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Navy Ensemble Aerosol Forecasting and Data Assimilation

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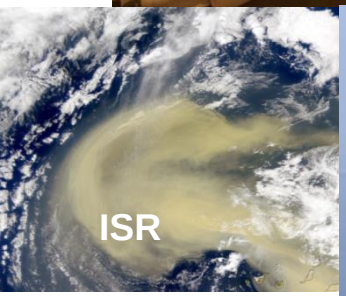
MAC-MAQ Conference, Davis, CA, September 13, 2019

Navy Aerosol Forecasting Overview

Navy aerosol forecasting provides environmental information to **support operations, Tactical Decision Aids, remote sensing, and battlespace prediction.**



Satellite-Based Products

- Data Assimilation Grade Aerosol Optical Depth (AOD)
- Fire Locating and Monitoring of Burning Emissions (FLAMBE) Smoke Emissions

Global Deterministic Modeling

- Navy Aerosol Analysis Prediction System (NAAPS) Operational (1/3°)
- NAAPS Inline (NAVGEM)
- NAAPS reanalysis (2003-present, 1°)

Mesoscale Modeling

- COAMPS Dust
- COAMPS with NAAPS species (new)

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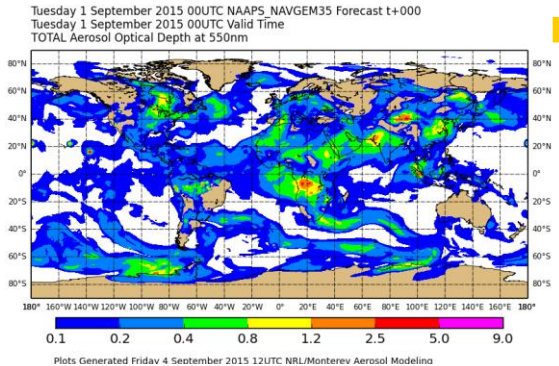
Navy Aerosol Analysis Prediction System (NAAPS): Operational Aerosol Forecasting

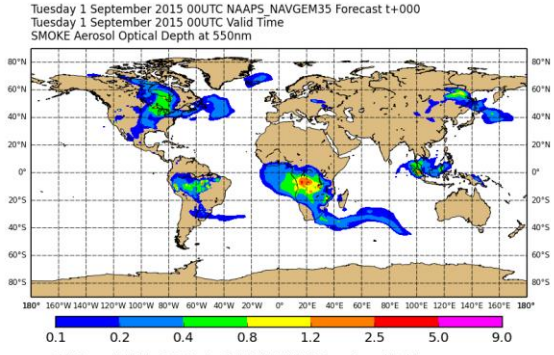
Aerosol Species: 4, bulk scheme
Meteorology: Offline, Navy Global Environment Model (NAVGEM)
Resolution: 1/3 degree
Forecast: 6 day, aerosol mass conc/AOD
Data Assimilation: NAVDAS-AOD, NRL MODIS AOD product

Total

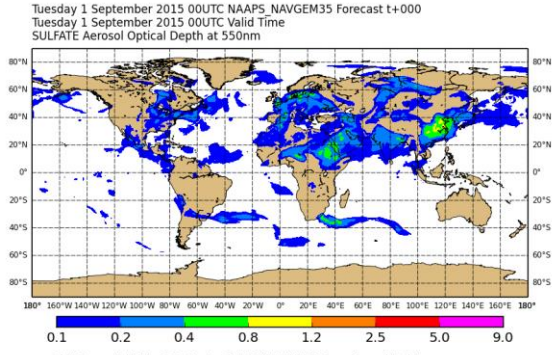


https://www.nrlmry.navy.mil/aerosol/

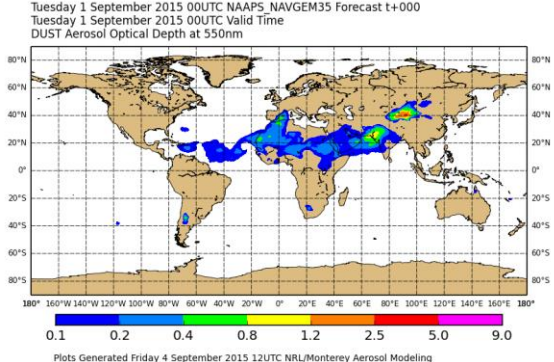
Smoke



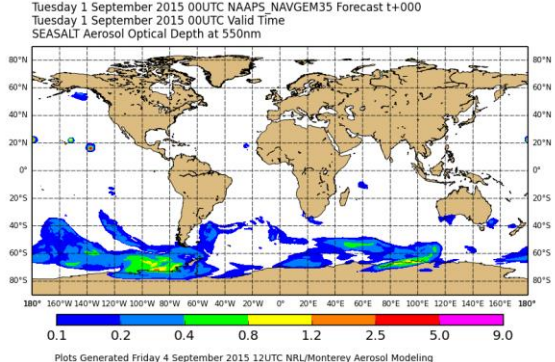
Anthro/Biogenic Fine



Dust



Sea Salt



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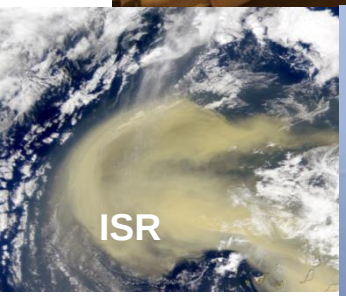

