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THE 2004 AEROSOL AND OCEAN SCIENCE EXPEDITION (AEROSE): A UNIQUE DATASET FOR INFRARED SATELLITE VALIDATION

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1. INTRODUCTION

The 2004 Aerosol and Ocean Science Expedition (AEROSE) was a multidisciplinary oceanographic field campaign conducted onboard the NOAA Ship *Ronald H. Brown* (NOAAS *RHB*) (see Figure 1) in the tropical North Atlantic Ocean from 29 February to 26 March 2004, with funding support granted to the NOAA Center for Atmospheric Sciences (NCAS) at Howard University (HU/NCAS). The AEROSE overall mission objectives are summarized as follows:

1. *Aerosol microphysics and transport.* To obtain a set of critical measurements to help characterize the impacts and microphysical evolution of Saharan dust aerosol transport across the Atlantic Ocean.
2. *Aerosol air-sea interactions.* To obtain bio-optics and oceanographic observations to assist in studying the effect of dust on the marine boundary layer, characterizing water masses throughout the transects, and investigating upwelling conditions off the Northwest coast of Africa.
3. *Aerosol radiometric impact on satellite remote sensing.* To provide complementary visible and infrared (IR) measurements and analysis that can support the validation of radiometric data and derived products from advanced satellite instruments, including the NASA Aqua Atmospheric Infrared Sounder (AIRS), the NOAA Advanced Very High Resolution Radiometer (AVHRR/3),and the NASA Terra/Aqua Moderate Resolution Imaging Spectroradiometer(MODIS).

Figure 1: The NOAA Ship *Ronald H. Brown* in Bridgetown, Barbados, just prior to departure for the 2004 Aerosol and Ocean Science Expedition.

The mission also included an educational/outreach component by providing support for, and benefitting from, hands-on participation of several international graduate and undergraduate students.

To accomplish the experimental goals, atmospheric and oceanographic measurements were obtained from a number of *in situ* and remote sensing instruments operated by a multi-institutional team of researchers described below. During the month of March 2004, the *RHB* set out from Bridgetown, Barbados traveling eastward toward Africa. Near the African coast, the ship turned north toward the Canary Islands. After a port-of-call in Las Palmas de Gran Canaria, the ship returned to San Juan, Puerto Rico on 26 March 2004. Note that the cruise track (mapped in Figure 2) was planned taking into account aerosol optical depth (AOD) climatology for the month of March (see Figure 3) derived from NOAA AVHRR Pathfinder Atmospheres (PATMOS) dataset (Jacobowitz *et al.*, 2003). The outbound Leg 1 was to maximize probabilities of

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encounters with aerosol events, whereas the return Leg 2 was to take samples under marine background aerosol conditions. While underway, the planned cruise track was adjusted slightly according to satellite imagery and aerosol model forecasts from the Navy Aerosol Analysis and Prediction System (NAAPS). The *RHB* subsequently encountered at least 2 significant Saharan dust events, during which aerosol and ocean observations were acquired, thus obtaining a unique complementary dataset of tropospheric aerosol transport and evolution.

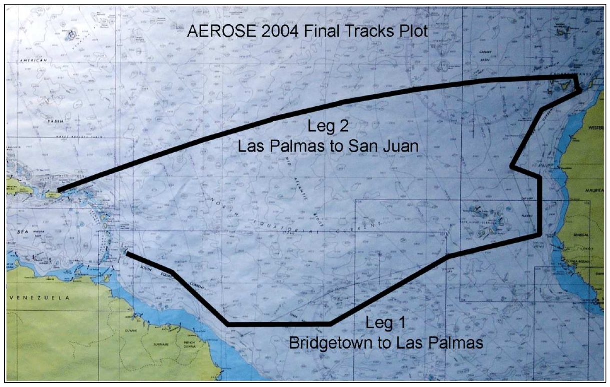

Figure 2: Cruise track of the NOAA Ship *Ronald H. Brown* in the tropical North Atlantic Ocean during the 2004 Aerosol and Ocean Science Expedition.

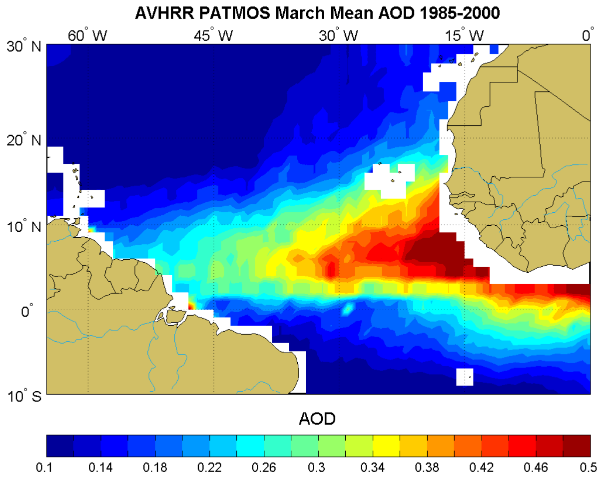

Figure 3: AVHRR PATMOS climatological mean tropospheric aerosol optical depth (AOD) for the months of March 1985–2000 (excluding 1992 because of the eruption of Mt. Pinatubo).

