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

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LONG-TERM GOALS

In this final year of 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, we find that the next generation of data feeds and associated technology present 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 for 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, in this grant we investigated 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. This work also led to the development of the world's first quasi-operational global multi-model ensemble, drawing from the world's operational data centers. This is the nucleus of a potential operational multi-model ensemble. As with other consensus-like products, such an ensemble is likely to remain top ranked.

OBJECTIVES

Our overarching goal is to investigate applied science aerosol observability issues related to the proper determination of observed product efficacy and information spreading. To this end the core methodology involves the development and application of an ensemble version of NAAPS and its subsequent ensemble based data assimilation system. At the same time, we have initiated the

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development of a multi-model ensemble across major centers including European ECMWF, Japanese JMA, NASA GMAO, NOAA NCEP and the Spanish BSC. Subcomponents of our effort 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 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 co-variability 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

As outlined in previous reports, in FY12 and 13, we developed the basic architecture of both the NAAPS single and ICAP-multi-model ensembles. Work performed in FY13 focuses on the application of these systems for better understanding aerosol observability. The spatial covariance fields are generated in an ensemble version of NAAPS (henceforth eNAAPS). Nominally eNAAPS is run quasi-operationally using the 20 NOGAPS ensemble members generated by FNMOC every 12 hours. Additionally, other members, based on perturbations to the NAAPS source function, are created.

Results from the initial stages of analysis led to a series of upgrades for eNAAPS sources and microphysics (such as a new pollution specie to replace sulfate) which are available for the deterministic operational version once the NAVGEM porting is complete.

Collinear with the development of eNAAPS has been the continued development of the multi-model ensemble. Based on members of the International Cooperative for Aerosol Prediction (ICAP), the ICAP Multi-model ensemble (or ICAP-MME) is the world's first quasi-operational aerosol ensemble, and is already seeing significant use across centers. There are four multi species models is ICAP-MME: ECMWF-MACC, JMA-MASINGAR, NASA GMAO-GEOS-5, and a locally run NRL NAAPS next generation. In addition to these, for the dust species only, we also incorporate NOAA NCEP's NGAC and the Barcelona Supercomputing dust models. Data for all models now goes back 18 months, with the time series for the core models going back 28 months.

Tools and display systems were also developed for analysis of ensemble products. Basic tools for analyzing ensemble variably, correlation length scales, and the most commonly employed "spaghetti plots" and rank histograms 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 analyses 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.

For ensemble based data assimilation we ported NAAPS into the NCAR *Data Assimilation Research Testbed (DART*) in years one and two. 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 ensemble based COAMPS dust source functions studies are already underway through 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.

Finally, additional verification tools need to be generated to evaluate improvements to the model. This not only allows model parameterizations, but also the satellite data assimilated into the models to be investigated and improved. In particular, technologies need to be created that can quickly evaluate new or updated satellite products, such as those being generated by VIIRS.

WORK COMPLETED

In FY 13, the following tasks were completed:

1) eNAAPS was fully exercised. Most importantly, in conjunction with Dean Hegg (University of Washington) we ported the current NAAPS sulfate model to a more generic "pollution" specie to account for the more dominant secondary organic aerosol loadings in the atmosphere. Once NAVGEM development and tuning is complete, we feel the NAAPS ensemble is ready for transition to 6.4.

2) We performed an extensive analysis of the ICAP multi-model ensemble for a one year period of performance. We rigorously compared ICAP-MEE and its single model components against

a series of continuous (e.g., RMSE, MAE etc.) and threat score based metrics. Regions of common success and difficulty over the globe were mapped.

3) Publications on eNAAPS and ICAP-MME were initiated, and at the end of the fiscal year rough drafts of findings will be complete

RESULTS

Research results for this project can be divided into areas of ensemble development, verification, and data assimilation. In FY11 & 12, focus was on development and data assimilation. For FY13, focus has been on verification and analysis, with additional effort on the creation of a pollution specie in NAAPS, and the tuning of the dust and smoke parameters.

