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Office of Naval Research Science & Technology

Navy Aerosol Forecasting: The Power in Ensembles

21st Annual GMU Conference on Atmospheric Transport and Dispersion Modeling

Fairfax, VA

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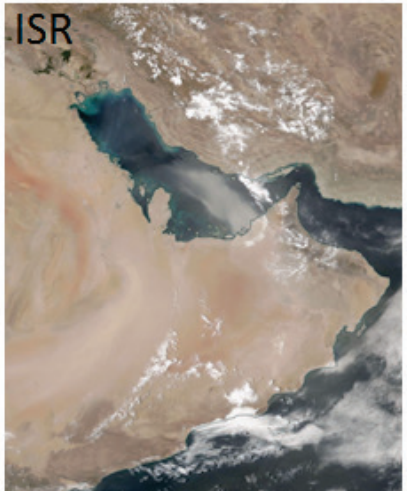
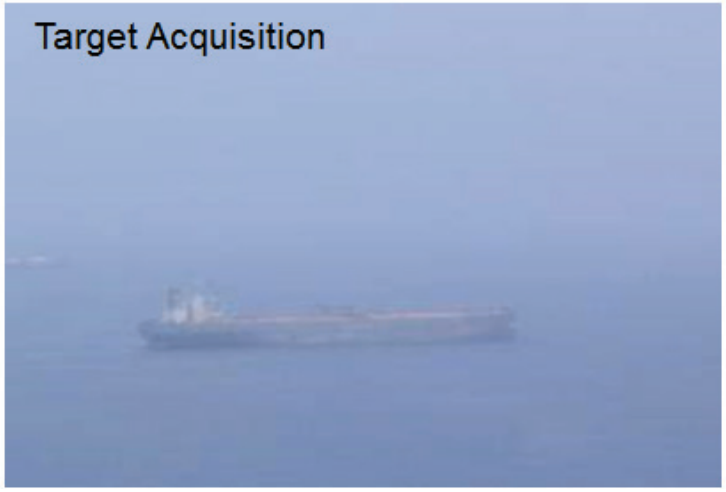
Navy Aerosol Forecasting: An Overview

Goal: Provide the underlying environmental data to support operations, Tactical Decision Aids, remote sensing, and battlespace prediction





Operational: FNMOC Aerosol Forecasts

1) **Global:** Navy Aerosol Analysis Prediction System (NAAPS)
   - -Dust, smoke, sea salt, anthropogenic/biogenic fine aerosol
   - -1/3 degree out to 6 days
2) **Mesoscale:** Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)
   - -Dust aerosol since 2001, NAAPS species in prototype

NRL: Apply research (field experiments, analysis, modeling studies) to improve current systems and develop new systems/tools for better forecast guidance.

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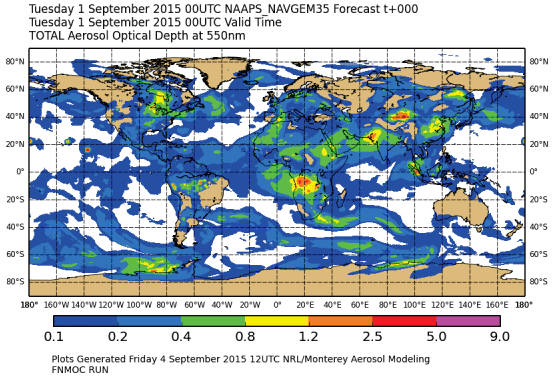
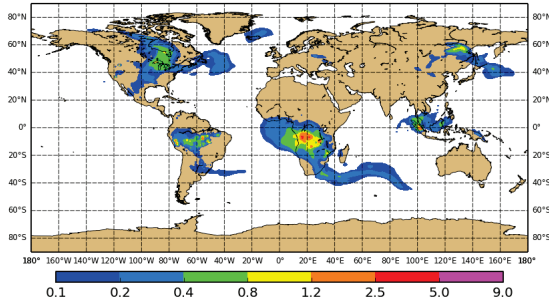
Operational Global Navy Aerosol Forecasting

1. **Forecast Model: NAAPS**
   - Offline, NAVGEM Met (winds, temp, humidity etc.)
   - 4 aerosol species, out to 6 days, 1/3 degree resolution
2. **Data Assimilation: Navy Variational Data Assimilation System for Aerosol Optical Thickness (NAVDAS-AOT)**
   - Forecast initial conditions
   - 2D-Var
   - AOT Obs (MODIS, VIIRS)

