City-Scale Methane Retrievals from the High-Altitude Lidar Observatory During the 2023 STAQS Campaign

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Abstract: The NASA Langley Research Center's High-Altitude Lidar Observatory (HALO) participated in the 2023 STAQS mission to study air quality and greenhouse gas concentrations across major metropolitan regions in the United States, such as Los Angeles, New York City, and Chicago. The spatiotemporal evolution of column and multi-layer methane, aerosol backscatter, extinction, depolarization, and mixed layer heights was observed by HALO during AM/PM single day flights and multi-day sampling of the same regions. Here, we show these measurements and assess HALO's capabilities for combined greenhouse gas and air quality measurements, novel profiling techniques for methane layer attribution, and the capability for a high-altitude lidar to provide emission estimates.

1. Introduction

Atmospheric methane is a prominent greenhouse gas (GHG) that plays an important role in climate change due to rising emissions and their subsequent impact on radiative forcing. This importance was codified by the recent U.S. Greenhouse Gas Center [1] initiative, which is a multi-agency effort to consolidate GHG information from observations and models. The center is targeting several areas of study such as diffuse (city scale) and large point source (e.g., oil and gas, waste management, and agriculture sectors) anthropogenic emissions and natural sources across scales (boreal to tropical wetlands). NASA is a stakeholder in providing accurate GHG observations to predict future sensitivity of climate to changes in emissions and provide data to inform policy changes in relevant sectors to minimize impacts on human health and livelihood.

During the summer of 2023, NASA deployed several aircraft and active/passive instrument combinations as a part of the Synergistic TEMPO Air Quality Science (STAQS) mission [2]. STAQS aimed to validate the TEMPO satellite by measuring repeated high-resolution maps of NO_2, HCHO, O_3, and aerosols across Los Angeles, New York City (NYC), Chicago, Toronto, and Baltimore/Washington DC. To complement the air quality measurements, a GHG-focused payload was also deployed to measure city-scale emissions twice a day over targeted cities. The combined active/passive remote sensing payload includes the NASA Langley Research Center's (LaRC) High-Altitude Lidar Observatory (HALO) lidar and the NASA JPL AVIRIS-NG imaging spectrometer. These instruments provided high resolution data to connect lessons learned from localized co-emissions of pollutants measured by TEMPO and GHGs for cross-benefit climate/air quality analysis. Here, we show an overview of the HALO instrument capabilities for city-scale sampling during the STAQS campaign across the different measurement domains.

2. Methods

NASA LaRC's HALO methane (CH_4) and aerosol lidar [3] was deployed on the NASA Gulfstream-III (G-III) aircraft as a part of the STAQS campaign with observing altitudes of 12 km (cloud dependent). For the STAQS campaign, HALO employed range-resolved Differential Absorption Lidar (DIAL) and Integrated Path DIAL (IPDA) techniques at 1645 nm for multi-layer and column and measurements of XCH_4 respectively, and the high spectral resolution lidar (HSRL) technique at 532 nm for retrievals of aerosol extinction, backscatter, and mixed layer heights (MLH). The HSRL channels compliment HALO's CH_4 capabilities by providing contextual information on the layered structure of the atmosphere and add critical capabilities to investigate aerosol and cloud induced biases that impact passive space-borne retrievals of column CH_4.

Figure 1 shows the measurement scenario from the G-III aircraft for the combined CH_4 and HSRL measurements. The online and offline wavelengths are overlaid on the CH_4 spectrum shown in Figure 2a, with the resulting weighting function from the IPDA retrieval shown in Figure 2b. From Figure 2b, it can be seen that the IPDA wavelengths have been chosen to have high sensitivity to the lower troposphere.

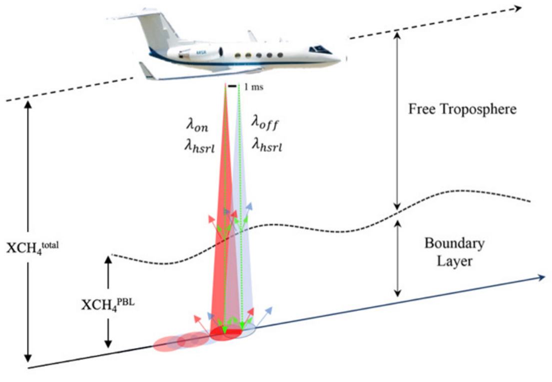

Figure 1. HALO's configuration during the STAQS campaign on the NASA G-III for column and multi-layer XCH_4 and HSRL aerosol measurements.

