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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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LONG-TERM GOALS

This project has initiated the world's first dialog among operational Numerical Weather Prediction (NWP) center developers on the best practices for aerosol model evaluation and validation through the development of single and multi-model ensembles. Given the development of aerosol forecasting systems at currently eight operational NWP centers, there is a proliferation of aerosol analysis and forecast products accessible by the community. However, outside of the crudest bias and correlation statistics, the community has not determined baselines or guidelines that can be used to evaluate model skill and assess model improvement. Complicating matters is the difference between deficiencies in aerosol models versus deficiencies in the underlying meteorology that drive them. The root cause of a shortcoming in aerosol forecasts is not easily tractable from commonly used metrics. Part of the challenge in defining evaluation metrics lies in the differences in practices across NWP centers. Each has a different set of core customers, such as regional air quality, climate physics, air and land operations or priors for remote sensing products. Consequently, the priorities of NWP centers for aerosol development vary considerably. The question "What makes a good aerosol model?" is therefore to a certain degree a matter of opinion. To help define best practices for Navy model evaluation, validation, and development we must trace model uncertainty and link them to common interests across centers. To this end, this project has led to the development of the world's first quasi-operational global aerosol consensus model of the leading center's deterministic aerosol models. This provides a baseline to which to compare individual models. This model has also been shown to have higher skill than any of its members. For comparison, a Navy Aerosol Analysis and Prediction System (NAAPS) reanalysis and a similarly designed forecast version have been developed to allow for model baseline comparisons.

This Naval Research Laboratory (NRL) effort will lead to the development of appropriate modeling scorecard elements for both the NAAPS as its driving meteorology from the Navy Global Environmental Model (NAVGEM). To further explore the details of the Navy aerosol modeling

system and its sensitivities, in parallel to the development of a multi-model ensemble, a 20 and 80 member NAVGEM driven single-model NAAPS ensemble is also generated. From this, the relationships between aerosol and meteorological model uncertainty can be traced. At the same time, this effort has resulted in a functioning Ensemble Kalman Filter (EnKF) data assimilation system to allow for realistic flow -dependent corrections in generating the model aerosol analysis. Once aerosol model uncertainties are identified and traced back to their root causes, educated discussions can be made about appropriate Navy scorecard items for both the aerosol and traditional meteorology components. From this, better decisions can be made in the prioritization of model development options.

Finally, this project will use the above score card information to propagate uncertainty from model space to electro-optical (EO) propagation space, including the development of forward optical models for light transmission and data assimilation. This research is leading to a relative understanding of the sensitivities in EO propagation prediction to uncertainties in aerosol microphysics and transport versus known uncertainties in NAVGEM.

OBJECTIVES

This project has continued to pursue four proposed 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 (Navy Operational Global Atmospheric Prediction System) 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 model 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 examination 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 EnKF approach. Application of optical models to this aerosol analysis will provide baseline information on EO 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), National Unified Operational Prediction Capability (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 objectives listed above are connected to three primary product lines for development: 1) Decadal period simulations for the NAAPS deterministic reanalysis; 2) the development of a flow-dependent analysis that includes lidar assimilation capability to constrain the vertical through EnKF techniques; 3) the combination and cross comparison of multiple global models through the International Cooperative for Aerosol Prediction (ICAP) Multi Model Ensemble; and finally 4) examination of model performance against field data.

WORK COMPLETED

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

a) NAAPS Reanalysis-Lead Dr. Lynch: The 2003-2014 NAAPS reanalysis serves as a baseline for our global modeling verification studies and provides a best available historical dataset to study Navy EO applications. Major upgrades funded in FY15 include:

   1) *Inclusion of data assimilation quality Multi-angle Imaging Spectroradiometer* (MISR) *aerosol optical thickness (AOT) in addition to the data assimilation* (DA)-*quality Moderate Resolution Imaging Spectroradiometer (MODIS) AOT in the NAAPS reanalysis, noticeably improving the model performance over the bright surfaces, e.g., desert and mountainous regions.*

   2) *An evaluation of the impacts of the transition from NOGAPS to NAVGEM meteorology and NAVGEM upgrades, and application of a resultant tuning of the dust source function.* For example, when NAVGEM 1.2 became operational (6 November 2013), with the inclusion of the eddy-diffusivity mass-flux vertical mixing scheme, the change in surface friction velocity led to dramatic increase in dust production over North Africa, so a tuned dust source function was applied.

   3) *The composition and submission of a paper detailing the NAAPS reanalysis and its validation.* The paper will shed light on future development and scoring of any aerosol reanalysis product within the scientific community. The paper is now under review for publication in Atmospheric Chemistry and Physics.

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

   1) *The development and distribution of two levels of ICAP MME products for public access in Climate and Forecasting (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.

2) *Evaluation of the diversity of aerosol optical thickness in analysis and forecasting modes of the models from the ICAP-MME and revisit of the first ICAP-MME result but with two more dust models (as the BSC and the UK-Met office dust product became available for over about a year).*

c) NAAPS ensemble (ENAAPS)-Lead Dr. Rubin: NAAPS and Data Assimilation Research Testbed (DART) EnKF data assimilation had been ported to the 20 member NAVGEM meteorological ensemble, including perturbations to aerosol source functions in the previous year. In the second year, the focus was spent on perturbation and optimizations studies, culminating in a paper submitted for publication. Key tasks included:

1) Evaluation of the impact of ensemble size, with comparison studies between 20 and 80 NAVGEM members.

2) Evaluation of the relative impact of using meteorological ensembles to source-perturbed ensembles, which are more common in the field.

3) Tests and impact assessment of the assimilation of AERONET (NASA's AErosol RObotic NETwork) sun photometer data to determine the effect of individual data points on aerosol analysis fields.

4) Studies on the impact of lidar assimilation on the model through evaluation of data assimilation correction fields.

d) Field data evaluation-Leads Dr. Reid, Dr. Kaku, and Mr. Sessions.

Performance of the NAAPS reanalysis, ENAAPS analysis and ICAP-MME analysis are assessed by comparison to community datasets. The evaluation includes aerosol loadings and AOTs as well as the associated meteorological dependencies. From this evaluation of the model aerosol analyses, we can prioritize future efforts to improve EO prediction. Specifically under this grant, we performed the following work:

1) In depth investigations in model behavior across forecasting centers for the Cape Verde and Kanpur India sites, which represent the two AERONET sites where the community performs best and worst, respectively.

2) Verification of the Spectral Deconvolution Algorithm (SDA) for partitioning AOT into fine mode and coarse mode components, and the extension of its use to nephelometry so that likewise in situ analyses can also be performed.

3) Initiation of an evaluation of model products with data from two field campaigns: Studies of Emissions, Atmospheric Composition, clouds, and climate coupling by Regional Surveys (SEAC^{4}RS) which provided an example of a two phase system of simple continental boundary layer with advected smoke aloft, and the United Arab Emirates Unified Aerosol Experiment (UAE^2) to investigate the role of the significant amount of pollution on regional AOTs which are commonly and mistakenly assumed to be pure dust.

4) We developed a new AOT retrieval using Scanning High-resolution Interferometer Sounder (S-HIS) radiance data from the NASA Hurricane and Severe Storm Sentinel (HS3) campaign. The HS3 global hawk payload included the Cloud Physics Lidar (CPL)

currently being used for evaluation of our HS-IR retrieval. Dropsondes further extended investigation of dust-induced biases to radiance based water vapor and temperature profiles.

