LASE MEASUREMENTS OF WATER VAPOR, AEROSOL, AND CLOUD DISTRIBUTIONS IN SAHARAN AIR LAYERS AND TROPICAL DISTURBANCES

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ABSTRACT

LASE (Lidar Atmospheric Sensing Experiment) on-board the NASA DC-8 was used to measure high resolution profiles of water vapor and aerosols, and cloud distributions in 14 flights over the eastern Atlantic region during the NAMMA (NASA African Monsoon Multidisciplinary Analyses) field experiment, which was conducted from August 15 to September 12, 2006. These measurements were made in conjunction with flights designed to study African Easterly Waves (AEW), Tropical Disturbances (TD), and Saharan Aerosol Layers (SALs) as well as flights performed in clear air and convective regions. As a consequence of their unique radiative properties and dynamics, SAL layers have a significant influence in the development of organized convection associated with TD. Interactions of the SAL with tropical air during early stages of the development of TD were observed. These LASE measurements represent the first simultaneous water vapor and aerosol lidar measurements to study the SAL and its impact on TDs and hurricanes. Seven AEWs were studied and four of these evolved into tropical storms and three did not. Three out of the four tropical storms evolved into hurricanes.

1. INTRODUCTION

The objective of the NAMMA mission was to examine: 1) the formation and evolution of tropical hurricanes in the eastern and central Atlantic and their impact on the U.S. east coast, 2) the composition and structure of the Saharan Air Layer (SAL), and 3) whether aerosols affect cloud precipitation and influence cyclone development. NAMMA was conducted from the Sal Island, Cape Verde, Africa. One of the focus areas of this field experiment was to study the interaction of the SAL with tropical disturbances that originate near the west coast of Africa.

The SAL originates over continental Africa and propagates over the Atlantic during the summer. Dust storms associated with the SAL can be as large as the size of continental U.S. and recur every 3-5 days. The SAL contains warm and dry air and is associated with midlevel easterly jet [1]. There is a temperature inversion at the base of the SAL. Higher temperature in these layers is maintained by absorption of solar radiation by suspended dust. Dunion et al. [1] point out that the presence and enhancement of a trade wind inversion associated with SAL can limit and inhibit vertical motions and thus development of convection in weak AEW. However, the SAL can also influence cloud microphysical properties and act as a source of atmospheric aerosols. Aged SAL mineral dust particles get coated by soluble sulfate and sea salt. This coating permits moistening of dust-based particles and allows them to act as cloud condensation nuclei leading to cloud formation and to the release of latent heat. Consequently the SAL can influence precipitation processes and dynamical properties of the tropical atmosphere. The characterization of the SAL is also important for developing and evaluating passive satellite retrieval techniques.

Water vapor is a key element for the understanding of the processes of precipitation, evaporation, and the release of latent heat. 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, [2] have 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 have been shown to be very sensitive to the surface layer moisture. Krishnamurti et al. [3] have shown that models which incorporate an explicitly resolved surface layer have been able to more accurately compute the strong moisture flux between the ocean and atmosphere resulting in more accurate prediction of the formation of hurricanes. Earlier NASA CAMEX missions have shown positive impacts of accurate, high resolution measurements of water vapor obtained by LASE on forecasts of hurricane track and intensity [4,5]. NAMMA measurements provide an opportunity to study the influence of accurate high resolution moisture profiles in the eastern Atlantic region associated with genesis of hurricanes. LASE measurements of water vapor and aerosols during NAMMA have provided a unique opportunity to characterize the SAL and the impact of the SAL on the development of organized convection associated with TDs. In this paper we present a brief description of LASE followed by a characterization of the SAL observations during NAMMA. An example of a tropical wave and its interaction with the SAL is presented. Examples of water vapor measurements over a moist tropical region and those associated with a dry air intrusion are given. Comparison of LASE measurements with GPS dropsondes are also presented.

