Data assimilation for aerosol: a primer

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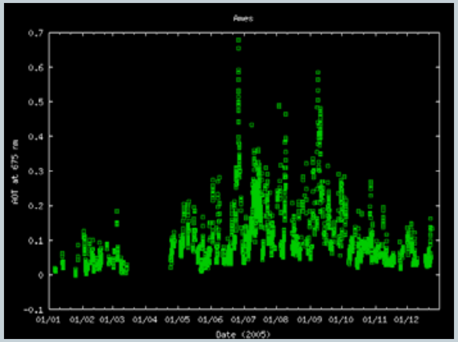
Overview

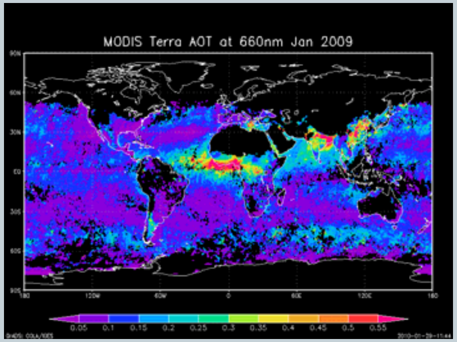
- Examples of data assimilation
- What is data assimilation ?
  - Concepts
  - Basic theory
  - Different methods
- Data assimilation for aerosol
  - A brief history
  - Particular issues
  - Applications
  - Future

Why assimilation?

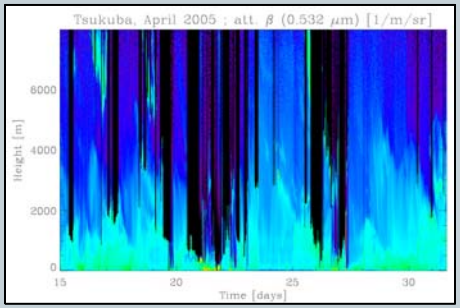
AERONET



MODIS



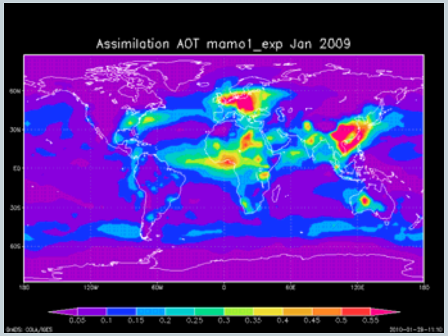
LIDAR



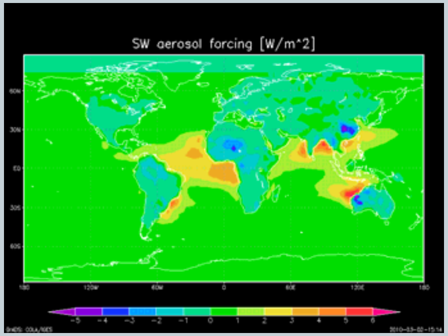
- Observables
- Errors
- Sampling

?

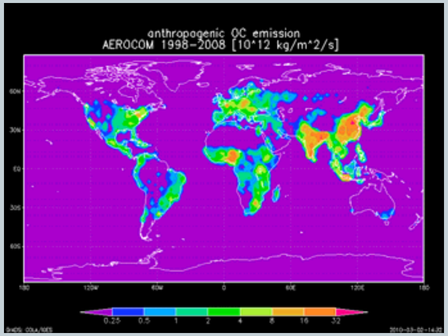
- Simulation
- Errors
- ‘Black box’



AOT etc.



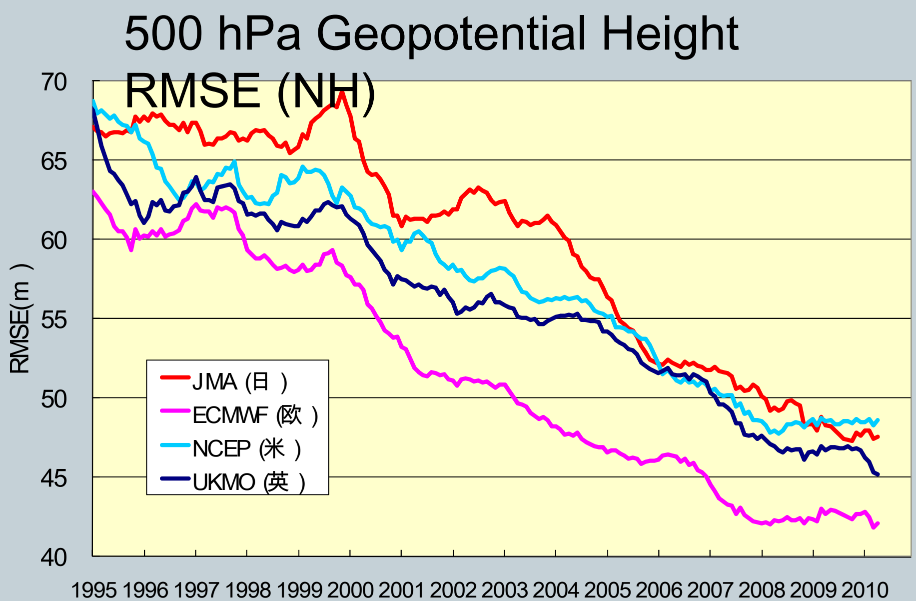
ARF



emission

Examples in the atmospheric sciences

- Meteorological reanalysis and forecast

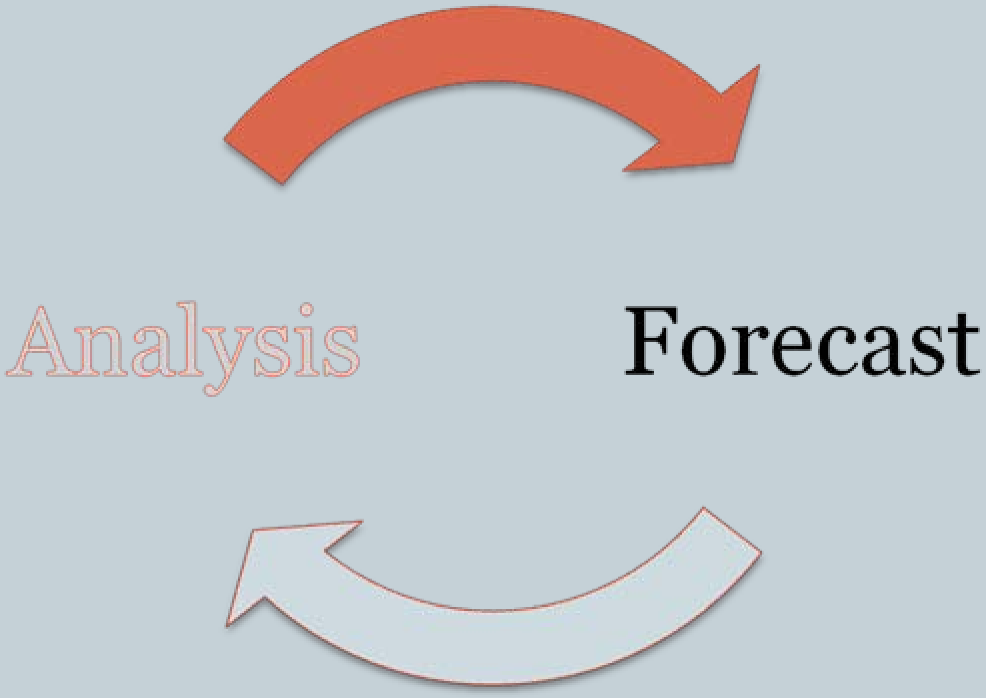


Courtesy
Y. Sato (T. Miyoshi)

