Optical Depth Assimilation for Operational Dust and Pollution Prediction

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Synopsis: The Marine Meteorology Division has developed and delivered the world's first operational system for the assimilation of aerosol optical depth (AOD) data from satellite sensors into an aerosol forecast model. This system, the NRL Atmospheric Variational Data Assimilation System–Aerosol Optical Depth (NAVDAS-AOD), is used to improve the Navy Aerosol Analysis and Prediction System (NAAPS), used by Department of Defense (DoD) and civilian users to forecast severe visibility-reducing dust, smoke, and pollution events. Implementation of NAVDAS-AOD at the Fleet Numerical Meteorology and Oceanography Center (FNMOC), which assimilates quasi-operational NASA Moderate Resolution Imaging Spectroradiometer (MODIS) data, has nearly halved errors in Navy aerosol forecasts.

Introduction and Rationale: Dust, smoke, and pollution forecasting has become an important application area for the Department of Defense. Whereas the DoD was traditionally concerned about aerosol effects on electro-optical (EO) propagation issues related to navigation, air operations, and ordnance delivery, recent applications include directed energy and EO surveillance and reconnaissance systems. Recent emphasis in poor-visibility areas such as the Arabian Gulf, Asia, and Africa has placed even greater demands on aerosol characterization and forecasting systems. Simultaneously, the broader research community has renewed interests in aerosol particles due to their impact on meteorology, geochemical cycles, and climate.

The Marine Meteorology Division has pioneered the field of global aerosol forecasting. Important firsts include (1) the development of NAAPS, the first operational global aerosol forecast model; (2) the first global use of satellite-based fire data for use in estimating forest fire and agriculture emissions; and (3) the world's first quasi-operational aerosol model verification system. These systems are used by DoD customers for operational visibility prediction, as well as by a host of civilian operational and scientific users.

Recently, NASA MODIS aerosol products have become reliably available in near real time. Unsurpassed for its efficacy and nearly daily coverage over the globe, the NASA MODIS products suite provides the bulk of global aerosol monitoring. Even so, before these data can be incorporated in models, several technical challenges related to product error characterization and aerosol redistribution must be met. NRL has met these challenges and devised the world's first operational aerosol optical depth system, the NAVDAS-AOD, which was transitioned to FNMOC in 2009.

System Overview: NAVDAS-AOD has three primary components: data acquisition and preprocessing, variational analysis, and feedback into NAAPS. The process begins with the acquisition of satellite aerosol optical depth data. While other data sources are or will be available, initial focus has been on near-real-time MODIS retrievals from the Terra and Aqua spacecraft, generated by the joint NASA/NOAA Near Real Time Processing Effort (NRTPE). These satellites give near-global coverage of AOD at a nadir resolution of 10 × 10 km and are downloaded from NRTPE with data latency of approximately 6 hours.

The most significant challenge in developing NAVDAS-AOD was the development of the preprocessor.[1] Before model assimilation can take place, error characterization must be understood and, preferably, systematic biases be removed. Remaining systematic high biases in particular can be very damaging as these will create isolated "plumes" in the analysis that will then propagate in the forecast. Major sources of systematic bias in satellite AOD include (1) cloud contamination, in which cloud edges are misidentified as dust or pollution, subsequently leading to a high bias; (2) lower boundary conditions, where whitecapping and glint on the ocean surface or bright desert surfaces are misinterpreted as aerosol particles, which reduce the top of atmosphere signal to noise; and (3) microphysical bias, where the optical properties of the aerosol particles are different from what is derived or assumed in the retrieval. Through a series of validation and verification studies, NRL developed a preprocessor that screens, aggregates, performs empirical corrections, and assigns final uncertainties for these types of biases. The resulting global data field over ocean is dramatically different from the original data (Fig. 1). While on average the preprocessor reduces AOD by 20% to 30% over oceans, significant cloud-related bias is removed from the southern oceans and North Pacific (approximately 50% correction). Microphysical bias results in an approximate 10% to 20% correction for areas of significant pollution and dust loading, respectively. Correcting for ocean surface wind speed also proved important for the background marine environment.

