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Use of Ensemble Datasets to Develop Best Practices for the Forecasting of Aerosol Impacts on Electro-Optical Propagation: What Makes a Good Aerosol Model?

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Document Number: N0001414WX20350
http://www.nrlmry.navy.mil/aerosol/

LONG-TERM GOALS

This project will initiate the world's first dialog with other operational Numerical Weather Prediction center developers on the best practices for aerosol model evaluation and validation and, based on their input, allow development of an aerosol modeling scorecard suitable for Navy use. Recently, there has been rapid development of aerosol capabilities across operational NWP centers, leading to a proliferation of aerosol analysis and forecast products. However, the community has not determined clear guidelines and baselines that can be used to evaluate model skill and assess model improvement, outside of the crudest bias statistics. The simple question "What makes a good aerosol model?" currently has no answer outside of simple column metrics at isolated sites. The challenge in defining evaluation metrics lies in the differences across NWP centers. Modeling centers are responding to the needs of a diverse set of customers, ranging from regional air quality, to the development of priors for remote sensing products, to air, ground and surface operations. As a result, the path to the development of NWP aerosol capabilities has been quite different and what constitutes an improvement for one model may not hold for another. Certainly, the underlying meteorology driving the aerosol models has some degree of independence, and the aerosol sources, microphysics and sinks have also been developed or drawn from a variety of air quality and climate data sources. These differences in meteorology and aerosol sources/parameterizations, developed from a particular aerosol heritage, lead to a significant amount of model tuning. The diversity between the various modeling center goals and modeling philosophies has led to some growing pains in the field. In order to move forward in defining best practices for model evaluation and validation, it is necessary to identify common interests across centers, such as the impact of aerosol particles on NWP skill. We will develop metrics that are agreed upon by the community to broadly address the most common aerosol users.

A second focus area of this research is to develop scores that are relevant to the Navy based on location and impact. Current aerosol model verification data sites are scattered and are often not in Navy areas of interest. Often data is available at sites are not even representative of the large air

masses in which they are imbedded. In addition, there is limited understanding of what the available metrics from these sites mean for Navy relevant parameters such as visibility, surface transmission, and infrared radiance perturbation (e.g., what does an RMSE of model aerosol optical thickens at Cape Verde off of Africa mean for our ability to correct a sea surface temperature retrieval at the surface?). Further, as aerosol model error covaries with the underlying NWP error, we can go a step further, and ask how does meteorological covariance between aerosol error and relative or specific humidity, for example, impact our ability to assess electro optical or atmospheric radiative effects? This project will allow us to determine how fundamental improvements in the NWP model help Navy EO propagation prediction.

OBJECTIVES

We propose four core goals that will build from the current foundation of the Navy ensemble aerosol modeling effort. These goals are highly interrelated, and are required to meet our final goal (#4) of a meaningful aerosol scorecard for EO propagation.

1) Transition from NOGAPS to NAVGEM: The recent transition from NOGAPS to NAVGEM as the Navy's core global meteorological model will enhance ensemble modeling once some technical challenges are overcome. For example, existing analysis and data assimilation code must be adapted to the new architecture.
2) Development of a broadly applicable aerosol analysis for EO propagation: Based on a combination of in situ, satellite, and model data, we will develop an aerosol analysis product that can be used for broad analysis of the global aerosol field, as well as provide a baseline for the verification of aerosol models. This product will fuse multiple satellite data sets, bound through an Ensemble Kalman Filter (EnKF) approach. Application of optical models to this analysis will provide baseline information on electro-optical propagation in the visible through IR. This analysis will then be used as the basis for the remaining verification and error propagation work.
3) Forward modeling and error assessment: We will forward model NWP and aerosol input through radiative models into EO space, and thus propagate error in metrics, such as aerosol optical thickness and speciation, to visible and infrared transmittance, energy budget and visibility. The application of findings to single and multi-model probabilistic aerosol models at NRL provides an excellent opportunity to understand current state of the art uncertainties and explore best practices in aerosol modeling. Through ongoing cooperation via the International Cooperative for Aerosol Prediction (ICAP), NUOPC style consolidation of aerosol related products and algorithms will be possible.
4) Development of a score card and evaluation of best practices: Based on the comparison of ensemble members to the aerosol analysis, we will develop an EO propagation scorecard to help identify areas of research that require special attention in EO modeling systems, followed by an evaluation of best practices. Examples of full error propagation include visibility, sea surface temperature, and beam power loss. Ultimately, our goal is to answer the question: What is a good global aerosol model for electro-optical propagation forecasting?