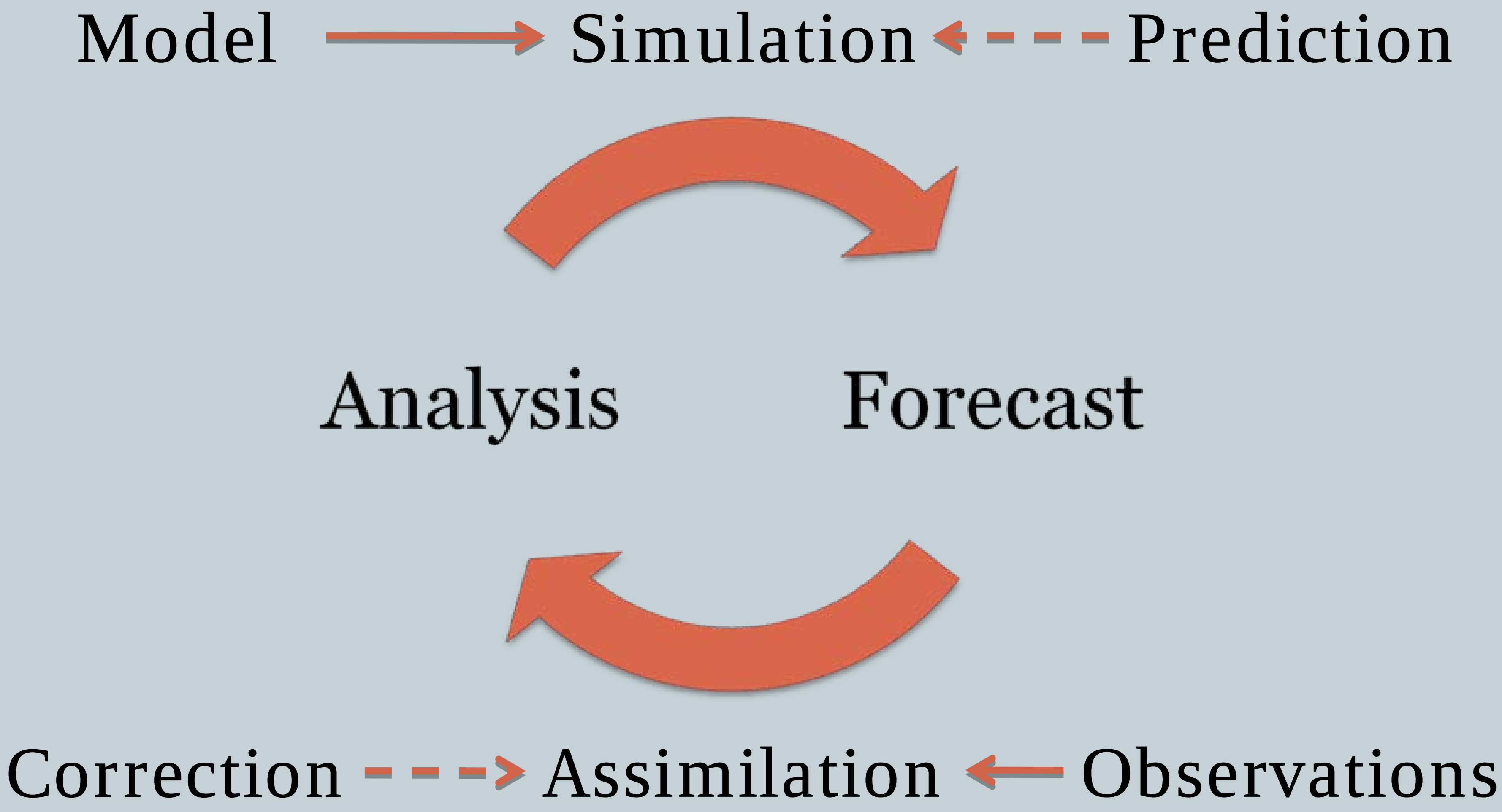
- CO_2 emission inversion (global)
- Storm forecasts (regional, 1 km resolution)

The analysis – forecast cycle

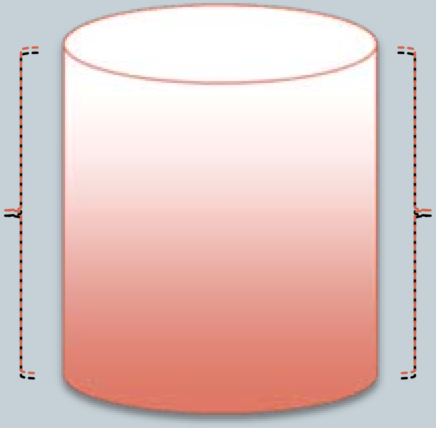
Model → Simulation



The analysis – forecast cycle



Assimilation as an optimal estimate

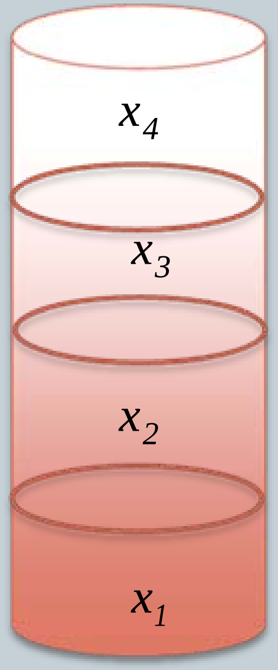


This is the common weighted average of two values, which is said to be *optimal* because the estimated error of this average is *minimal*.

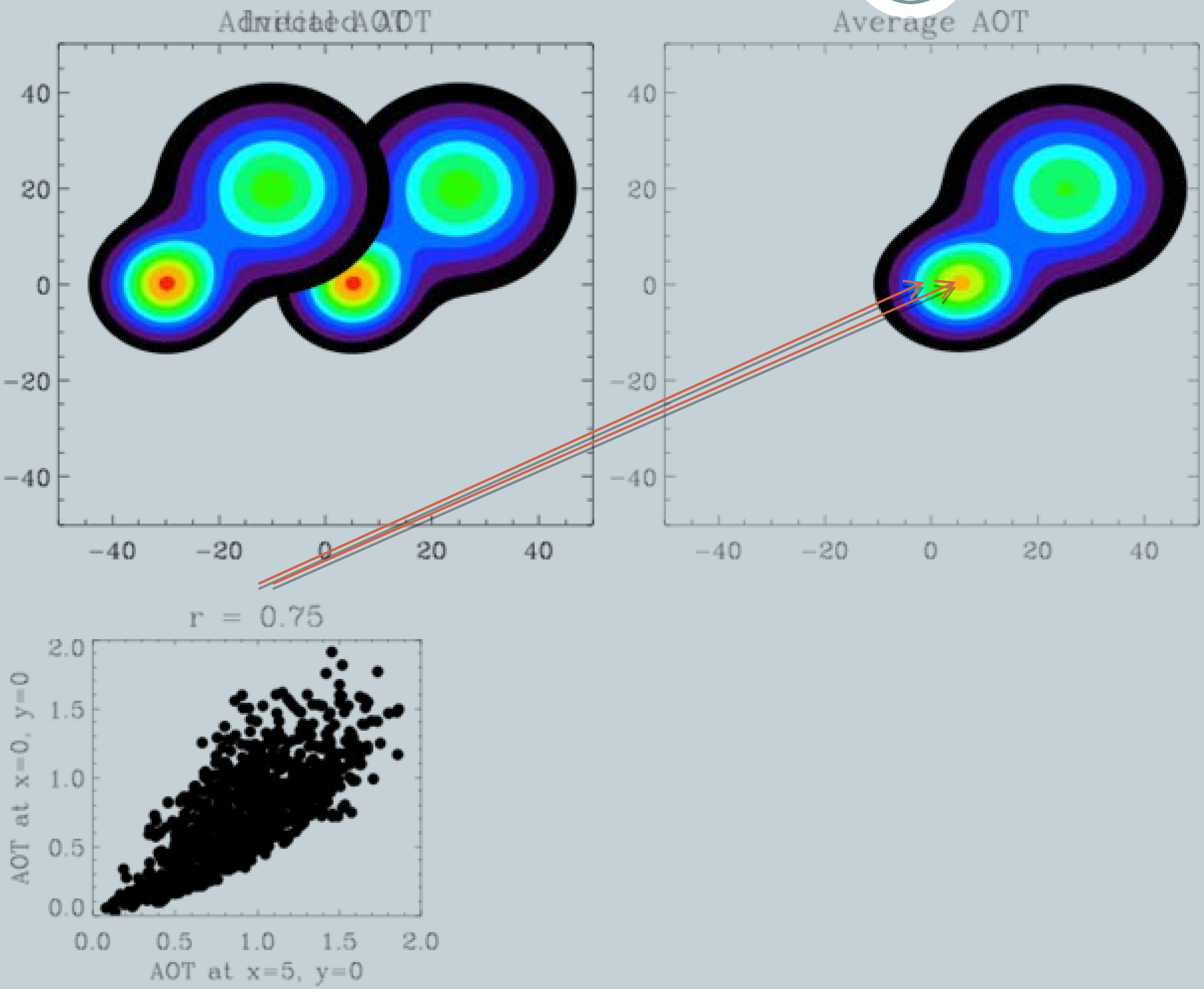
This may seem an non-sensical example, but bear with me.