Building on the first airborne demonstration of clear air range-resolved CH_4 absorption [3], HALO was modified for the STAQS campaign to demonstrate similar CH_4 profiling capabilities albeit with a much more capable HgCdTe detector [4]. The direct DIAL measurement of range-resolved CH_4 provides a unique complement to the standard IPDA column and partial column measurements.

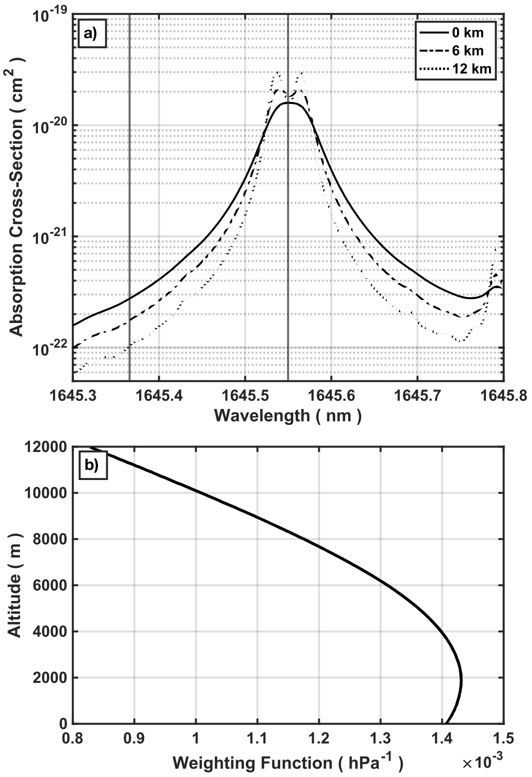

Figure 2. a) HALO CH_4 absorption cross-sections for surface level, 6 km and 12 km. b) the pressure weighting function for the online and offline wavelengths, showing lower tropospheric sensitivity.

Additionally, a Picarro package was installed on the G-III to provide in-situ measurements of CH_4, CO_2, and CO at flight altitude, during dedicated in-situ spirals, and during takeoff and landing. Across the campaign, there were several opportunities to perform spiral maneuvers from flight altitude to the surface in order to evaluate the lidar data collected during the subsequent overpasses. Figure 3 shows an example of an in-situ CH_4 spiral profile from June 26th 2023 over the Edwards Air Force Base from ~12 km to 600 m MSL. At the bottom of the spiral a missed approach was performed to enable a contiguous CH_4 profile from flight altitude to 20 m above the surface. Overlaid is the HALO XCH_4 overpass mean and standard deviation and the in-situ XCH_4 generated from the HALO integration path and spectroscopy.

High accuracy from the HALO measurements can be seen at a 2 km spatial average.

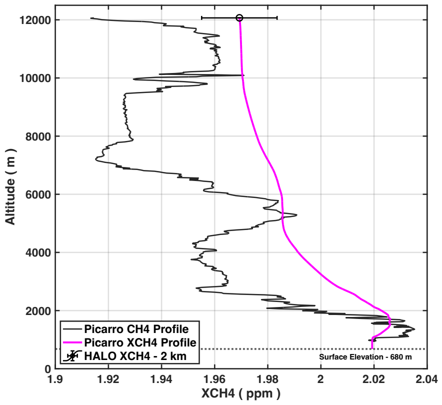

Figure 3. July 26th 2023 Comparison between HALO XCH$_4$ and in-situ derived XCH$_4$ from a spiral descent over Edwards Air Force Base. The black in-situ CH$_4$ profile serves as the input to the magenta in-situ derived XCH$_4$ using the HALO integration path and spectroscopy.