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Mesoscale Modeling

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Global Ensemble Modeling

- Ensemble NAAPS (0.5-1°)
- ICAP Multi-Model Ensemble

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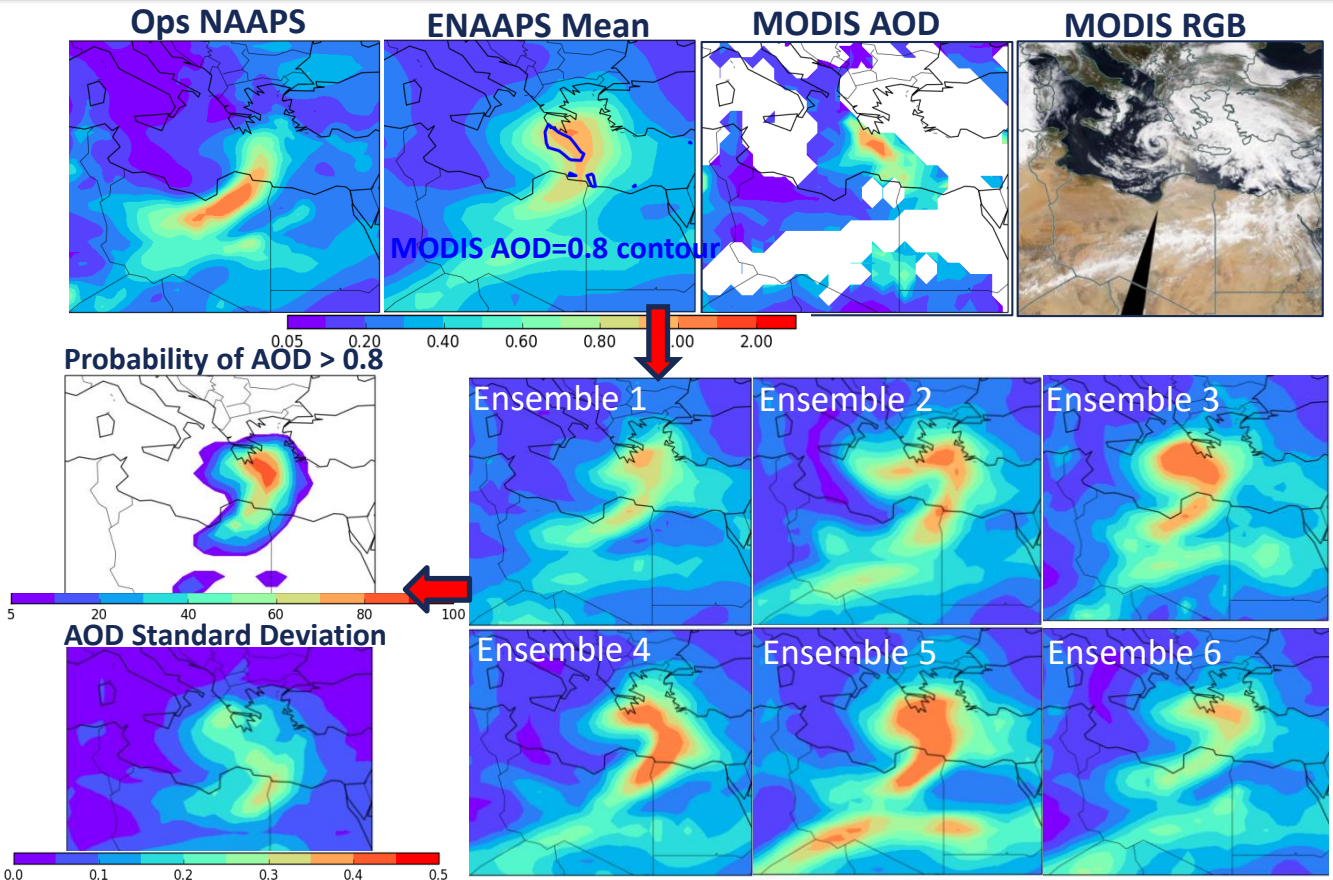
Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): 24-Hour Forecast, April 6, 2019

ENAAPS aerosol ensemble is a valuable complement to operational, deterministic NAAPS.

When NAAPS fails to produce a big aerosol event, the ensemble provides a range of outcomes (intensity/position dust).

Probabilistic products are being tested for conveying ensemble information to forecasters.



Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): Ensemble Data Assimilation

Kalman Filter Equation:

$$x_a = x_b + K[y_o - Hx_b],$$
$$K = BH^T(R + HBH^T)^{-1}$$

x_a= analysis

x_b= background (6-hr forecast)

K=Kalman gain matrix

$y_o - Hx_b$=obs-background in obs space

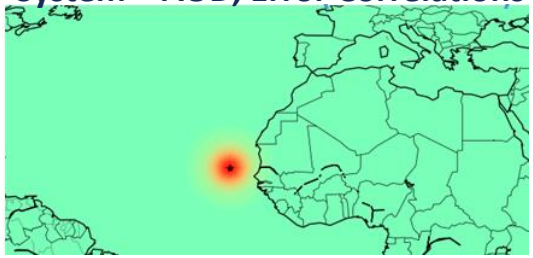
BH^T=background error covariance in obs space

$(R + HBH^T)^{-1}$=total error covariance

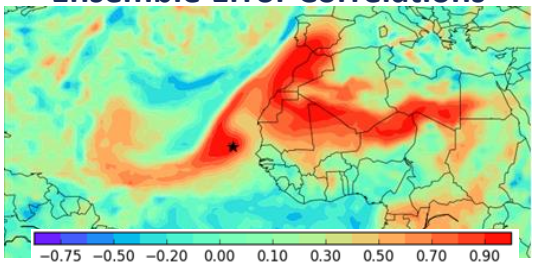
Ensemble Advantage:

Time-varying and flow dependent forecast uncertainties for generating better forecast initial conditions.

