Airborne Lidar Measurements of Water Vapor, Aerosols, and Clouds During the NASA CAMEX-4 Experiment

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1. Introduction

The LASE (Lidar Atmospheric Sensing Experiment) system was operated on the DC-8 during CAMEX-4 and conducted measurements during 13 long-duration flights including measurements over Hurricanes Erin and Humberto, and Tropical Storms (TS) Chantel and Gabrielle. The main objectives for the participation of LASE during CAMEX-4 was: to provide real-time water vapor and cloud profiles to assist in flight planning and execution, to assess the utility of high resolution water vapor profiles in forecasting storm track and intensity, and to evaluate the water vapor profiles measured by the DC-8 and ER-2 dropsondes.

2. LASE Instrument and Operations

The LASE system was developed at the NASA Langley Research Center as an autonomous DIAL system to measure profiles of atmospheric water vapor, aerosols, and clouds from the high altitude ER-2 aircraft (Browell et al., 1997). 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 CAMEX-4, 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 output laser energy at 815-nm was about 100 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 large signal dynamic range (10^6).

3. LASE Measurements and Analysis

The DC-8 conducted 13 flights during CAMEX-4 including 5 long duration flights over Hurricanes Erin and Humberto, and Tropical Storms (TS) Chantel and Gabrielle. LASE operated in the nadir and zenith modes simultaneously during these flights. A list of the measurement objectives and specific LASE achievements during the 13 flights are listed in Table 1. Flights over Hurricane Erin and TS Gabrielle were considered to be Optimal Data Assimilation Flights (ODAF). Some of the main objectives of these flights were: assess the impact of high resolution water vapor and wind measurements on forecasts of hurricane intensity and track, obtain high resolution water vapor measurements to characterize water vapor inflow regions, and evaluate ER-2 and DC-8 dropsonde water vapor measurement performance in conjunction with NOAA HRD synoptic surveillance flights. The LASE capability for profiling tropospheric water vapor, aerosols, and clouds has been demonstrated during previous field experiments (Browell et al., 1997; Ismail et al., 2000; Browell et al., 2001). LASE measurements from CAMEX-4 were used to derive profiles of aerosol scattering ratios, water vapor mixing ratios, and relative humidity (RH). Range corrected and background subtracted off-line signals were used in deriving the scattering ratios using atmospheric number densities from DC-8 dropsondes (Ismail et al., 2000). Molecular, water vapor, aerosol, and cirrus cloud extinctions were used in removing biases due to signal attenuation. The scattering ratios were derived from measurements where a clean region value was observed at high altitude, occurring in at least one location over the entire flight. The resolutions of aerosol scattering data are 60 m (vertical) and 600 m (horizontal). Water vapor measurements were retrieved from the LASE data by taking into consideration all atmospheric and instrument effects as outlined by Browell et al. (1997). LASE signals were vertically smoothed and horizontally averaged to obtain nominal water vapor profile resolutions of 330 m (vertical) by 40 km (horizontal) in the nadir and 1 km (vertical) by 70 km (horizontal) in the zenith. RH profiles were derived using the water vapor profiles from LASE and temperature profiles derived from the DC-8 Microwave Temperature Profiler (MTP). For a nominal flight altitude of 10 km, the rms error in the MTP retrieved temperature profile is <1 K within 2 km of the aircraft, and degrades to <2 K within the range of 1 km above the surface. Relative humidity profiles are computed using LASE water vapor profiles and MTP temperature profiles as described by Ferrare et al. (2000).

LASE measurements were made on September 10, 2001 to characterize the moisture environment associated with Hurricane Erin that was situated at 35.5 N latitude and 65.1 W longitude. Sustained winds of