3. Measurements

The measurements acquired during the STAQS campaign provide a robust dataset to evaluate the differences in CH$_4$ concentrations between major metropolitan cities, the diurnal variations of CH$_4$ within the cities, and the temporal evolution across multiple flight days. Additionally, coupling between CH$_4$ and the depth of the mixed layer can be investigated to understand the potential connection between boundary layer mixing and CH$_4$ concentrations.

The early segment of STAQS flights consisted of AM/PM sorties over the Los Angeles basin. Figure 4 shows an example of the types of data collected throughout the STAQS campaign by the HALO instrument. The June 27th, 2023 Los Angeles PM raster is shown where HALO collected HSRL derived MLH’s and IPDA derived XCH$_4$ (2 km along track averaging). The XCH$_4$ was cloud cleared and additional data preliminary screening was applied for quality assurance. Contrasting the clear delineation between deeper inland and shallower marine boundary layers, a north/south XCH$_4$ gradient can be seen across the basin with values ranging from 2-2.05 ppm in the northern collection region to ~1.9 ppm in the central/southern regions.

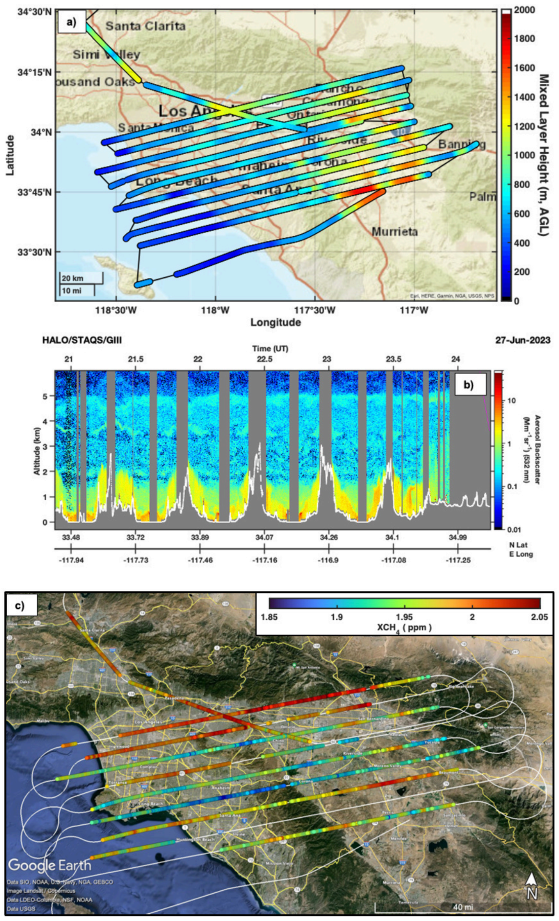

Figure 4. June 27th, 2023 Los Angeles PM Raster. a) HALO MLH derived from the 532 nm HSRL Aerosol Backscatter in panel b. c) HALO XCH$_4$ averaged to 2 km along track. Spatial variations across the Los Angeles basin can be seen in MLH and XCH$_4$.

Figure 5 shows an example of the July 26th, 2023 NYC AM/PM raster flight patterns to provide an evolutionary view of the city-scale aerosol derived MLH and IPDA derived XCH$_4$. The city-scale change in boundary layer height and XCH$_4$ can be seen readily between AM (Fig. 5a-b) and PM (Fig. 5c-d) flights, with a significant evolution of the mixed layer depth and increased CH$_4$ concentrations. Typical MLH and XCH$_4$ products are reported at 100 m along track (a 20 s smooth is applied post retrieval, 10 s is nominal) and 1.5-2 km along track, respectively, providing access to understanding the evolution at the small and city scales. Notably across NYC, the mixed layer depth and CH$_4$ concentrations do not change consistently and significant variations along a single line and sections of the city can be seen. Figure 5e-f show histograms of the cumulative retrievals for each raster pattern.