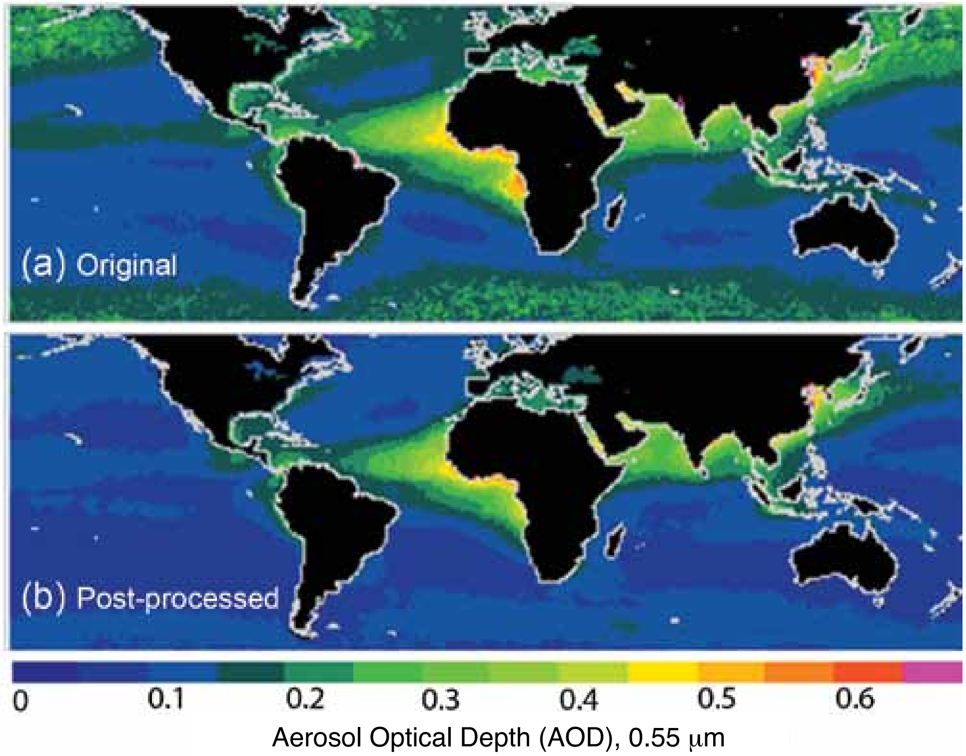

FIGURE 1
Comparison of mean aerosol optical depth (AOD) for 2007 from the NASA MODIS instrument (a) before and (b) after pre-processing. Note significant changes in the southern oceans and North Pacific due to the removal of cloud artifacts. Also note more subtle changes in dust in the Arabian Gulf and off the African and Asian coasts due to correction of micro-physics errors.

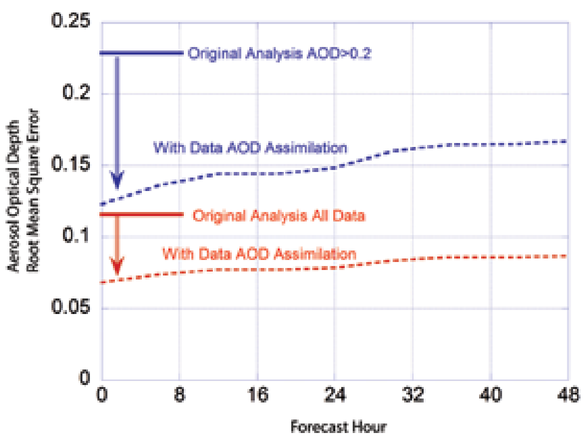

FIGURE 2
Average NAAPS root-mean-square error improvement for aerosol optical depth (AOD) at coastal Sun photometer sites. Given are the original T = 0 analyses (solid), and error by forecast hour with AOD data assimilation (dashed).

After preprocessing, revised data undergoes 2D variational analysis with the NAAPS model via the core NAVDAS system.[2] The resulting 2D global AOD analysis is then fed back into NAAPS in three dimensions, based on the initial model vertical distribution. When observed AODs are significantly larger than in the NAAPS model, vertical redistribution follows a climatology based on the NASA Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data set.

Based on comparisons with the NASA Aerosol Robotic Network (AERONET) network of Sun photometers, NAVDAS-AOD has reduced NAAPS root-mean-square errors by 25% to 40% for both the analysis and the 48-hour forecasts over the world coastal sites (Fig. 2). Some sites, such as those near Africa, see even greater improvements.

Other versions of the preprocessor and NAVDAS-AOD under development include the application of overland AOD, conversion to 3D variational analysis, and the addition of other passive and active sensors (e.g., CALIPSO).

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Measurements of Water Vapor from the Lower Stratosphere to the Upper Mesosphere

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Introduction: Water vapor in the stratosphere (~15 to 50 km) and mesosphere (~50 to 90 km) is the primary source of the OH radical and other hydrogen compounds, and is therefore important in ozone chemistry. In addition, water vapor entering the stratosphere is extremely sensitive to temperatures at the tropical tropopause, and is therefore relevant to our understanding of how and where air rises from the troposphere into the stratosphere. Also, because water vapor is an important greenhouse gas, measuring the amount of water vapor in the atmosphere is extremely useful for understanding global climate change.