Concepts: definitions

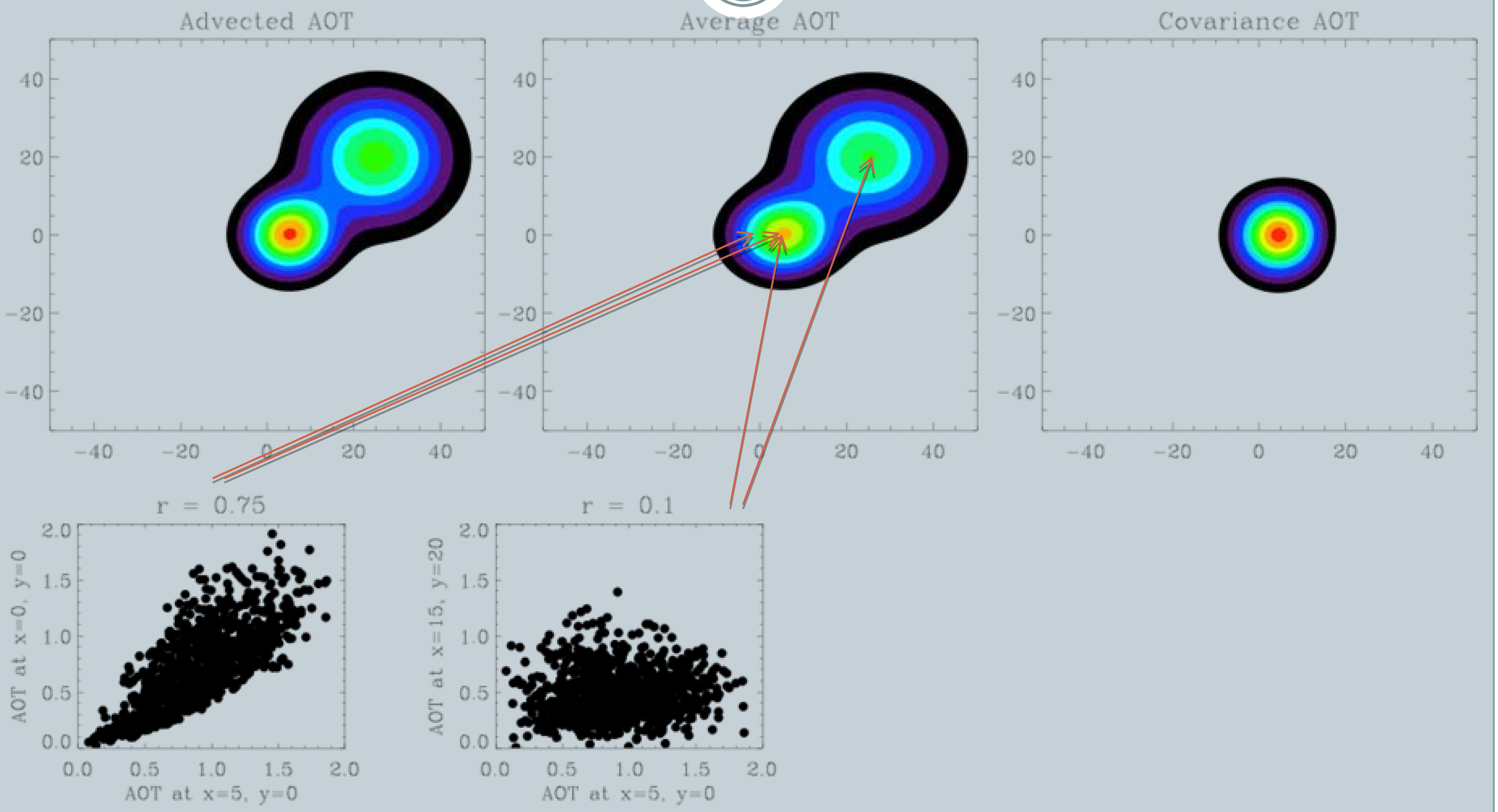
- Model state: atmospheric state of aerosol, **x**
- Observations: diverse set of measurements, **y**
- Observational error covariance, **R**
- Observation operator, **H**
- Innovation, **y - H x**



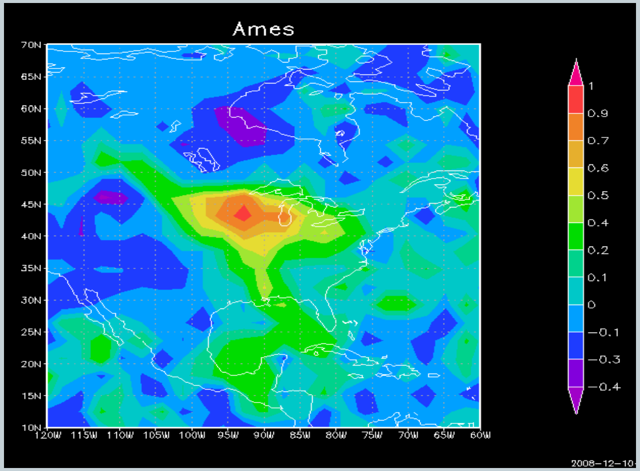
Concepts: model prediction covariance



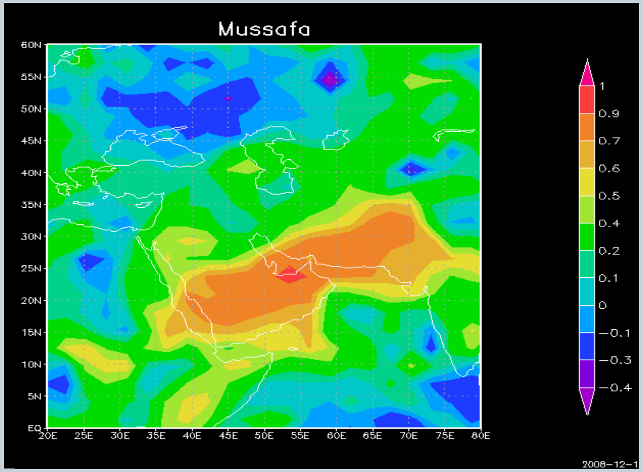
Concepts: model prediction covariance

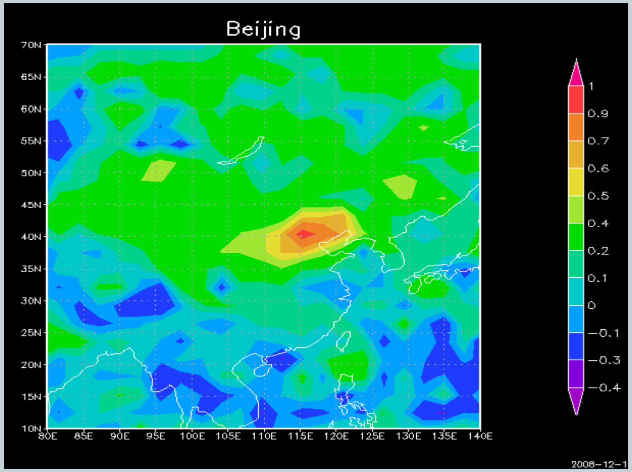


Aerosol model prediction covariance



Shown are AOT correlations (normalized covariances) at a single time but different locations for the SPRINTARS aerosol model (areas are similar in size), calculated using a perturbed ensemble simulation.