APPROACH

This project will build on existing aerosol ensemble forecasting and verification architecture created in a previous ONR 322 grant. The first priority was Objective 1; to update the NAAPS ensemble from

the existing NOGAPS architecture to NAVGEM. The 2013 year has seen significant changes in both the deterministic NWP modeling (moving from NOGAPS to NAVGEM) as well numerous improvements to NAAPS. Changes in NAVGEM work their way into the aerosol model in such areas as surface winds, precipitation, and relative humidity. Normally, the aerosol model needs to be tuned to account for changes in the mean bias in these quantities. It is expected that the NOGAPS meteorological ensemble will also transition to NAVGEM and will require tuning as well. This is functionally straightforward and can be completed in year one, although some time will be required to retune the aerosol model based on the new NAVGEM meteorology. At the same time as this update, we will add additional models to the ICAP-MME. UKMO data was released in the first year, and several other centers have asked for inclusion.

Also in the first year, we began to consolidate the numerous satellite aerosol products used in assimilation. For example, while NRL uses a perturbed version of the standard MODIS AOT retrieval, NASA GMAO uses its own neural network AOT product. While the NRL AOT product has superior RMSE, the NASA GMAO product has vastly better coverage. Recently, an opportunity has also arisen to utilize more European products. Likewise, JMA and ECMWF have their own products, parts of which we will incorporate and consolidate to ultimately combine the best aspects of each. In addition to AOT products, fire and anthropogenic emission products will be collected and compared. These will be paired with other surface observations into a multi-year analysis field suitable for baseline verification of models. Already, NRL 7544 works closely with Prof. Jianglong Zhang at the University of North Dakota on model verification and improvement. At the end of the first year, we have examined many commonly used products, performed independent evaluations, and devised an assessment of product advantages and disadvantages. From this, a multi-year satellite analysis field will be generated.

WORK COMPLETED

This grant supports work along a number of parallel efforts. Major components for work completed include:

a) Navy Aerosol Analysis and Prediction System (NAAPS) Reanalysis: The 2000-2014 NAAPS reanalysis serves as a baseline for our global modeling verification studies and provides a best available historical dataset to study Navy electro-optical applications. Major upgrades funded in FY14 include:

1) *The identification and evaluation of the impact of NOGAPS upgrades over the reanalysis period, thus allowing a consistent dataset over the reanalysis period.* For example, upgrades of the NOGAPS land surface parameterization in August 2006 had significant effects on modeled dust emissions. Significant efforts were devoted to minimize this type of impact through tuning of aerosol sources in NAAPS and/or test using ECMWF meteorological reanalysis which has consistent physics throughout the time period.
2) *An evaluation of the initial impacts of the transition from NOGAPS to NAVGEM meteorology, with continued monitoring as rapid upgrades continue into the model.*
3) *Parallel NAAPS runs using the NRL standard AOT product and the new NASA AOT Neural-net satellite products were conducted and evaluated.*

b) ICAP Multi Model Ensemble (ICAP-MME): The ICAP-MME is a multi-model ensemble of quasi-operational global aerosol models run daily for AOT forecasts out to 120 hrs. The ICAP-MME

allows NRL to monitor the progress of the global aerosol forecasting community and provides a readymade test-bed for forecast model scorecard development. Major work in FY2014 includes:

1) The addition of the UK Met-office unified model's dust product in ICAP MME, thus increasing dust members to seven.
2) *The development of two levels of ICAP MME products for public access in CF-compliant netCDF format*: the AOTs of coarse and fine mode aerosols and dust aerosols for the general public; and the speciated AOTs from all models for the ICAP members. We are currently waiting for public release permission to turn on these data streams.
3) *The composition and submission of a paper detailing the ICAP-MME and its relative performance to its member models*. The paper is now in for minor revisions for publication in Atmospheric Chemistry and Physics.

c) NAAPS ensemble (eNAAPS): NAAPS has been ported to the 20 member NAVGEM meteorological ensemble, including perturbations to aerosol source functions. While eNAAPS is run quasi-operationally at NRL, it is mostly used as a developmental test bed for data assimilation and verification efforts.