WVMS Instruments: The ground-based Water Vapor Millimeter-wave Spectrometer (WVMS) instruments have been measuring water vapor from ~40 to 80 km and total column water vapor since the early 1990s from Network for the Detection of Atmospheric Composition Change (NDACC) sites at Mauna Loa, Hawaii (19.5°N, 204.4°E), Lauder, New Zealand (45.0°S, 169.7°E), and Table Mountain, California (34.4°N, 242.3°E). These instruments retrieve water vapor profiles by measuring the pressure-broadened 22 GHz water vapor lines, and are preferably deployed at dry, high-altitude sites, where the water vapor in the dry stratosphere and mesosphere can be observed through a minimal amount of tropospheric (surface to ~15 km) water vapor.

While these ground-based microwave measurements of water vapor in the upper stratosphere and mesosphere from 40 to 80 km are ideal for long-term change detection,[1] they do not always detect shorter-term multiyear variations such as the increase in stratospheric water vapor that was observed by the NRL Polar Ozone and Aerosol Measurement (POAM) satellite instrument in 2001.[2] We have, therefore, incorporated state-of-the-art technologies, including fast Fourier transform (FFT) spectrometers, to extend the range of the WVMS measurements to cover the atmosphere from 26 to 80 km.

Successful Deployment of New Instrument: The first successful deployment of such an instrument has been to the Table Mountain site (Fig. 3), where from December 2008 to May 2009, WVMS measurements showed good agreement with coincident Microwave Limb Sounder (MLS) water vapor measurements from the Aura satellite. Figure 4 shows the spectrum of the measurements made by this WVMS system on January 28, 2009. The measurements are integrated over the entire day in order to obtain adequate signal-to-noise. Also shown in this figure is the water vapor profile from 0 to 20 km (note the log scale) and from 0 to 80 km. The water vapor profile between ~10 km and ~26 km comes primarily from climatology, since the measurement is not sensitive in this range.

During the December 2008 to May 2009 period, WVMS measurements were also compared with radiosondes launched from the nearby Edwards AFB and Vandenberg AFB, and the new WVMS measurements showed skill at detecting variations in mid-tropospheric water vapor. The WVMS instrument at Table Mountain also participated in the NASA Measurements of Humidity in the Atmosphere and Validation Experiments (MOHAVE) campaign in September 2009, where it was compared with balloons, lidars, GPS total column measurements, and several satellite measurements.

Future of Water Vapor Measurements: The Mauna Loa site has been prepared for simultaneous deployment of a new WVMS instrument alongside the existing instrument. These instruments will be compared for approximately 1 year in order to ensure that there is no disruption to the long-term trend data taken from the Mauna Loa site. While until now the

FIGURE 3
The WVMS instrument at Table Mountain.

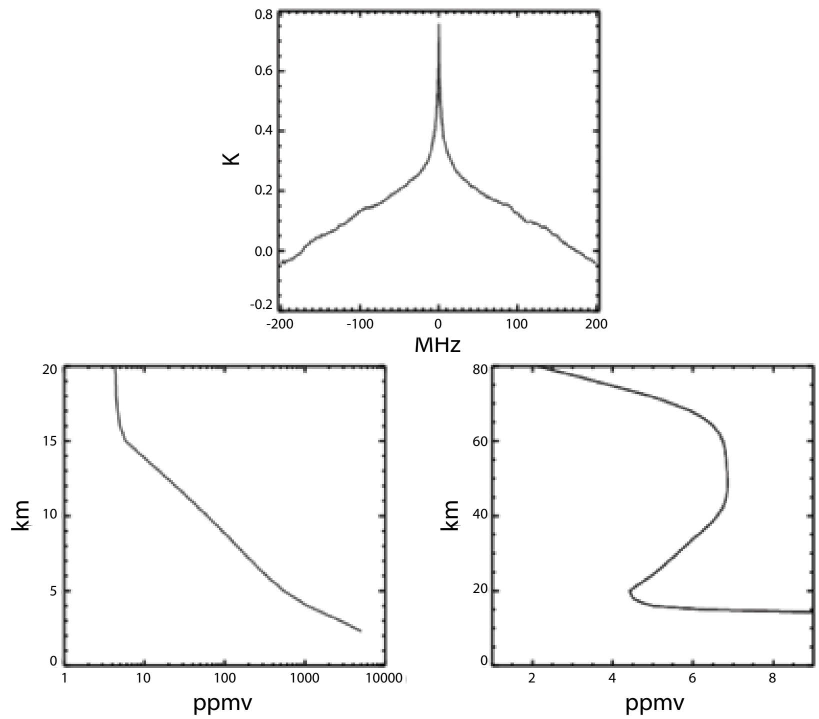

FIGURE 4
Top: Brightness temperature spectrum as measured by the WVMS instrument on January 28, 2009. A baseline has been subtracted. Bottom left: Water vapor in the troposphere. The profile begins at the 2.3 km altitude of the measurement site. Bottom right: The water vapor profile from 0 to 80 km. Note how much drier the stratosphere and mesosphere are as compared to the surface.