Data assimilation methods

1) The (ensemble) Kalman Filter equation:

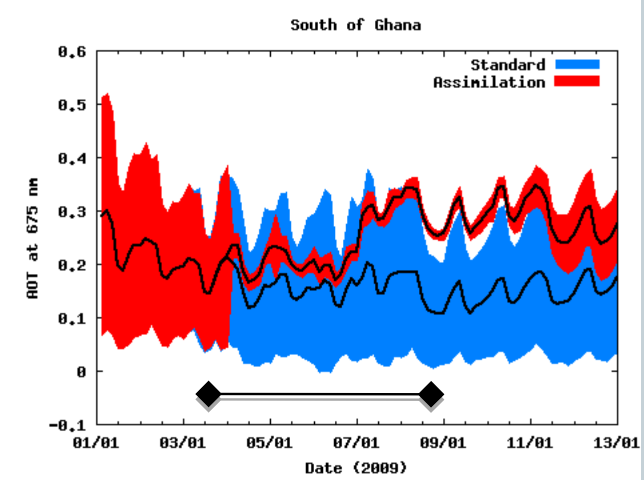
Identical for linear models

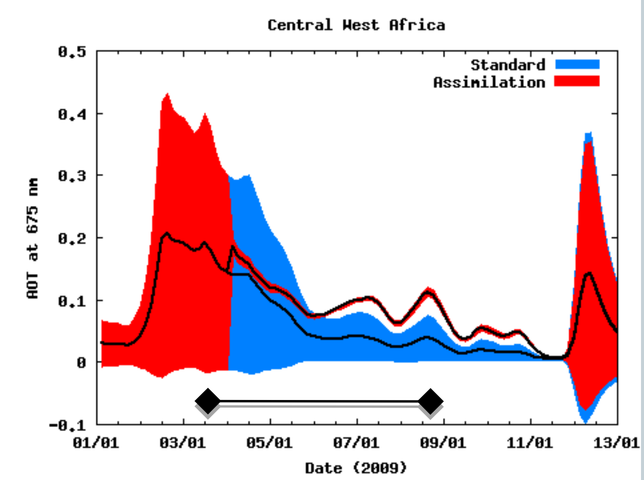
2) The variational approach (xD-VAR):

xD-VAR vs EnKF

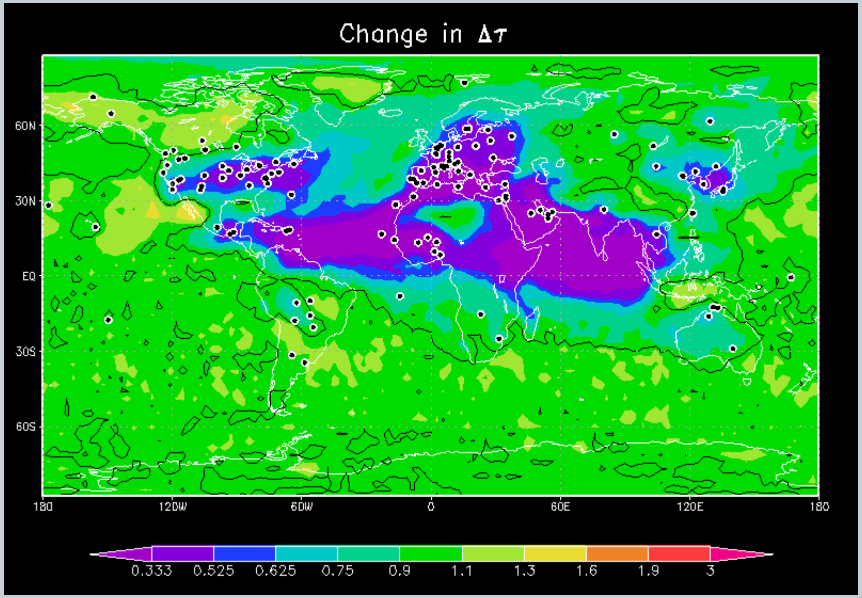
- Actual advantages depend on implementation: everybody cuts corners and builds bridges!
- xD-VAR:
  - allows non-linear model and observation operators.
  - cost function may have additional terms (constraints)
  - 4D-VAR: analysis is solution to model equations
- EnKF:
  - uses flow-dependent model prediction covariant
  - allows easier development and maintenance
- 4D-VAR and EnKF competitive (e.g. Kalnay et al. 2007)
- In NWP, a hybrid scheme, building on the individual strengths of both methods, seems the future

Ensemble Kalman filter





The prediction error in AOT (ensemble spread) evolves naturally, i.e. according to the physics of the model and the information content of the observations.

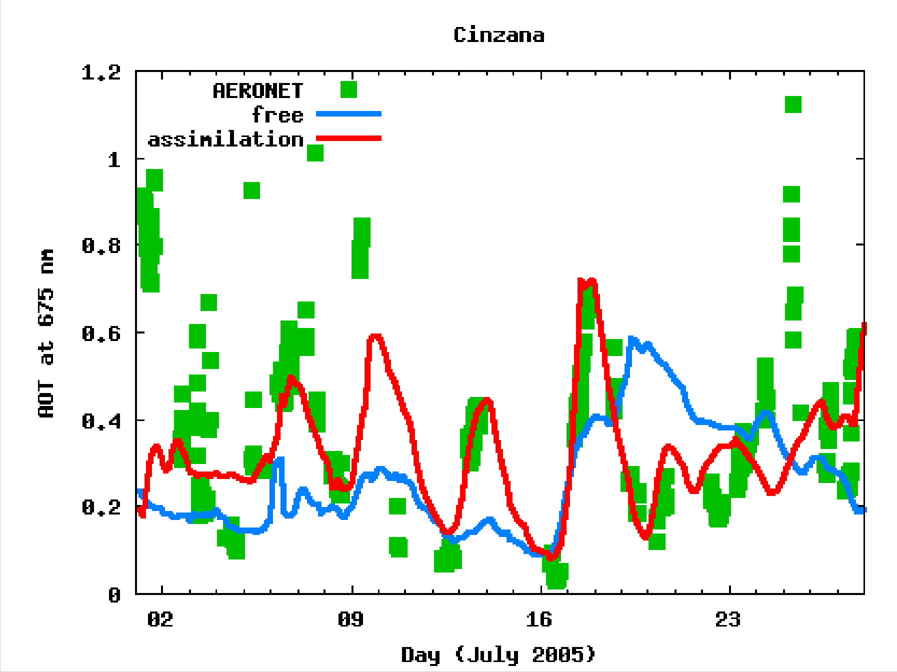


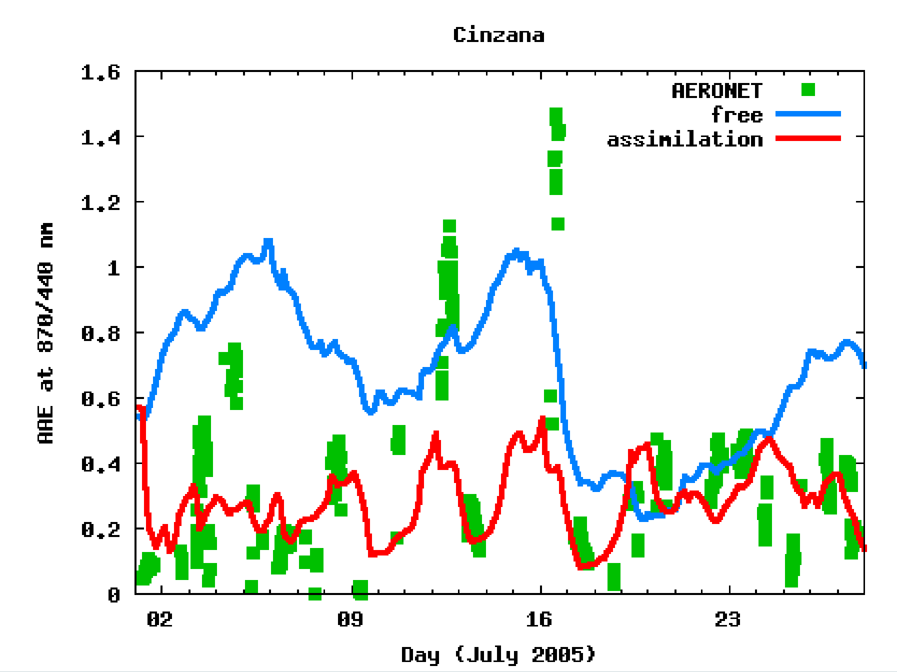
A brief history of aerosol assimilation

Year	Authors	Scheme	Observations	Comments
2000	Fonteyn et al.	4D-VAR	SAGE-II extinction	Stratospheric aerosol
2001	Collins et al.	OI	AVHRR AOT	
2005	Henzing et al.	OI	ATSR AOT	
2005	Yu et al.	OI	MODIS AOT	
2005	Weaver et al.		radiances	
2007	Generoso et al.	3D-VAR	POLDER AOT & fine mode	Size information
2008	Zhang et al.	3D-VAR	MODIS AOT	NRL
2008	Zhou et al.	3D-VAR		Dust only
2008	Lin et al.	EnKF	PM_{10}	Dust only
2008	Yumimoto et al.	4D-VAR	ADNET extinction	LIDAR, dust only
2009	Benedetti et al.	4D-VAR	MODIS AOT	ECWMF
2009	Tombette et al.	OI	EMEP PM_{10}	
2010	Sekiyama et al.	EnKF	CALIOP backscatter	LIDAR
2010	Schutgens et al.	EnKF	AERONET AOT & AE	Size information
2011	Zhang et al.	3D-VAR	CALIOP extinction	LIDAR, NRL