2. LASE SYSTEM

The LASE DIAL system was developed at the NASA Langley Research Center in 1995 [6] and has subsequently participated in over 12 field experiments while deployed onboard the NASA ER-2, P-3, and DC-8 aircraft. LASE was operated onboard the DC-8 during NAMMA. The laser system 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. During NAMMA, LASE operated locked to a strong water vapor absorption line at 817.223 nm and electronically tuned to other spectral positions on the side of the absorption line. In this mode, LASE transmitted up to three (on- and off-line) wavelength pairs that together permitted profiling of water vapor across the entire troposphere. Total laser output pulse energy was about 90 mJ in each of the on- and off-line laser pulses transmitted at 5 Hz. This energy was nominally split in a 7:3 ratio for transmission in nadir and zenith orientations, respectively. The nadir detector system used two silicon avalanche photo diodes and three digitizers to cover a signal dynamic range of 10^6.

3. SAL CHARACTERIZATION

An example of an intense SAL in the region of eastern Atlantic near the coast of NW Africa is shown in Figure 1. These data have been derived from METEOSAT IR observations on September 5, 2006. A NASA DC-8 flight was dedicated to characterize the SAL and conduct cloud microphysics measurements. This flight was conducted along a line at 19˚N latitude from Sal Island, Cape Verde into continental Africa and back. LASE measurements of aerosol scattering ratio and water vapor distributions over the ocean and continental Africa are shown in Figure 2. Aerosol scattering ratios were derived from the off-line wavelength that was positioned at about -35 pm away from the strongly absorbing H_2O line at 817.223 nm. Corrections for absorption by water vapor, air, and aerosol extinction) were applied to retrieve the aerosol scattering profiles [7]. The layer extended from near the surface to about 6 km in altitude. The most intense region of scattering was located at higher altitudes over the ocean compared that over the land.

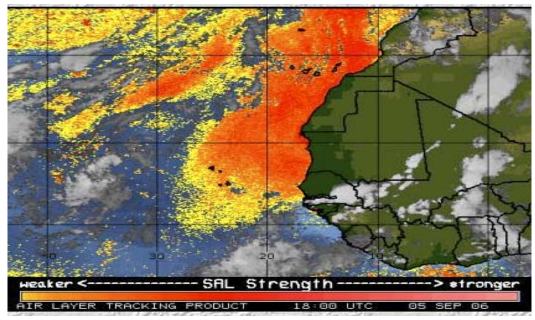

Figure 1. Satellite imagery of the distribution of SAL over the eastern Atlantic observed on September 5, 2006.

Aerosol scattering values ranged up to 20 and intense scattering associated with localized cloud formations were observed from regions near 4.5 km as seen in Figure 2a. Higher levels of moisture were observed in the layer over the oceanic region (Figure 2b) compared to that over the land indicating interactions with tropical moist air. The localized cloud regions showed nearly 100% relative humidity (RH) values; these RH values were computed using LASE water vapor profiles and GPS dropsonde temperature profiles. This SAL was

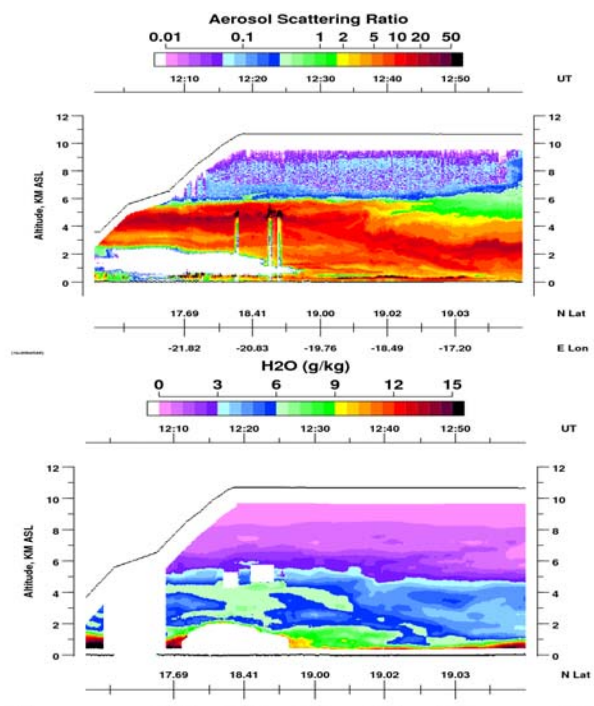

Figure 2. Aerosol scattering ratio over SAL (a) top, and Water vapor mixing ratio measurements (b) bottom from LASE.

sampled by direct in situ sampling instruments onboard the DC-8 during the return portion of the flight. LASE observations were used to guide the in situ sampling. In situ sampling confirmed regions of high RH as obtained from LASE data in regions of localized clouds embedded in SAL.

