Aerosol Impact on Infrared METOC Data Assimilation

Douglas L. Westphal  
Naval Research Laboratory  
7 Grace Hopper Ave, Stop 2  
Monterey, CA 93943-5502  
phone: (831) 656-4743  fax: (408) 656-4769  email: westphal@nrlmry.navy.mil

James R. Campbell  
Naval Research Laboratory  
7 Grace Hopper Ave, Stop 2  
Monterey, CA 93943-5502  
phone: (831) 656-4555  fax: (831) 656-4769  email: james.campbell@nrlmry.navy.mil

Benjamin C. Ruston  
Naval Research Laboratory  
7 Grace Hopper Ave, Stop 2  
Monterey, CA 93943-5502  
phone: (831) 656-4020  fax: (831) 656-4769  email: ruston@nrlmry.navy.mil

Annette L. Walker  
Naval Research Laboratory  
7 Grace Hopper Ave, Stop 2  
Monterey, CA 93943-5502  
phone: (831) 656-4722  fax: (831) 656-4769  email: walker@nrlmry.navy.mil

Document Number: N0001415WX00409, N0001415WX00835  
http://www.nrlmry.navy.mil/aerosol

GOALS

This work addresses the impact of radiatively-important aerosol particle features on radiance assimilation procedures used in the Earth System Prediction Capability (ESPC) model components Navy Global Environmental Model (NAVGEM) and HYbrid Coordinate Ocean Model (HYCOM). Mineral dusts, in particular, are active infrared absorber/emitters, with layer heights regularly reaching to and above 5 km above mean sea level. Our effort focuses on characterization of dust impact on thermal/water vapor profile radiance-based retrievals in the tropical Atlantic. The area is frequently subject to large dust storm intrusions from the nearby Saharan Desert. We further examine the impact of optically-thin cirrus clouds on these infrared retrieval processes, highlighting sea surface temperature bias consistent with previous work, as ancillary unscreened and uncharacterized components of the column-integrated radiance profile.
OBJECTIVES

The primary objective of this research is to develop quantitative estimates for aerosol particle radiance bias on infrared retrievals used as data assimilation inputs for ESPC model components. These results will serve as the basis for evaluating radiatively-active aerosol particles in the NRL Atmospheric Variational Data Assimilation (NAVDAS) and NAVDAS-AR (accelerated representer) assimilation systems for the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) and/or NAVGEM and the Navy Coupled Ocean Data Assimilation (NCODA) system for HYCOM. We focus our experiments on mineral dusts because their relative global frequencies of occurrence, relatively high corresponding optical thickness and common layer top heights of 5 km above sea level enhance their activity at infrared wavelengths.

A secondary task is the concurrent analysis of optically-thin cirrus cloud contamination of infrared radiance-based retrievals. Exhibiting visible optical depths < 0.3, these clouds are transparent in satellite-based radiometric imager and sounder datasets, and thus go unscreened as datasets used in current radiance assimilation procedures in NAVGEM and HYCOM. Similar to aerosols then, though clearly unresolvable by current environmental prediction models, they represent an inherent signal that can be conceptualized and reported for ranges of potential bias in unfiltered assimilation-input datasets. Consistent with previous work investigating the impact of unscreened dust particle presence on sea surface temperature retrievals, we solve corresponding sea surface temperature (SST)-retrieval bias for unscreened optically-thin cirrus (OTC; defined as cloud optical depth ≤ 0.3) presence using a forward radiative transfer model.

This work establishes the effective “limits of detection” for hyperspectral infrared sensors with respect to aerosol and optically-thin cirrus presence. A next step toward a fully interactive system, which is beyond the scope of this project, requires additional development of advanced radiative transfer analytics, including an examination of the translation of infrared radiance to temperature and moisture with respect to various dust parameters such as particle size. These sensitivities, called Jacobians, provide derivatives describing changes of radiance caused by changes in the particle size, type, and amount. Some simple approximations to these Jacobians can be performed within the limits of the experimental design.

The first year of this project was dedicated to an analysis of satellite and surface-based observations of dust plume occurrence and advection over the tropical Atlantic, and thus an aggregation of datasets collected by the CALIPSO satellite lidar, MODIS and VIIRS satellite radiometric imagers, IASI, AIRS and CrIS hyperspectral infrared satellite profilers, AERONET sun photometer network and the Micro Pulse Lidar (MPL) network. These data have then been paired with NAVGEM and NAAPS (Navy Aerosol Analysis and Prediction System) output to develop a 1-Dimensional Variational (1D-Var) experimental assimilation procedure that evaluates the limits of detection for dust presence and sensitivity of thermal/moisture profiles to dust infrared bias. Further analysis was conducted for SST bias in the presence of unscreened thin cirrus.