This paper focuses on the radiometric component (third mission objective described above) by presenting the relevant data along with some preliminary analyses. These data will be used to address key questions pertinent to satellite remote sensing and radiative transfer modeling. Because aerosols remain a source of bias in satellite IR retrieval products (e.g., Nalli and Stowe, 2002, and references therein), the AEROSE complementary data is invaluable for satellite validation studies proposed in this paper.

2. DATA

Radiometric and *in situ* data pertinent to studying the impact of tropospheric dust aerosol upon satellite IR spectra and retrievals are described in the following subsections.

2.1 Shipboard/Radiometric

2.1.1 Marine Atmospheric Emitted Radiance Interferometer (M-AERI)

The University of Miami (UM/RSMAS) M-AERI is a ship-based Fourier transform spectrometer (FTS) that measures calibrated high resolution (0.5 cm^{-1}) IR radiance spectra (Level 1B) of the atmosphere and ocean surface over the range of $\simeq$550–3000 cm^{-1}(Minnett *et al.*, 2001). During AEROSE, observations were made from $\simeq$8.2 m above sea level off starboard (see Figure 4) at 1 downlooking and 2 uplooking view angles. The downlooking view primarily observes surface-leaving upwelling radiance at 55° relative to the local zenith (originating outside of the ship's wake), whereas the uplooking views observe downwelling atmospheric emitted radiance at 0° and 55° from zenith.

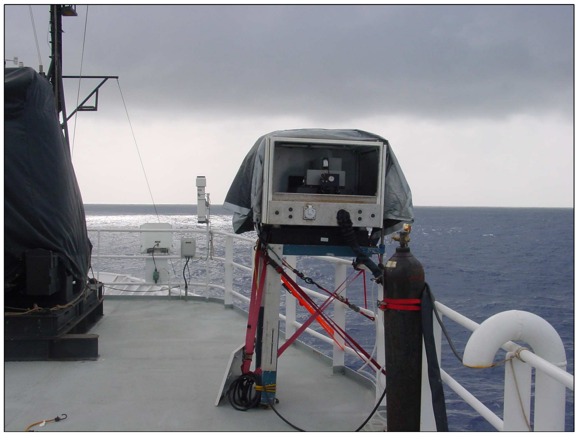

Figure 4: The UM/RSMAS Marine Atmospheric Emitted Radiance Interferometer (M-AERI) onboard the *Ronald H. Brown* during AEROSE Leg 2 operations in March 2004.

The M-AERI spectral radiances are used for retrievals of geophysical parameters (M-AERI Level 2 products). These include high accuracy ($\lesssim$0.1 K absolute) radiometric skin SST, IR sea surface emissivity and surface air temperature (Smith *et al.*, 1996), along with atmospheric boundary layer profile retrievals of temperature and water vapor (with $\simeq$20 min sampling to provide near continuous monitoring and resolution of micrometeorological phenomena)(e.g., Feltz *et al.*, 1998).

2.1.2 Calibrated Infrared In situ Measurement System (CIRIMS)

The University of Washington Applied Physics Laboratory (UW/APL) designed and engineered the CIRIMS instrument (see Figure 5), an autonomous shipboard narrowband radiometer system that obtains calibrated downlooking and uplooking radiances for accurately measuring skin SST ($\simeq$0.1 K absolute) to validate SST from the Terra/Aqua MODIS (Jessup *et al.*, 2002). The CIRIMS has been operating onboard the *RHB* beginning in June 2003 as part of a National Ocean Partnership Program (NOPP) funded Skin SST Demonstration Project (2003–2005). During AEROSE, skin SST observations were obtained from $\simeq$15.5 m above sea level off starboard at 1 downlooking (45° from nadir) view angle. The skin SST observations were made available to AEROSE shipboard researchers throughout cruise operations for near-real-time analyses while at sea.

