DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Aerosol Observability and Data Assimilation Investigations in Support of Atmospheric Composition Forecasts

Jeffrey S. Reid, James R. Campbell, Edward J. Hyer, and Walter Sessions
Naval Research Laboratory
7 Grace Hopper Ave., Stop 2
Monterey, CA 93943-5502
phone: (831) 656-4725 fax: (831) 656-4769 email: jeffrey.reid@nrlmry.navy.mil

Document Number: N0001411WX20876
http://www.nrlmry.navy.mil/aerosol/

LONG-TERM GOALS

In this project we initiated a 3 year effort by the Naval Research Laboratory Code 7544 to enable Navy aerosol forecasting to take full advantage of available data feeds through the investigation of fundamental atmospheric composition observability. The next generation of data feeds and associated technology presents a number of challenges and opportunities which require attention. These include: 1) The transition from NASA EOS sensors to the next generation of diversified operational and near real time data sources; 2) The move to a constellation approach to global atmospheric composition observing, 3) The expected near real time availability of US and European lidar data; 4) The enhanced availability of surface and aircraft observations, and 5) Increased aerosol model demands for such applications as joint surface-atmosphere retrievals, directed energy(DE), and intelligence, surveillance, and reconnaissance (ISR). This increase in the number of potential data sources, coupled with further efficacy demands, creates an imperative need to understand the nature of global aerosol observability and the development of realistic uncertainties for composition observations, retrievals and model products. Outstanding problems facing the community relate to such issues as observation bias, representativeness, and information spreading for the myriad of sporadic data sources available. To meet this need, we propose to investigate the use of these diverse flows of data using ensemble and ensemble data assimilation technologies to be incorporated into the Navy Aerosol Analysis and Prediction System (NAAPS)/Navy Variational Analysis Data Assimilation-Aerosol Optical Depth (NAVDAS-AOD) framework.

OBJECTIVES

Our overarching goal is to ultimately investigate applied science aerosol observability issues related to the proper determination of observed product efficacy and information spreading. To this end the core methodology will be through the development and application of an ensemble version of NAAPS and its subsequent ensemble based data assimilation system. Subcomponents include;

1) The development of an ensemble-based NAAPS system which makes use of the FNMOC NOGAPS ensemble data set: Here we will use the base NAAPS model, including the data assimilation system and run in parallel with the 20 NOGAPS fields, further perturbed with 10

to 30 additional perturbations to source and sink functions. This version of NAAPS will be prepared for eventual transition to 6.4 and FNMOC if the Navy so desires.

2) The development of key verification metrics of models and observations alike: Based on initial simulation of the ensemble, we will investigate appropriate error metrics for Navy satellite and model products that account for the non-Gaussian, spatially correlated nature of biases present in the environment. This objective includes the development of probabilistic tools for forecasts. These can then be applied to satellite observations for model verification.

3) Investigation into the nature of available satellite and in situ observations including their flow dependant correlation lengths for use in NAVDAS-AOD: The optimal mix of meteorological and source/sink perturbations for the NAAPS ensemble for given computational constraints will be identified. A particular emphasis will be on the application of these methods to aerosol vertical distribution.

4) The incorporation of NAAPS in to the NCAR Data Assimilation Test-bed (DART): Once the NAAPS ensemble model is running quasi-operationally and is well understood, we will port NAAPS to the DART package at NCAR. This is the first step in developing our ensemble-based data assimilation system.

5) The creation of a research grade ensemble-based data assimilation system: Based on our experience with the DART system, we anticipate being able to have the ability to harvest and develop a robust ensemble based data assimilation system. This will be used to supplement the existing 3DVAR aerosol data assimilation system currently in use. Emphasis in this system will be on sparse or isolated observations such as provided by lidars, sun photometers and surface reports. In addition, ensemble covariability studies will be carried out to address phenomenological questions such as modes of atmosphere/aerosol coupling.

6) Collaborate with other centers to derive an aerosol consensus for severe events: It has been shown that for many extreme events consensus forecasting is a top performer. In this objective we wish to investigate the applicability of performing multi-model consensus of GMAO, ECMWF and other centers to investigate the predictability and extent of significant aerosol events.