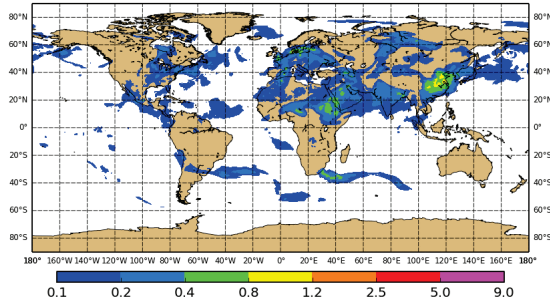
Total



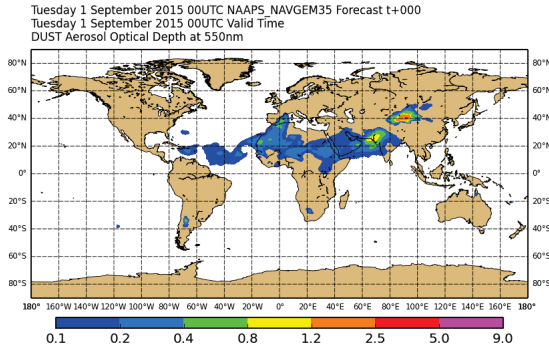
Smoke



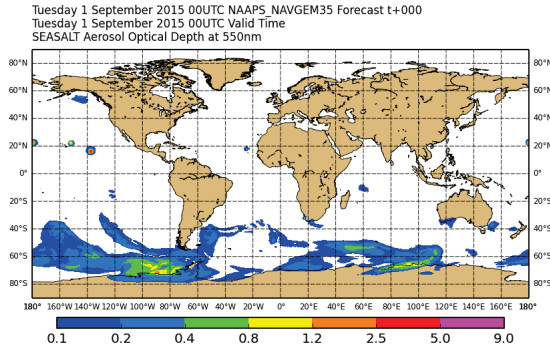
Anthro/Biogenic Fine



Dust



Sea Salt



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

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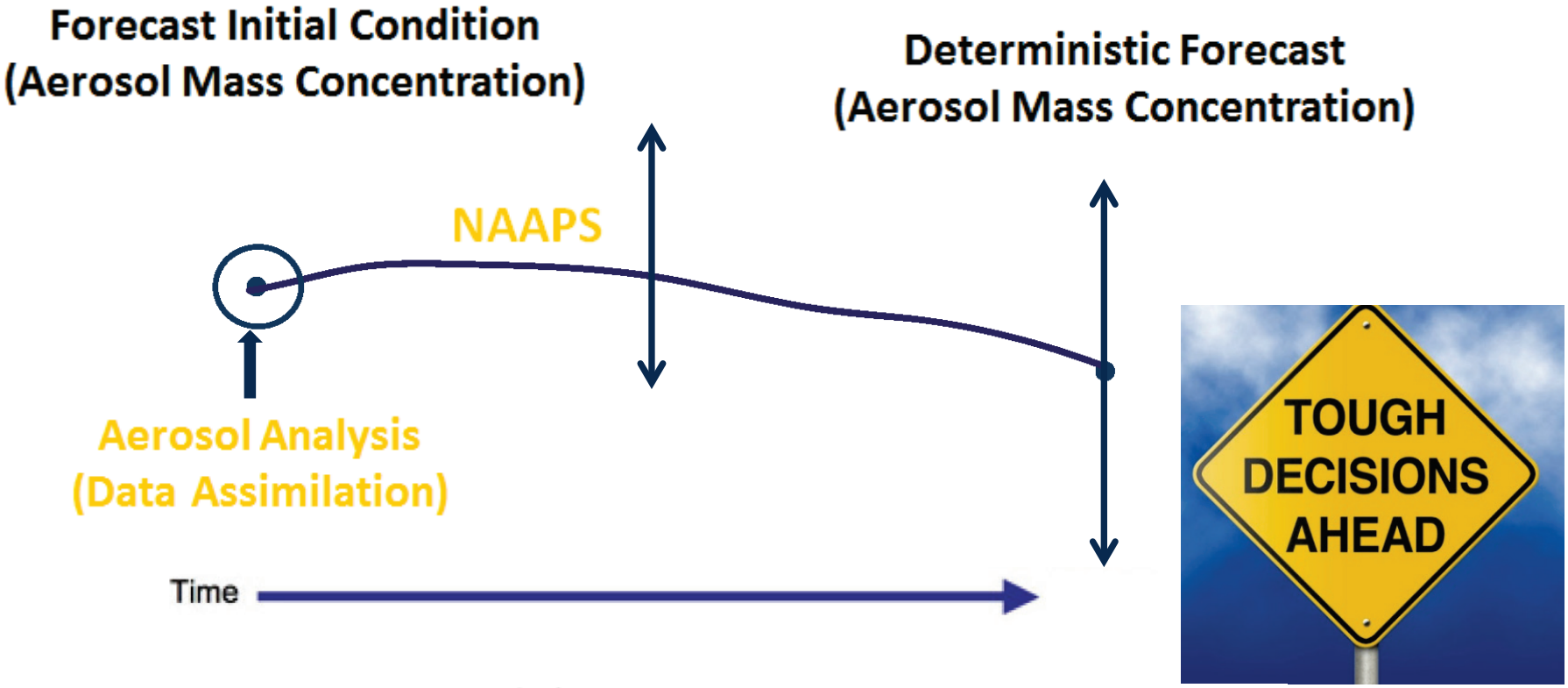
The Deterministic Perspective



Initial Condition (IC) Uncertainty

Model Uncertainty:
Physics
Meteorology
Emissions

Forecast Uncertainty

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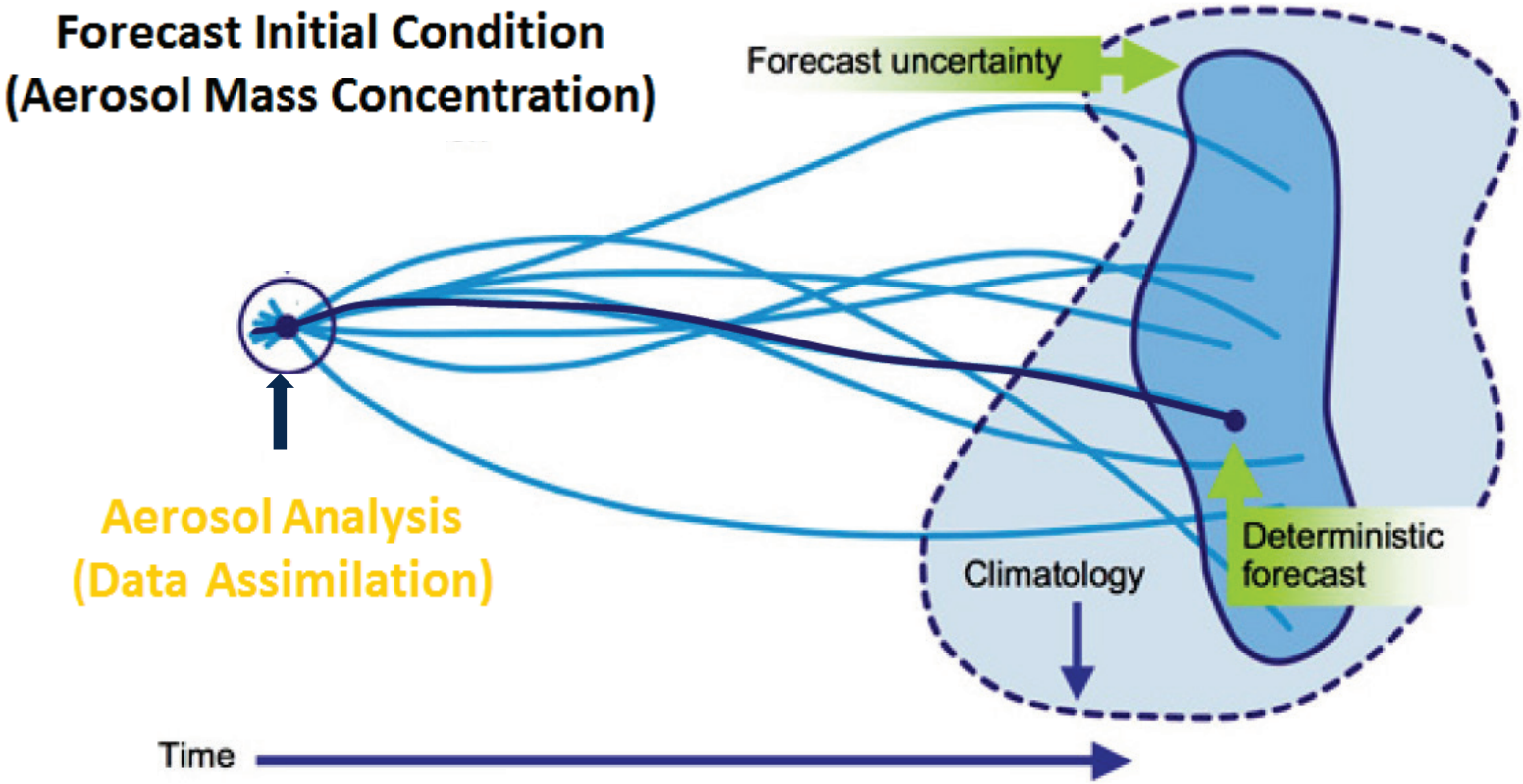
The Ensemble Perspective



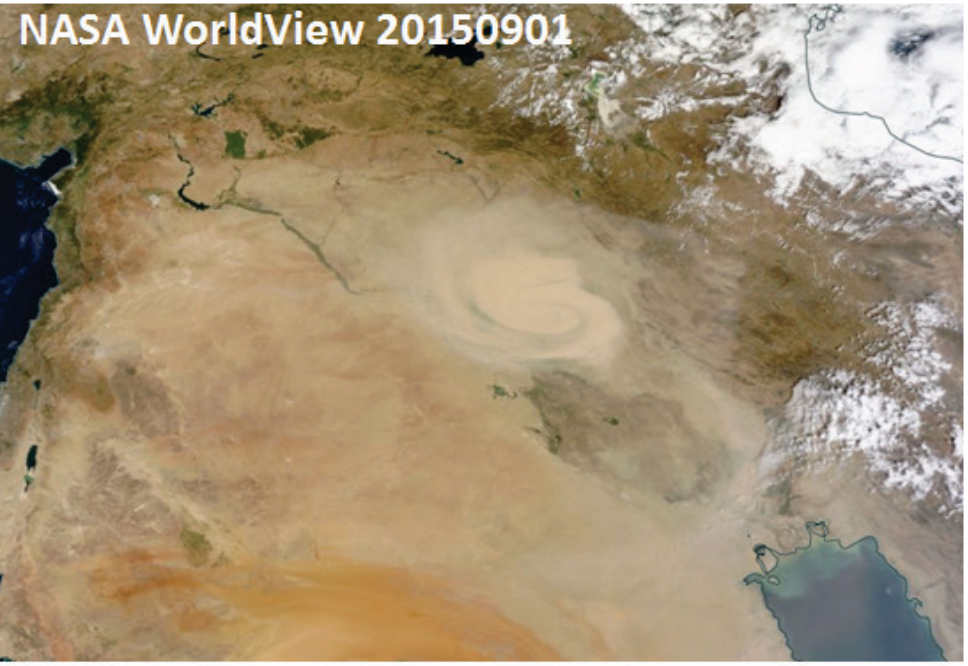
Perturbations in ICs across ensemble members

