Airborne Lidar Measurements of Atmospheric Column CO2 Concentrations to Cloud Tops in the Arctic

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Introduction

Globally distributed atmospheric CO_2 concentration measurements with high-precision, low-biases, and full seasonal sampling are crucial to advance carbon cycle sciences. However, two thirds of the Earth's surface is typically covered by clouds, and passive remote sensing approaches from space are limited to cloud-free scenes. NASA Goddard had developed a pulsed, integrated-path differential absorption (IPDA) lidar approach to measure atmospheric column CO_2 concentrations, XCO_2, from space as a candidate for NASA's ASCENDS mission. Measurements of time-resolved laser backscatter profiles from the atmosphere also allow this technique to estimate CO_2 and range to cloud tops in addition to those to the ground with precise knowledge of the photon path-length.

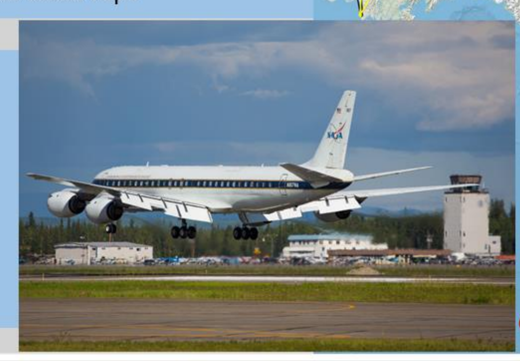
We demonstrate this measurement capability using airborne lidar measurements from the summer 2017 ASCENDS/ABoVE airborne science campaign in Alaska. It is the first time our airborne lidar measurements were made in the Arctic. We show retrievals of XCO_2 to ground and to cloud tops to fill measurement gaps and help resolving vertical and horizontal gradient of CO_2 in cloudy conditions. The XCO_2 retrievals from the lidar are validated against in situ measurements during spiral-down maneuvers.

This all-sky measurement capability for the future space carbon missions will be particularly valuable for the regions with persistent cloud cover, e.g., tropical ITCZ, west coasts of continents with marine layer clouds, and the southern ocean with highest occurrence of low-level clouds. Lidar measurements to cloud tops help fill these significant gaps, provide a more complete picture of the CO_2 distribution. They also will benefit atmospheric transport modeling as well as global and regional carbon budget estimates.

Overview of the Airborne Campaign
July 20 – Aug. 8, 2017

- Pulsed IPDA lidar measurements of XCO_2 over long flight lines
- Lidar measured XCO_2 in Arctic, for first time
  - Had a diverse set of atmospheric & surface conditions
- Analysis of XCO_2 measurements to ground showed:
  - Gradients in XCO_2 & enhancements from wildfires
- Lidar also measured height-resolved backscatter profiles
- Allowed partial-column XCO_2 retrievals to cloud tops

Campaign flown on NASA DC-8, carrying:
- Goddard CO_2 Sounder Lidar
- Goddard Picarro, *in situ*
- LaRC AVOCET & DLH, *in situ*

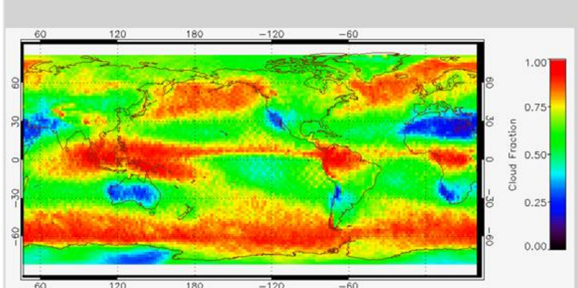


- 8 flights
- 55 hours lidar measurements
- 47 spirals for validation with in-situ

