Aerosol Data Assimilation

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Outlines

- **Global distributions of aerosol events**
- **Recent progress in aerosol data assimilation**
  - **Data assimilation schemes**
  - **Available observations**
- **Data sources and Challenges**
- **Examples of passive and active based aerosol data assimilation**
- **ICAP and ICAP-MME**

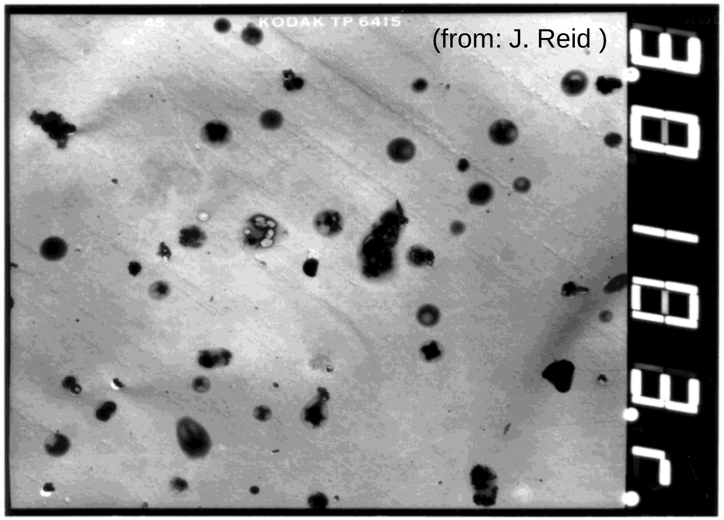
Aerosols: suspended particles in air

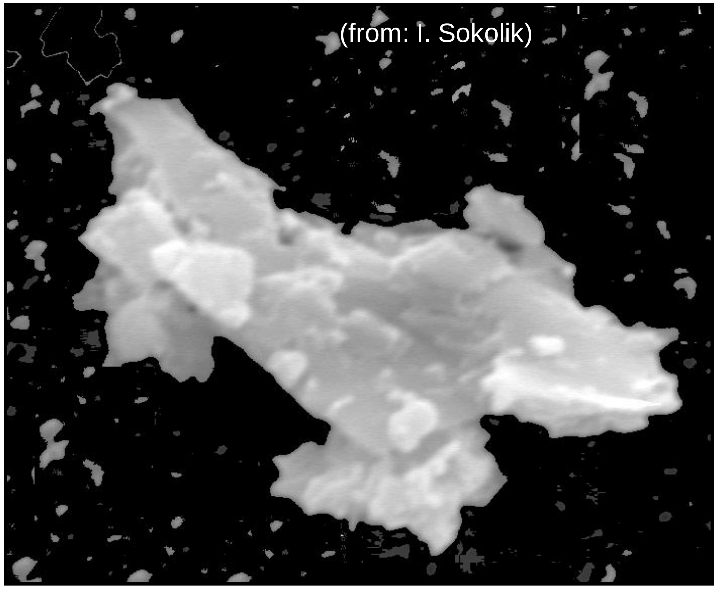
Problems?

•Aerosols are short lived, have very large spatial and temporal variations in both their physical and chemical properties.

•Yet, aerosols have important climate impacts, and act as the “seeds” for cloud formation.

•Major aerosol types: smoke, dust, pollutant, and sea salt.





Why do we care?

- Aerosol particles affect climate

  Scattering solar (SW) energy -- direct effect

  Absorbing solar (SW) /earth emitted (LW) energy -- direct effect

  Modify cloud properties (brighter clouds, longer cloud life time, indirect effects)

  Absorbing aerosols heat air columns and evaporate clouds, semi-direct effect

- Aerosol particles affect air quality

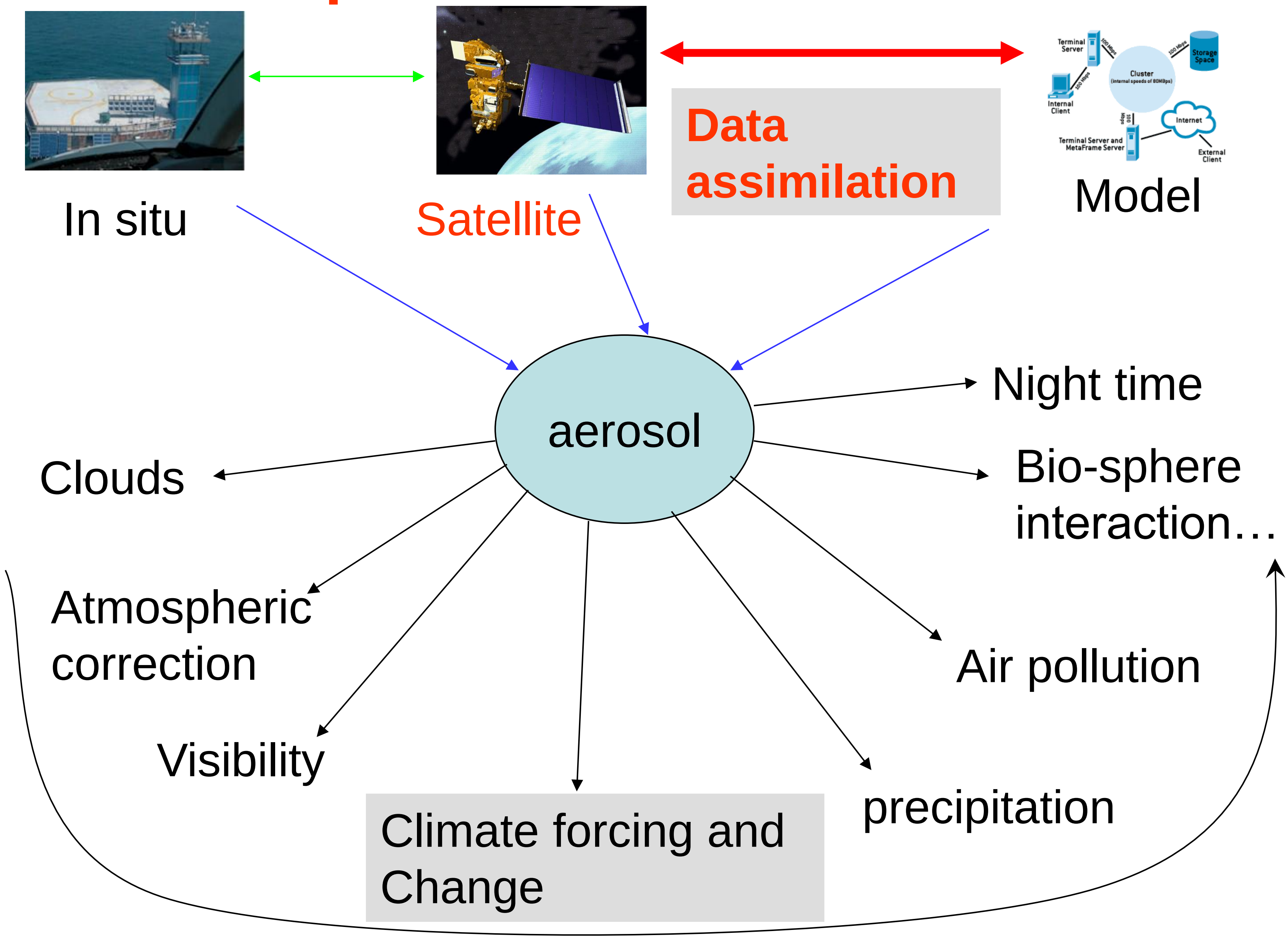
  E.g. Particulate Matter pollution (PM2.5 pollution)

- Aerosol particles affect visibility

  E.g. diverting aircrafts, military applications

- Aerosol particles affect …

Aspects of aerosol science



Assimilation Schemes

•Assimilation of column integrated aerosol optical thickness (AOT) using **2-D/3-D/4-D Var and Ensemble Kalman filter** (e.g., Zhang et al., 2008; Benedetti et al., 2009; Schutgens et al., 2010; Collins et al. 2001; Yu et al. 2003; Generoso et al. 2007; Adhikary et al. 2008; Tombette et al. 2009; Niu et al. 2008; Lin et al. 2008; Kahnert et al. 2008; Pagowski et al. 2012)

•Assimilation of surface and space-based aerosol lidar profiles using **3-DVAR or 4-D ensemble Kalman filter** methods (e.g., Yumimoto et al., 2008; Uno et al., 2008**;** Schutgens et al., 2010; Sekiyama et al., 2010; Zhang et al., 2011)

•Assimilation of multiple-wavelength AOD to constrain particle size distribution (e.g. Saide et al. 2013, **3-DVAR**)

•Assimilation of surface measurements of particle mass with diameters less than 2.5 μm (PM2.5) (Schwartz, et al., 2012; Li et al., 2013; Lee et al., 2013; Jiang et al., 2013, **3-DVAR, OI**)

Assimilation Schemes (International Cooperative for Aerosol Prediction Multi-Model Ensemble (ICAP-MME)

	ECMWF-MACC	Navy NAAPS	JMA MASINGAR	NASA GEOS-5	BSC-NMMB	NOAA NGAC	UKMO
Aerosol type	**Complete**	**Complete**	**Complete**	**Complete**	Dust	Dust	Dust
Assimilation Scheme	4DVAR	2D VAR ENKF	ENKF	3D VAR			4DVAR ENKF

- ECMWF-MACC: European Centre for Medium-Range Weather Forecasts-Monitoring Atmospheric Composition and Climate Model
- Navy NAAP: Navy Aerosol Analysis and Prediction System
- JMA MASINGAR: Japan Meteorological Agency-Model of Aerosol Species in the Global Atmosphere
- NASA GEOS-5: NASA GMAO Goddard Earth Observing System Version 5
- BSC-NMMB: Barcelona Supercomputing Center-National Materials and Manufacturing Board
- NOAA NGAC: NOAA-National Geospatial Advisory Committee
- UKMO: United Kingdom Met Office

Sessions et al., Development towards a global operational aerosol consensus: basic climatological characteristics of the International Cooperative for Aerosol Prediction Multi-Model Ensemble (ICAP-MME), Atmos. Chem. Phys., 15, 335–362, doi:10.5194/acp-15-335-2015, 2015

Data Sources (Passive-based, traditional products)

Traditional passive-based aerosol products (aerosol optical thickness, size parameters)

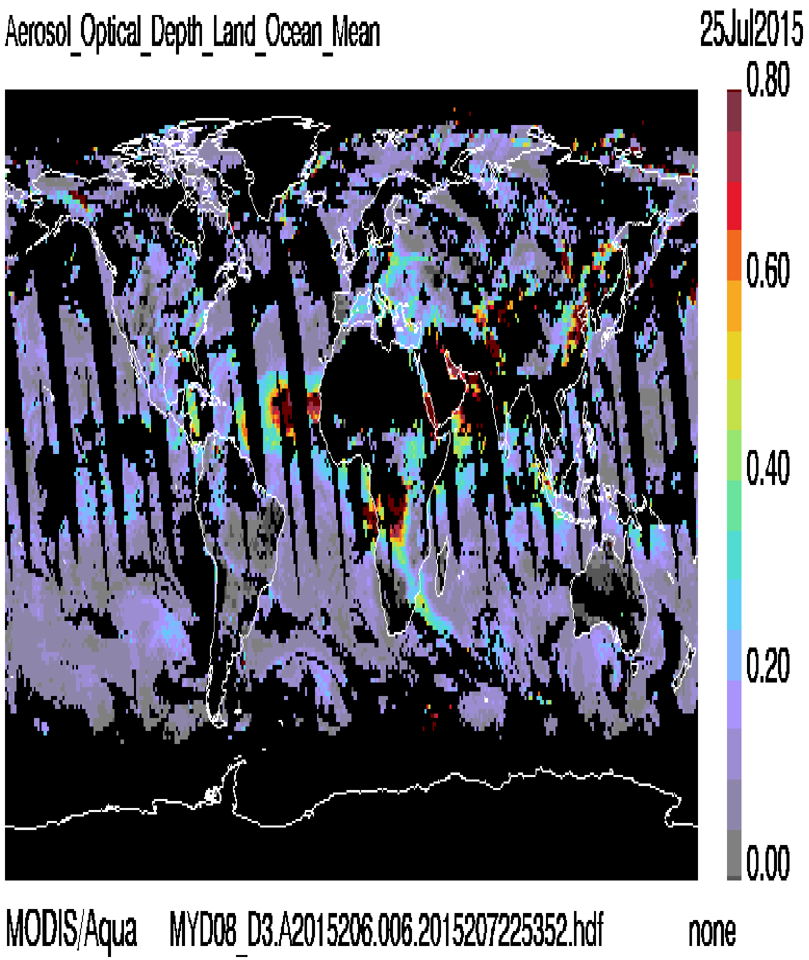
•Moderate Resolution Imaging Spectroradiomete (MODIS, 7 channels) e.g. Deep Blue, Dark Target, MAIAC

•Multi-angle Imaging SpectroRadiometer (MISR, 4 channels)

•Advanced Very High Resolution Radiometer (AVHRR, one or two channels)

•Geostationary Operational Environmental Satellite (GOES, one channel)

•Visible Infrared Imaging Radiometer Suite (VIIRS)



http://modis-atmos.gsfc.nasa.gov/IMAGES/08_D3.html

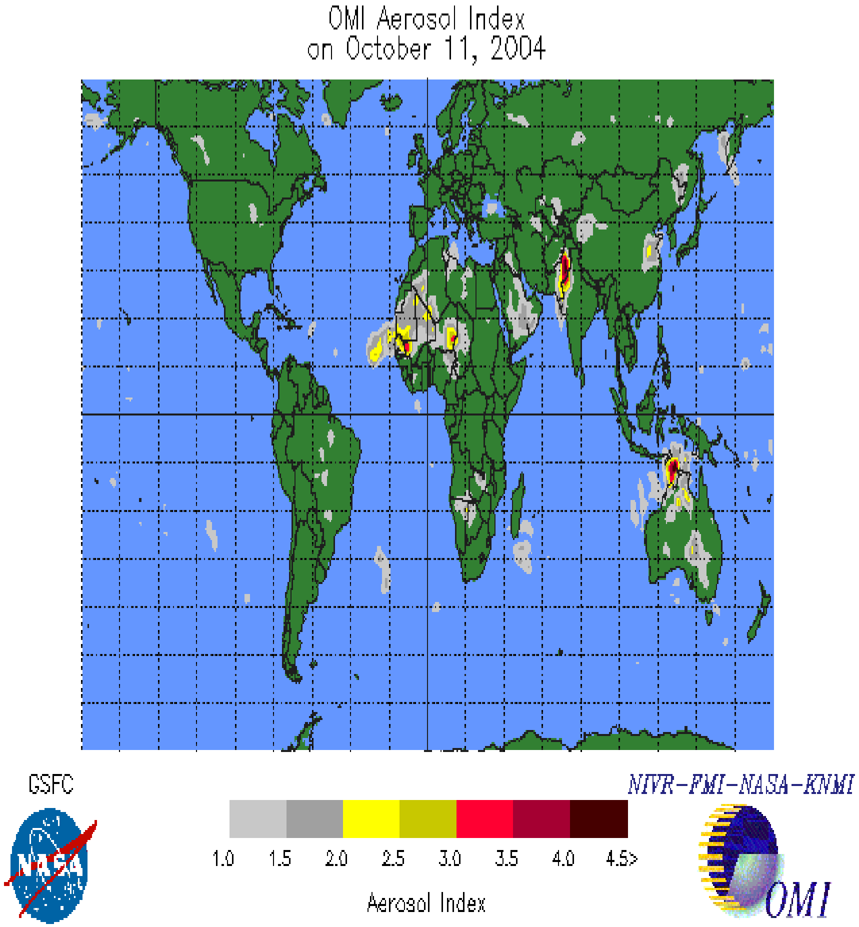
Data Sources (passive-based non-traditional aerosol products)

