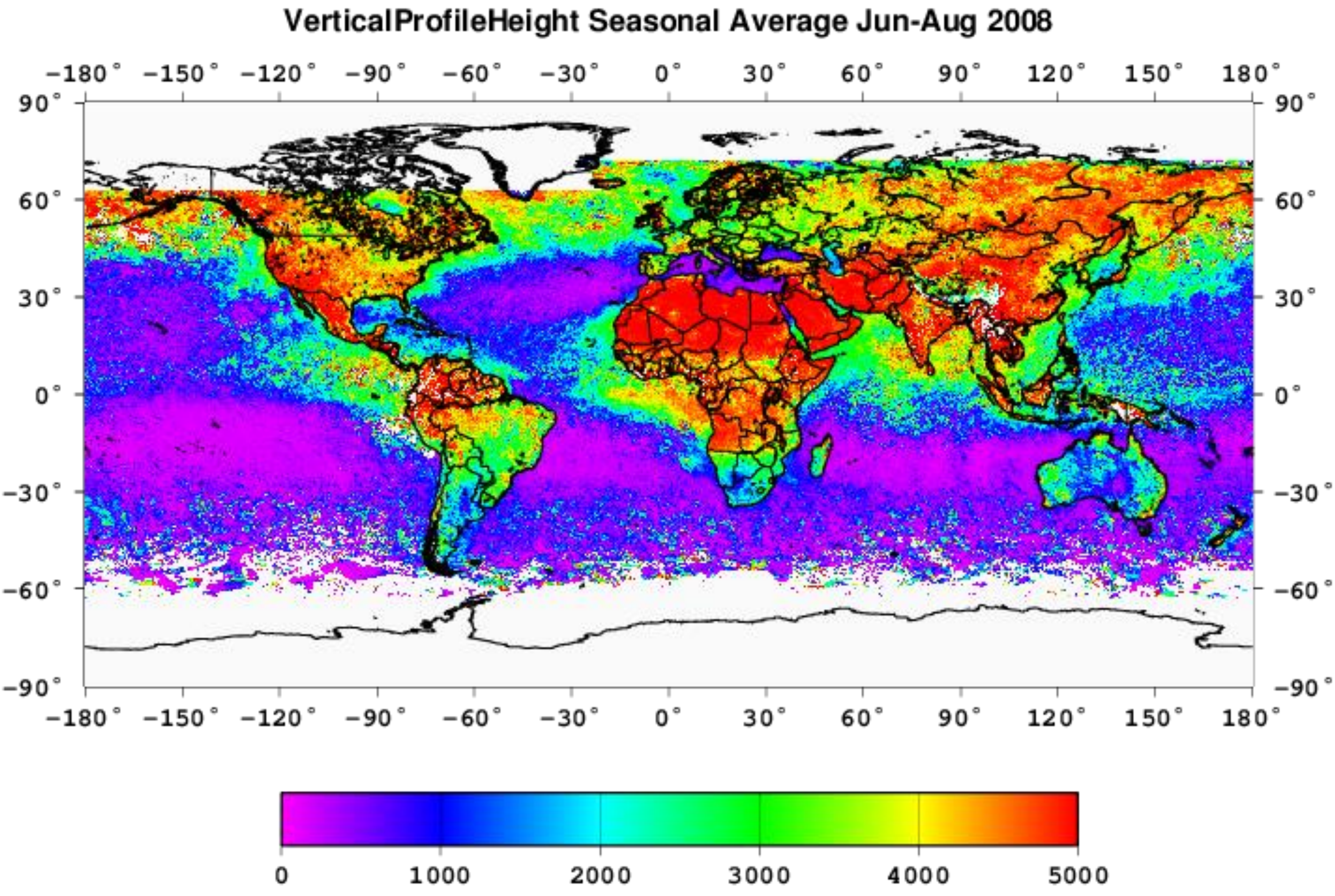
Halemaumau Crater ash plume



Aerosol Mean Height: June – August, 2008

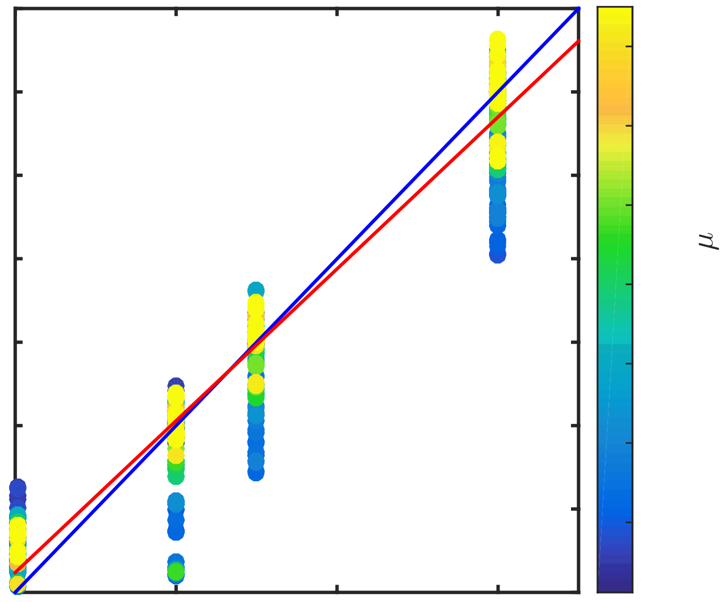
PARASOL/GRASP

No assumptions!!!

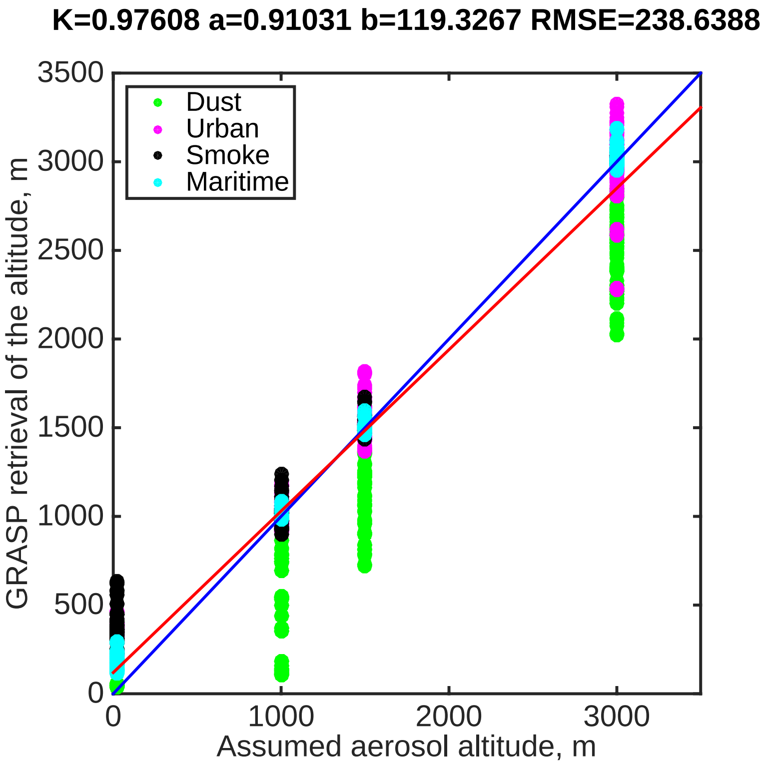


Sensitity tests for retrieving aerosol MEAN HEIGHT

For different AOD

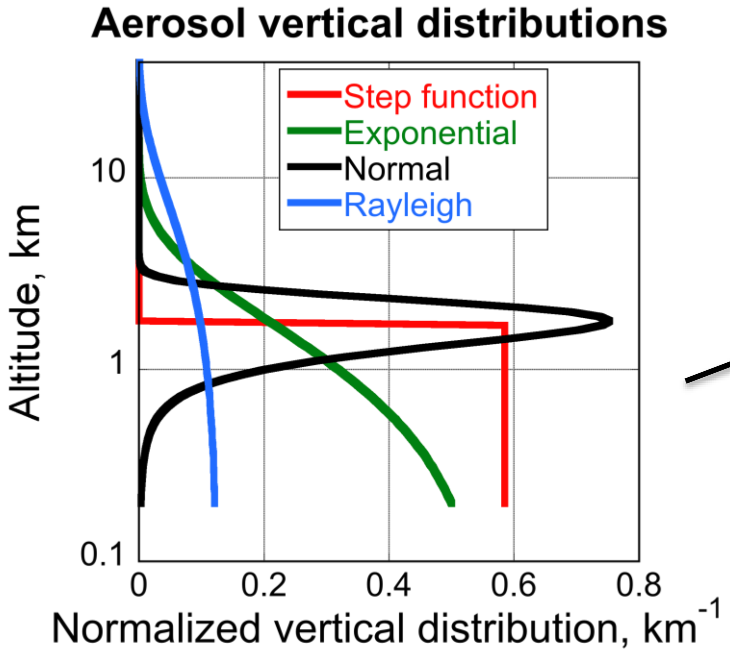


For aerosol types



Conclusion of sensitivity tests:

- ✓ *PARASOL data have solid sensitivity to aerosol height;*
- ✓ *Sensitivity is higher to fine mode aerosol and less to large non-spherical dust;*
- ✓ *There is dependence on assumption about atmospheric aerosol vertical profile.*

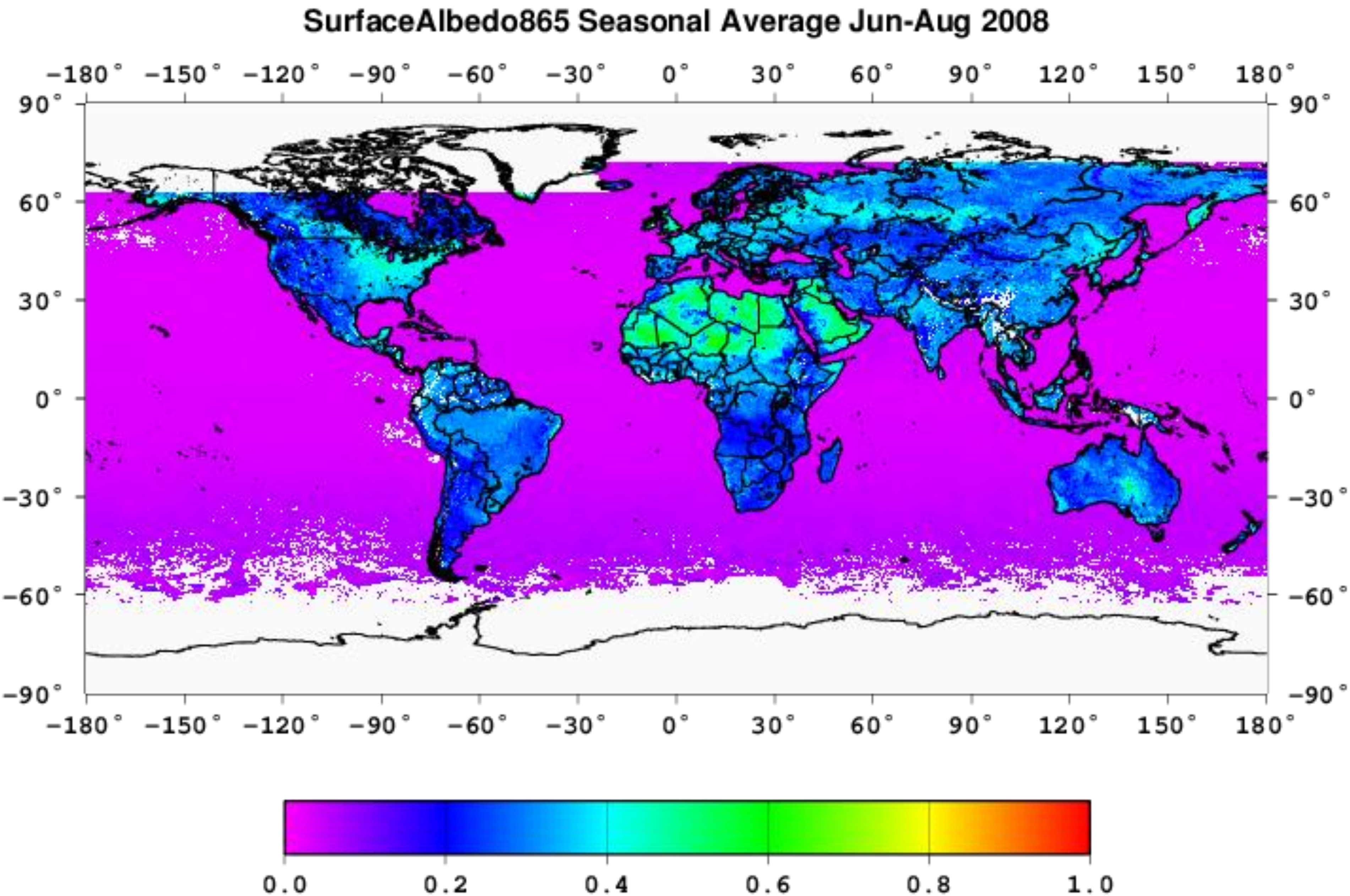


Which profile to use?

DHR(870): June – August, 2008

PARASOL/GRASP

No assumptions!!!