The second year of the project has focused on conducting experiments using the 1D-Var radiance assimilation procedure using case study datasets compiled in Year 1. Tests have been conducted to identify and quantify biases in temperature and moisture profiles attributable to dust radiative effects, and how these vary in magnitude versus background NAVGEM fields. We have thus paired NAAPS with a replica of NAVGEM/NAVDAS-AR in one-dimensional space to simulate basic implementation of an operational coupled system, conceptualizing the impact of thermal/moisture profile bias induced...
by radiance assimilation that includes no prior information of the radiative state of optically-
thin/active-infrared target layers.

We have further completed an analysis of long-wave infrared satellite-based SST for cold bias due to
unscreened OTC in MODIS, VIIRS and AVHRR datasets. An experiment was designed to apply OTC
cloud contamination characteristics derived from collocated Aqua-MODIS and CALIOP data pairs
consistently across both VIIRS and AVHRR, in order to run radiative transfer model simulations that
estimate OTC cold biases for each of the three platforms. The result is a first-order estimate of the
relative (per observation) and absolute (bulk annual mean) cold biases apparent in operational SST
products due to unscreened, and ultimately unresolvable due to their optical diffusivity, cloud
presence.

**APPROACH**

We’ve applied a three-phase approach to solving and evaluating dust infrared bias on thermal infrared
sounder profile assimilation for NAVDAS and NAVGEM. The first phase considers datasets
generated from combined model-based analyses and satellite measurements, in order to identify
suitable test cases for analysis. Shown in Fig. 1 for 14 June 2015 are NAAPS surface dust
concentrations (g/kg) at 1200 UTC over central and western Africa, MODIS true-color imagery at
1500 UTC off the west African coast and a CALIPSO lidar backscatter composite corresponding with
the orbital track superimposed on the MODIS image. This case study serves as the basis for
investigating dust thermal infrared impact on NAVDAS satellite infrared sounder assimilation.

The second and third phases of the analysis reflect the consideration of NAAPS analyses for regional
dust in the tropical eastern Atlantic. A 1D-Var retrieval has been developed based on the RTTOV
(Radiative Transfer for TOVS) radiative transfer model as a practical and reasonable proxy for the
operational system assimilating sounder radiance data. The 1D-Var retrieval applies spectral
brightness temperature observations from IASI, CrIS and AIRS and uses these to correct a background
profile from NAVGEM. The 1D-Var has to be provided errors for both the observation and the
atmospheric background state from NAVGEM. With these inputs provided the 1D-Var can be used to
assess how a given profile of dust from NAAPS affects surface temperature, and the temperature and
moisture through the atmospheric column. Each of the three-phase inputs to such a system has a co-
located NAVGEM model atmospheric profile and surface state, the satellite infrared (IR) hyperspectral
radiances, and the NAAPS dust profile. This tool is thus the first fully interactive dust assimilation
system combining aerosol optical depth (AOD) assimilation with that of the IR radiances.

The areas focused on in this analysis represent the Saharan dust boundary, where a subset of IR
radiances both with and without dust contamination has been examined. The fundamental goal of the
project was to quantify and understand the impact of assimilating dust-contaminated radiances when
the radiative effects of the dust (and/or thin cirrus) have not been taken into account. An examination
of these cases with the 1D-Var system is now providing the quantification needed to define
temperature and moisture error in the vertical in the presence of dust. Further, the examination of the
observations themselves, which along with CALIPSO and MODIS, can pinpoint the affected pixels
and provide estimate of the range of radiance deviations with respect to aerosol loading. This, in turn,
can be assessed in follow-on efforts relative to the broader 4D-Var assimilation package downstream
in NAVDAS-AR, to assess how significant these biases are when introduced to the global model.
Shown in Fig. 2 is the initial step in applying the 1D-Var model assimilation system. Corresponding with the observations in Fig. 1, this composite represents the difference in spectral infrared brightness temperature rendered by the RTTOV model with (red) and without (blue) accounting for dust aerosol as provided by NAAPS. The atmospheric state for both cases was identical, and based on background temperature, moisture and ozone profiles from NAVGEM near 1510 UTC (red star in Fig. 1). Again, Fig. 1 shows the difference between the CrIS observation and the simulation from RTTOV. The differences only appear in the 8-12.5 µm region which is expected as the 6-8 µm region is opaque due to water vapor, and the region greater than 13 µm are CO2 sounding channels which peak higher in the atmosphere than where the dust has an impact. The 8-12.5 µm region has a significant magnitude of brightness temperature difference due to the dust impact, which for this case is consistently about 2K throughout this spectral region. Further, this aligns with qualitative estimates which were made by inspection of the infrared imagery along with the CALIPSO and MODIS images which could help to identify the pixels contaminated by dust. Examining numerous cases it was found that the NAAPS input was being treated reasonably well in the radiative transfer (RTTOV) model context. The impact of NAAPS dust can range from 2-5K for a variety of aerosol loading profiles.