Passive-based non-traditional aerosol products

•Ozone Monitoring Instrument (OMI) aerosol index and absorbing aerosol products

•AI = 100 $\log_{10}(I_{360}^{Meas} / I_{360}^{Calc})$

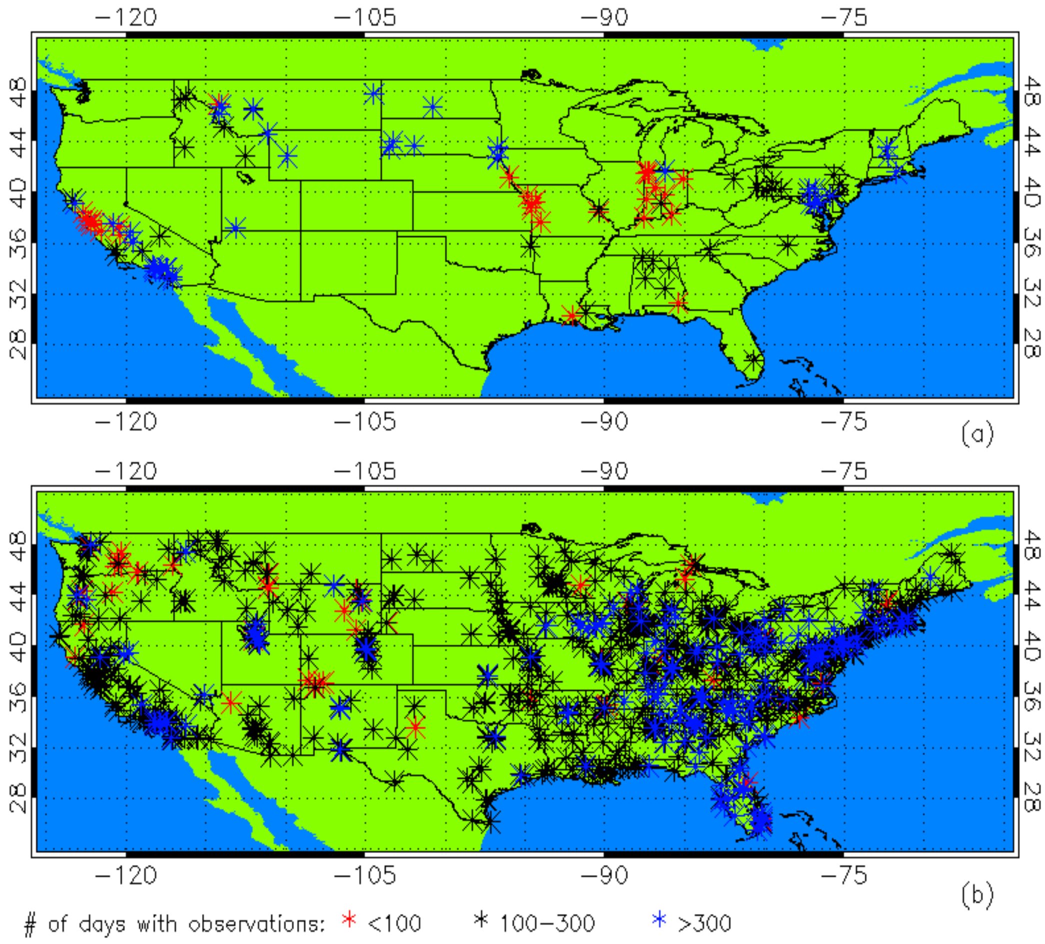
I_{360}^{Meas} and I_{360}^{Calc} are the measured and calculated radiance at the 360 nm spectral channel respectively. No aerosol is included in the calculation.



http://www.knmi.nl/omi/research/product/product_generator.php?info=page&product=aerosol&flavour=OMAERUV&long=Aerosol%20absorption%20optical%20thickness%20and%20single%20scattering%20albedo

Data Sources (non-traditional products)

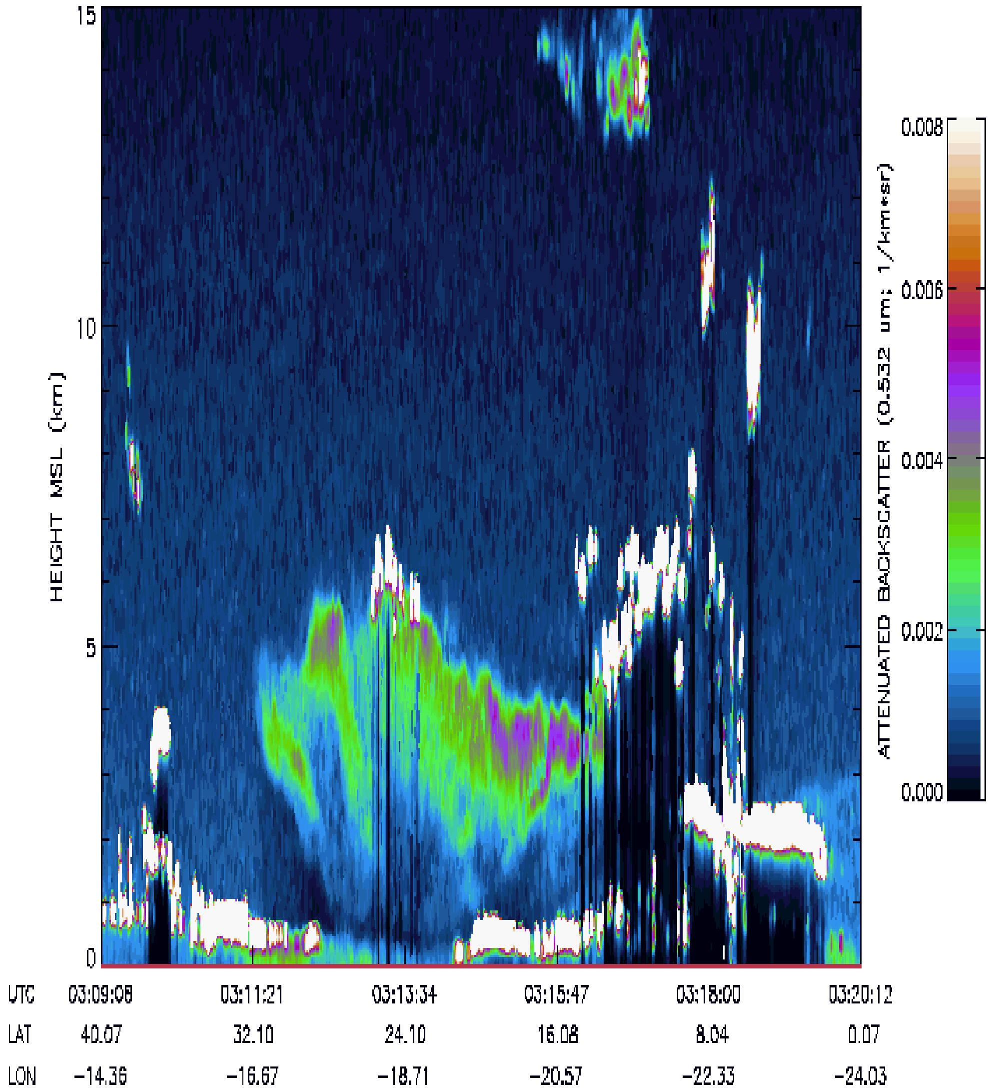
- Surface measurements of particle mass with diameters less than 2.5 µm (PM2.5)
- The Federal Reference Method (FRM), a filter-based method, is used to measure PM2.5 concentration over a continuous 24-hr period.
- Hourly PM2.5 concentrations are also reported for some EPA sites.



Example for 2008-2009, U.S. Environmental Protection Agency (EPA) sites with available $PM_{2.5}$ measurements at (a) hourly and (b) daily intervals, respectively.

Data Sources (active-based)

- Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)
- Cloud-Aerosol Transport System (CATS)
- Earth Clouds, Aerosols and Radiation Explorer (EarthCARE)



Total / attenuated backscatter, aerosol extinction

Data source for Validation

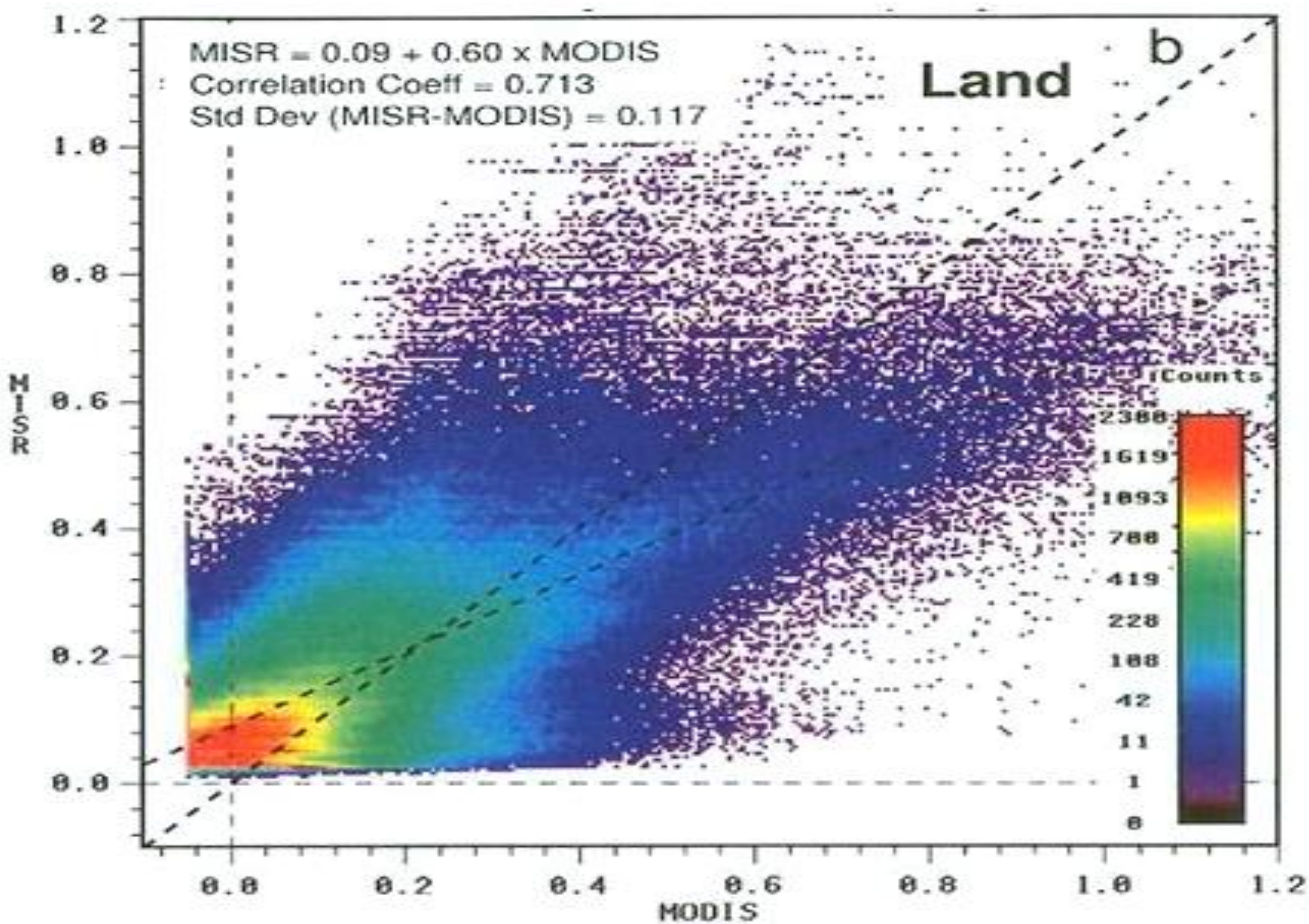
- **AE**rosol **RO**botic **NET**work (AERONET)

  http://aeronet.gsfc.nasa.gov/

- Micro-Pulse Lidar Network (MPLNET)

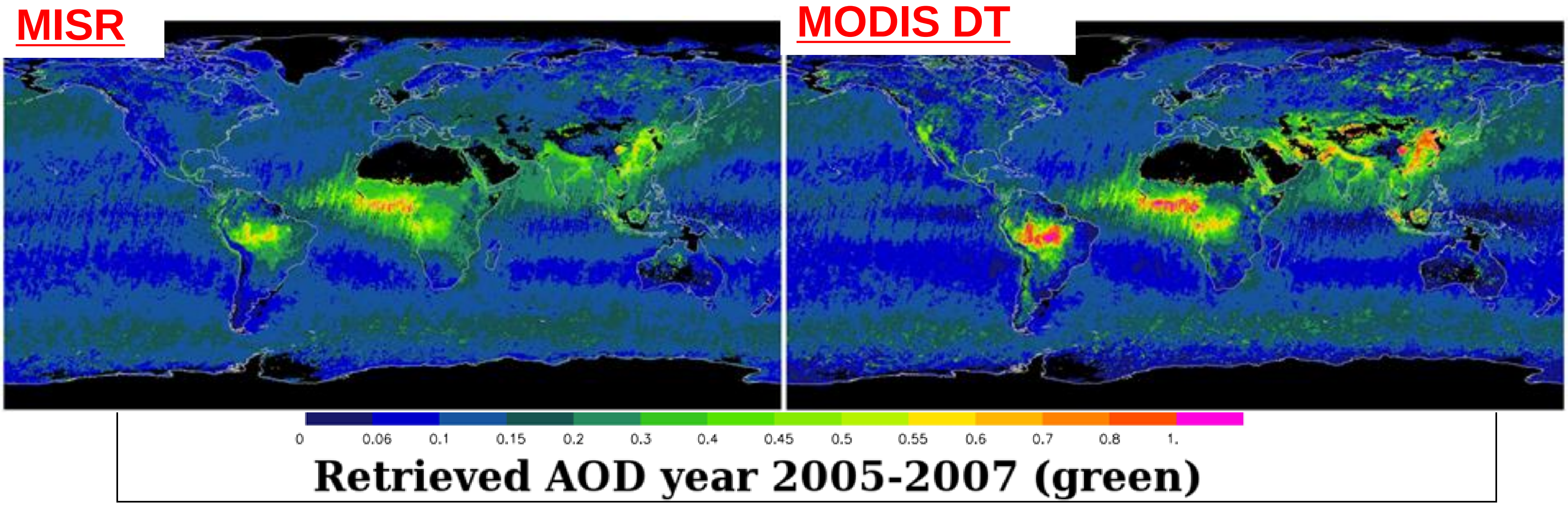
  http://mplnet.gsfc.nasa.gov/

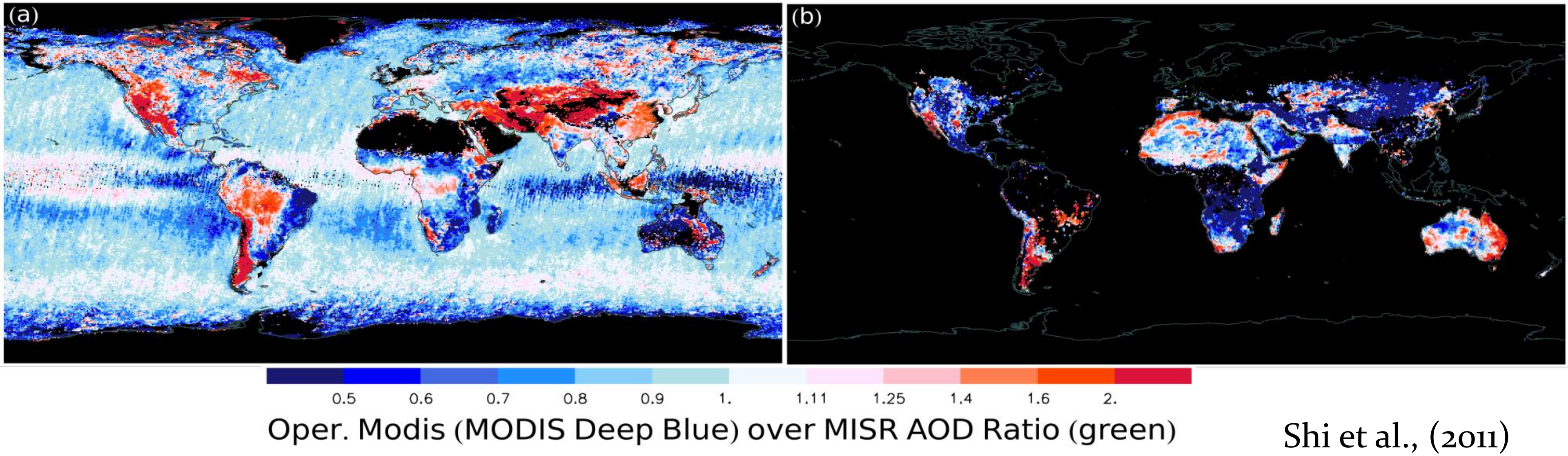
Data sources and challenges



Kahn et al., (2009)