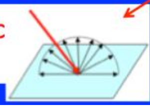


GRASP BRDF/BPDF models

1. Ross-Li (***Ross, (1981); Li, X., Strahler (1992))***:

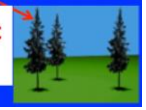
$$BRDF_{Ross-Li} = a_{iso}(\lambda) \cdot (1 + a_{vol} f_{vol} + a_{geom} f_{geom})$$

Isotropic term:



Volumetric term:

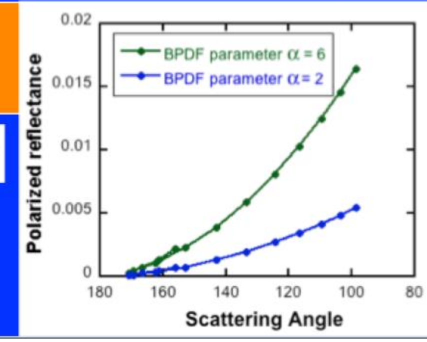
Geometric term:



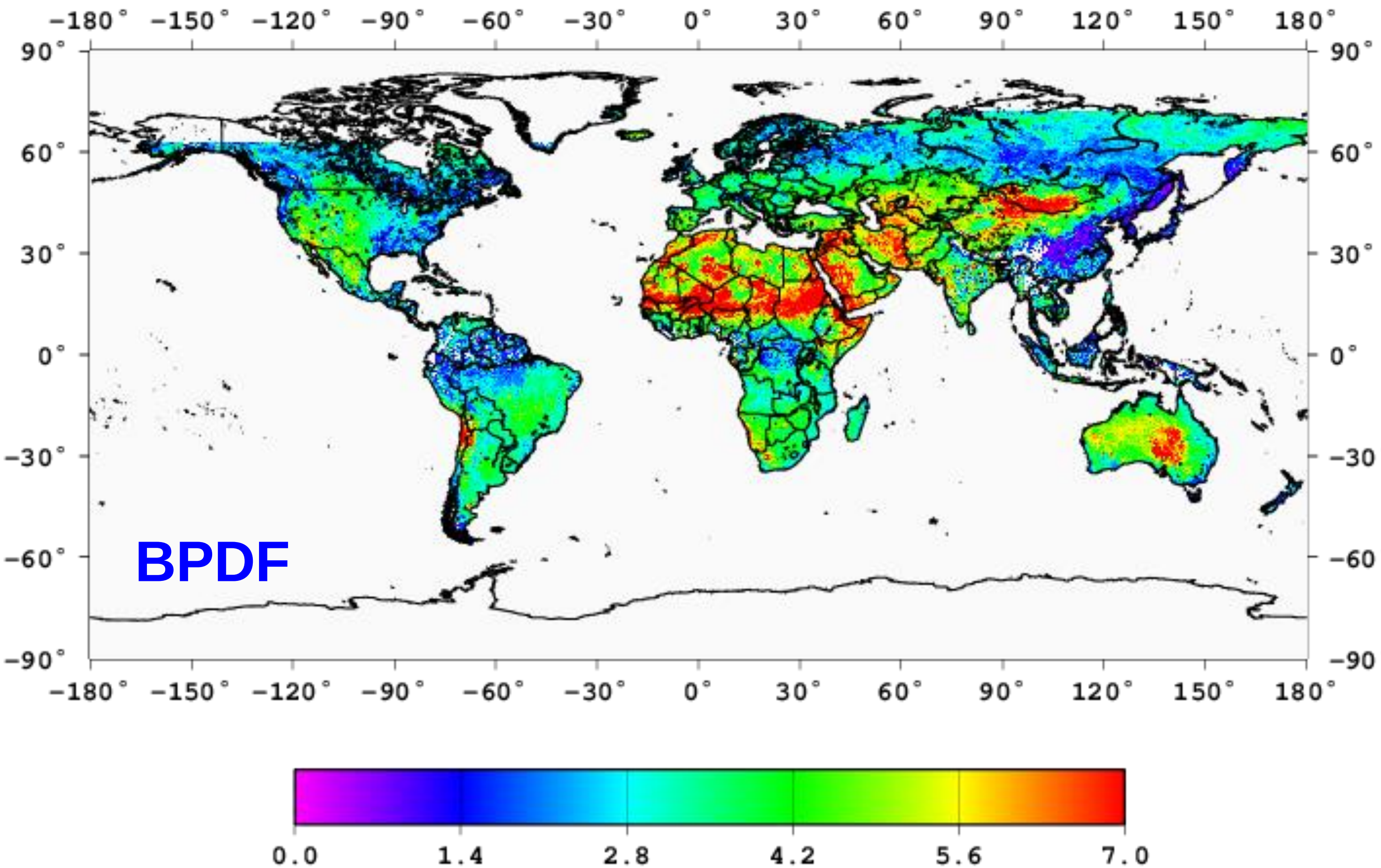
2. One-parametric BPDF model (*Maignan et al., 2009*)**:**

$$R_p(\vartheta_v, \vartheta_0, \varphi) = \alpha f(\vartheta_v, \vartheta_0, \varphi) F_p(m, \gamma)$$

$-F_p(m,\gamma)$ is the element F_{21} of the Fresnel scattering matrix

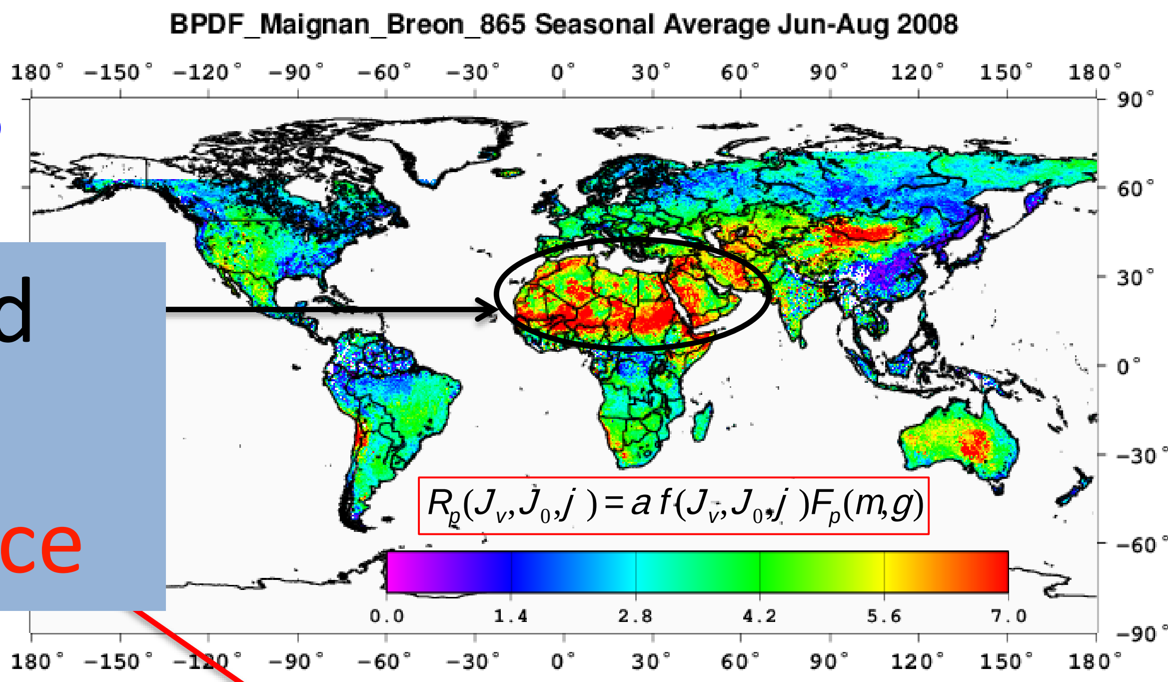


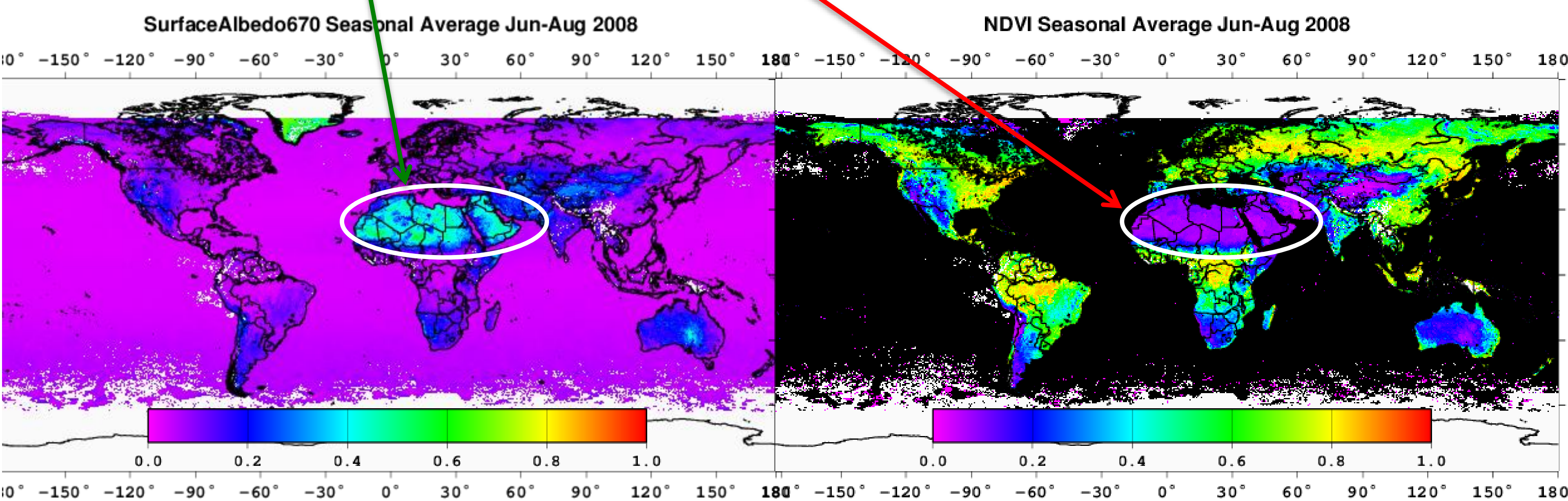
BPDF_Maignan_Breon_565 Seasonal Average Jun-Aug 2008



Advanced surface retrieval with GRASP

The same NDVI and DHR but different Polarized reflectance





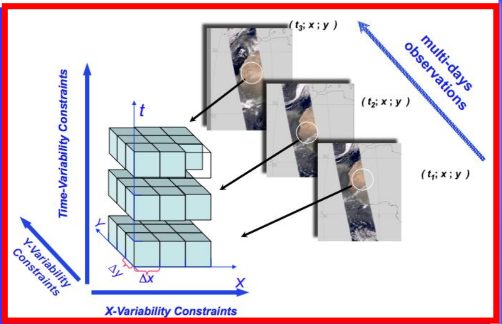
Polarized reflectance provides new information about surface type!

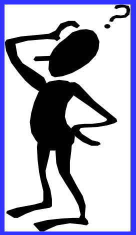
MERIS:

- radiances at seven wavelengths:

(413, 443, 490, 510, 560, 665, and 870 nm);

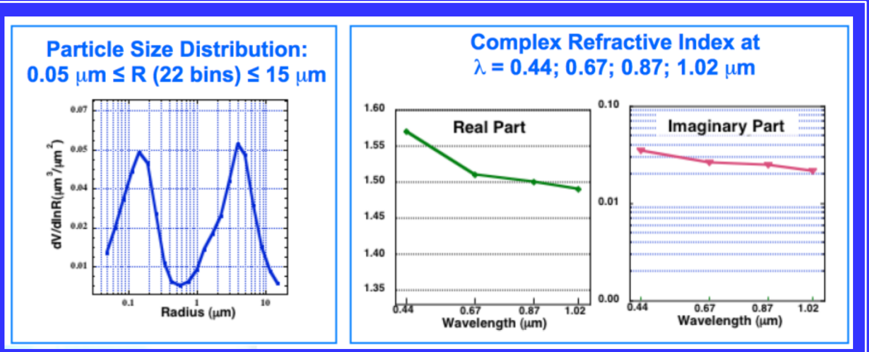
- single view





AEROSOL:

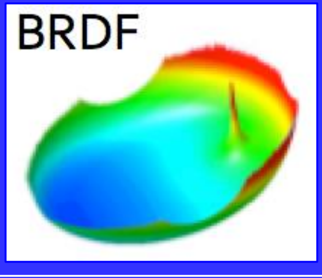
- size distribution (5 or more bins);
- spectral index of refraction (7 λ);
- sphericity;



SRFACE:

- BRDF

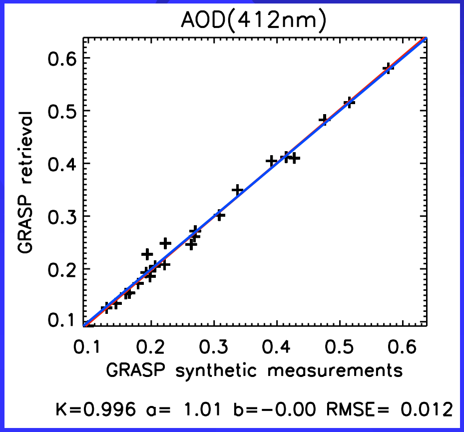
(3 spectrally dependent parameters);

