LASE Measurements of Water Vapor, Aerosol, and Cloud Distributions in Saharan Air Layers and Tropical Disturbances

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ABSTRACT

The Lidar Atmospheric Sensing Experiment (LASE) on board the NASA DC-8 measured high-resolution profiles of water vapor and aerosols, and cloud distributions in 14 flights over the eastern North Atlantic during the NASA African Monsoon Multidisciplinary Analyses (NAMMA) field experiment. These measurements were used to study African easterly waves (AEWs), tropical cyclones (TCs), and the Saharan air layer (SAL). These LASE measurements represent the first simultaneous water vapor and aerosol lidar measurements to study the SAL and its interactions with AEWs and TCs. Three case studies were selected for detailed analysis: (i) a stratified SAL, with fine structure and layering (unlike a well-mixed SAL), (ii) a SAL with high relative humidity (RH), and (iii) an AEW surrounded by SAL dry air intrusions. Profile measurements of aerosol scattering ratios, aerosol extinction coefficients, aerosol optical thickness, water vapor mixing ratios, RH, and temperature are presented to illustrate their characteristics in the SAL, convection, and clear air regions. LASE extinction-to-backscatter ratios for the dust layers varied from 35 ± 4 to 45 ± 6 sr, well within the range of values determined by other lidar systems. LASE aerosol extinction and water vapor profiles are validated by comparison with onboard in situ aerosol measurements and GPS dropsonde water vapor soundings, respectively. An analysis of LASE data suggests that the SAL suppresses low-altitude convection. Midlevel convection associated with the AEW and transport are likely responsible for high water vapor content observed in the southern regions of the SAL on 20 August 2008. This interaction is responsible for the transfer of about 7 × 10^15 J (or 8 × 10^3 J m^-2) latent heat energy within a day to the SAL. Initial modeling studies that used LASE water vapor profiles show sensitivity to and improvements in model forecasts of an AEW.

1. Introduction

The National Aeronautics and Space Administration (NASA) aircraft (NASA DC-8) component of the NASA African Monsoon Multidisciplinary Analyses (NAMMA) field experiment was conducted from Sal Island, Cape Verde, from 15 August to 12 September 2006 (Zipser et al. 2009). The main objectives of the NAMMA mission were to examine the formation and evolution of tropical cyclones (TCs), establish the composition and structure of the Saharan air layer (SAL), and assess SAL affects on TC development. The NAMMA campaign extended and complemented the international African Monsoon Multidisciplinary Analysis (AMMA) field experiment, which was conducted prior to and concurrent with NAMMA over the African mainland (Haywood et al. 2008). To address NAMMA objectives, the DC-8 carried an extensive payload of both remote and in situ instruments and conducted extensive tropospheric sampling in the region off the northwest coast of Africa, between the mainland and the eastern range limit (~30°N and 38°W) of National Oceanic and Atmospheric Administration (NOAA) research aircraft that were conducting coordinated Saharan Air Layer Experiment (SALEX)
research of African easterly waves (AEWs; Thorncroft and Hoskins 1994a,b) and the potential development of AEWs into major Atlantic hurricanes is of great interest because nearly 85% of intense (or major) hurricanes have their origins as AEWs (Landsea 1993). Seven AEWs were studied during NAMMA, three of which intensified to form Tropical Storms Debby and Ernesto and Hurricane Helene (Zipser et al. 2009). An examination of the SAL in the NAMMA domain indicated that the SAL was a quasi-steady-state feature, with significant modulations of aerosol content and a periodicity of ~5 days from 15 August to 15 September 2006. There were only three minor (1–2 day) breaks when the SAL was not over-spreading the NAMMA study region. However, satellite imagery and forecasts during NAMMA showed the occurrence of rapid enhancements and subsequent decreases in aerosol content of the SAL every few days. Episodic SAL events with distinctive boundaries and sudden intensity enhancements as seen in satellite imagery (and confirmed by lidar backscatter observations) are termed “SAL events” in this paper.

The SAL is a synoptic-scale feature containing warm, dust-laden air transported from the Sahel and Saharan regions of northern Africa (Carlson and Prospero 1972). The layers are formed when high-speed easterly winds liberate mineral dust from the sun-baked surface and dry convection simultaneously disperses the dust throughout the mixed layer, which can reach as high as 500 hPa in summer. Results from AMMA suggest that the descent of the higher speed nocturnal northeasterly winds of the Harmattan to the surface in the early morning hours (Bou Karam et al. 2008) is responsible for quasi-continuously feeding the SAL with dust. The SAL propagates westward in regions behind and occasionally in front of AEW disturbances. Propagation of the SAL from the west coast of Africa over the moist, cool marine boundary layer (MBL) creates a strong temperature inversion above the MBL that suppresses vertical exchange between the two layers (Carlson and Prospero 1972).

From analyses of satellite imagery and radiosondes, Dunion and Velden (2004) have reported the large-scale structural and dynamical characteristics of the SAL. The SAL contains warm and dry air with a temperature inversion at the base (~800–900 hPa) and is associated with a midlevel (~600–800 hPa) easterly jet. Dunion and Velden pointed out that these characteristics of the SAL tend to inhibit convection and TC development. This inference is also supported by other studies. A study of TC activity over a 25-yr period over the Atlantic indicated a strong anticorrelation between TC activity and dust (i.e., SAL) events (Evan et al. 2006). Lau and Kim (2007a,b) suggest that dust within the SAL reduces the level of solar radiation reaching the surface, which in turn causes a lowering of the sea surface temperature. They point out that an excess of Saharan dust in the 2006 premonsoon season, as compared to 2005, was mainly responsible for reducing sea surface temperature in North Atlantic, possibly contributing to the marked decrease in TC activity in 2006. On the other hand, Karyampudi and Carlson (1988) concluded that the SAL is important, if not necessary, in the initial development of AEWs. Karyampudi and Pierce (2002) found that the SAL had a positive influence on the genesis of two Atlantic storms through enhancement of baroclinic instability. The SAL can also influence cloud microphysical properties and act as a source of cloud condensation nuclei (CCN) enhancing convective intensity (Khain et al. 2005; Jenkins et al. 2008). Recent studies (Jenkins and Pratt 2008; Twyoh et al. 2009) using data collected during NAMMA postulated that SAL dust particles can act as CCN, which in turn can influence cloud microphysics, latent heat release, vertical transport and convection development, and precipitation.