Example: AERONET assimilation

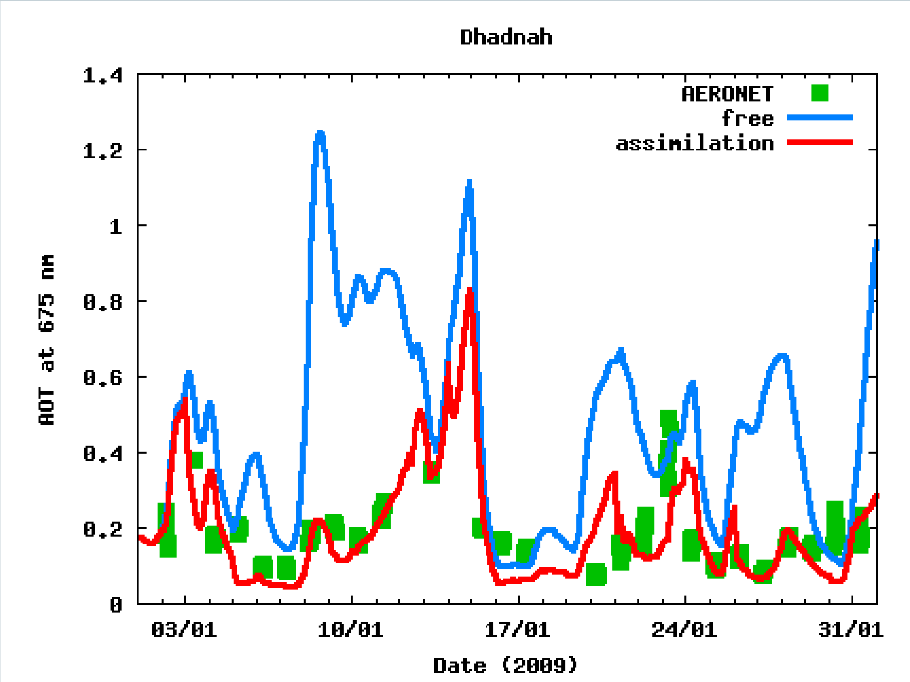
- AERONET AOT & AE assimilated in an EnKF
- Overall improvement, especially for dust storms
- Limited global coverage





Example: CALIOP assimilation

- CALIOP nighttime *att. backscatter* assimilated in an EnKF
- Improves agreement with AERONET *AOT*
- CALIOP covers mainly free troposphere

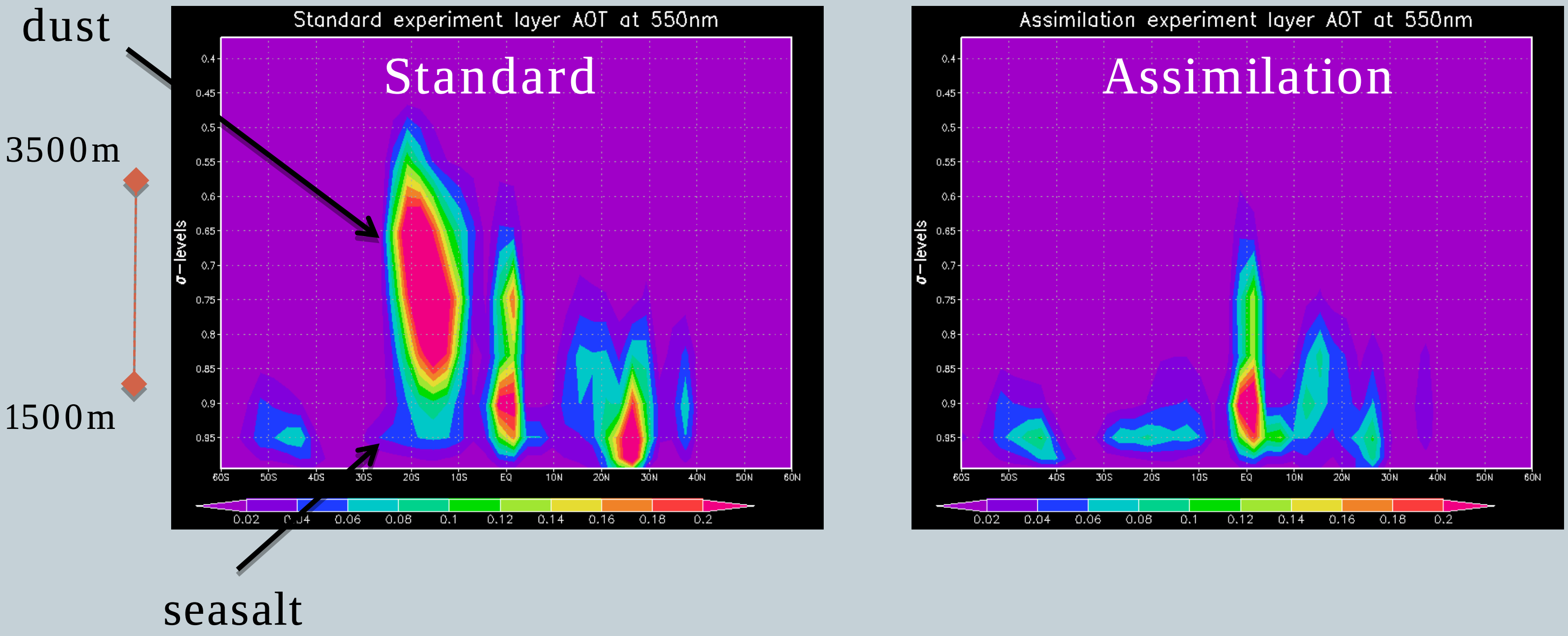


with E. Oikawa, Tokyo U.

Example: MODIS assimilation

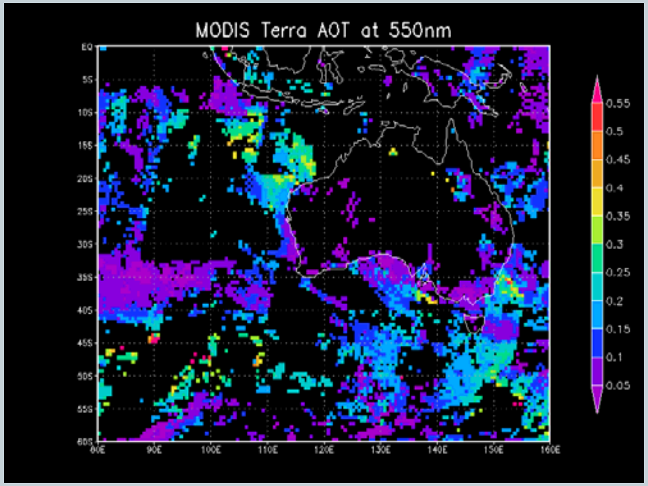
- MODIS AOT and AERONET AOT & AE are assimilated in an EnKF
- The forecast and analysis can have different profile shapes