<u>Pollution development and tuning:</u> Figure 1 demonstrates before and optimized versions of eNAAPS, based on NOGAPS deterministic meteorology. The largest single improvement was due to the incorporation of secondary organic aerosol mass into the sulfate specie, creating a "fine mode pollution specie." Areas of consistent difficulty for NAAPS including East Asia, the Indian sub-continent, and the eastern United States, have been dramatically improved. The mechanism uses maps of isoprene, terpene and aromatic emissions, largely from the MACC and MEGAN source functions, to develop a new source for fine mode particles. This source is not static, but is based on environmental conditions and the pre-existing aerosol load. Thus, this formulation does not technically add any additional aerosol or gas species to be carried in the model. In addition to this, based on the previous ensemble Kalman filter work, the dust source map and biomass burning emission have been improved. In Asia, the Indian sub-continent and sub-Saharan Africa, RMSE values were improved by 40%. Mean innovations to account for the lacking source function for fine mode organic aerosol particles were also dramatically reduced.

<u>Ensemble development and analysis:</u> In year three we examined a number of case studies of severe dust and biomass burning events. An example of this is depicted in Figure 2, where both the eNAAPS "spaghetti plot" and several other ICAP-MME members are presented. In all of these cases, while a dust front was predicted by all model members, magnitudes differed greatly. Diversity in the models could be tracked back to a dust source in the Taklimakan desert. Aerosol data assimilation in and of itself does not help in this situation, as the dust is generated in a desert area where aerosol optical thickness retrievals are rare and inaccurate. Further, during transport, dust was masked by a frontal cirrus shield. However, using the NRL dust enhancement product we could determine semi-quantitatively which ensemble members were performing correctly. In an operational setting, forecasters could use the ensemble in this way with Navy imagery to accurately forecast a wave of dust passing over the Korean Peninsula and the Sea of Japan.

<u>Verification:</u> Both eNAAPS and ICAP MME underwent extensive verification and analysis in FY13. From this, a common climatology was generated and areas of common difficulty among models were identified. Examples of both these aspects are presented in Figure 3. In the upper set of panels, total, fine, and coarse mode AOT medians and geometric standard deviations are presented for the ICAP-MME ensemble average. Inset as dots on this figure are AERONET verification values. Overall, we find that all models from all centers tend to underestimate AOT globally against AERONET. Further, while all models reproduce major aerosol features (e.g., dust plumes in Africa and Asia, major biomass burning regions, etc.), there are at times very large differences in mean amplitude and minimum AOT. Particularly large differences exist in in the mid-latitude oceans, presumably due to differences in sea

salt source functions. In both cases, these are important findings that will lead to future work to further improve aerosols source/sink functions and data assimilation.

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 2). In these areas we will collaborate with Dr. Hansen and Dr. Whitcomb who are working on METOC impacts, decision aids, and scorecards.

TRANSITIONS

We have begun 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.

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

Journal Publications

Toth, T. D., J. Zhang, J. Campbell**.**, J. S. Reid**,** et al., 2013, Investigating elevated Aqua MODIS aerosol optical depth retrievals over the mid-latitude Southern Oceans through intercomparison with co-located CALIOP, MAN, and AERONET datasets, *J. Geophys. Res*, in press

Eck, T. F., B. N. Holben, J. S. Reid, et al., (2013), A seasonal trend of single scattering albedo in southern African biomass burning particles: Implications for satellite products and estimates of emissions for the world's largest biomass burning source, J. Geophys. Res., 118*, doi:*10.1002/jgrd.50500.

Johnson, R. S., Zhang, J., Hyer, E. J., Miller, S. D., and Reid, J. S. (2013), Preliminary investigations toward nighttime aerosol optical depth retrievals from the VIIRS Day/Night Band, Atmos. Meas. Tech., 6, 1245-1255, doi:10.5194/amt-6-1245-2013.

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

Khade, V. M., J. A. Hansen, J. S. Reid, and D. L. Westphal, (2013), Ensemble filter based estimation of spatially distributed parameters in a mesoscale dust model: experiments with simulated and real data, Atmos. Chem. Phys., 13, 3481-3500, doi:10.5194/acp-13-3481-2013.

Shi, Y., Zhang, J., Reid, J. S., Hyer, E. J., and Hsu, N. C., (2013), Critical evaluation of the MODIS Deep Blue aerosol optical depth product for data assimilation over North Africa, Atmos. Meas. Tech. 6, 949-969, doi:10.5194/amt-6-949-2013, 2013.

Other Publications

Eck, T. F., B. N. Holben, J. Schafer; T. Berkoff, J. S. Reid, et al., (2012) Observed enhancements in aerosol optical depth in the vicinity of cumulus clouds during DISCOVER-AQ , American Geophysical Union Fall Meeting, Dec. 3-7 San Francisco, CA, A13K-0328.