Fields of water vapor concentration are a key component for understanding processes of precipitation, evaporation, and latent heat release in cloud systems. The lack of adequate and accurate moisture measurements with sufficient vertical and horizontal resolutions limits the ability of most numerical models to represent these processes. Krishnamurti et al. (1994) found that deficiencies in the modeling of moisture and diabatic processes are due in part to the lack of knowledge of the tropical humidity fields. Model forecasts are very sensitive to the surface layer moisture. Krishnamurti and Oosterhof (1989) showed that models that incorporated an explicitly resolved surface layer were able to more accurately compute the strong moisture flux between the ocean and atmosphere, resulting in more accurate prediction of the formation of hurricanes. Results from the NASA Convection and Moisture Experiment (CAMEX) missions demonstrated the positive impacts of accurate, high-resolution measurements of water vapor obtained by LASE on hurricane track and intensity forecasts (Kamineni et al. 2003, 2006). To investigate the potential impact of the SAL on North Atlantic climatologies, Dunion and Marron (2008) used Caribbean radiosondes to re-examine the Jordan (1958) mean hurricane season tropical sounding. They found that during the hurricane season, the tropical Atlantic is dominated by multiple atmospheric events (e.g., dry SAL and moist tropical non-SAL) and that a single mean sounding like Jordan’s does not adequately represent these unique air masses. LASE NAMMA high-resolution measurements provided an opportunity to study the influence of moisture distributions in the eastern Atlantic region on TC
development and to examine the three-dimensional structure of the air masses described by Dunion and Marron (2008). The mission also provided an opportunity to compare LASE data with other remote and in situ measurements. Some LASE observations related to individual SAL events during NAMMA have already been reported in the literature (Jenkins and Pratt 2008; Jenkins et al. 2008; Twohy et al. 2009; Zipser et al. 2009).

Prior to NAMMA, the AMMA (Redelsperger et al. 2006) special observation period (SOP) was conducted over the West African continent during 1 June–15 July 2006 and was dedicated to examining surface–ocean–atmosphere interactions during the monsoon onset. These observations of dust and convective events during AMMA are also applicable to NAMMA. Elemental analysis of atmospheric dust showed that the dust originated from several surface locations in North Africa (McConnell et al. 2008). Observations from airborne and surface meteorological devices and from satellites, together with ECMWF analysis, were used to show the mobilization, lifting, and structure of dust layers resulting from meteorological events in the intertropical discontinuity (ITD) region (Flamant et al. 2007, 2009; Bou Karam et al. 2008, 2009). Mobilization of dust by dry cyclogenesis in the ITD and lifting by orographic features significantly contributes to the amount of dust that is available for long-range transport (Bou Karam et al. 2009). In addition, injections of dust by gravity currents into and above the SAL north of the ITD have been postulated (see Flamant et al. 2007) to contribute to dust from West Africa.

In this paper, we present an observational overview of the LASE water vapor, aerosol, and cloud measurements made during NAMMA. Three case studies were selected for detailed analysis: (i) a stratified SAL, with fine structure and layering (unlike a well-mixed SAL), (ii) a SAL with high RH, and (iii) an AEW surrounded by SAL dry air intrusions. These features are unique for their locations and the coincidence of dust with moist air. For these case studies, NAMMA data are analyzed to address the following:

(i) What is the nature of the vertical structure of the thermodynamics and mineral dust content of SAL events in the eastern North Atlantic (ENATL)? Are they both well mixed within the layer or are there discrete vertical structures, especially of the dust? Are there any consistencies of the vertical structure of the dust (e.g., layering) that were seen in the LASE data or does that structure vary significantly from SAL event to SAL event?

(ii) What is the nature of the transitional environment between AEWs and surrounding SAL events in the ENATL?

(iii) Are there any notable differences between the horizontal and vertical thermodynamic structures of moist tropical versus SAL environments in the ENATL?

We first briefly describe the LASE system and its data products and then review DC-8 flight tracks that show the large area surveyed during NAMMA. Examples of LASE SAL and AEW observations are presented to characterize the features and assess the outcome of their interactions. LASE aerosol extinction and water vapor profiles are compared with DC-8 in situ observations and rawinsonde soundings, respectively. A summary of the latitudinal distribution of moisture and associated SAL aerosol backscattering profiles is also presented.

2. LASE system and measurements during NAMMA

a. LASE system

The LASE differential absorption lidar (DIAL) system was developed at the NASA Langley Research Center in 1995 (Browell et al. 1997) and has subsequently participated in 12 field experiments while deployed onboard the NASA ER-2, P-3, or DC-8 aircraft (see, e.g., Browell et al. 2005). LASE was routinely operated onboard the DC-8 during NAMMA. The transmitter consists of a double-pulsed Ti:sapphire laser that operates in the 815-nm absorption band of water vapor and is pumped by a frequency-doubled Nd:YAG laser. Total laser output pulse energy is about 90 mJ in each of the on- and offline laser pulse pairs that are transmitted at 5 Hz. This energy is nominally split in a 7:3 ratio for transmission in the nadir and zenith directions, respectively. The nadir detector system uses two silicon avalanche photo diodes and three digitizers to cover a signal dynamic range of $10^6$. During NAMMA, LASE operated locked to a strong water vapor absorption line at 815.223 nm and was electronically tuned to other spectral positions on the side of the absorption line. In this mode, LASE transmitted up to three (on- and offline) wavelength pairs to capture the full dynamic range of water vapor distributions. This method of operation permitted profiling of water vapor from near the surface to the upper troposphere and aerosol and cloud profiles from near the surface to the lower stratosphere. LASE has demonstrated the ability to measure high-resolution water vapor distributions over the 0.01 g kg$^{-1}$ to $>20$ g kg$^{-1}$ mixing ratio range with an accuracy of 10% or 0.01 g kg$^{-1}$, whichever is larger (Browell et al. 1997). Measurements during a number of other field experiments have shown that LASE water measurements in the tropospheric regions agree well with other remote and in situ measurements (Ferrare et al. 2004; Behrendt et al. 2007).
b. LASE data products

LASE provided two main data products: profiles of water vapor mixing ratios (g kg\(^{-1}\)) and aerosol scattering ratios (ratio of aerosol to molecular backscattering corrected for water vapor absorption and estimated aerosol extinction). These digital data are available from the NASA Earth Observing System Data and Information System (EOSDIS) data centers. Images of LASE water vapor mixing ratio, aerosol scattering profiles, and cloud distributions are also available online (at http://asd-www.larc.nasa.gov/lidar/). Relative humidity profiles were also produced as secondary data products from LASE-derived profiles of mixing ratio and profiles of temperature from dropsonde/rawinsonde observations.