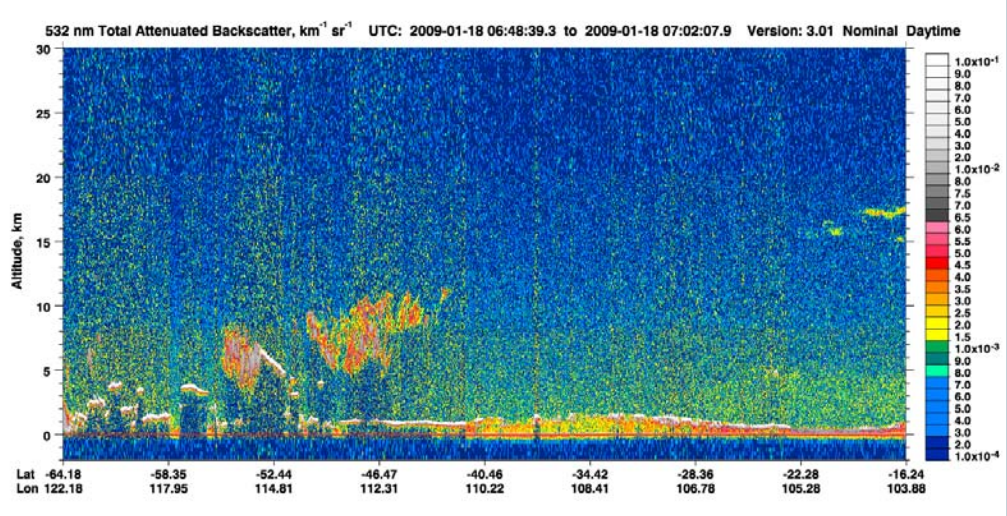
Off the west coast of Australia



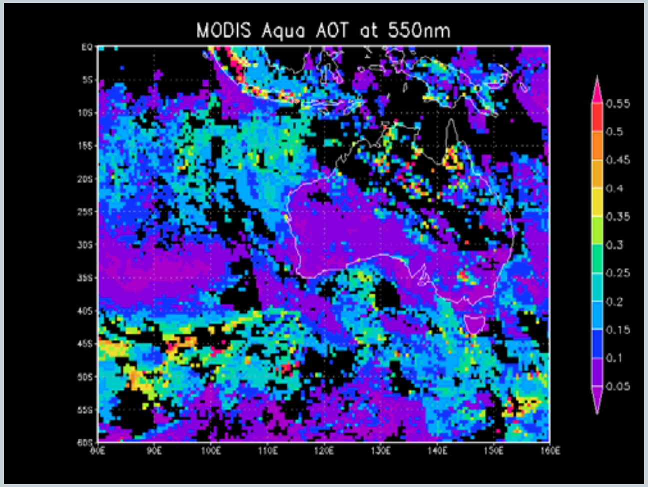
Various observations i.c. previous experiment