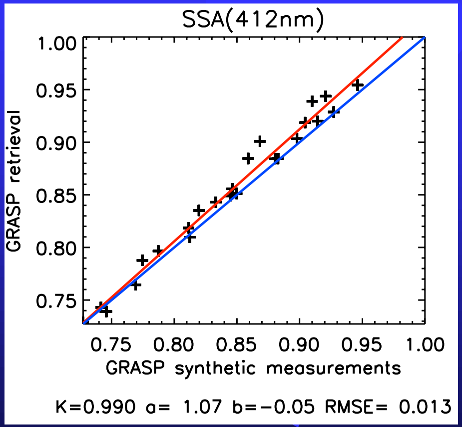


41 = (5 (SD) +14 (ref. ind.) + 1 (nonsp.) + 21 (BRDF))

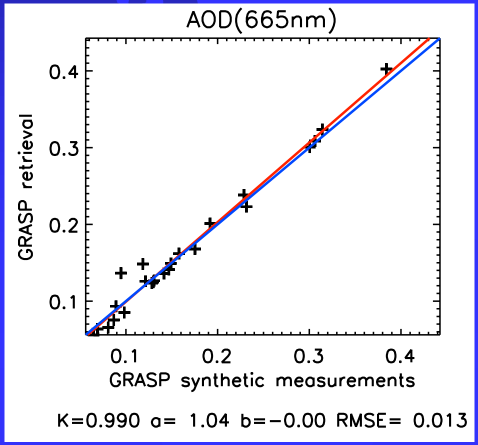
The concept MERIS/GRASP retrieval works good with synthetic measurements

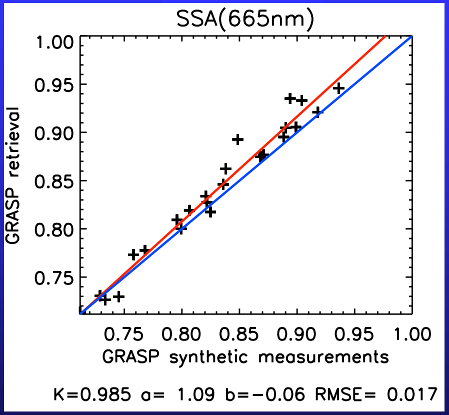
AOD



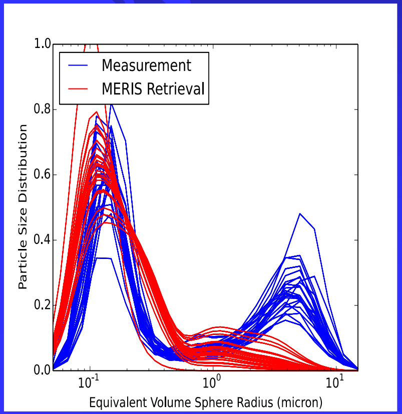


SSA

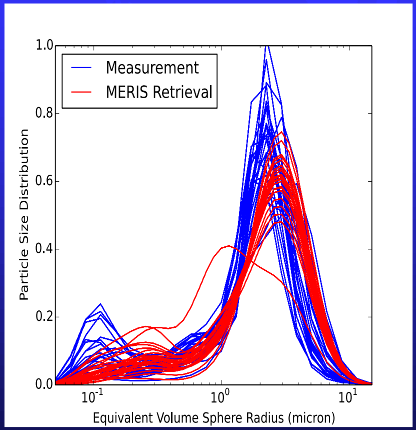




Smoke



Dust



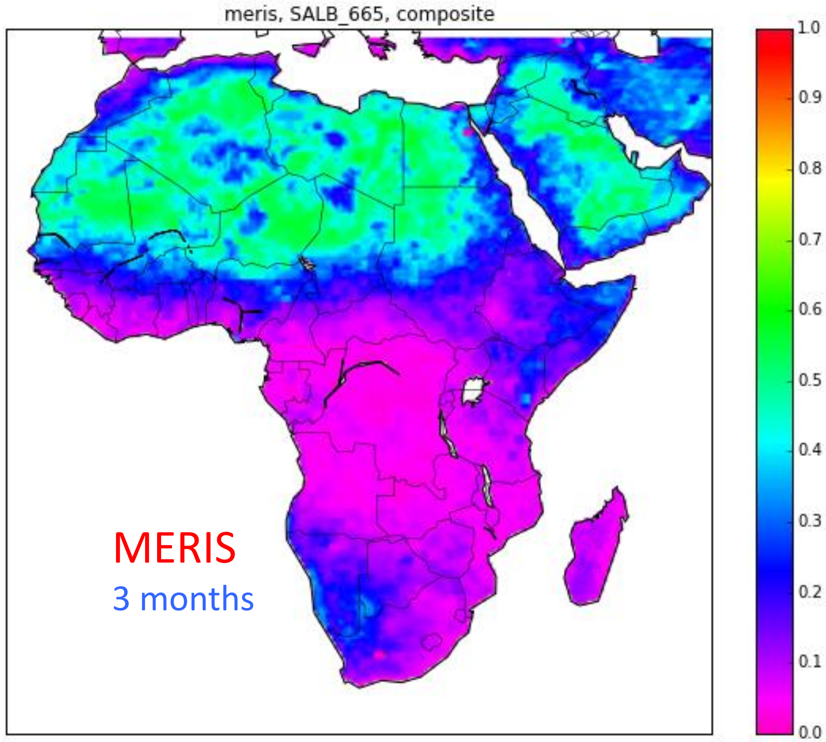
GRASP: Generalized Retrieval of Aerosol and Surface Properties

Dubovik et al. 2011, 2014

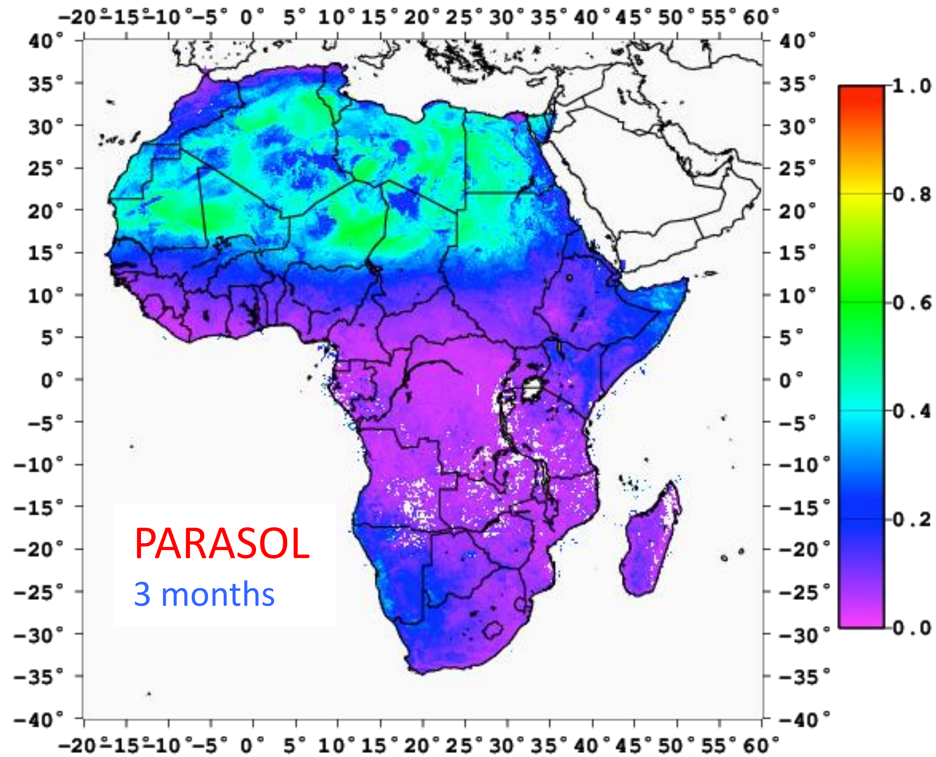
Retrieves both: surface (over land) and detailed aerosol properties

First results: surface

GRASP/MERIS 3 months average DHR (January - March 2008)



SALBEDO670 Seasonal Average January-March 2008



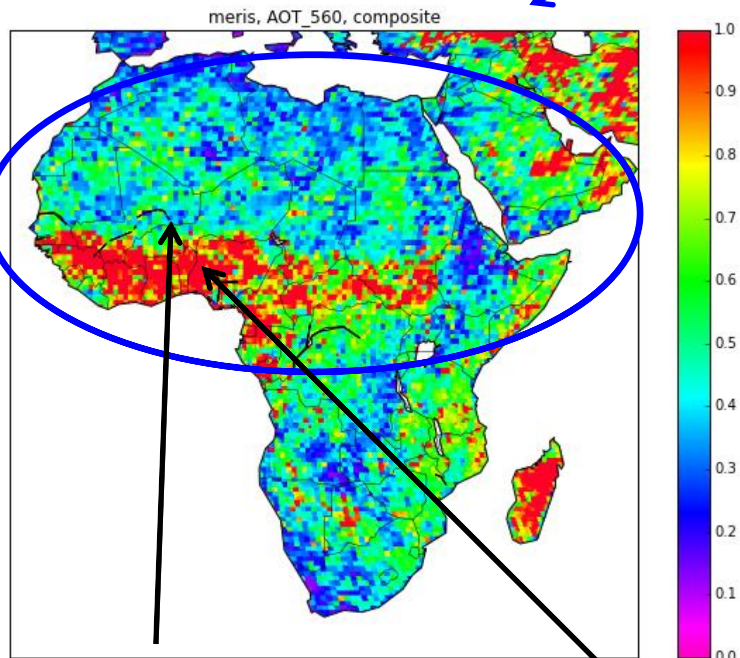
Excellent agreement!

***GRASP**: First results: aerosol*

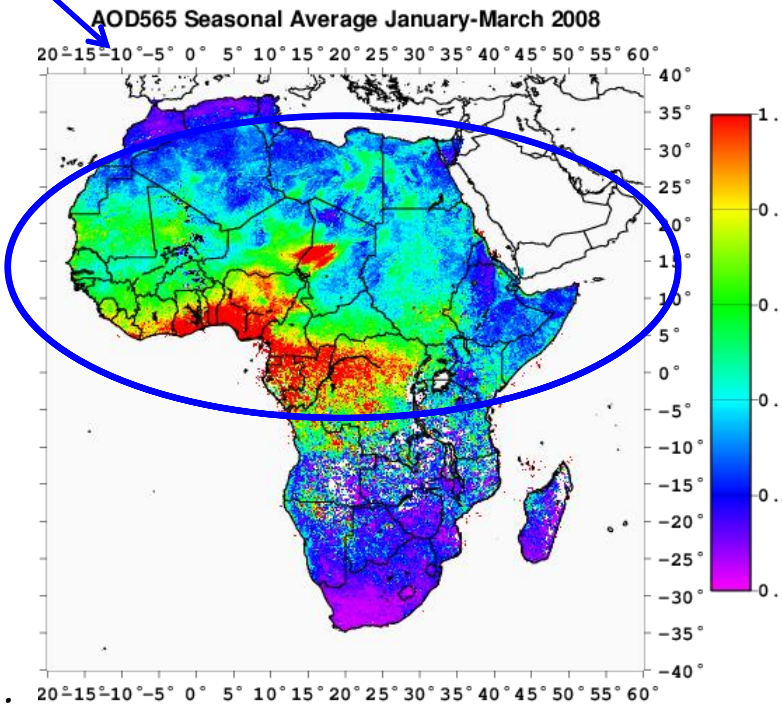
Bright surfaces

AOD560 (January-March 2008)