APPROACH

Work performed in FY11 focused on the development of NAAPS single model and, in partnership with other operational centers globally, the creation of a first of its kind multi-model ensemble. In preparation for years 2 and 3 we also began to examine the use of Ensemble Kalman Filter (EnKF) methods as a data assimilation engine for NAAPS.

Our first task for this project was to develop the modeling framework to run and display an ensemble version of NAAPS (henceforth eNAAPS) quasi-operationally. Nominally we use the 20 NOGAPS ensemble members generated by FNMOC every 12 hours. On top of these, we will generate another 8-20 members based on perturbations to the NAAPS source function. The selection process, how these draws will be made, is critical. On one hand, we could simply scale all source functions +/- some percent; this would maximize correlation lengths and ultimately influence plumes at the continental scale. On the other hand, performing draws on the 6 hourly model time step will shorten correlation lengths to individual event levels. Establishing the proper balance of draws coupled with the computational cost of each model simulation will require a great deal of back-and-forth between model development and the analysis components of the project. This balance will also drive computer and storage requirements procured under this grant.

After the model was running quasi-operationally, adequate tools and display system were developed. Basic tools for analyzing ensemble variably, correlation length scales, and the most commonly employed "spaghetti plots" were largely adapted from existing Matlab code into Perl, Python and IDL framework currently used in 7544 and FNMOC. Online verification products based on AERONET, satellite data and own analysis are being developed.

In a similar manner to eNAAPS, we cooperate with other meteorological centers over the globe which are developing global aerosol prediction capabilities. By pulling data from such centers as ECMWF, JMA, NASA GMAO, and NOAA NCEP, we created a first of its kind global aerosol multi-model ensemble. For comparison purposes, products generated are similar in nature to eNAAPS.

While we view this first half of the development component to be straightforward, beneficial to Navy needs and of very low risk, the bulk of the effort in years two and three will be towards the much higher risk/reward ensemble based data assimilation effort. The Japan Meteorological Agency (JMA) and its funded researchers have made significant progress in the application of Ensemble Kalman Filter (EnKF) to aerosol modeling. Due to the extensive lidar network maintained by the Japanese National Institute for Environmental Studies (NEIS), coupled now with space based CALIOP lidar data, the Japanese have a solid observing system for the assimilation of major dust and pollution outbreaks with a particular emphasis on boundary layer aerosol particles. This capability is in line with many US Navy needs and should be applied. Our course of action is to port NAAPS into the NCAR *Data Assimilation Research Testbed (DART).* DART hosts numerous ensemble–based data assimilation tools including the core components of an EnKF system. Both NOGAPS and COAMPS have already been ported to DART and in fact ensemble based COAMPS dust source functions studies are already underway under a joint project with Dr. Hansen. Hence, in house knowledge already exists to expedite this process. Included in this budget is additional travel money so that NRL developers can spend the required time at NCAR to make this port happen.

WORK COMPLETED

1) An ensemble version of NAAPS (eNAAPS) was created running off of the 20 member NOGAPS ensemble.

2) A multi-model ensemble of Navy, ECMWF, JMA and NASA GMAO global aerosol fields was created. Names the International Cooperative for Aerosol Prediction (ICAP) ensemble, products include mean/spread plots, "spaghetti" plots, and event threat scores.

3) A website has been created for the distribution of both eNAAPS and the ICAP ensemble.

4) Online verification tools have been generated for scoring of ensemble members.

5) Performed preliminary work on the use of the Data Assimilation Research Testbed (DART) for ensemble based data assimilation in NAAPS has begun.

RESULTS

Research results for this project can be divided into areas of ensemble development, verification, and data assimilation.

Ensemble Development: 7544 developed collinearly both the eNAAPS single model and ICAP multi-model ensemble, both of which became quasi-operational in late December 2010. Data for eNAAPS is available to the general public via the 7544 website (http://www.nrlmry.navy.mil/aerosol/) at (http://www.nrlmry.navy.mil/aerosol/NAAPS_ens.php). An example of these products is presented in Figure 1. In a webpage of similar style, the ICAP multi-model data is available (Figure 2). However, as the model centers are tuning their models, we currently do not advertise this site outside of the ensemble participants. A new site where individual models are not identified is under construction.