RESULTS

Results for this effort can be classified according to the nature of the verification problem being addressed, including a) the NAAPS reanalysis for a decadal baseline; b) the ENAAPS/EnKF assimilation work for the development of an improved flow-dependent aerosol analysis; c) the ICAP Multi-Model ensemble to combine and compare global models from different centers; and finally d) model evaluation against available datasets. Results for these efforts are briefly discussed below.

NAAPS Reanalysis-lead performer Dr. Lynch: The NAAPS reanalysis was produced using a version of NAAPS with regionally-tuned source functions at its core and data assimilation of quality-controlled Terra and Aqua Collection 5 MODIS and MISR AOT. Aerosol wet deposition in the tropics is constrained with satellite retrieved precipitation. Dry deposition parameters over ocean are also adjusted by minimizing the AOT analysis increments in the data assimilation. The reanalysis fine and coarse mode 550nm AOTs are found to have good agreement with AERONET observations, with a global average root mean square error around 0.1 for both. The AOT RMSE decreases 50% when monthly averaging is applied. Despite the static pollution source functions used in NAAPS, the reanalysis develops decadal trends that are largely in line with other studies using stand-alone satellite products. This result gives us confidence in the reanalysis and its ability to simulate the global aerosol environment.

Figure 1 shows the monthly mean NAAPS reanalysis and AERONET L2 modal AOT at six AERONET sites, chosen for their relatively long-term record under different aerosol regimes. The selected sites and their associated regimes include: 1) Alta Floresta in the Amazon, dominated by biomass burning smoke during the burning season; 2) Beijing in East Asia, dominated by anthropogenic fine mode aerosols year round with mixed dust and pollutions in the spring time; 3) Cape Verde off the west coast of North Africa, dominated by Sahara/Sahel dust; 4) Goddard Space Flight Center (GSFC) in Maryland, dominated by anthropogenic fine mode aerosols; 5) Solar Village in the Arabian Peninsula, dominated by dust; and 6) Venice Italy, dominated by pollution-related fine mode aerosols and influenced by Saharan dust in spring time. Overall, the reanalysis follows the seasonal and interannual variability in AERONET data quite well. The decreasing trends observed at Alta Floresta, GSFC, and Venice, the increasing trends observed at Beijing (slight) and Solar Village, and the insignificant trend observed at Cape Verde qualitatively agree with AERONET. Over GSFC, the reanalysis captures the evident drop in total and fine mode AOT since 2008, which is likely a result of effective regulation of industry emissions.

There are numerous applications of the NAAPS reanalysis. It is ideal for quick and consistent identification of large aerosol events, both globally and regionally. It is also being employed as a reference for comparison and provides general background aerosol information without temporal or spatial discontinuity for field campaign analysis. For climate and applied science use, the NAAPS reanalysis provides global and regional AOT climatologies and can be used in different time scale analyses, from daily to inter-annual.

ENAAPS & EnKF Development-lead performer Dr. Rubin: The ENAAPS-DART system was implemented in the previous research year with a 20 member ensemble. Problems were previously

noted with ENAAPS-DART long-range aerosol transport in the tropics. This issue was rectified this year and ENAAPS-DART now outperforms the current operational NAVDAS-AOD system for long-range transport, such as Atlantic dust transport events impacting the Caribbean and the United States. It was also found that ENAAPS-DART has the ability to capture sharp gradients in aerosol features, unlike NAVDAS-AOD which tends to smooth out aerosol features. An example is shown for an Atlantic dust transport event with the ENAAPS-DART system capturing the sharp leading edge of the dust front (Figure 2). Additional studies have been conducted with ENAAPS-DART, including the evaluation of ensemble sizes up to 80 ensemble members. Initial results indicate that performance gains can be achieved (i.e. decrease in RMSE) at AERONET sites by moving from the 20 to 80 member ensemble. These studies focused solely on AOT assimilation from the MODIS. Additional work has been conducted to evaluate the use of ground-based observational networks in ensemble data assimilation, using ENAAPS-DART. Data assimilation of AOT observations from NASA's Aerosol Robotic Network (AERONET) were conducted in both ENAAPS-DART and the Navy's current variational data assimilation system, NAVDAS-AOD. It was found that ensemble data assimilation is able to spread sparse observational information, from AERONET ground-based networks for example, in a more realistic manner than the current variational method (Figure 3). This result is important as there are a number of new aerosol-related observations available that are spatially limited, including Lidar observations for constraining the aerosol vertical distribution. The demonstrated ability of the EnKF to make better use of sparse observations than the variational approach, indicates that ensemble data assimilation should be the focus of future aerosol data assimilation efforts.

With respect to lidar assimilation, the ability to assimilate aerosol vertical observations in ENAAPS-DART was added in the previous research year. Experiments were conducted on a global scale and the results were not as expected, with a lack of large adjustments in the vertical. The difficulties encountered are not unique as the aerosol forecasting community has been largely unsuccessful at tackling this problem. In order to really understand the impact of Lidar assimilation on aerosol fields in the EnKF data assimilation system, the problem was whittled down to a single site (Huntsville, Alabama) that can be used to develop a good understanding of the problem. High Spectral Resolution Lidar (HSRL) measurements are available at the Huntsville, Alabama site and are being used to evaluate Lidar assimilation of satellite-based measurements (CALIOP). The first step was to determine the true uncertainty of the Lidar measurements. Accurately quantifying the uncertainty in a measurement is an important component of data assimilation since the uncertainty determines the weighting the observation has on the prior forecast. The next step is to assimilate Lidar observations at this single site in order to understand the EnKF behavior. If the ensemble data assimilation on its own can't produce realistic results in the vertical, a hybrid approach (combined error covariances from the ensemble and variational systems) may be considered. Insights from the single site experiments will be used to move from single site to global scale Lidar assimilation.

ICAP-MME-lead performer Dr. Lynch: A whole year of AOT forecasts from all seven ICAP model members were collected at NRL Monterey and used to generate the ICAP-MME global AOT model consensus. This new ICAP-MME analysis includes two more dust models (Barcelona Supercomputer Center (BSC) and UK Met office) than appeared in the first ICAP-MME analysis and evaluation published in Sessions et al. (2015). Consistent with Sessions et al., (2015), the ICAP-MME outperforms individual models for both total and fine mode AOTs. This is generally true for dust AOT as well, but as large bias exists in some models, ICAP ranks in the middle for select dusty sites. The high dust bias models include the BSC model and NAAPS at the time when NAVGEM was upgraded to include the eddy-diffusivity mass-flux vertical missing scheme. The NAAPS dust source function

was tuned to accommodate the increase in surface friction velocity associated with the NAVGEM upgrade. We also requested BSC to adjust their dust emissions in their model.

The individual ICAP models are independent of each other in their underlying meteorology as well as their aerosol sources, sinks, microphysics and chemistry, leading to differences in AOT forecasts across the members. Additionally, for models with AOT data assimilation, there is diversity in the assimilation methods, the AOT data that is assimilated, and the pre-assimilation quality-control screening and bias correction of AOT observations that also leads to differences in the AOT analyses across the models. With this in mind, the diversity of AOT in analysis and forecasting modes of the ICAP models was evaluated. As an application of the ICAP-MME products, this analysis identifies regions of diversity between model analyses and forecasts. It was found that polluted and mixed fine-coarse environments of India, China, and the Sahel pose the most difficulty for aerosol simulations.