LASE aerosol measurements for all practical purposes are at a single wavelength of 815 nm (very minute wavelength differences exist between the off lines and the three wavelength pairs that are transmitted). Retrievals of profiles of aerosol extinction and aerosol optical depth are the subject of ongoing research and are generated on a case-by-case basis. To derive aerosol extinction profiles from the LASE data, an estimate of the “lidar ratio” or the ratio of extinction to backscatter (\(S_a\)) is needed. As an example, LASE measurements above and below an elevated dust layer observed on 20 August 2006 were used to determine transmission through the layer. The estimated transmission was then used to derive a value of the aerosol optical depth of the layer, which was then used to calculate an average \(S_a\) for the layer of 36 ± 5 sr at the LASE wavelength of 815 nm. Note that this value is somewhat smaller than the value inferred from the results of Liu et al. (2008). They used data from the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) on NASA’s Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite to derive lidar ratios at 532 and 1064 nm for Saharan dust observed over the Atlantic Ocean and the Gulf of Mexico during August 2006, within a few days of the LASE measurements. The lidar ratios derived from the CALIOP data at two locations over the Atlantic Ocean were 41 ± 4 sr (532 nm) and 55 ± 5 sr (1064 nm) and 41 ± 6 sr (532 nm) and 54 ± 13 sr (1064 nm), respectively. Note that the observed values of \(S_a\) at 1064 nm were considerably larger than the modeled value of \(S_a = 30\) for dust aerosol that is used in the CALIOP aerosol extinction retrieval algorithms (Liu et al. 2005; Omar et al. 2006). The value of \(S_a = 36\) reported here for the LASE measurements is within the wide range (30 to 80 sr) of measured \(S_a\) values corresponding to dust (for a review see, e.g., Liu et al. 2008). As an example, Vaughan (2004) used data from the spaceborne Lidar in Space Technology Experiment (LITE) to derive values of \(S_a = 26 ± 4.8\) sr (532 nm) and \(S_a = 35 ± 18.4\) sr (1064 nm) for elevated dust layers near the Saharan desert. The \(S_a\) of 36 sr derived from LASE measurements over a lofted SAL layer with clean air above at 6.5 km and below near the base of the layer at 1.2 km permitted extinction profile retrieval with the least uncertainties. For all available NAMMA profiles, \(S_a\) values in the range of 35 to 45 were found to yield good agreement between LASE and in situ aerosol extinction. This variability is likely caused by variations in the size, composition, and shape of the dust particles and ambient RH (Müller et al. 2007). We used the least uncertain, LASE-derived \(S_a\) value of 36 along with a lidar inversion technique (Fernald 1984) to derive profiles of unattenuated aerosol backscatter and extinction profiles throughout the mission. Aerosol optical depths for SAL layers are then obtained by integration of aerosol extinction profiles (Ferrare et al. 2000).

The aerosol scattering ratio (ASR) and extinction profiles have a vertical resolution of 60 m and horizontal resolution of 2.1 km, whereas the water vapor mixing ratio and RH profiles have a vertical resolution of 330 m and horizontal resolution of 42 km.

c. DC-8/LASE flight tracks during NAMMA

DC-8 flight tracks are presented in Fig. 1 and illustrate the geographic coverage and density of the airborne dataset. From a base of operations at Sal Island, Cape Verde, flights were conducted between 15 August and 12 September over a study area extending from near the coast of Africa to about 35°W and from about 6° to 22°N. LASE operated during all flights but was unable to acquire data during portions of flights when the aircraft was in clouds. Seven AEWs and associated SAL events were sampled during NAMMA.

3. Examples of aerosol and water vapor distributions during AEWs with SAL events

a. 19 August 2006

AEW 1 (the AEW numbering system is taken from Zipser et al. 2009) emerged from the coast of North Africa on 11 August 2006. Meteosat-8 split window imagery (Dunion and Velden 2004) and microwave-derived total precipitable water (TPW) satellite imagery (Alishouse et al. 1990) from the constellation of DMSP satellites and the Advanced Microwave Scanning Radiometer (AMSR-E) on Aqua indicated that beginning on 14 August, two features were evident near the eastern edge of this AEW: a well-developed mesoscale convective system (MCS) along the southern portion of the AEW and a large SAL event a few degrees north of
that MCS. The limits of the wave (trough) are defined using brightness temperature values in the Geostationary Operational Environmental Satellite (GOES) SAL imagery (Dunion and Velden 2004) and areas ≤45 mm of TPW (J. P. Dunion 2010, unpublished manuscript). As the MCS tracked to the northwest over the next few days, it moved into the SAL environment to its north and by 17 August most of its associated convection had diminished. This same SAL event began to move rapidly to the west-southwest; by the early evening of 18 August, it had completely overspread the Cape Verde Islands. Early that same day, a vigorous MCS moved off the African coast and was positioned along the southern edge of this large SAL event. Meteosat-8 and TPW satellite imagery also indicated that this MCS was located on the western edge of a relatively small-scale AEW (AEW 2) that began moving off the coast early on 19 August (Fig. 2a).

As described by Dunion and Velden (2004), the GOES (and Meteosat) SAL imagery uses split window infrared imagery to track a combination of the SAL’s dry and/or dusty air. Although this imagery is not able to detect the relative contributions by each of these components of the SAL to the total signal, it is able to provide a synoptic indication of the relative dryness and dustiness of individual SAL events (yellow to pink shading). Oceanic areas that are not specified by cloud or SAL in the imagery indicate areas of moist tropical air (Dunion and Marron 2008). It should be noted that this satellite product is not able to track the SAL over land and therefore a land mask is applied to the imagery.

Figure 2b shows TPW derived from microwave channels on AMSR-E and the constellation of Special Sensor Microwave Imager (SSM/I) satellites (J. P. Dunion 2010, unpublished manuscript). The location of the SAL 1 and AEW 2 (trough) are indicated in Fig. 2 and were both transected and sampled by the DC-8 on 19 August. Figure 2c shows the NCEP Global Forecast System (GFS) analysis of 700-hPa winds over the NAMMA region at 0000 UTC on 19 August. The GFS analysis showed predominantly easterly flow at 700 hPa west of about 10°W. An easterly jet at this level was located near the coast at 18°N, 16°W with wind speeds of about 20 m s⁻¹. Closer to the surface, there were strong (>15 m s⁻¹) northerly winds, north of about 18°N, which appeared to be associated with the trough near 27°N, 10°W. Note the anticyclonic (clockwise) circulation associated with the SAL at the 700-hPa level.

The main objectives of the 19 August DC-8 mission (see Fig. 2a for flight track) were to sample the AEW (which eventually formed Hurricane Ernesto) and the SAL and to conduct a brief underflight of the “A-Train” satellites to obtain CALIPSO and CloudSat validation data. Low- to midlevel cloud drift and mid- to upper-level water vapor winds from the University of Wisconsin–Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) (not shown) indicated that the vorticity center associated with the MCS that was sampled near 7°N, 26°W that day was positioned a few degrees to the west of the AEW trough. During this period, analyses from UW-CIMSS indicated that the tropical disturbance (AEW 2) was under the influence of 10–25 kt
Fig. 2. (a) Meteosat-8 split window image showing the distribution of the SAL on 19 Aug 2006. The DC-8 flight track is also shown in white and the segment of data shown in Fig. 3 is highlighted by red dashed lines. The location of Sal Island, Cape Verde, is indicated by the blue star and the CALIPSO flight track is indicated by a black dashed line. (b) Total precipitable water vapor (TPW) from the Remote Sensing Systems global TPW dataset for 18 UTC on 19 Aug 2006. TPW is derived from the 19-, 22-, and 37-GHz microwave channels on the constellation of SSM/I satellites, the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and AMSRE-E on Aqua. The black polygon represents the DC-8 flight track and the color scale is TPW in mm. (c) NCEP GFS analysis of 700-hPa winds for 0000 UTC for the same day where color represents wind speed in m s$^{-1}$.