Verification: Key to the ensemble system development is verification, which is underway at the aforementioned distribution websites. An example plot against AERONET is presented in Figure 3. In cooperation with ONR sponsored elements at the University of North Dakota, our own analysis verification system has been created where forecasts are compared to that time period's post data assimilation analysis. This allows for very rapid evaluation of forecast model health in a contiguous manner.

Data Assimilation: Output from eNAAPS has been utilized in DART tools to study ensemble output spread and error covariance for specific cases. Focus has been on Asian dust and pollution events which showed a high degree of spread in the forecast magnitude in aerosol optical depth. In general, such areas appear to be associated with diversity in frontal location. Frontal location in turn is associated with frontal strength and ultimately precipitation. This precipitation uncertainty propagates into the wet deposition algorithms in NAAPS, ultimately modulating aerosol loading and forecast EO propagation impacts. These cases will be used as starting points for investigations for EnKF assimilation in eNAAPS in FY12.

IMPACT/APPLICATIONS

We expect much of this work to be of immediate use to the warfighter. Just as the current NRL aerosol page is frequently used in the METOC community, we expect these ensemble products to be of immediate applicability. To begin with, in key portions of the globe we can generate dust, smoke, or pollution "Spaghetti plots" for each of the meteorological members (Figure 4) or independent models. These can also be shown spatially as areas of high variability (Figure 1c). In these areas we will collaborate with Dr. Hansen who is working on METOC impacts, decision aids, and scorecards.

TRANSITIONS

We have begun discussions with FNMOC to transition eNAAPS to operations.

RELATED PROJECTS

This project is tightly coupled to a number of ONR 32 programs, particularly those of Professor Jianglong Zhang at the University of North Dakota. Our primary transition partner is Douglas Westphal, who is principal investigator on the Large-Scale Aerosol Model Development (PI: Doug Westphal). New data-processing and visualization systems are being adapted for aerosol research through the COAMPS-On Scene(COAMPS-OS®)[1] IVPS charts program (PI: John Cook). We have also begun working with Jim Hansen on his ONR -funded project for the use of ensemble data assimilation in the prediction of atmospheric constituents.

PUBLICATIONS

Akagi, S. K., R. J. Yokelson, C. Weidinmyer, M. J. Alvarado, **J. S. Reid**, T. Karl, J. D. Crounse, and P. O. Wennberg (2011), Emission factors for open and domestic biomass burning for use in atmospheric models, Atmos. Phys. and Chem, 11, doi:10.5194/acp-11-4039-2011, 4039–4072, 2011.

Chew, B. N., **J. R. Campbell**, **J. S. Reid**, D. M. Giles, E. J. Welton, S. V. Salinas and S. C. Liew (2011), Tropical cirrus cloud contamination in sun photometer data, Atmos. Environ., in press, expected publication date late September 2011.

Eck, T.F., B. N. Holben, A. Sinyuk, R. T. Pinker, P. Goloupm H. Chen, B. Chatenet, Z. Li, R. P. Singh, S. N. Tripathi, **J. S. Reid**, D. M. Giles, O. Dubovik, N. T. O'Neill, A. Smirnov, P. Wang, and X, Xia,(2010), Climatological aspects of the optical properties of fine/coarse mode aerosol mixtures, J. Geophys. Res., 115, D19205, doi:10.1029/2010JD014002.

Hansell, R. A., **J. S. Reid**, S. C. Tsay., T. L. Roush, and O. V. Kalashnikova, A sensitivity study on the effects of particle chemistry, asphericity and size on the mass extinction efficiency of mineral dust in the terrestrial atmosphere: From the near to thermal IR, Atmos. Chem. And Phys., 11, 1527-1547.
Hyer, E. J., J. S. Reid, and J. Zhang, An over-land aerosol optical depth data set for data assimilation by filtering, correction, and aggregation of MODIS Collection 5 optical depth retrievals (20110, Atmos. Meas. Tech.. 4, 379-408, doi:10.5194/amt-4-379-2011.