Differences physics, numerical methods, inputs etc. across ensembles

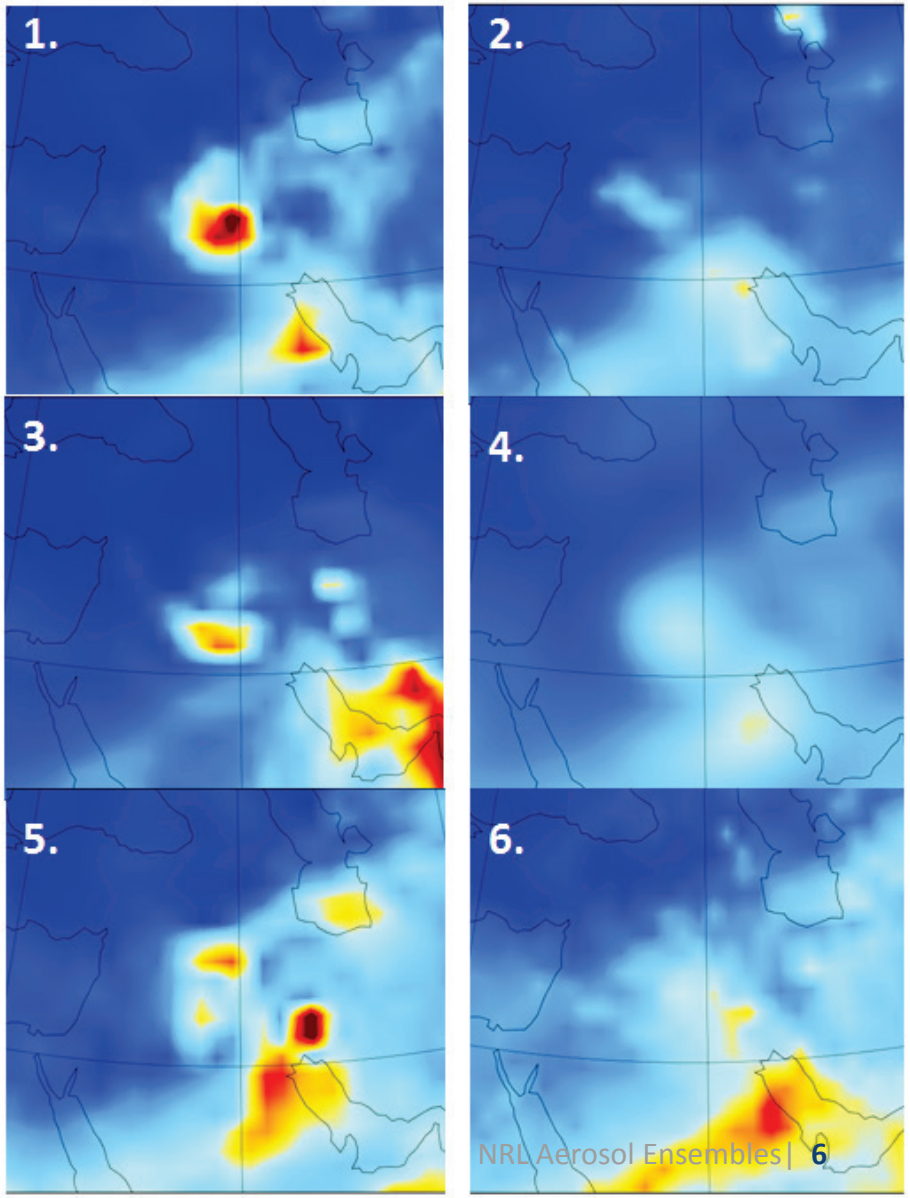
Range in Forecast Outcomes:

Probabilistic Information for Forecasters

The Ensemble Perspective from NWP Centers



- Some members miss the event (2,4)
- Some members hit the event (1)
- Position and strength vary (1,3,5,6)



Dust Aerosol Optical Thickness

ICAP-MME

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Navy Global Aerosol Prediction: Ensemble Product Lines

New Probabilistic Aerosol Prediction Capabilities

Multi-Model Ensemble

ICAP MME

- AOT consensus of deterministic models from centers out to 5 days
- Historically top performer
- New parameters in future

Provides reliable forecast guidance and serves as a research/reference dataset (e.g. TIGGE NWP)

Single Model Ensemble

Ensemble NAAPS (ENAAPS)

- 20-80 ensemble members
- EAKF data assimilation
- Moving towards operations

Using observations more effectively for data assimilation

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Navy Global Aerosol Prediction: ICAP Multi-Model Ensemble

Members of the International Cooperative on Aerosol Prediction (ICAP)

Organization	BSC	Copernicus/ ECMWF	JMA	Meteo France	NASA	US Navy	NOAA	UKMO
Model	NMMB/BSC-CTM MONARCH	~~MACC~~ CAMS	MASINGAR	MOCAGE	GEOS-5	NAAPS	NGAC	MetUM
Status	QO	O-24 hrs	QO	O	QO	O	O	O
Meteorology	Inline NMMB	Inline IFS	inline AGCM	Offline ARPEGE	Inline GEOS-5	Offline NAVGEM	Inline GFS	Inline UM
Resolution	1.4x1 (0.7x0.5)	0.4x0.4	~~0.56x0.56~~ 0.375x0.375	~~2x2~~ 1x1	0.25x0.31	0.33x0.33	1x1	0.35x0.23
levels	24 (48)	60	40	47	72	60	64	70
DA	LETKF^{p}	4DVar	2DVar LETKF^{p}	2018	2DVar +LDE	2DVar/3DVar ^{p}, EnKF^{p}	NA	4DVar
Assimilated Obs	DAQ MODIS+DB	DAQ MODIS+DB	MODIS, Himawari-8^{p}, CALIOP^{p}	NA	Neural Net MODIS	DAQ MODIS, AVHRR^{p} VIIRS^{p} CALIOP^{p}	NA	MODIS Dust AOT
Species	Dust Sea Salt BC, OC (POA,SOA) Sulfate	BC, OC Dust Sea Salt Sulfate	BC, OC Dust Sea Salt Sulfate	BC, OC Dust Sea Salt Sulfate	BC, OC Dust Sea Salt Sulfate Nitrate	Anthro+bio B. Burn Dust Sea Salt	Dust BC, OC Sea Salt Sulfate	Dust
Size Bins	8 (dust, salt) Bulk (BC, OC, Su)	3	10 (dust, salt), Bulk (BC, OC, Su)	6	5	1	5	2
Bio. Burn. Emissions	GFAS	GFAS	GFAS	GFAS	QFED	FLAMBE	GBBEPx	NA

*Green means proposed. Red means changes occurred last year. "p" means prototype.