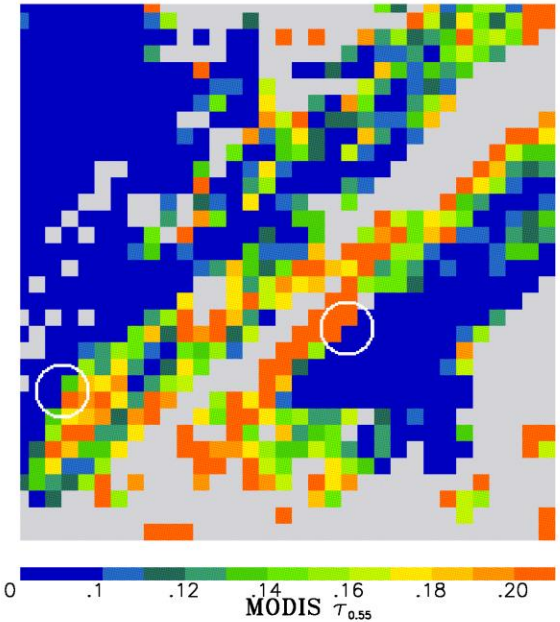
Data sources and challenges

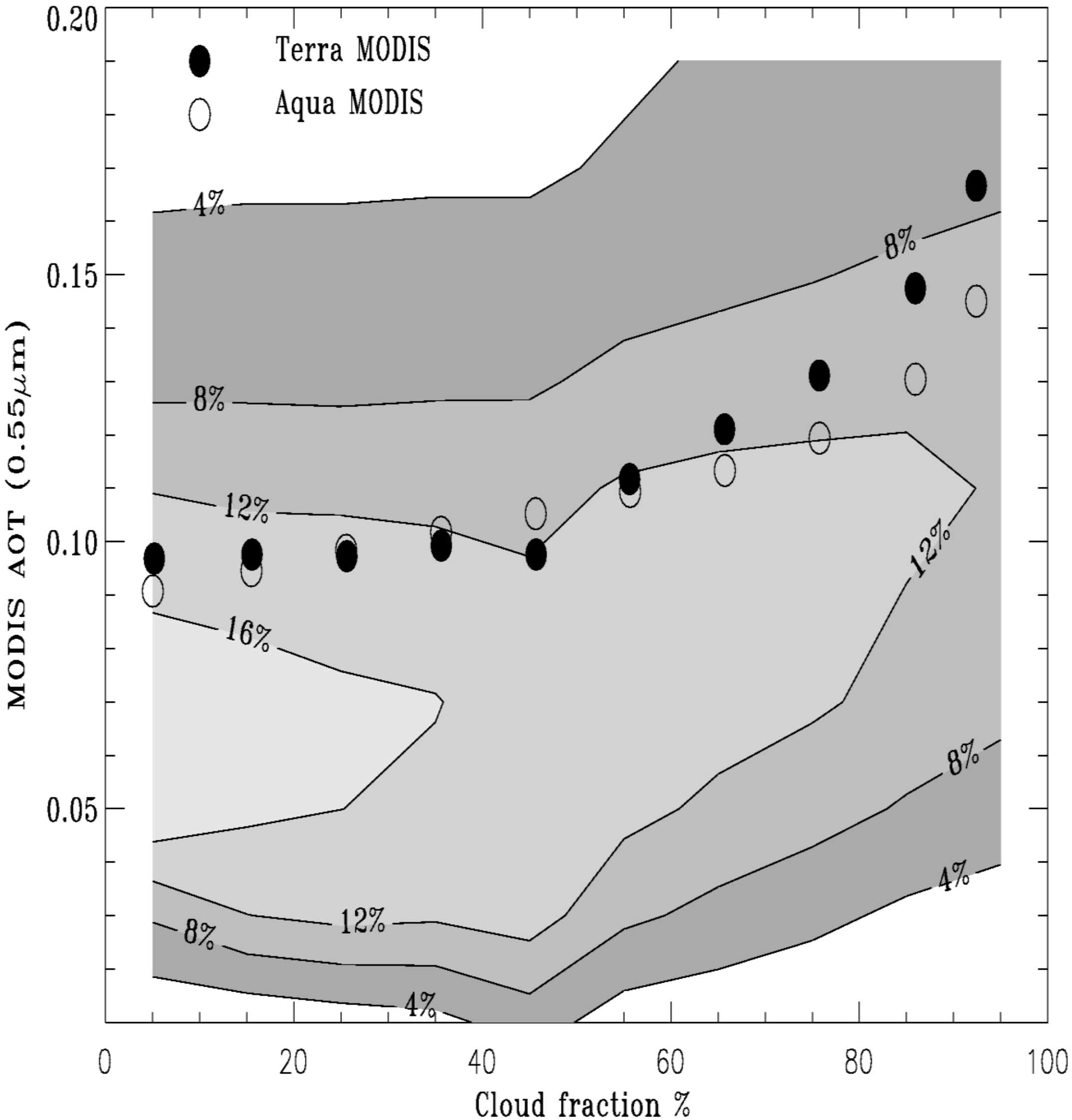




Shi et al., (2011)

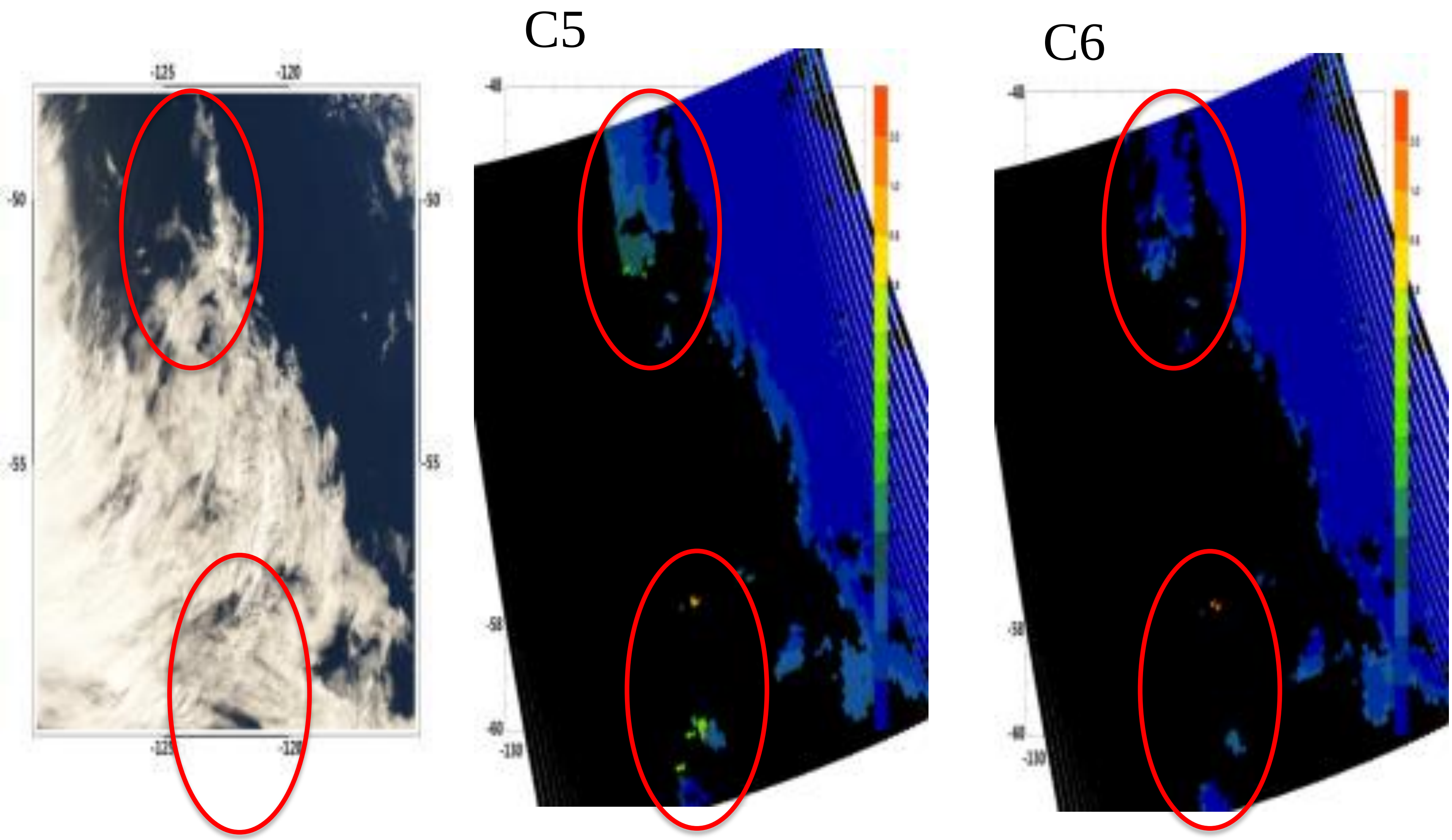
Sources of uncertainties: cloud contamination





Zhang et al., (2006)

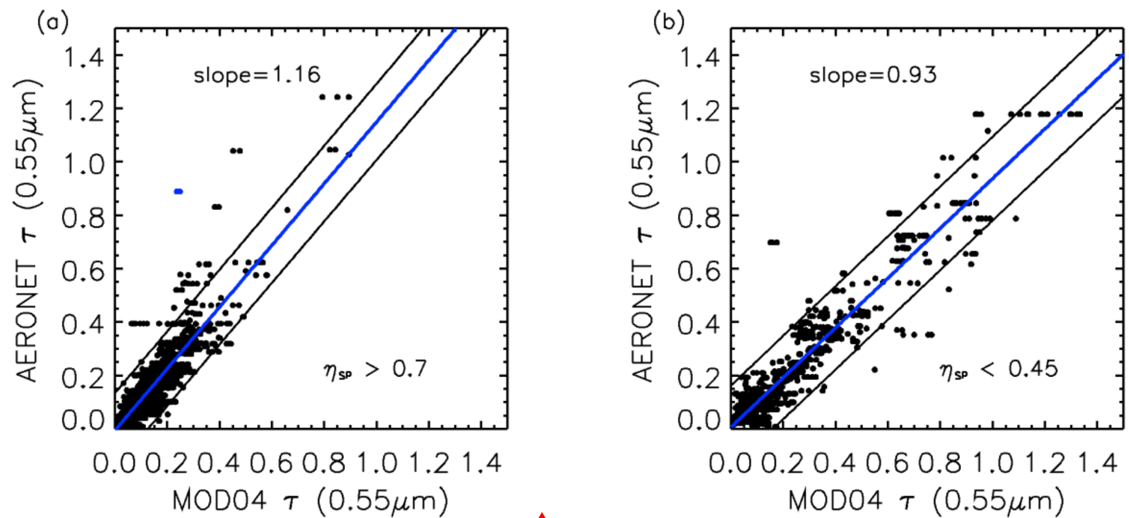
Cloud contamination, new MODIS products are better, but issues still exist

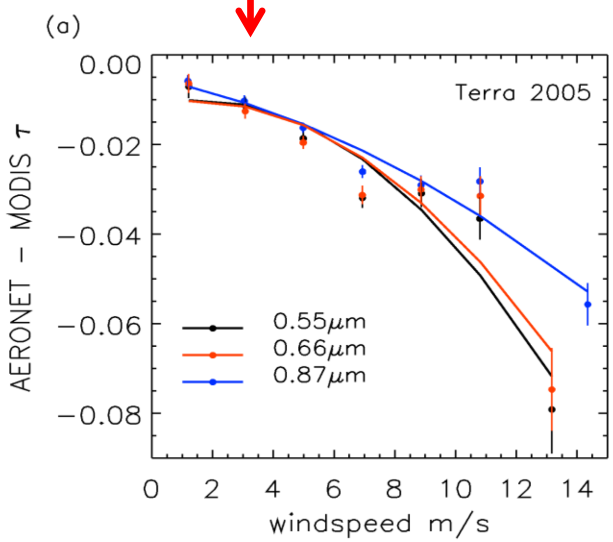


Shi et al., (2014)

Sources of uncertainties: surface contamination and aerosol microphysical bias

Example of wind (low boundary condition) related bias, from C5 MODIS DT (Shi et al., 2011)

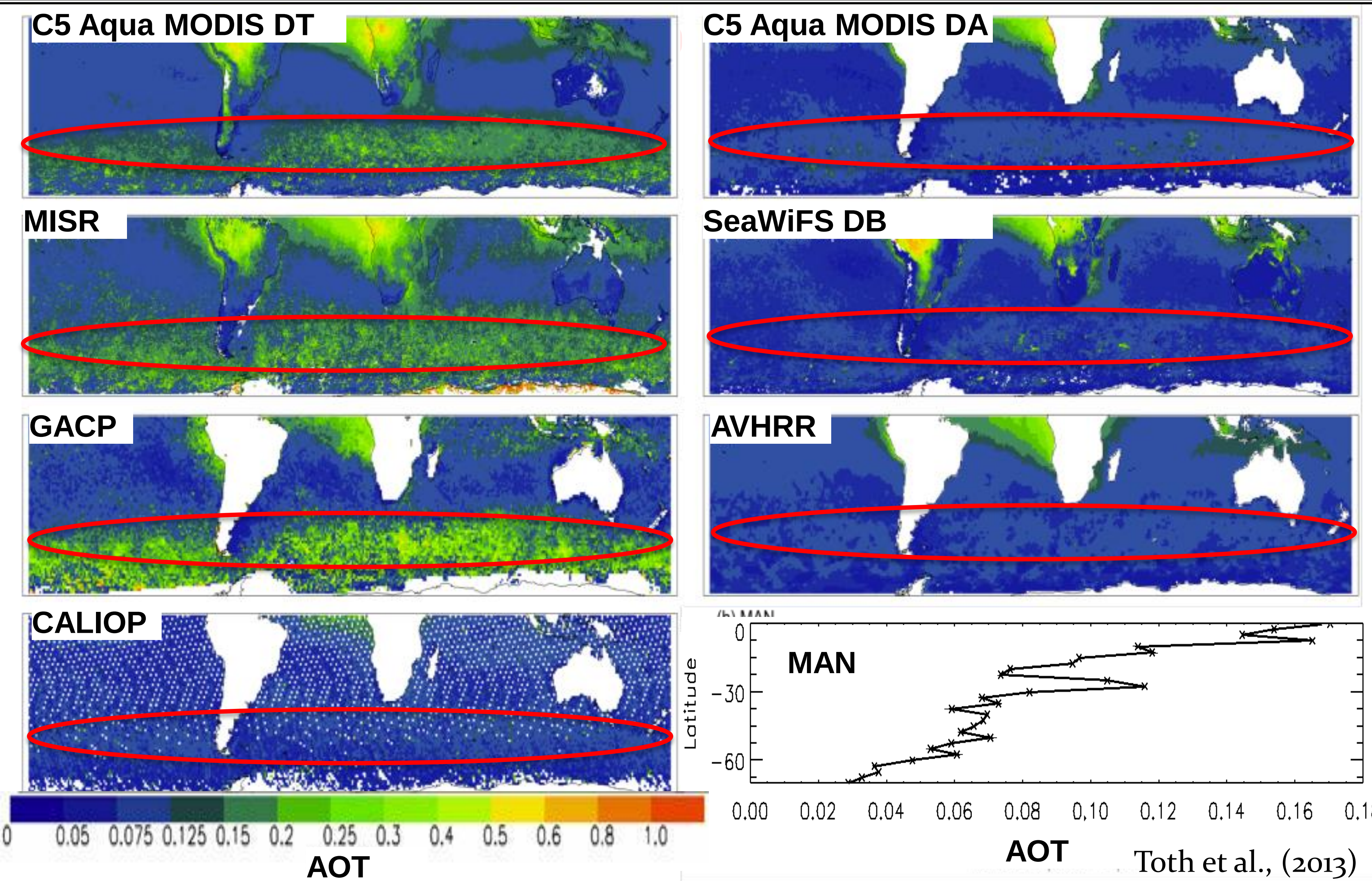




Example of aerosol microphysical bias (Shi et al., 2011). C5 MODIS DT data from 2005 are used

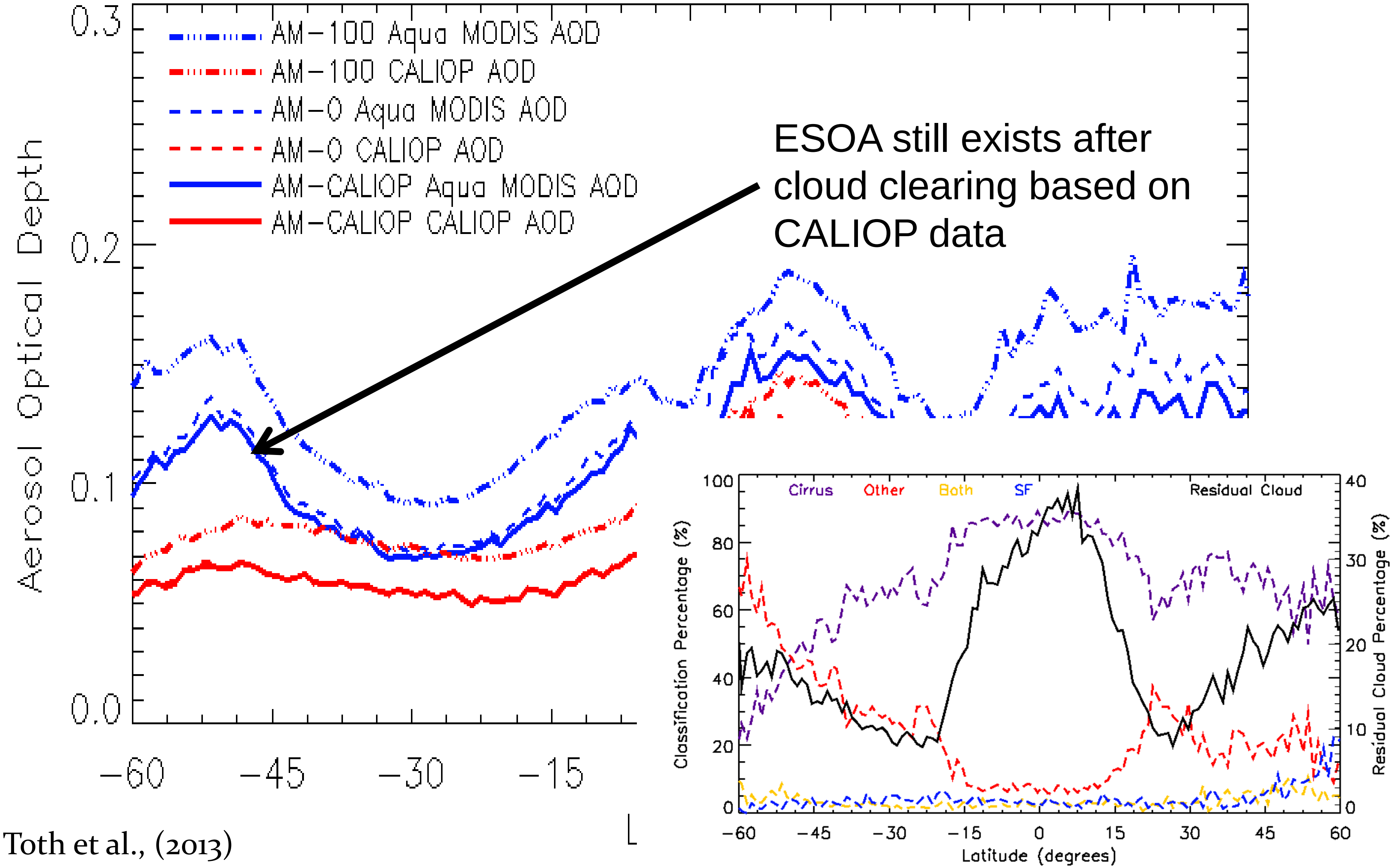
Shi et al., (2011)

Other sources of uncertainties?
Enhanced Southern Ocean Anomaly (ESOA)?