Lyapustin, A., Y. Wang, I. Laszlo, R. Kahn, S. Korkin, L. Remer, R. Levy, and **J. S. Reid** (2011), Multi-angle implementation of atmospheric correction (MAIAC): Part 2 Aerosol Algorithm, J. Geophys. Res., 116, D03211, doi:10.1029/2010JD014986.

Shi, Y., J. Zhang, **J. S. Reid**, B. Holben, E. J. Hyer, and C. Curtis(2011), An analysis of the collection 5 MODIS over-ocean aerosol optical depth product for its implication in aerosol assimilation, Atmos. Chem. And Phys., 11, 557-565.

Smirnov, A., B. N. Holben. D. M. Giles, I. Sutsker, N. T. O'Neill, T. F. Eck, A. Macke, P. Croot, Y. Courcoux, Y., S. M. Sakerin, S. M., T. J. Smyth, T. Zielinski, G. Zibordi,J. I. Goes, M. J. Harvey, P. K. Quinn, N. B. Nelson, V. K. Radionov, C. M Duarte, R. Losno, J. Sciare, K J. Voss, S. Kinne, N. R. Nalli, E. Joseph, K. K. Moorthy, K. D. S. Covert, S. K. Gulev, G. Milinevsky, L. Larouche, S. Belanger, E. Horne, M. Chin, L. A. Remer, R. A. Kahn, **J. S. Reid**, M. Schulz,C. L. Heald, J. Zhang, K. Lapina, R. G. Kleidman, J. Griesfeller, B. J. Gaitley, Q. Tan, T. L. Diehl,(2011), Maritime aerosol network as a component of AERONET- first results and comparison with global aerosol models and satellite reterivals, Atmos. Meas. Tech., 4, 583-597.

Zhang, J., J. R. Campbell, **J. S. Reid**, D. L. Westphal, N. L. Baker, W. F. Campbell, and E. J. Hyer (2011), Evaluating the impact of assimilating CALIOP-derived aerosol extinction profiles on a global mass transport model, Geophys. Res. Lett., 38, L14801, doi:10.1029/2011GL047737.

[1] COAMPS-OS® is a registered trademark of the Naval Research Laboratory.

Zhang, J., and **J. S. Reid** (2010), A decadal regional and global trend analysis of the aerosol optical depth using over water MODIS and MISR aerosol products, Atmos. Chem. and Phys., 10, 10949–10963.