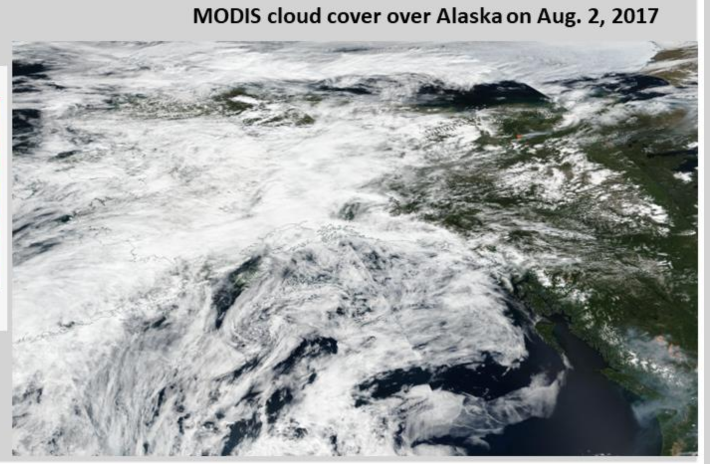
XCO2 Measurements to Cloud Tops

- *Typically, 2/3 of the Earth's surface is covered by clouds.*
- *Cloud cover causes major measurement gaps in space-based passive missions.*
- *Pulsed CO2 lidar help fill these gaps with measurements to cloud tops!*

Annual mean total cloud fraction from CloudSat and CALIPSO

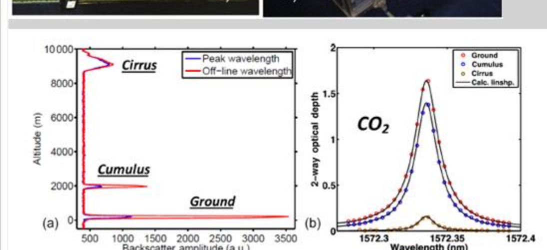


MODIS cloud cover over Alaska on Aug. 2, 2017



Airborne CO_2 Sounder Lidar

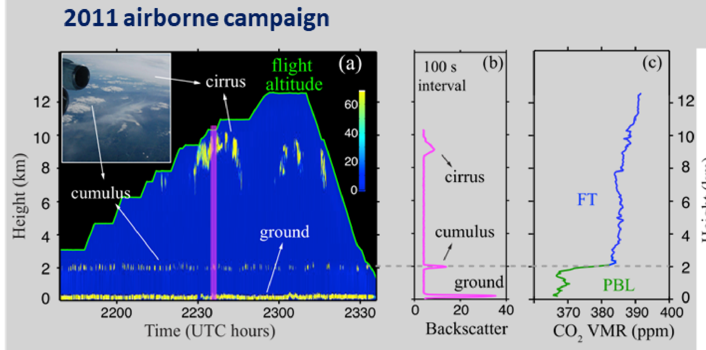
- Measures column CO_2 absorption using 1572.335 nm line.
- Pulsed Direct Detection IPDA lidar - laser pulses at 10 kHz rate
- Laser pulses stepped in 30 wavelengths across line ~ 300 scans/sec
  - All wavelengths offset locked relative to CO_2 line center
  - Laser pulse spectra narrow (0.2 pm) => CO_2 line fully resolved
- Time resolved receiver, photon sensitive detector
- Measures backscatter profile, range & samples of CO_2 absorption
- XCO_2 retrievals every 1-sec:
  - Line shape samples, aircraft alt., range to scattering surface
  - Atmospheric state (DC-8 measurements, GEOS-5,or radiosondes)
  - Spectroscopy: HITRAN with line-mixing



Abshire et al., 2013, 2014, 2018; Mao et al., 2018, 2021; Kawa et al., 2018; Ramanathan et al., 2013, 2015, 2018; Allan et al., 2018; Sun et al., 2021, 2022

Previous work: XCO_2 retrievals to cloud tops and cloud slicing

Ramanathan et al., 2015
2011 airborne campaign



- Demonstrated resolving CO2 vertical gradients and measuring CO2 mixing ratio in the planetary boundary layer
- Lidar data were averaged over 10-sec or 100-sec and XCO2 retrievals had large standard deviation