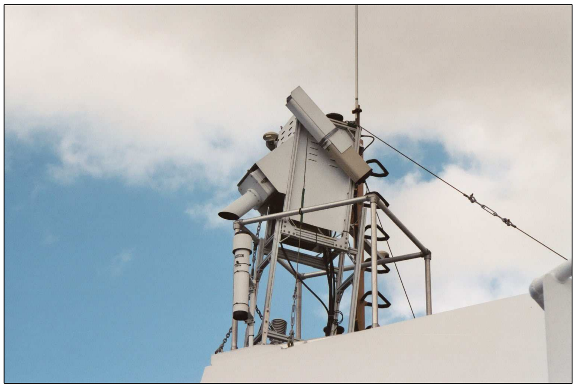

Figure 5: The UW/APL Calibrated Infrared In situ Measurement System (CIRIMS) onboard the *Ronald H. Brown* during AEROSE.

2.1.3 Microtops Handheld Sunphotometer

During the cruise, two commercial Microtops handheld sunphotometers (provided and operated by HU/NCAS; see Figure 6) were used to obtain uplooking observations of total column aerosol optical depth (AOD) in 5 different bands in the solar spectrum centered on $\lambda = 0.34$, 0.38, 0.87, 0.936 and 1.02 μm.

Figure 6: Microtops handheld sunphotometers used for taking simultaneous observations of AOD onboard the *RHB* during AEROSE. Pictured are Howard University investigators Prof. E. Joseph (background) and graduate student F. Mensah (foreground).

2.2 Shipboard/In situ

2.2.1 Vaisala RS80/90 Radiosondes

In situ observations of temperature and water vapor profiles were obtained throughout cruise operations using commercial Vaisala RS80 and RS90 balloon-borne radiosondes. Note that RS80 rawinsondes were used for all but the last 2 days of operations, providing wind vector profiles over that period as well. During the planning stages of AEROSE, frequent radiosonde observations (RAOBs) were sought to support mission objectives in the following 3 ways:

1. To provide independent *in situ* data for satellite (and M-AERI) profile retrieval validation studies.
2. To provide the necessary profile data for conducting forward radiance calculations and investigations.
3. To observe tropospheric air mass advection and/or modification associated with Saharan dust transport.

Through the joint collaboration of HU/NCAS, UM/RSMAS and the University of Wisconsin-Madison Cooperative Institute for Satellite Meteorological Studies (UW/CIMSS), the AEROSE mission was equipped to conduct launches with a 3-hourly sampling frequency throughout both cruise legs, with launch times coordinated to coincide with Aqua twice-daily satellite overpasses. Note that this launch frequency approximately doubles that obtained during the 1996 Combined Sensor Program (Post *et al.*, 1997), and pushes the limits of data acquisition obtainable from a single receiver. HU/NCAS also provided ozone sondes, but unfortunately they were not compatible with the *RHB* Vaisala receiver. To achieve 3-hourly, 24-7 sonde operations, a team consisting of approximately 10 students and scientists were assigned to a rotating shift that included slight perturbations to optimize simultaneity with the ascending and descending Aqua overpasses.

2.2.2 UW/APL 2 m Bulk SST

To complement CIRIMS, UW/APL has installed two through-the-hull instrument ports on the *RHB* at 2 m and 3 m depths. The ports are located in the bow thruster room on the starboard side directly above the ship standard 5 m intake. These ports were instrumented with two SeaBird model SBE-39 temperature sensors to provide accurate bulk temperatures at intermediate depths between the CIRIMS skin SST and the ship's 5 m intake temperature. Note that bulk SSTs were obtained only from the 2 m sensor during AEROSE (the 3 m sensor was not operational during that time).

UM/RSMAS also obtained intermittent measurements (i.e., while holding station) of shallow bulk layer SST from a surface float at $\simeq$3–5 cm depth. Preliminary analyses at UM/RSMAS show that this measurement complements the temperature distribution at other points in the water column.

2.3 Aqua Satellite

The shipboard data acquired during AEROSE are useful for validation of numerous remotely sensed satellite data, including

- NOAA-KLM AVHRR/3 (SST, AOD and Clouds)
- Geostationary Operational Environmental Satellite (GOES-East) Imager (SST, AOD and Clouds)
- EUMETSAT Meteosat Second Generation (MSG) (SST, AOD and Clouds)
- SeaWiFS (Aerosol, Clouds, Chlorophyll-a)
- Synthetic Aperture Radar (SAR) (Winds, surface features)
- TRMM Microwave Imager (TMI) (SST, Winds)
- WindSat/Coriolis (SST, Winds)
- Terra/Aqua MODIS (Aerosol, Clouds, SST, Chlorophyll-a)

This paper will limit its focus to data collected from advanced sensors found on the NASA Aqua satellite: the AIRS, AIRS/Visible Near Infrared and Advanced Microwave Sounding Unit (ASMU-A).