Toth et al., (2013)

ESOA can't be fully explained by cloud contamination…



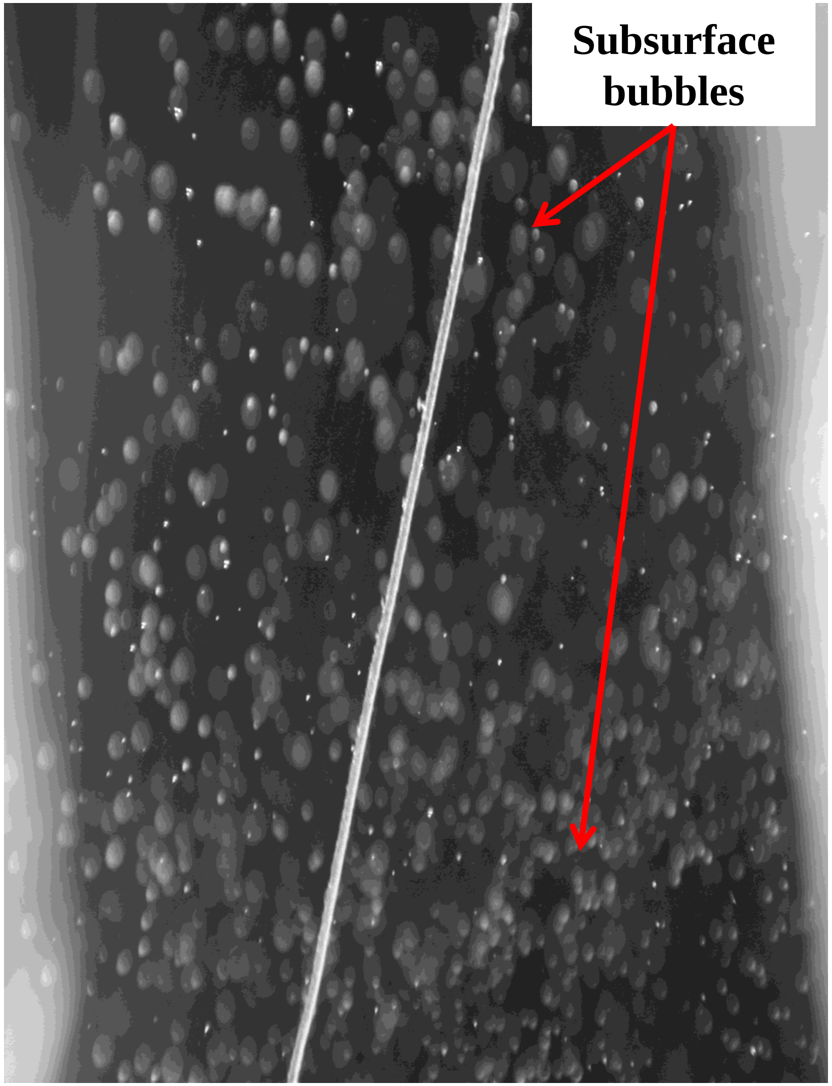
Toth et al., (2013)

Sub-surface bubbles are the cause for ESOA?

• **Whitecaps are simply air bubbles on the surface. However, they have significantly different lifetime: minutes to hours for subsurface bubbles vs seconds for whitecaps (e.g. Johnson and Cooke, 1981).**

• **These persistent bubbles have been recognized as a complicating term in retrievals of water-leaving radiance (Zhang, 2001; Zhang and Lewis, 2002).**

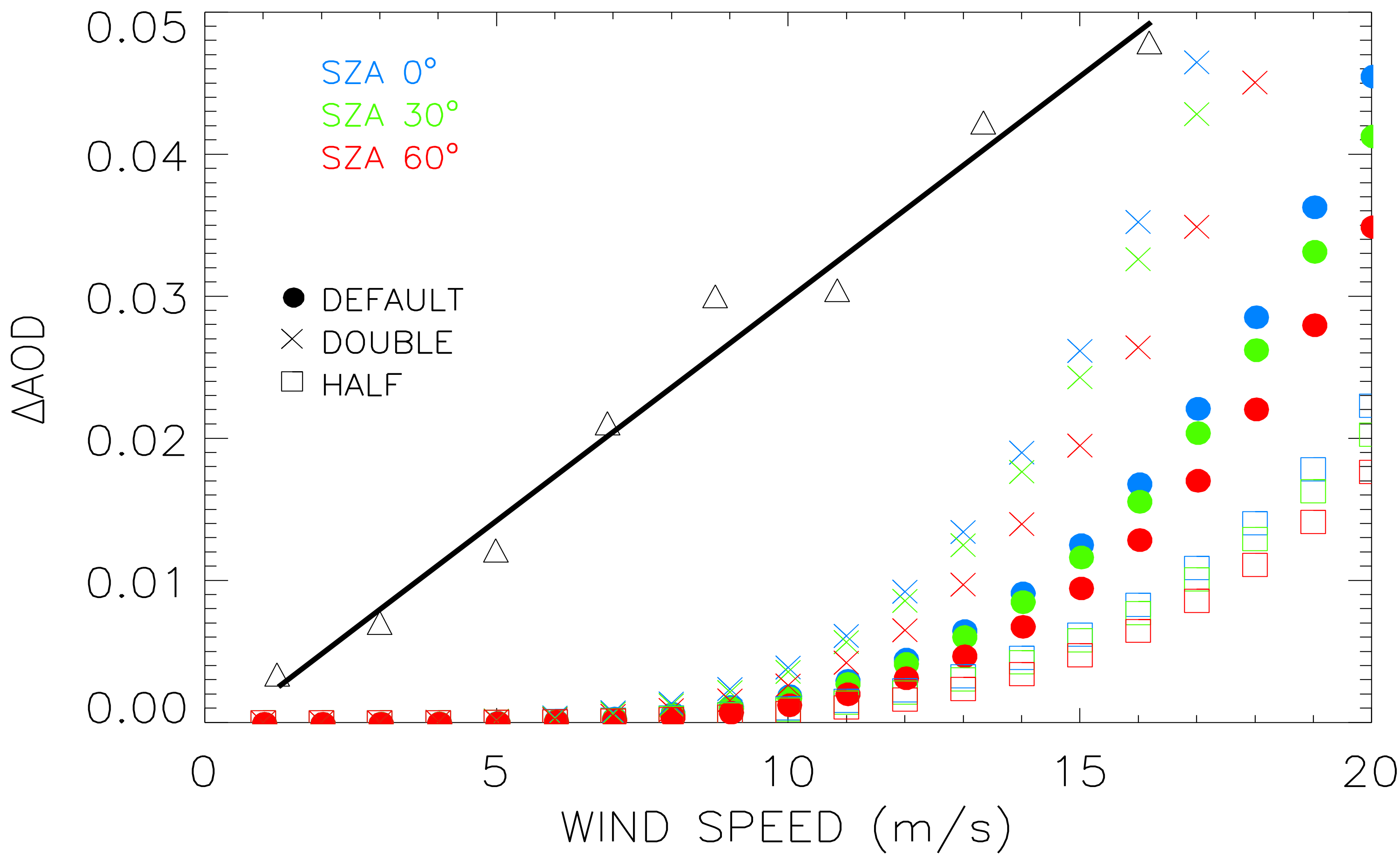
• **Ship wakes offer an "anthropogenic" example on how long bubbles can persist in the ocean and alter the albedo.**



Christensen et al., (2015)

Not really

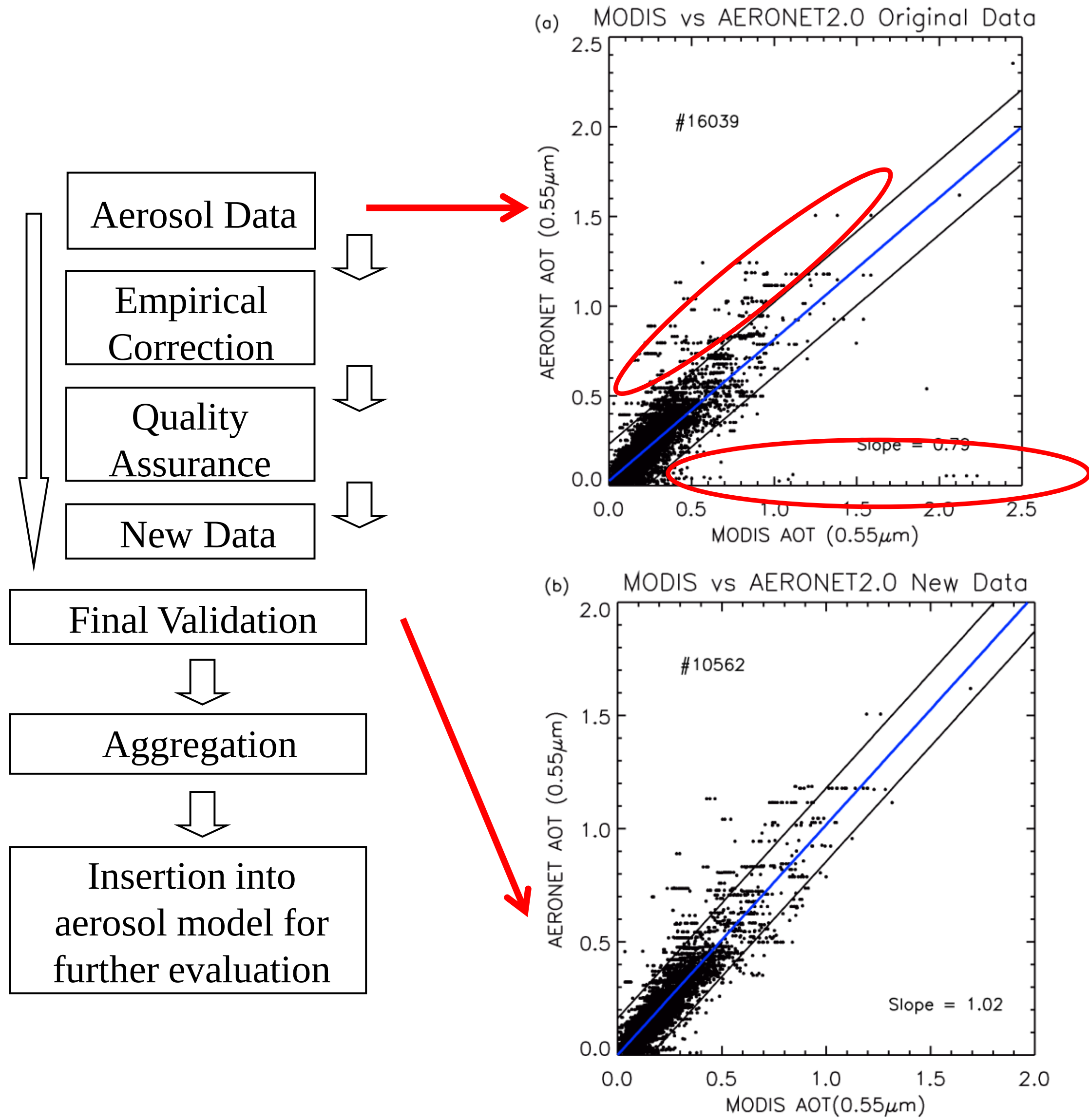
Impact of bubbles on AOD retrievals



Christensen et al., (2015)

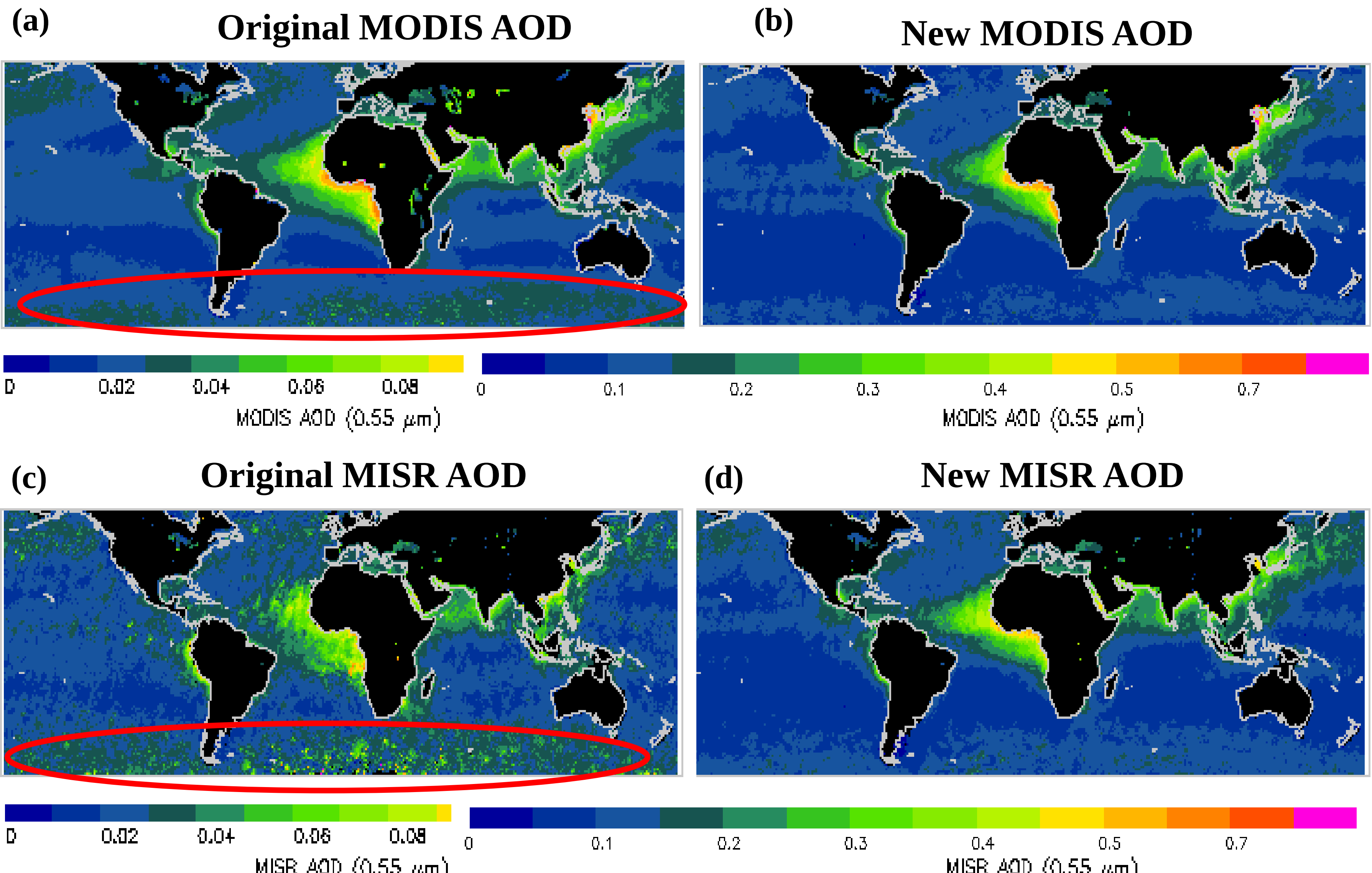
Constructing data-assimilation grade aerosol products
Example: Over-ocean MODIS DT satellite AOD data

- We begin with NRTPE Collection 5 MOD04 AOD data. Shown is 2005 annual average.
- QA: Data are screened using spatial tests and thresholds. Empirical corrections are made based on satellite and NOGAPS environmental data.
- End result: more than 50% correction in data over southern oceans and Asian outflow to the north Pacific. 15-20% reduction in error globally.



