Understanding greenhouse gases: Insights from the CoMet airborne missions using lidar complemented by passive-remote-sensing, and in-situ instruments

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Abstract: In 2018, the CoMet series of airborne missions was launched under the auspices of the German Aerospace Center (DLR). From this point onward, large-scale field campaigns are organized regularly every few years, in collaboration with partner institutions, to understand the anthropogenic and natural fluxes of the greenhouse gases CO_2 and CH_4, using the German research aircraft HALO. In addition to scientific objectives, the CoMet field campaigns aim to promote technological developments necessary for new and future Earth observation satellites, validate current greenhouse gas satellite measurements, and prepare new satellite missions, in particular the upcoming German-French methane lidar mission MERLIN. One of the core instruments of CoMet is the IPDA lidar CHARM-F, which was developed at DLR as an airborne demonstrator, testbed, and validation tool for MERLIN.

1. Introduction

Climate warming remains a critical 21st-century challenge, driven primarily by the increase in greenhouse gases (GHGs) in the Earth's atmosphere, notably carbon dioxide (CO_2) and methane (CH_4). These GHGs, both influenced by human activities, play a crucial role in the Earth's climate system. Together, CO_2 and CH_4, globally contribute to about 82% of the anthropogenic radiative forcing [1,2].

However, it is not only human activities but also large natural sources such as the extended wetlands in the tropics and arctic/boreal regions that matter [3]. Wetland vegetation takes up and stores carbon and its decomposition releases CO_2 and CH_4. These processes that are expected to accelerate in a warming climate make the global wetlands one of the most important albeit least understood sources and sinks in the global GHG budget. Despite efforts to understand both anthropogenic and natural fluxes, there are still significant knowledge gaps that hinder our ability to predict and effectively mitigate global warming as envisioned in the Paris Agreement.

To address these gaps, accurate measurements of greenhouse gas concentrations in the atmosphere, from which fluxes can be inferred, are essential. Satellite remote sensing instruments are key to closing the gaps. However, current satellite instruments (e.g., GOSAT-1/-2 or TROPOMI) face challenges in providing accurate measurements of GHGs, particularly in the tropics and Arctic since they are characterized by extensive cloud cover that hinders the continuous measurement of greenhouse gases through passive remote sensing. In the Arctic, low sun angles and low surface albedo further reduce the signal-to-noise ratio. Lidars such as the upcoming German-French methane lidar mission MERLIN [4] show much promise, since they are independent of sunlight and can measure in cloud gaps.

Bridging local ground-based observations with global satellite data is critical. Instrumented research aircraft are capable to fill this gap. For this purpose, the CoMet series of airborne missions has been established under the auspices of German Aerospace Center (DLR).

The CoMet missions, starting with CoMet 1.0 in 2018, have successfully tested remote sensing and in-situ payloads, and their synergies, provided data for regional modeling of CO_2 and CH_4, identified deficiencies in transport models, and supported satellite validation. CoMet 2.0 Arctic, conducted in 2022, focused on northern boreal and Arctic regions. CoMet 3.0 Tropics is scheduled for 2026 and will take place in the South American Tropics. The CoMet missions are also part of validation activities for existing passive remote sounding GHG satellites (e.g. OCO-2, GOSAT, or Sentinel 5-P) as well as the preparation of future ones (e.g. CO2M). Specifically, they serve to prepare the validation activities for the first active CH_4 satellite mission, MERLIN [4], that is currently built under the aegis of the German and French space agencies (DLR and CNES) and is scheduled for launch in the 2028 timeframe. The next but one edition of CoMet, CoMet 4.0 VALISE, will serve as one of the core validation activities for MERLIN.

2. Airborne instrumentation

As the flagship of the CoMet missions serves the German research aircraft HALO (D-ADLR, Figure 1). Originally, a jet aircraft of the Gulfstream G550 type, it has been modified with significant provisions to make it suitable for scientific use [5]. HALO has a maximum range of about 10,000 km or > 10-h endurance, a ceiling altitude of 14.5 km and is able to carry a scientific payload of up to 3,000 kg. For CoMet, a suite of sophisticated remote sensing and in-situ instruments is deployed onboard to measure greenhouse gases, and ancillary data. Slight adaptations were applied to the scientific payload of HALO between CoMet 1.0 and CoMet 2.0. (Table 1). For example, the imaging spectrometer MAMAP2DL complemented the remote sensing payload.

Figure 1. The German research aircraft HALO (https://halo-research.de/).

