Multi-layer retrievals of atmospheric CO$_2$ mixing ratio using multi-wavelength pulsed lidar measurements from aircraft

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Going beyond column-averaged retrievals

- Column-averaged GHG measurements work well, but…
  - Boundary layer CO₂ (or CH₄) is most important
  - The need for BL CO₂ drives high-accuracy requirements on total column
  - Small biases can cause significant errors in carbon flux retrievals
- Measurements with even a few vertical layers can provide valuable CO₂ (or CH₄) profile information
Vertical CO$_2$ information from lidar

- Unique capabilities of lidar
  - Measurement of atmospheric backscatter
  - Accurate ranging
  - High spectral resolution

- Two techniques for solving for two vertical layers
  1. Measurements from ground and clouds: Cloud-slicing
  2. Analysis of absorption line shape: Multi-layer retrievals

Will show examples from airborne measurements using both techniques
Lidar Cloud Slicing
Pulsed lidar returns

- Time-resolved lidar profiles completely separate echoes from different surfaces
Two-level measurements via Cloud Slicing

- Make column absorption & range measurements to ground and to cloud tops
- Difference the measurements to get bottom layer CO₂
Clouds in the measurement

Near Iowa City, Iowa, Aug 10\textsuperscript{th} 2011

Cirrus Clouds

Cumulus Clouds
Backscatter Profile History

- Backscatter reveals cloud layers

Altitude

Time

360 380 400

Conc. (ppm)

From in-situ sensor in spiral down

Cirrus

Free troposphere

Cumulus

Boundary Layer

Ground
Using cloud slicing to cumulus cloud tops to measure boundary layer CO₂

- Differential measurement -> more scatter (10 ppm)
- Measurements in agreement with in situ data (<5 ppm)
• With 2 cloud layers, can get 3-level CO₂ information!
Features of lidar cloud-slicing retrievals

- Works for many types of thin or broken cloud
  - Need enough backscatter to fit the lineshape
- Uses photons that are otherwise discarded
- No \textit{a priori} information needed (initial - uniform fixed XCO$_2$)
- Shot-noise limited measurement.
  - Noise from cloud & ground reflections
  - Depends on transmittance of cloud layer
- Robust, low-bias measurement
  - Independent of upper air modeling
Multi-layer retrievals
Analyzing the line shape: 2-Level measurements via *multi-layer* retrievals

Exploits varying pressure broadening vs altitude to resolve concentration in two layers

- Use vertical slicing point (here 2 km) from backscatter profiles
- Solve for top & bottom CO₂ concentrations via a 2-parameter fit to absorption line shape
- Parameters are independent and unconstrained
Lidar’s high Spectral Resolution enables line shape analysis

- Layer linewidth
  - Top = 1200 MHz
  - Bot. = 2000 MHz
- Current instrument spectral resolutions:
  - GOSAT: ~ 6000 MHz
  - TCCON: ~ 600 MHz
  - Sounder: ~ 5 MHz
- CO₂ sounder has the requisite spectral resolution
Example of Multi-layer retrieval line fit

- Lidar profile matches in situ data
- Error contour is highly elliptical
  - Aspect ratio $\approx 20:1$
  - Due to similarity in top and bottom lineshapes.

100 s average

Flight at 12.5 km alt.

Bottom layer CI = $\pm 15$ ppm

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Boundary Layer CO$_2$ using multi-layer retrievals

- Lidar gives a measure of the BL CO$_2$
- Bias <5 ppm for top layer, <9 ppm for BL
- Measurement quality limited by 0.4 pm (5 MHz, 2x10$^{-4}$ cm$^{-1}$) wavelength calibration accuracy
- Wavelength accuracy will be improved to <1 MHz for 2014 ASCENDS campaign
Conclusions

- CO₂ Sounder approach measures both range and line shape
- Allow solving for vertically-resolved column concentrations
- Using airborne measurements, have demonstrated *two-level measurements* column using both:
  - Lidar cloud slicing
  - Multi-layer retrievals using abs. lineshape
- No *a priori* information or constraints used
- Both approaches require longer averaging times
- Optimization of techniques is ongoing
- Both techniques should work globally work from space as well