Mao et al., 2018
2014 airborne campaign

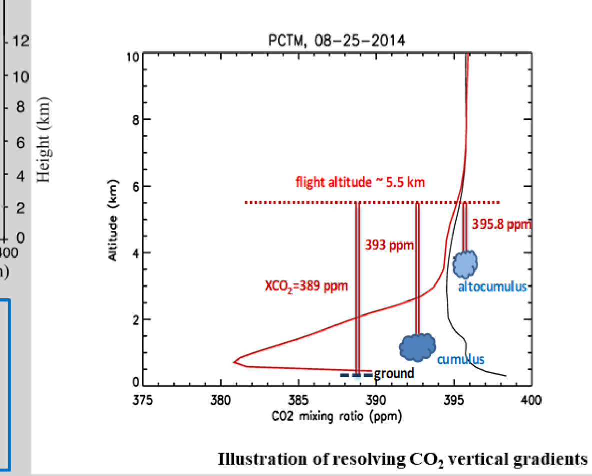
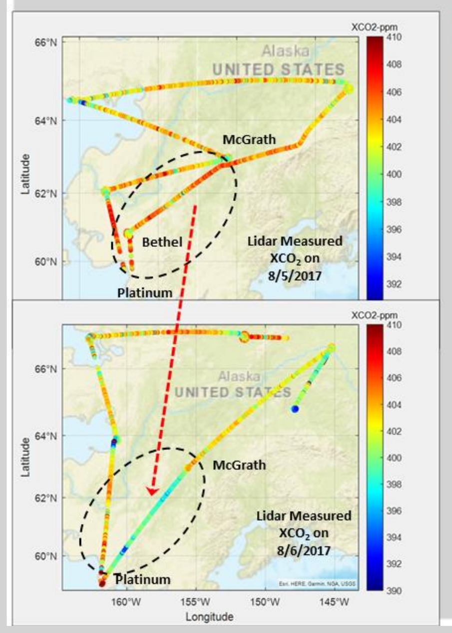
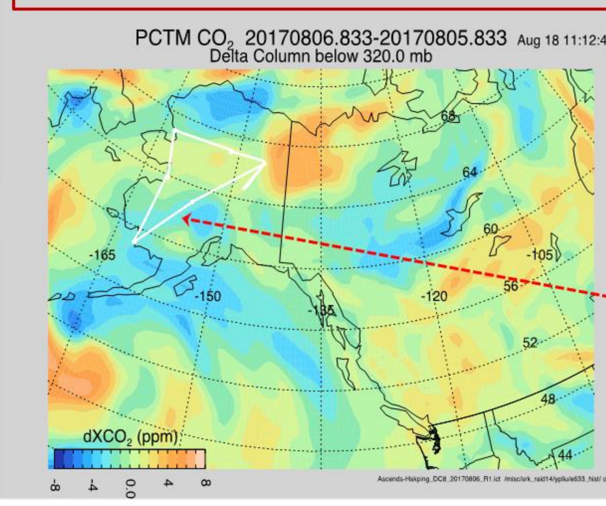


Illustration of resolving CO_2 vertical gradients

Example: XCO_2 measurements to ground
- quantifying horizontal gradients and synoptic scale variations



- Lidar measurements show ~6 ppm drop in XCO_2 to ground over Southern Alaska with 24 hours
- Consistent with PCTM model simulations