Shi et al., 2011, Shi, 2009

Constructing data-assimilation grade aerosol products
Example: Over-ocean MODIS DT satellite AOD data

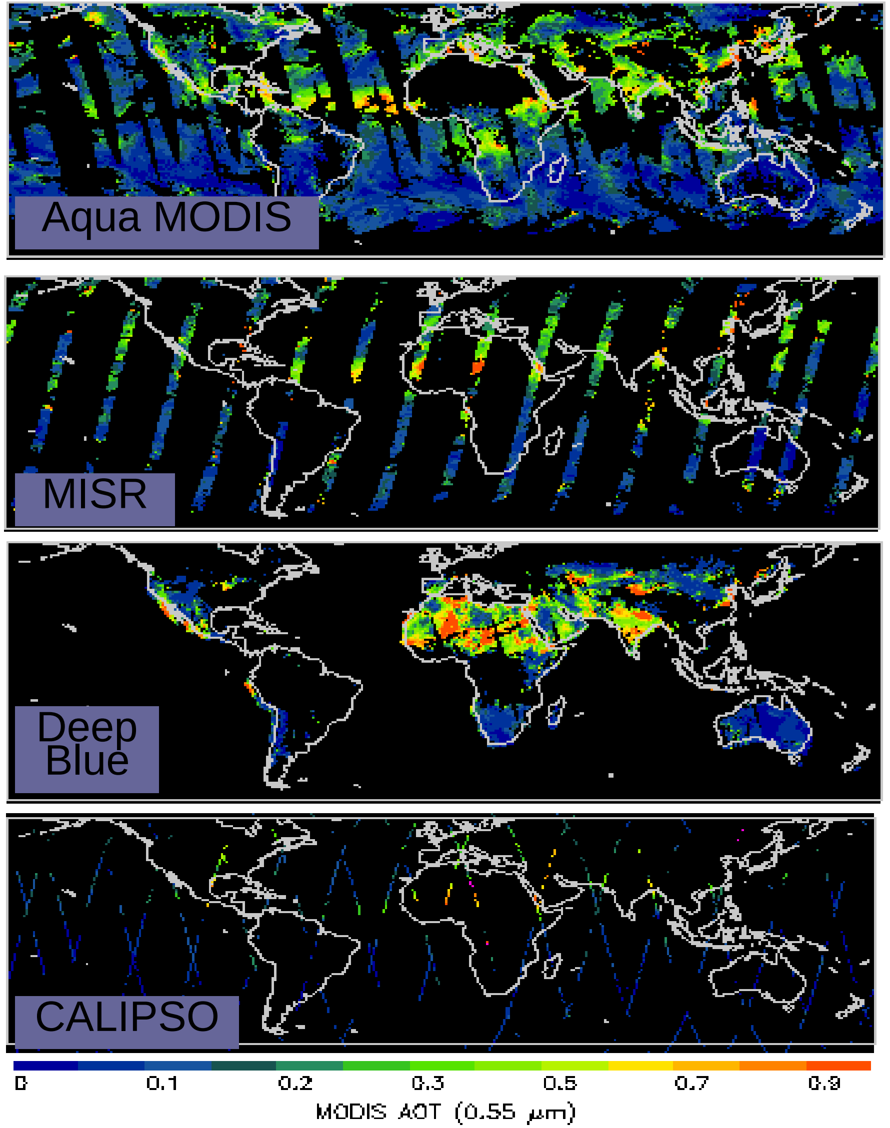


Shi, 2009

Other outstanding data related issues

- sun synchronous only data, need nighttime retrievals
- Lidar assimilation
- Need to utilize geostationary data
- Hard problems but are approachable in near future

Daily coverage



Examples of passive and active based aerosol data assimilation

Example of aerosol optical depth data assimilation (NRL *NAVDAS-AOD, early version*)

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{P}_b\mathbf{H}^T[\mathbf{H}\mathbf{P}_b\mathbf{H}^T + \mathbf{R}]^{-1}[\mathbf{y} - H\{\mathbf{x}_b\}]$$

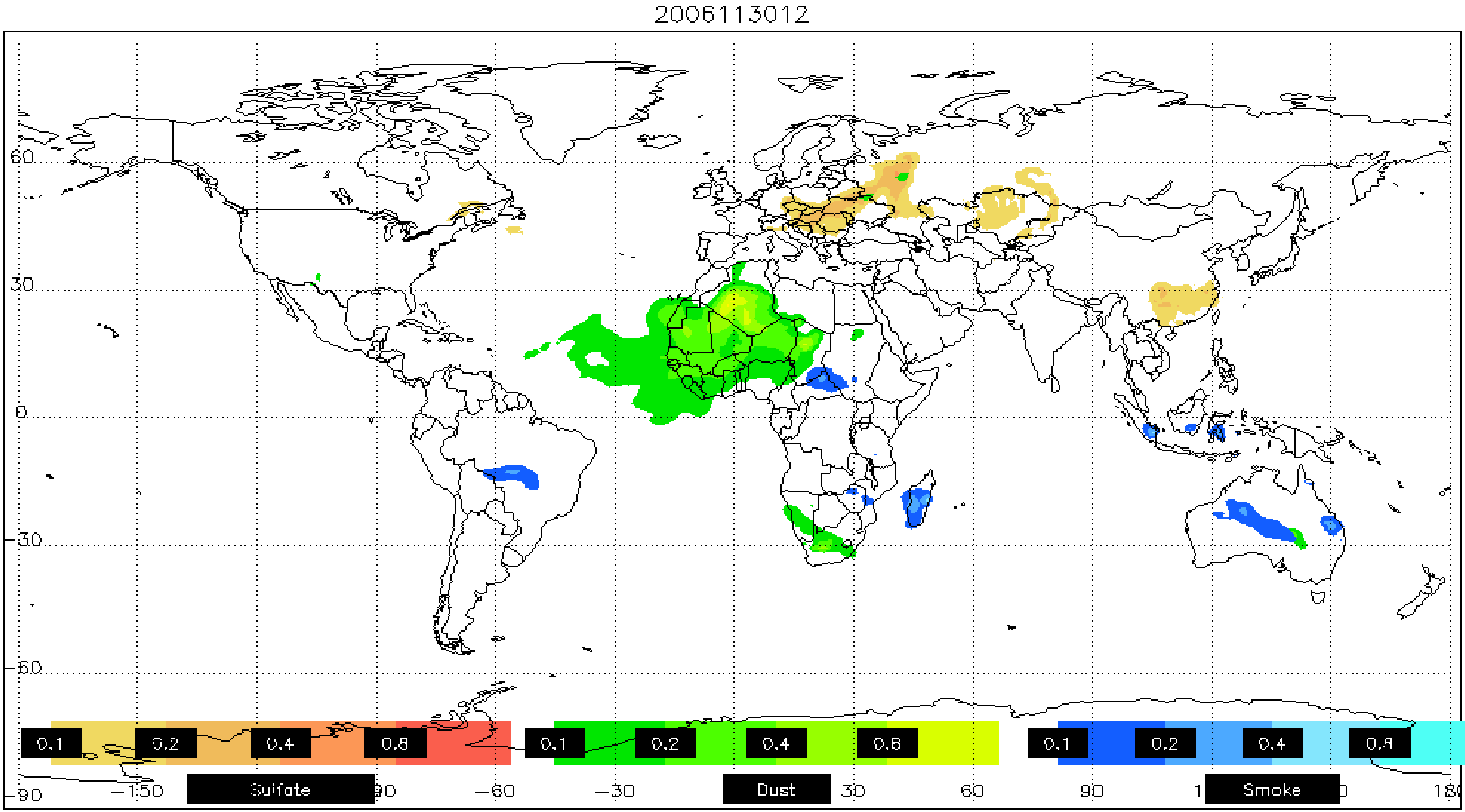
- **Observation errors (R) are determined from sun-photometer observations**

- **Back ground errors (P) are determined from both sun-photometer observations (error variance) and MODIS aerosol product (error correlation length)**

- **H (forward operator) is partitioned based on FAROP (Forecast of Aerosol Radiative Optical Properties)**

Example of aerosol optical depth data assimilation (NRL *NAVDAS-AOD, early version*)

NRL Aerosol Analysis and Prediction System (NAAPS)



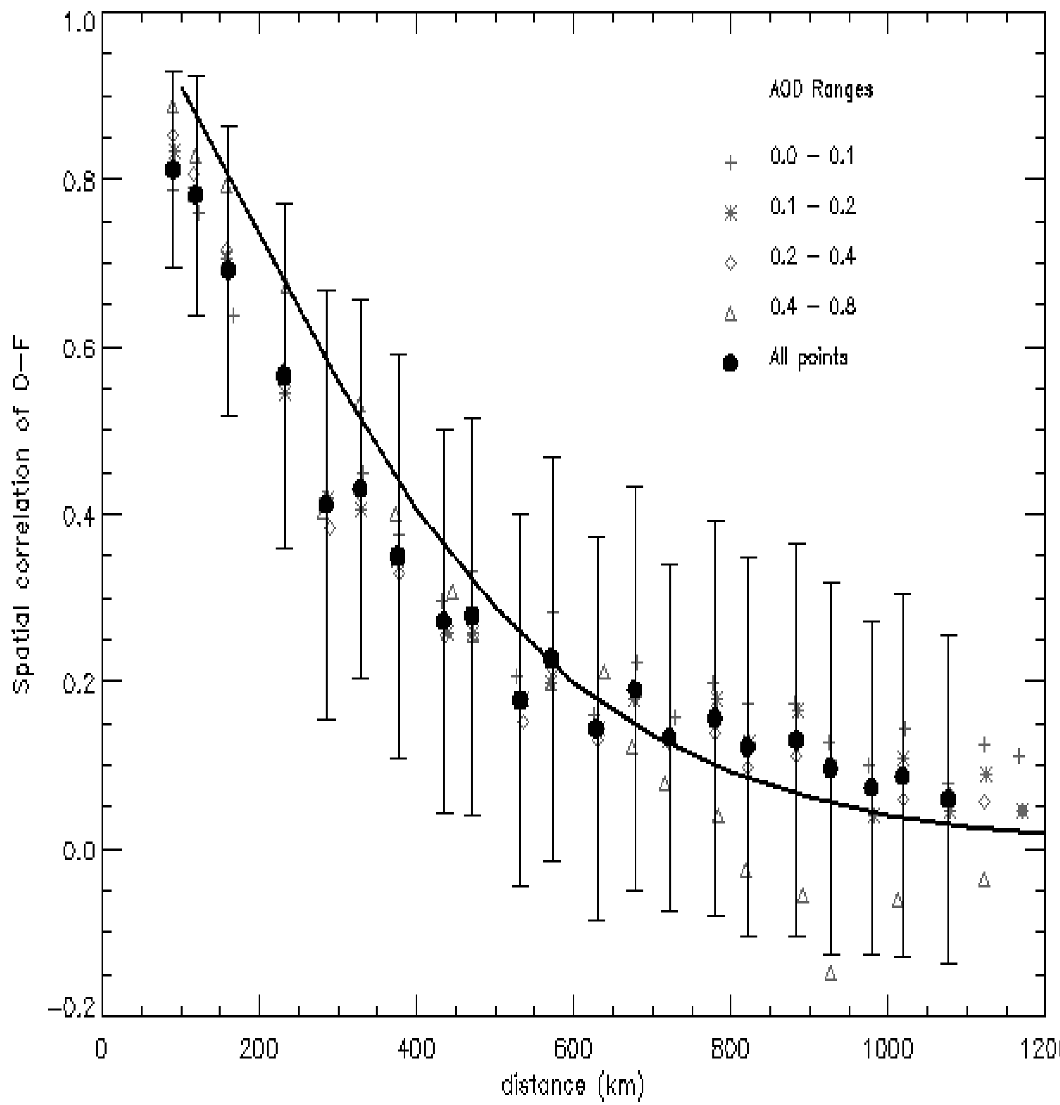
Sulfate AOT

Dust AOT

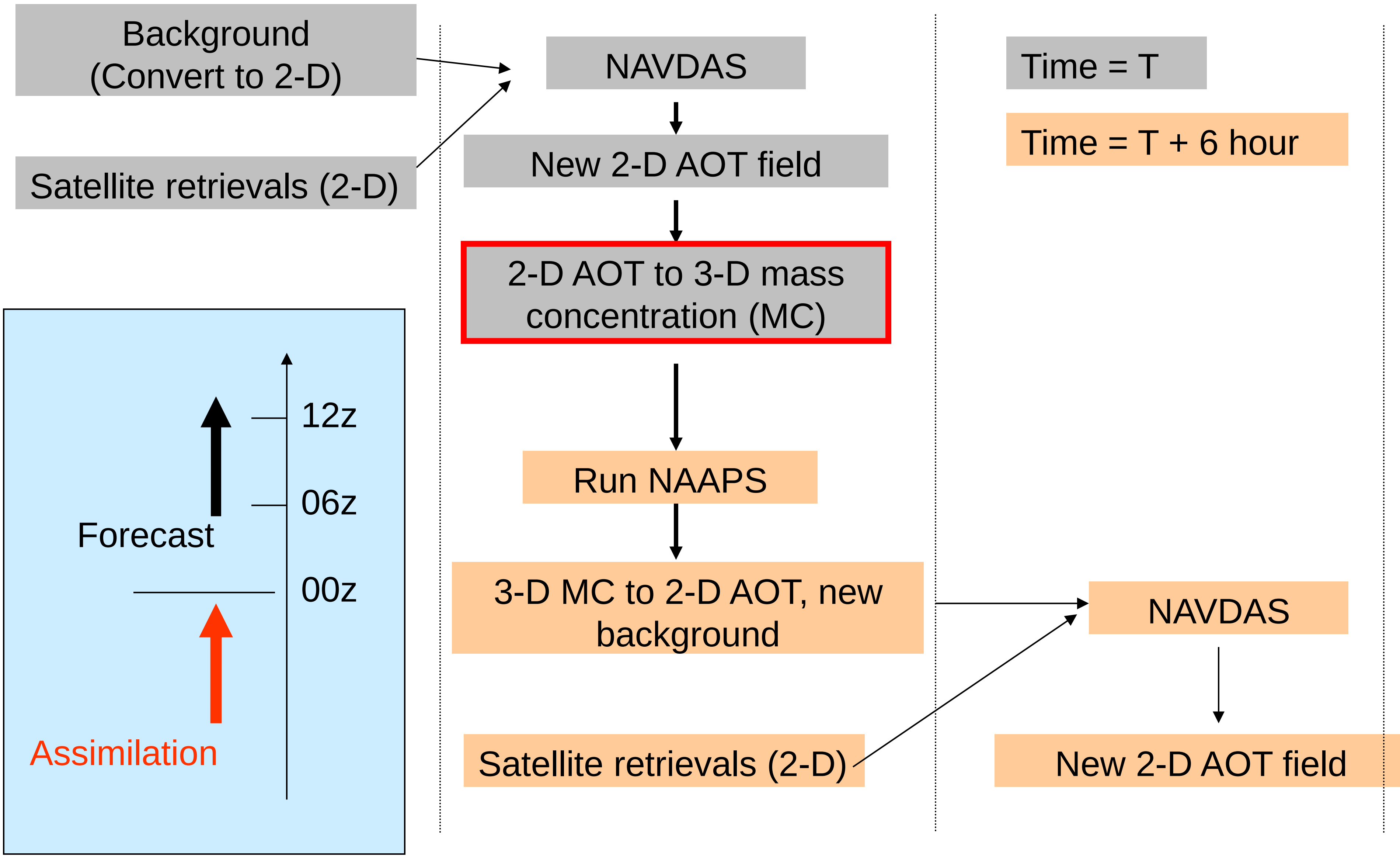
Smoke AOT

Example of aerosol optical depth data assimilation (NRL *NAVDAS-AOD, early version*)

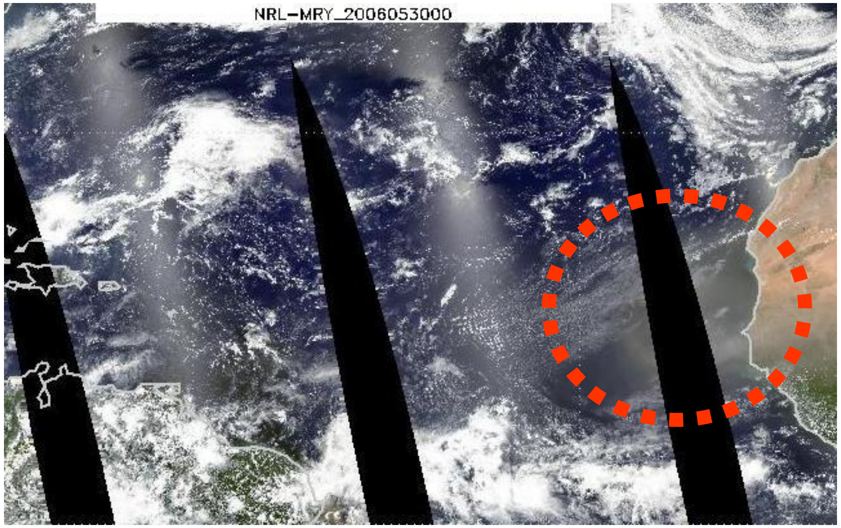
- For Jan-June 2006
- Combined observations from both Terra and Aqua MODIS level 3 aerosol products (new) are used
- Horizontal background error correlation model (SOAR)
- Background error correlation length is set to 200km
- No error correlation for satellite observations



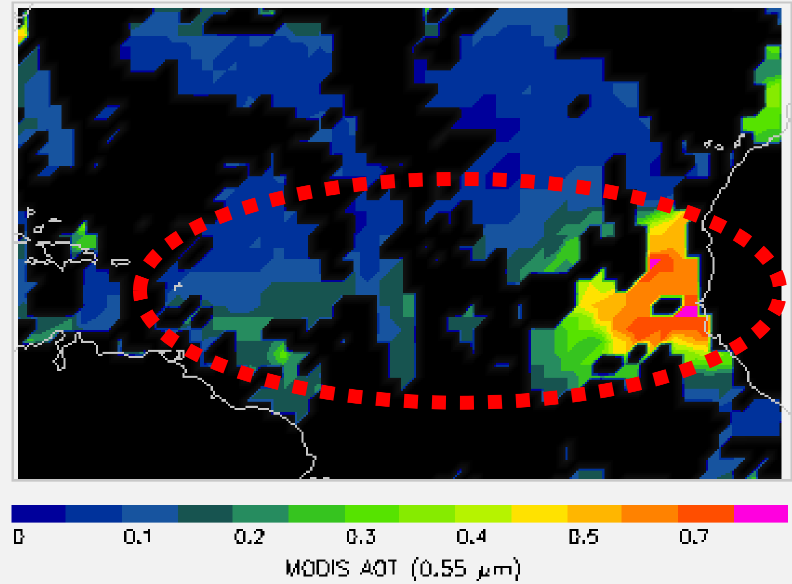
Example of aerosol optical depth data assimilation



