



AirCore-HR: A high resolution column sampling to enhance the vertical description of CH₄ and CO₂

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Abstract. An original and innovative sampling system called AirCore was presented by NOAA in 2010 (Karion et al. 2010). It consists of a long ($> 100\text{m}$) and narrow ($< 1\text{cm}$) stainless steel tube that can retain a profile of atmospheric air. The captured air sample has then to be analysed with a gas analyzer for trace mole fraction. In this study, we introduce a new AirCore aiming at improved resolution along the vertical with the objectives to: (i) better capture the vertical distribution of CO₂ and CH₄,

5 (ii) provide a tool to compare AirCores and validate the estimated vertical resolution achieved by AirCores. This AirCore-HR (high resolution) consists of a 300 m tube, combining 200 m of 1/8 in. (3.175 mm) tube and a 100 m of 1/4 in. (6.35 mm) tube. This new configuration allows to achieve a vertical resolution of 300 m up to 15 km and better than 500 m up to 22 km (if analysis of the retained sample is performed within 3 hours). The AirCore-HR was flown for the first time during the annual StratoScience campaign from CNES in August 2014 from Timmins (Ontario, Canada). High-resolution vertical profiles of CO₂ and CH₄ up to 25 km were successfully retrieved. These profiles revealed well defined transport structures in the troposphere (also seen in CAMS-ECMWF high resolution forecasts of CO₂ and CH₄ profiles) and captured the decrease of CO₂ and CH₄ in the stratosphere. The multi-instruments gondola from the flight carried two other low-resolution AirCore-GUF that allowed to perform direct comparisons and study the underlying processing method used to convert the sample of air to greenhouse gases vertical profiles. In particular, degrading the AirCore-HR derived profiles to the low resolution of AirCore-GUF yields an excellent match between both sets of CH₄ profiles, and shows a good consistency between vertical structures of CO₂ and CH₄. These results fully validate the theoretical vertical resolution achievable by AirCores. Finally, the uncertainties associated with the measurements are assessed, yielding an average uncertainty below 3 ppb for CH₄ and 0.25 ppm for CO₂ with the major source of uncertainty coming from the potential loss of air sample on the ground and the choice of the starting and ending point of the collected air sample inside the tube. In an ideal case where the sample would be fully retained, it would be possible to know precisely the pressure at which air was sampled last and thus to improve the overall uncertainty to about 0.1 ppm for CO₂ and 2 ppb for CH₄.



1 Introduction

Understanding the global atmospheric budget of the two major greenhouse gases (GHG) emitted by human activities, carbon dioxide (CO_2) and methane (CH_4), is essential for predicting their future concentration levels. To that end, several efforts have been dedicated to improve monitoring capabilities of these gases. Under coordination from the World Meteorological

5 Organization (WMO), a global atmospheric CO_2 and CH_4 monitoring network of surface-based stations has been established (GCOS, 2011) to provide continuous information on their atmospheric concentrations. Although essential to infer surface fluxes, these surface measurements are sparse and lack information pertaining to the vertical structure of the atmospheric CO_2 and CH_4 . In order to improve spatial coverage, several satellite-based missions have been developed to monitor greenhouse gases from space. Observation in the short-wave infrared (SWIR) enable retrieving total atmospheric columns, during daytime, 10 and mostly over land. SWIR missions include the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) spanning 2003–2012 (Frankenberg et al., 2011; Wecht et al., 2014), the Greenhouse Gases Observing Satellite (GOSAT) since 2009 (Hamazaki et al., 2007; Butz et al., 2011) and more recently the Orbiting Carbon Observatory (OCO- 15 2) for CO_2 only (Crisp et al., 2004; Hammerling et al., 2012). Observations of terrestrial radiation in the thermal infrared (TIR) provide information mostly on mid-tropospheric columns, by day and night, over land and sea. Missions include the Atmospheric Infrared Sounder (AIRS) since 2002 (Crevoisier et al., 2003; Xiong et al., 2010), the Tropospheric Emission Spectrometer (TES) from 2004–2011 (Worden et al., 2012) and the Infrared Atmospheric Sounding Interferometer (IASI) since 2007 (Crevoisier et al., 2009a, b, 2013; Xiong et al., 2013). Vertical profiles of CO_2 and CH_4 are also available from limb measurements such as from the Atmospheric Chemistry Experiment (ACE-FTS) (Foucher et al., 2011). These satellite based vertical profiles mainly cover the upper troposphere and low stratosphere with a low vertical resolution.