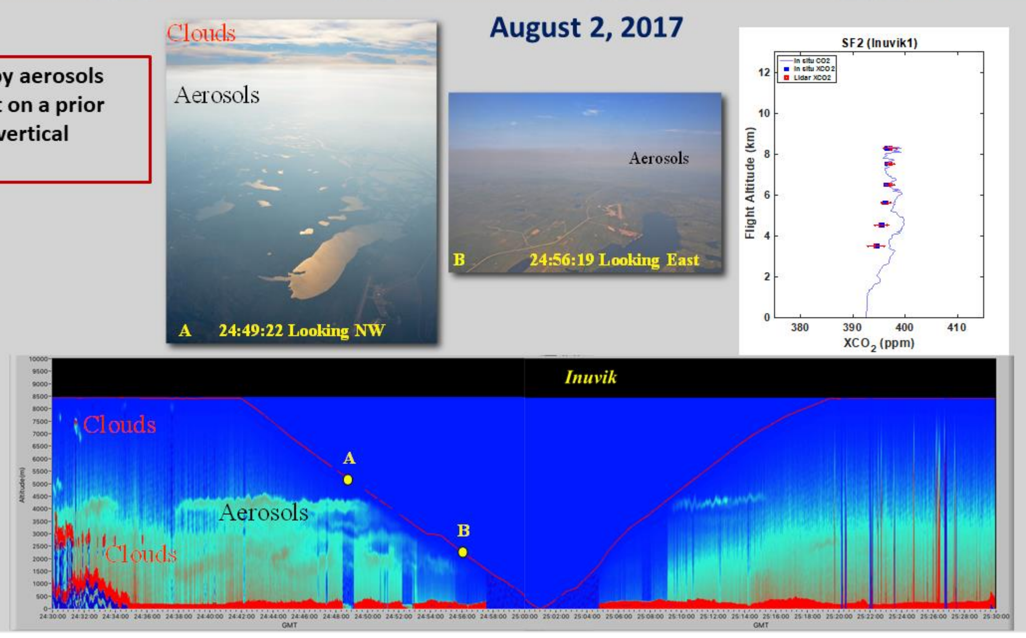


PCTM simulations show significant XCO_2 drop from 8/5 to 8/6

Example: XCO_2 measurements to ground under hazy conditions

- Unaffected by aerosols
- Independent on a prior
- Sensitive to vertical gradients