2.3.1 Atmospheric IR Sounder (AIRS)

AIRS is an IR grating spectrometer capable of obtaining high resolution spectra (>2300 channels) over the spectral range 649–2677 cm^{-1} (e.g., Aumann *et al.*, 2003). The absolute accuracy for brightness temperatures is specified to be 3%. The spectral resolution enables a relatively high vertical water vapor profile resolution (compared to narrowband channel radiometers) specified to be $\simeq$2 km with 10% accuracy (e.g., Fetzer *et al.*, 2003). The nadir horizontal resolution at the surface is $\simeq$15 km.

The AIRS instrument system also includes a visible near-IR (Vis/NIR) sensor capable of synergistically providing enhanced cloud detection during daylight (e.g., Gautier *et al.*, 2003). The AIRS Vis/NIR instrument measures reflected radiance in 4 solar spectrum channels (3 narrowband and 1 broadband) with a nadir ground resolution of 2.28 km.

2.3.2 Advanced Microwave Sounding Unit (AMSU-A)

The AMSU-A is a passive microwave radiometer that obtains radiance measurements in 15 channels to derive temperature profiles from the surface up to $\simeq$40 km. The brightness temperature absolute accuracy is specified to be 1.5 K (e.g., Fetzer *et al.*, 2003). Because clouds are transparent in the microwave, the instrument is capable of retrieving profiles under cloudy conditions (unlike AIRS, for which clouds are opaque). However, the AMSU vertical resolution is coarser, as well as the horizontal resolution at the surface ($\simeq$45 km). Each AMSU-A "footprint" overlaps 3×3 AIRS footprints, which are synergistically combined to estimate a "cloud-cleared" AIRS spectrum for the 40 km footprint (Susskind *et al.*, 2003). The cloud-cleared AIRS spectra are then used for geophysical parameter retrievals with high vertical resolution.

3. PRELIMINARY RESULTS

3.1 M-AERI and CIRIMS Skin SST

M-AERI and CIRIMS are two distinctly different IR sensors with different measurement principles and inversion algorithms, thus they provide independent radiometric measures of skin SST for cross-validation. The accuracy of skin SST data from M-AERI and/or CIRIMS is germane to cal/val efforts for advanced IR sensors (e.g., Smith *et al.*, 1996; Nalli and Smith, 1998, 2003; Hagan and Minnett, 2003). Although both instruments have operated simultaneously on a number of previous cruises (e.g., Jessup *et al.*, 2002), AEROSE constitutes the first set of observations under extreme Saharan dust conditions. As with prior cruises onboard the NOAAS *RHB*, both M-AERI and CIRIMS conducted observations off the starboard, with M-AERI installed on the forward 02 Deck ($\simeq$8.2 m above sea level) and CIRIMS located on the 05 Deck on top of the Pilot House ($\simeq$15.5 m above sea level). The M-AERI and CIRIMS relative configuration onboard the *RHB* are illustrated in Figure 7.

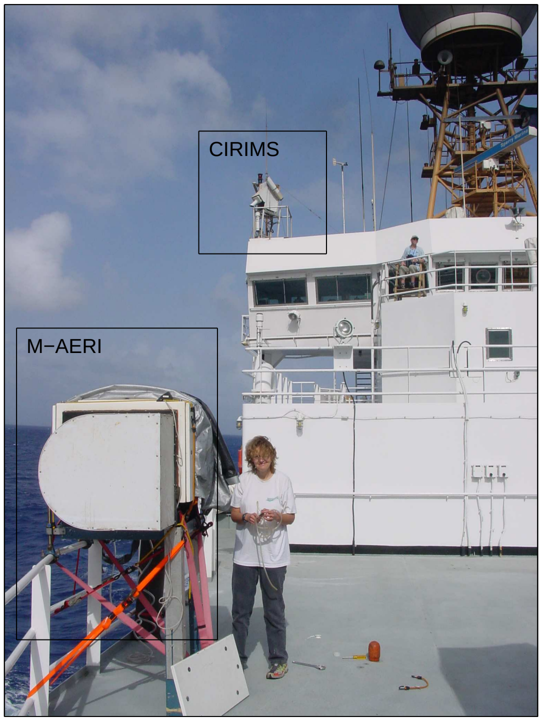

Figure 7: M-AERI and CIRIMS instrument configuration onboard the *RHB* during AEROSE. Pictured next to M-AERI is UM/RSMAS investigator Dr. M. Szczodrak, who was performing critical maintenance during Leg 2 operations.

