Remote sensing of atmospheric carbon dioxide and wind fields

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A novel laser instrument design has been developed for measuring vertical and horizontal profiles.

Carbon dioxide (CO$_2$) is the dominant anthropogenic greenhouse gas. Over the past century, the CO$_2$ concentration in the atmosphere has increased significantly. To predict future CO$_2$ levels, the global carbon cycle must be understood. Most monitoring to date has been conducted at the Earth’s surface, but vertical profile measurements in the troposphere have been limited to campaign-style aircraft and commercial airline observations, with limited spatial and temporal coverage. Recently, however, accurate tropospheric vertical CO$_2$ profiles have become a necessary component for inverse techniques in computer simulations that aim to improve quantification and understanding of the global CO$_2$ budget and global climate changes.$^1$

Knowledge of present carbon sources and sinks, including their spatial distribution and temporal variability, is essential for predicting future atmospheric concentration levels. Moreover, wind information is an important parameter for transport simulations and inverse estimations of surface CO$_2$ flux. Differential absorption lidars (light detection and ranging)—DIALs—are good for obtaining vertical CO$_2$ profiles. Using remote sensors for lower and middle troposphere measurements can reduce uncertainties involved in estimating the carbon sources and sinks. DIAL and Doppler lidar techniques have several advantages over passive approaches for high-precision and range-resolved CO$_2$ concentration and wind measurements.

We have developed a direct detection 1.6$\mu$m-wavelength DIAL technique to perform range-resolved measurements of vertical CO$_2$ concentration profiles in the atmosphere.$^{2,3}$ We are using this, together with an incoherent Doppler-lidar system, to perform simultaneous atmospheric CO$_2$ concentration and wind speed profile measurements. Figure 1 shows the schematic diagram of the combined CO$_2$ DIAL and incoherent Doppler lidar system.

Our 1.6$\mu$m DIAL system consists of an optical parametric generator (OPG) transmitter, which is excited by a laser-diode-pumped neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser with a high repetition rate, and the receiving optics. These are a near-IR photomultiplier tube (PMT) with high quantum efficiency that operates in photon-counting mode, and a 60cm aperture telescope that is larger than that used in the coherent detection method. Laser beams, at three wavelengths around the CO$_2$ absorption line (1.6$\mu$m), are transmitted alternately to the atmosphere for measurements of CO$_2$ concentration and temperature profiles. We have also developed an offset wavelength locking system for precise laser tuning, and use CO$_2$-DIAL processing algorithms to improve measurement accuracy.

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Figure 2. Photograph of the trailer that contains the mobile CO\textsubscript{2}-DIAL and incoherent Doppler lidar system.

Figure 3. An example vertical CO\textsubscript{2} mixing-ratio profile. The integration time for this measurement was 30 minutes and the range resolution (dz) was 300m. ppm: Parts per million.

We use high-power OPG in our DIAL system as the transmitter for the incoherent Doppler lidar that we installed in a mobile trailer (see Figure 2). The receiving optics of this scanning lidar includes a near-infrared PMT, a fiber-Bragg-grating (FBG) filter that detects Doppler shift, and a 25cm aperture telescope. The lidar’s laser beam is directed to the sky by steering a mirror coaxially with a motorized scanner that provides coverage over a 0–360\degree azimuth and 0–52\degree elevation range.

We have successfully made a 1.6\textmu m DIAL vertical CO\textsubscript{2} profile measurement up to an altitude of 7km. This measurement had a random error of less than 1.0\% over the integration time of 30 minutes, and a range resolution of 300–600m. An example CO\textsubscript{2} mixing ratio profile is shown in Figure 3. The absorption cross sections of gas and air density vary with atmospheric temperature and pressure so precise temperature and pressure profiles are necessary for accurate CO\textsubscript{2} mixing-ratio measurements by DIAL. Our measurement technique can be used as an alternative to the radio sonde data, typically obtained close to the lidar sites, that is normally used to acquire the temperature and pressure profiles in DIAL analyses. For our measurement, the CO\textsubscript{2} DIAL was operated in range-height indicator (RHI) mode.

The 2D measurement results indicate inhomogeneity in the boundary layer (see Figure 4). We also measured vertical CO\textsubscript{2} concentration profiles and wind profiles simultaneously. The elevation angle was fixed at 52\degree and CO\textsubscript{2} concentration profiles were obtained up to an altitude of 1km, with 200m height resolution. We obtained vertical wind vector profiles up to an altitude of 5km altitude, with 1km altitude resolution and from two different viewing directions.

Figure 4. An example vertical scanning measurement of the CO\textsubscript{2} mixing ratio in range-height indicator mode. The range resolution (dr) was 150m.

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Our direct detection 1.6\(\mu\)m CO\(_2\) DIAL system has been developed for measurements of day- and night-time vertical CO\(_2\) profiles. The system is now being updated for measurements of 3D CO\(_2\) distributions and wind fields. The system is installed in a 6m trailer and can be moved to sites of interest. We are planning mobile measurements of CO\(_2\) concentrations around several sink and source regions using the system.

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References