Field Evaluation-lead performers Dr. Reid, Dr. Kaku, and Mr. Sessions: This fiscal year we performed global and regional analyses for both Navy models and ICAP-MME members. Comparisons of global analyses against AERONET continued to be performed, examining in detail sites that have good agreement and performance between models as well as sites with universal poor performance between models. However, our focus this year turned to datasets collected during field campaigns. In particular, the focus has been on SEAC^{4}RS which represents a "simple" case of a mid-latitude boundary layer, to 7SEAS for a marine environment, and finally UAE^2 to investigate the role of pollution in a region that is mistakenly thought of only for dust. In addition, we provided the first true verification of the SDA to take advantage of the global dataset of nephelometer data. Finally, HS3 was examined in detail to understand the role of dust in interfering with top of atmosphere retrievals of temperature and water vapor.

While model performance is continuously evaluated at numerous AERONET sites (e.g., Figure 1), early in FY2015 we examined ICAP-MME member model performance in detail for two sites: Cape Verde where all members performed well, and Kanpur, where all models performed poorly. The good performance at Cape Verde was expected for multiple reasons. First, Saharan Africa spawns the largest aerosol feature in the world, with dust protruding out into the Atlantic as far as South America and Caribbean. Consequently, modelers spend considerable effort tuning for these aerosol features and thus perform better at this site than any other. However, despite this uniformity of good results, parametrizations that go into the models are very different - especially in regard to dust source functions. Further, the models were also found at this site to correlate with each other better than observations. This is indicative of some form of missing physics in the models. On the other hand, all models performed poorly in Kanpur India, in the heart of the Indo-Gangenic plain. An example for 2013 fine and coarse mode AOT from AERONET is presented in Figure 4. While some fine (e.g., pollution and smoke) and coarse (dust and fog/haze) aerosols are captured, in general the models underestimate or miss entirely severe aerosol events. Further, while the models do adequately capture the pre-monsoon (spring) season, performance is particularly poor in winter months. We deduced this is a result of multiple factors. Most importantly, the global models have difficulty capturing the strong planetary boundary layer inversions which result in trapped aerosol particles at high humidity. A second issue was found to be a result of errors in data assimilation systems. In regions where aerosol particle concentrations and AOTs are very high, satellite retrievals fail. Thus there are data voids in precisely the regions where the data are needed most. However, retrievals are made along the edges. Data assimilation systems then spread this information into the data void regions. Thus, even if the background model captures these events, the edge effects of observations drag the AOTs down, leaving a significant low bias. We expect that EnKF systems may be able to alleviate these effects.

In FY15 we also applied sun photometer methods of extracting fine and coarse mode light scattering to nephelometer data. This methodology, the SDA (developed by Norm O'Neill of the University of Sherbrooke), is used operationally by the AERONET program and NRL Monterey to separate fine mode AOT from the coarse mode. Thus, models can be verified along the contribution of fine mode particles as pollution and smoke versus coarse model particles of dust and sea salt. By adapting the SDA method to nephelometry, fine and coarse mode scattering can now be derived from the extensive field datasets in the community. With accurate input, SDA is able to predict the fine and coarse mode scattering and extinction coefficient partition in global data sets representing a range of aerosol regimes, as demonstrated in part by Figure 5. However, in low-extinction regimes commonly found in the clean marine boundary layer, SDA output accuracy is sensitive to instrumental calibration errors. Nevertheless, this effort not only verifies the application of the SDA+ method to in situ data, but by inference verifies the method as a whole for a host of applications, including AERONET. Ultimately, the SDA methodology shows significant improvement over the current status quo of using Ångstrom exponents to estimate the contribution of fine mode aerosols to scattering and extinction coefficients where direct measurements of fine and coarse mode contributions are not available. Study results open the door to much more extensive use of nephelometers and PSAPs, with the ability to calculate fine and coarse mode scattering and extinction coefficients in field campaigns that do not have the resources to explicitly measure these values.

For field campaigns, significant effort was placed in the analysis of the August to September 2013 SEAC^{4}RS campaign. SEAC^{4}RS was a joint NASA and NRL mission to study the nature of aerosol particles in the southeast United States. From an aerosol modeling point of view, this region is a "slow pitch" for mid latitude pollution and meteorology. Of particular use was the deployment of the University of Wisconsin Space Science Center (SSEC) High Spectral Resolution Lidar (HSRL) to Huntsville, AL. At the same location early afternoon radiosondes were released by Penn State. Thus, this site is idea for examining boundary layer development, and its influence in aerosol extinction. An example is given in Figure 6, with lidar, radiosonde and model (NAVGEM and NAAPS) for a simple polluted boundary layer. From 12-24 Z (or 7 AM to 11 PM local time) we can see the development and decay of the boundary layer in the HSRL signal. For the radiosonde release at 19:50 Z (2:50 PM local time), we see a well-developed mixed layer with an inversion height at ~2 km. Aerosol light extinction builds with altitude, with a maximum at the base of the inversion due to the increase in relative humidity in altitude and corresponding hygroscopic growth by aerosol particles. However, the NAVGEM global model has difficulty replicating this boundary layer structure, and as a consequence NAAPS missed the peak in extinction at the top of the mixed layer. While this does not have too much of an impact in the forecast of AOT, it does have significant implications for estimating aerosol extinction at the surface, and the assimilation of lidar data. Indeed, while qualitatively we have demonstrated lidar assimilation, we believe that such uncertainties in the vertical explain the aforementioned mixed EnKF assimilation results. We find this as a systematic problem in mid latitude boundary layers, and believe that the development of NAVGEM boundary layer related parametrizations be a high priority for EO applications.

For investigation of the Middle East and the Arabian Gulf in particular, the UAE^2 campaign of 2004 is an indicator of Arabian Gulf aerosol performance. The typical mid-visible AOT experienced by the Arabian Gulf region in the summer monsoon months is high at >0.4 to 0.5 compared to global over land average of 0.2 (Figure 7). Dust particles are highly influential in the Arabian Gulf region, comprising 76% of the coarse mode aerosol (aerosols with a diameter between 10 μm and 2.5 μm) mass concentration and 38% of the $PM_{2.5}$ aerosol (aerosols with a diameter of less than 2.5 μm) mass concentration, on average. While this region is well known for dust, our field observations suggest

very high loadings of fine mode aerosol particles, principally sulfates. Sulfate, nitrate and trace metals were also present in the coarse mode, and negatively impacting air quality at the $PM_{2.5}$ aerosol concentration level. Indeed, we found $PM_{2.5}$ aerosol levels classified as healthy for only 4% of the time, and reaching unhealthy for 24% of the days sampled (Figure 8). Similar values can be attributed to "clear" and severely impeded EO propagation. PM_{10} and $PM_{2.5}$ aerosol particles were attributed to natural and anthropogenic sources using Positive Matrix Factorization analysis. Natural sources included six distinct dust signatures from six different regions and sea salt. Anthropogenic sources included metals, metalloids, sulfate and nitrate interactions with natural dust, as well as emissions from oil refineries and mobile sources. This dataset will be used to evaluate the global aerosol models in year three.