Plotted in the top of Figure 8 are skin SSTs concurrently measured by M-AERI and CIRIMS, along with bulk SSTs obtained from the UW/APL 2 m sensor and standard 5 m ship intake, for the entire AEROSE cruise. The data gaps are because of suspended operations during the port-of-call in Las Palmas (15–17 March 2004) and quality control filtering. The two skin SSTs agree reasonably with each other and also capture the small scale oceanographic frontal features observed in the bulk measurements (although the skin was systematically cooler as would be expected from the sustained Trade Winds). However, the plot of M-AERI/CIRIMS skin differences (middle plot) reveal a small systematic difference between the two measurements. The cause of this difference is not completely understood as of this writing. For reference, daily binned total column optical depth observations from the Microtops sunphotometer are shown in the bottom plot. (note that the large degree of scatter is due to cloud contamination; cloud-free AOD is thus estimated from the lower envelope depicted with the red line). There does not appear to be any direct correlation between AOD and the skin SST differences. It should be noted that because of the slightly different instrument heights and view angles, the sensor fields-of-view would have differed somewhat.

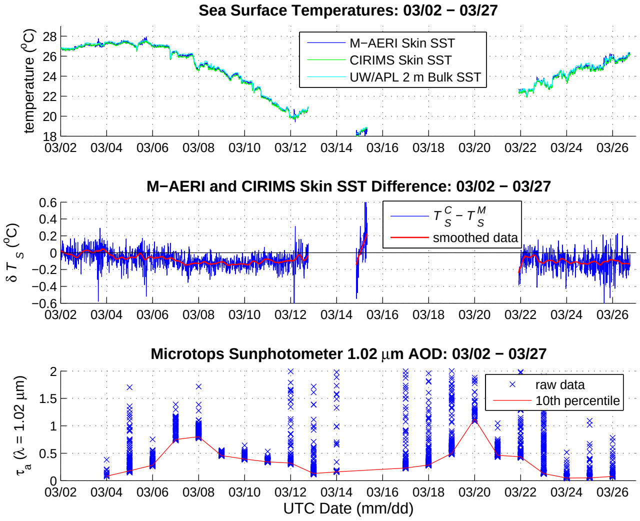

Figure 8: (Top and middle): AEROSE time series plots of M-AERI and CIRIMS skin SST, and UW/APL 2 m bulk SST, along with (bottom) Microtops sunphotometer total column optical depth ($\lambda = 1.02$ μm) (daily bins). The lower envelope (10th percentile shown with a red line) provides an estimate of the cloud-free AOD.

3.2 AIRS and M-AERI IR Spectra

On 7 March 2004 the *Ronald H. Brown* entered the first major dust event of the AEROSE cruise. Shown in Figure 9 are before and after photographs of the M-AERI prior to and during the dust event. Figure 10 shows the dust plume as observed in the AIRS Vis/NIR granule overpass on 7 March. Note that M-AERI was making IR spectral observations throughout this period.

Displayed in Figure 11 are plots of M-AERI mean brightness temperature spectra (zenith view) for the days 6 and 7 March 2004. Figure 12 shows AIRS spectra nearly coincident in space and time with the *RHB* on these two days. Both the M-AERI and

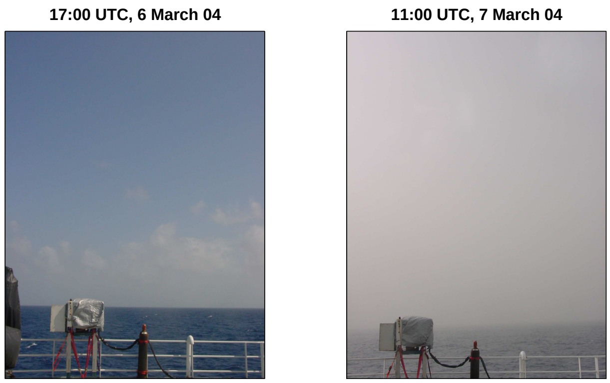

Figure 9: Photos of M-AERI just prior to (left), and during (right), the Saharan dust event of 7 March 2004.

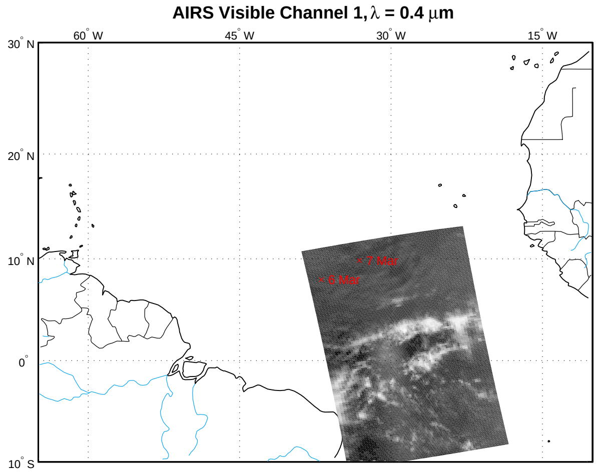

Figure 10: AIRS Vis/NIR ($\lambda = 0.4$ μm) overpass granule during the Saharan dust event of 7 March 2004. Locations of the NOAAS *Ronald H. Brown* are also shown.