3. The CHARM-F lidar

One of the core instruments of the CoMet payload is the integrated path differential absorption lidar CHARM-F. To our knowledge, it is currently the only airborne IPDA lidar capable to measure the column-integrated dry-air mixing ratio of both greenhouse gases, CH_4 (at 1645 nm) and CO_2 (at 1572 nm) at the same time [6,7].

Table 1. HALO Instrumentation during CoMet 1.0 and Comet 2.0 Arctic

Instrument	Owner	Description	I or RS[a]
CHARM-F	DLR	IPDA lidar; CO_2 and CH_4 columns	RS
MAMAP2DL[b]	U Bremen	Imaging SWIR spectrometer; CO_2 and CH_4 anomalies	RS
miniDOAS [c]	U Heidelberg	Differential optical absorption spectrometer (DOAS)	RS
specMACS [b]	LMU Munich	Hyperspectral imager; Land surface properties, clouds, aerosol	RS
HALO-JIG	MPI-BGC	Cavity Ringdown Spectrometer (CRDS); CO_2, CH_4, H_2O, CO	I
HALO-JAS	MPI-BGC	Flask sampler; ^{2}H, ^{13}C, and ^{18}O isotopes (in CO_2 and CH_4)	I
MIRACLE [b]	DLR	Cavity Ringdown Spectrometer (CRDS) with intermediate sampling; CH_4, CO_2, C_2H_6, $^{13}C(CH_4)$	I
BAHAMAS	DLR	HALO basic data acquisition system; pressure, temperature, humidity, aircraft attitude data	I
Dropsondes	DLR	Meteorological sondes; pressure, temperature, humidity, wind profiles	I
FOKAL	Menlo/DLR	Miniaturized frequency comb; Frequency reference for CHARM-F	

[a] I: in-situ; RS: remote sensing [b] during CoMet 2.0 Arctic, only [c] during CoMet 1.0, only.

4. Past missions: CoMet 1.0 and CoMet 2.0 Arctic

During CoMet 1.0, in spring of 2018, HALO was based in Oberpfaffenhofen, Germany and successfully completed 9 scientific flights (Table 2, Figure 2). The measurement flights were designed to capture individual CH_4 and CO_2 plumes from e.g. coal mine venting and coal-fired power plants in Europe, respectively, but also to measure large and regional scale GHG gradients between Scandinavia and North Africa and to provide comparisons with ground-based remote sensing instruments such as the FTIR interferometer. Apart from HALO, several other aircraft, and ground-based measurements, including wind lidars - to support information about the boundary layer wind - were deployed in the Upper Silesian Coal Basin, Poland. Extensive modeling activities supported the observations. Significant results were published in a special issue of AMT/ACP/GMT [8].

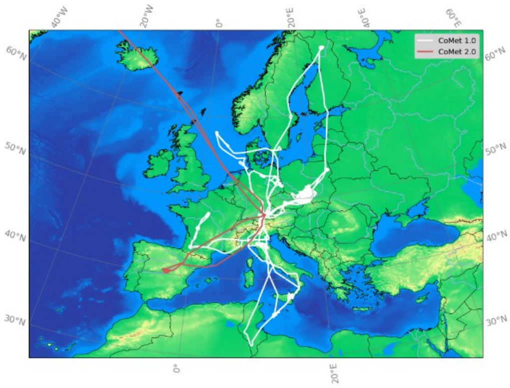

Figure 2. Flight tracks of HALO during CoMet 1.0 (white) and CoMet 2.0 Arctic (red) over Europe. Several CoMet 1.0 flights concentrated on the Upper Silesian Coal Basin which is a significant hot spot of methane emissions in Europe. During CoMet 2.0 Arctic, one flight was performed to address methane emissions from landfills in the vicinity of Madrid, Spain.

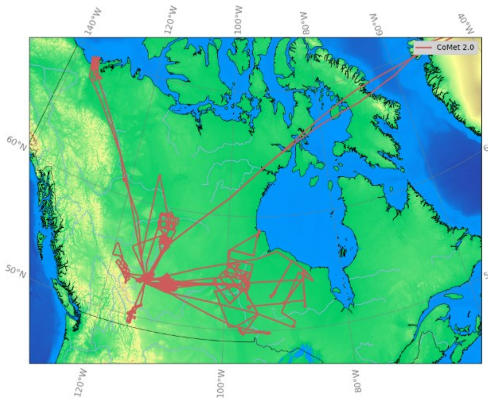

Figure 3. Flight tracks of HALO during CoMet 2.0 Arctic (red) over Canada. 15 research flights (excluding transfer) were carried out focusing on anthropogenic sources (oil&gas extraction, coal mining, and landfills) and boreal arctic wetlands.