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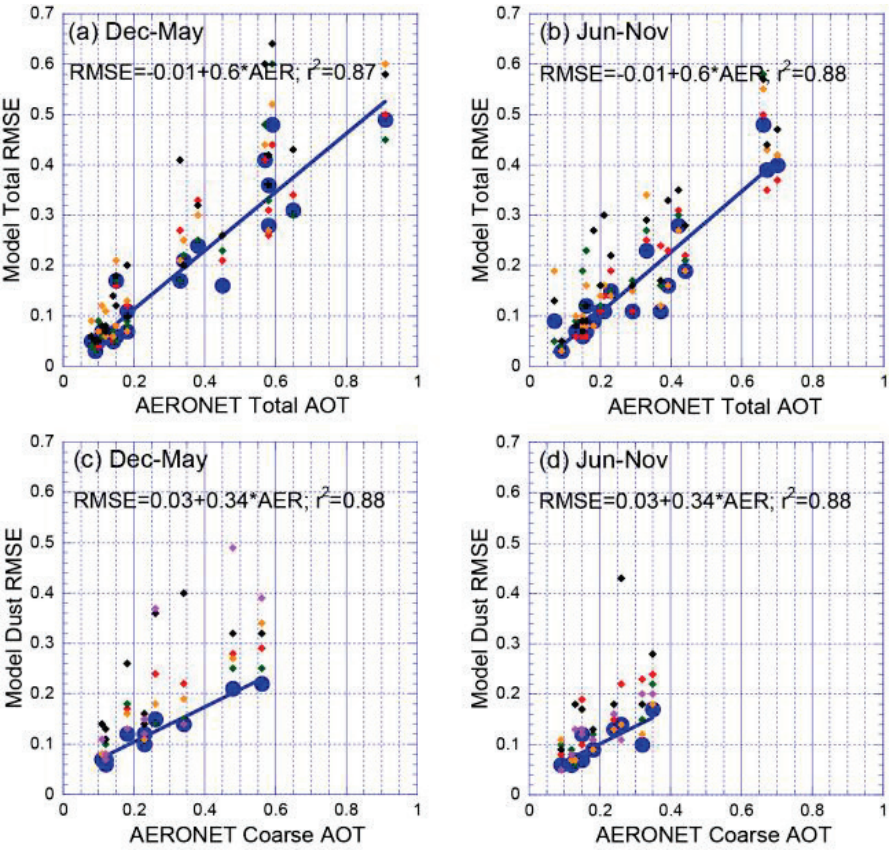
Navy Global Aerosol Prediction: ICAP Multi-Model Ensemble

ICAP-MME is the top performer.

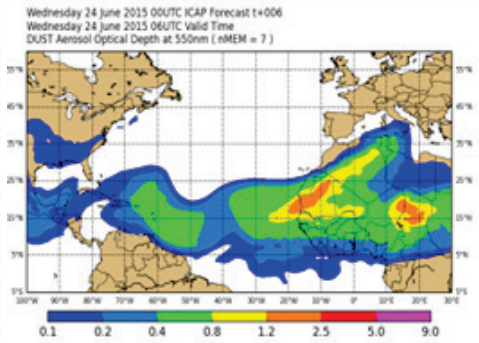


Sessions et al. 2015

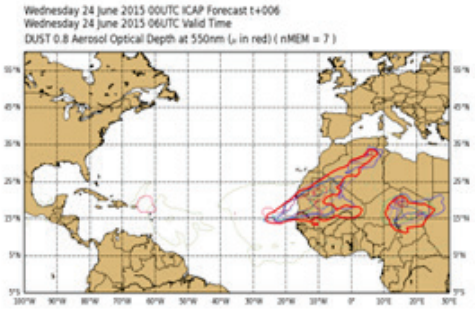
Benefits of having an ensemble:

Probabilistic products with independence among ensemble members.

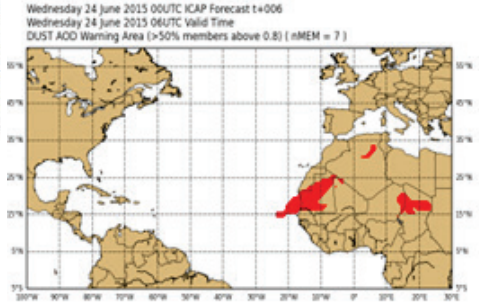
African Dust reaching DC, June 23, 2015



1. Ensemble Mean

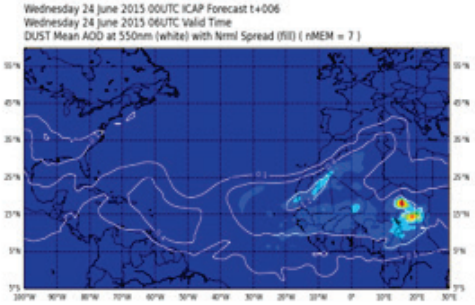


2. AOT Contour (0.8)



3. Dust Warning Product

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



4. Normalized Ensemble Standard Deviation

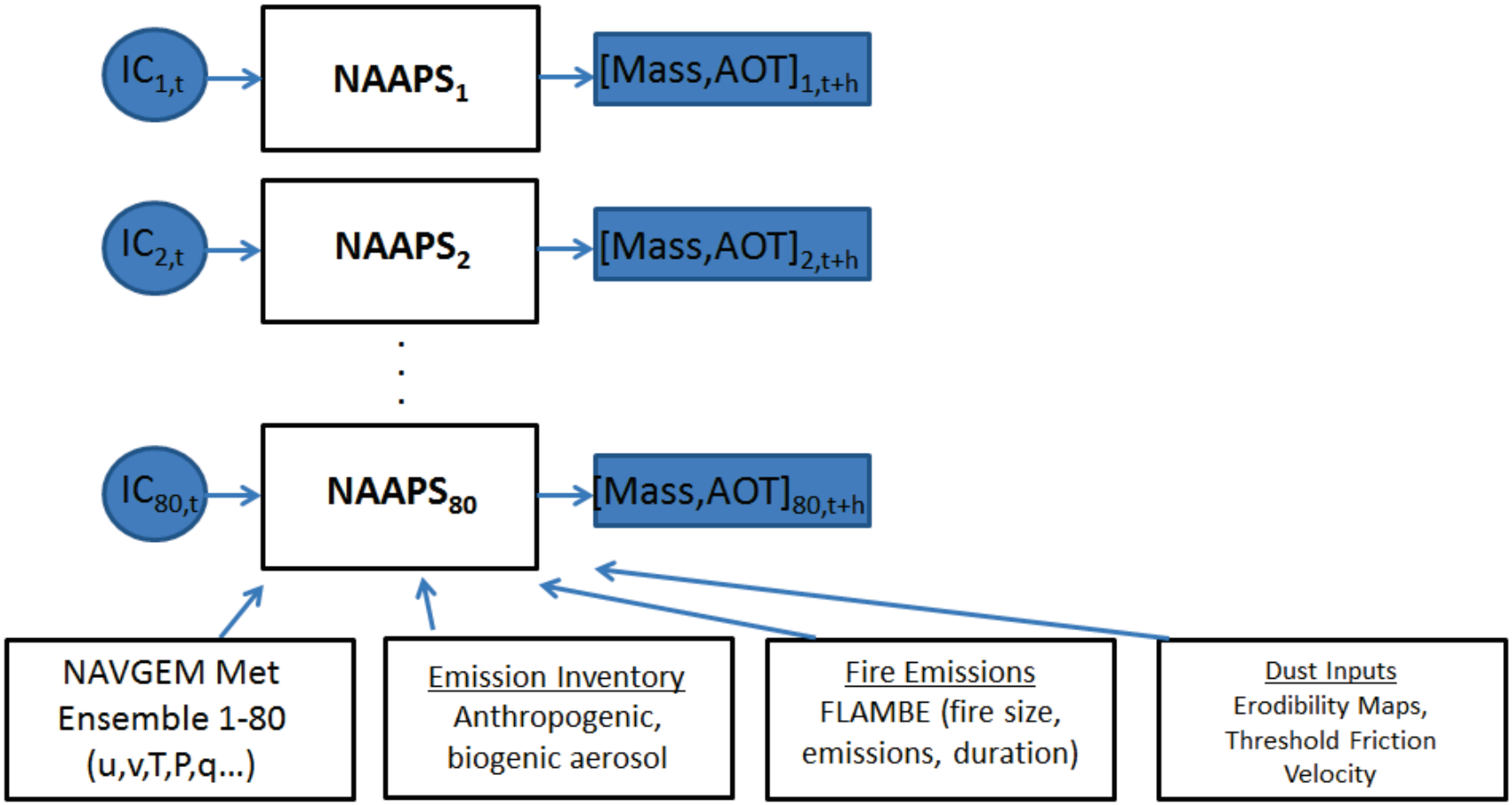
Used by WMO Sand and Dust Storm Warning System (SDS-WAS)

https://sds-was.aemet.es/forecast-products/dust-forecasts/sds-was-and-icap-ensemble-forecasts