AIRS spectra show the impact of the Saharan air layer (SAL) upon the spectral features within LWIR window region. The reduced difference in brightness temperatures across the 833–910 cm^{-1} (11–12 μm) spectral region is clearly evident (bottom plots), and there is increased signal in the vicinity of the O_3 band (960–1100 cm^{-1}). There are at least two reasons for these spectral differences, these being the large increase in dust aerosols along with the mid-level intrusion of dry air (e.g., see Figure 14). Note the spectral features observed by M-AERI and AIRS are inverted as would be expected. For M-AERI, enhanced lower-tropospheric spectral absorption at a temperature warmer than the upper-atmosphere (and cold space) enhances the observed brightness temperatures. For AIRS, enhanced lower-tropospheric absorption at a cooler temperature relative to the surface causes a net attenuation and decrease in brightness temperatures. The spectral temperature difference illustrated in Figure 12 has been used for aerosol and SAL detection algorithms from split-window narrowband imagers (e.g., Dunion and Velden, 2004); the detailed spectral signatures contained in hyperspectral observations may be valuable for refining such methodologies or developing new ones. These plots also demonstrate the need for a follow-up cruise (AEROSE II, currently being sought for July 2005) that would implement O_3 sondes.

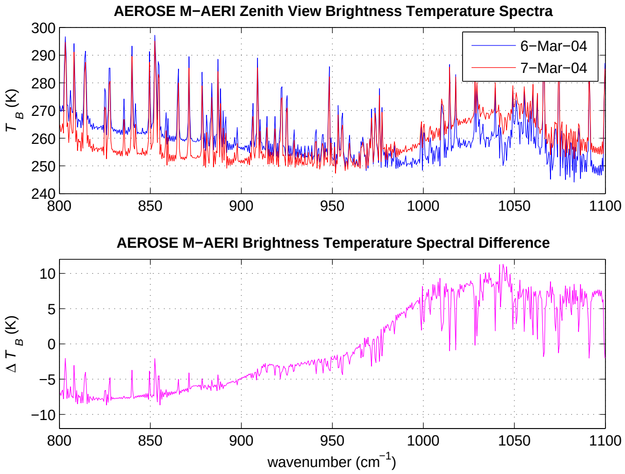

Figure 11: (top) AEROSE M-AERI mean brightness temperature spectra for days 6 and 7 March 2004, and (bottom) brightness temperature spectral differences.

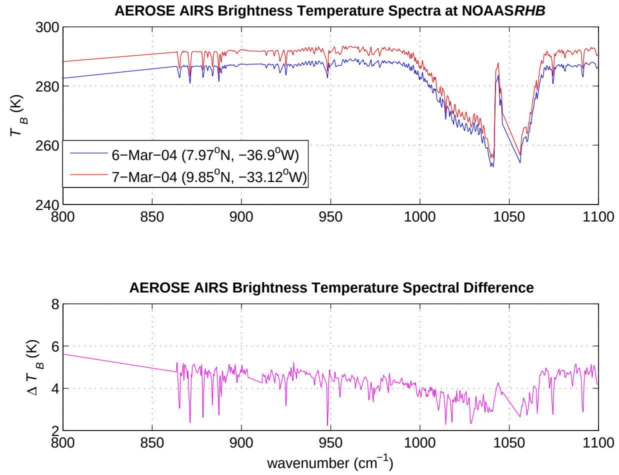

Figure 12: (top) AIRS brightness temperature spectra for NOAAS *Ronald H. Brown* overpasses during AEROSE on 6 and 7 March 2004, and (bottom) brightness temperature spectral differences.