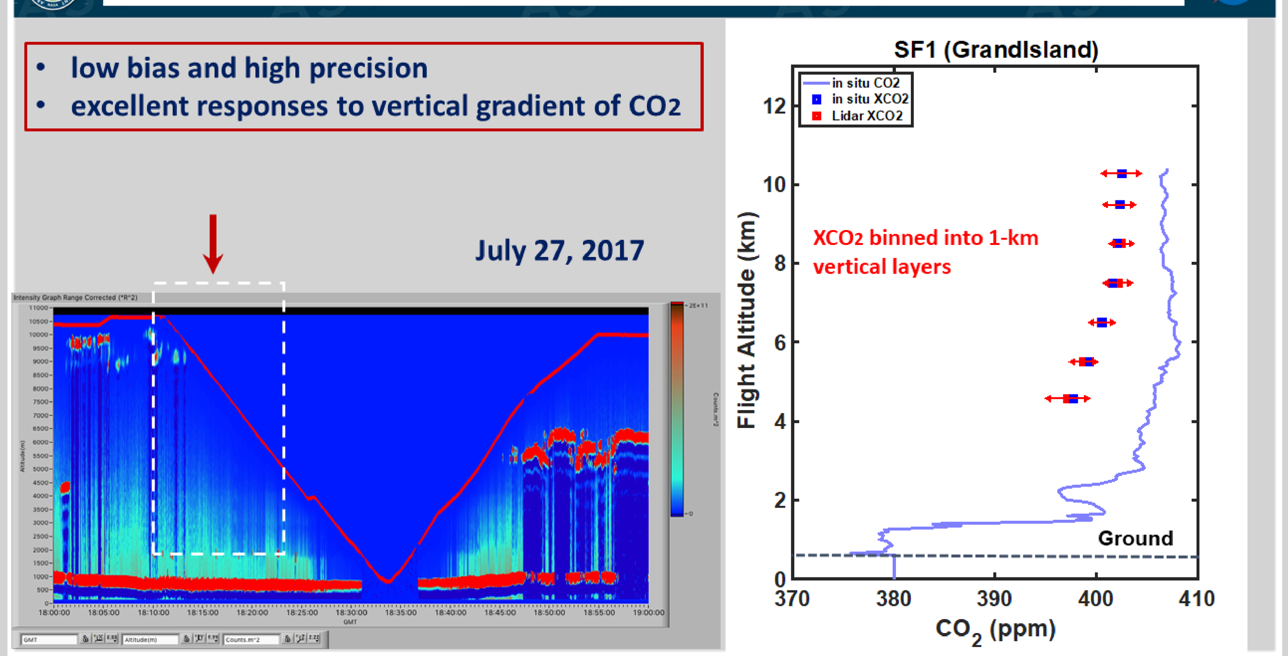
August 2, 2017



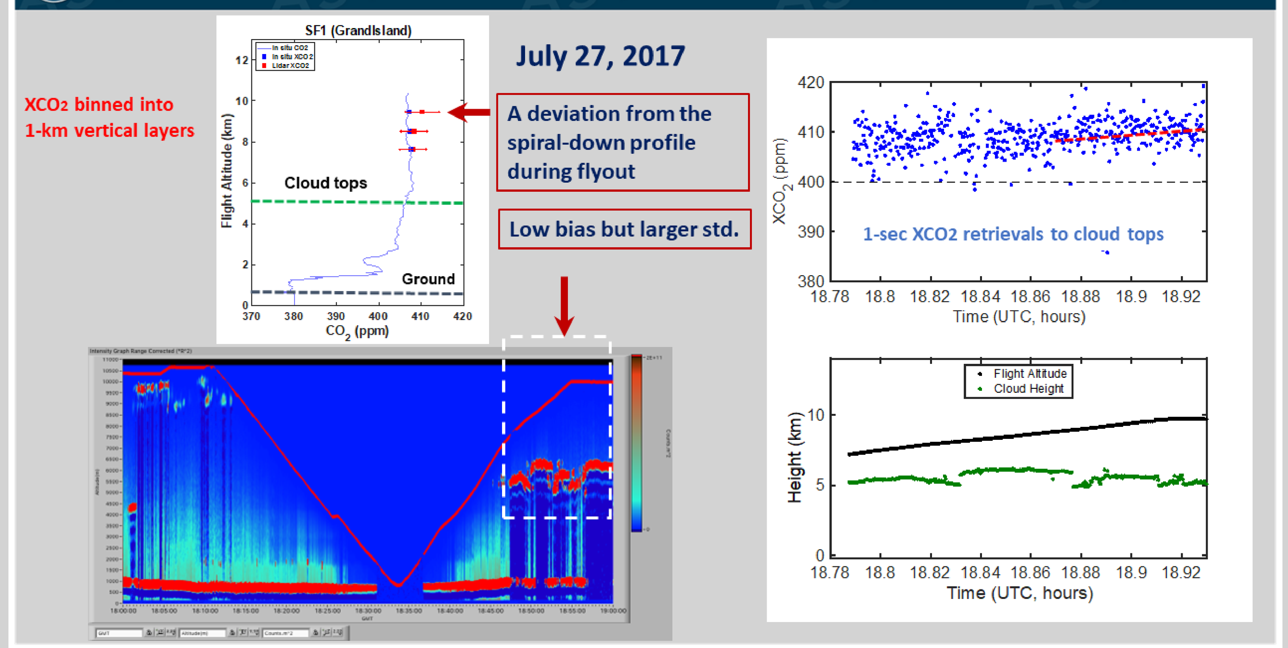
Example: XCO_2 retrievals to ground at Grand Island, NE