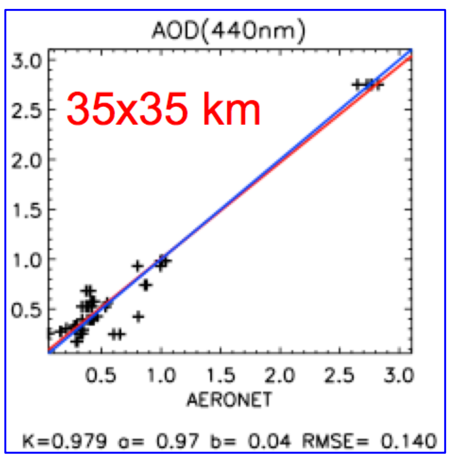
MERIS



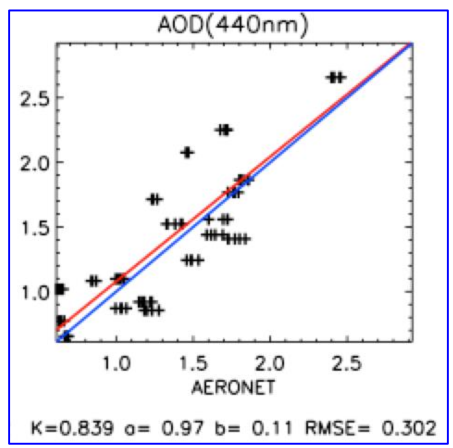
PARASOL



Banizoumbou, Niger



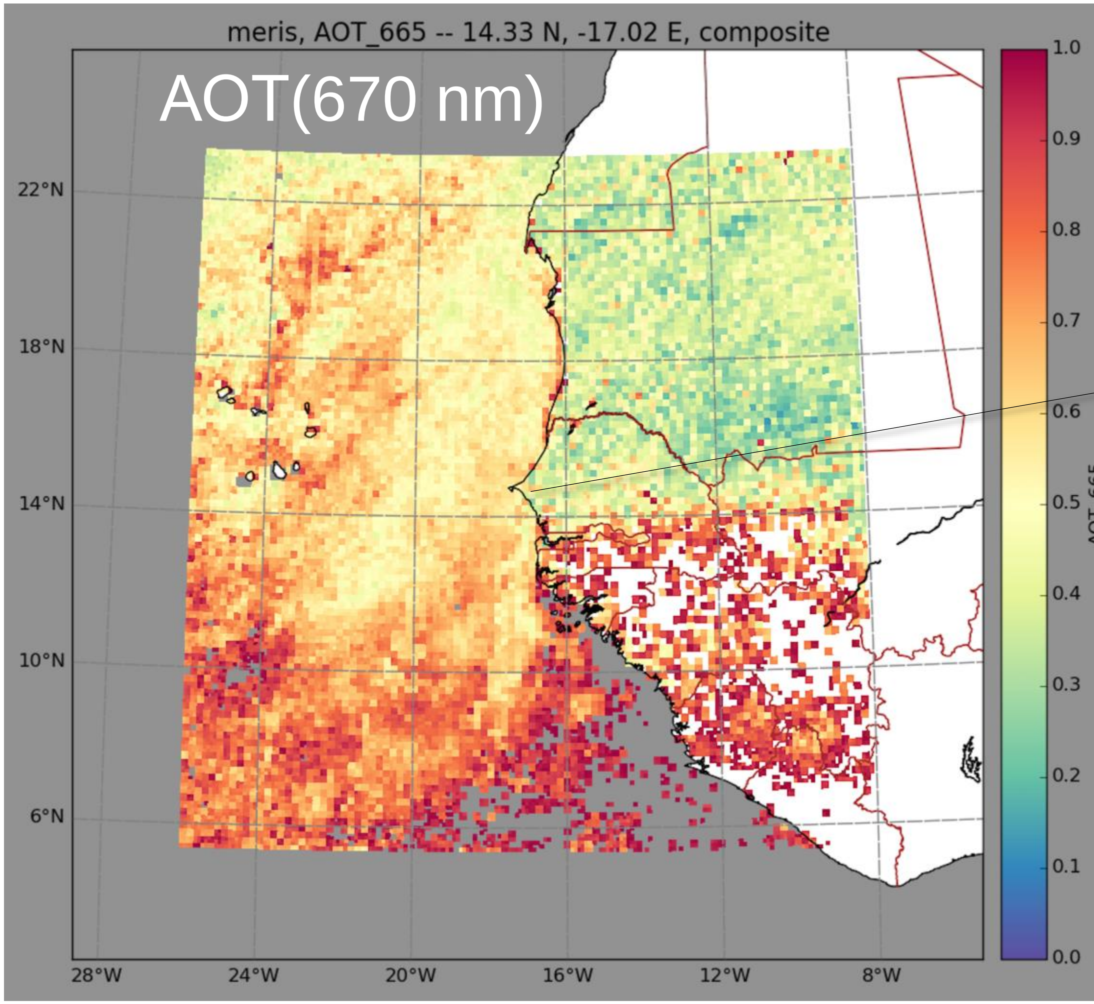
Ilorin, Niger



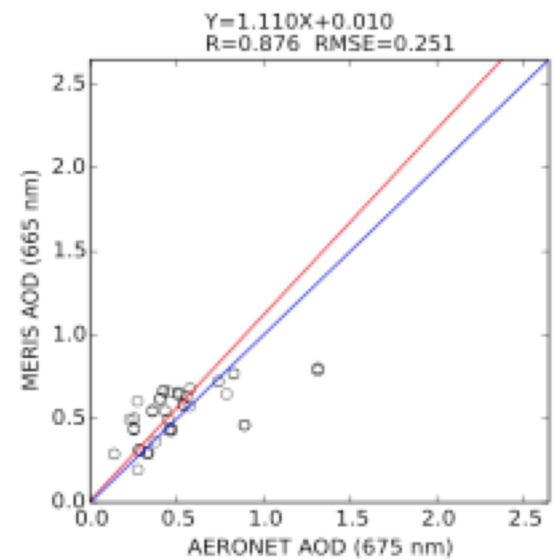
AERONET validation

GRASP/ MERIS – land/water

(January - March 2008, 10 km resolution)



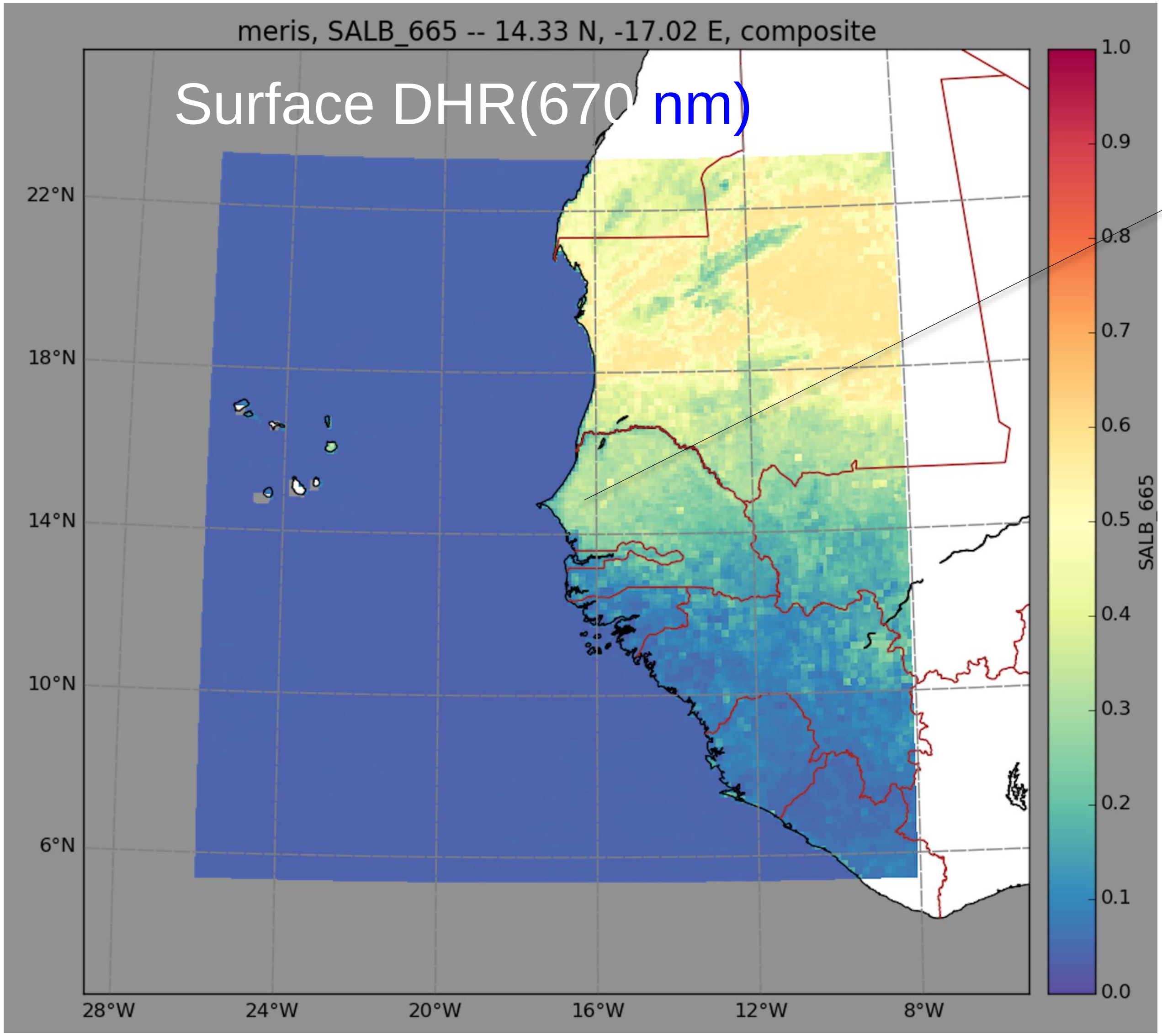
Dakar AERONET validation

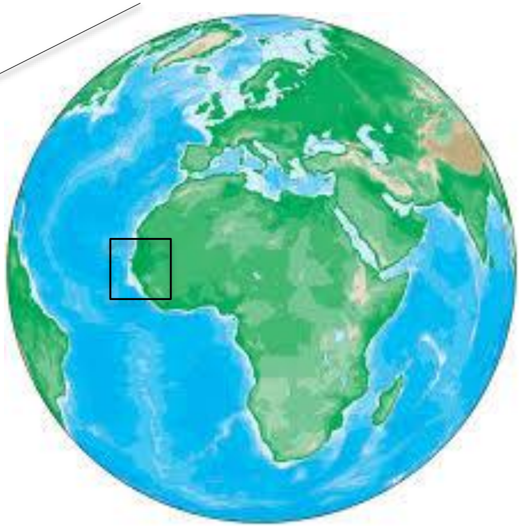


ESA CAWA project

GRASP/ MERIS retrieval – land/water

(average January - March 2008, 10 km resolution)





ESA CAWA project

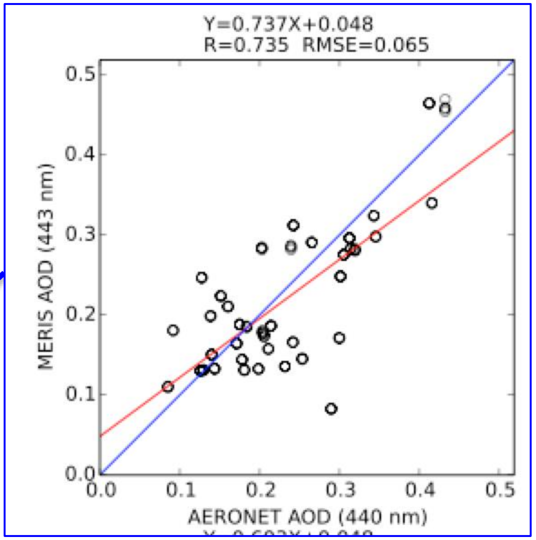
GRASP/ MERIS

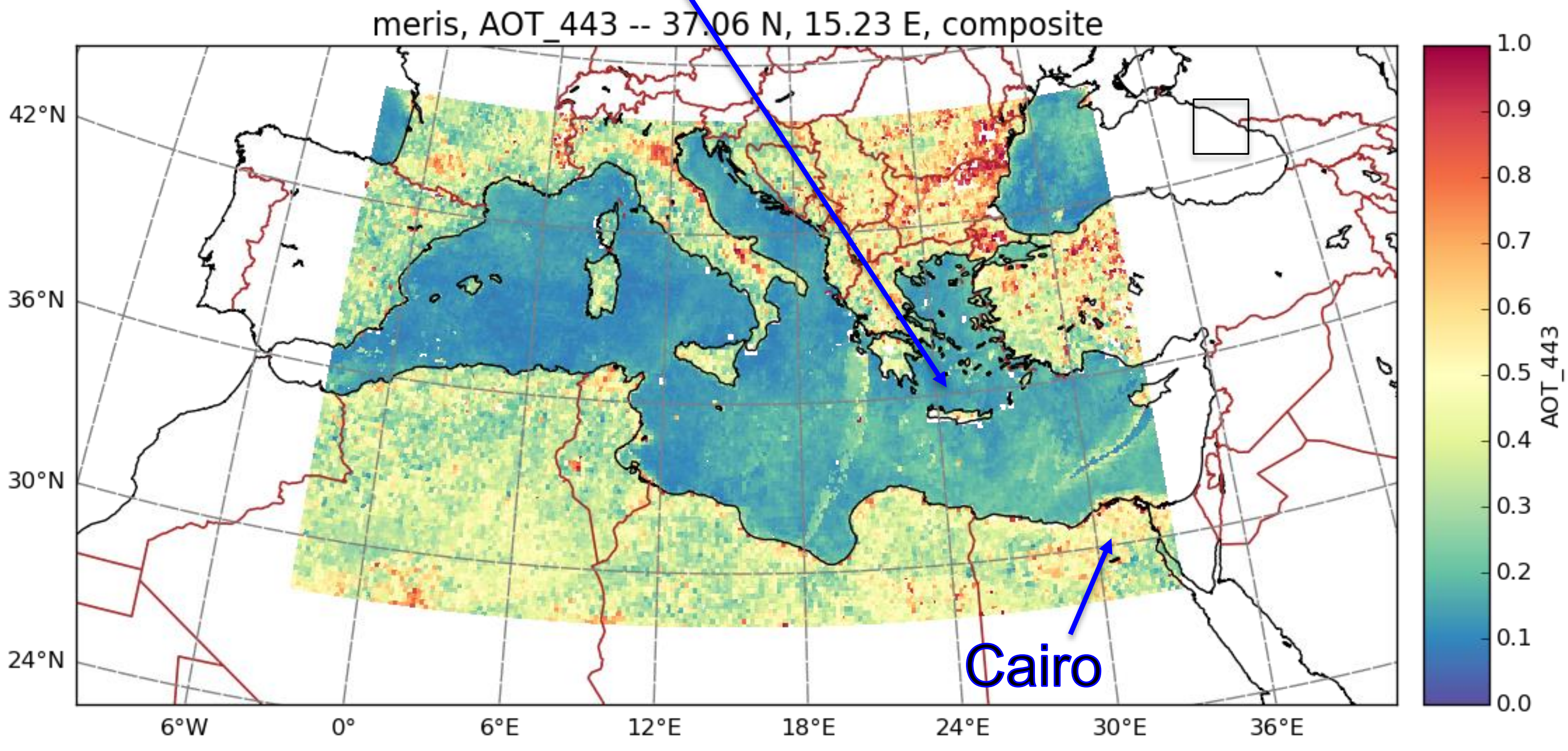
(January - March 2008, 10 km resolution)

No assumptions !!!