3.3 AIRS-RAOB Matchups

Validation of the Aqua AIRS/AMSU/HSB sounding suite is an important task necessary for product error characterization and improvements (e.g., Fetzer *et al.*, 2003). A unique matchup dataset of Aqua AIRS/AMSU granules (ascending and descending) coinciding with *RHB* sonde launches has been created to support validation of AIRS/AMSU data products and forward models under extreme Saharan dust conditions over the open ocean. There are a total of 42 AIRS-RAOB matchup granules available. Figure 13, shows the AMSU-A granule brightness temperatures ($\nu = 23.8$ GHz) overlayed with the *RHB* sonde launch locations for the Leg 1 East-West transect only (16 granules). Note that because the cruise was at equatorial latitudes, where subsequent AIRS orbital scan lines do not overlap, there were several occasions when the ship was located outside the scan range of AIRS. AEROSE validation studies of AIRS cloud-cleared radiances, profile and skin SST retrievals, and forward radiance modeling of aerosols, will all be the subject of future work.

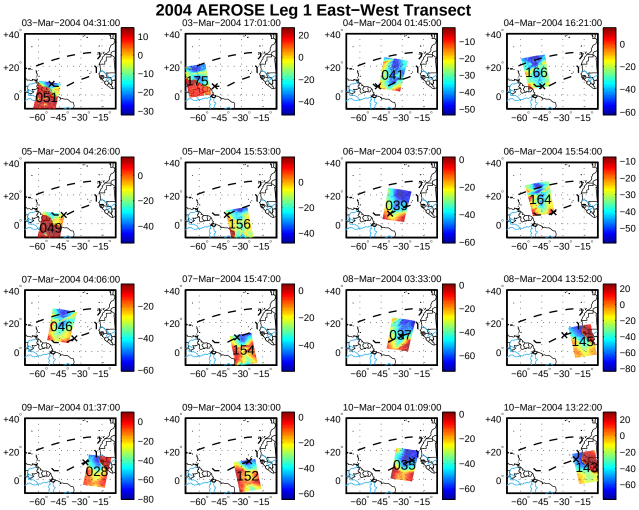

Figure 13: AIRS-RAOB matchups for AEROSE Leg 1 East-West transect. Shown are data granules of AMSU-A 23.8 GHz brightness temperatures (granule number superimposed) along with sonde launch locations.

3.4 RAOB and M-AERI Profiles

AEROSE 3-hourly sonde operations commenced on 3 March 2004. The sampling frequency enabled observation of marine boundary layer evolution and Saharan air mass advection (results to be published in a forthcoming paper). The frequency of sondes enables validation of M-AERI retrievals of lower tropospheric temperature and humidity profiles. Plotted in Figure 14 are contour plots of profile evolution derived from RAOB data for 8 March 2004 (when the *RHB* was still within the first major dust event).

M-AERI retrievals derived using *a priori* guess profiles defined by the NOAA National Centers for Environmental Prediction (NCEP) model, and sonde data at 50% and full sampling, are shown in Figures 15, 16 and 17, respectively. The M-AERI retrievals using sonde data reproduce the RAOB profiles quite well. In most cases M-AERI improves the NCEP guess field, although the results are less than optimal because the NCEP model had difficulty with resolving the dry Saharan air layers observed by the sondes above 1000 m.

4. SUMMARY

The 2004 Aerosol and Ocean Science Expedition (AEROSE) has yielded a unique complementary dataset of tropospheric mineral dust aerosols during significant Saharan dust events. Atmospheric and oceanographic measurements were acquired from a number of *in situ* and remote sensing sensors. Data collected from the expedition will be valuable for addressing key questions relevant to IR satellite remote sensing and radiative transfer modeling. Shipboard radiometric data pertinent to studying the impact of tropospheric dust aerosol upon satellite IR spectra and retrievals included observations from the Marine Atmospheric Emitted Radiance Interferometer (M-AERI), the Calibrated Infrared In situ Measurement System (CIRIMS) and Microtops handheld sunphotometer. Vaisala RS80/90 radiosondes were launched ≃3 hourly, including Aqua overpass times, and standard meteorological data and ocean surface temperatures were acquired by the *RHB* ship observing platform. Validation studies of satellite derived skin SST are possible against the high-accuracy radiometric and *in situ* SST observations acquired onboard the ship. Satellite derived marine AOD (e.g., from AVHRR and/or MODIS) can be validated using the sunphotometer observations. Validation of AIRS data products (temperature and water vapor profile retrievals, cloud-cleared radiances, forward radiance model) is also possible using coincident Vaisala radiosondes launched during Aqua overpass times, as well as coincident M-AERI uplooking boundary layer profile retrievals. Given co-located hyperspectral downlooking AIRS and uplooking M-AERI observa-