(5.1–12.9 m s$^{-1}$) of northeasterly vertical wind shear and was associated with a broad area of east–west-oriented low-level (850–925 hPa) convergence (not shown).

Figures 3a–c show a cross section of LASE measurements during the south to north segment of the flight, which is the red dotted line segment a–b in Fig. 2a and left to right in Fig. 3. During this transect, the aircraft sampled a broad area of upper-level cirrus at 12 km in the south and then conducted an en route descent to characterize the SAL properties with in situ instruments. Fig. 3a shows the distribution of aerosols and clouds. To preserve the cloud observations, these data in Fig. 3a have not been corrected for aerosol attenuation. The structure of aerosol scattering associated with SAL between 1 and 6 km is seen at higher latitudes beginning near 11°N. A number of dropsondes were released during this flight.
FIG. 3. LASE measurements of (a) aerosol scattering ratio profiles, (b) water vapor mixing ratio profiles, and (c) RH profiles associated with the SAL event on 19 Aug 2006. The locations of GPS dropsondes release are indicated by arrows (Fig. 3a). Very dry air subsiding to lower altitudes is seen at point A in Fig. 3b. Blank regions indicate data-void regions due to cloud attenuation or data-blind regions close to the aircraft. The altitude of the aircraft is indicated by the black line. Significant loss of data occurs during aircraft ascent and descent, and when the aircraft is at low altitudes.
Figure 3b shows water vapor mixing ratio profiles during this segment of the flight. The southern segment shows deep convection associated with AEW 2 (Fig. 3a) up to 10°N latitude with high-altitude cirrus (12 km). On the northern side of this convective region, there is an absence of high-altitude clouds and very dry air (water vapor mixing ratios ~0.05 g kg⁻¹) appears to be subsiding to lower (~7 km) altitudes (near point A in Fig. 3b). This feature is fairly common in LASE data and is an indicator of subsidence that would accompany the deep convection associated with the AEW 2 and the ITCZ. However, there are no direct observations of vertical winds in these very clean regions to confirm this. The RH image (Fig. 3c) shows generally low RH (35%–55%) over most of the SAL region (indicated by high aerosol scattering regions up to 6 km in Fig. 3a). Convection (as evidenced by cloud amount) decreased to the north of the convection–SAL interface (Fig. 3a, at ~9°N), suggesting that the SAL suppresses vertical transport. Using thermodynamic variables from dropsondes deployed at the locations shown in Fig. 3a, convective available potential energy (CAPE) values of <125 J kg⁻¹ were calculated for this period, which suggests that the air mass was not profoundly unstable at any point. Further, K indices decreased from 36 to 30, indicating increasing stability along the south-to-north flight leg. Convective inhibition (CIN) values derived from dropsondes within the region of the SAL at 1759 and 1813 UTC were −105 and −183 J kg⁻¹, respectively, which indicated a tendency to inhibit convection as compared to the values of 0 and −10 J kg⁻¹ at 1710 at 1645 UTC, respectively, in regions south of the SAL in Fig. 3. The later GPS dropsonde profiles that were launched in the SAL also indicated temperature inversions between 850 and 925 mb that were not present in the earlier profiles. Figure 4 shows temperature and potential temperature (θ) profiles from the 1813 UTC GPS dropsonde (potential temperature θ profile derived from the dropsonde temperature), as well as a 1-min-averaged, aerosol-scattering ratio profile from LASE recorded at 14°N, 26.45°W near the southern edge of the SAL. The temperature profile shows a strong inversion at the bottom of the SAL at ~800 m. At the top of this inversion a ~1.4 km a maximum in temperature of 24°C was observed. This maximum temperature was about 5°C higher at this altitude than the average (18.5°C) of all 82 GPS dropsondes launched in the region during the NAMMA campaign. Note that the changes in the lapse rate at altitudes of 0.8, 1.8, 3.5, 5.0, and 6.5 km coincide with enhancements in aerosol scattering ratio. This illustrates the relationship between the finescale, layered structure of aerosols (aerosol scattering) and temperature structure in the SAL. The higher temperatures in the SAL originated over northern West Africa and are maintained and enhanced by a combination of daytime heating due to absorption in the shortwave and longwave cooling (Carlson and Benjamin 1980; Zhu et al. 2007). These studies have shown that net heating rates depend on the amount of aerosol loading. Lower lapse rates (due to higher temperatures resulting from increased heating rates) in layers in conjunction with enhanced scattering seen in Fig. 4 are consistent with analyses given in Carlson and Benjamin (1980) and Zhu et al. (2007).

The positive slope (dθ/dz) of potential temperature over the SAL layer indicates enhanced static stability. However, the stability within the SAL layer (1.5–6 km) is slightly less than within the base inversion layer between 1 and 2 km. GPS dropsonde temperature measurements within the SAL at other locations during this flight and on other flights show similar features. Temperatures measured at the base of the SAL and/or top of the MBL during NAMMA were higher by 5°–8°C than measured in dust-free regions at comparable altitudes. (G. Chen et al. 2009, unpublished manuscript, hereafter GChen). This range of temperatures in the SAL is consistent with the 5°–10° warming (relative to the Jordan mean tropical sounding in 1958) that was noted by Diaz et al. (1976).

Figure 2a shows the CALIPSO track underflown by the DC-8 on 19 August 2006. An analysis of the CALIPSO lidar (CALIOP) data suggests that the SAL extends to a height near 6 km (A. Omar et al. 2009, unpublished manuscript). The presence of high clouds and daylight background lowered the CALIOP signal-to-noise ratio and prevented it from detecting the SAL.
fine structure seen by LASE. A $S_0$ ratio of 35.7 sr at 532 nm was derived from CALIPSO measurements, which is within the range of LASE measurements at 815 nm.

b. 20 August 2006

By 20 August, the trough associated with AEW 2 was located several hundred kilometers to the southwest of the Cape Verde Islands (Fig. 5a). The objectives for the 20 August DC-8 mission included additional sampling of AEW 2 and the large SAL event to its north and executing a microphysics profiling module in deep convection. Intensification of the AEW brought the two features closer together because the convective part of the AEW expanded, providing a good opportunity to sample the transitional region between the AEW and the SAL. Analyses from UW-CIMSS indicated that AEW 2 remained under the influence of 10–25 kt of northeasterly vertical wind shear and was still associated with a broad area of east–west-oriented, low-level (850–925 hPa) convergence (not shown). The TPW analysis in Fig. 5b shows the region of the intensified AEW 2 (trough).