Table 1. LASE measurements during CAMEX-4

Date	Flight Number	Flight Duration (hours)	Objectives	Tropical Storm/Hurricane	LASE Measurements
8/15	5	4.8	Transit to JAX	N/A	Extensive data (4.0 hrs) (aerosol, wv, clouds distrib). Mostly clear sky across country.
8/18	6	3.5	Andros Island Calibration Flight	N/A	3.5 hours of LASE data. Excellent Atmospheric conditions with some cirrus.
8/20	7	7.5	Convection Emphasis with vertical structure, also rainband patterns flown	TS Chantel	+6.5 hrs of aerosol,Wv and cloud distro. Lots of clouds from approx 19:30 UT to end of mission.
8/25	8	2.0	Instrument test flight	N/A	+1.0 hrs of aerosol, wv, cloud distro. Fairly clear skys. Lots of aerosol fine structure.
9/03	9	5.0	KAMP #1 Convective structure of a precipitating system	N/A	+3.0 hrs of aerosols, wv, and cloud distro. Lots of structure, clouds, and cirrus above the DC-8.
9/06	10	1.0	Instrument Check/Convection	N/A	0.5 hrs of aerosols, wv, and cloud distro. Lots of clouds above and below DC-8 and other structure
9/07	11	5.0	KAMP #2, Convection in precipitating storm	N/A	+4.5 hrs of aerosols, wv, and cloud distro. Lots of clouds above and below DC-8
9/09	12	5.0	KAMP #3, Convection in precipitating storm.	N/A	+4.5 hrs of aerosols, wv, and cloud distro. Lots of clouds above and below DC-8.
9/10	13	8.0	Optimal data assimilation to collect comprehensive data on winds, temp, and moisture structue of the storm.	Hurricane ERIN	8.0 hrs of aerosols, wv, and cloud distro. Occasionally in and out of cirrus clouds. Excellent data set.
9/15	14	8.0	Optimal data assimilation and to map flow fields and thermodynamic fields in a rotated pattern.	TS GABRIELLE	+7.5 hrs of aerosols, wv, and cloud distro. In and out of cirrus above and below DC-8. Excellent data when not in the clouds.
9/19	15	5.0	KAMP #4, Sample a convective system to obtain radar and microphysics data	N/A	4.5 hrs of aerosols, wv, and cloud distro. Inand out of cirrus above and below Dc-8 throughout this flight. When not in clouds, has good data.
9/22	16	8.0	QPF mission and to map the conditions near a developing storm center, including flow fields and thermodynamics.	TS HUMBERTO	7.0 hrs of aerosols, wv, and cloud distro. In and out of cirrus above and below DC-8. Lots of excellent data and structure when not in clouds.
9/23	17	7.5	COVES #1, Convection, structure, and mapping of the inner storm	Hurricane HUMBERTO	6.0hrs of aerosols, wv, and cloud distro. Excellent data when not in the storm. Lots of structure.
9/24	18	8.0	COVES #2, Convection, structure, and mapping of the storm	Hurricane HUMBERTO	7.0hrs of aerosols,wv, and cloud distro. Excelllent data when not in the storm. Lots of structure.

105 kts and a clear eye with a diameter of 30 km were associated with this storm. This mission included 8 dropsondes from the ER-2 operating in the lower stratosphere over the eye of the storm and 9 dropsondes from DC-8 in all quadrants of the hurricane. It was conducted in close coordination with measurements from NOAA operational aircraft. The DC-8 flew at an altitude of 28000 ft and circumnavigated the hurricane. The DC-8 flight track overlaid on satellite imagery is shown in Figure 1. LASE nadir measurements of water vapor mixing ratio, aerosol scattering ratio, and relative humidity profiles are also shown in the figure. Blank regions indicate lack of reliable measurements due to cloud influence/attenuation. Moisture levels were high in the northeastern quadrant where a number of rain bands were located with water vapor mixing ratios exceeding 5 g/kg up to and above 6 km. Dry air was located in the subsiding region in the northwest of the storm, and water vapor varied by more than an order of magnitude in the mid- and upper-troposphere. Regions of high relative humidity (>80%) were well correlated with observation of clouds with aerosol scattering ratios exceeding 6.

LASE measured the fine-scale structure of the moisture field associated with Tropical Storm Gabrielle on September 15, 2001. After landfall over Florida, the storm reemerged over the Atlantic and was located near 30 N latitude and 79 W longitude. The storm exhibited unusual structure with convection in the north and northeastern quadrants and dry air in the south and southeast. The presence of dry air entrainment in the southeast prevented rapid redevelopment of the storm. A time series of water mixing ratios at an altitude of 8 km showed that the water vapor mixing ratios varied nearly by two orders of magnitude (from about 0.03 g/kg to >2.0 g/kg) from the SE to north of the storm. From the LASE measurements, profiles of water vapor mixing ratio, RH, and scattering ratio profiles were derived. These measurements were used to define the moisture structure of the storm, for comparisons with dropsondes from DC-8, and to provide input to hurricane forecast models developed at the Florida State University (FSU).