Navy Variational Data Assimilation System – AOD, Error Correlations



Ensemble Error Correlations

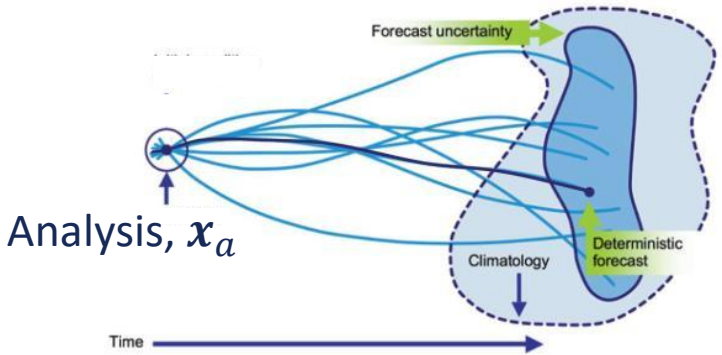


Error correlations determines the spatial impact of obs in system.

Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): System Configuration

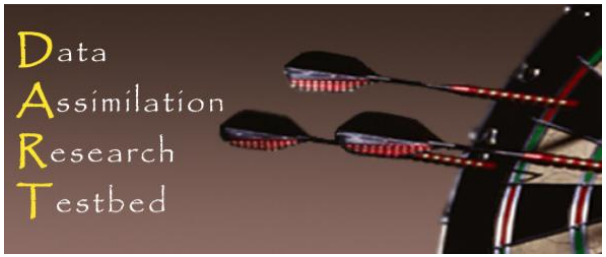
ENAAPS Forecast:

DA-Cycling: 6-Hr (x_b), 80 ensembles (0,6,12,18 UTC)
Long Forecast: 5-Day, 20 ensembles (0,12 UTC)



1. Varying initial conditions (Data Assimilation).
2. Perturbed NAVGEM meteorology (Ensemble Transform).
   McLay et al. 2008, 2010
3. Perturbed aerosol emissions (Gaussian Distribution).
   Rubin et al. 2016

Data Assimilation:



Ensemble Adjustment Kalman Filter (EAKF), 0,6,12,18 UTC
Anderson 2001

Observations:
NRL Data Assimilation Quality
MODIS AOD
AERONET AOD (as of April, 2019)

Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): DA Development

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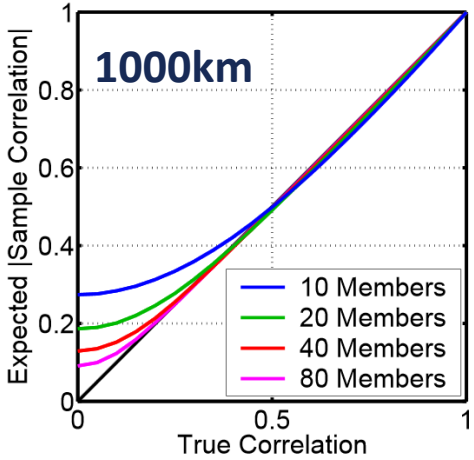
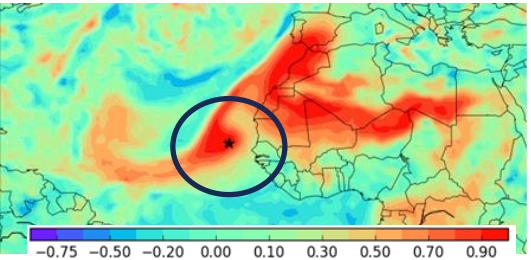
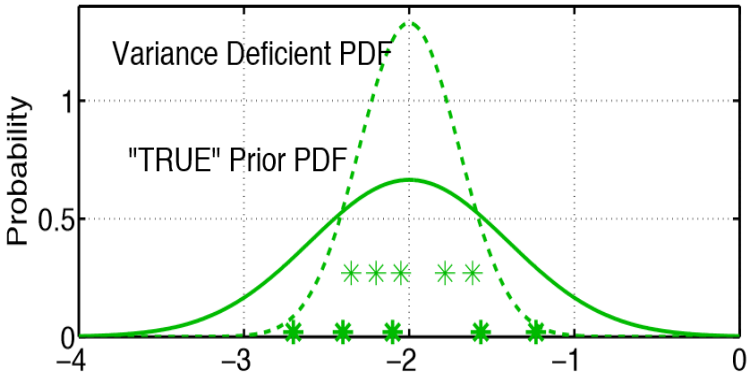
1. Localization