By 20 August 2006 convection associated with AEW 2 had expanded and deepened (as seen in infrared satellite imagery; not shown) and was interacting with the SAL event to the north. Clouds associated with AEW 2 had advanced to 15°N latitude from their position at 10°N the previous day (contrast Figs. 2a and 5a). Distortions in the split window imagery of the southern SAL boundary of in the 10°–15°N region are the result of obscuration of the SAL by cumulus and cirrus cloud in the middle to upper levels that were associated with the AEW 2 convection (Williams 2008). These distortions are a consequence of intensification of the AEW convection and northward propagation of the convective activity. LASE measurements from a segment (segment c–d in Fig. 5a) of the flight are shown in Fig. 6. The general orientation of the flight during this segment was from the southwest to the northeast (left to right in Fig. 6). As a consequence of the intensification of AEW 2, there are clouds resulting from considerable convection in the southern tip of the SAL. Relative humidity profiles shown in Fig. 6c were derived from LASE water vapor mixing ratio and GPS dropsonde (DC-8)–rawinsonde temperature profiles that were interpolated to match the spatial resolution of LASE profiles. Clouds with relative humidity values near 100% are embedded and entrained within many areas of the SAL’s southern boundary. Cirrus clouds associated with deep convection reach high altitudes to the south and a cirrus shield covers the southern portions of the SAL to 15.6°N. High water vapor mixing ratios and high RH (70%) are observed over the whole segment of the SAL (Figs. 6b,c). This is in contrast to the SAL example in Fig. 3 with RH distributions in the range of 35% to 60% that are more characteristic of SAL events. High water vapor mixing ratios and high RH, along with the mushroom-shaped blooming of enhanced water vapor mixing ratios (and RH) on top of the mid-altitude cloud at locations A and C in Fig. 6, are indicators of convection as the source of enhanced moisture in this segment of the SAL as a result of the intensification of AEW 2. The intensification of AEW, presence of clouds within the SAL and high moisture at locations B, D, and E are further indications of moistening of this lofted SAL by the interaction of the AEW through midaltitude level convection (defined as the convection that reaches above the top of the inversion and limited to about a 2.5–6.5-km altitude range).

LASE data from a segment (segment a–b, highlighted red in Fig. 5a) of the flight through AEW 2 to the south and the SAL to the north (left to right) are shown in the aerosol extinction profile image (Fig. 7a). The blank V-shaped region is caused by the loss of data from the zenith channel during ascent and descent and by signal saturation/attenuation effects. The SAL sits atop the MBL at about 1 km and appears prominently in the altitude range of 1–6 km in orange, green, and blue colors. Note that as the SAL emerges from the African coast it is undercut by a cool marine layer causing its base to gradually rise as it is advected further to the west. A good example of this feature can be seen in Fig. 1 of Twohy et al. (2009). As was seen in Fig. 3a, low-level convection in the southern region (as inferred from clouds below 2 km on the left-hand side in Fig. 3a) appears to decay at the SAL boundary (~12°N near 1455 UTC), suggesting that some aspect of the dry, dusty SAL air mass suppresses vertical transport. Aerosol optical thickness values obtained by integrating LASE-derived, aerosol extinction profiles over the altitude of the SAL (1.2 to 7 km; black line plot in Fig. 7a) ranged from 0.05 to 0.4. A thin cloud layer is seen at 1540 UTC at 7-km altitude. Attenuation of the lidar beam by clouds prevents retrievals of extinction profiles below the clouds (at point C). The aircraft flight conducted in situ sampling of the SAL from 1540 to 1640 UTC.

Profiles of water vapor mixing ratio and RH recorded during this flight segment indicate that the SAL moistens to an RH of 60%–80% in the SAL–AEW interaction region. Compared to the previous day observations (Fig. 3b), water vapor mixing ratios over the observed SAL-altitude range are higher by an average ~2 g kg$^{-1}$. Figure 7a shows that low-level convection (defined as the convection that is limited to altitudes below the top of the inversion seen at about 2.5 km) has a relatively insignificant influence on the SAL. Figure 7c shows continuity in the RH filament that extends from the area of the low-level convection in the lower left segment of the figure to the area of elevated RH in the SAL layer at
Fig. 5. (a) Meteosat-8 split window image showing the distribution of the SAL on 20 Aug 2006. The DC-8 flight track is also shown and the segments of data shown in Figs. 6 and 7 are highlighted by black dashed (c–d) and red dashed (a–b) lines, respectively. The location of Sal Island, Cape Verde, is indicated by the blue star. (b) TPW from the Remote Sensing Systems global TPW dataset for 1800 UTC on 20 Aug 2006. TPW is derived from the 19-, 22-, and 37-GHz microwave channels on the constellation of SSM/I satellites, TRMM/TMI, and AMSRE-E on Aqua. The black polygon represents the DC-8 flight track and the color scale is TPW in mm.
FIG. 6. LASE measurements of (a) aerosol scattering ratio profiles, (b) water vapor mixing ratio profiles, and (c) RH profiles from the c–d segment of flight on 20 Aug 2006 (Fig. 5a). Letters A, B, C, D, and E identify midaltitude clouds with blank regions below the clouds due to laser signal attenuation effects.
FIG. 7. LASE measurements of (a) aerosol extinction profiles, (b) water vapor mixing ratio profiles, and (c) RH profiles from the a–b red dashed segment of flight on 20 Aug 2006 (Fig. 5). The profile of aerosol optical depth (black line) of the SAL is overlaid on the aerosol extinction image (Fig. 7a). Blank regions indicate data-void regions due to cloud attenuation or data-blind regions close to the aircraft. The altitude of the aircraft is indicated by a black dotted line. Significant loss of data occurs during aircraft ascent and descent, and when the aircraft is at low altitudes.
point A. This is misleading because it is mainly due to the lower resolution of RH data compared to the aerosol scattering ratio data shown in Fig. 7a. A close examination shows that the enhancements in aerosol scattering seen at point A and B are not well correlated with RH in Fig. 7c. However, there is significant enhancement of RH in the region near point D, which is close to the cirrus at point C, indicating that the processes for development of the midlevel cirrus may be contributing to some enhancement of water vapor mixing ratios and RH in the SAL. The general enhancement of water vapor and RH in this SAL is likely the result of convection (see Fig. 6; the distortion in the SAL image seen in Fig. 5a is likely the result of the obscuration of the SAL by visible/subvisible cirrus) and transport from other locations. The SAL, in this case, is serving as a medium for storage of latent heat transported from other regions.

It can also be seen that in some areas of the SAL the RH enhancements are correlated with higher aerosol scattering (E) and in other areas they are not. A portion of this noncorrelation may be caused by variations in the hygroscopic properties of the aerosol particles due to their chemical composition, origin, and history (McConnell et al. 2008; Twohy et al. 2009). Although a study of the Gobi Desert dust particles mixed with pollution in Asian plumes indicated that the dust particles were not very hygroscopic (Howell et al. 2006), some dust particles within the SAL were observed to act as cloud condensation nuclei during at least one of the NAMMA flights (Twohy et al. 2009). It is likely that the SAL consists of some dust particles that are mildly hygroscopic from their origin and may become more hygroscopic later by interaction with atmospheric gases (Twohy et al. 2009).