AOT(440)

Crete AERONET validation





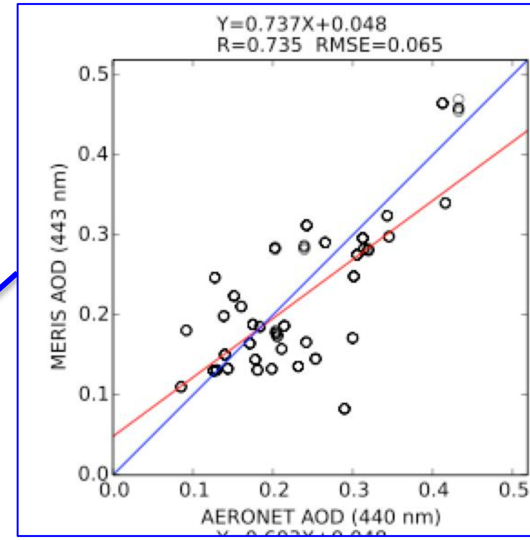
Cairo

GRASP/ MERIS

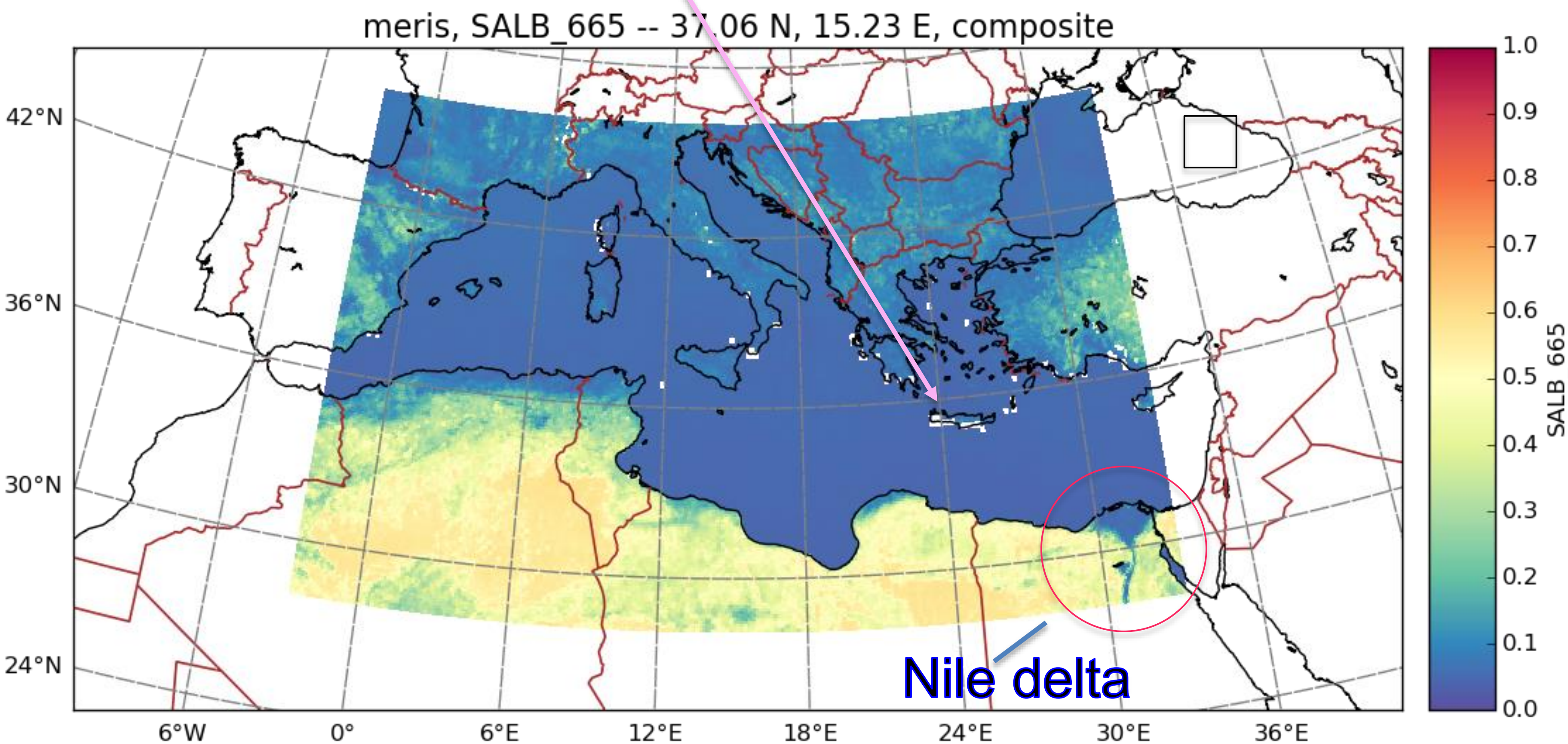
(January - March 2008, 10 km resolution)

No assumptions !!!

Crete AERONET validation



DHR(670)

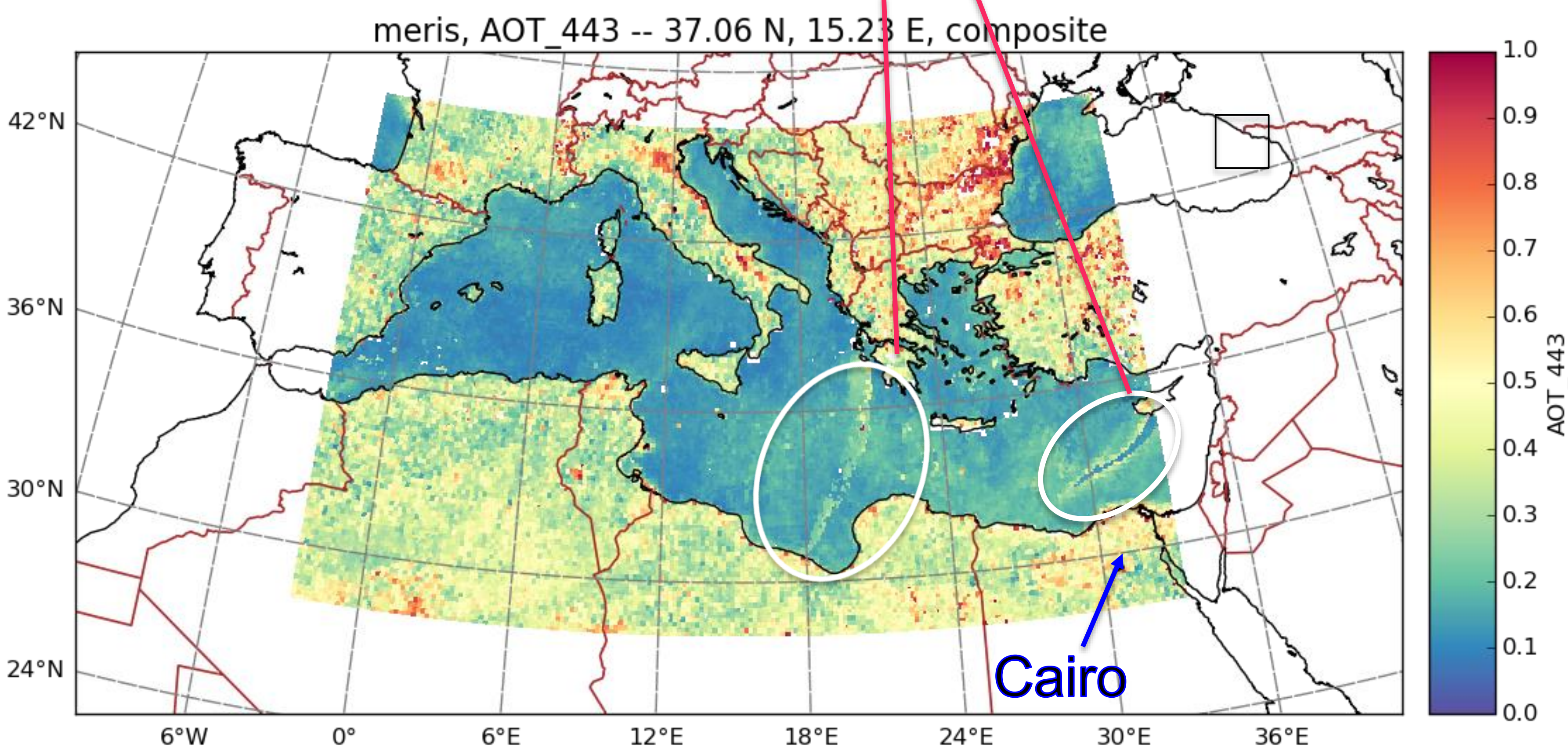


GRASP/ MERIS

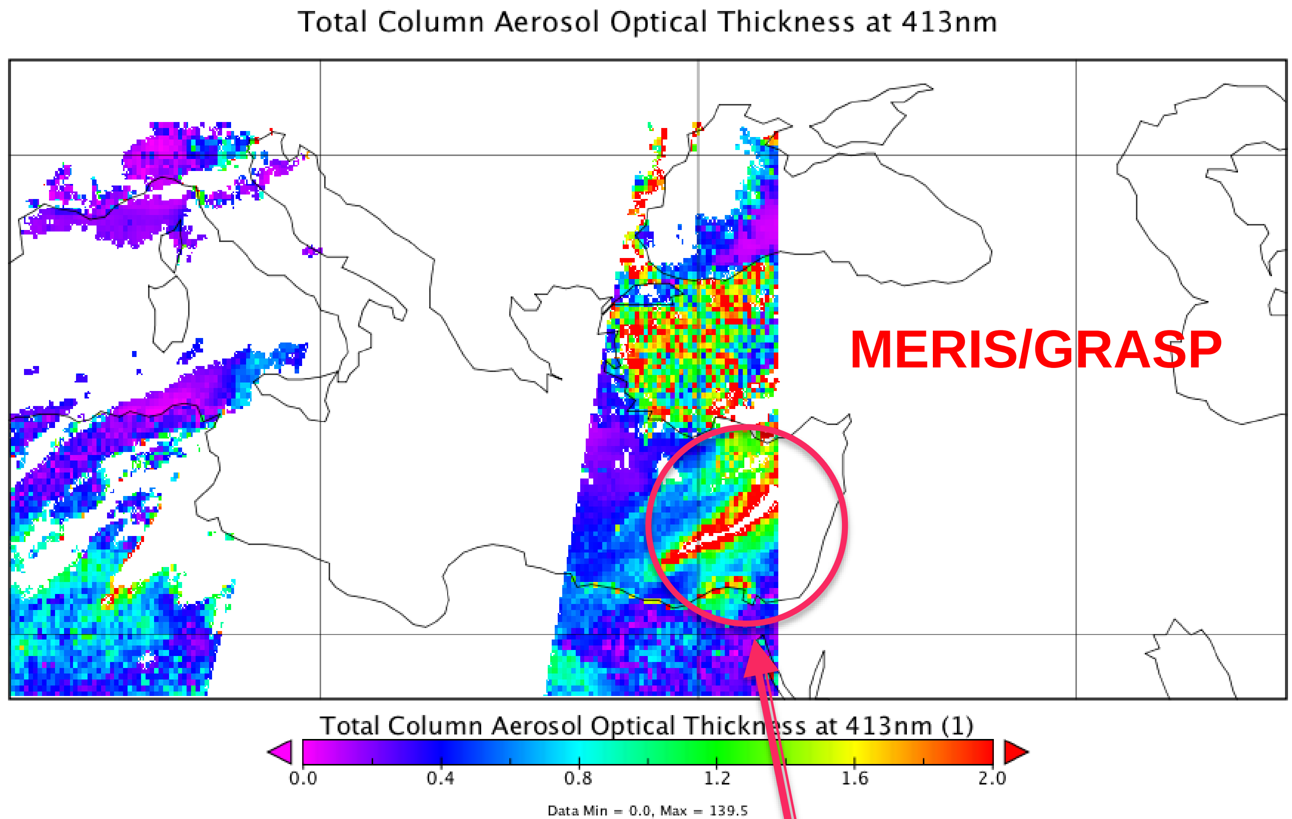
(January – March, 2008, 10 km resolution)