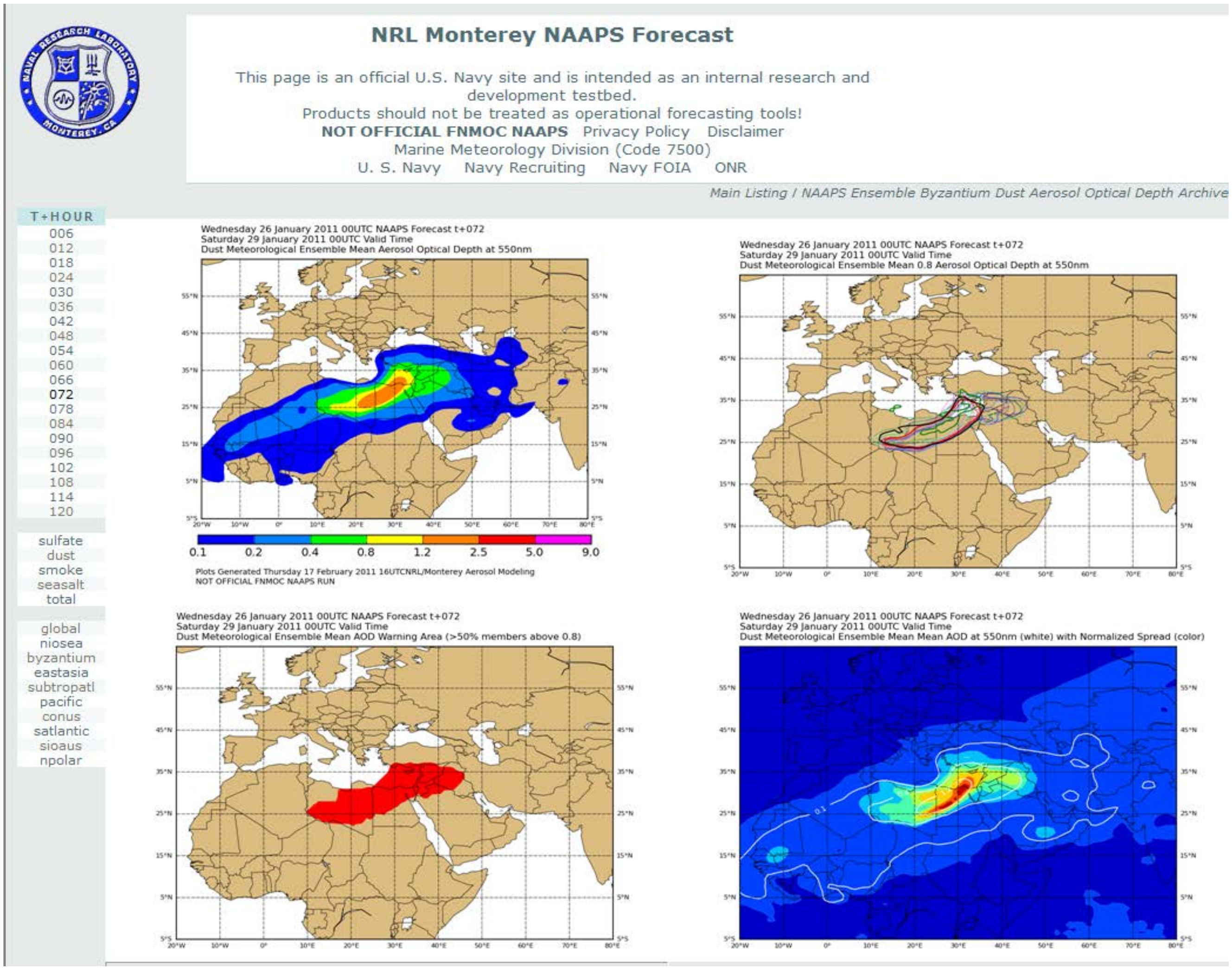

Figure 1. Example output for the quasi-operational ensemble NAAPS (eNAAPS) from the NRL aerosol website. Shown in the 72 hour forecast initiated on January 26st for the Africa/Europe domain. Given are (upper left) ensemble mean, (upper right) spaghetti plot for aerosol optical depth >0.8, (lower left) dust warning area where 50% or more members predict dust optical depths >0.8, and (lower right) mean and standard deviation of the ensemble AODs.