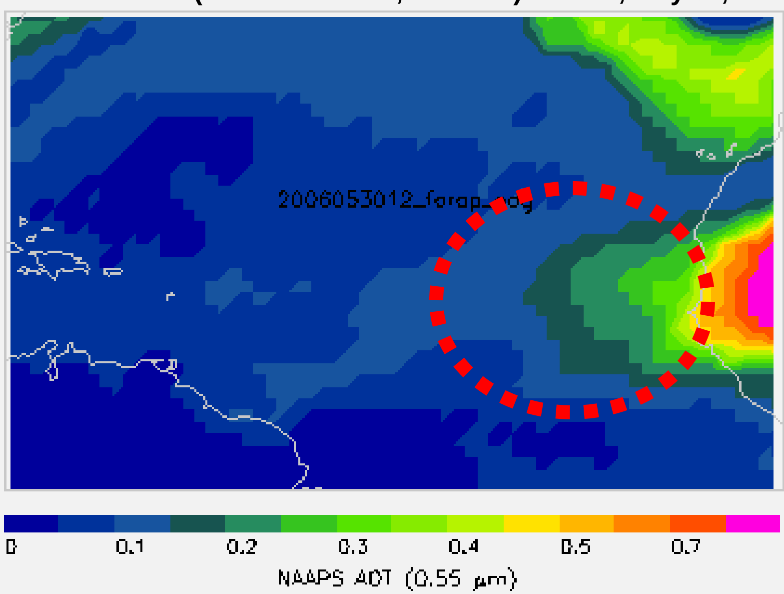
MODIS Level 1B RGB composite for May 30, 2006



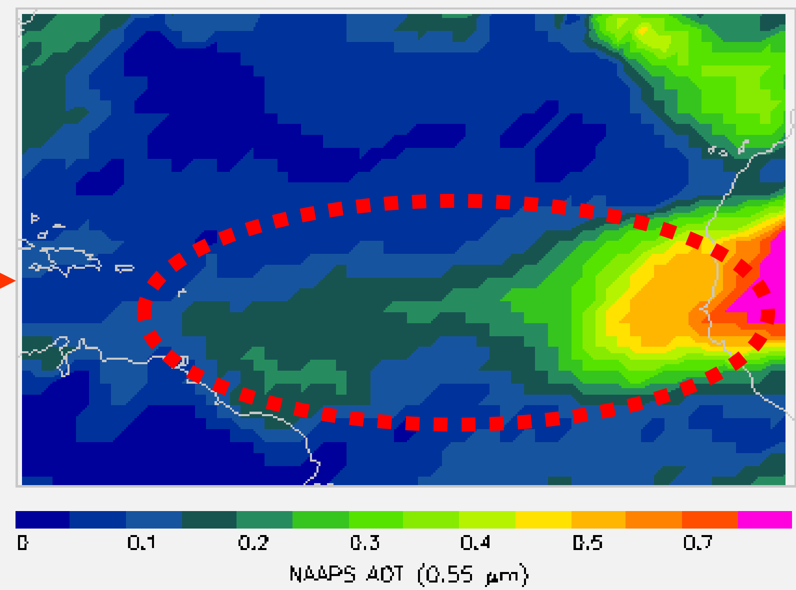
MODIS retrieved AOT for 09-15Z, May 30, 2006



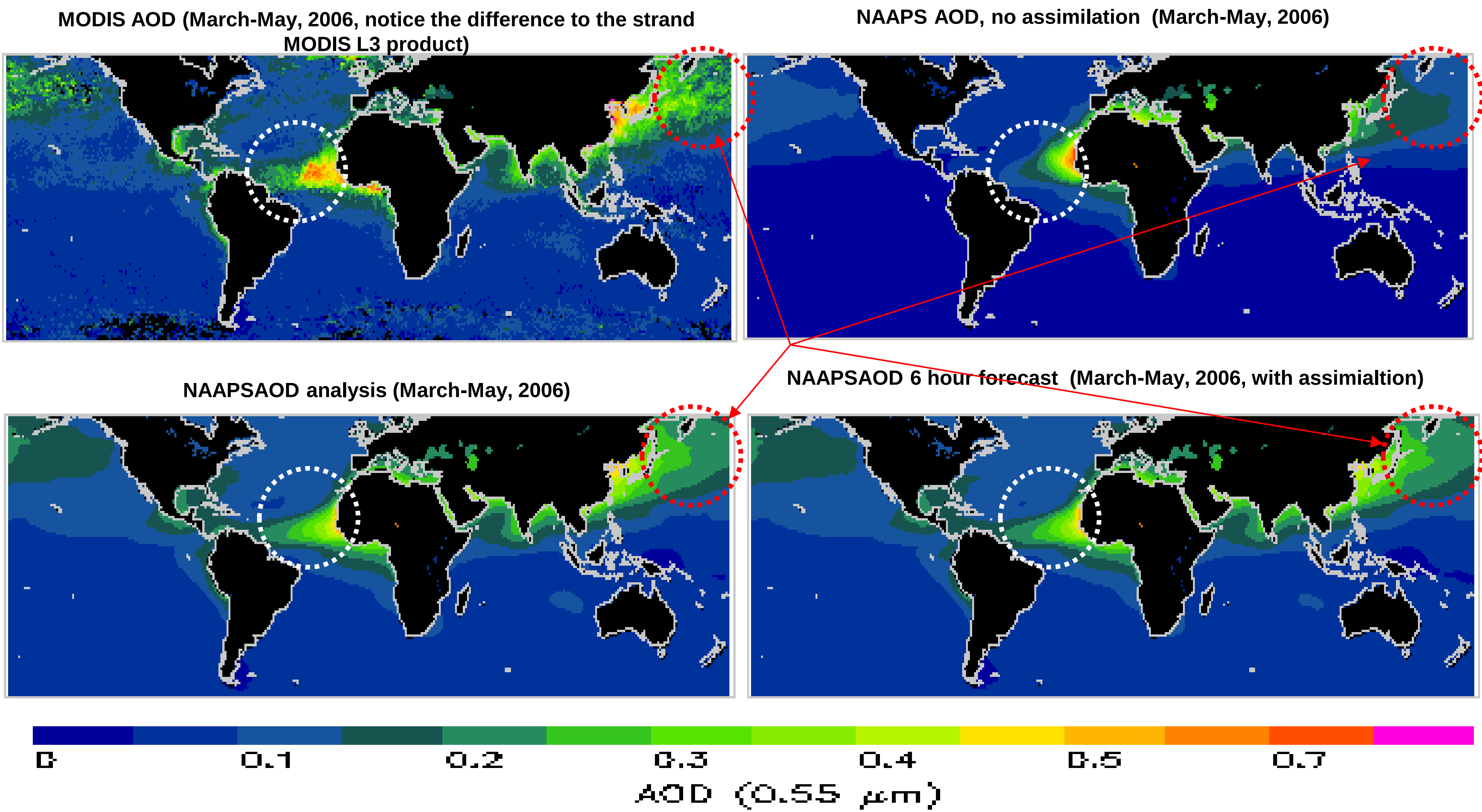
NAAPS AOT (no assimilation, forecast) for 12Z, May 30, 2006



NAAPS AOT analysis with 5 month data assimilation

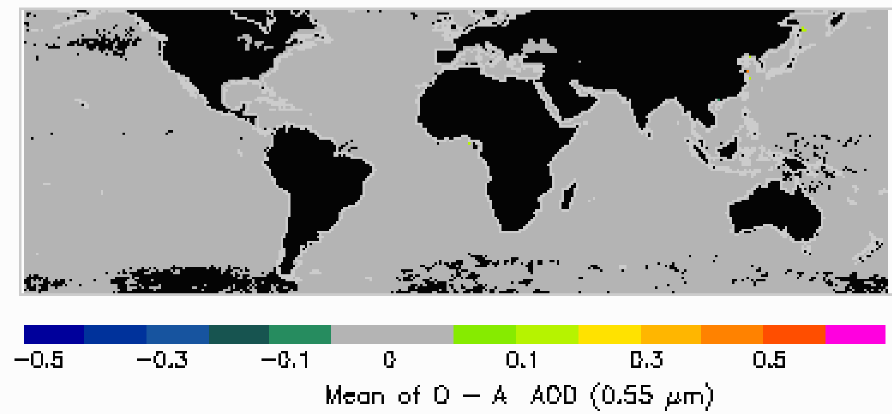


Example of aerosol optical depth data assimilation (NRL *NAVDAS-AOD, early version*)

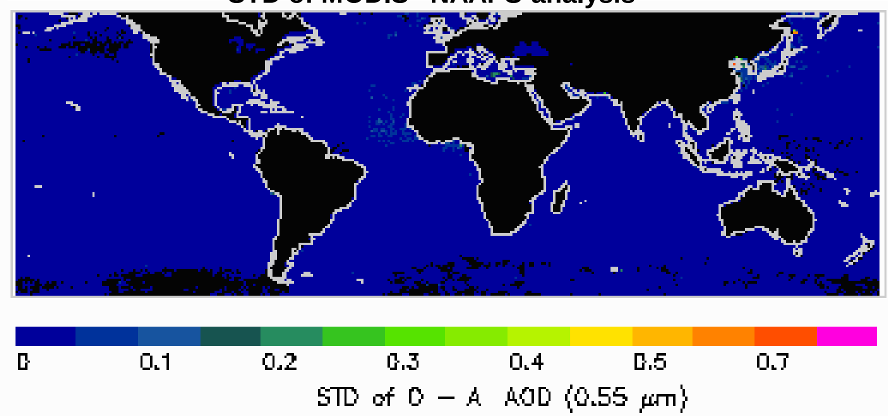


Example of aerosol optical depth data assimilation (NRL *NAVDAS-AOD, early version*)

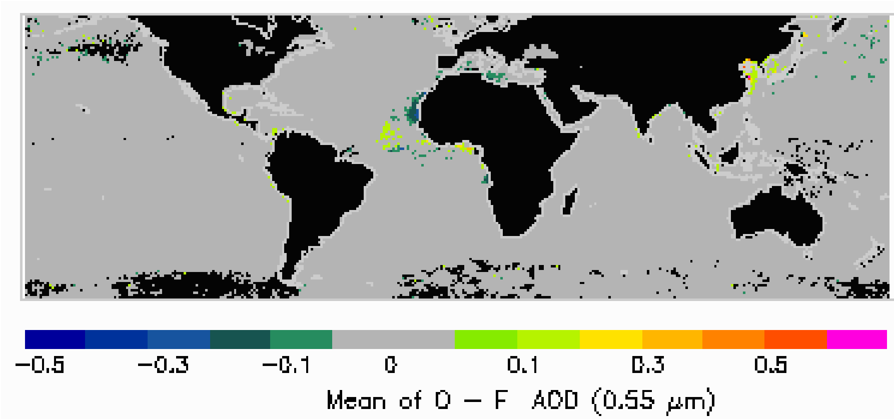
Mean of MODIS –NAAPS analysis



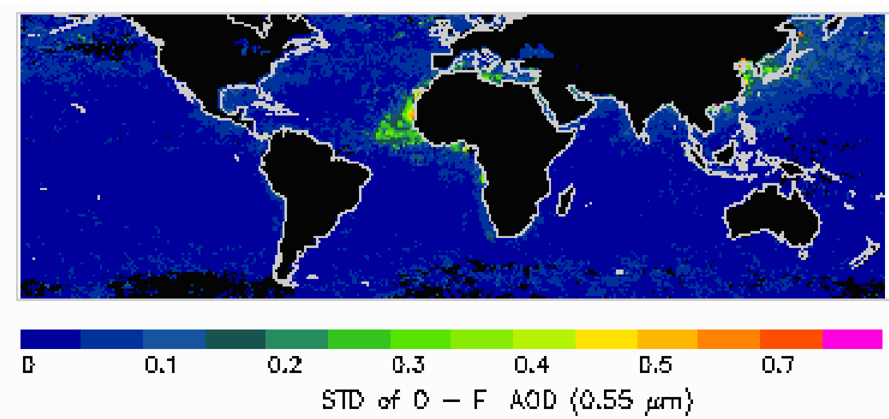
STD of MODIS –NAAPS analysis



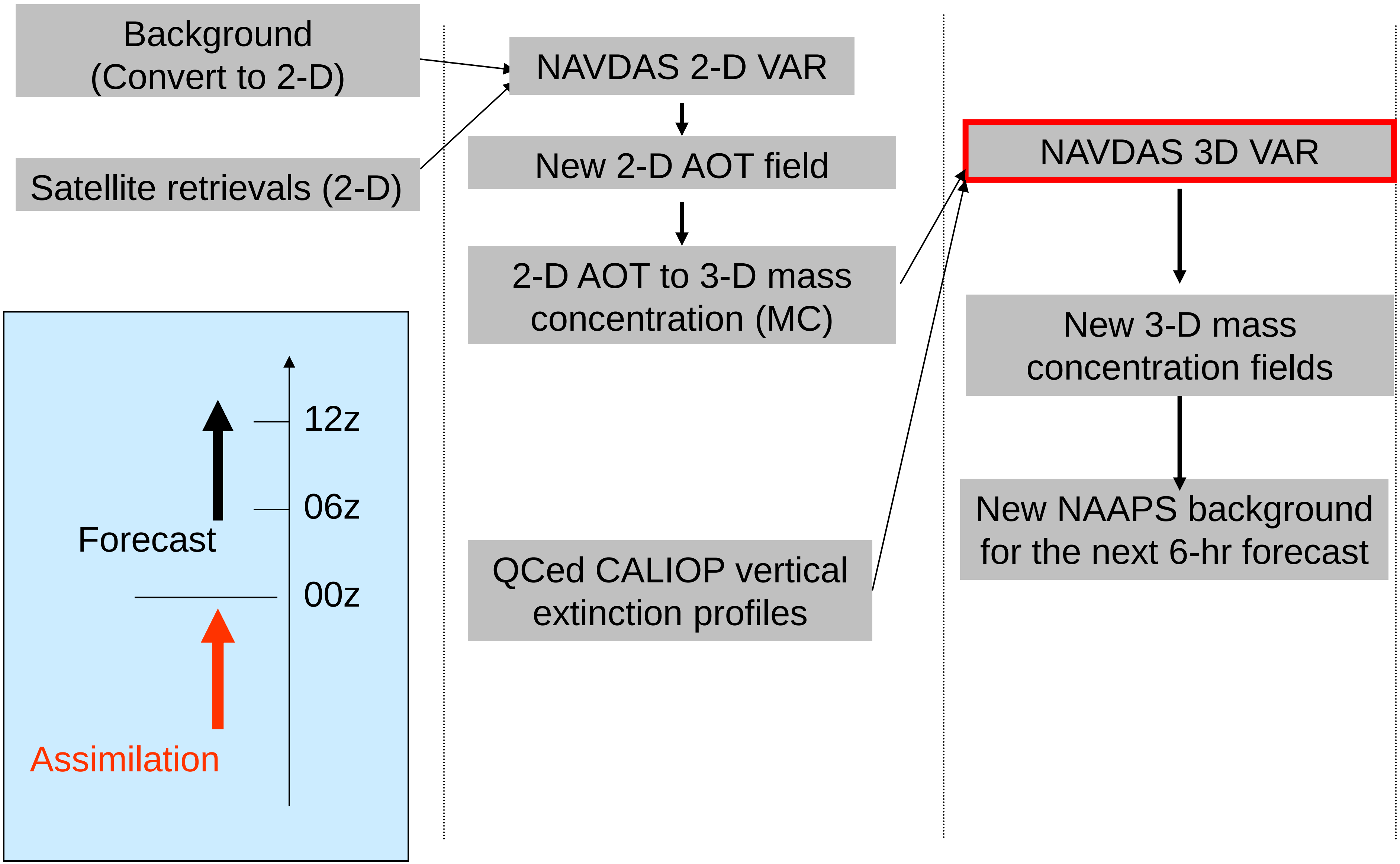
Mean of MODIS –NAAPS6 hour forecast



STD of MODIS –NAAPS6 hour forecast

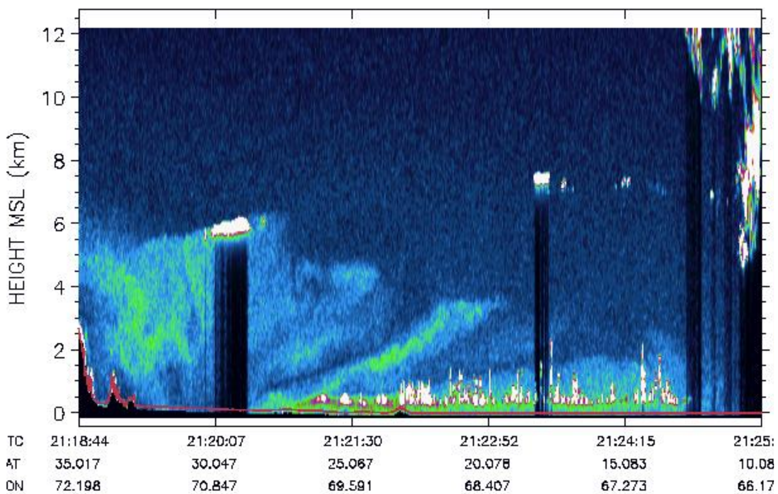


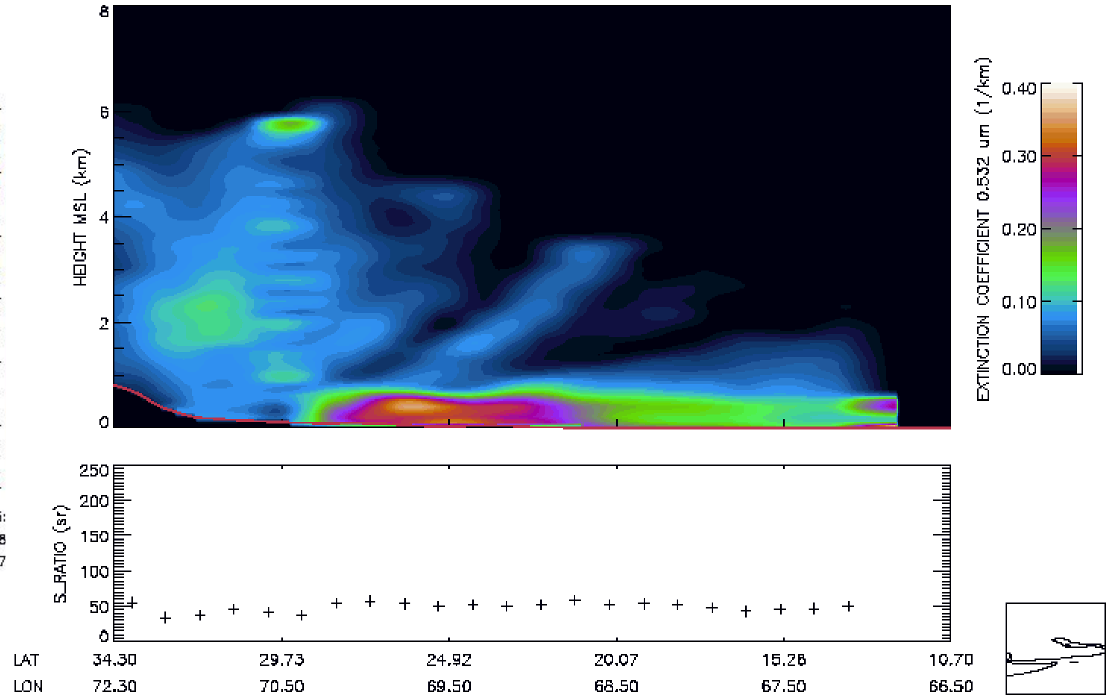
Example of CALIOP data assimilation (NRL *NAVDAS-AOD, early version*)