3.1 **Aerosol extinction and optical thickness**

Aerosol extinction profiles and optical thickness values (at 817 nm) were derived from the LASE measurements during NAMMA. An example of the retrieval aerosol extinction profile in SAL is shown in Figure 3a. In order to derive these profiles, the ratio of aerosol extinction/backscatter ("lidar ratio") was derived directly from the LASE data. LASE measurements both above and below an elevated dust layer were used to derive an estimate of transmission through the layer from which a value of the lidar ratio = 36 sr was obtained [7,8]. Also shown in Figure 3a are the extinction profiles at three wavelengths derived from the DC-8 in situ nephelometer measurements of aerosol scattering and PSAP measurements of absorption when the DC-8 descended through the dust layer. The LASE and in situ retrievals of aerosol extinction for the elevated dust layer are in excellent agreement. Aerosol optical thickness profiles derived from the LASE aerosol extinction data for this flight are shown in Figure 3b. These values represent the aerosol optical thickness above each altitude. The SAL optical thickness ranged from 0.05 to 0.5.

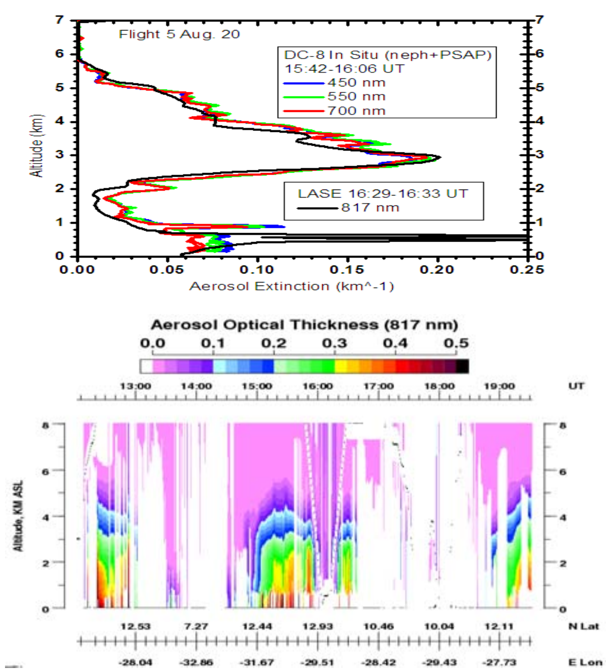

Figure 3. Aerosol extinction profiles from LASE compared with in situ measurements (a) top, and aerosol optical thickness of SAL (b) bottom.

4. SAL INTERACTION WITH AEW

Seven tropical waves were studied during NAMMA. Three of these systems developed into hurricanes (Ernesto, Debby, and Helene), one into tropical disturbance (Gordon), and three waves did not develop. SALs appear to act as a deterrent to the development of storms. An example of LASE data associated with a weak wave that interacted with SAL on August 26, 2006 is given in Figure 4. On this case, the SAL was located below 4 km altitude over most of the DC-8 flight region. High levels of moisture (>6 g/kg up to 6 km altitude) and convection were observed through the SAL and the DC-8 flight sampled cirrus clouds associated with this convection. An intrusion of low humidity air into the convective region of the tropical wave was associated with a ridge located to the southwest of the wave as seen in Figure 4. Interaction with the SAL and the dry layer air appear to have dissipated this wave. Two other waves observed during September 3-4, and 8-9, 2006 that interacted with strong SALs did not develop into storms. On the other hand two strong waves with well organized convection continued to develop while interacting with SALs and later developed into Hurricanes Debby and Helene. Although Debby did indeed form but other observations indicate that it appeared to be inhibited by the SAL. SALs were present in all quadrants of these two developing storms and various degrees of moistening within the dust layers was observed.