Navy Global Aerosol Prediction: Ensemble NAAPS

Accounts for uncertainty with 20-80 ensemble members:

1. Initial conditions (aerosol mass)
2. Meteorology (NAVGEM ensemble)
3. Emissions (perturbed emissions across members)



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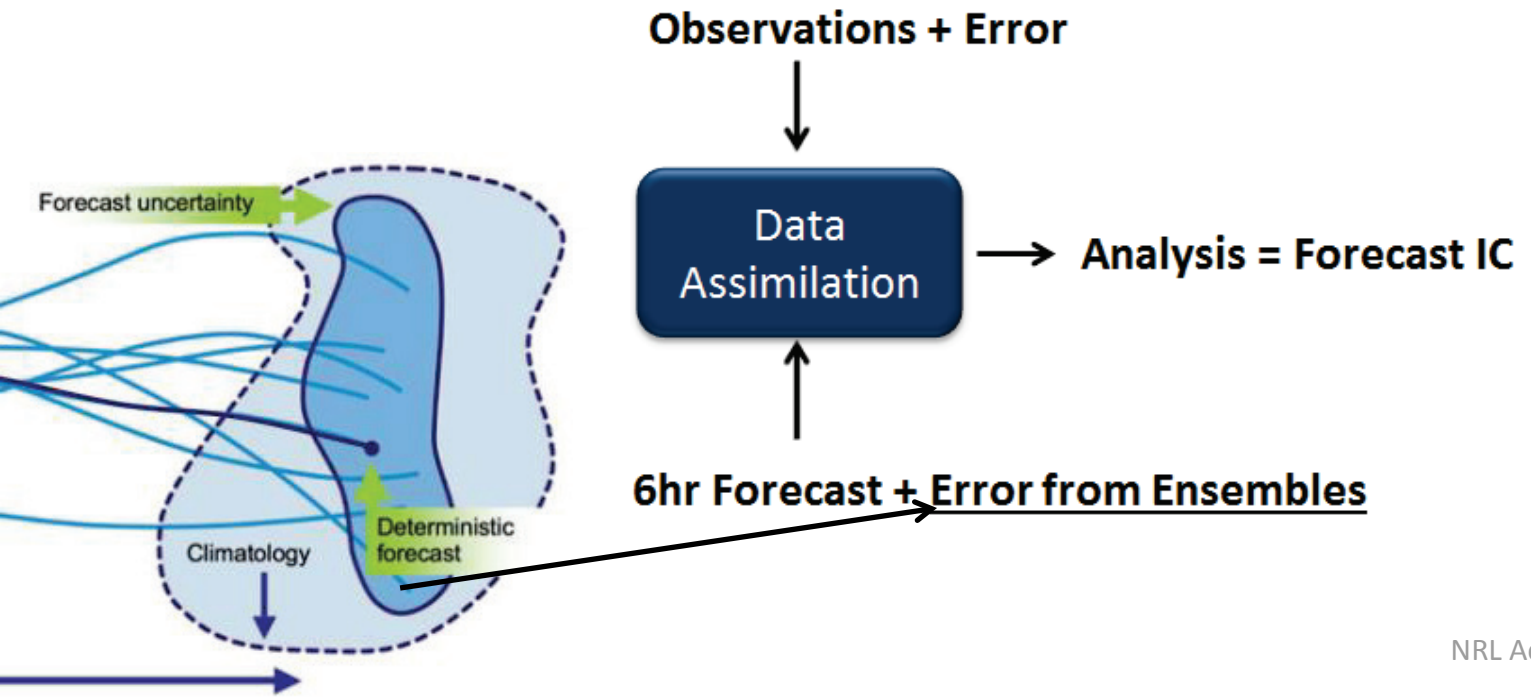
Development Efforts have focused on **data assimilation**:

1. ENAAPS coupled to an EAKF data assimilation (DART) to take advantage of flow-dependent forecast errors.



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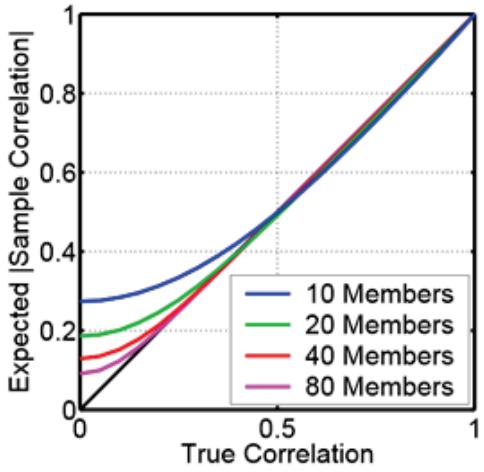
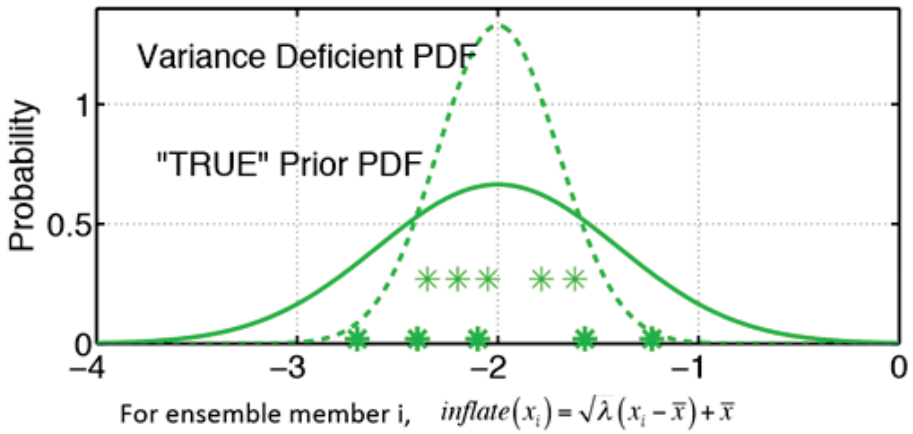
2. Ensemble system was optimized to minimize error, produce representative ensemble spread.