As a final aspect of model scoring, a test system was required specifically for aerosol impacts on meteorological data assimilation. This required the project team to shift towards novel observation sources and analyses. In a joint venture with the Robert Holz at the University of Wisconsin Space Science and Engineering Center (SSEC), this project supports the graduate education of Walter Sessions, who formally was an ensemble model developer at NRL Monterey, to evaluate dust-meteorology radiative transfer. The multi-year HS3 campaign provided an opportunity to explore the aerosol information content and the impact of dust on the infrared retrievals within the hyper-spectral infrared (HS-IR) using the SSEC Scanning High-resolution Interferometer Sounder (S-HIS) airborne instrument onboard one of the mission's Global Hawks. The dearth of hurricanes and active dust transport during the 2013 season, along with the collocation of airborne CPL backscatter profiles and dropsonde data, make HS3 an ideal dataset for evaluating passive sensor techniques and impact of dust on sounder and surface retrievals. Seven science flights were executed out of Wallops Island, VA focusing on the subtropical Atlantic and Gulf of Mexico basins. Aerosol direct effect impacts on sounder retrievals of water vapor and temperature within and without the SAL (Saharan Air Layer) were non-negligible; observed brightness temperature biases for dust-laden fields of view regularly exceeded 3 K for dust layers elevated above 2 km. Our retrieval (e.g., Figure 9) was developed to help models address dust layers in nighttime scenes is based on an optimal estimation technique with forward model calculations performed by the Line-by-Line Radiative Transfer Model with Discrete Ordinates RT (LBL-DIS). Uncertainty within the retrieval system is currently being fully evaluated. Preliminary results points to layer geometry as the largest source of uncertainty. This necessitates *a priori* constraint of layer height and thickness from NAAPS to reduce the residual AOT variance between CPL and S-HIS retrievals to less than 0.02 for cloud free and dust dominated fields of view. Evaluation of these techniques applied to the current suite of HS sounders (CrIS, IASI, AIRS) will begin in 2016, followed rapidly by studies within the assimilation testbed framework already developed.

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. At the same time, it forges stronger relationships with other developers to improve interagency cooperation. 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 Fleet Numerical Meteorology and Oceanography Center (FNMOC) to transition ENAAPS to operations and they indicated that scorecard products are also highly desired. In pursuit of these scorecards, we have also entered into conversations with developers in NRL Code 7530 to improve internal scorecards for NAVGEM development which should impact many data products used by downstream users. In FY15, we have had several inquiries on the possibility to operationalize the ICAP MultiModel Ensemble, and the ensemble output for the first time appeared in a National Weather Service (NWS) forecast discussion.

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. New data-processing and visualization systems are being adapted for aerosol research through the COAMPS-On Demand System (COAMPS-OS®) and its visualization program. We have also worked extensively with Jim Hansen on his ONR-funded projects, and gratefully acknowledge the support of global modeling developers who support out ensemble modeling efforts though data and advice, including Nancy Baker, William Campbell, Tim Hogan, Justin McLay, Carolyn Reynolds, and Tim Whitcomb. Finally, we expect this work to lead into the upcoming MURI on coastal data assimilation to start FY2016.

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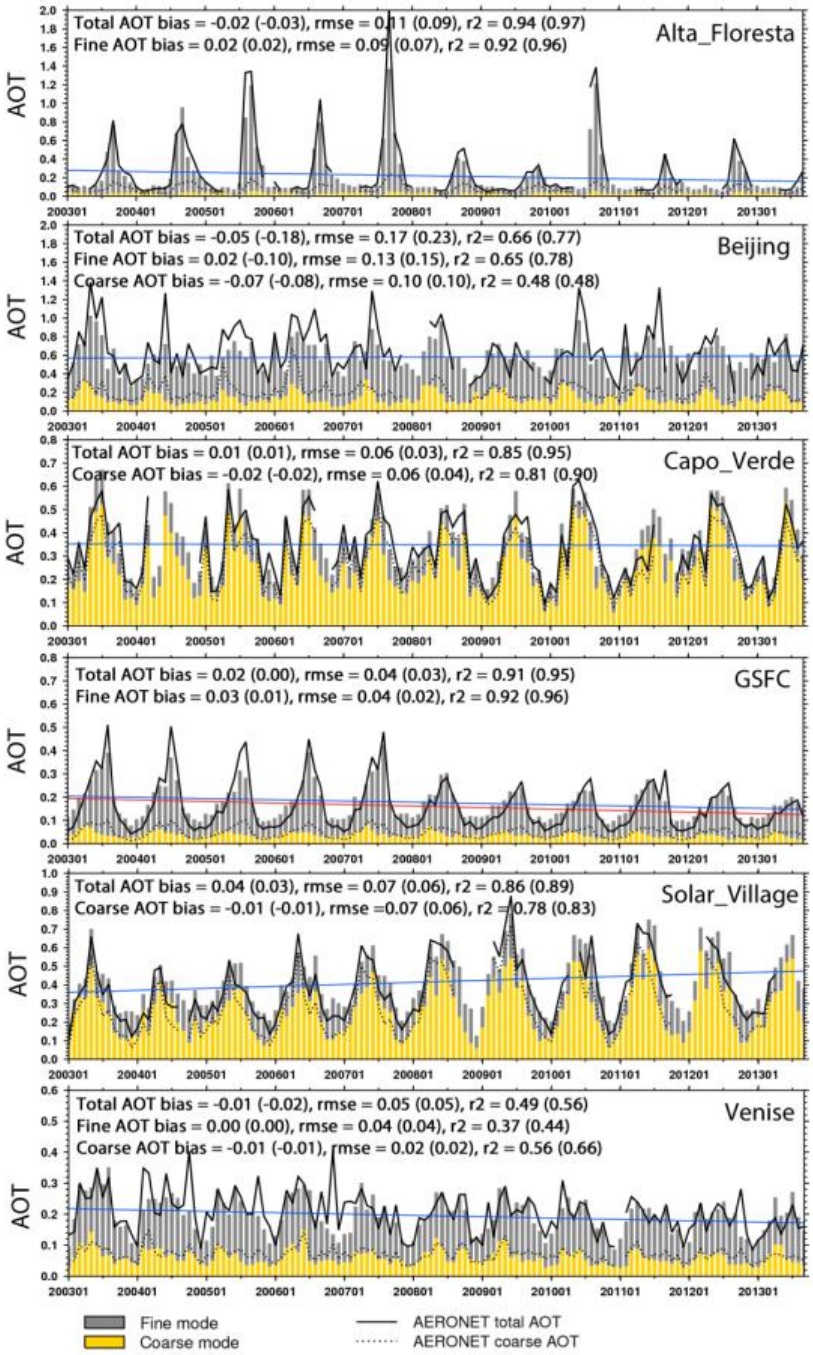

Figure 1. Monthly mean 550 nm reanalysis and AERONET L2 mode AOTs at 6 AERONET sites, Alta Floresta in the Amazon, Beijing in East Asia, Cape Verde (aka Capo Verde) off the west coast of North Africa, GSFC in East CONUS, Solar Village in Arabian Peninsula, and Venice in Italy. The solid blue line is a linear regression of the reanalysis total AOT. The red solid line is a linear regression of the AERONET total AOT, only available when there is continuous data through the time. Monthly mean AERONET AOT is obtained only when the total number of 6-hourly AERONET data exceeds 10 to ensure temporal representativeness. Annotations for each time series show bias, root mean square error (RMSE) and squared Pearson correlation coefficient (r^2) of monthly averages for unpaired comparisons; paired comparisons, using reanalysis values sampled to match available AERONET data, are shown in parentheses.