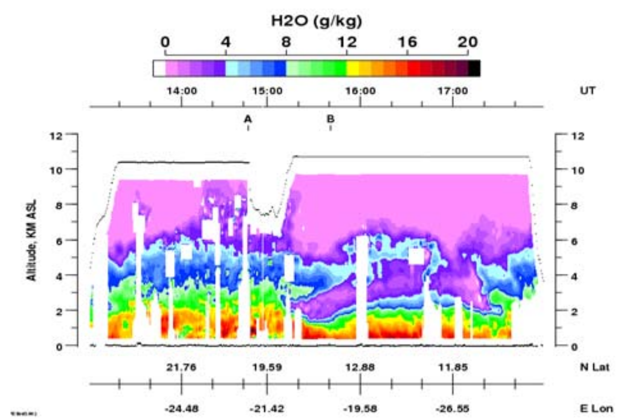

Figure 4. Moisture distribution from LASE in and around a tropical wave observed on august 26, 2006.

5. COMPARISON WITH DROPSONDES

Seventeen GPS dropsondes were deployed during the flight on August 26 2006 (Figure 4). While dropsondes provide ancillary temperature and wind measurements, LASE provided continuous curtain profiles of moisture and aerosol distributions. Two example comparisons of LASE water vapor measurements with dropsondes are given in Figures 5a,b that were made at points A and B identified in Figure 4. High moisture and cloudy regions were associated with measurements at A (Figure 5a), and dry regions at B (Figure 5b). Figure 5a shows good agreement between LASE and dropsondes. However, LASE data are noisy due to extinction by cirrus clouds underneath the DC-8. Figure 5b shows excellent agreement over the entire altitude range including the dry regions. While LASE and dropsondes measurements agreed well in general, it was found that water vapor profiles measured by dropsondes manufactured before 2001 were dryer than LASE water vapor profiles by about 10%; water vapor profiles from dropsondes manufactured after 2004 were in better agreement with the LASE water vapor profiles.

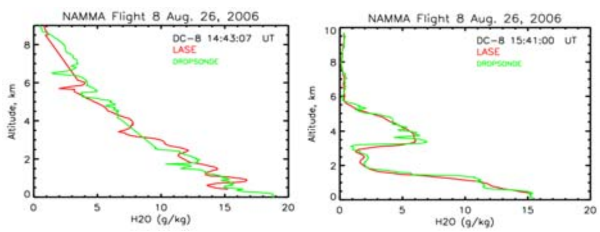

Figure 5. Comparison of LASE and dropsonde measurements over cloudy regions (a) left, and dry regions (b) right observed on August 26 2006.

6. CURRENT ACTIVITIES

Images of LASE measurements of water vapor and aerosol scattering ratio profiles from 14 NAMMA flight are available at NASA Langley lidar website: http://asd-www.larc.nasa.gov/lidar/. These LASE moisture measurements are being assimilated in numerical weather prediction models at Florida State University to study their impact on hurricane genesis and development. Plans are also underway to use LASE SAL measurements along with GOES and METEOSAT split window and SSM/I TPW imagery data to study 4-D evolution of the SAL. A synopsis of these activities will be included in this presentation.

7. SUMMARY

LASE measurements have been used to derive water vapor mixing ratios and aerosol scattering ratios. Relative humidity profiles have been derived for selected data sets, using temperature profiles from dropsondes, to study transport of air masses and the humidification of dust aerosols. The dust layers over the ocean and the continent were found to range in altitude from near surface to 6 km. Aerosol scattering ratios at 817 nm ranged from 0 to >20, and their layer optical thickness ranged from 0 to >0.5. Dust layers were generally anti-correlated with the water vapor distributions; however, highly attenuating (cloud) regions with high (~100%) RH were occasionally observed within the dust layers. Moistening of dust layers in regions of convection was observed with largest increases in moisture observed in the lower altitude regions. Convection was generally suppressed in the vicinity of the dust layers. Dust layers were situated generally north of the TD; however, dust layers were also observed in and around the TD. LASE water vapor, aerosol and cloud measurements during NAMMA provided an opportunity to compare with in situ aircraft, dropsonde, and satellite observations. Examples of LASE measurements along with their relationship with the AEW, at various stages of their development will be presented in this paper.

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