- low bias and high precision
- excellent responses to vertical gradient of CO2

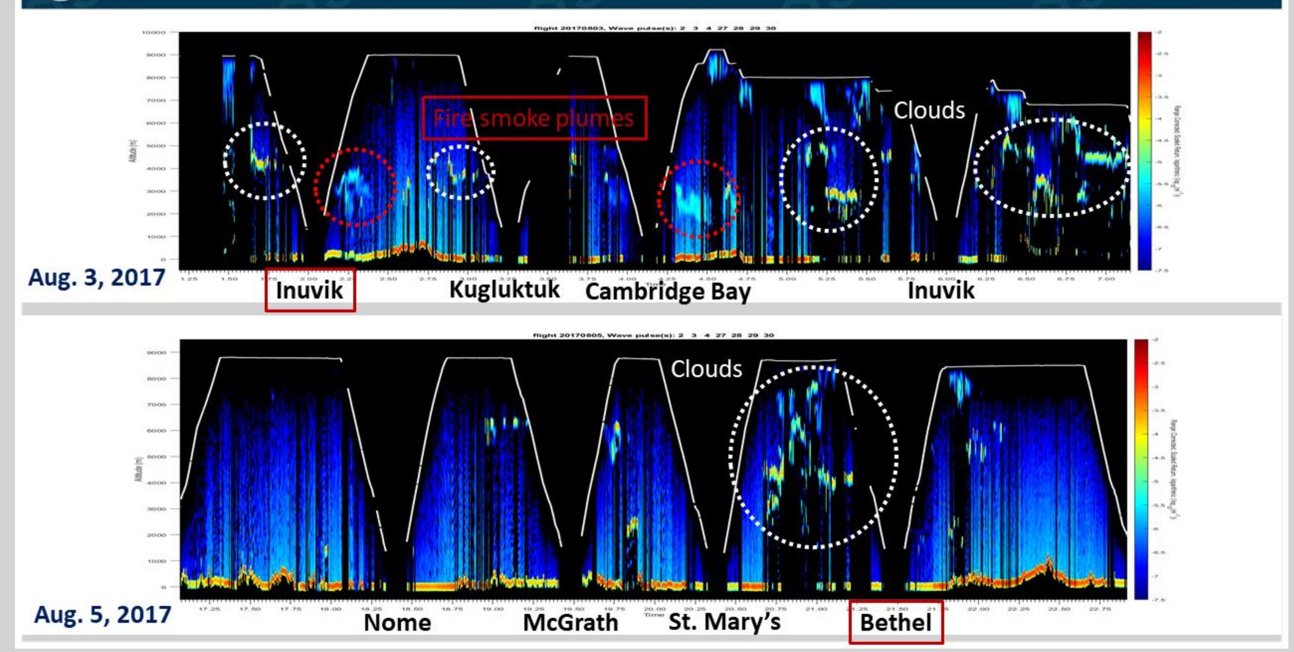
July 27, 2017



Example: XCO_2 retrievals to cloud tops at Grand Island, NE



Example: measurements to cloud tops in the Arctic

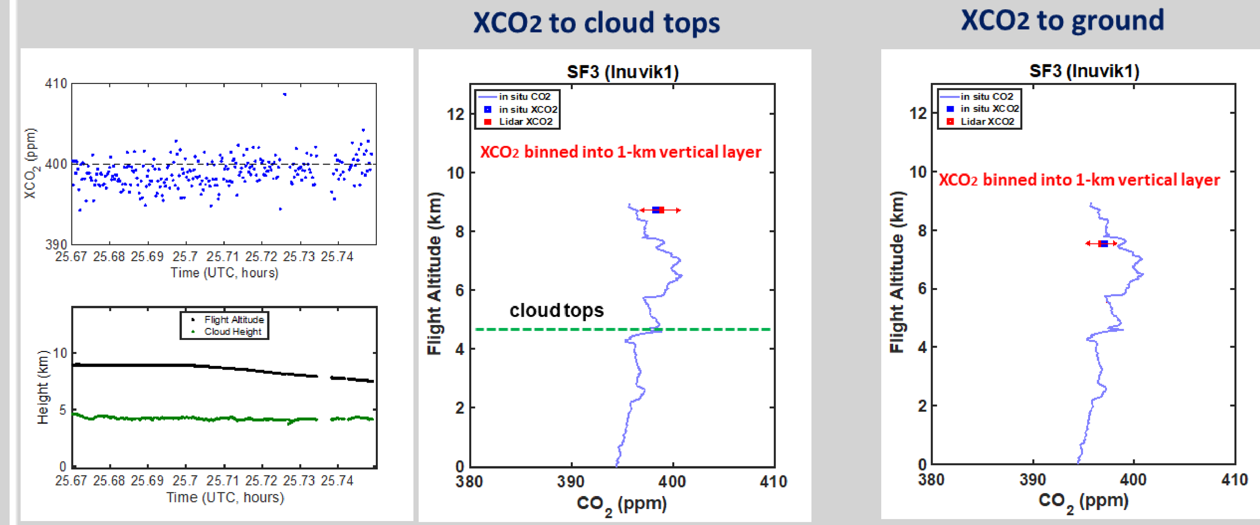


Example: XCO_2 retrievals to ground and cloud tops at Inuvik, AK

- Low bias and high precision
- Allowed cloud slicing for the vertical gradient of CO2