1) The major effort towards eNAAPS development was through a new implementation of an ensemble-based aerosol data assimilation system with the Navy's NAAPS model (ENAAPS-DART). While NAAPS had been run with DART in the past, a significant effort was undertaken to optimize the EnKF data assimilation capabilities, resulting in fair comparisons to the currently optimized 2Dvar aerosol data assimilation system.
2) Also in FY14, this grant funded the first ensemble-based data assimilation of LIDAR observations for constraint of aerosol vertical distributions. We see this as a major milestone in Navy aerosol forecasting development capabilities.

RESULTS

The development of the NAAPS reanalysis system resulted in numerous scientific insights in basic aerosol science and the applied simulation field. Perhaps most interesting is the reanalysis' ability to reproduce decadal long trends in AOT despite the use of static pollution source functions. Figure 1 shows the reanalysis' depiction of the trend in AOT, which shows significant decadal sized enhancement in AOT over southwest, southern and east Asia. Over the Arabian Peninsula, there has been decreasing precipitation, likely resulting in enhanced dust erodibility. In Southern and east Asia, pollution emissions have been increasing, whereas in the United States and Europe, emission controls are clearly effective. The reanalysis' ability to reproduce these trends gives us confidence in its ability to simulate the global aerosol environment.

The NAAPS reanalysis was also employed to begin benchmarking differences between the approaches of different centers to data assimilation. As an initial trial, we benchmarked a new AOT retrieval product using the purely empirical neural network algorithm that is currently assimilated into NASA's GEOS-5 for aerosol forecasts. A potential advantage of this product is its increased daily spatial coverage relative to the bias-corrected AOT product that is currently used for the Navy's operational aerosol forecasts with the NAAPS model. The new neural network AOT product was evaluated relative the standard bias-corrected product to determine if it can be used to improve simulation skill. It was determined that while the new NASA product had increased coverage, the incorporation of the

new product results in statistically insignificant differences in aerosol simulation skill. Additionally, biases were identified in the new product under high aerosol loading conditions and near cloud edges. Clear dipoles in the data assimilation correction fields were identified with assimilation of cloud-contaminated AOT observations (Figure 2). An increase in aerosol loading occurs with the incorporation of the cloud-contaminated observation, followed by a decrease to remove the non-existent aerosol feature. With many new data products becoming available for aerosol data assimilation, the identified dipoles in the assimilation corrections fields are being explored as a means for automating the observation verification process.

For the ICAP MME ensemble, a recent paper was composed by Sessions et al., (2014) that outlined the ICAP-MME performance relative to its member models. Basing metrics on comparisons to 21 regionally representative Aerosol Robotic Network (AERONET) sites, all models generally captured the basic aerosol features of the globe. However, there is an overall AOT low bias among models, particularly for high AOT events. Biomass burning regions have the most diversity in seasonal average AOT. The southern oceans, though low in AOT, also have high diversity demonstrating the communities continued struggle with sea salt modeling. In regard to root mean square error, as expected, the ICAP-MME placed first over all models worldwide, and was typically first or second in ranking against all models at individual sites. These results are encouraging. As more global operational aerosol models come on line, we expect their inclusion in a robust operational multi-model ensemble will provide valuable aerosol forecasting guidance.