Example of CALIOP data assimilation (NRL *NAVDAS-AOD, early version*)

- NASA-generated Level 2 0.333 km CALIOP cloud detection product (cloud detection)
- 1° along-track averages (to fit with NAAPS resolution)
- Convert from attenuated backscatter to extinction coefficient



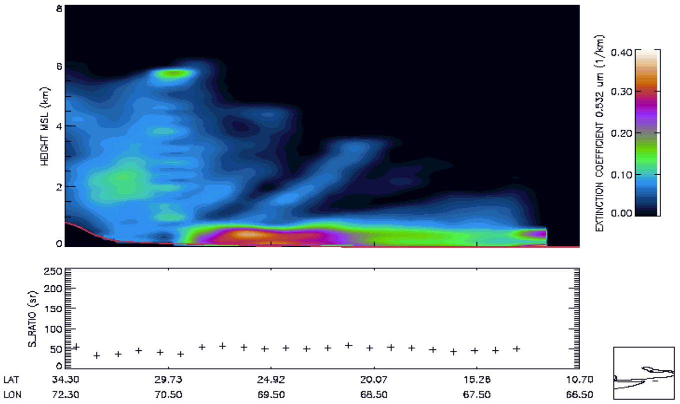


Campbell, J. R., J. S. Reid, D. L. Westphal, J. Zhang, E. J. Hyer and E. J. Welton, CALIOP aerosol subset processing for global aerosol transport model data assimilation, *J. Sel. Top. Appl. Earth Obs. and Rem. Sens.*, doi:10.1109/JSTARS.2010.2044868, *3*, 203-214, 2010.

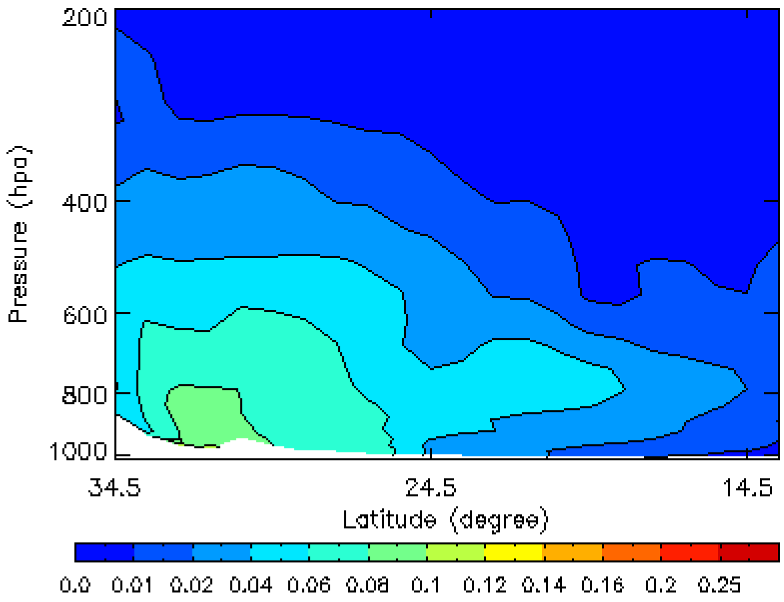
Example of CALIOP data assimilation (NRL *NAVDAS-AOD, early version*)

CALIOP extinction coefficient solution is constrained by model AOD after 2DVAR step (MODIS/MISR DA; *Campbell et al*., 2010). 3DVAR assimilation is then performed, and ...

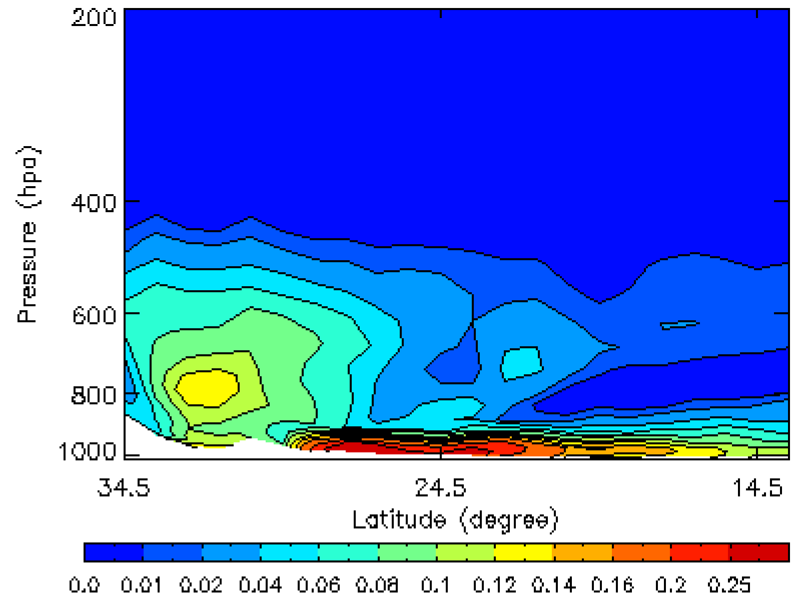
- Vertical distribution of aerosol is more reasonably depicted
- Analysis and forecast skill are improved significantly
- System compatible with future missions (EarthCARE, CATS)



2DVAR Analysis

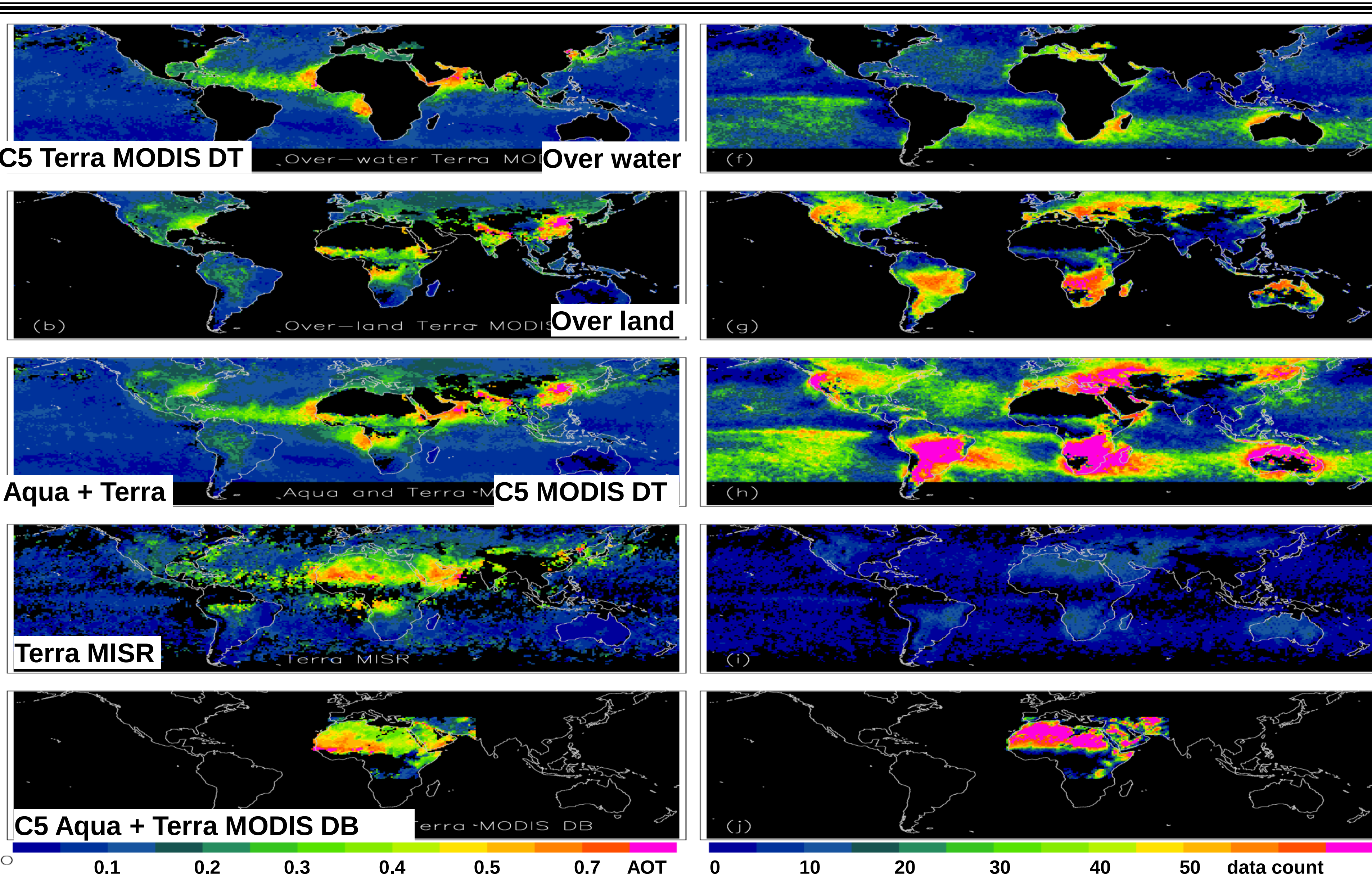


2D/3DVAR Analysis



Zhang et al., 2011

Example of multi-sensor assimilation



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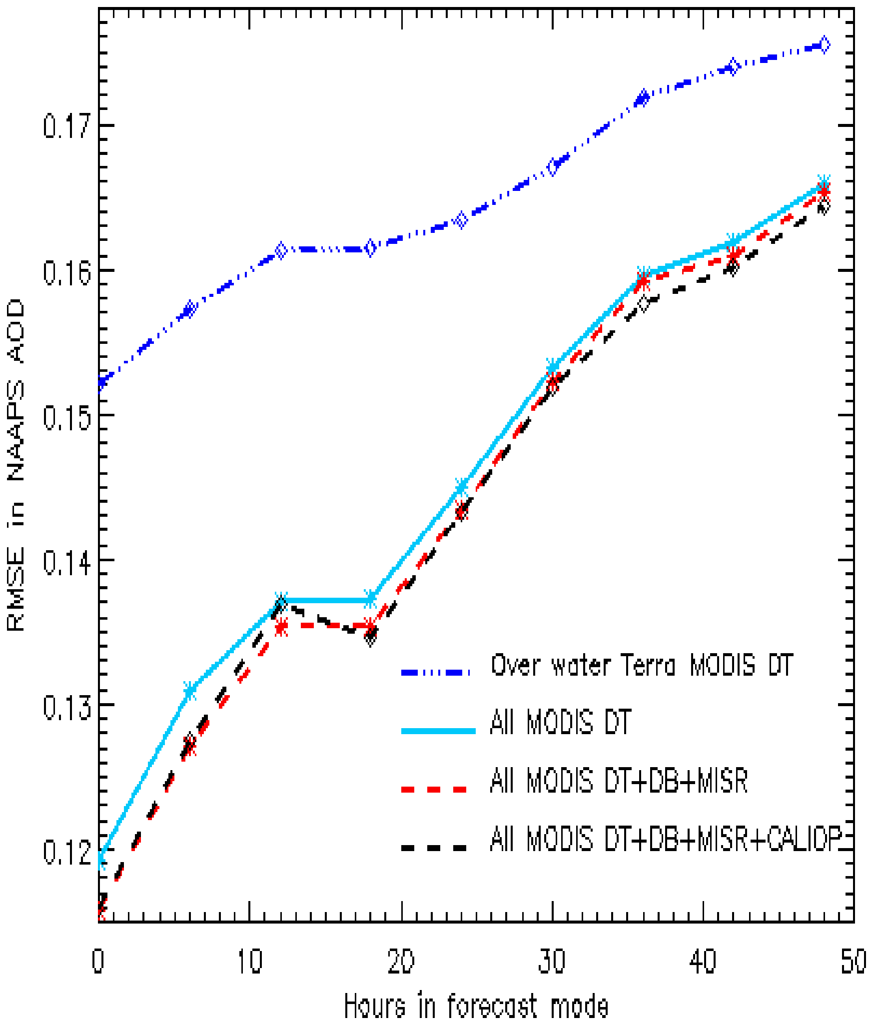
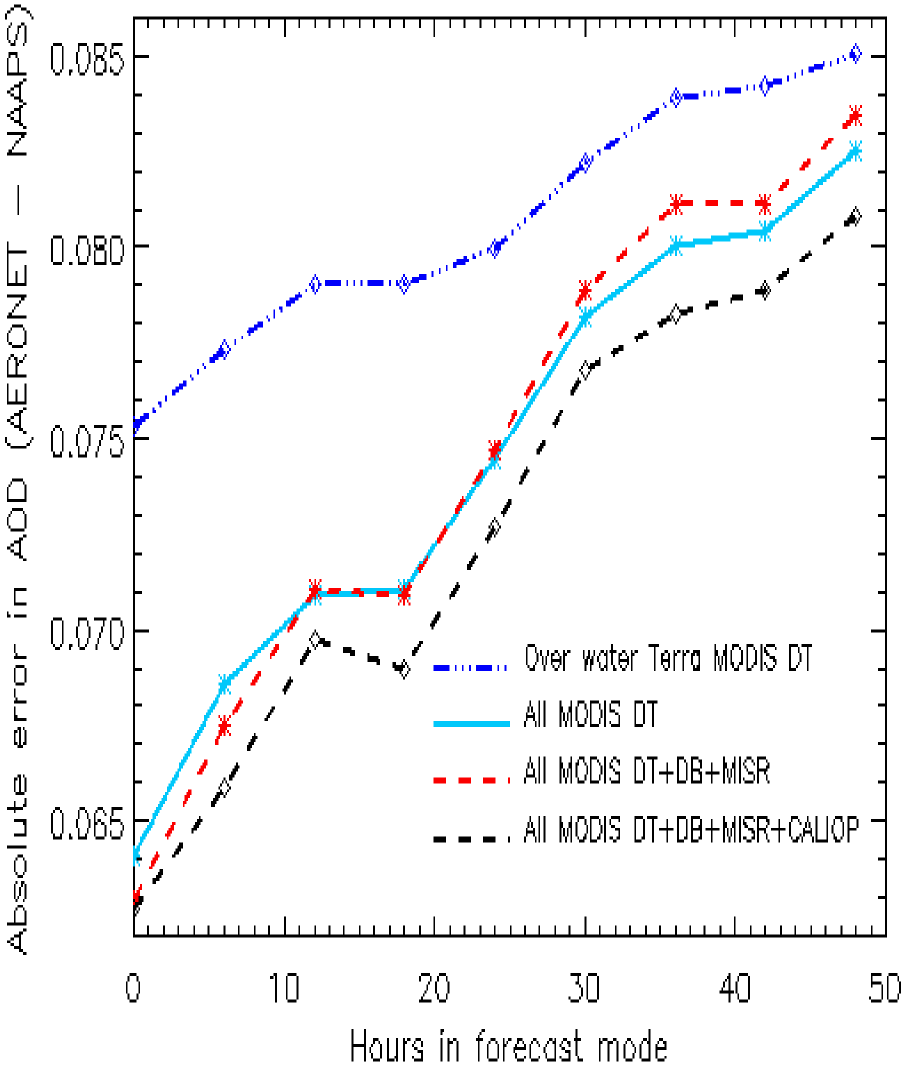
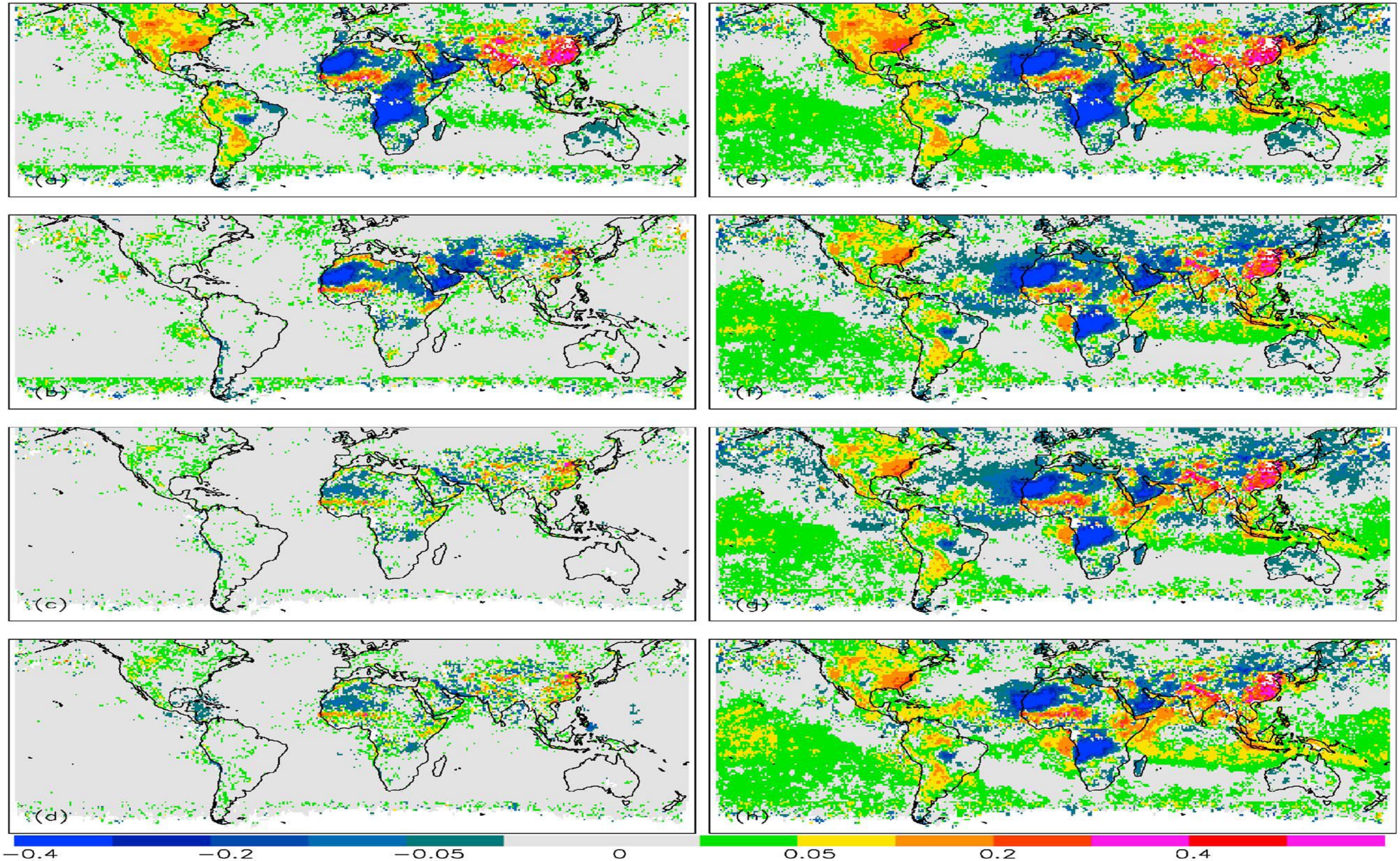