August 3, 2017

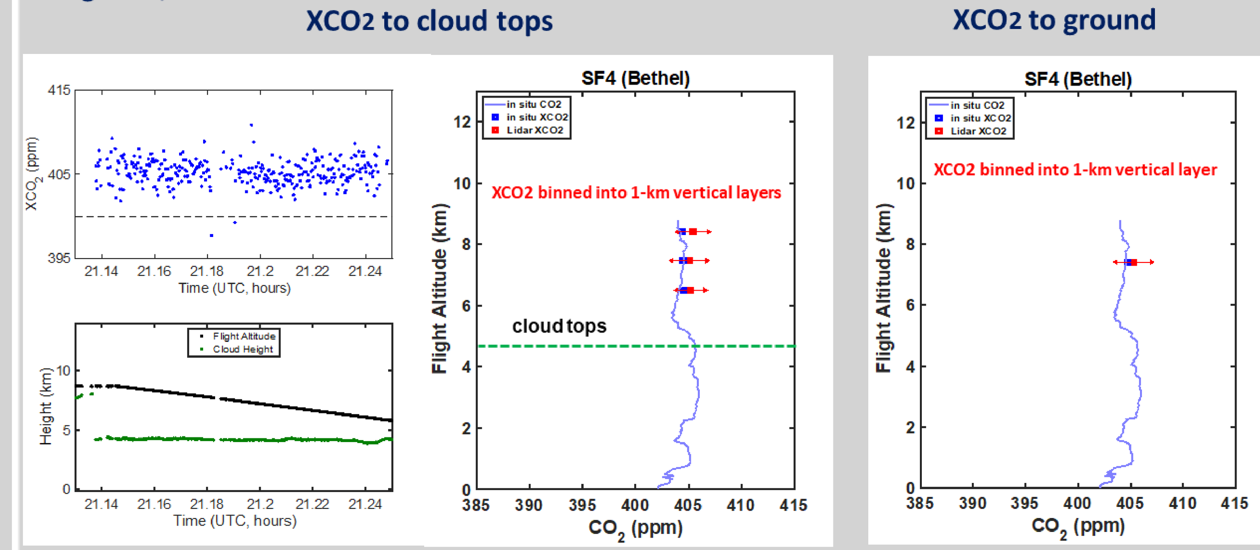
XCO2 to cloud tops — XCO2 to ground



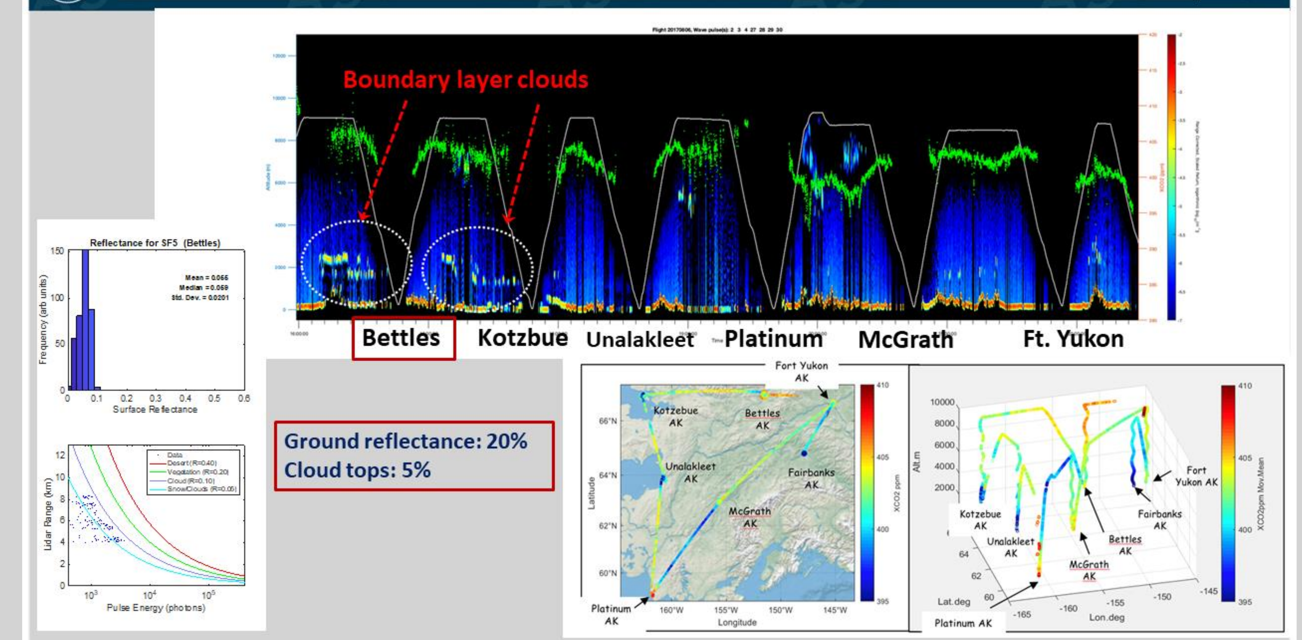
Example: XCO_2 retrievals to ground and cloud tops at Bethel, AK