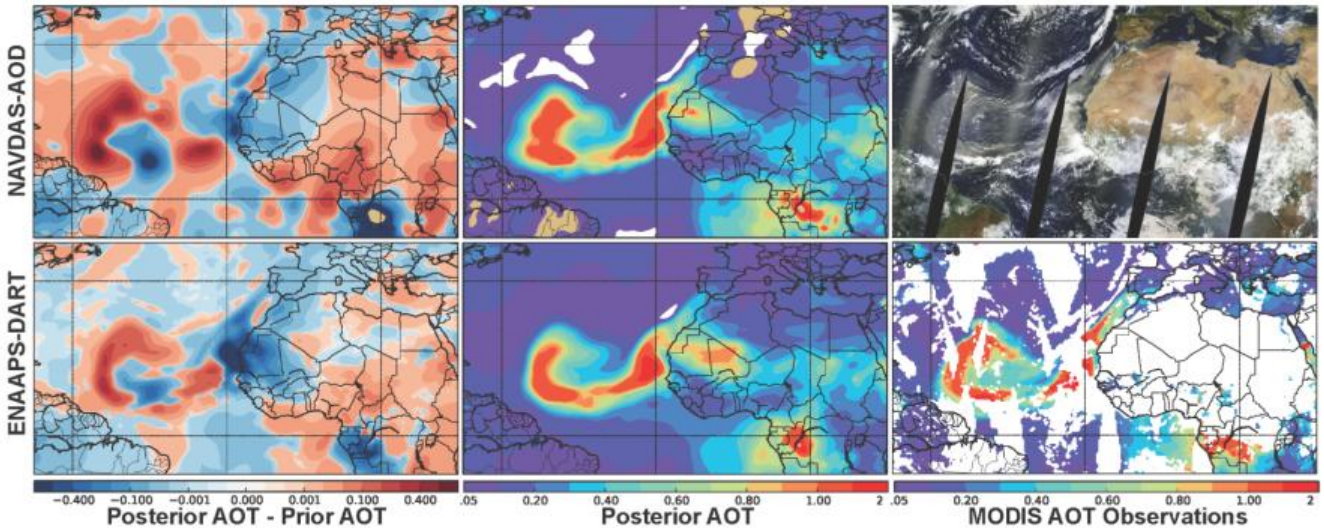

Figure 2. An example dust transport case off the coast of West Africa (August 1, 2013). Analysis increments (posterior AOT – prior AOT) and posterior AOT at 550nm are shown for the variational NAVDAS-AOD data assimilation (top row) and the Ensemble Kalman Filter data assimilation from ENAAPS-DART (bottom row). Also shown are MODIS observations, including a MODIS visible image and a plot of all available MODIS AOT (550nm) observations for the dust event from Terra and Aqua.

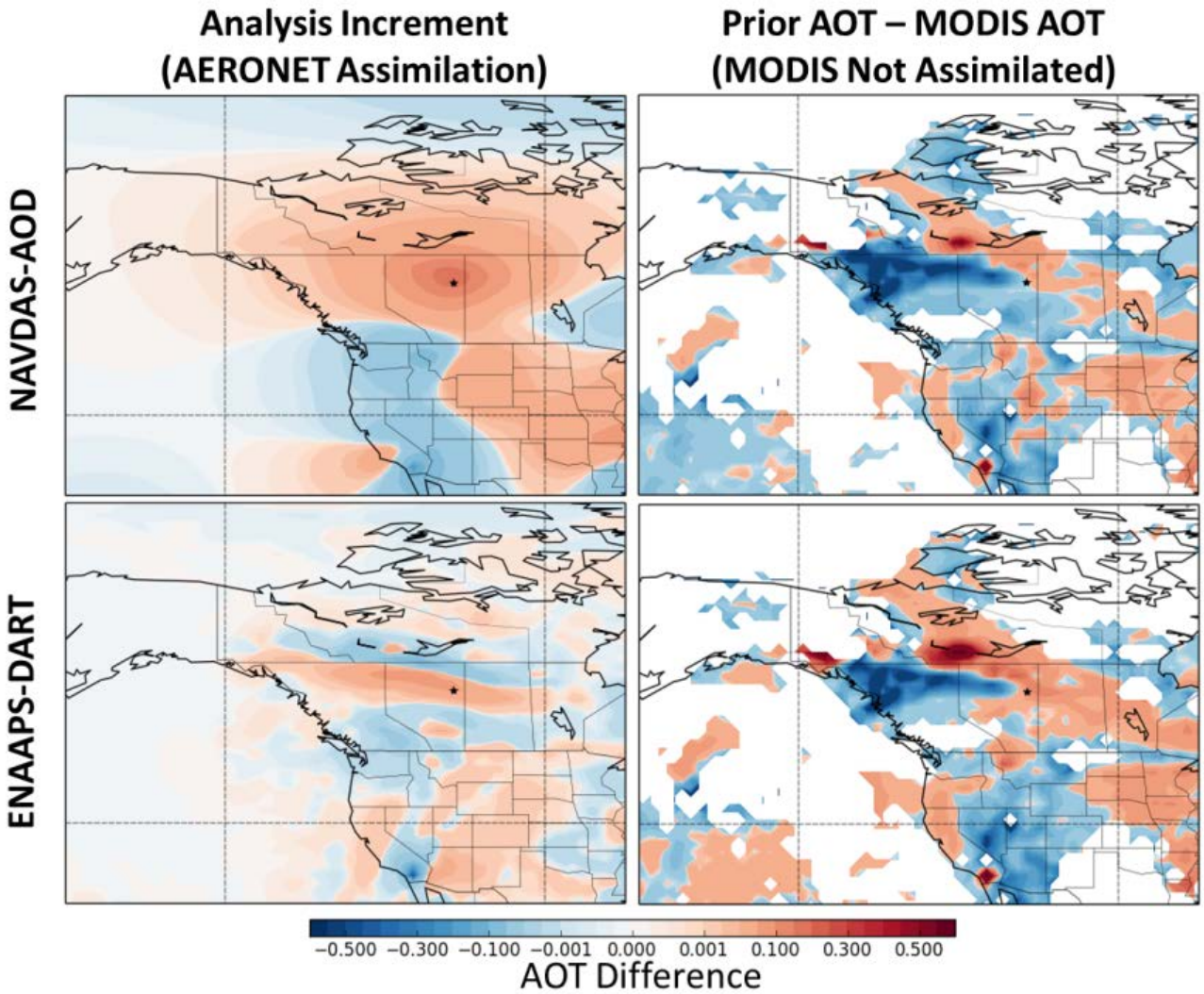

Figure 3. AERONET AOT (550nm) assimilation results for an example smoke case in the North American Boreal region (July 18, 2013). The assimilated AOT observation is from the Fort McMurray AERONET site, highlighted with a star. Analysis increments (posterior AOT – prior AOT) are shown for the variational NAVDAS-AOD and for ENAAPS-DART (EnKF) for the AERONET AOT assimilation. Also shown is the difference between the prior AOT (before assimilation) and MODIS AOT observations. The comparison to MODIS AOT is independent, since it is not assimilated, and provides a sense of spatial bias in the AOT forecast. Note that the NAVDAS-AOD correction is a circular increase in AOT around the observation at Fort McMurray, despite having both positive and negative bias relative to MODIS. On the other hand, ENAAPS-DART corrections are spatially consistent with the bias around Fort McMurray due to the flow-dependent nature of the system.