Finally, the how and whys to successful EnKF aerosol modeling within the NAAPS framework were explored through a new aerosol data assimilation system (ENAAPS-DART). The current operationally-run aerosol data assimilation system (NAVDAS-AOD) uses a variational approach which requires apriori assumptions about the model error. The Ensemble Kalman Filter, on the other hand, is based on the use of an ensemble of model simulations to define the model error, thereby, allowing the error to evolve nonlinearly in time. In theory, this representation of the model error should provide a more accurate adjustment of forecasts to new observations, resulting in a reduced error in the analysis state (Hamill and Whitaker 2005). The new system uses a 20-member ensemble of NAAPS simulations which incorporate the NOGAPS meteorology ensemble and draws from aerosol source functions. ENAAPS-DART has been tested and compared to NAVDAS-AOD as a baseline for assimilation of AOD observations. Results indicate comparable performance at AERONET sites, especially near source regions, with NAVDAS-AOD out-performing the ENAAPS-DART system for long-range aerosol transport events in the tropics. However, ENAAPS-DART allows for observational information to be spread in a more realistic manner than the current system as shown by the flow-dependent correction fields in Figure 3. This is an important advantage of EnKF. The results of the study point to the need for a hybrid assimilation system that takes advantage of the power of the variational methods to impact the state fields combined with the ability of the EnKF to realistically spread information. A further advantage of EnKF is its ability to assimilate vertically resolved observations. Up until recently, vertically-integrated AOT observations were the only piece of information used to constrain aerosol forecasts. Certainly, space-based LIDAR instruments, such as CALIOP, have information that is now available about the vertical structure of aerosol in the atmosphere. Assimilation of LIDAR observations is expected to have a large impact on simulation skill since atmospheric lifetime and horizontal advection of aerosol are tightly coupled to the vertical profile. The ability to assimilate CALIOP observations has already been added to the new ENAAPS-DART system with an example shown in Figure 4. Since CALIOP observations have a limited spatial footprint, EnKF is an ideal data assimilation methods due to its ability to spread observational

information in a realistic manner. Testing is currently underway to determine the impact of the CALIOP observations.

IMPACT/APPLICATIONS

The most significant Navy impact for this work is the development of a set of metrics to evaluate how Navy sponsorship of aerosol systems is improving prediction of Navy relevant METOC parameters. By performing joint verification studies with other centers, this project will allow for a more rapid Navy adoption of aerosol modeling best practices. Finally, this work also allows for a much needed worldwide discussion of how aerosol prediction verification should be performed

TRANSITIONS

We have had discussions with FNMOC to transition eNAAPS to operations. We are currently waiting for the next set of revisions of NAVGEM to take place. Once the NOGAPS ensemble transitions to the NAVGEM ensemble, we anticipate a final round of model optimization to take place before we initiate 6.4 work. Proposed scorecard products are highly desired at FNMOC.

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 demand System (COAMPS-OS®)[1] IPVS-Charts application (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

Journal Publications in Print

Meskhidze, N., M. D. Petters, K. Tsigaridis, T. Bates, C. O'Dowd, J. Reid, E. R. Lewis, B. Gantt, M. D. Anguelova, P. V. Bhave, J. Bird, A. H. Callaghan, D. Ceburnis, R. Chang, A. Clarke, G. de Leeuw, G. Deane, P. DeMott, S. Elliot, M. C. Facchini, C. W. Fairall, L. Hawkins, Y. Hu, J. G. Hudson, M. S Johnson, K. C. Kaku**,** W. C. Keene, D. J. Kieber, M. S. Long, M. Mårtensson, R. L. Modini, C.L. Osburn, K. A. Prather, A. Pszenny, M. Rinaldi, L. M. Russell, M. Salter, A. Sayer, A. Smirnov, S. R. Suda, T. D. Toth, D. R. Worsnop, A. Wozniak, S. R. Zorn (2013)., Production mechanisms, number concentration, size distribution, chemical composition, and optical properties of sea spray aerosols. Atmos. Sci. Lett., **14**(207–213) doi:10.1002/asl2.441/

Toth, T. D., J. Zhang, J. R. Campbell, E. J. Hyer, J. S. Reid, Y. Shi, and D. L. Westphal (2014). Impact of data quality and surface-to-column representativeness on the $PM_{2.5}$ / satellite AOD relationship for the contiguous United States, Atmos. Chem. Phys., 14, 6049-6062, doi:10.5194/acp-14-6049-2014.