August 5, 2017

XCO2 to cloud tops — XCO2 to ground



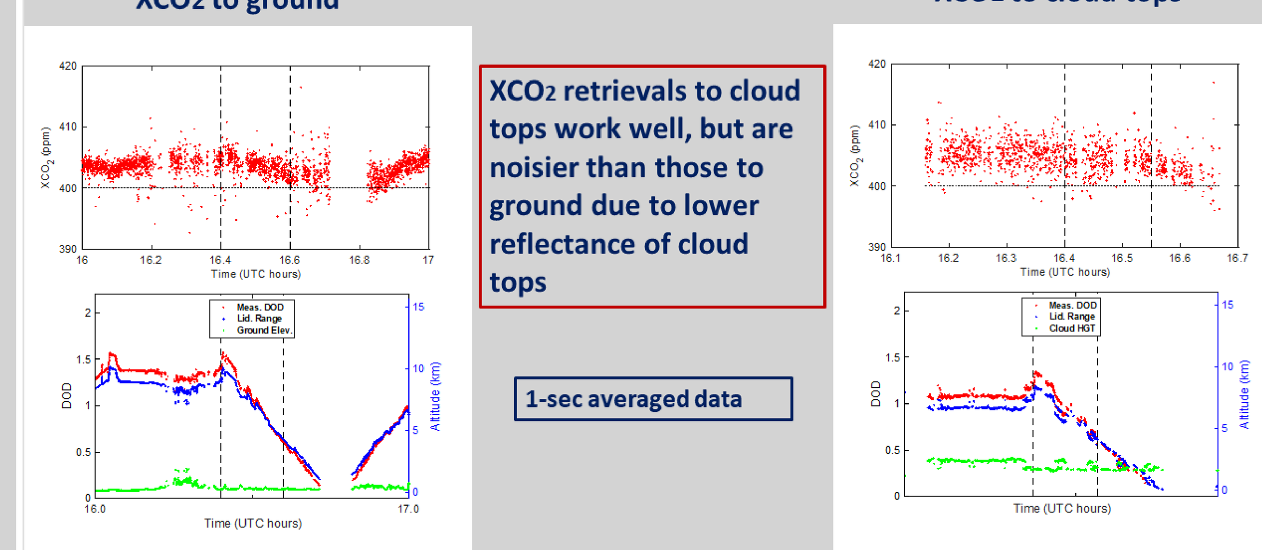
Flight over northern & western Alaska on Aug. 6, 2017



Example: XCO_2 retrievals to ground and cloud tops at Bettles, AK

August 6, 2017

XCO2 to ground — XCO2 to cloud tops



Summary

- 2017 ASCENDS/ABoVE airborne campaign: 8 flights and 47 spiral down maneuvers

  CO_2 Sounder lidar measured XCO_2 to ground: clearly showed gradients, precision: ~ 1-ppm for 1-sec average
- Lidar also measured vertically-resolved aerosol backscatter profiles every 1-sec

  Allowed measurements of cloud top heights & XCO_2 to them every 1-sec.
- Retrievals of XCO_2 to cloud tops worked well:
  - Reflectivity of cloud tops was ~ 5% -> typ. Std. dev. (1-sec) were ~1.5 ppm, much smaller than those from previous campaigns, attributed to technology advances, e.g., step-locked laser and high-sensitive detector
  - Assessing bias near spiral-down locations where have *in-situ* CO_2 profiles
- Lidar measurements of XCO_2 to cloud tops are valuable, esp. from space
  - Allow partial (upper) column XCO_2 in dark & cloudy regions (many in the Arctic)
  - Allow using cloud slicing to estimate vertical segments of XCO_2 in the free troposphere & in the planetary boundary layer

ABoVE 9th SCIENCE TEAM MEETING
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Data Access:

- Abshire, J.B., J. Mao, H. Riris, S.R. Kawa, and X. Sun. 2022. ABoVE/ASCENDS: Active Sensing of CO2, CH4, and Water Vapor, Alaska and Canada, 2017. ORNL DAAC, https://doi.org/10.3334/ORNLDAAC/2050
- Sun, X., P.T. Kolbeck, J.B. Abshire, S.R. Kawa, and J. Mao. 2022. ABoVE/ASCENDS: Atmospheric Backscattering Coefficient Profiles from CO2 Sounder, 2017. ORNL DAAC, https://doi.org/10.3334/ORNLDAAC/2051

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- NASA ABoVE & Terrestrial Ecology programs

Questions ?

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