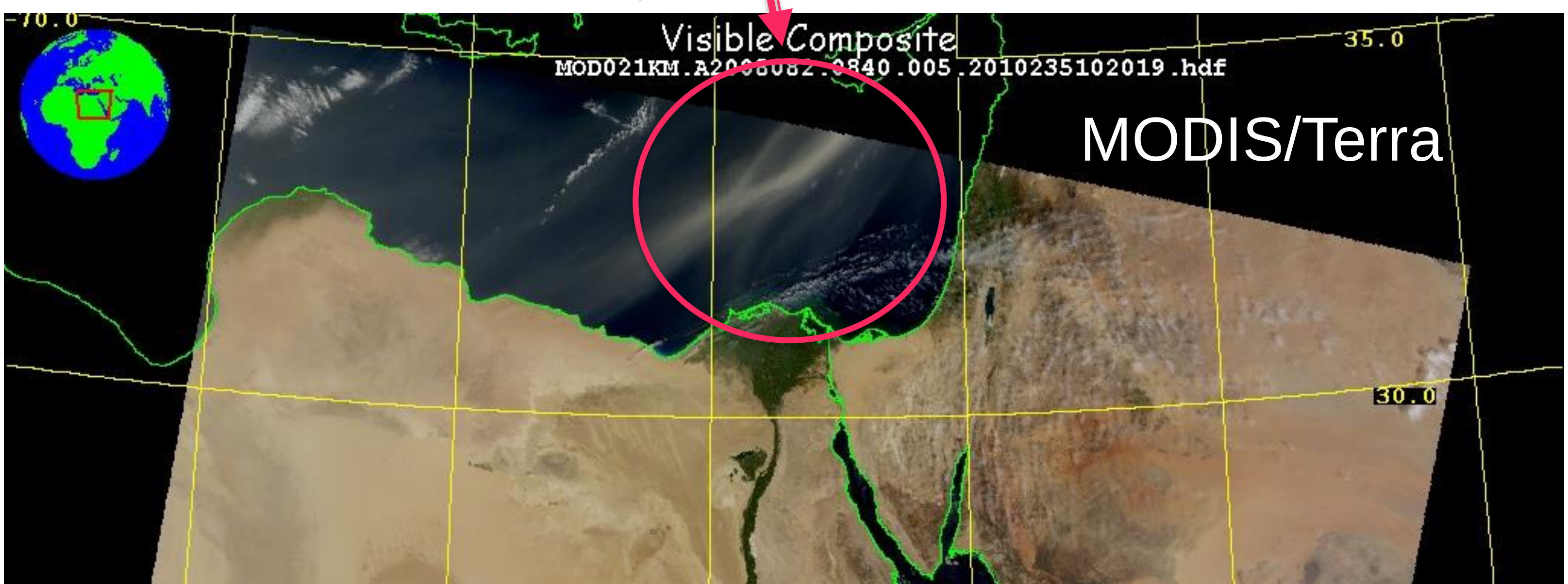
AOT(440)

Real or artifacts ???



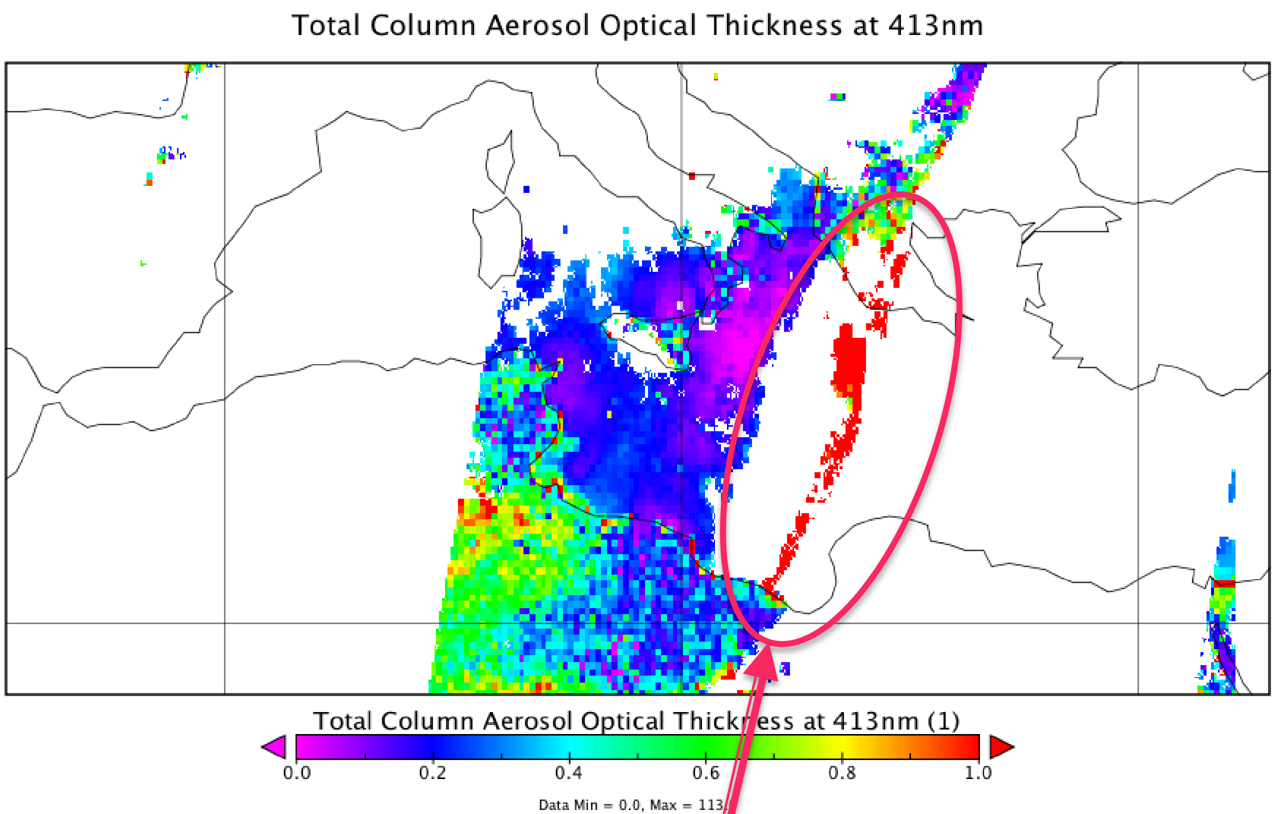
March, 22, 2008

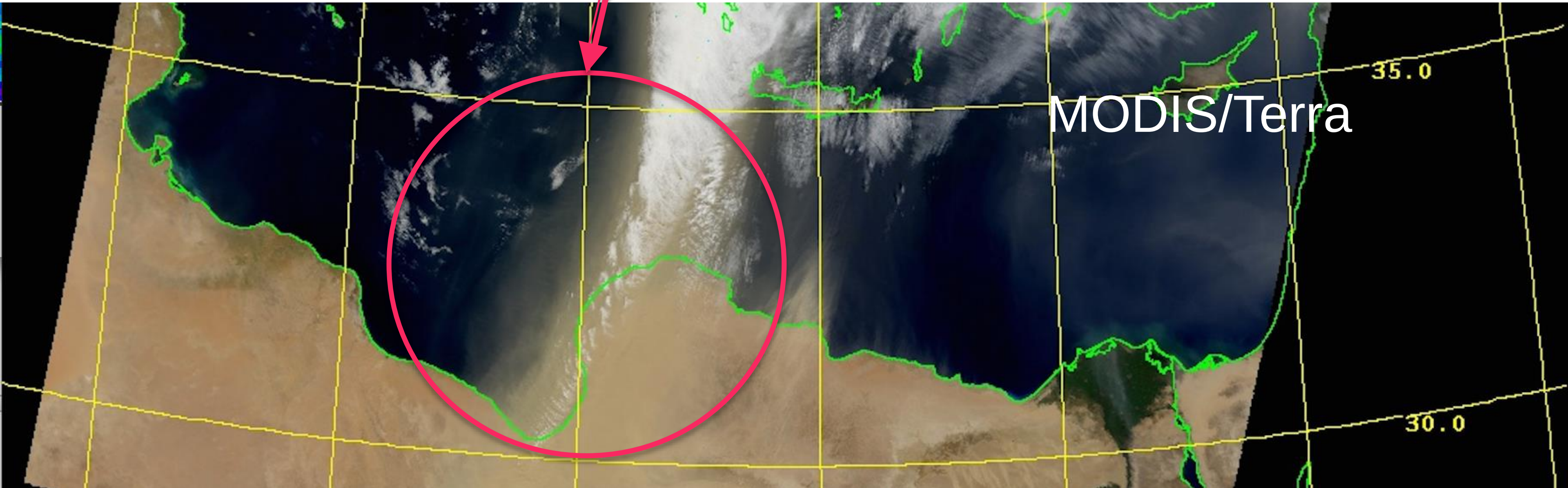




March, 23, 2008

MERIS/GRASP





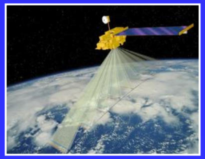
Conclusions:

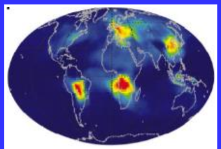
GRASP concept: retrieval of aerosol and surface simultaneously under minimum assumptions

✓ *GRASP/PARASOL retrieval are promising for diverse products:*
- *Aerosol AOD (even over bright surfaces) and size distributions;*
- *Aerosol absorption, refractive index etc.,*
- *Aerosol height; non-sphericity (???);*
- *BRDR + BPRF*

✓ *First results are very promising for several satellte sensors :*
- PARASOL, MERIS, *GOCI (geostationary)* ;

✓ Promising for synergy retrievals etc. ;
- etc.