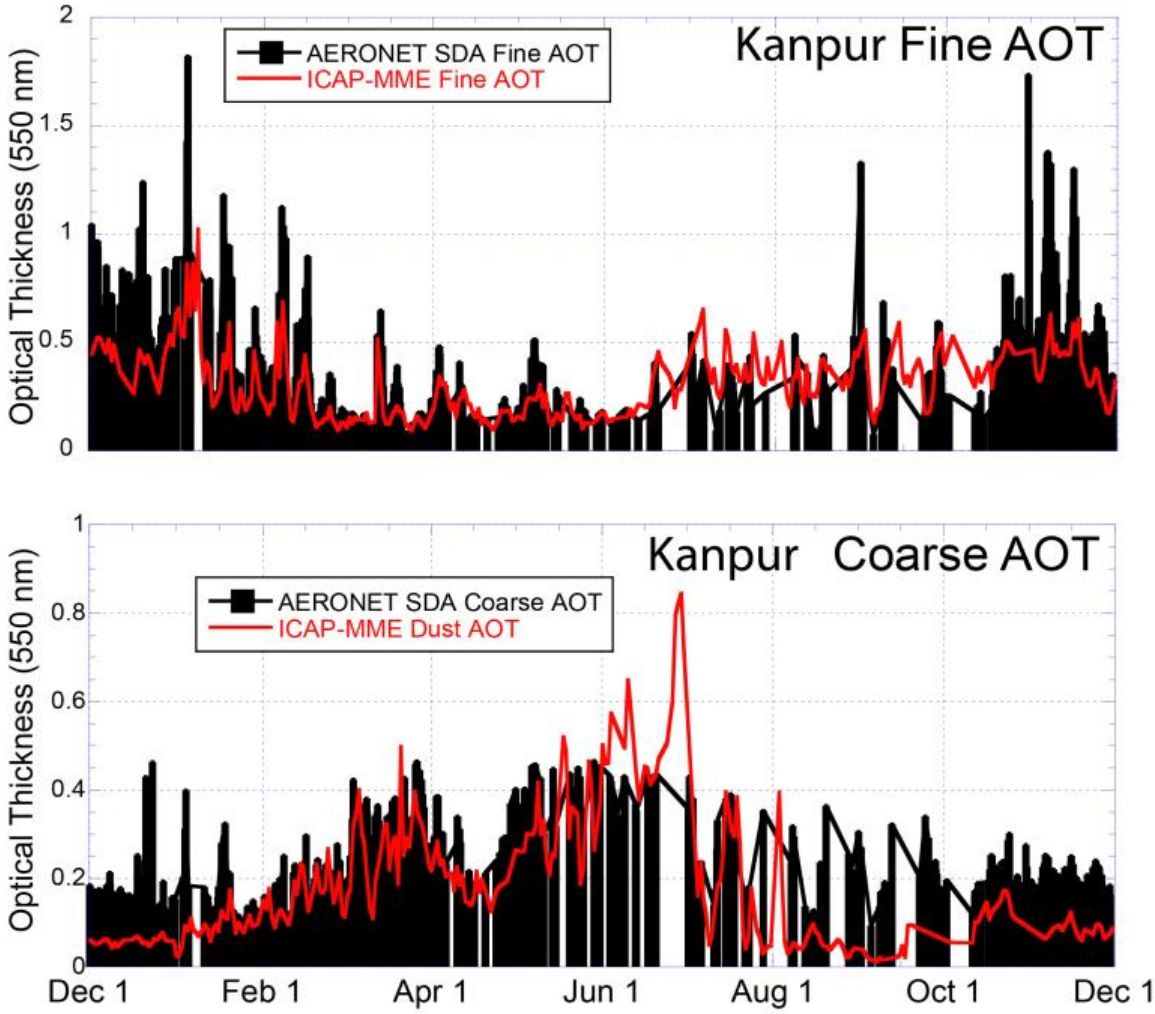

Figure 4. Fine (e.g., pollution and smoke) and coarse (e.g., dust and fog) mode Aerosol Optical Thickness (AOT) for the Kanpur India site for the year 2013. Included are the AERONET observations (Black) and the ICAP Multi Model Ensemble (ICAP-MME) means (red). While the global models captured significant events, the largest events are either underestimated or missing entirely. In particular, there is poor performance in the winter months when boundary layer inversions are strongest.