20 One of the main challenges for any satellite-based measurements is data evaluation and the comparability to WMO standards. To that end the Total Column Observing Network (TCCON) (Wunch et al., 2010) has been established. It consists in a network of upward looking Fourier Transform Spectrometers (FTS) and has been widely used to evaluate retrievals of total columns from SWIR space missions (e.g. Houweling et al., 2014). TCCON provides column-averaged retrievals that do not have any vertical resolution and also require independent evaluation of the data.

25 Precise and regular vertical profile measurements from the surface to above the tropopause are currently missing to evaluate total or partial columns of GHG retrieved either from the ground or from space and to tie them to the calibrated measurements of the WMO.

Several aircraft missions contribute to provide vertical information with regular measurements along commercial airlines such as the CONTRAIL project (Machida et al., 2008) and the CARIBIC project (Schuck et al., 2009). Other less regular 30 aircraft campaigns are also dedicated to study GHG at a local scale (Zhang et al., 2014; Chen et al., 2010; Karion et al., 2013; Crevoisier et al., 2006, 2010; Sweeney et al., 2015) or from pole to pole such as the HIPPO project (Wofsy, 2011). Such vertical profiles are usually limited to 12 km.

To overcome this limitation, several instruments to measure CO_2 and CH_4 profiles have been developed. Commonly used techniques include Fourier Transform spectrometer (FTS) measurements such as the Michelson Interferometer for Passive



Atmospheric Sounding (MIPAS) (Oelhaf et al., 1991), cryogenic samplers (e.g Schmidt and Khedim, 1991; Engel et al., 2008) to capture air in flasks at different altitudes along the balloon flight to be analyzed at a later stage, and laser diode spectrometers such as the Spectromètre Infra Rouge pour l'Etude de l'Atmosphère par Diode Laser Embarquées (SPIRALE) (Moreau et al., 2005) or Pico-SDLA instruments (Durry et al., 2004; Ghysels et al., 2011; Joly et al., 2007). All these instruments require to
5 be flown on heavy balloon-borne platforms. They can thus not be flown on regular basis.

In this context, an original and innovative atmospheric sampling system called AirCore has been developed at the National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL) (Karion et al., 2010) from an idea originally developed and patented by Pieter Tans (Tans, 2009). It consists of a long and thin stainless steel tube shaped in the form of a coil which can sample the surrounding atmosphere and preserve a profile. This new system allows balloon
10 measurements of GHG vertical profiles from the surface up to approximately 30 km. The vertical resolution is ultimately determined by the length and diameter of the tubes.

Since the development of the first AirCore (Karion et al., 2010), new and lighter AirCores have been developed at NOAA, Groningen University and Goethe University Frankfurt. These lighter AirCores capture a smaller volume of air leading to a slight decrease in the achievable vertical resolution. This paper focuses on the development of an AirCore that allows retrieving
15 profiles of GHG with a higher resolution along the vertical, with the following objectives: (i) to better capture the vertical distribution of atmospheric CO₂ and CH₄, in the troposphere, UTLS and stratospheric regions, (ii) to provide a tool to compare low resolution AirCores and validate the theoretical resolution achievable by AirCores.

The design of this new high-resolution AirCore, named AirCore-HR, is presented in section 2 together with the description of experimental settings and processing method. Section 3 describes the first flight of AirCore-HR. Section 4 describes the
20 resulting CO₂ and CH₄ high resolution profiles, associated uncertainties, and compares high and low resolutions profiles retrieved from 2 AirCores. Section 5 gives the conclusion.

2 AirCore-HR design, experimental setup and processing method

The general principle of an AirCore is illustrated in Fig.1. First, in a preparation phase, the tube is filled with a calibrated gas standard. It is placed under a balloon with one end of the tube open and the other end closed. During the ascent phase, as the air
25 in the tube equilibrates with ambient pressure, the initial fill gas evacuates. After reaching an upper limit, where only a small fraction of the initial fill gas remains in the tube, the AirCore starts a descent phase. During this phase, as it maintains pressure equilibrium along the descent, the tube samples the ambient air. On the ground, the tube is closed, retaining the sampled profile to be analyzed with an analyzer for trace gas mole fraction.