Gaspari and Cohn Localization

2. Inflation (Multiplicative vs Adaptive)



$$inflate(x_i) = \lambda(x_i - \bar{x}) + \bar{x}$$

λ=inflation factor

Adaptive Inflation = λ varies in space and time

(Anderson 2007)

3. Ensemble Generation

Source ensemble
Met ensemble
Met+Source

4. Ensemble Size

ENAAPS Experiment Table

Experiment name	Ensembles	Inflation
Source, const	Source, 20 members	10 % constant covariance inflation
Source, adaptive	Source, 20 members	Adaptive inflation
Meteorology, adaptive	Meteorology Only, 20 members	Adaptive inflation
Met+Source, adaptive	Meteorology+Source, 20 members	Adaptive inflation
Met+Source, 80	Meteorology+Source, 80 members	Adaptive inflation

Experiment Time Period: July-Aug, 2013

Rubin et al. 2016

Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): DA Development

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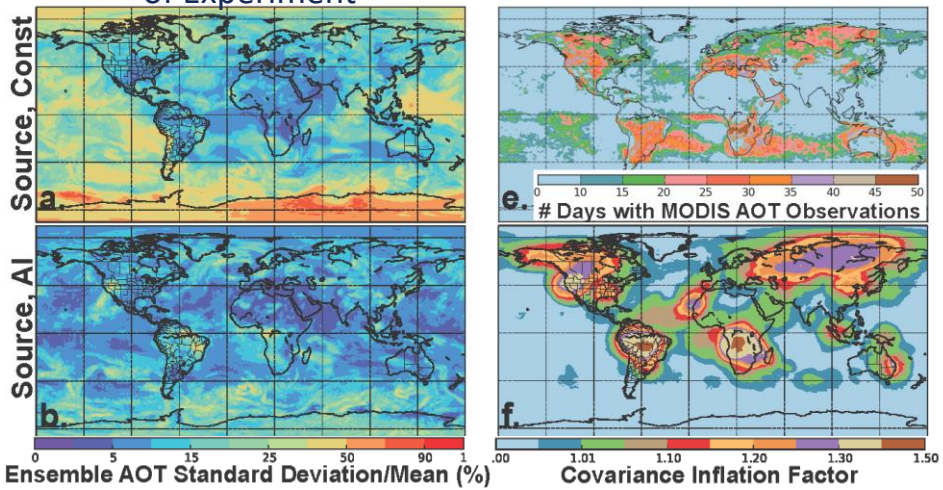
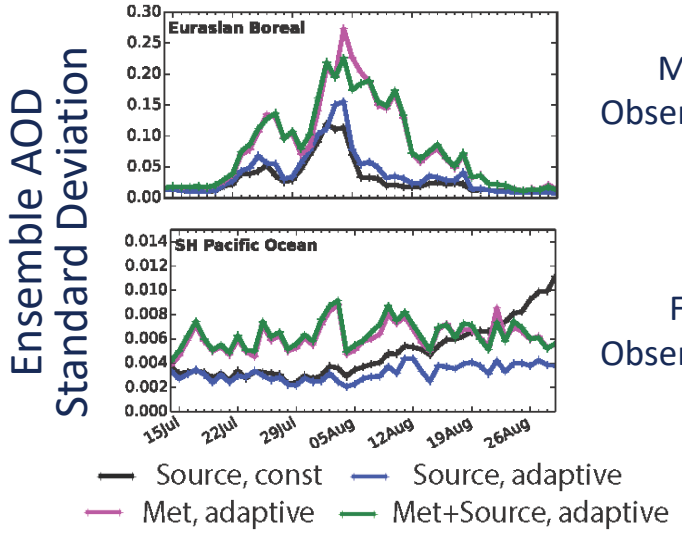
Ensemble Spread at End of Experiment



Experiment Time Period: July-Aug, 2013

Constant multiplicative inflation: no constraint on ensemble spread where observations are limited ➡ continuous growth in spread.



Many Observations

Few Observations

Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): DA Development

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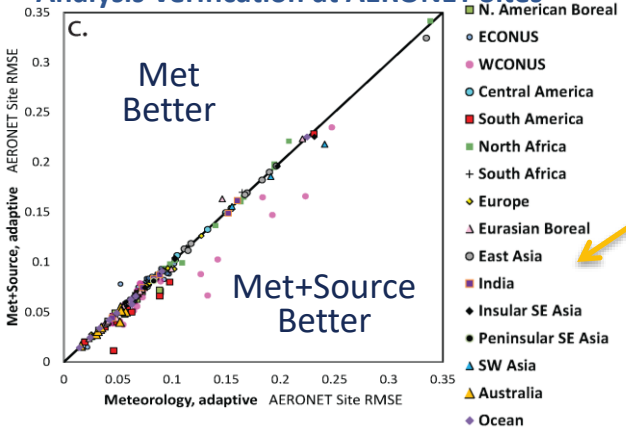
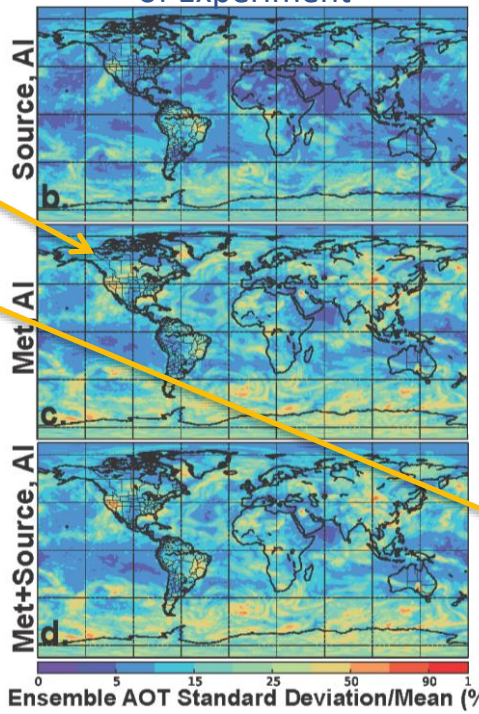
- Meteorology ensemble dominant source of ens spread.
- Source perturbations helped with ensemble distribution in large aerosol source regions (Boreal Fires).