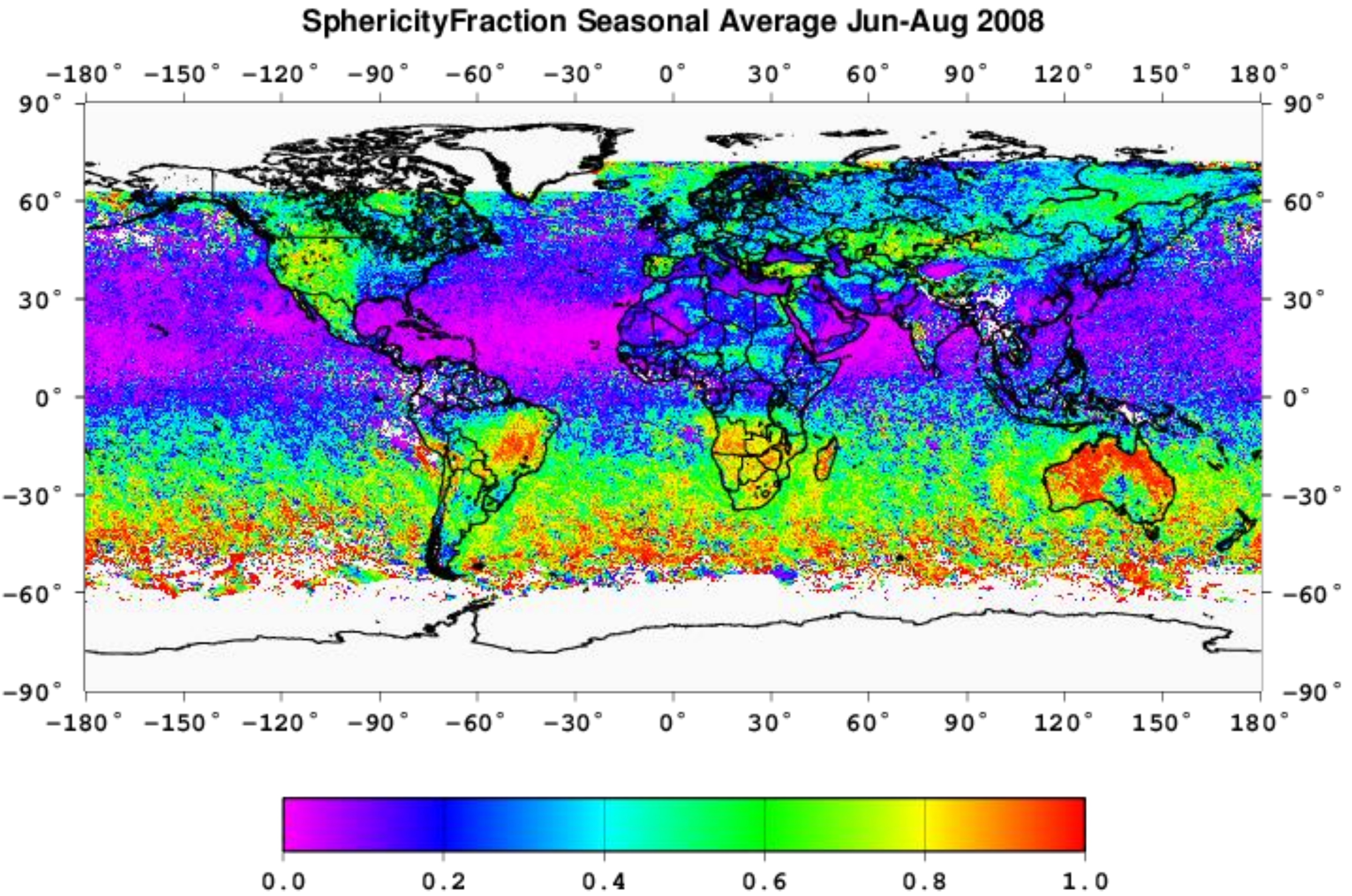





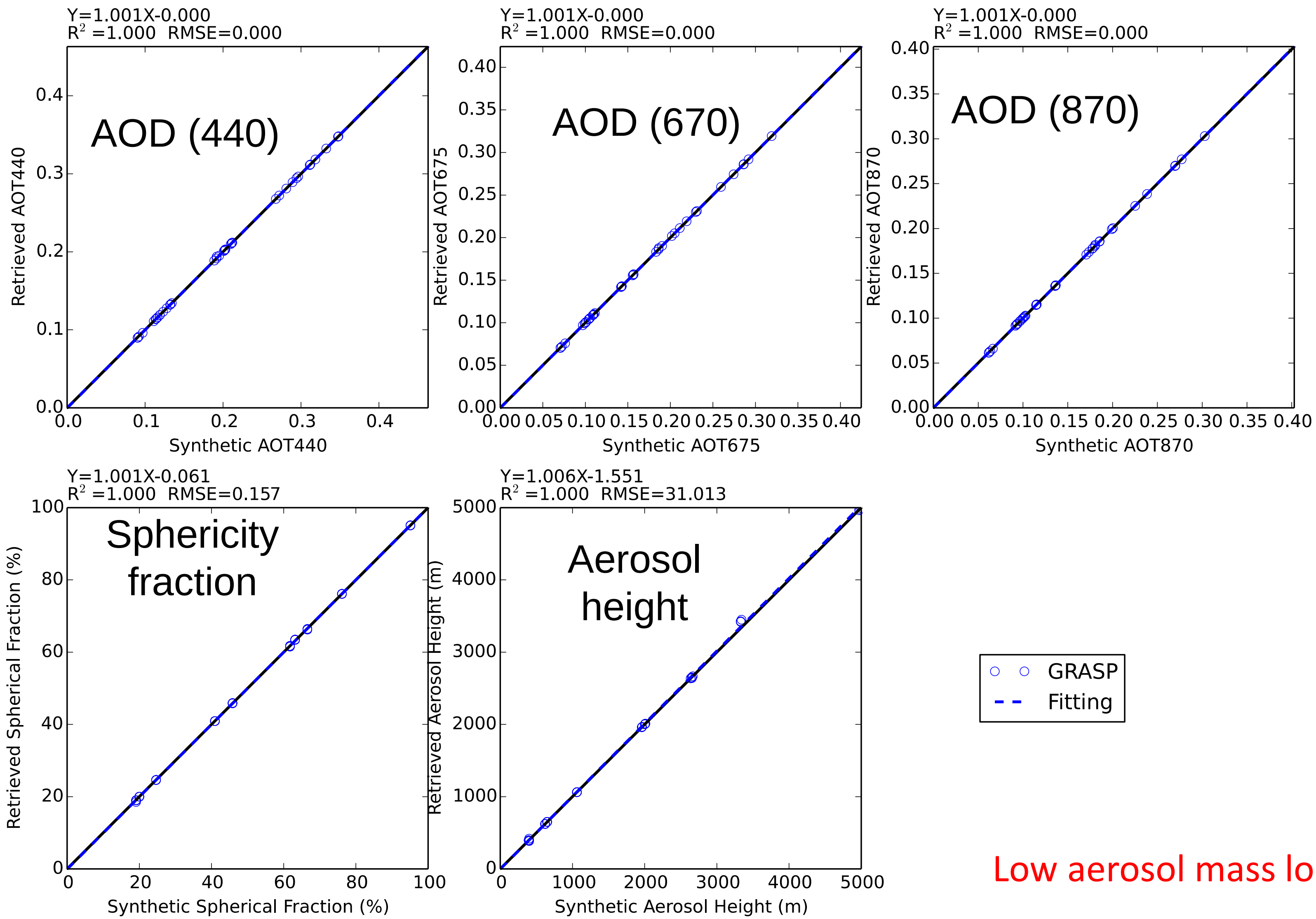
Sphericity fraction : June – August, 2008

PARASOL/GRASP

No assumptions!!!



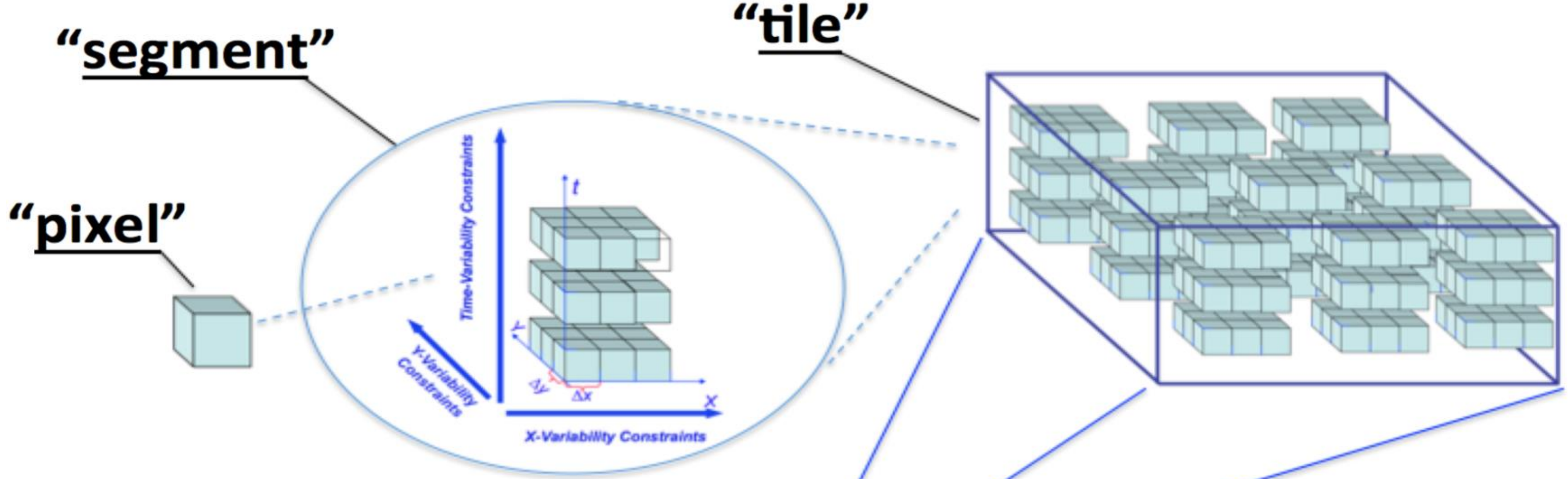
Retrieval of Non-Sphericity and Aerosol Layer Height from Synthetic Measurements

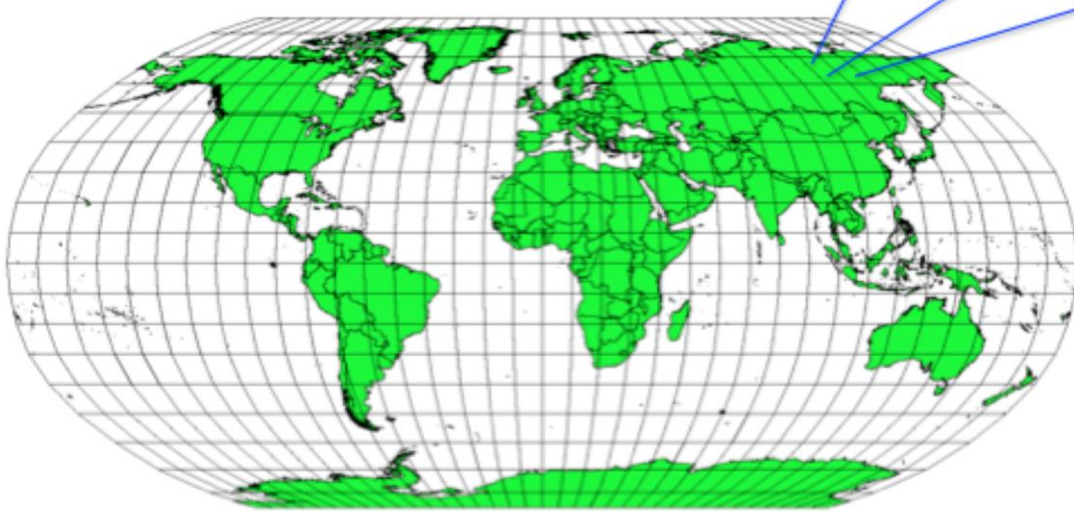


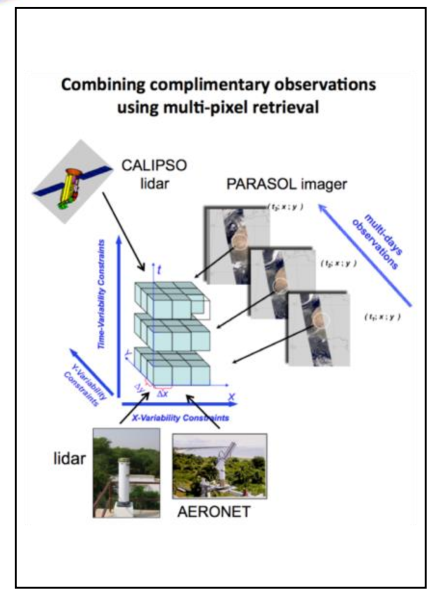
Low aerosol mass loading!

The concept of multi-pixel retrieval

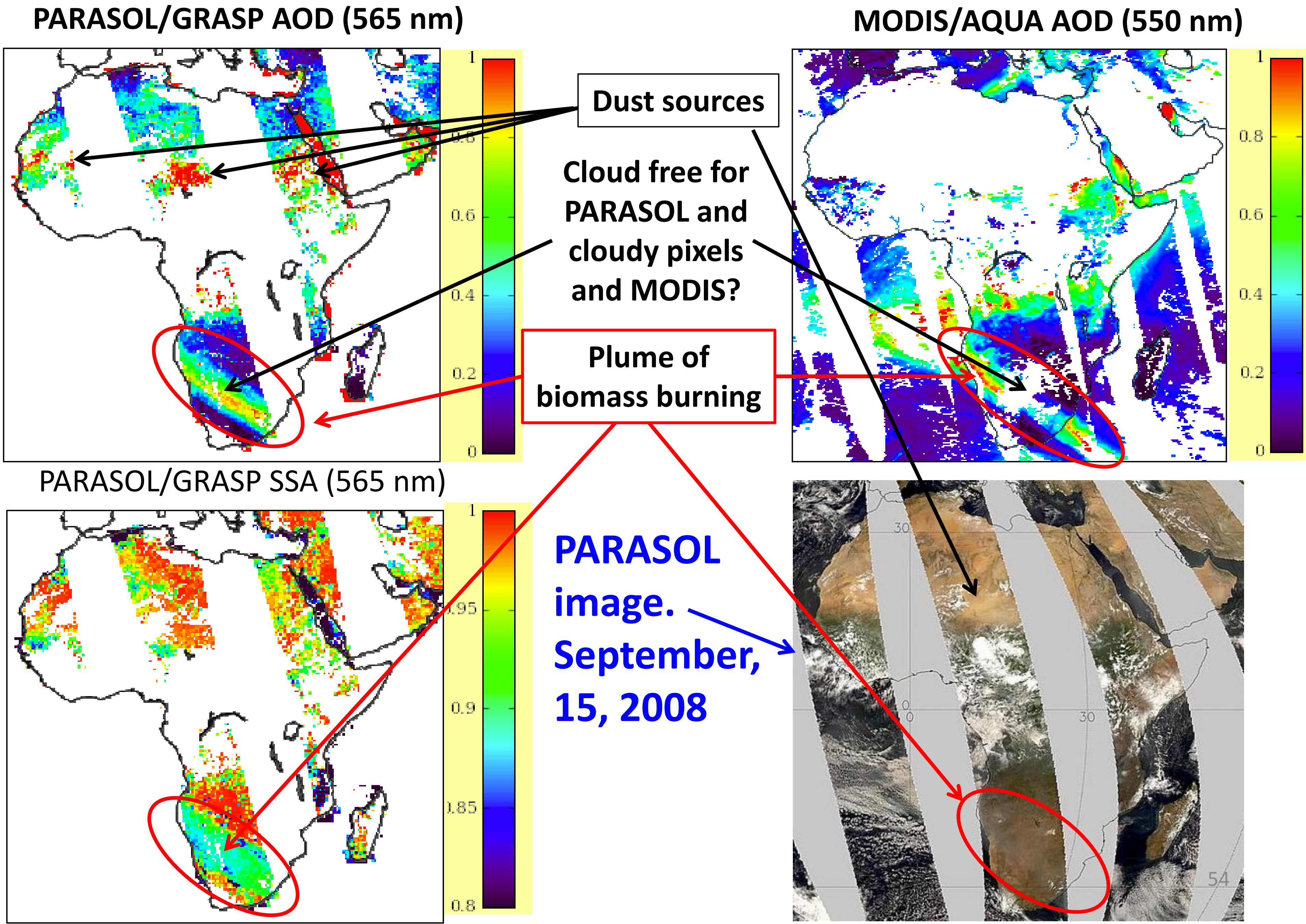
Dubovik et al. 2011







Aerosol sources identification with GRASP (AOD, SSA, AE)