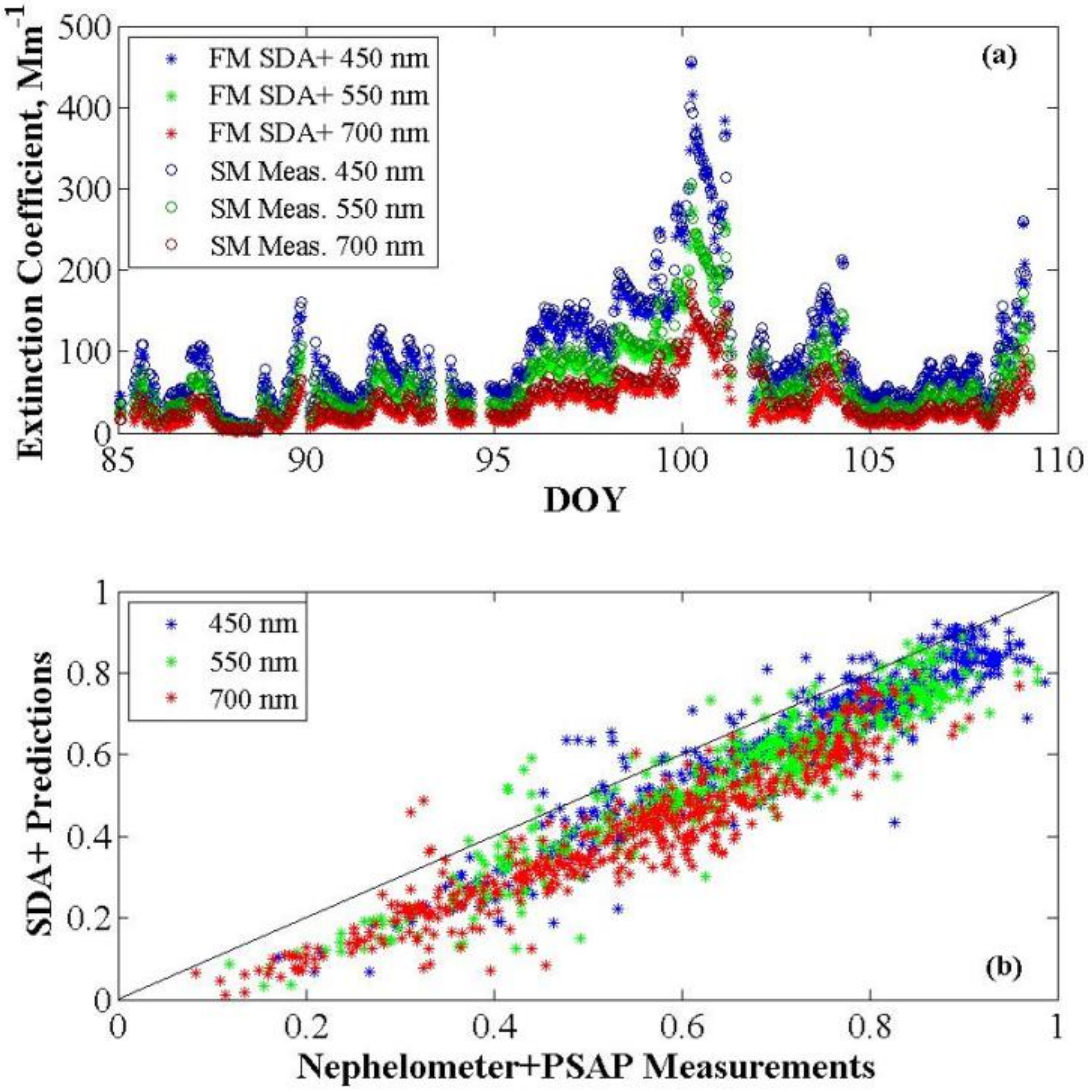

Figure 5. A time series (a) of the measured Submicron Mode (SM) and SDA-calculated Fine Mode (FM) extinction coefficient aboard the R/V Ronald H. Brown (PMEL) during a field campaign in the north-east Pacific, 2001. Bottom graph (b) shows Fine Mode Fraction extinction predicted by SDA+ versus the equivalent Submicron Fraction derived from PSAP and nephelometer extinction coefficient measurements. Plots for scattering coefficient predictions and measurements show similar agreements. A one-to-one line is provided for reference in Figures 2(b), and the correlation between the measured and SDA+ calculated extinction at 450 nm, 550 nm, and 700 nm wavelength is 0.99, 0.98 and 0.97, respectively.

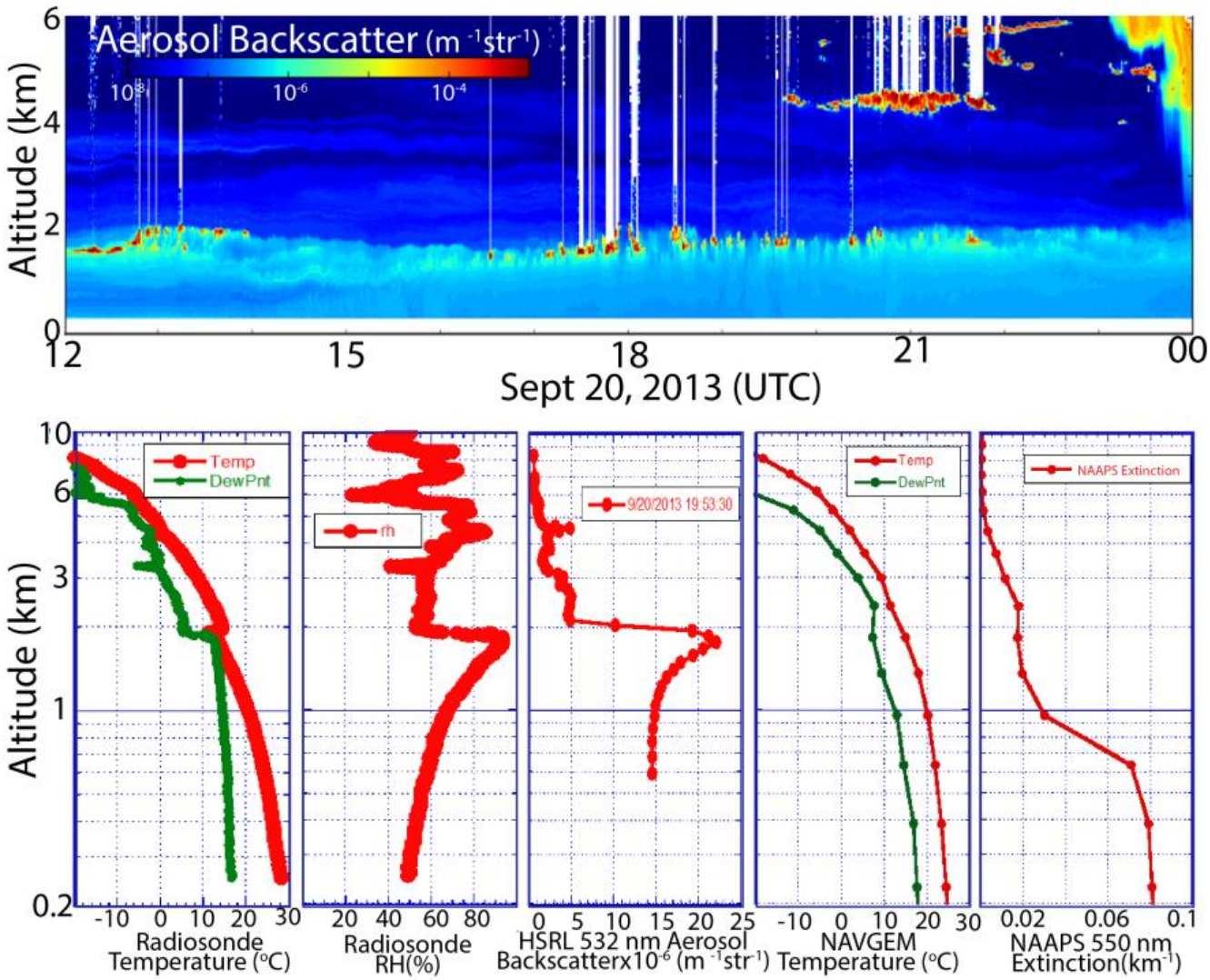

Figure 6. Time series of aerosol backscatter for September 20, 12-24 Z for the Huntsville Al site during the SEAC4RS mission. Also shown is a 19:50z released radiosonde temperature, dew point and relative humidity with an associated HSRL aerosol backscatter for when the balloon was near the top of the boundary layer. In comparison is the corresponding NAVGEM temperature and dew point profile with the ambient NAAPS 550 nm light extinction.