1. Localization



2. Inflation



3. Ensemble Generation

Source ensemble
vs
Met ensemble
vs
Met+Source

Rubin et al. 2016, ACP

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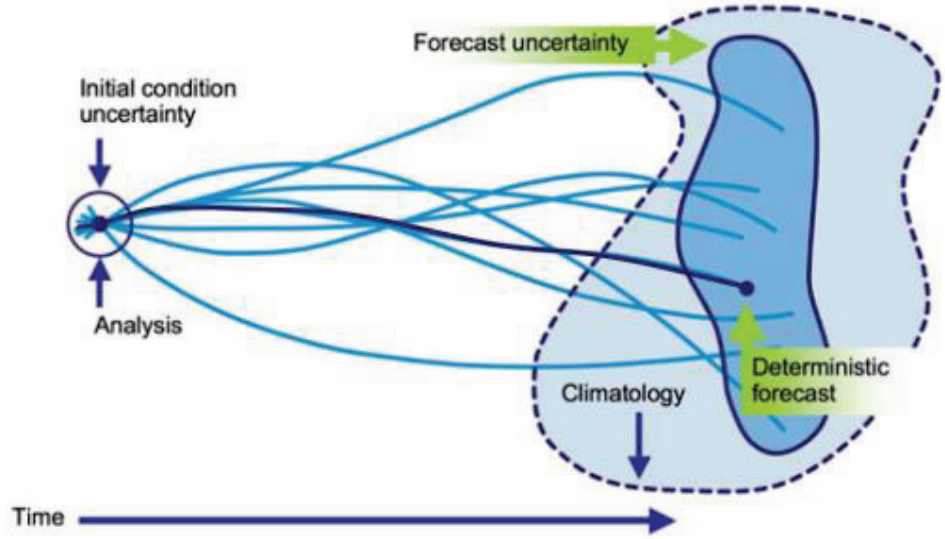
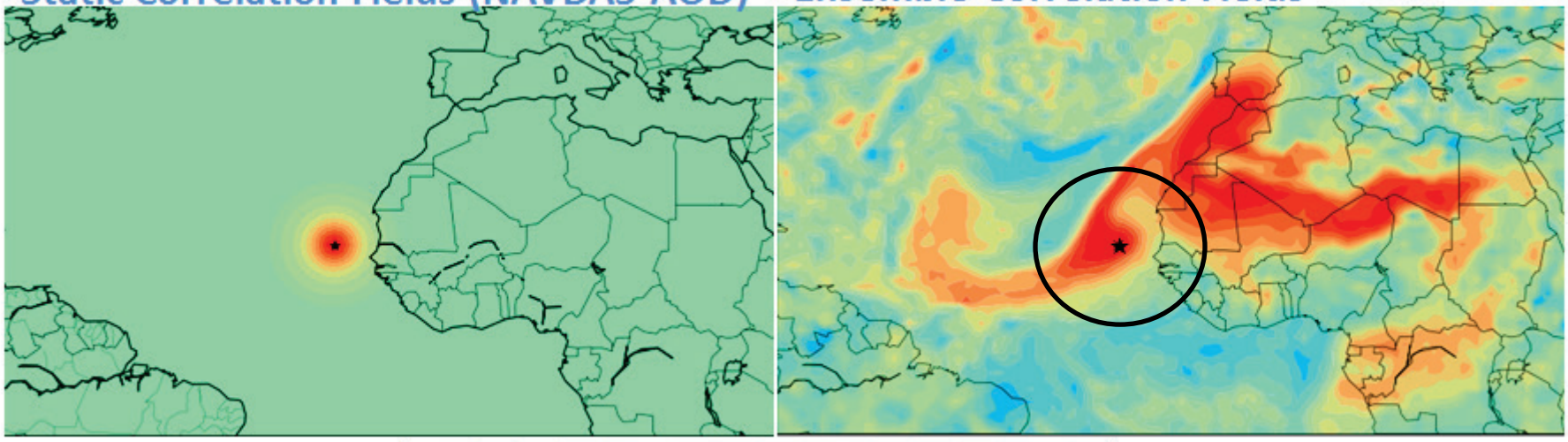
Flow-Dependence: Making better use of observational information

- Ensembles provide a means for representing flow-dependent forecast uncertainty that varies in space and time.
- Flow-dependent representation of uncertainty results in a better data assimilation analysis.



Static Correlation Fields (NAVDAS-AOD)

Ensemble Correlation Fields



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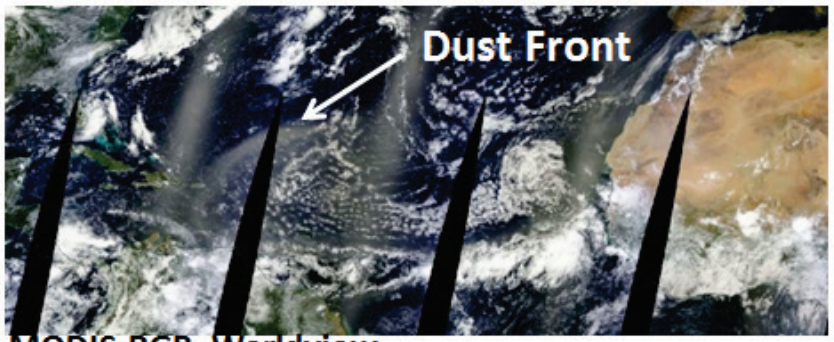
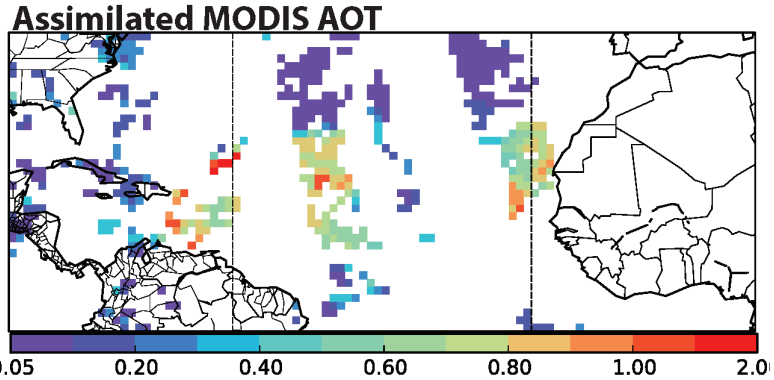
Flow-Dependence: Making better use of observational information

Saharan dust event case study on August 2, 2013



MODIS RGB, Worldview

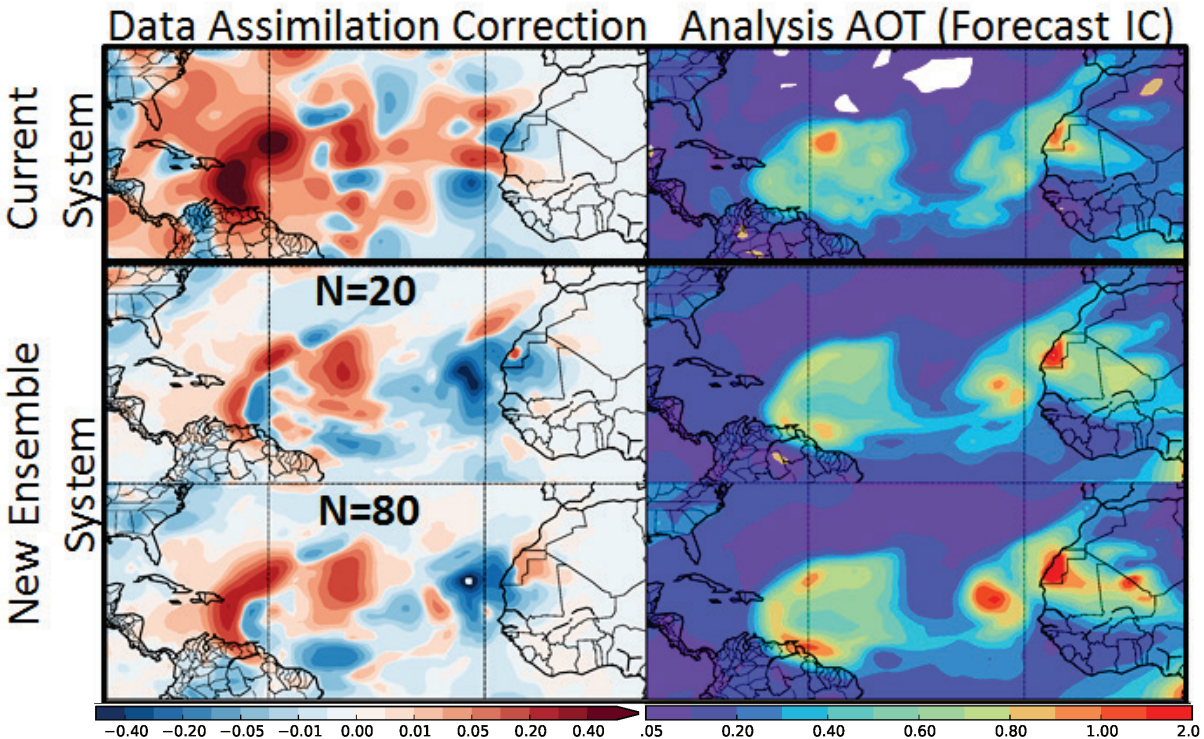


Current System: Observationally driven, produces large DA corrections. Issues with shape.

New Ensemble System: Captures dust front shape.