Dunion and Velden (2004) argue that the SAL suppresses convection due to (i) the introduction of dry, stable air; (ii) its midlevel easterly jet, which enhances vertical wind shear; and (iii) the enhancement of the trade wind inversion by local heating associated with solar extinction by dust. It is likely that the SAL, in general, tends to suppress convection. We postulate that interaction with the AEW is responsible for the rapid increase in water vapor (about 2 g kg\(^{-1}\)) over the altitude range 2–6 km along the southern edge of the SAL that occurred between 19 and 20 August 2006. A rough estimate of the transfer of the latent heat energy during this period was made by using the latitudinal extent of the SAL (\(\sim 5^\circ\)), the shape of the SAL (Figs. 6 and 7), and the longitudinal extent of the region of erosion of the SAL (\(\sim 15^\circ\); Fig. 5a) containing enhanced water vapor. The region for this calculation is between 10\(^\circ\) and 25\(^\circ\)N and 25\(^\circ\) and 40\(^\circ\)W. This net increase of the mass of water vapor in the SAL of about \(2.9 \times 10^{12}\) kg is equivalent to a transfer of energy of about \(7 \times 10^{15}\) J or about \(8 \times 10^{3}\) J m\(^{-2}\). The increase of water vapor makes the modified SAL environment more amenable to convection (Keil et al. 2008) and could promote intensification of neighboring AEWs. This transfer of water vapor is equivalent to the transfer of about 65% of water vapor from an AEW of about \(5^\circ \times 5^\circ\) in size. Even smaller portions of such a rapid energy exchange (loss) could dampen the development of some weak AEWs. However, the SAL does not necessarily prohibit the development of larger, more convectively active AEWs into major TCs. Instead, the sharp inversion at the base of the SAL along with vertical wind shear could inhibit convection and act as a barrier or threshold for the intensification of the AEW (Dunion and Velden 2004).

Optical parameter measurements made by in situ sensors on the DC-8 during this portion of the flight provided an opportunity to assess the value of \(S_a\) and aerosol extinction profiles derived from the LASE data. Aerosol scattering and absorption coefficients measured with a three-wavelength TSI, Inc., nephelometer and a three-wavelength particle soot absorption photometer (PSAP; GChen), respectively, were combined to derive aerosol extinction. Lidar signals measured below and above the SAL layer at this location were used to derive the aerosol optical depth and lidar ratio as described in section 2b. The aerosol extinction profile obtained from LASE measurements at 1632–1633 UTC is compared with the in situ profiles in Fig. 8. The high LASE aerosol extinction values below \(\sim 700\) m are due to the presence of low-level boundary layer clouds. There is a very good agreement in magnitude and structure between the 450-, 550-, and 700-nm in situ and LASE 815-nm aerosol extinction profiles at this location. These data also illustrate the lack of wavelength dependence in SAL extinctions. In situ measurements of particle size distributions by the DC-8 indicate the dust had a volume-mean diameter of between 2 and 3 \(\mu m\), which yielded measured Angstrom exponents of \(\leq 0\) (GChen). Similar LASE in situ comparisons performed on other days (9 August, 30 August, and 5 September, not shown) suggest that higher (40–45 sr at 815 nm) lidar ratios than the 36 sr used here may produce even better agreement. This variation in the SAL lidar ratio is not surprising since, as was discussed in section 2b, \(S_a\) varies significantly with dust properties (i.e., size, shape, composition) and RH.

4. Moisture distributions and comparison with GPS dropsondes

26 August 2006

A vigorous AEW emerged from the coast of North Africa early on 25 August 2006 behind a large SAL event located to its north and west (Fig. 9b; AEW 4).
This AEW (and associated trough) emerged into the eastern North Atlantic at a fairly high latitude (15°–16°N) and tracked west–northwest over the next several days, moving directly into the nearby SAL. Not surprisingly, Meteosat-8 infrared satellite imagery indicated that the convection associated with this tropical disturbance rapidly dissipated as it tracked into the SAL’s dry, dusty environment (Fig. 9a). Figure 9b shows the TPW distributions in the experiment region and the location of the AEW 4 that is surrounded by dry air (≤45 mm TPW) associated with the SAL to the west and south. Time-lapse TPW imagery also indicated that as the AEW tracked over the eastern North Atlantic, the SAL event out ahead of it began to wrap around the western and southern portions of the AEW’s broad vorticity center.

NASA’s DC-8 sampled the large SAL event and the environment of AEW 4 on 26 August when the disturbance was located near the Cape Verde Islands (Fig. 9b). The primary mission objectives were to map the AEW circulation, as well as the thermodynamics and aerosols of the surrounding SAL. Low-level cloud-drift winds and analyses from UW-CIMSS (not shown) indicated that the vorticity center associated with the AEW was located near 17°N, 26°W, just west of the Cape Verde Islands. Analyses from UW-CIMSS also indicated that during this period, the tropical disturbance (Fig. 9b; AEW 4) was under the influence of 5–20 kt of vertical wind shear and was associated with a broad area of low-level (850 hPa) vorticity. The DC-8 sampled the moisture associated with the AEW during the initial part of the mission (~1300–1500 UTC) and later sampled the dry SAL air mass that was wrapping around the southwest and southeast quadrants (~1500–1730 UTC).

The presence of clouds resulting from convective activity with the AEW influenced measurements of water vapor distributions from the 26 August 2006 flight (Fig. 10) in the first half of the flight and near 1500 UTC. The presence of clouds causes attenuation of lidar signals leading to decreasing the precision of measurement and or loss of data (blank regions in Fig. 10). The DC-8 conducted in situ sampling of the air associated with the cirrus that was located at altitudes >6 km from 1415 to 1520 UTC. Water vapor measurements from LASE and the two GPS dropsondes dropped into the high-moisture/cloudy and dry regions at points A and B (Fig. 10a), respectively, are compared in Figs. 10b,c. Although the LASE profile is somewhat noisy due to cirrus cloud attenuation, Fig. 10b shows good agreement between the remote (LASE) and in situ (GPS dropsonde) measurements. However, Fig. 10c shows excellent agreement between LASE and the GPS dropsonde over the entire altitude range including the dry regions, which exhibited highly variable aerosol scattering. Keil et al. (2008) have shown that low moisture at low altitudes suppresses convective development. The presence of low- to midlevel dry air around the western and southern perimeter of the AEW on 26 August 2006 may be partly responsible for the nondevelopment of this AEW. In addition, the presence of 5–20 kt of vertical wind shear and a broad area of low-level (850 hPa) vorticity may also be contributing factors for the nondevelopment of the AEW. At Florida State University, data assimilation of GPS dropsonde and LASE data are being conducted for a mesoscale model [The National Center for Atmospheric Research’s (NCAR’s) Advanced Research Weather Research and Forecasting model (ARW-WRF)]. These mesoscale prediction experiments are designed to explore the sensitivity of AEW 4 (Fig. 9b) forecasts to these data inputs. The 26 August case, where the AEW weakened during very dry conditions brought about by dry air intrusions, is of special interest. Preliminary analysis shows that the modeled AEW was too wet, based on operational first-guess analysis. This control forecast resulted in a developing storm. However, when that experiment was repeated using the LASE humidity profiles, we noted that the dry air of the LASE soundings modified the initial state and resulted in a rapid weakening of this NAMMA AEW, as observed.