Analysis Verification at AERONET Sites

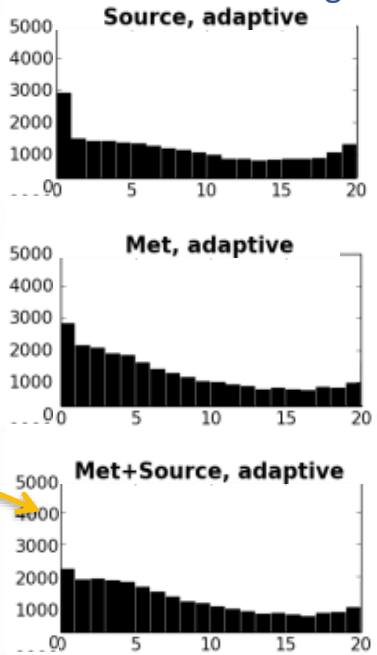


- Smaller analysis RMSE with met+source ensemble.

Ensemble Spread at End of Experiment



Rank Histograms for Eurasian Boreal Region



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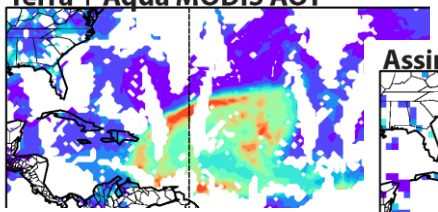
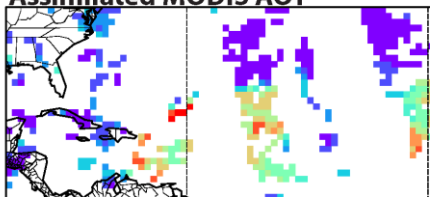
Saharan dust event case study:

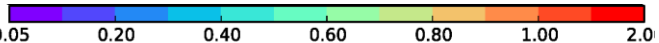
MODIS RGB, Worldview

Terra + Aqua MODIS AOT

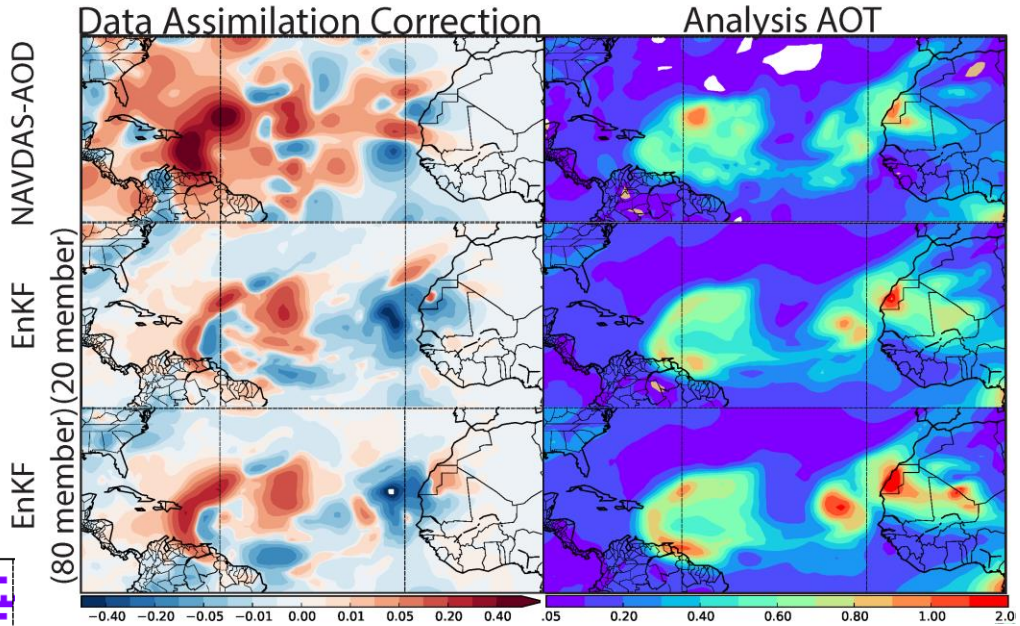


Assimilated MODIS AOT





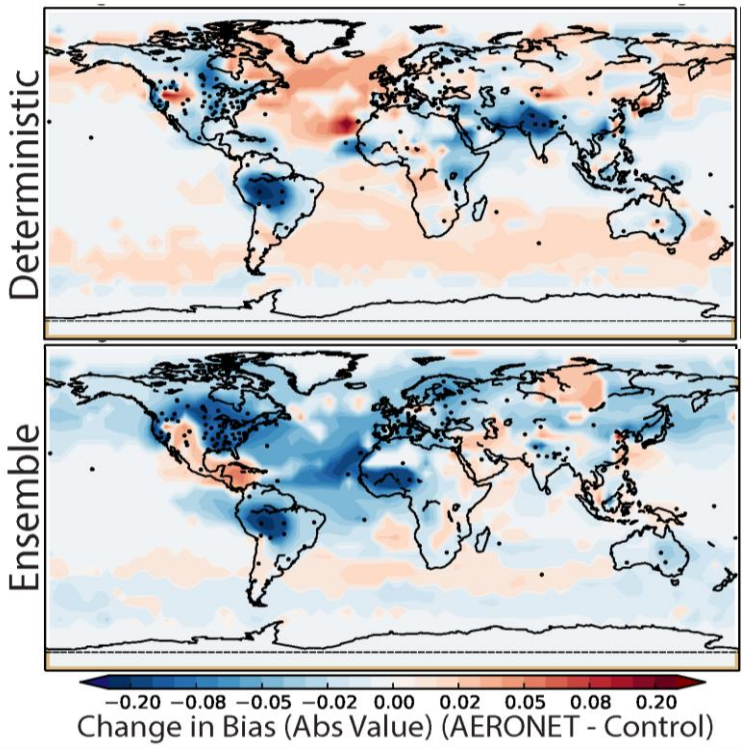
EAKF captures dust front shape/magnitude with 80 ensembles.



AERONET verification confirmed reduced RMSE with 80 ensembles, especially high AOD sites (>0.8).

Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): Sparse Observation Assimilation

July-Sept, 2013, Control = no DA

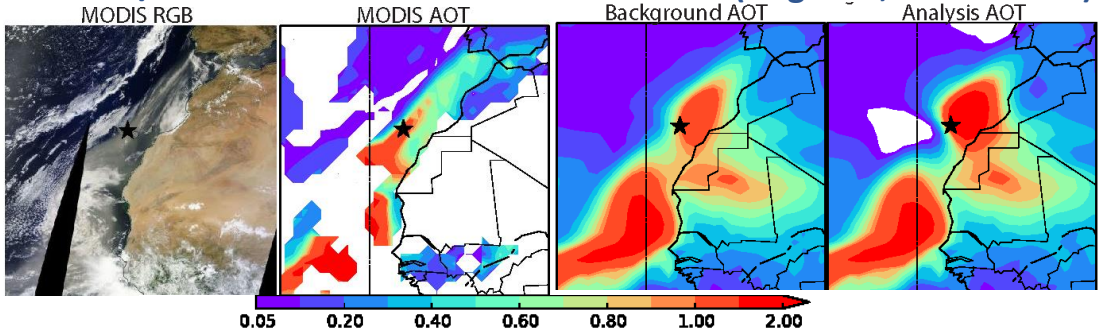


Rubin et al. 2017

Only ground-based AERONET AOD observations are assimilated (● = obs site)

1. Analysis verified with MODIS AOD.
2. Largest error reduction in high observation density regions.
3. Large increases in error can occur with NAVDAS-AOD (2D-Var data assimilation).

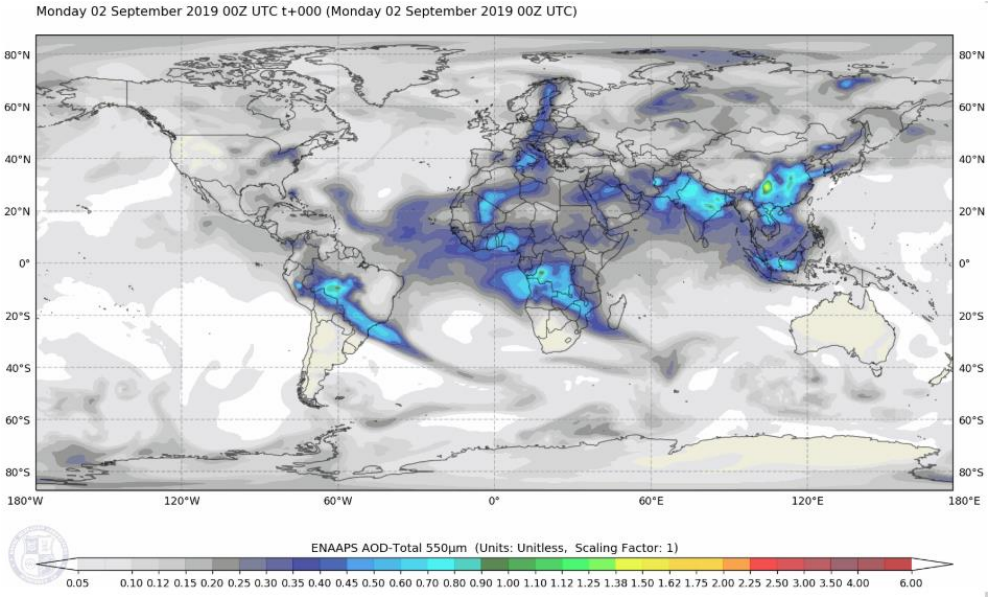
NAAPS/NAVDAS-AOD AERONET Assimilation (August 1, 2013 12UTC)



AERONET assimilation increased error in high AOD gradient regions in 2D-Var.

Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): Operational Transition

ENAAPS with EAKF data assimilation (MODIS + AERONET, 80 ensembles) is currently running as a near-real-time aerosol forecasting system at the Navy DSRC.



ENAAPS mean AOD September 2, 2019

Transition to operations (Fleet Numerical Meteorology and Oceanography Center) is currently underway and expected to be completed in FY20.

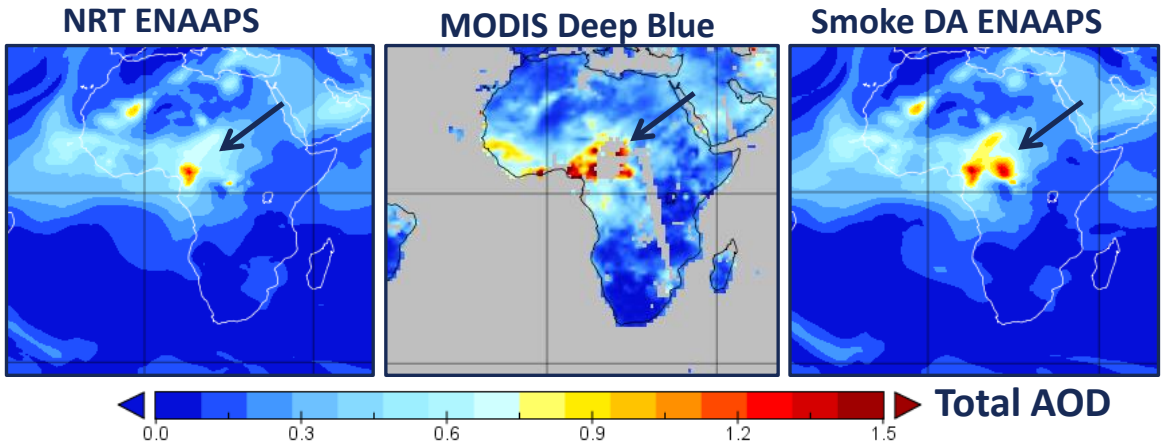
Ensemble Navy Aerosol Analysis Prediction System (ENAAPS): Aerosol Source Assimilation

Goal: Extend impact of assimilated obs on forecast by allowing observations to adjust emissions.

Experiment: Smoke emissions impacted by AOD assimilation in ENAAPS (EAKF).

- Ensemble of FLAMBE emissions to represent smoke uncertainty.
- Updated emissions are used for both DA cycling and forecast.

Example: Sahel Smoke 2019022512, analysis



$$Smoke_{Emiss}[lat, lon] = Smoke_{Emiss}[lat, lon] \frac{Post\ SmokeEmiss[lat, lon]}{Prior\ SmokeEmiss[lat, lon]}$$

Peak smoke events better captured in analysis and forecast.

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

Organization	BSC	Copernicus/ ECMWF	JMA	Meteo France	NASA	US Navy	NOAA	FMI	UKMO
Model	MONARCH	CAMS	MASINGAR	MOCAGE	GEOS-5	NAAPS	NGAC/FV3GFS-Chem	SILAM	MetUM
Status	QO	O-24 hrs	QO	O	QO	O	O	O	O
Meteorology	Inline NMMB	Inline IFS	inline AGCM	Offline ARPEGE	Inline GEOS-5	Offline NAVGEM	Inline GFS/FV3GFS	Offline IFS	Inline UM
Resolution	1.4x1 (0.7x0.5)	0.4x0.4	0.375x0.375	1x1	0.125x0.15	0.33x0.33	1x1/0.25	0.5x0.5	0.35x0.23
levels	24 (48)	~~60~~ 137	40	47	72	60	64	60	70
DA	LETKF^p	4DVar	2DVar LETKF^p	2018	2DVar +LDE	2DVar 3DVar, EnKF^p	NA	3Dvar^p, 4Dvar^p, EnKF^p	4DVar
Assimilated Obs	DAQ MODIS+DB	DAQ MODIS DT+DB PMAp	MODIS L3, AHI^p, CALIOP^p	NA	Neural Net MODIS	DAQ MODIS, AVHRR^p VIIRS^p CALIOP^p	NA	NA	MODIS Dust AOT
Species	Dust, Sea Salt BC (POA,SOA)bio Sulfate (POA, SOA)anthro	BC, OC Dust, Sea Salt Sufate, Nitrate, Ammonium	BC, OC Dust Sea Salt Sulfate	BC, OC Dust Sea Salt Sulfate, Nitrate, Ammonium	BC, OC Dust Sea Salt Sulfate Nitrate	Anthro+bio B. B. Smoke Dust Sea Salt	Dust BC, OC Sea Salt Sulfate	BC, Dust, OC, Sea Salt, Sulfate, Nitrate, B.B. Smoke	Dust
Size Bins	8 (dust, salt) bulk for others	3 (dust, salt), bulk for others	10 (dust, salt), bulk for others	6	5 (dust, SS), 2(BC, OC), 3(NI*), bulk sulfate	bulk	5 (dust, SS), 2(BC, OC), bulk sulfate	4 (dust), 5 (SS), 3 (B.B. Smoke), 2 (sulfate), bulk for others	2
Antho. & Biogenic Emission	HTAPv2.1 (anthro), MEGANv2.04 (biogenic)	MACCity (anthro), MEGAN (biogenic)	MACCity	MACCity (anthro.) MEGAN-MACC (biogenic)	EDGAR V4.1/4.2, AeroCom Phase II, GEIA	MACCity, BOND, POET	EDGAR V4.1+CEDS AeroCom Phase II, GEIA	MACCity, STEAM, MEGANE, HTAP(Coarse PM)	NA
Bio. Burn. Emissions	GFAS	GFAS	GFAS	GFAS	QFED	FLAMBE	GBBEPxV2	GFAS, IS4FIRES	NA