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

Zhang, J., J. R. Campbell, E. J. Hyer, J. S. Reid, D. L. Westphal, and R. S. Johnson (2014), Evaluating the impact of multisensor data assimilation on a global aerosol particle transport model, J. Geophys. Res. Atmos., 119, 4674–4689, *doi:*10.1002/2013JD020975.

Other Publications

Alfaro-Contreras, R.,J. Zhang, J. S. Reid, J. R. Campbell(2013), Evaluating the Impact of Smoke Particle Absorption on Passive Satellite Cloud Optical Depth Retrievals, AGU Fall Meeting, San Francisco, A51A-0004, Dec 9-13 2013.

Eck, T. F., B. N. Holben, J. Shafer, D. M. Giles, J. Kim., Y. J. Kim, J. S. Reid, K. E. Pickering, J. H. Crawford, A. Sinyuk, N. Trevino(2013), Observations of the Interaction of Aerosols with Cloud or Fog during DRAGON Campaigns from AERONET Ground-Based Remote Sensing , AGU Fall Meeting, San Francisco, A21D-0073, Dec 9-13 2013.

Lynch, P., J. S. Reid, J. Zhang, D. L. Westphal, J. R. Campbell, C. A. Curtis, D. Hegg, E. J. Hyer, W. Sessions, Y. Shi, J. Turk (2013), A 10-year global gridded Aerosol Optical Thickness Reanalysis for climate and applied applications, AGU Fall Meeting, San Francisco, A53K-03, Dec 9-13 2013.

Reid, J. S., E. J. Hyer, J. Zhang, T. F. Eck, and J. Wang(2013), Signal, scale, and context: Making sense of high resolution AOT data (Invited), AGU Fall meeting, San Francisco, A24C-02, Dec 9-13 2013.

Toth, T. D., J. Zhang, J. S. Reid, D. L. Westphal, J. R. Campbell, E. J. Hyer, and Y. Shi(2013), Impact of Data Quality and Surface-to-Column Representativeness on the PM2.5/Satellite AOD Relationship for the Continental United States, AGU Fall meeting, San Francisco, A43D-0304, Dec 9-13 2013.

Toth, T. D., J. Zhang, J. R. Campbell, E. J. Hyer, J. S. Reid, Y. Shi, and D. L. Westphal(2014), An evaluation of utilizing passive and active satellite aerosol products as proxies for surface-based PM2.5 concentrations, 13th Annual Student Conference, AMS Annual Meeting, 2014.

Zhang, J., J. S. Reid, J. R. Campbell, E. J. Hyer, Y. Shi, and R. Alfaro-Contreras(2014), Investigating the Impact of Cloud and Aerosol Contamination in Satellite Products used for Climate Forcing Studies, Sixth Symposium on Aerosol-Cloud-Climate Interactions, AMS Annual Meeting, 2014.