Results of a detailed comparison of LASE measurements with the 81 GPS dropsonde moisture profiles recorded during NAMMA are summarized in Figs. 11a,b. In general, LASE and dropsondes measurements agreed to within about 10% over the full altitude range (Fig. 11a). However, it was found that water vapor profiles measured by GPS dropsondes manufactured during or before 2004 (model Rev. D/GPS1211) were systematically
FIG. 9. (a) Meteosat-8 split window image showing the distribution of the SAL on 26 Aug 2006. The DC-8 flight track is also shown with UTC hours labeled, and the segment of data shown in Fig. 10 is highlighted by red dashed lines (a–b). The location of Sal Island, Cape Verde is indicated by the star symbol. (b) TPW from the Remote Sensing Systems global TPW dataset for 1800 UTC on 26 Aug 2006. TPW is derived from the 19-, 22-, and 37-GHz microwave channels of the constellation of SSM/I satellites, TRMM/TMI, and AMSRE-E on Aqua. The black polygon represents the DC-8 flight track and the color scale is for TPW in mm.
drier than LASE water vapor profiles by 10% or more (Fig. 11b). Water vapor profiles from GPS dropsondes manufactured after 2004 (model Rev. F) were in much better agreement with the LASE water vapor profiles, indicating that the older dropsondes had a dry bias. Previous studies have shown dry biases in the GPS dropsondes as a result of packaging and the age of the GPS dropsondes (Kooi et al. 2002; Vance et al. 2004) and newer dropsondes do not appear to show this bias (Wang 2005).

5. Geographic distribution of aerosols and water vapor during NAMMA

Latitudinal distribution of aerosols and water vapor

The latitudinal distribution of aerosol extinction profiles from LASE measurements is shown in Fig. 12a. Figure 12a was constructed by including all NAMMA LASE measurements of vertical extinction profiles binned into 0.5 km (altitude) × 0.25° (latitude) cells. Cloud screening of the data was performed by setting an aerosol scattering ratio (ASR) threshold. The ASR threshold was 100 below 6 km and 30 above 6 km; values greater than these thresholds are considered to arise from clouds. A broad low-level peak in lower tropospheric aerosols was found near 17°N. This is similar to observation of dust from CALIPSO by Yorks et al. (2009). This may be related to the mean position of the ITD over Africa during the summer (Bou Karam et al. 2009). The peak near 17°N is also linked with the total ozone mapping spectrometer (TOMS) dust climatology as published by Engelstaedter and Washington (2007). It should, however, be noted that the dust climatology given by Engelstaedter and Washington (2007) in their Fig. 2 has a potential bias during the summer months due to the obscuration of dust that is present beneath the cirrus in the Sahelian region (see discussion by Williams 2008).

The low-level features at 17°N and near 22°N are artifacts of clouds associated with the MBL and are not significant.

Higher aerosol loading below 1-km altitude between 12° and 22°N is thought to be the result of downward mixing of dust from the overriding SAL (Twohy et al. 2009; GChen). The MBL depth generally ranged from 0.2 to 1 km. Enhanced scattering seen at low latitudes up to 15 km is the residue from cloud screening. The overall average aerosol extinction profile for the whole campaign is given in Fig. 12b. No significant longitudinal dependence in SAL extinction was observed within the NAMMA study area (Fig. 1). The average profile of the aerosol scattering ratio from all SAL events is shown in Fig. 12c. Only events that met the criterion of aerosol scattering ratio exceeding 4.0 in the profile and a minimum layer thickness of 2 km were used to denote SAL regions. Other observations are treated as non-SAL events. The aerosol scattering ratios ranged up to 20 with an average of ~10 over the altitude region 2–6 km. In general, the altitude of the SAL ranged from near surface to about 6.5 km (see Figs. 3, 4, 6, and 7). Figure 12d displays over 3900 LASE observations of cloud-free atmospheric optical thickness (AOT) from the surface (i.e., 30 m) to 8 km. These AOT values include an estimated
AOT value of ~0.04 due to the presence of sea salt aerosols (GChen). Dust layers were observed in 2640 of the 3900 individual observations. The SAL AOT ranged from 0.05 to 0.6 and averaged 0.36 ± 0.14. Using the mass extinction efficiency value of 0.8 m² g⁻¹ derived by GChen from NAMMA in situ measurements, the average column dust mass loading is estimated to be 0.45 ± 0.14 g m⁻². Kaufman et al. (2005) used the Moderate Resolution Imaging Spectroradiometer (MODIS) data to estimate aerosol mass loading from dust. Using the observed NAMMA average SAL optical depth of 0.36, the estimated mass loading is about 1 g m⁻². However, Kaufman et al. used an efficiency factor of 3.7 instead of 8 in the present work. When the efficiency factor of 8 is used, the corrected mass loading estimated from MODIS is about 0.46 g m⁻², which is in good agreement with our result of 0.45 g m⁻².

Latitudinal distributions of RH and water vapor mixing ratios are shown in Figs. 13a,b. RH values show a decrease in the range from about 11° to 20°N over the 2–6-km altitude range associated with the presence of the SAL. RH and mixing ratio profiles over well-defined SAL and non-SAL (also called mixture; events that did not meet the criterion of clear SAL events) regions are shown in Figs. 13c and 13d, respectively. For both parameters, SAL profiles are drier than non-SAL events in the lower altitude region, but the differences above 3 km are not significant. This could be the result of the sampling strategy during NAMMA that focused on studying AEWs and the transition region between the SAL and AEWs. As a consequence of this strategy, many of the flights did not reach deep into central portions of the SAL with dry air extending to higher altitudes. Comparison of LASE water vapor measurements with observations of Dunion and Marron (2008) for the SAL and non-SAL events is shown in Fig. 13d. The average NAMMA non-SAL profile (blue curve) indicates very little difference with the Dunion and Marron non-SAL moisture measurements (blue dots). However, the NAMMA SAL profile (red curve) above 2 km is considerably moister than the Dunion and Marron measurements (red dots). This probably is the result of NAMMA DC-8 sampling strategy that tended to specifically target AEWs. Note that the SAL GPS dropsonde temperature profile near the base of the SAL (Fig. 13e) is about 4°C warmer than non-SAL profile. This explains the relatively lower RH in SAL regions compared to what is expected from the mixing ratio profiles. The average enhancement of temperature at the top of the base inversion region of the SAL (near 2 km) was about 4°C compared to that in the non-SAL regions. The average SAL temperatures were warmer compared to temperature profiles from non-SAL regions from the surface to 3 km and slightly cooler (~1°C) above 3 km. This temperature distribution in the lower and upper regions of the SAL is consistent with characteristics of the SAL events observed in the Atlantic previously (Carlson and Prospero 1972). The temperature distributions in the SAL are a result of its origins over the hot Sahara Desert and the balance between heating due to shortwave absorption and longwave cooling. Zhu et al. 2007 have studied the radiative impact of the dust, which indicates warming below 4 km and slight cooling above 4 km for the Saharan dust.