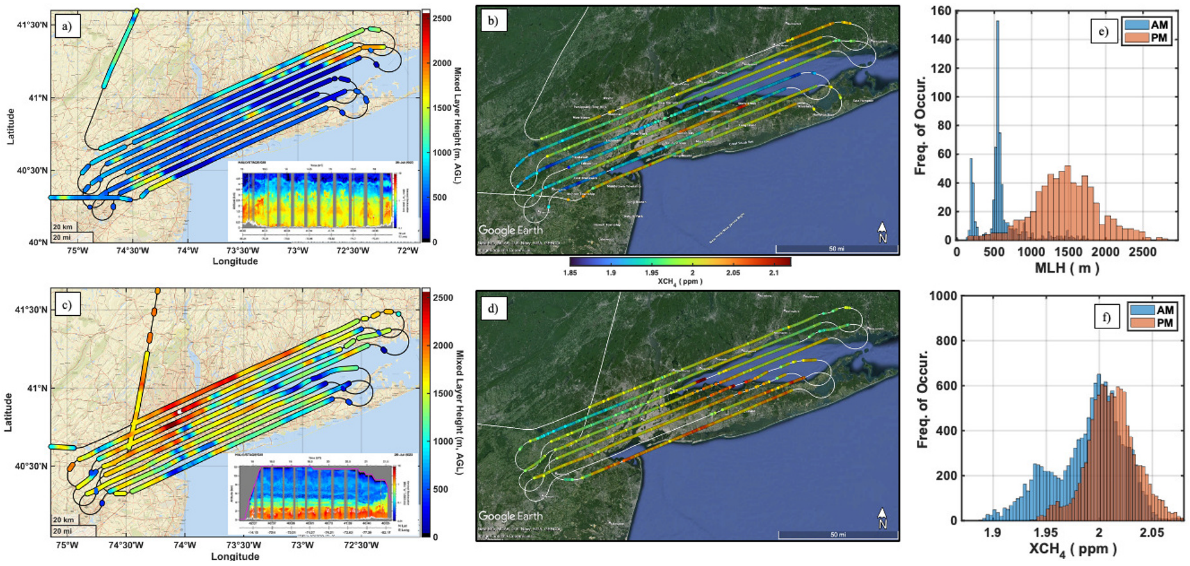

Figure 5. HALO Mixed Layer Height and XCH_4 retrievals over New York City on July 26th, 2023. The top row (a-b) shows the AM retrievals. The middle row (c-d) shows the PM retrievals. The bottom row (e-f) shows the histograms of AM/PM MLH and XCH_4 from the raster flight patterns. The panel insets of (a,c) show the HSRL derived 532 nm aerosol backscatter coefficient used in the MLH algorithm.

The AM MLH and XCH_4 both show a bimodal nature, likely indicative of the distribution of retrievals made over land vs. water, bolstered by one mode of the distribution being made of shallow MLHs of <500 m. The PM data shows follows a normal distribution for both MLH and XCH_4, with the AM vs. PM XCH_4 showing a net difference of ~30 ppb at the peaks of each distribution.

4. Summary

Airborne measurements of CH_4 and aerosol optical properties during the STAQS campaign provide a unique venue for investigating the city-scale emissions in large metropolitan cities across the United States. The initial data shows that significant variations in XCH_4 can be seen between AM and PM observations with analogous changes in mixed layer depth being observed as well. Further studies are underway to aggregate statistics and tease out connections within and across cities (West Coast vs. East Coast, for example) and analyze the capabilities afforded by the clear air profiling DIAL channels within HALO.

5. References

[1] United States Greenhouse Gas Center, ‘https://earth.gov/ghgcenter’, last accessed: March 26th, 2024.

[2] STAQS – Synergistic TEMPO Air Quality Science Campaign – ‘https://www-air.larc.nasa.gov/missions/staqs/’, last accessed: March 26th, 2024

[3] Barton-Grimley, Rory A., et al. "Evaluation of the High Altitude Lidar Observatory (HALO) methane retrievals during the summer 2019 ACT-America campaign." *Atmospheric Measurement Techniques* 15.15 (2022): 4623-4650.

[4] Sun, Xiaoli, et al. "HgCdTe avalanche photodiode detectors for airborne and spaceborne lidar at infrared wavelengths." *Optics express* 25.14 (2017): 16589-16602.