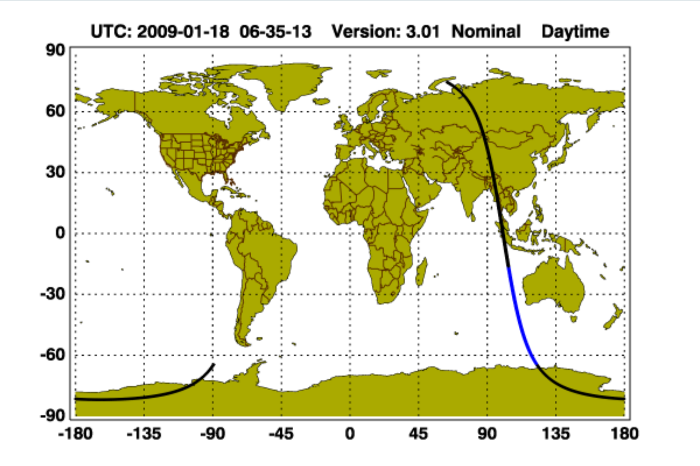
Assimilated





For comparison



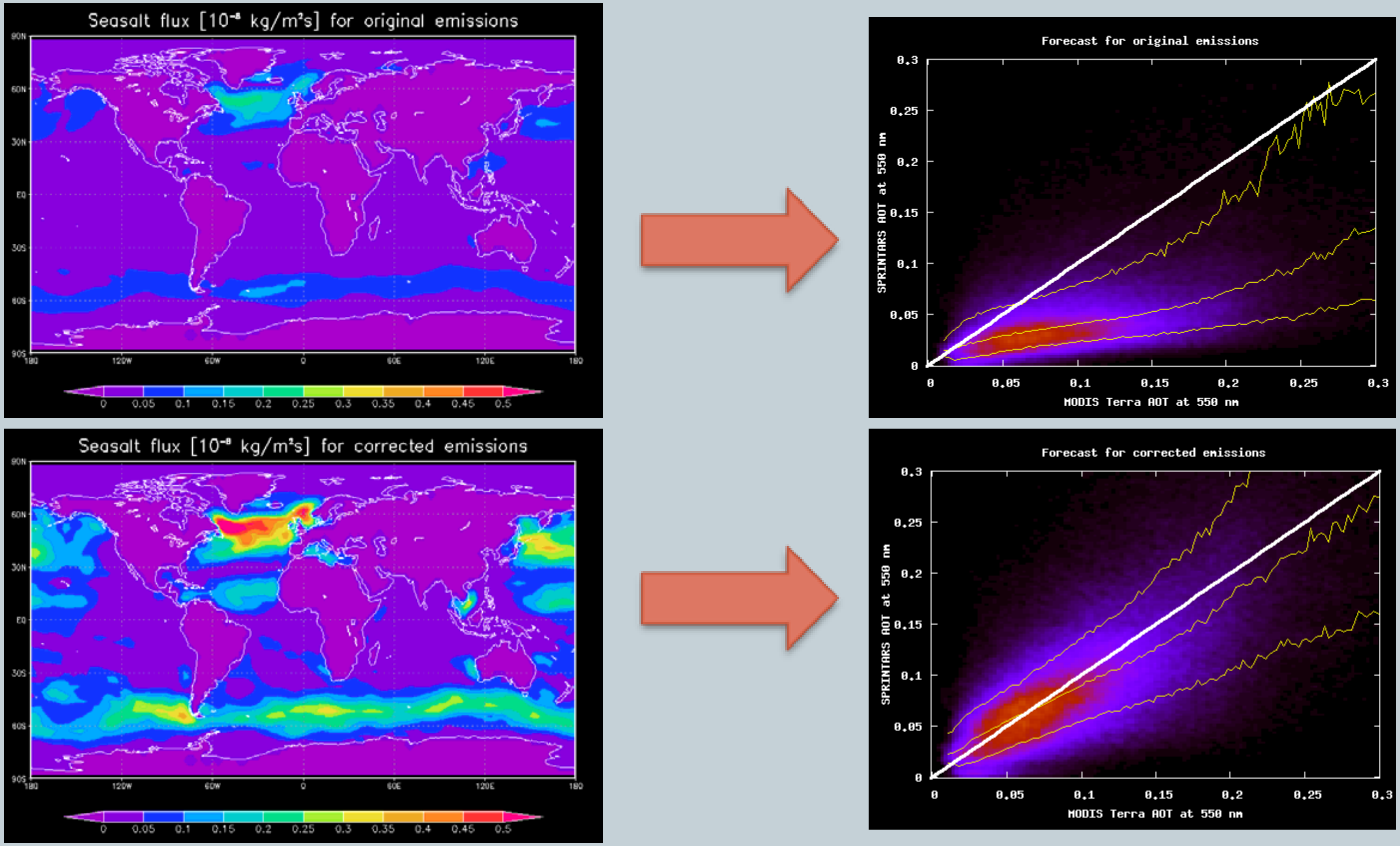


Example: parameter estimation

- MODIS AOT is used to infer emissions with an EnKF

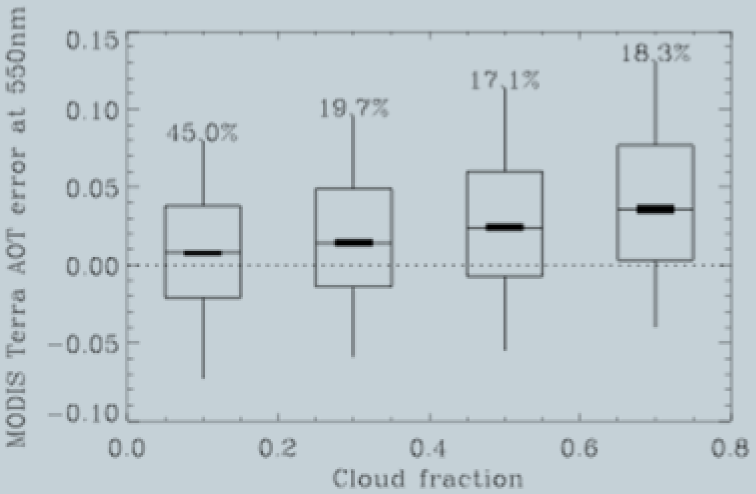
Original emissions

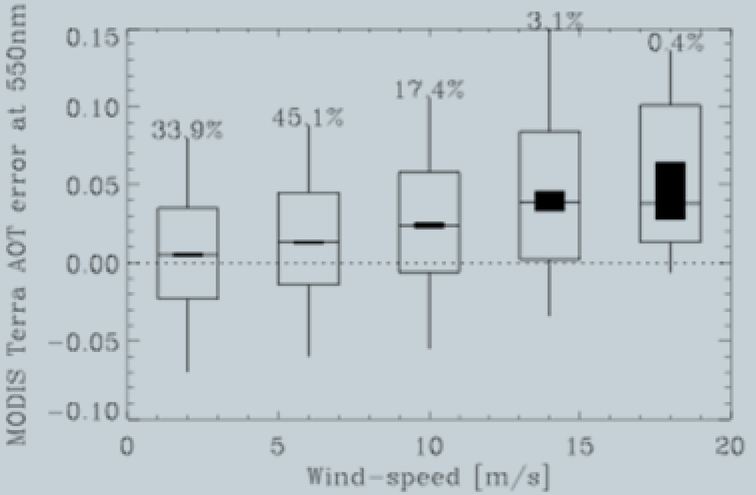
Corrected emissions



Issue: quality of observations

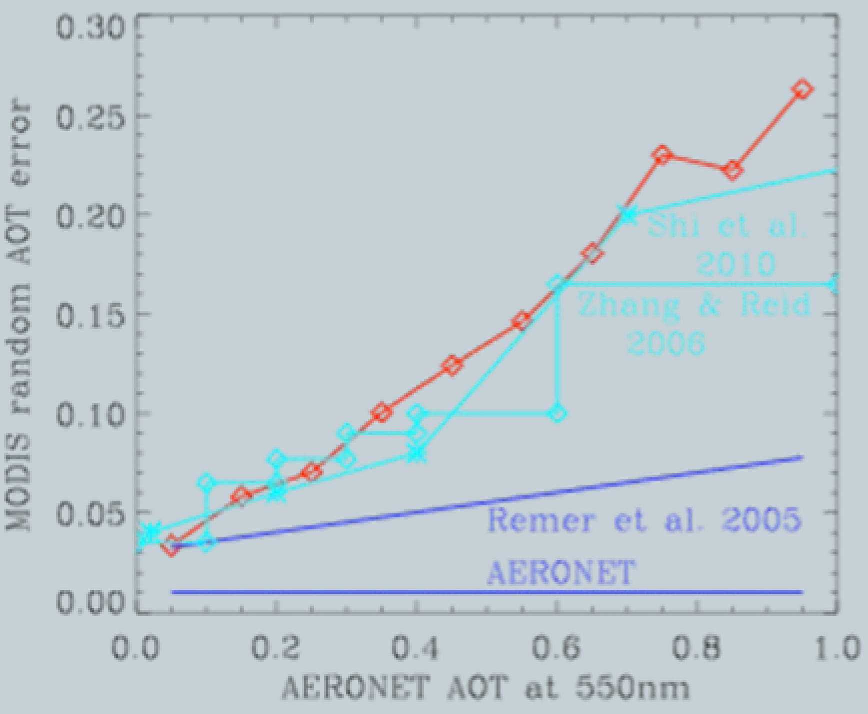
- Observations should:
  - Have QC screening
  - Have no biases
  - Have known errors
  - Representative at grid size
- So far only MODIS has received scrutiny (e.g. Zhang & Reid 2006, Shi et al. 2011, Hyer et al. 2011)
- What truth do we use?
  - AERONET by default





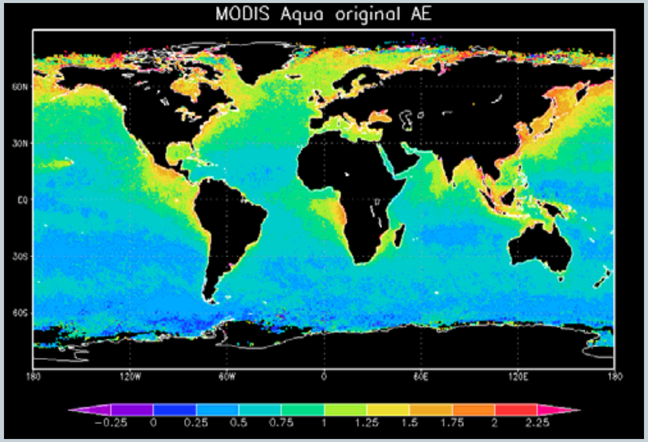
Issue: quality of observations

MODIS AOT error estimate:

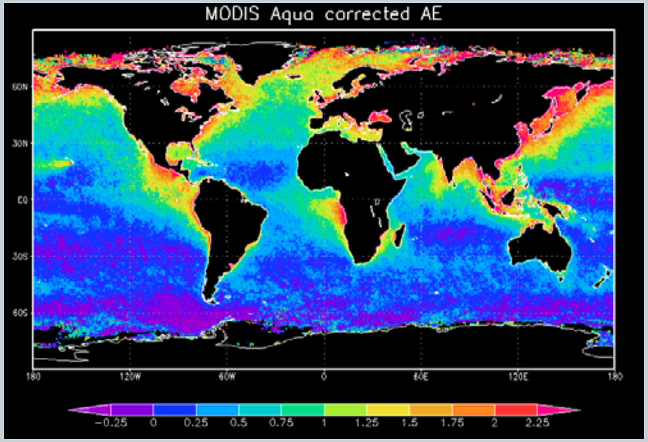


MODIS AE bias correction:

Original AE



Corrected AE



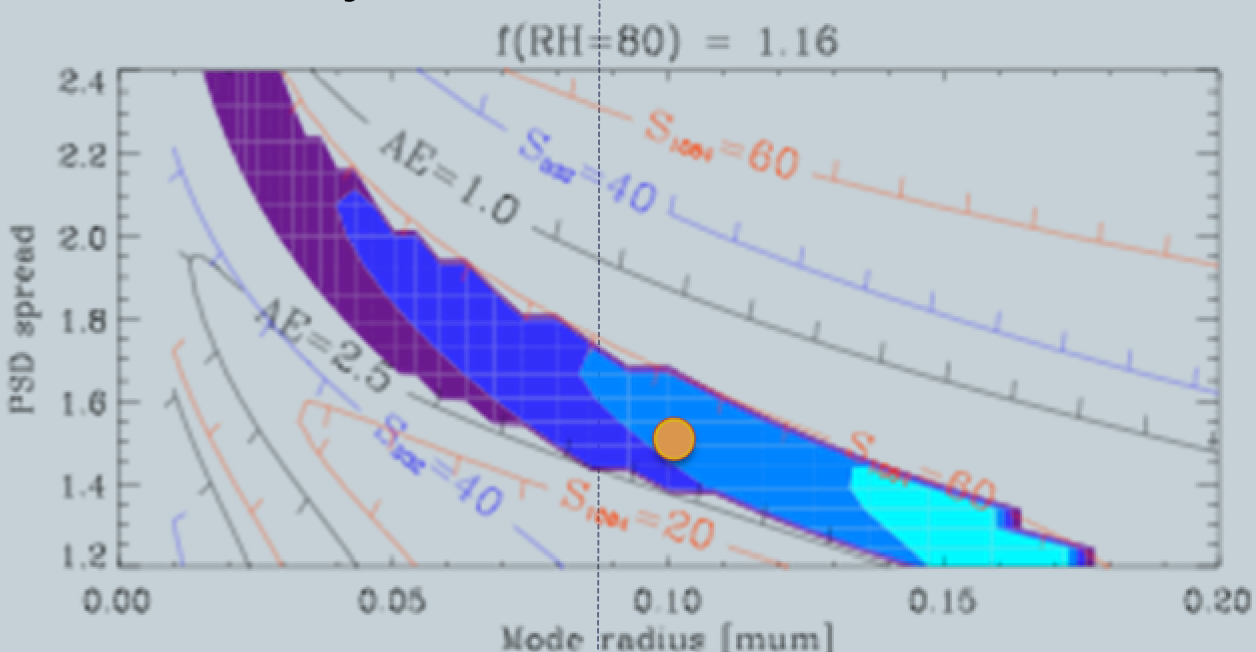
With M. Nakata, Kinki U.