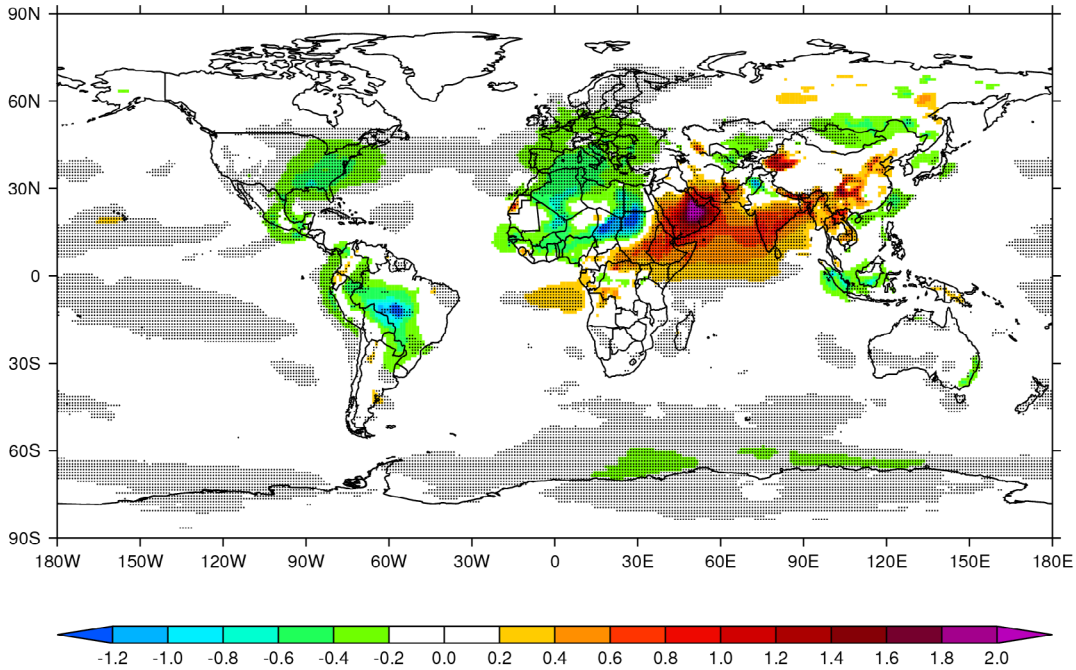

Figure 1: Spatial distribution of 2000-2013 AOT trend using NAAPS reanalysis (Units of 10* AOT per decade). TDotted areas imply statistical significance to the trend. These trends are consistent with Zhang and Reid (2010)'s and Hsu et al. (2012)'s studies using stand-alone satellite products, which implies the good quality of NAAPS AOT reanalysis. Of particular note is the increasing trend in dust over the Arabian Peninsula related to a downward trend in precipitation as well as increasing trend in India and Asia due to ever increasing anthropogenic emissions. Conversely, AOTs are decreasing over the eastern United States and Europe due to improved pollution controls.