6. Discussion and conclusions

LASE measurements from the NAMMA field experiment presented a unique opportunity to study the SAL in the vicinity of AEWs. From these LASE measurements the aerosol characteristics (profiles of aerosol scattering ratios, aerosol extinction coefficients, and aerosol optical depths) of the SAL and water vapor...
distributions in the SAL and moist tropical atmosphere were derived. The characteristics of the SAL (high aerosol scattering, high temperatures and inversions near the base that are generally located on top of the MBL, and vertical wind shear) are similar to those observed at other locations (Dunion and Velden 2004). Extinction profiles derived using these values agreed well with soundings calculated from in situ measurements. Temperature profiles from GPS dropsondes show the characteristic temperature inversion at the base of the SAL with significantly enhanced temperatures at the top of this inversion. The average temperature at the base of the SAL at about 2-km altitude was higher than the non-SAL (mixture) temperature by about 4°C. The average SAL temperature below about 3-km altitude was higher than the moist tropical non-SAL environment, and above 3 km it was slightly lower (by ~1°C). SAL aerosol optical depths ranged from 0.05 to 0.6 and averaged 0.36 ± 0.14. The aerosol scattering ratios in the middle of the SAL ranged from 5 to 20. The SAL generally extended up to 4- to 6.5-km altitude, but in some instances SAL tops were seen as low as 3 km. MBL heights ranged from 0.2 to >1 km. Changes in lapse rate with altitude were found to coincide with layering of aerosols within the SAL; these changes are likely caused by an increased shortwave absorption in the dust layers. These LASE measurements can be coupled with retrievals of radiation fluxes at the top of the atmosphere (TOA), at the surface, and within the atmosphere from the Clouds and the Earth’s Radiant Energy System (CERES) instruments that operated during NAMMA aboard the Terra and Aqua spacecraft to study the impact of the SAL on the radiation budget throughout the atmospheric column. These studies would also improve our understanding of the thermodynamic environment in the region and address important questions regarding the effect of the SAL on atmospheric temperature structure and stability and regional sea surface temperatures.

Although some observations were made of the SAL away from convective regions, the primary focus of the DC-8 flights was to study the environment of AEWs and their interactions with the SAL. Many examples from LASE suggest that the SAL suppresses low-level convection seen at the interface of the SAL and the tropical convective regions. As discussed by Dunion and Velden (2004), the SAL is associated with stable dry air and wind shear that are likely to suppress convection. Our observations indicate that SAL–AEW interactions lead to the rapid transfer of latent heat energy (water vapor) across the SAL–AEW interface. Intensification of an

![Figure 12](image_url)
AEW and midaltitude convection appear to enhance the water vapor mixing ratio and RH in the southern regions of the SAL on 20 August 2006. This transfer of energy, in the absence of other mechanisms that intensify AEWs, could suppress development of weak AEWs. However, the SAL does not necessarily limit the eventual development of stronger AEWs into strong TCs as was observed in the development of many strong storms during NAMMA (e.g., Hurricane Helene).

Except for the regions that were totally obscured by lidar signal attenuation by clouds, LASE measurements of water vapor demonstrated its capability to capture the full dynamic range of water vapor distributions over the entire range of flights. Such measurements are known to improve water vapor data assimilation and numerical weather forecasts (Rizvi et al. 2002; Wulfmeyer et al. 2006). Forecast studies at FSU are in progress. The results of these studies show a strong sensitivity to and improvements in forecasts when using LASE water vapor profiles as in the case of the nondeveloping AEW on 26 August 2006. The results of these will be reported in a separate publication (T. Krishnamurti et al. 2009, unpublished manuscript).

Water vapor mixing ratio profiles from NAMMA (that were away from pristine SAL layers) were generally found to be similar to the tropical water vapor profiles observed by Dunion and Marron (2008) in the Caribbean during the hurricane season. LASE measurements of a wide range of water vapor distributions during this mission were compared with in situ GPS dropsonde...
measurements and agreed well within 10%. However, a batch of older GPS dropsondes (Rev. D/GPS1211 dropsondes) that were manufactured before 2004 were found to have a significant dry bias.

Additional areas of future research that can benefit from LASE moisture measurements include the following. First, in a recent review of NAMMA, Zipser et al. (2009) express the opinion that the development of AEWs is strongly sensitive to the humidity field. They state that waves north of 15°N were typically concentrated at low levels and dry while the systems south of 15°N typically were in the midtroposphere and rainy. These are the types of systems where a moisture analysis from LASE and its assimilation in mesoscale models can help in providing a clearer distinction between these northern and southern systems.

One of the main objectives of the NOAA–Atlantic Oceanographic and Meteorological Laboratory (AOML)–Hurricane Research Division’s first Saharan Air Layer Experiments (SALEX) in 2005 and 2006 was improving the understanding of how the SAL’s dry air, midlevel easterly jet, and suspended mineral dust affect Atlantic TC intensity and assessing how well these components of the SAL are represented in forecast models. These are areas where the LASE-based analysis of the atmospheric state can help improve model forecasts as well as the basic understanding of the SALEX science issues.

Another objective of SALEX that can benefit from LASE measurements is related to the question “Are the most important influences of the SAL the ingestion of dry air into the AEW?” Such injections of dry air can be seen from water vapor and TPW imagery from satellites, but for improved quantitative understanding of the spatial and temporal nature of these events, model simulations that include four-dimensional assimilation of moisture are required. The operational models provide descriptions of moisture but can have large wet or dry biases in the moisture field. Profiles of RH from collocated GFS and GFDL model analysis during SALEX suggest that although both models were capturing the general moisture trends below, within, and above the SAL, they tended to overestimate the SAL’s midlevel dryness. For the small sample shown, GFS and GFDL overestimated the SAL’s midlevel moisture by as much as 40%–50% RH. As demonstrated in the case of 26 August 2006, LASE can provide the vertical and horizontal details of the moist conditions and dry air intrusions needed to improve model forecasts.

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