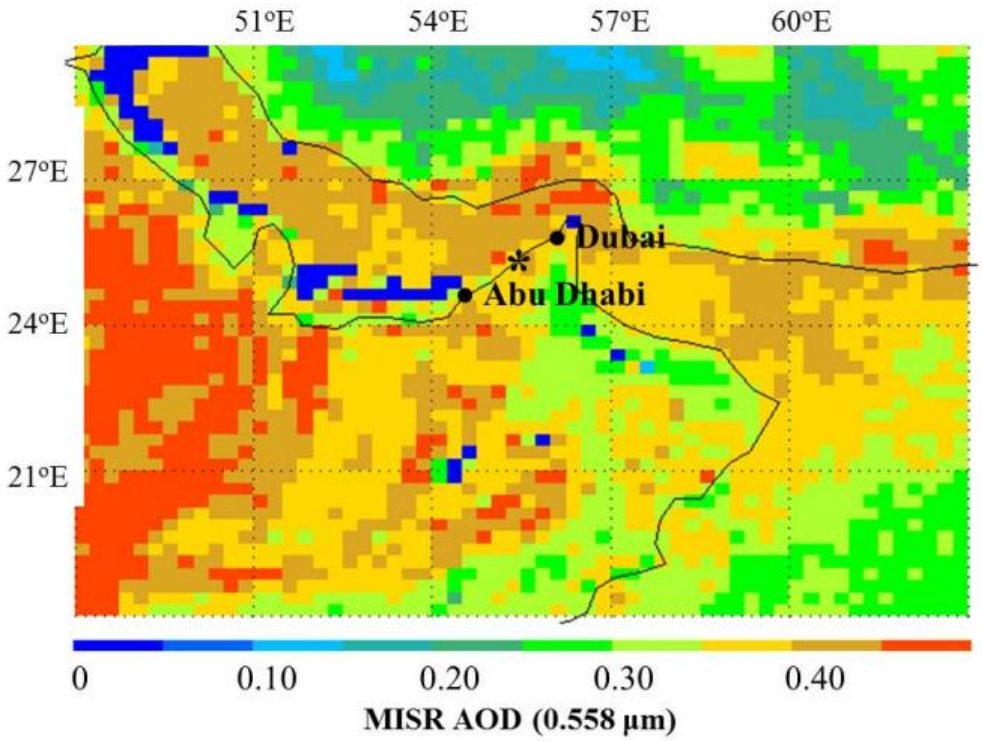

Figure 7. The Multi-angle Imaging SpectroRadiometer (MISR) 0.558 µm Aerosol Optical Thickness (AOT) from 2004-2006 over the UAE[2] study period (Aug.-Sept, 2004). The star shows approximately where the aerosol samples were collected.

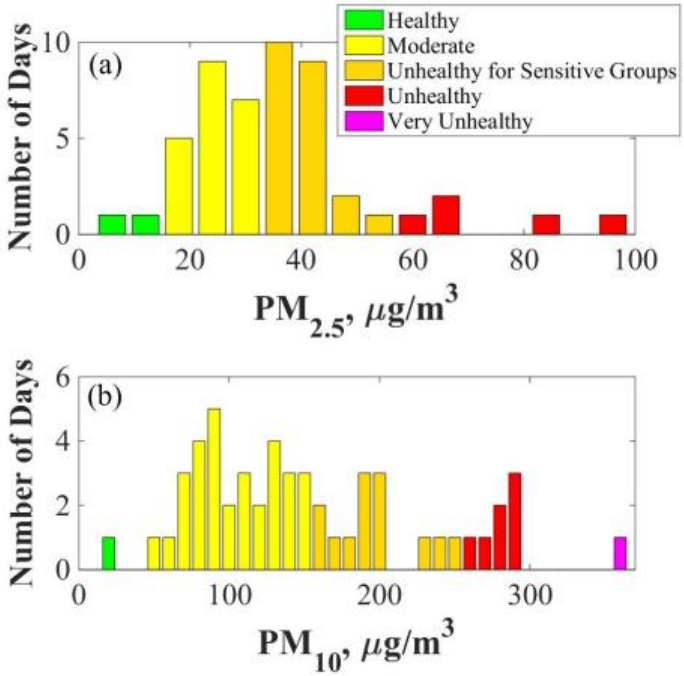

Figure 8. Histograms of the $PM_{2.5}$ aerosol mass concentration (top) and the PM_{10} aerosol concentration (bottom) observed during the UAE[2] campaign. The colors correspond to the Air Quality Index (AQI) as defined by the EPA. The classifications for $PM_{2.5}$ (in µg/m3) are Healthy: 0-12, Moderate: 13-35, Unhealthy for Sensitive Groups: 36-55, Unhealthy: 56-150, and Very Unhealthy: >150. The classifications for PM_{10} (in µg/m3) are Healthy: 0-54, Moderate: 55-154, Unhealthy for Sensitive Groups: 155-254, Unhealthy: 255-354, and Very Unhealthy: >355. Roughly 100 $\mu g\ m^{-3}$ of PM_{10} and 20 of $PM_{2.5}$ corresponds to mid visible light extinction of 0.05 km^{-1}.

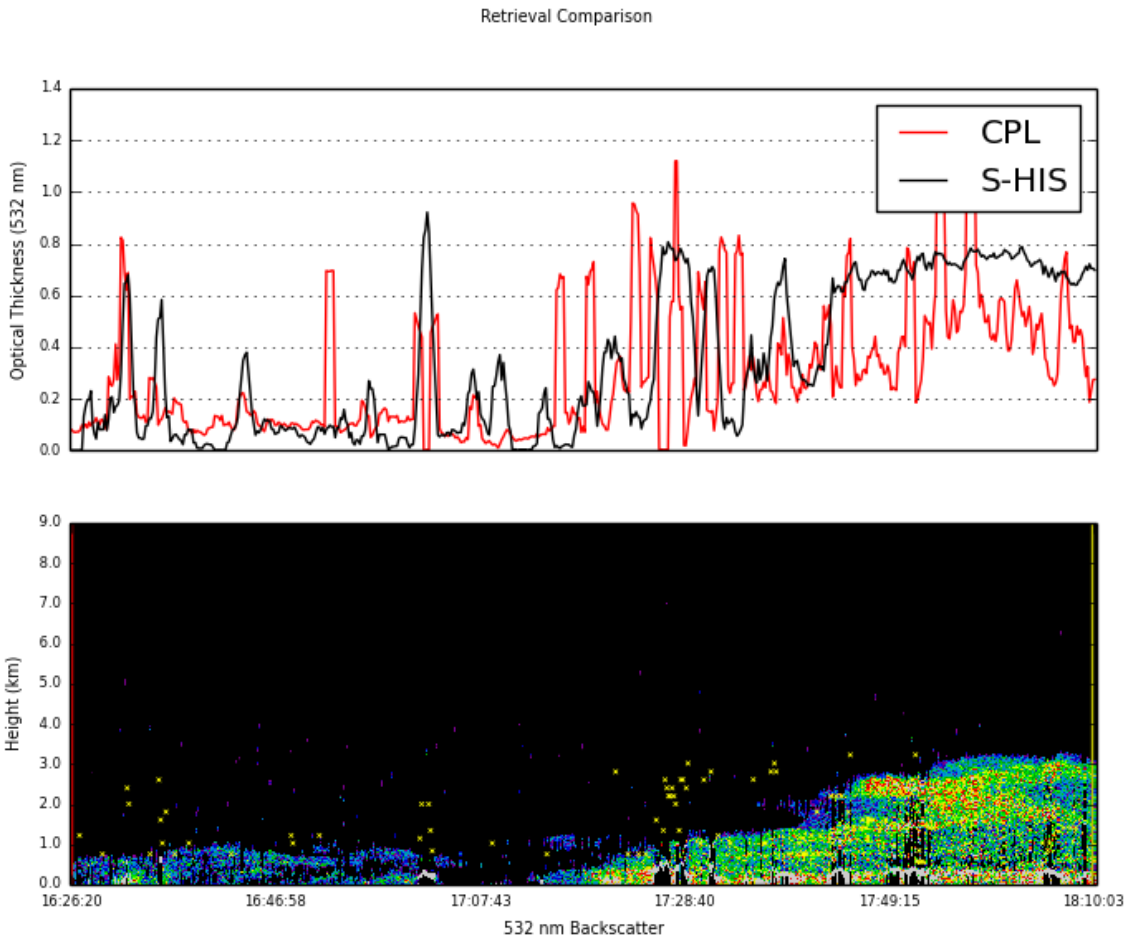

Figure 9. Example retrievals from an HS3 flight segment. Top panel shows aerosol optical thickness retrievals from CPL and S-HIS sensors, nadir facing onboard the global hawk. Bottom panel provides context in the form of the CPL 532 nm channel backscatter of elevated dust with imbedded low-level cloud features.