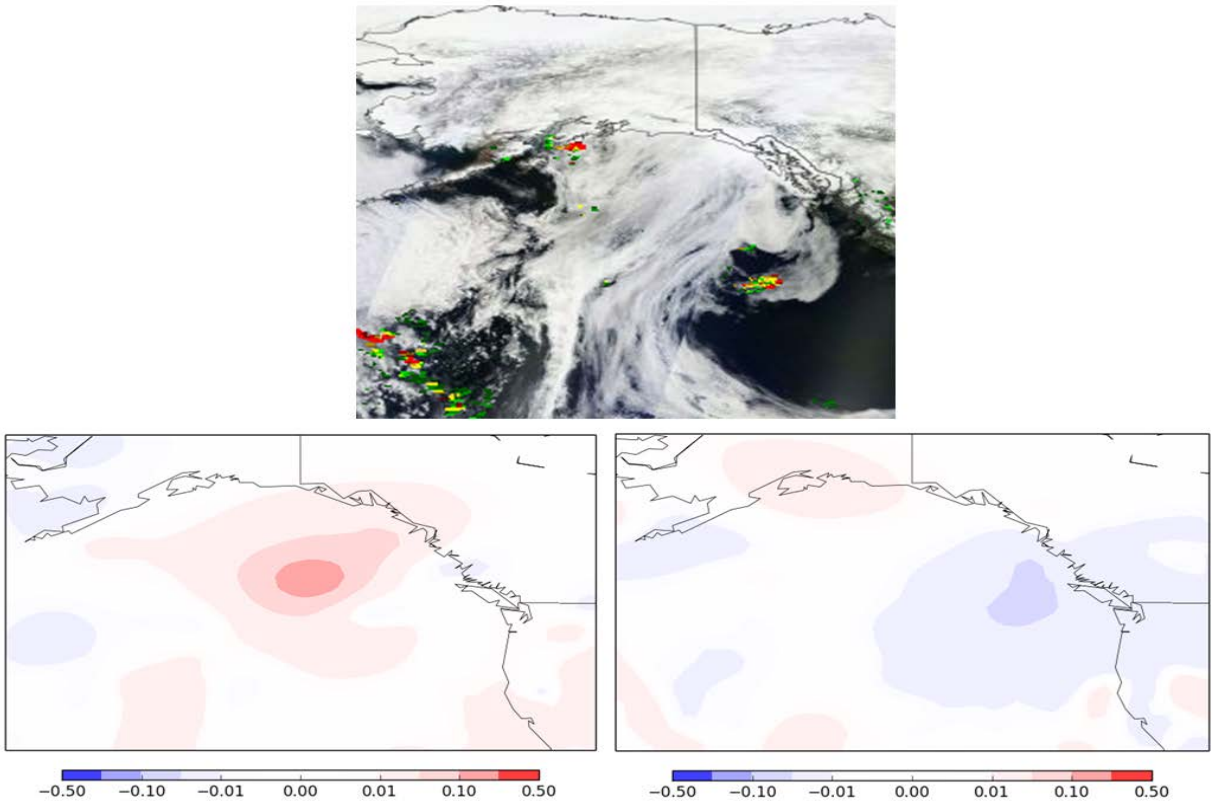

Figure 2. MODIS RGB image with overlayed standard product AOT observations for May 4, 2013 (top). It is clear that these observations are cloud contamination along cloud edges. The bottom two figures show dipoles in the correction fields for assimilation of these observations on May 4, 2013 (left) and May 5, 2013 (right). On the left, the aerosol loading is increased with the incorporation of cloud-contaminated observations followed by a subsequent decrease (right).

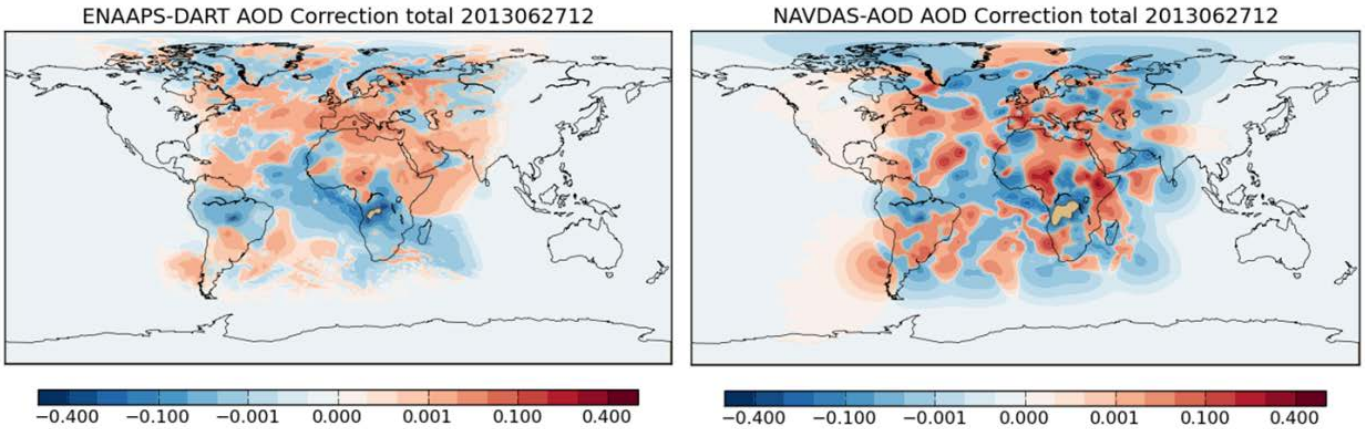

Figure 3. Data assimilation aerosol optical depth correction fields (posterior minus prior) for the new ENAAPS-DART system (left) and the current operationally-run NAVDAS-AOD system (right) for June 27, 2013, 12Z. The flow-dependent correction fields of ENAAPS-DART are a major advantage over the NAVDAS-AOD system.