Figure 3 depicts how these brightness temperatures impact the model innovation steps. Temperature and moisture increments are produced by the 1D-Var which are added to the background profile from NAVGEM to produce the retrieval. The differences in these increments can be very informative on how mishandled dust could impact an assimilation system. Increments produced by the 1D-Var are shown in Figure 3, both with dust (red) and without (blue). The increments for temperature and moisture are distinct, both in relative magnitude, sign and their distribution within the vertical. These data show definitively and quantitatively that even relatively shallow (i.e., up to 5 km) infrared absorbers like dusts if mistreated could significantly impact assimilation inputs within NAVGEM. Further, this strongly motivates the basis for integrating NAVGEM, NAVDAS and NAAPS to render more accurate assimilation input and innovation within the model. It is of note that the current NAVGEM and corresponding NAVDAS-AR uses quality control procedures to screen out these dust impacted pixels. This study clearly shows, if the quality control were removed and the system tried to assimilate these pixels, that the increments in both temperature and moisture would most likely be in opposite directions than if the dust were properly accounted for. Further, the result from the current NAVGEM system with its quality control in place is simply an un-modified background state with no observational influence.

A paper is being developed to report these results. Included will be an analysis of the relative sensitivities in differences between the no-aerosol and with-aerosol innovation profiles over the eastern Tropical Atlantic for summers 2006-2014, pairing CALIOP dust profiles (background truth) with NAAPS profiles (model functionality). After determining the significance of the problem in this study, our final goal is to evaluate how well the model captures real-world variability within the system. This final component will enhance the rationale for continuing 6.4 developments that integrate aerosol profiles within NAVDAS-AR to properly constrain corresponding radiances.

To study OTC contamination of operational SST products, unscreened cloud contamination within the Level 2 Aqua-MODIS SST product in the tropics (MOD28; 30°S-30°N) for the year of 2012 were characterized using collocation with Version 3 Level 2 cloud profiles from CALIOP. OTC contamination characteristics from collocated Aqua-MODIS/CALIOP data pairs were then used to estimate corresponding SST retrieval cold biases for MODIS, AVHRR and VIIRS. Respective SST retrievals for all three sensors were modeled using the Santa Barbara DISORT Atmospheric Radiative Transfer model (SBDART). Two-dimensional OTC-contaminated cold bias matrices were solved after
simulating a hypothetical OTC layer, 1.5 km thick, between 10.0 and 18.0 km cloud top height above mean sea level (solved in 0.25 km segments) and COD between 0.0-0.3 (in 0.01 segments) for both a cloud structured with a constant optical extinction coefficient (‘block cloud’) and with a linearly-decreasing extinction coefficient value from cloud top to cloud base of five-to-one (“fallstreak”). Relative and absolute OTC SST cold biases were then estimated by multiplying the corresponding instrument matrix by occurrence frequency estimated from Aqua-MODIS/CALIOP. This approach is depicted in Fig. 4a-c, showing corresponding OTC frequencies and bias (results summarized below) for the MODIS, AVHRR and VIIRS, respectively.

**WORK COMPLETED**

FY15 activities built on FY14 accomplishments to apply case studies as the basis for investigating infrared contamination of satellite sounder profiles to understand their impact on NAVDAS-AR/NAVGEM assimilation. A 1D-Var radiance assimilation model coupled with a forward radiative transfer model has been developed to conduct experiments evaluating dust mass concentration profiles relative to thermal radiance contamination. Further, as follow-on to previously-funded research, we have finished a study of unscreened optically-thin cirrus cloud contamination of satellite infrared radiances used in sea surface temperature retrievals over the global tropics. One publication is pending describing the basis for 1D-Var radiance assimilation and bias due to active infrared aerosol targets, which will be written and published in FY16. Two publications came out of the SST effort: Bogdanoff *et al.* (2015) and Marquis *et al.* (2015).

1. Based on the 14 June 2015 case study depicted in Fig. 1, we designed the first component of the 1D-Var infrared sounder radiance assimilation model (Fig. 2). At this stage, brightness temperatures solved by the model using NAVGEM background temperature, moisture and ozone profiles are compared with satellite radiances for no-aerosol and with-aerosol scenarios to investigate baseline differences in primary input sounder datasets.

2. The second component of the 1D-Var assimilation model was designed to derive differences in model-innovated temperature and moisture profiles relative to a background NAVGEM analysis, again for no-aerosol and with-aerosol scenarios. We can now quantitatively evaluate the differences in model innovation due to the presence of dusts that are active at infrared wavelengths.