WVMS instruments have been used together with satellite data to measure changes in water vapor, it is not clear whether satellite measurements of water vapor in the stratosphere and mesosphere will be available in the future. WVMS instruments may, therefore, be the primary source of data for future water vapor trends in this region of the atmosphere.

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[Sponsored by NASA and ONR]

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Long-Range Optical Communications Link

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Introduction: The Electro-Optics Technology Section and the Photonic Materials and Devices Section successfully demonstrated a high-speed, long-range, free-space optical laser communication (lasercom) link between Fort Story and Fort Monroe, in Virginia, during the Trident Spectre 2009 exercise. The total range of the link was 28 km — a range approaching Earth curvature line-of-sight limited range (Fig. 5). The link gives a fully bidirectional fast Ethernet link (100 Mbps) with packet error rates less than 1% at all times. Lasercom provides an alternate data path to standard radio frequency communication links. The Trident Spectre exercise demonstrated that lasercom can provide the U.S. Navy and Marine Corps with greatly increased connectivity, low probability of intercept and detection, and path diversity to increase overall communications reliability.

Capabilities: Dual Mode Optical Interrogator (DMOI) lasercom terminals developed by Novasol, Inc., in collaboration with NRL were used for the Trident Spectre exercise. These terminals use free-space propagation of eye-safe telecommunication wavelength lasers (wavelength of 1550 nm) through the atmosphere to enable fiberless optical communications. The DMOI terminals are designed to automatically track moving targets and can themselves be operated on moving platforms. Optical communications electronics developed jointly by NRL and Smart Logic, Inc., were connected to the DMOI terminals to enable the 100 Mbps fast Ethernet data links between DMOI terminals. Communications terminals of this

FIGURE 5
Image showing endpoints of the free-space optical (FSO) link.

type can be used to connect networks separated by large distances without laying optical fiber, which is either costly for fixed locations or impossible for mobile platforms.

For the Trident Spectre 2009 exercise, one DMOI was installed at the top of the Cape Henry Lighthouse at Fort Story in Virginia Beach, Virginia. Across the Chesapeake Bay, a second DMOI was installed in an observation tower atop the historic Fort Monroe battlement. Similar communications terminals were used on USS *Comstock* during Trident Warrior 2008 (Fig. 6) to enable real-time bidirectional communications during Maritime Interdiction Operations (MIO) exercises on USNS *Yukon*. Similar NRL demonstrations were performed during the Trident Warrior 06 and Seahawk 07 exercises and for many years at NRL's lasercom test facility at the Chesapeake Bay Detachment.

Results: Several types of data at varying rates were transferred over the course of the Trident Spectre 2009 exercise. Multiple computers and high-resolution Internet protocol video cameras (2560 × 1920 pixels at Fort Story and 2048 × 1536 pixels at Fort Monroe) were connected to the optical link at Fort Story and Fort Monroe through standard Ethernet switches. Laptop computers on either end were used to simultaneously display the multiple camera feeds, enable full net meeting functionality (duplex voice communication, chat, remote desktop, etc.), run packet error rate testing software, and conduct high-speed file transfers (greater than 100 MB transfers in approximately 45 s). The typical bandwidth used for simultaneous operation of all data sources was greater than 50 Mbps, with peak demonstrated data throughput of 91 Mbps. Using a special file transfer protocol developed at NRL, ABPACK, more than 1500 files were successfully transmitted via the link. Packet error rate testing was performed simultaneously with other network traffic over the course of the 3 days of testing with a measured average packet error rate of 0.2%. As demonstrated by the low average packet error rate, errors were rare and had no impact on network performance.

Summary: The Trident Spectre 2009 28-km direct lasercomm link was a complete success. The data link was established early each day of the 3-day demonstration and remained on throughout the day. Network

FIGURE 6
Michele Suite and the DMOI underway aboard USS *Comstock* (LSD 45).

conductivity between Fort Story and Fort Monroe was maintained throughout the day, allowing a standard network connection between the two sites that typically do not have high-speed communications. All standard Ethernet traffic was successfully transmitted through the link, resulting in a highly reliable link that required almost no user intervention — as desired for any communication link. Use of this link or similar lasercom links for future Trident Spectre exercises and other exercises requiring high-speed conductivity is likely. The success of lasercom in numerous NRL demonstrations and its capabilities to augment standard radio frequency communications have pushed this technology to the point where operational military use of lasercom systems is probable in the very near future.

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