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AIRBORNE LIDAR FOR MEASUREMENTS OF ATMOSPHERIC GASES AND AEROSOLS

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INTRODUCTION

Major advances have taken place in recent years in the development and application of airborne lidar systems in the measurement of ozone (O_3), water vapor (H_2O), and aerosols in various regions of the atmosphere. In recent field experiments, simultaneous measurements of O_3 and aerosol distributions were made above and below the NASA DC-8 aircraft in tropospheric investigations on long-range flights over the southern tropical Atlantic as part of the NASA Global Tropospheric Experiment (GTE)/Transport and Atmospheric Chemistry near the Equator--Atlantic (TRACE-A) field experiment conducted during the summer of 1992 and over the western Pacific as part of the GTE/Pacific Exploratory Mission-West field experiment conducted during the winter of 1994 (PEM-West B). During the 1992 Airborne Arctic Stratospheric Expedition-II, large-scale stratospheric distributions of O_3 and Pinatubo aerosols were measured with an airborne lidar system on long-range flights across the wintertime Arctic vortex. The first airborne lidar investigations of H_2O and aerosol distributions were conducted using an advanced solid-state laser transmitter in daytime and nighttime flights on the NASA Wallops Electra aircraft in 1991, and other advanced H_2O lidar systems are under development.

The differential absorption lidar (DIAL) technique used in the remote measurement of O_3 and H_2O distributions from airborne platforms has been reviewed in several recent papers,[1-3] and since 1980, airborne DIAL systems have been applied to the measurement of O_3 and aerosol distributions in many field experiments.[1,3-7] This paper describes the DIAL systems used in the most recent field experiments identified above and presents some of the results of O_3, H_2O, and aerosol/cloud measurements made during these investigations. Characteristics of the advanced airborne DIAL systems that are under development are also described.

AIRBORNE LIDAR SYSTEM FOR OZONE AND AEROSOLS

An airborne DIAL system has been developed to simultaneously measure O_3 and aerosol profiles above and below the aircraft.[1] In this system, two frequency-doubled Nd:YAG lasers are used to pump two high-conversion-efficiency, frequency-doubled, tunable dye lasers. The four lasers are mounted on a structure that supports all of the laser power supplies, the laser beam transmitting optics, and the dual telescope and detector packages for simultaneous nadir and zenith measurements. In tropospheric O_3 investigations, one of the frequency-doubled dye lasers is operated at 289 nm for the DIAL on-line wavelength, and the other one is operated at 300 nm for the off-line wavelength. The DIAL wavelengths are produced in sequential laser pulses with a time separation of ~300 μs to ensure that the same atmospheric scattering volume is sampled at both wavelengths during the DIAL measurement. For tropospheric investigations, half of the energy in each of the ultraviolet (UV) beams is transmitted in the zenith and nadir directions. The dye laser output at 600 and 582 nm that is left after the frequency-doubling process and the residual 1064-nm output from the frequency-doubled Nd:YAG laser are also transmitted for aerosol profile measurements. The output beams are transmitted out of the aircraft coaxially with the receiver telescopes through 40-cm-diameter quartz windows. In stratospheric investigations, the on- and off-line wavelengths are 301 and 311 nm, respectively, and all the UV laser pulses are transmitted in the zenith direction. Two orthogonally polarized beams at both 600 and 1064 nm are also transmitted in the zenith for aerosol backscatter and depolarization measurements.

The backscattered laser energy at each laser wavelength is collected by two back-to-back 36-cm telescopes. The lidar returns in the UV, visible, and infrared are separated with dichroic optics and directed onto different detectors. The analog signals from the detectors are digitized at 10 MHz to 12-bit accuracy, and the average digitized signals are stored every 3 seconds (average of 15 lidar returns) on 8-mm magnetic tape. Ozone concentrations and aerosol distributions are calculated in real time, and the output can be displayed on a video screen or can be continuously plotted in color with two ink-jet plotters for in-flight and post-mission analysis. Detailed characteristics of the current airborne DIAL system and the O_3 DIAL technique are given in Refs. 1 and 3.

RECENT OZONE AND AEROSOL INVESTIGATIONS

Large-scale O_3 and aerosol distributions were recently investigated with the airborne DIAL system in the troposphere over the tropical Atlantic during TRACE-A and in the Arctic stratosphere during AASE-II. The following sections present a brief discussion of the general characteristics of the air masses observed during these two field experiments.

TRACE-A--The TRACE-A field experiment was conducted during September-October 1992 to determine the source of high O_3 that occurs in the troposphere over the tropical Atlantic between Africa and Brazil during the burning season. The DIAL-derived atmospheric cross sections of O_3 and aerosol distributions from the surface to above the tropopause were used to provide the large-scale perspective on the state of the atmosphere and its composition.

During TRACE-A, the airflow over the tropical Atlantic in the southern hemisphere was predominantly from the east (Africa) in the lower troposphere (below 8 km) and from the west (Brazil) in the upper troposphere. Convective storms in Brazil transported the gases contained in extensive fire plumes from near the surface to the upper troposphere where O_3 was photochemically produced and advected eastward over the Atlantic. In central Africa, the fires were widespread, and in the absence of convective storms, the fire plumes were advected to the west over the Atlantic at altitudes below 6 km. Airborne DIAL measurements showed considerable variability in O_3 and aerosol distributions with strong dependence on transport of air masses from regions associated with biomass burning. There was a positive correlation between O_3 and aerosols found downwind of biomass burning regions when the plumes were not involved in convection. The degree of photochemical O_3 production in the plumes appeared to be dependent on the age of the plume. High O_3 (>75 ppbv) was observed in the plumes below 6 km, and in the upper troposphere, O_3 often exceeded 100 ppbv from photochemical O_3 production in outflows from Brazil and from stratospheric air transported into the troposphere in intrusion events. The airborne DIAL data were used to help determine the relative contribution of the various processes on the buildup of high O_3 over the tropical southern Atlantic.