Geiszler, D. A., J. Cook, S. Chen, M. Frost, P. Harasti, C. Hutchins, Q. Zhao, J. S. Reid, D. Martinez, R. A. Allard, T. J. Campbell, T. A. Smith, and L. McDermid, (2013), COAMPS-OS®: An atmospheric/ocean/wave prediction system for the coastal environment. American meteorological Society Annual Meeting, January 5-12, Austin TX.

Hyer, H. J., J. S. Reid, J. Zhang, C. A. Curtis, (2013), Satellite aerosol observations for air quality: matching the scales of observations and applications, American Geophysical Union Fall Meeting, Dec. 3-7 San Francisco, CA, A11L-01.

Hyer, E. J., J. Zhang, J. S. Reid, W. R. Sessions, C. A. Curtis, and D. L. Westphal, (2013), Operational assimilation of aerosol optical depth from NPP VIIRS in a global aerosol model, American meteorological Society Annual Meeting, January 5-12, Austin TX.

Johnson, R. S., J. Zhang, J. S. Reid, E. J. Hyer, S. D. Miller, (2012), Impact of VIIRS on Multi-Sensor Aerosol Optical Depth Data Assimilation, American Geophysical Union Fall Meeting, Dec. 3-7 San Francisco, CA, A13J-0318.

Shi, X., J. Zhang, J. S. Reid, B. Liu, R., Deshmukh, (2013), Critical evaluation of cloud contamination in MISR aerosol product using collocated MODIS aerosol and cloud products, American Geophysical Union Fall Meeting, Dec. 3-7 San Francisco, CA, A13J-0310.

Zhang, J., J. S. Reid, J. R. Campbell, E. J. Hyer, R. S. Johnson, Y. Shi, and D. L. Westphal, (2013), Sensitivity of aerosol climate forcing to the existing satellite observations, American Meteorological Society Annual Meeting, January 5-12, Austin TX.