3. We designed a coupled forward radiative transfer model and sea surface temperature retrieval system for evaluating the potential bias due to unscreened optically-thin cirrus clouds. The system considers a hypothetical cirrus cloud 1.75 km thick with cloud top heights varying between 10.5 and 16.5 km above mean sea level and optical depths between 0.0-0.3 (Fig. 2). This conceptual model thus evaluates potential bias for any number of possible cloud occurrence scenarios in the tropics. Such optically-thin cirrus occurs upwards of 60% in the tropics, with most clouds going unscreened in passive radiometer composite datasets.
RESULTS

FY15 results based on work completed are as follows.

1. We have demonstrated temperature and moisture bias in thermal sounder assimilation over the eastern Tropical Atlantic due to the unresolved presence of dust aerosols. The proper accounting for aerosol loading can create substantial differences in NAVGEM increments of temperature and moisture in magnitude, sign and vertical distribution.

2. We have solved radiance bias in operational sea surface temperature retrievals in the tropics due to unscreened optically-thin cirrus (OTC). We used Aqua MODIS collocated with CALIOP to describe the frequency of OTC occurrence and extrapolated these results across AVHRR and VIIRS to model algorithm retrieval biases apparent in all three sensors/products. OTC are present in approximately 25% of quality-assured MODIS SST datasets. Relative cold biases for any single contaminated observation, when unscreened OTC are present, range from 0.63-1.02°C for the three sensors. This results in an absolute tropical cold bias due to OTC of 0.16-0.26°C in long-term annual averages.

IMPACT/APPLICATIONS

Current FNMOC NAVDAS assimilation includes thermal infrared hyperspectral radiances to render improved vertical profiles of temperature and moisture. Thermally-active aerosols, like dust, are presently not considered for potential radiance contamination. We have demonstrated that failure to reconcile these radiances causes relatively significant error in the innovated model analysis. We are working with NAVDAS developers to motivate 6.4 projects that integrate NAAPS and NAVDAS to render more accurate assimilation inputs.

Current NAVO sea surface temperature retrievals used for HYCOM come from VIIRS, which is difficult to evaluate for potential cloud contamination (no collocated lidar instrument, as opposed to Aqua MODIS). We are communicating with product developers to investigate potential strategies for bias mitigation.

PUBLICATIONS


Figure 1: (a) NAAPS dust surface concentration analysis for 12Z 14 June 2015 over central and western Africa; (c), NASA MODIS radiometric true-color image at 15Z over eastern Tropical Atlantic and West Africa, with NASA CALIPSO satellite lidar track superimposed; (c) CALIPSO satellite lidar profile of Level 1 attenuated backscatter corresponding with orbital track in (B) near 15Z. Levels of enhanced backscatter through 5 km MSL reflect a dust layer consistent with that in (a). Elevated layers above 10 km reflect cirrus cloud associated with cloud system in (b).
Figure 2: Differences in spectral infrared brightness temperature rendered by the 1DVAR model, based on background NAVGEM thermal and moisture profiles for 14 June 2015 near 1510 UTC (red star in Fig. 1b and c), versus CRiS with no aerosol considered (blue) and with aerosol considered (red). The differences seen between 8 and 14 µm show the impact of considering dust in the assimilation step. Brightness temperature differences at these bands are most sensitive to the dust present in the column at the observation time. It is these differences that are propagated through the assimilation to induce errors in the innovated NAVGEM analysis.
Figure 3: Based on differences in brightness temperatures in Fig. 2, 1DVAR model innovation differences in rendered temperature (°C) and moisture profile (g/kg) having assimilated the no-aerosol profile (blue) based on CRiS brightness temperatures and that with aerosol considered (red). On the left, the corresponding NAAPS 500 nm aerosol extinction coefficient profile (km⁻¹) is shown for this case, with an aerosol optical depth of 0.39. The two plots on the left show the potential innovation impact on the model from dust radiance bias. The sign of the temperature difference induced within the model is out of phase with the profile generated using the NAAPS dust profile. Similar bias is seen from the moisture profile, including an anomalous moistening of the layer below 800 hPa.
Figure 4: SBDART radiative transfer model simulations of potential SST retrieval cold bias for an unscreened optically-thin cirrus (OTC) as a function of cloud top height and optical depth for (a) MODIS, (b) AVHRR, and (c) VIIRS algorithms. Overlaid on each composite are relative Aqua-MODIS/CALIOP collocated cirrus contamination percentage occurrence frequencies (%). Since cloud contamination is assumed constant across the three sensors, these data show that MODIS is the least susceptible algorithm to OTC, though the difference is slight. Most contamination takes place at the lowest optical depths, though these still coincide with cold biased SSTs on the order of 1-2 °C. These data are assimilated, and error budgets not properly accounted for, which imparts unnecessary bias in to models like HYCOM.