Issue: simulated observations **H x**

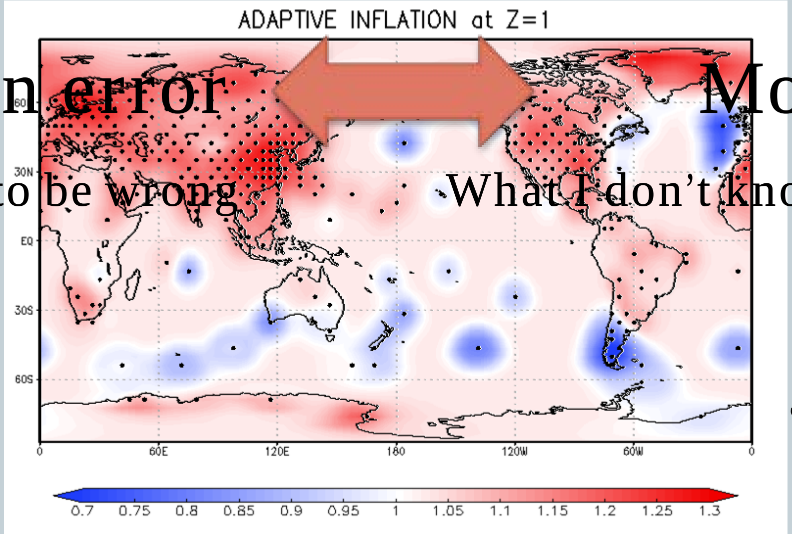
- In most models:

Bias is likely

- C_{ext} depends on assumed
  - size distribution
  - Refractive index
  - Wet growth



Issue: model errors



Prediction error

What I know to be wrong

Model error

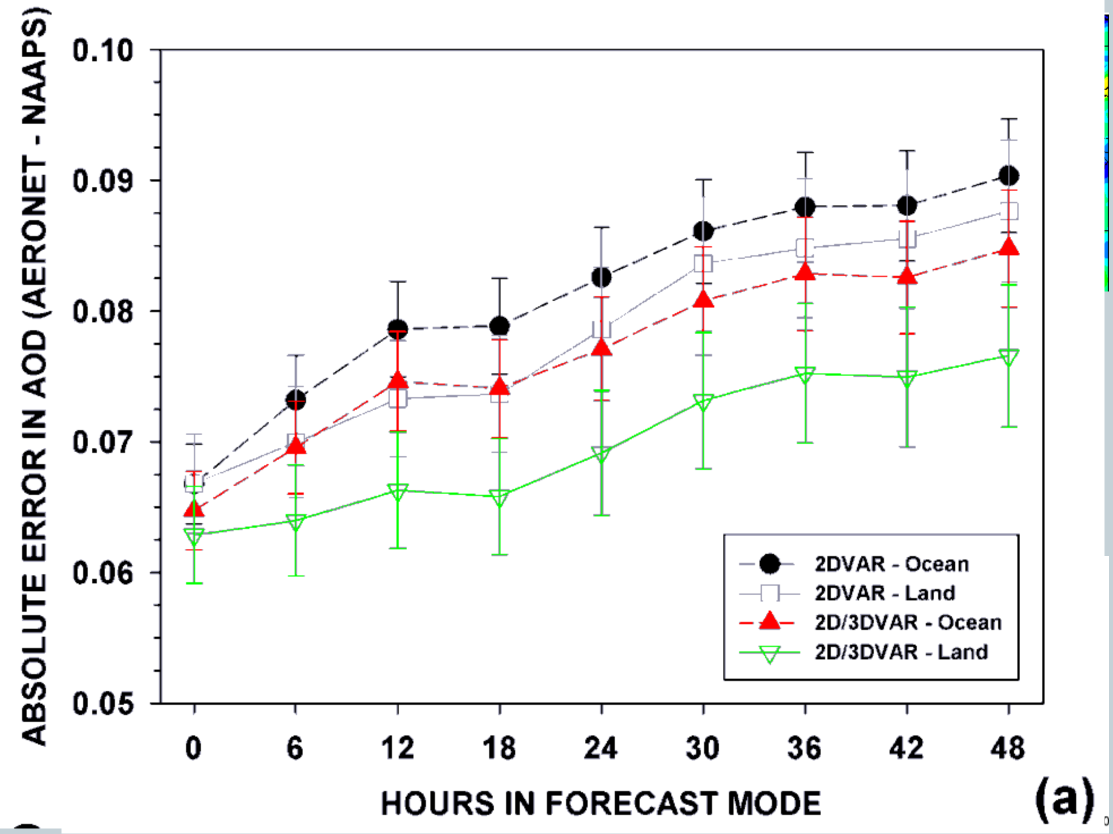
What I don't know to be wrong

Courtesy T. Miyoshi

- Parametric errors
- Unaccounted processes
- Unresolved grid scales
- The issue receives a lot of attention in NWP (e.g. Dee & da Silva 1999, Nichols 2003, Li et al. 2009)

Operational aerosol assimilation

- ECMWF
  - 4D-VAR
  - MODIS AOT
- NRL
  - 3D-VAR
  - MODIS AOT
- NASA GSFC
  - PSAP
  - MODIS AOT



Courtesy A. Benedetti

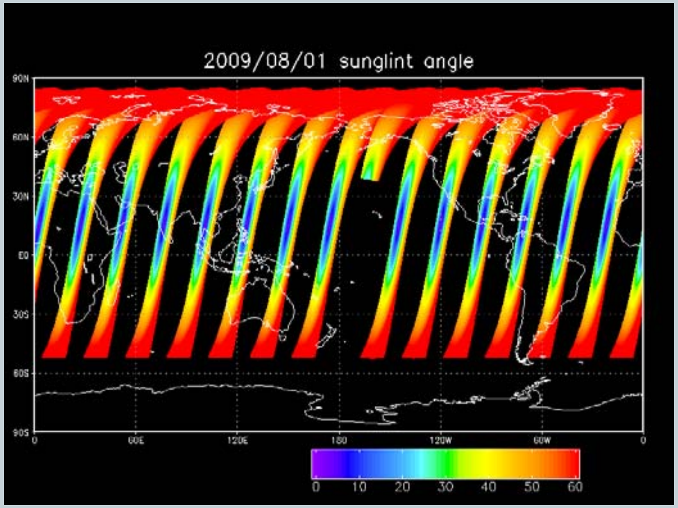
Courtesy J. Zhang

Courtesy A. da Silva

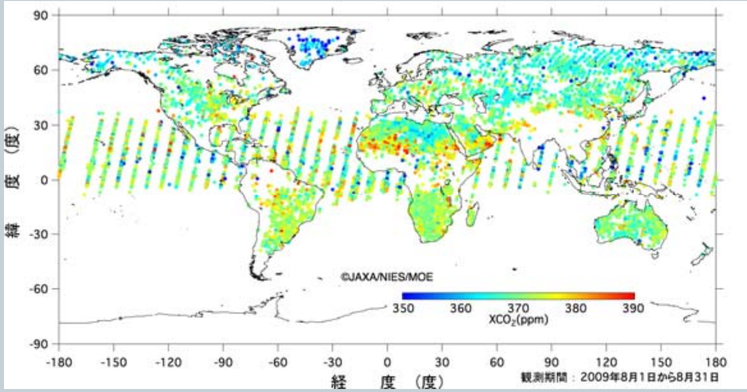
- (Tokyo U. and (separately) JMA)
  - EnkF

Aerosol assimilation for GOSAT

- Greenhouse gases Observing satellite
  - FTS for CO_2
  - Imager for clouds and aerosol
- SWIR measurements are most sensitive to CO_2 where the imager is least sensitive to aerosol
  - Ocean: sun-glint
  - Land: high albedo
- Assimilation improves global simulation, simulation fills in imager's blind spots



Courtesy S. Fukuda



Courtesy Imasu

The (near) Future

- Aerosol forecasts / reanalysis
- Diverse sensors, complimentary observations
  - MISR over land, CALIOP
  - AE or fine mode fraction, SSA
  - Radiances
- (Direct/indirect) Aerosol Radiative Forcing estimate
- OSSE: observing network design
  - Information content of network
- Model parameter estimation
  - Source & Sinks
- Integrated Assimilation – Retrieval cycle
  - Most retrievals use implicit climatology
  - Assimilation as retrieval

Summary

Assimilation allows the integration of disparate observations and model simulations into an comprehensive picture of the aerosol system.

- Model fills in observational gaps
- Observations fill in the model gaps

A new and exciting field with many applications!