Airborne Arctic Stratospheric Expedition-II--The DIAL system was operated in the zenith mode from the NASA DC-8 aircraft to obtain profiles of O_3 and aerosols in the 14-30 km altitude range during the AASE-II field expedition conducted in January-March 1992. Eleven flights were made into the wintertime Arctic vortex to study the chemistry and meteorology associated with polar O_3

depletion. Aerosols from the Mount Pinatubo eruption in June 1991 were observed across the entire Arctic region during AASE-II. Outside the Arctic vortex the Pinatubo aerosols were found to extend over the 12-26 km altitude range with an aerosol peak near 20 km. The Pinatubo aerosol distribution at the center of the Arctic vortex extended from the tropopause to about 17 km in January and to about 18.5 km in March. The center of the Pinatubo layer remained near 15 km for the entire period. The O_3 distribution observed over the 12-25 km altitude range with the lidar system showed a clear transition across the Arctic vortex edge with the O_3 profile generally decreasing in altitude by about 1.5 km from outside to inside the vortex. The vertical O_3 distribution outside the vortex showed an increase in the O_3 mixing ratio from about 0.4 ppmv (parts per million by volume) at 14 km to about 4.8 ppmv at 23 km. Inside the center of the vortex, the O_3 distribution was found to have a constant increase from about 0.8 ppmv at 14 km to about 4.2 ppmv at 23 km. Between January and March, the observed O_3 depletion was limited to $\leq$15% in the altitude region from 15-20 km with a maximum localized decrease of about 25% at 18 km.

Airborne DIAL data from the GTE/PEM-West B field experiment conducted during February-March 1994 will also be presented in this paper.

AIRBORNE LIDAR SYSTEM FOR WATER VAPOR AND AEROSOLS

Recent atmospheric investigations of H_2O and aerosol distributions were conducted with an airborne DIAL system that used a narrowband, tunable alexandrite laser as the on-line transmitter and an Nd:YAG-laser-pumped dye laser as the off-line transmitter.[8-9] Both of these lasers were operated in association with the H_2O absorption lines in the 727-nm region. The alexandrite laser used three intracavity tuning elements to produce an output linewidth of $\leq$1.1 pm. The tuning elements included a five-plate birefringent tuner, a 1-mm-thick solid etalon, and a 1-cm air-spaced etalon. A wavelength stability of ±0.35 pm was achieved by active feedback control of the two Fabry-Perot etalons using a frequency stabilized He-Ne laser as a wavelength reference. The three tuning elements were synchronously scanned over a 150-pm range with microprocessor-based scanning electronics.

The receiver system was similar to the system described above for the O_3 DIAL measurements. The detector optics consisted of a collimating lens, a beam-splitter, and an interference filter with a bandwidth of 0.38 nm and a transmission of 32%. After transmission through the filter, the return signals were directed onto the detector, which could be either a photomultiplier tube or an avalanche photodiode. The same data system described above for the O_3 DIAL system was used in the H_2O DIAL system.[9]

WATER VAPOR AND AEROSOL INVESTIGATIONS

The first extensive observations of H_2O and aerosols in the lower troposphere were made during the spring of 1990 and the summer of 1991. Water vapor measurements were made on flights at night over the ocean, during the day over land and ocean, and across a cold front. Daytime H_2O distributions obtained by the airborne DIAL system as the Electra crossed over the coast of Virginia clearly showed the decrease in the mixed layer depth from about 1.7 km over land to less than 1 km over the water. The mixed layers were moist with dry atmospheric conditions aloft. Regions with enhanced H_2O concentrations were correlated with higher aerosol backscattering in the lidar data. The airborne DIAL measurements showed for the first time the detailed H_2O and aerosol structure that occurs in the free troposphere and in the mixed layer over different land and marine regimes. In addition, the first high-spatial resolution distribution of H_2O was obtained across a cold front. These experiments have provided new insights into atmospheric processes involving H_2O, and they will serve as a basis for future H_2O investigations, including studies of cloud formation and the effect of H_2O on the Earth's climate system.

In addition to the regional H_2O studies that can be conducted with the above airborne DIAL system, there is a need for global measurements of tropospheric H_2O, aerosols, and clouds to address many questions important to climate change, meteorology, and hydrology. The DIAL technique has the potential for providing high-resolution H_2O measurements from space, and the technology is being developed to achieve this objective.[10] An autonomous H_2O DIAL system called the Lidar Atmospheric Sensing Experiment (LASE) is under development as a precursor to a spaceborne DIAL system. The LASE system is being developed for measurements of H_2O and aerosols from a high-altitude aircraft, and the laser transmitter in LASE is based upon a diode-injection-seeded Ti:Sapphire laser operating in the 820-nm region. The first engineering flight of LASE is planned for May 1994, and an extensive series of engineering flights will be conducted in summer of 1994. The Lidar In-space Technology Experiment (LITE) is also being developed at NASA LaRC for demonstration of multiple-wavelength lidar measurements of aerosols and clouds from the Shuttle.[11] The LITE system is scheduled to fly in September 1994, and it is expected that a system similar to LASE will be developed for the demonstration of a DIAL H_2O measurement capability from space using the LITE facility or a low-altitude satellite.

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