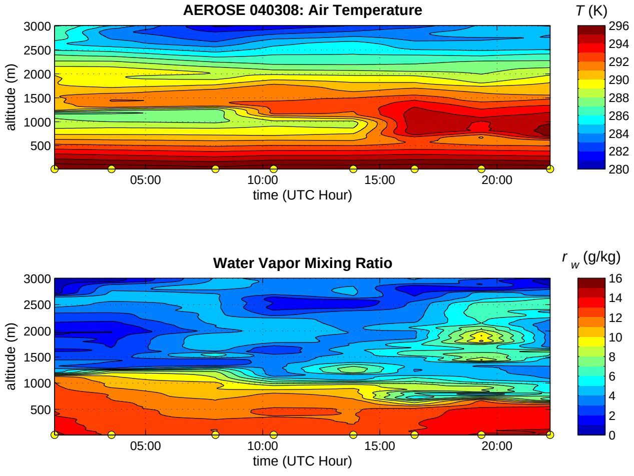

Figure 14: Contour plots of lower tropospheric temperature (top) and water vapor mixing ratio (bottom) derived from 3-hourly RAOBs on 8 March 2004. Sonde launch times are shown by yellow circles.

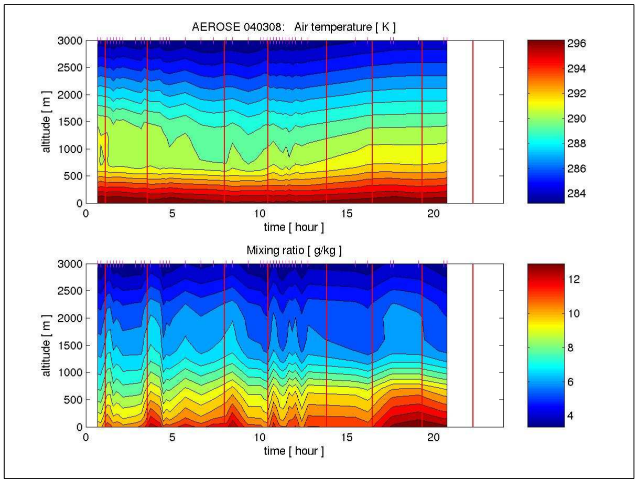

Figure 15: Contour plots of lower tropospheric temperature (top) and water vapor mixing ratio (bottom) retrieved from M-AERI on 8 March 2004 using NCEP model as first guess.

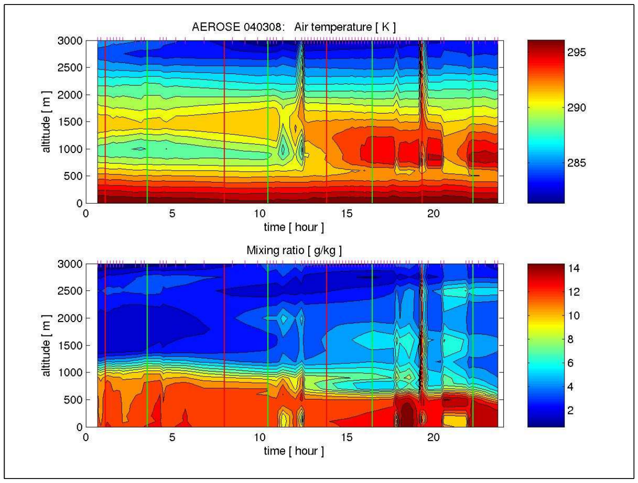

Figure 16: Same as Figure 15 except using sonde data at 50% sampling (6 hour interval) as first guess.

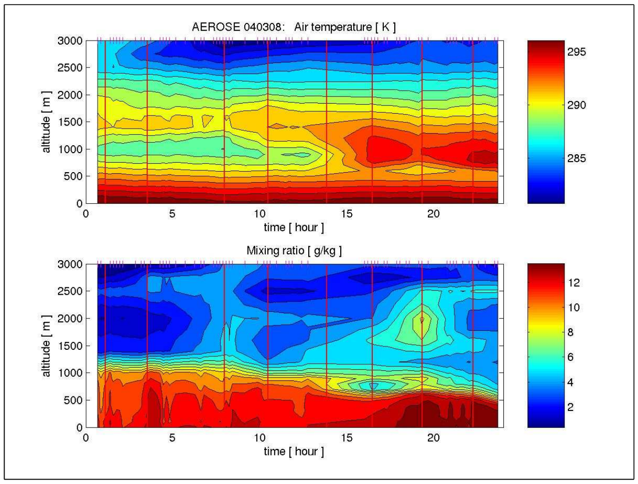

Figure 17: Same as Figure 15 except using sonde data at full sampling (3 hour interval) as first guess.

tions, along with coincident observations of aerosol, detection, and potentially isolation, of the IR spectral signature of Saharan dust aerosols over the ocean can be sought for improved retrievals of aerosol IR radiative properties.

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