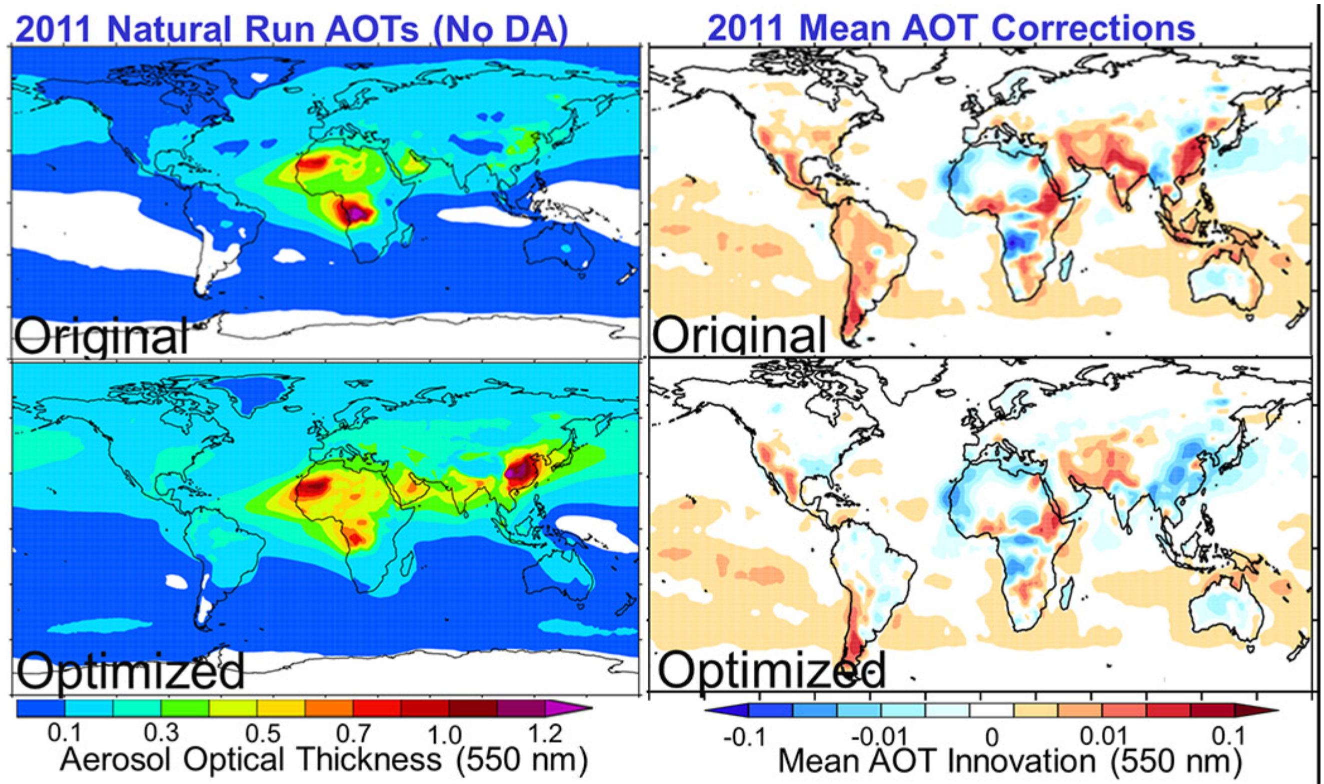

Figure 1. Original and optimized Aerosol Optical Thickness (AOT) and mean AOT innovation with the original NAAPS, and an optimized version which included the incorporation of secondary organic aerosol in the model.

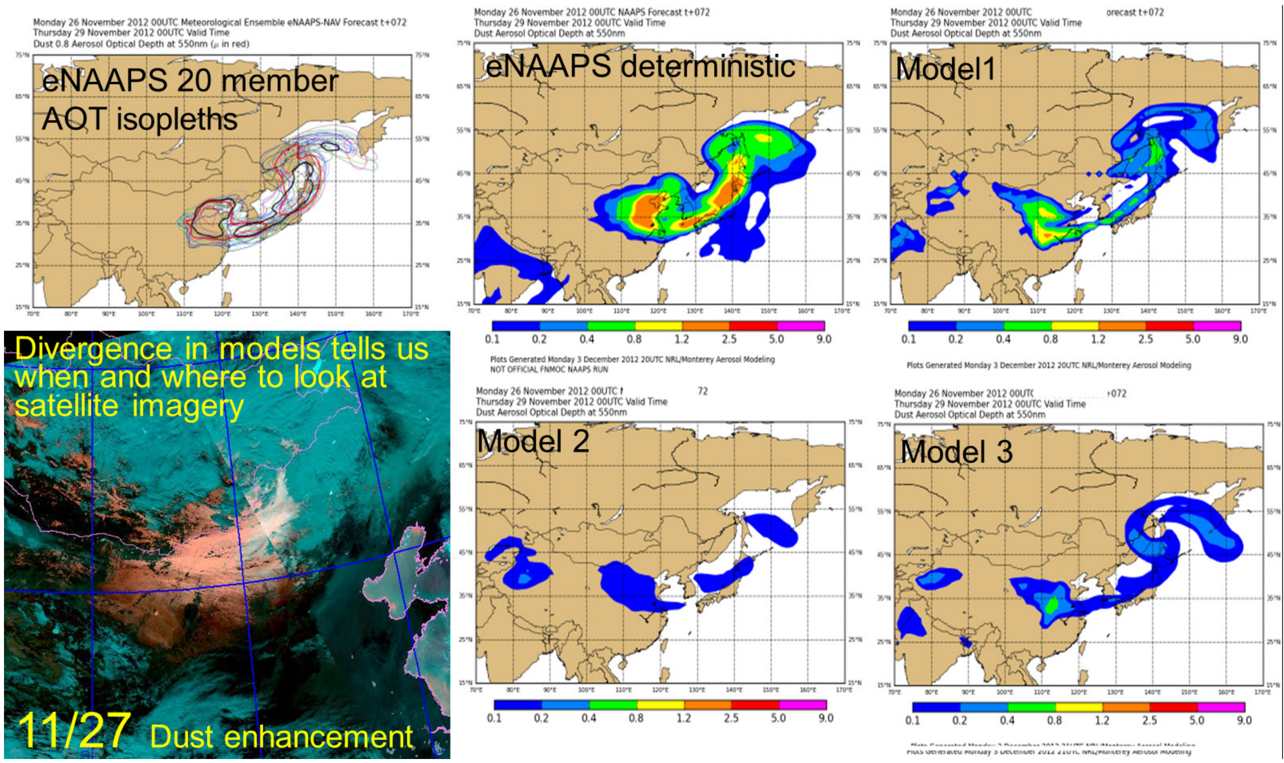

Figure 2. An example of differences within eNAAPS and the ICAP Multi-Model Ensemble (ICAP-MME) for a single 72 hour dust event in November 2012.