Zhang et al., 2014

Example of multi-sensor assimilation

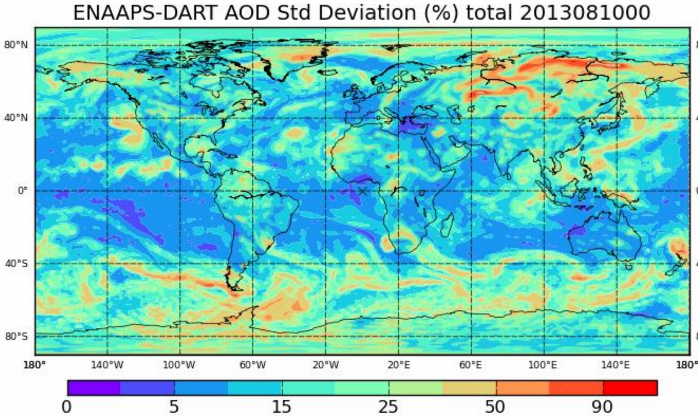


O-A/O-F (AOT, 550nm)

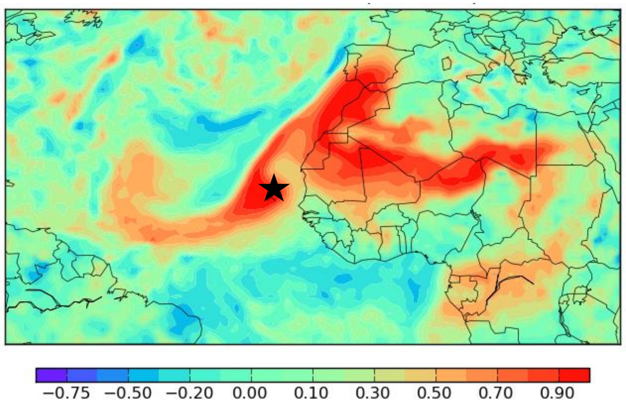
Zhang et al., 2014

ENAAPS-DART (Ensemble Kalman Filter)

1. Ensemble spread represents forecast uncertainty



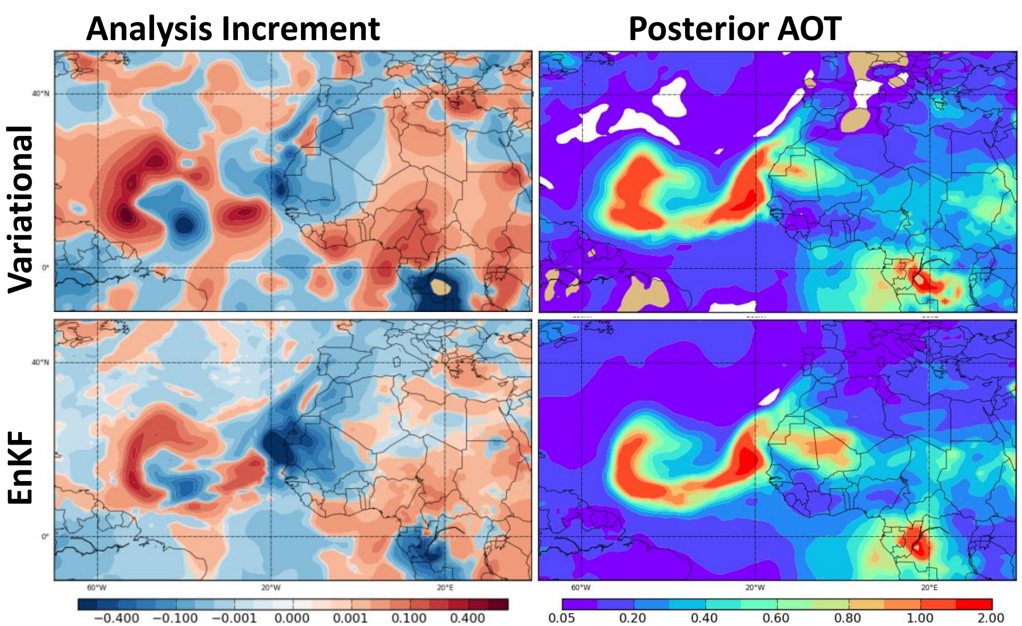
2. Ensemble covariance used to realistically spread observational information



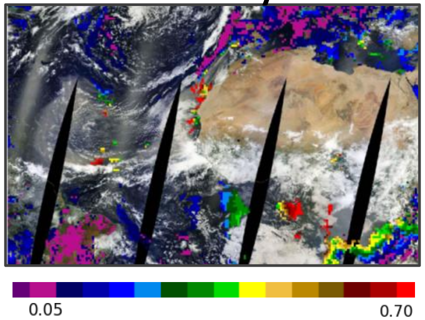
Correlation Fields for an Atlantic Dust Transport Event

20 member ensemble

3. More realistic corrections to model state fields ➡ capture sharper gradients

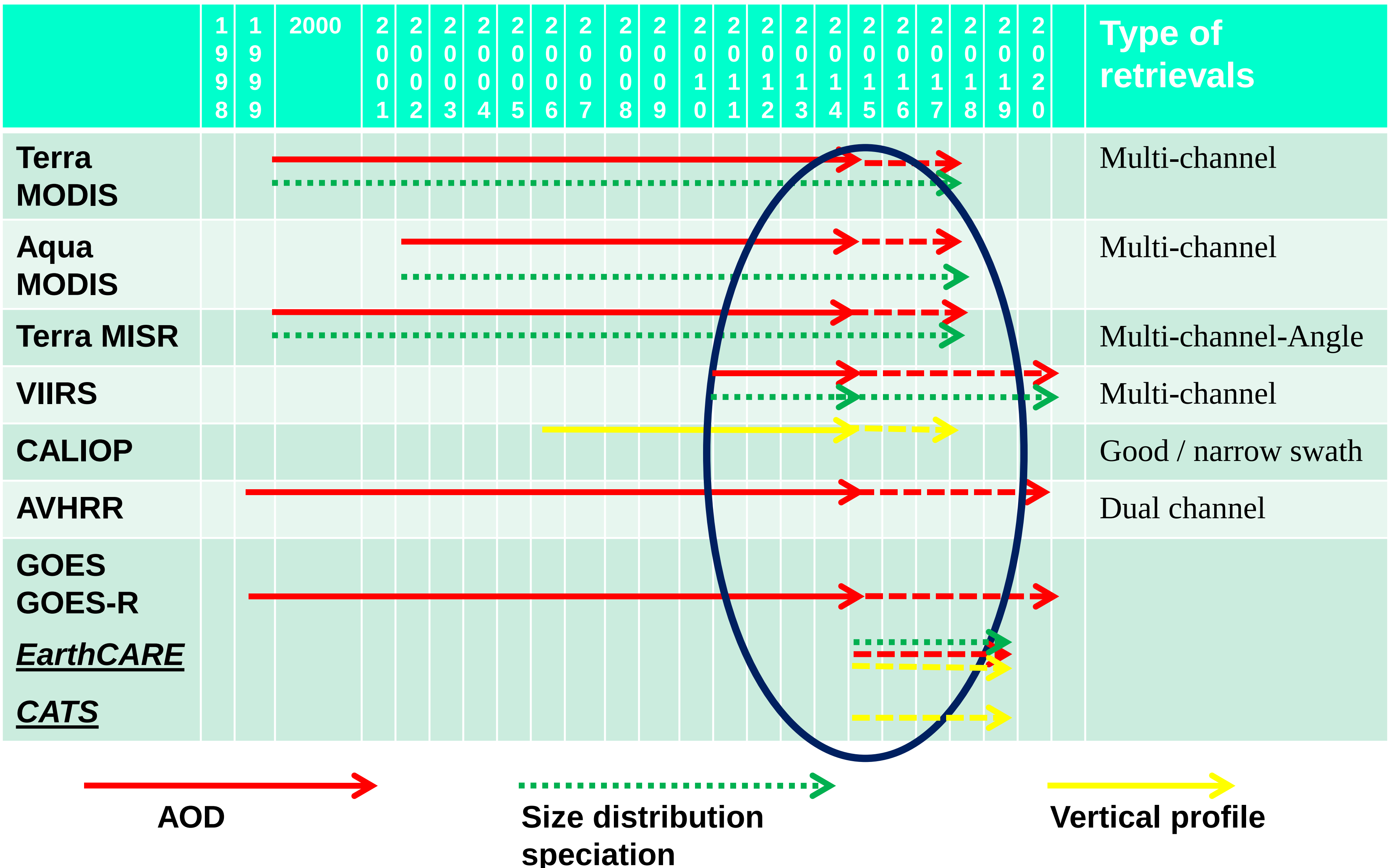


MODIS image with assimilated AOT overlay



Rubin et al. 2015

Road Map: Operational Aerosol Sensors (NASA and NOAA)



ICAP/ICAP-MME

http://icap.atmos.und.edu/

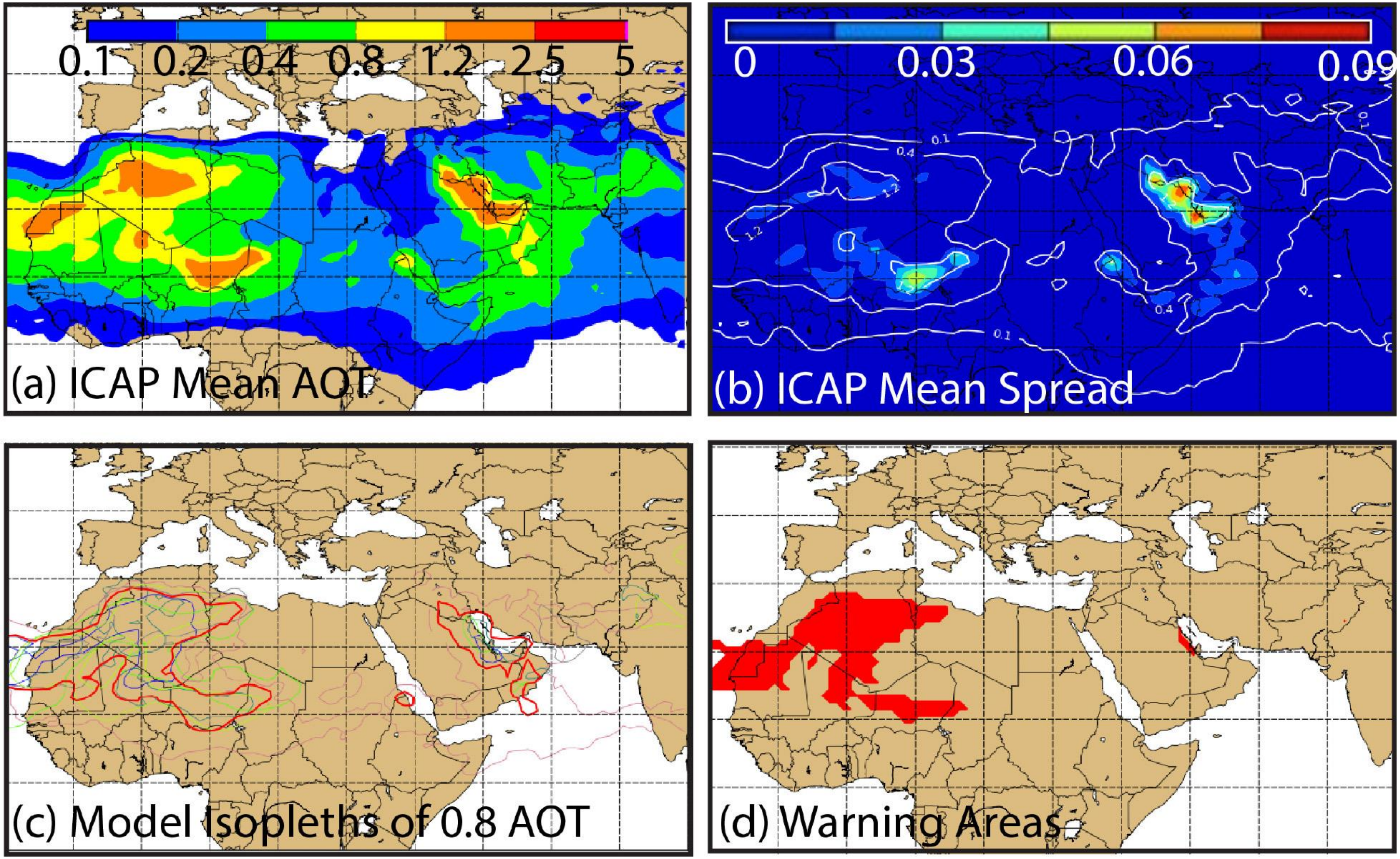
ICAP/ICAP-MME

International Cooperative for
Aerosol Prediction Multi-Model Ensemble (ICAP-MME)

	ECMWF-MACC	Navy NAAPS	JMA MASINGAR	NASA GEOS-5	BSC-NMMB	NOAA NGAC	UKMO
Aerosol type	Complete	Complete	Complete	Complete	Dust	Dust	Dust
Assimilation Scheme	4DVAR	2D VAR ENKF	ENKF	3D VAR			4DVAR ENKF

Sessions et al., 2015

ICAP/ICAP-MME



Sessions et al., 2015

Summary

- Aerosol modeling and forecast efforts have made a significant progress in the recent 10 years.
- Data quality is a critical issue for data assimilation
- Night time observations are needed. VIIRS observations bring hope.