GRASP/MERIS: AOD(560 nm), January – March 2008

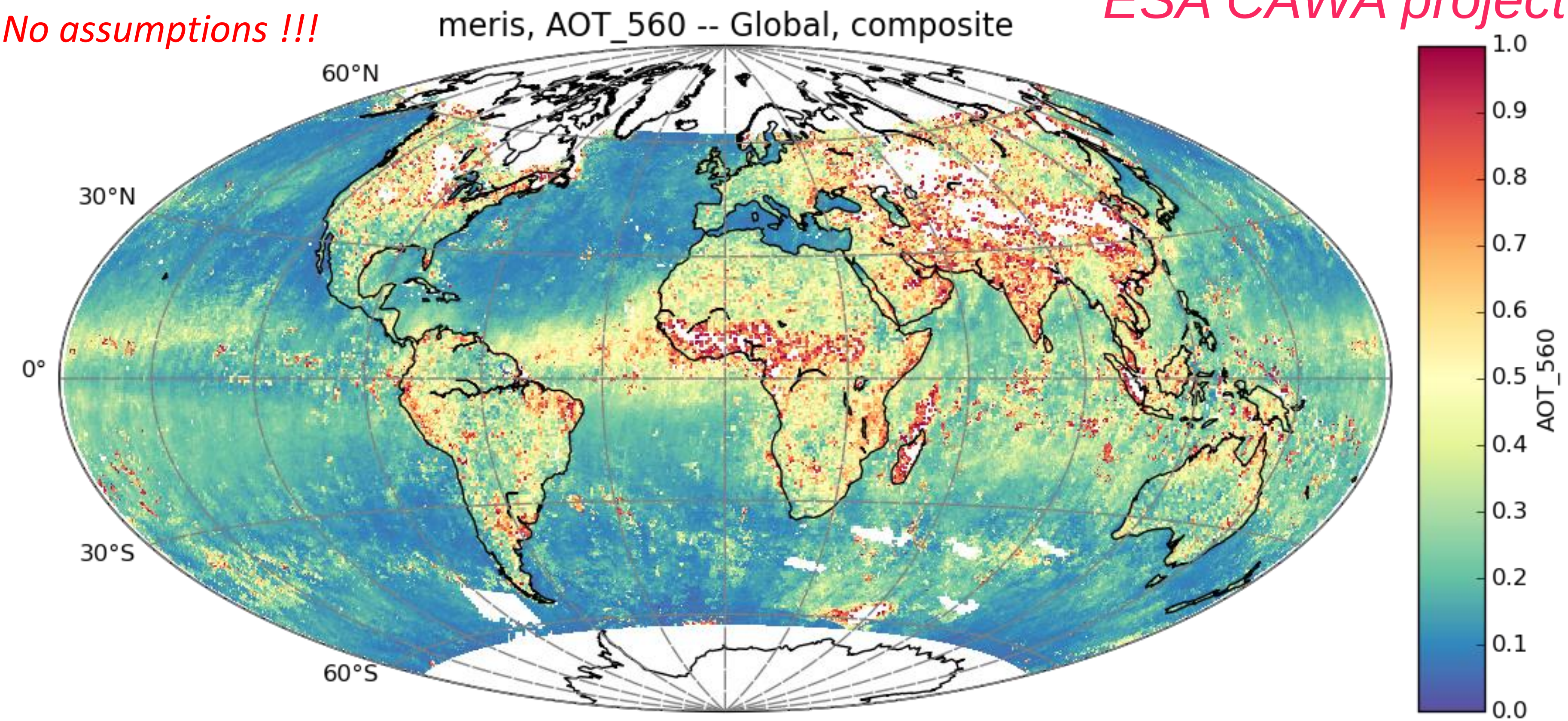
GRASP is somewhat slow compared to conventional retrievals, but easily mitigated using advanced IT technology such as GPGPU

Catalysts

First results: Aerosol, 35 km resolution

ESA CAWA project

No assumptions !!!



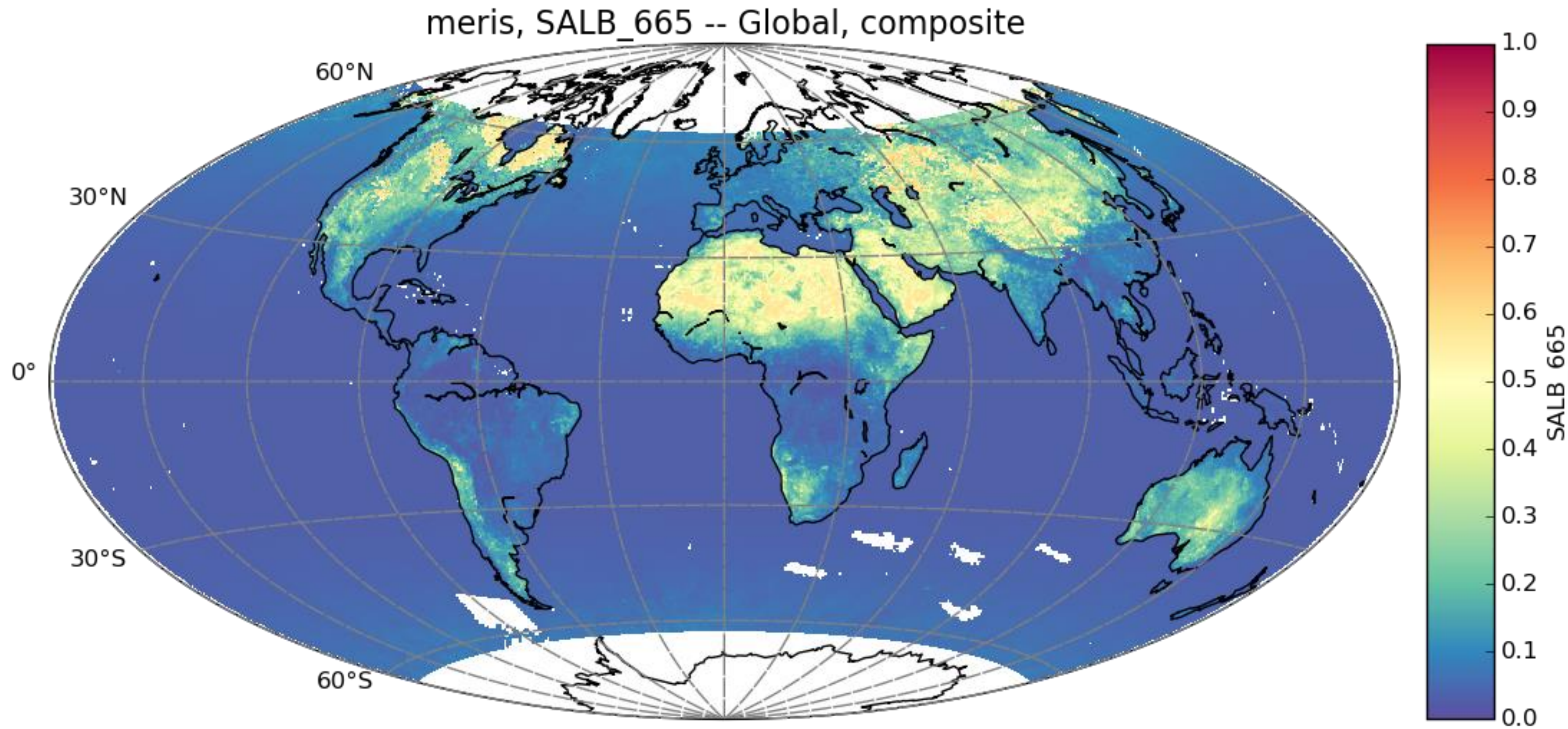
GRASP/MERIS: AOD(560 nm), January - March 2008

Retrieves both: surface (over land) and detailed aerosol properties

No assumptions !!!

ESA CAWA project

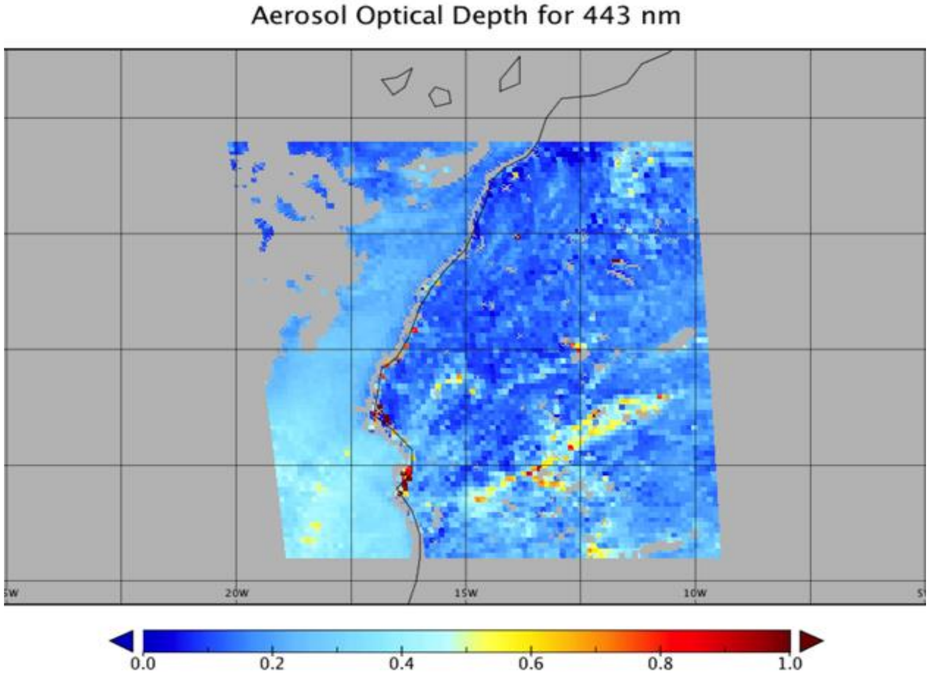
First results: Surface reflectance, 35 km resolution



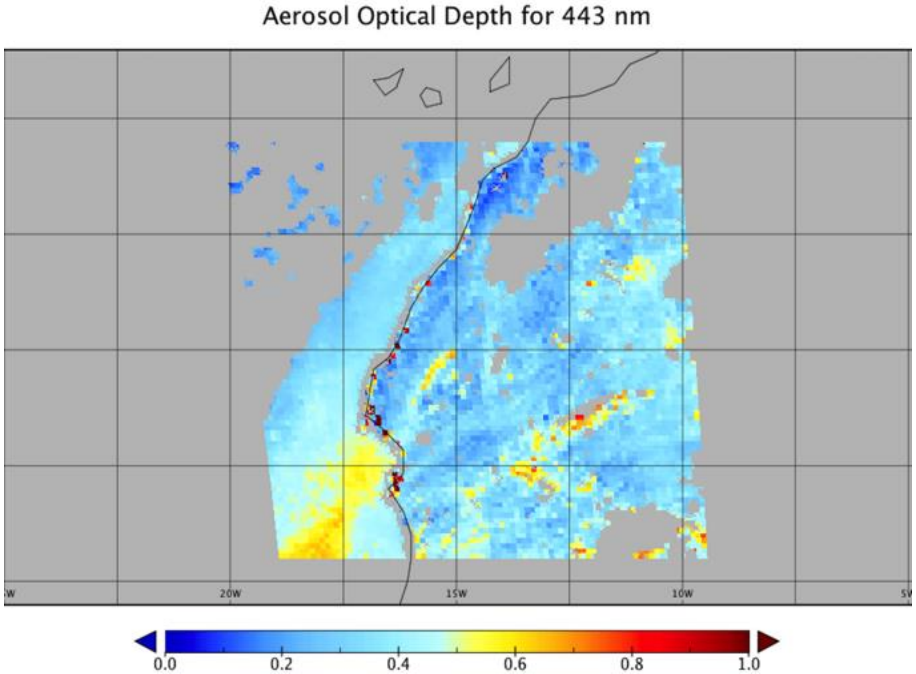
AOD retrieval in Ocean/Land zones

West coast of Africa (23N,-15W)

June 11, 2008



August 14, 2008



What is done

- Reduced number of Gaussian quadrature in forward RT and Jacobean matrix calculations.
  Used initially: 10(7) To speed up: 7(3)
- Reduced number of Fourier expansion term.
  Used initially: 10 To speed up: 5
- Reduced accuracy of RT-calculation:
  Initial absolute accur.: 0.0001 To speed up: 0.001
- Reduced number of bins in Size distribution.
  Used initially: 9 To speed up: 5
- Reduced number of iterations in inversion.
  Used initially: 12 To speed up: 6