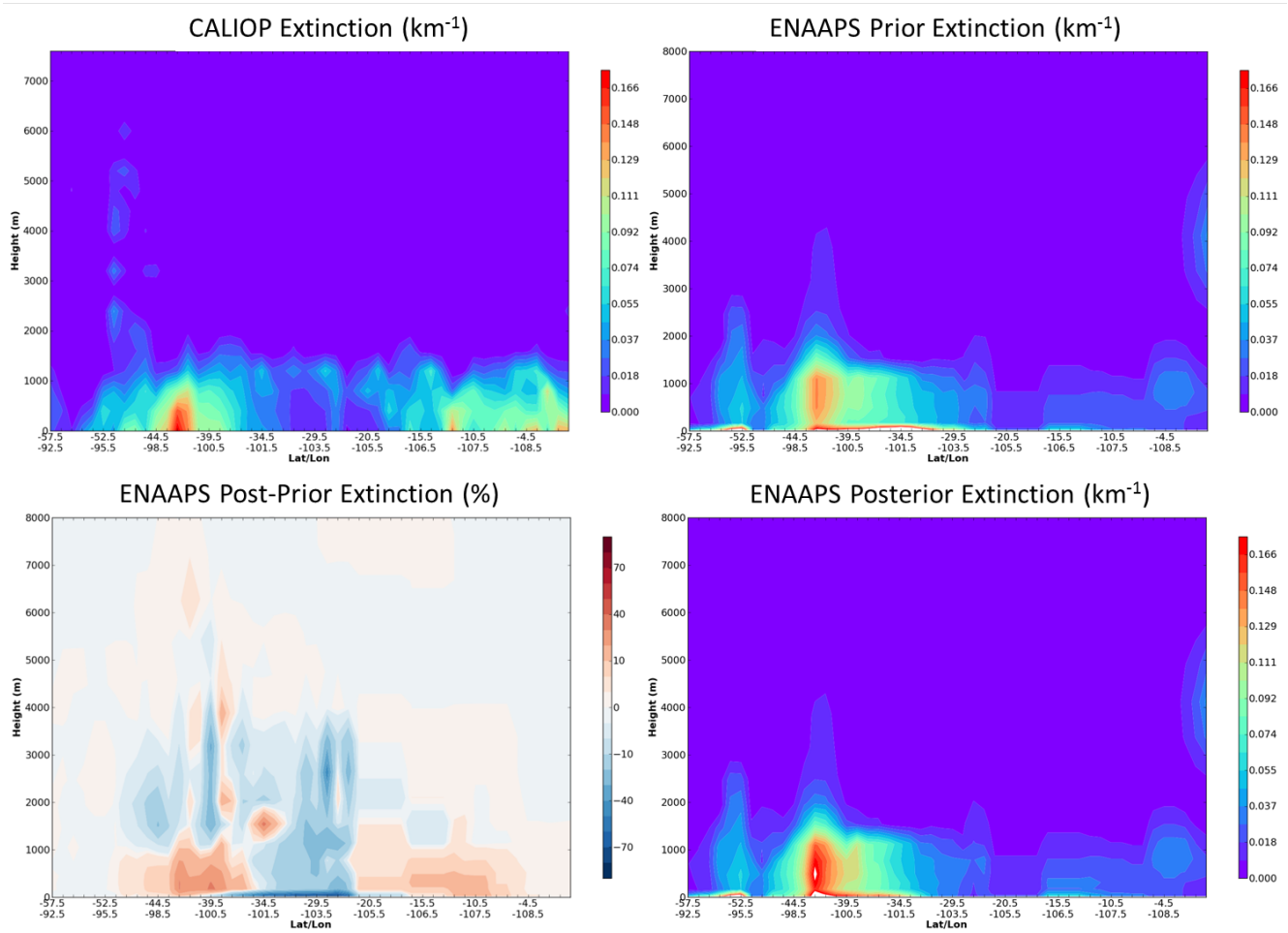

Figure 4. Sample results for CALIOP assimilation in ENAAPS-DART on August 1, 2013, 18Z. Results are shown along the CALIOP curtain and include the CALIOP extinction coefficient (km^{-1}) observations (upper left), the prior ENAAPS mean extinction coefficient along the same curtain (upper right), the change in mean extinction coefficient due to data assimilation on a percent basis (lower left), and the posterior ENAAPS mean extinction (lower right).