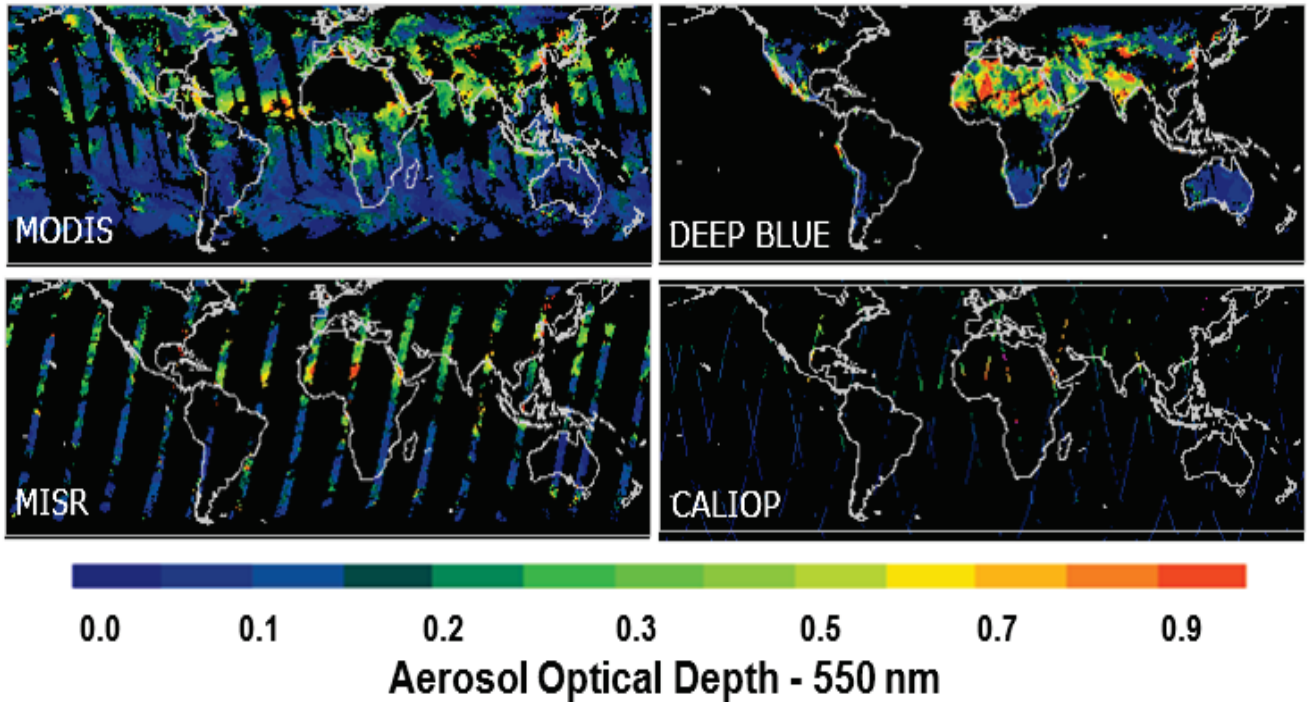
***Significant improvement with 80 members in magnitude and position**

Rubin et al. 2016, ACP



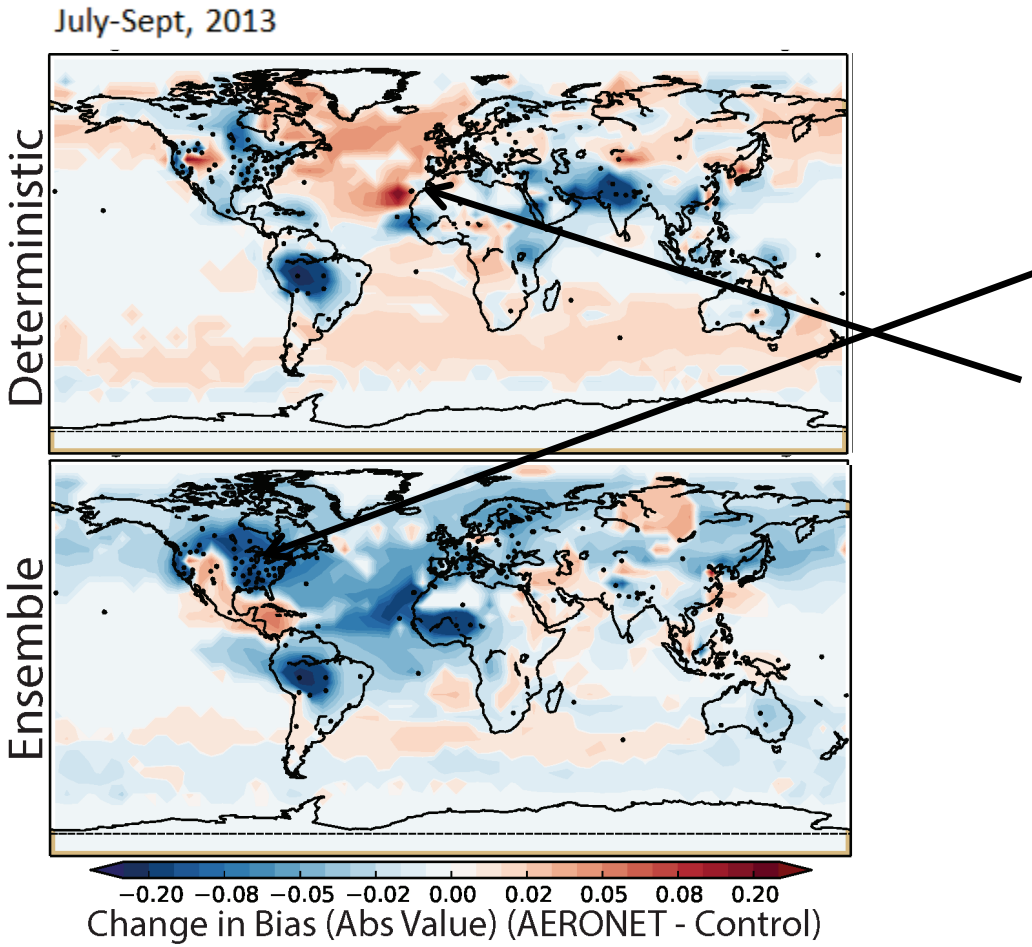
Flow-Dependence: Making better use of observational information

Many aerosol-related data streams that have limited spatial coverage relative to MODIS…



Can we make better use of sparse observations for generating our forecast initial conditions with ENAAPS?

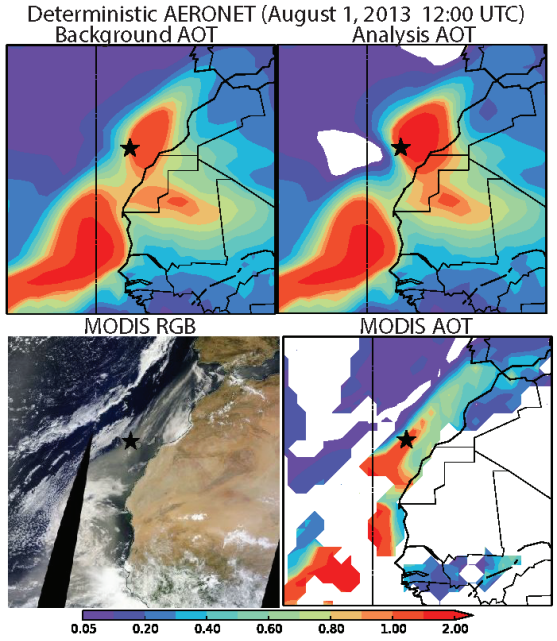
ENAAPS: Impact of AERONET Assimilation on AOT Analysis RMSE