LASE data are undergoing final processing for submission to final archive. Comparisons of processed LASE water vapor data with the Airborne Atmospheric Profiling System dropsondes that were released from the DC-8 are currently being processed. Dropsondes were released periodically during the flights and provided wind, temperature, and moisture data. However, LASE measurements of water vapor field were made continuously, and comparison of moisture profiles from the two sensors is one of the objectives of this research. A preliminary analysis indicates that the water vapor measurements agree well in general and that the dropsonde water vapor measurements are slightly dryer (by about 5-10%) in the mid- to upper-troposphere. This may be due to a generally known dry bias in the Vaisala humidity sensor produced by outgassing by desiccants and aging of the sensors (Wang et al., 2002). Preliminary digital data have been provided to the Florida State University to initiate forecast modeling.

4. LASE Plans

Preliminary LASE digital data and images are already available from CAMEX-4 archive. We plan to complete final processing of LASE nadir and zenith data and submit these data to the CAMEX archive before June 1, 2002. We are collaborating with FSU to process ODAF mission data first. We plan to complete dropsonde (DC-8 and ER-2) water vapor comparisons and complete retrievals of RH profiles from LASE nadir and zenith water vapor and MTP/dropsonde temperature profiles.

5. Conclusions

LASE measurements showed large variations of moisture in the upper-troposphere that reflected dynamics associated with these weather systems. Initial comparisons of water vapor with dropsondes showed general agreement with a slight dry bias in the sondes in the upper troposphere. The availability of LASE profiles of moisture helps in the definition of moisture convergence which is a key parameter in the modeling of cumulus convection which provides the heating for hurricanes.

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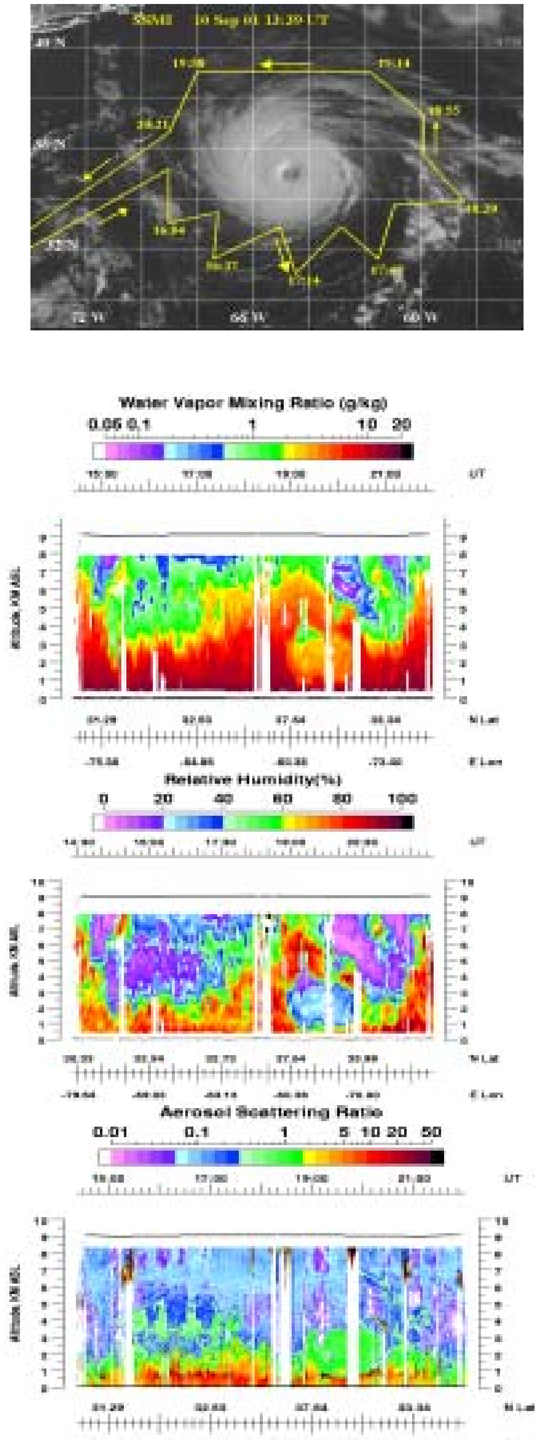

Figure 1. (top) CAMEX-4 DC-8 flight track around Hurricane Erin on September 10, 2001. (bottom) water vapor mixing ratio, relative humidity, and aerosol scattering ratio derived from LASE nadir measurements.