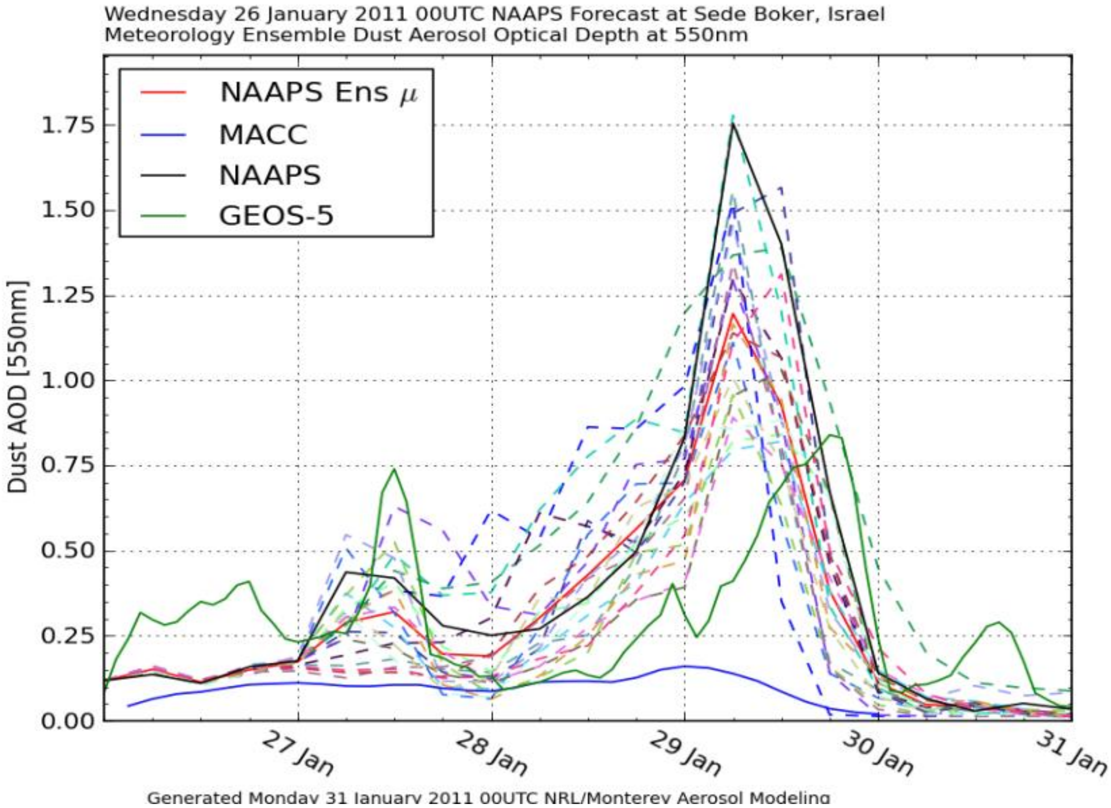

Figure 2. Multimodel ensemble output for Navy eNAAPS, ECMWF MAAC, operational NAAPS and NASA GMAO GEOS-5 for a dust event in northern Africa for January 29th, 2011 as also used in Figure 1.

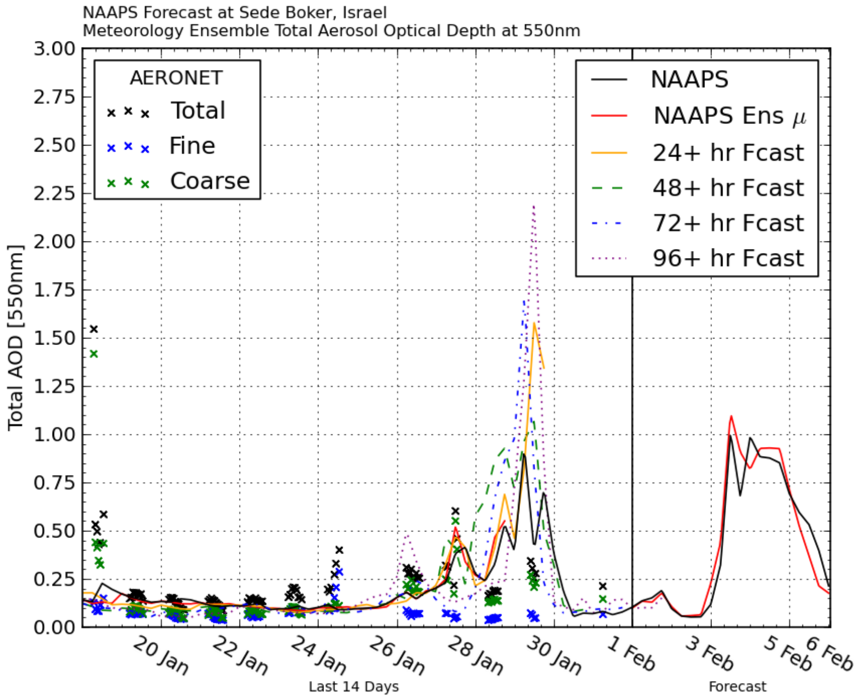

Figure 3. Example verification plot showing NAAPS, eNAAPS forecast data against AERONET sun photometer data for the January 29th 2011 dust event.