*Control = no data assimilation

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

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



Rubin et al. 2017, JGR

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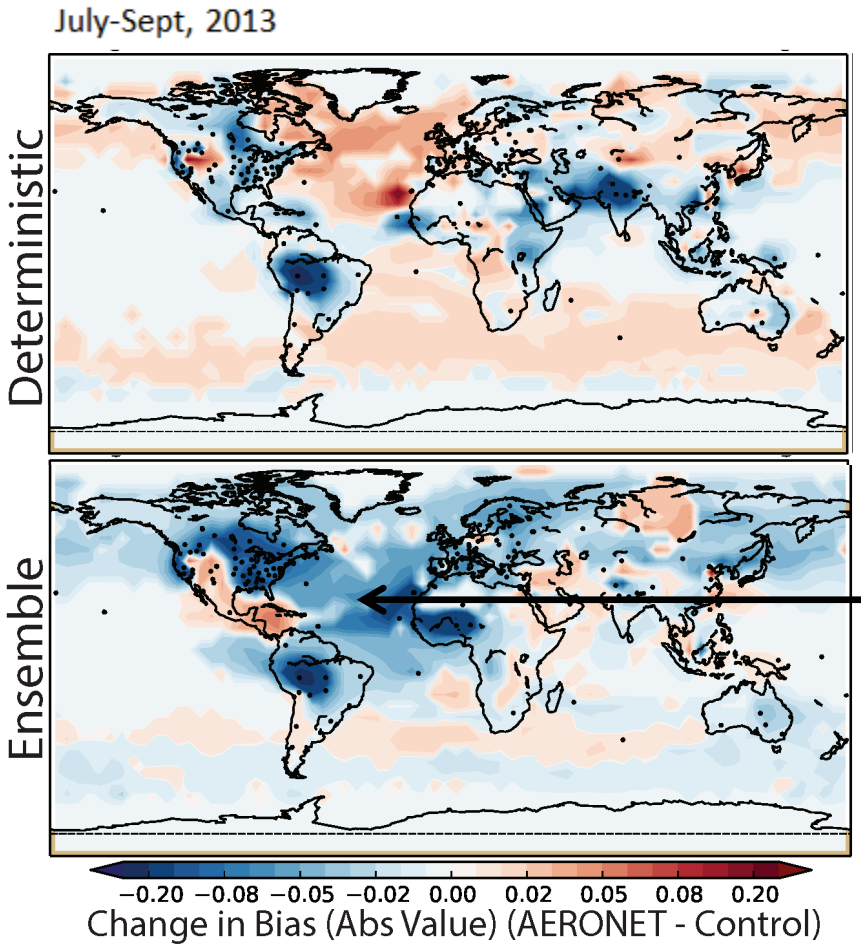

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Rubin et al. 2017, JGR

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1. **Analysis verified with MODIS AOT**
2. **Largest error reduction in high observation density regions**
3. **Large increases in error can occur with NAVDAS-AOD (2D-Var data assimilation)**
4. **The spatial extent of the error reduction is much greater with the ensemble (EAKF)**

Demonstrates the importance of flow-dependent error for assimilating sparse aerosol-related observations.

This is expected to apply to other observational data as well (lidar, aircraft, ship etc.).

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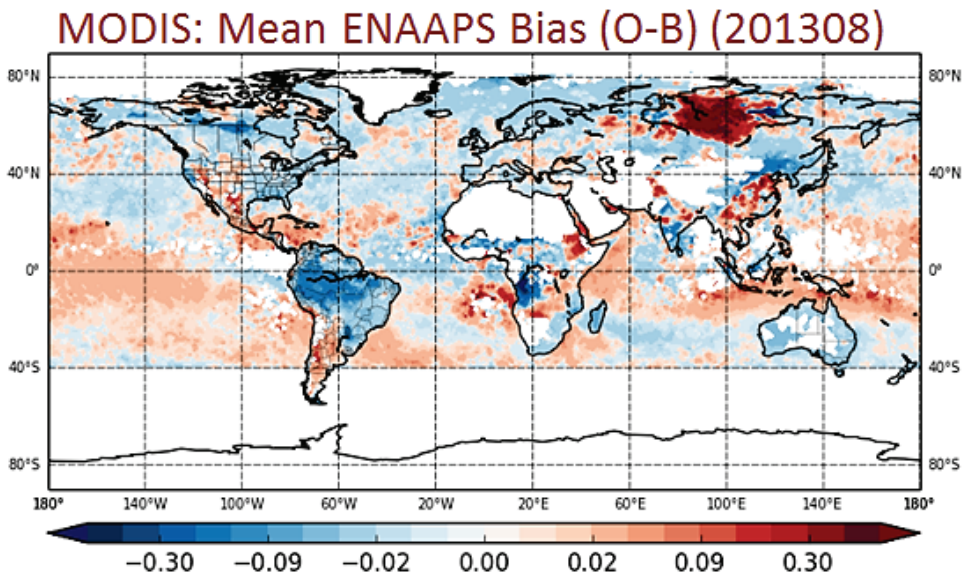
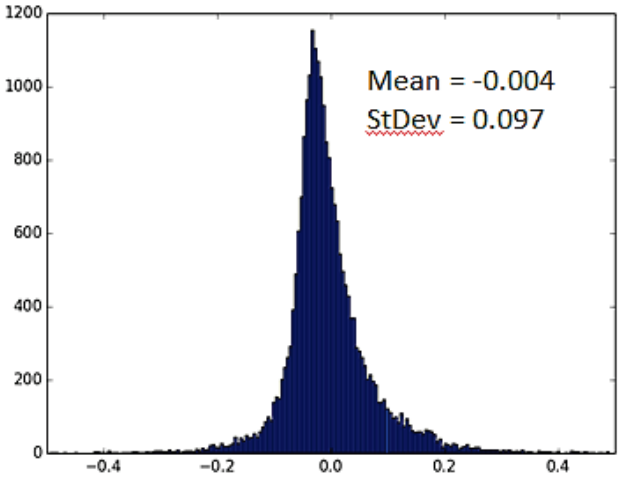
Ongoing ENAAPS Efforts

Bias in the ensemble mean…

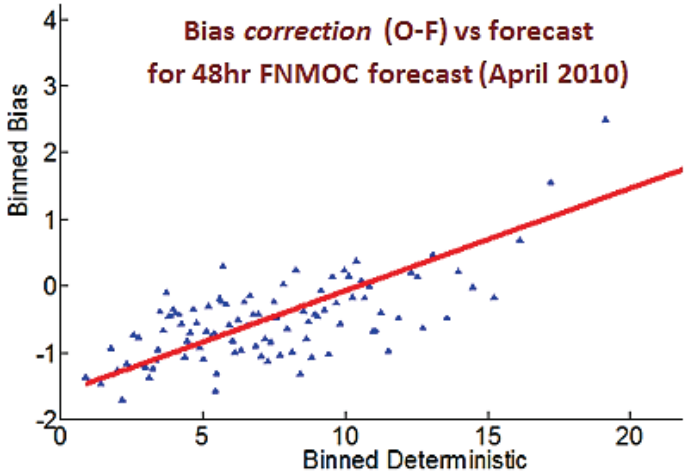


AERONET: ENAAPS Bias (O-B) (201308)



Systematic errors lead to bias in the ensemble mean and spread:

State-dependent bias correction being implemented.



The regression line is used to map forecast to bias correction, and is a function of forecast lead and location.

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Navy Ensemble Capabilities Moving Forward

ICAP-MME:

- Continues to be generated at NRL Monterey on a daily bases for AOT (total, fine, coarse, dust).
- New fields may be added in the future (e.g. surface PM).
- Data are available on the Global Ocean Data Assimilation Experiment web page (ftp://usgodae.org/pub/outgoing/nrl/ICAP-MME)

ENAAPS:

- ENAAPS is moving towards operational implementation.
- It is now capable of cycling for near real time forecasts on Navy DSRC machines, a first step towards operations.
- 80 ensemble members for assimilation, 20 member subset for forecasts.
- Current research underway to further improve ensemble performance, including bias correction.

Ensembles forecasts contain additional pieces of information, relative to a deterministic forecast. As a result, ensembles are becoming increasingly common for aerosol prediction as a means to improve forecast guidance.