- The ICAP-MME is run daily w/ 1x1 deg res at 00Z for 6 hrly fcasts out to 120 hrs w/ a 1-day latency.
- Modal AOT (550nm) and dust AOT (550nm) data in NetCDF is available publically.
- Green means proposed. Red means changes occurred last year. “p” means prototype.

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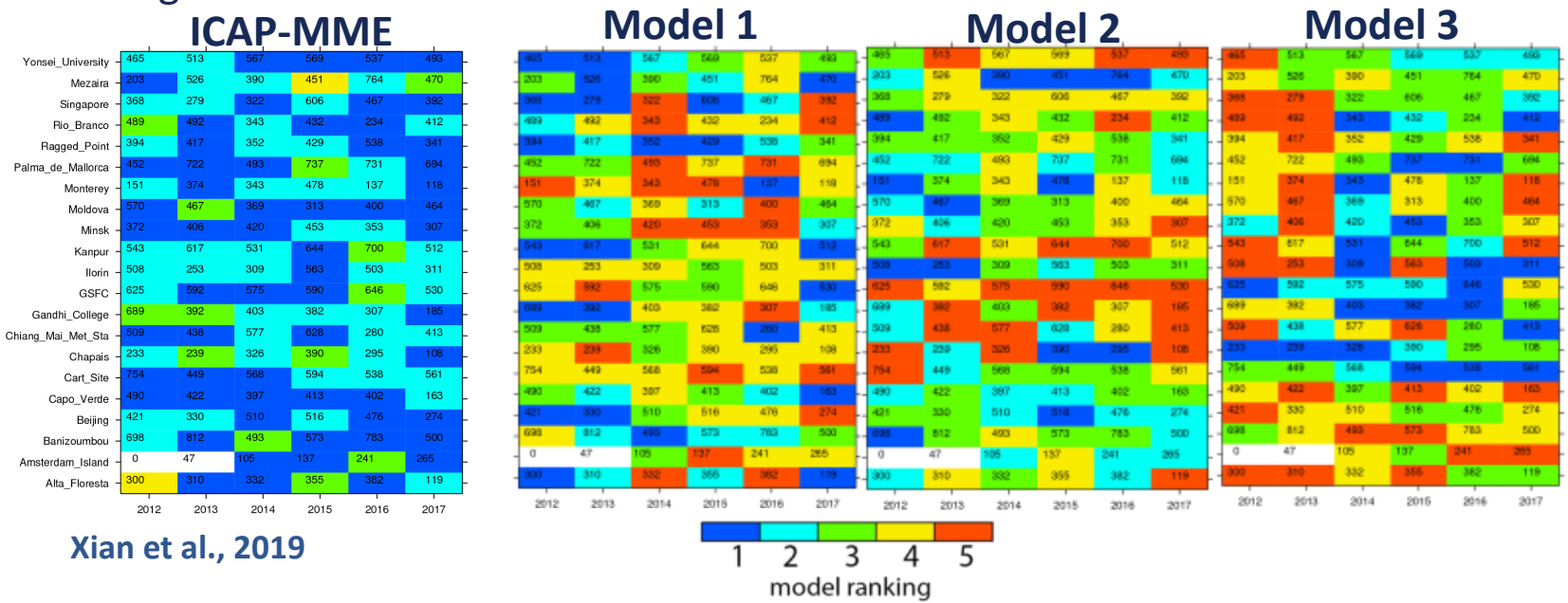
International Cooperative for Aerosol Prediction: Multi-Model Ensemble (ICAP-MME)

Ranking of all models in terms of total AOD RMSE for 72-hr fcst over 2012-2017



Xian et al., 2019

- ICAP-MME performance is stable and reliable over the years compared to individual models.
- ICAP-MME AOD RMSE is not always the lowest for a given species/site/year, but is relatively low and stable.
- Consensus MME wins in the long run because of its averaging of independent models.
- ICAP-MME netcdf data files available on USGODAE server for AOD. PM output in development.

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Navy Ensemble Aerosol Forecasting and Data Assimilation: Summary

- Ensemble systems are high priority for Navy aerosol prediction.
- ENAAPS single model ensemble was developed to provide probabilistic information to Navy forecasters and also to take advantage of flow-dependent errors for data assimilation.
- EAKF does a better job at spatially using observational information than current operational 2D-Var system.
- ENAAPS is currently NRT, assimilates MODIS and AERONET AOD.
- Transition to operations expected in FY20 (Fleet Numerical Meteorology and Oceanography Center).
- Ongoing DA efforts focused on aerosol/meteorology interactions, geared towards next generation Navy prediction system.
- NRL also generates the daily ICAP multi-model ensemble product, which is a top performer for AOD forecasts. Currently working on a surface PM product.