Table 2. Overview about CoMet 1.0 and CoMet 2.0 Arctic

Campaign	Flight hours	Distance
CoMet 1.0 (Apr. -May 2018)	63	44.000 km
CoMet 2.0 Arctic (Aug, -Sept. 2022)	135	80.000 km

While this first CoMet mission in 2018 focused on anthropogenic sources of the major greenhouse gases, its successor mission (https://comet2arctic.de/) was conducted in Canada in order to target highly relevant natural fluxes of Arctic wetlands (Table 2, Figure 3). Secondary objectives were oil and gas fields, coal mines, and wildfires. CoMet 2.0 Arctic is connected to the Arctic Methane and Permafrost Challenge (AMPAC) initiative of ESA and NASA.

As an exemplary measurement of methane emissions from wetlands and the capabilities of CHARM-F, Figure 4 shows the measured enhancement of the methane column below the flight altitude of HALO during two flights over the vast wetlands between Lake Winnipeg and Hudson Bay. The methane enhancements which are on the order of < 1.5%, only, appear to show a very coherent spatial distribution for the two

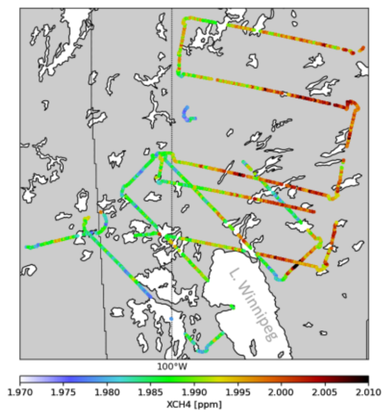

Figure 4. Enhancements of the methane column in ppm measured by CHARM-F over the wetlands north-east of Lake Winnipeg, Manitoba, along two HALO flights.

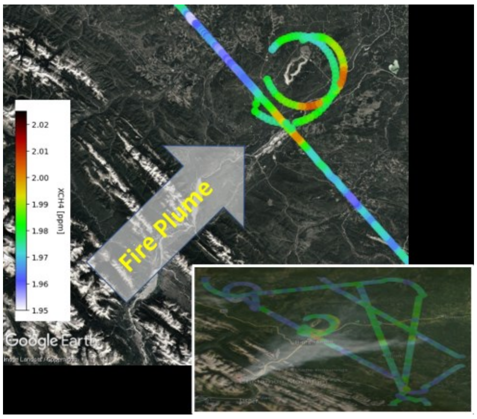

Figure 5. Enhancements of the methane column in ppm measured by CHARM-F over a fire plume. The insert depicts this plume in a VIIRS satellite image.

flights that are separated by 8 days. More detailed analyses of the respective wetland fluxes with the aid of models is underway.

Also, CH_4 signatures in a fire plume were detected by CHARM-F when flying over a wildfire in the Rocky Mountains (Figure 5). While this has been achieved for CO_2 and for a much larger fire plume [9], this is, to our knowledge, the first-time lidar measurement of CH_4 emissions from wildfires which are a very relevant source of CH_4, globally.

5. Future missions: CoMet 3.0 Tropics and CoMet 4.0 VALISE

Following the first two successful CoMet missions, the third one (CoMet 3.0 Tropics) is currently scheduled for July-August 2026 and will target areas in South America including the highly relevant Amazon and Pantanal wetlands in Brazil. The Amazon basin alone is estimated to contribute about 15% of global wetland emissions and approximately 8% of all global emissions [2,3]. However, these regions are characterized by extensive cloud cover that hinders the continuous measurement of GHGs through passive remote sensing. Therefore, monitoring and quantifying these methane fluxes are scientific priorities. Again, inverse modeling approaches using high resolution atmospheric models will be utilized building on the experience from CoMet 1.0 and CoMet 2.0 Arctic.

All those field campaigns serve as forerunners for the core validation activities of MERLIN which will take part after the launch and commissioning phase of MERLIN that is scheduled for ~2029. This exercise, CoMet 4.0 VALISE (VALIdation of SpacebornE Instruments), is foreseen to take place in Europe and beyond validation of upcoming GHG satellites, including, but not limited to MERLIN, aims to quantify regional emissions, and support emissions reporting.

International contribution to these upcoming activities is highly welcome.

6. Acknowledgements

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