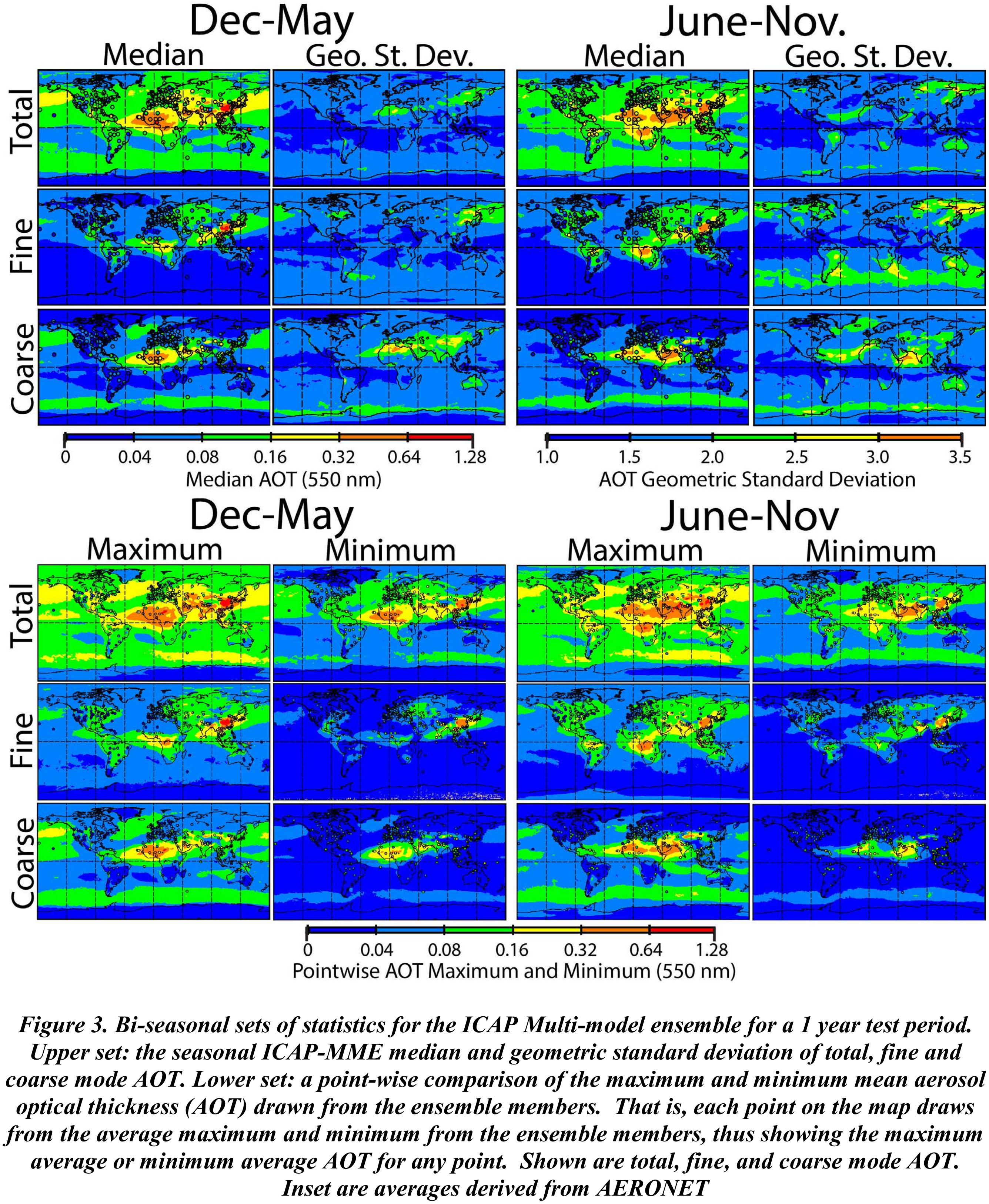

Figure 3. Bi-seasonal sets of statistics for the ICAP Multi-model ensemble for a 1 year test period. Upper set: the seasonal ICAP-MME median and geometric standard deviation of total, fine and coarse mode AOT. Lower set: a point-wise comparison of the maximum and minimum mean aerosol optical thickness (AOT) drawn from the ensemble members. That is, each point on the map draws from the average maximum and minimum from the ensemble members, thus showing the maximum average or minimum average AOT for any point. Shown are total, fine, and coarse mode AOT. Inset are averages derived from AERONET