2.1 Relation between AirCore design and vertical resolution

AirCores can be designed in a variety of configurations that determine the vertical resolution that can be achieved with the instrument. The resolution directly depends on the molecular diffusion and shear flow diffusivity otherwise known as Taylor dispersion inside the tube (Karion et al., 2010). The two major criteria in designing an AirCore are thus: (i) keeping the tubes
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diameter sufficiently thin to avoid turbulent regime at the sampling flow rates; (ii) constraining the total weight to fit the specific flight requirements of their carrier (weather balloons, stratospheric balloons, planes...) while allowing for sampling of a sufficient amount of air for the planned analysis.

2.1.1 Impact of diffusion and dispersion on the vertical resolution

- 5 As described in Karion et al. (2010), at the flow rates of gas entering the AirCore during flight (<235 sccm (standard cubic centimeters per minute)) and during analysis (30 to 120 sccm) the flow in the AirCore-HR is expected to be laminar. Molecular diffusion and Taylor dispersion affecting the sample can then be expressed in terms of an effective diffusion coefficient D_{eff} :

$$D_{eff} = D + \frac{a^2 \bar{V}^2}{48D} \quad (1)$$

where D is the molecular diffusivity of the different molecules in the surrounding gas, a is the tube's inner radius, and \bar{V} is the average velocity of the air inside the tube. In air, at 20°C and 1000 hPa, D is $0.16 \text{ cm}^2 \cdot \text{s}^{-1}$ for CO_2 , while for CH_4 , it is $0.23 \text{ cm}^2 \cdot \text{s}^{-1}$ (Massman, 1998). The distance of diffusion X_{rms} is then given by:

$$X_{rms} = 2\sqrt{2D_{eff}t} \quad (2)$$

where t represents a given storage time. Diffusion and dispersion are considered only during a given storage time and analysis (i.e. from the moment the tube is sealed with the captured sample until the end of the analysis). The factor 2 in front of the square root comes from diffusion in both directions.

Equation 2 can be expressed in terms of a fraction of pressure in the atmosphere:

$$\Delta P = P_{max} \frac{X_{rms}}{L} \quad (3)$$

where ΔP represents the effective resolution and P_{max} the pressure at the surface when the coil is closed. L is the total length of the AirCore. In the case of 2 tubes or more, ΔP can be calculated independently for each tube.

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In addition to the effects of diffusion and dispersion, which are the main drivers of the resulting vertical resolution, the smearing effect of the cell of the analyzer during analysis has to be taken into account. The analyser used in this study (Picarro Cavity RingDown Spectrometer (CRDS) G2310) pulls the sample at 110 sccm and measuring at 0.5 Hz makes one measurement every 3.7 scc (standard cubic centimeters). The analyser cell has a standard volume of approximately 6 scc, since it is 35 cc in volume, but is maintained at 187 hPa (140 torr) and 45°C. The flow rate of the analyser and its effective cell size impact 25 the resolution, especially for air sampled at low pressure (i.e. above the tropopause) where very little volume of air is sampled by the AirCore.

2.1.2 Aiming for a high resolution AirCore

To appreciate the value of the AirCore-HR it is important to understand the factors that determine the resolution of an AirCore. 30 The first factor is the sample cell of the analyzer that will limit the number of independent measurements over the sampled



volume. The second factor is the diffusion distance (explained above) which, depending on the diameter of the tube and the lag between when air was sampled and when it is analyzed, will eventually limit the sampling resolution of the AirCore.

At mid latitudes, air sampled over a 10 hPa descent between 20 and 30 hPa represents about 3 km of vertical distance whereas air sampled over a 10 hPa descent between 450 and 460 hPa represents about 200 m of vertical distance. This has 5 a direct consequence for the observation of the stratosphere, for which the sampled air needs to be preserved while sampling as much of it as possible. This can be achieved by combining sections of tubes of different diameters. A given volume of air is indeed affected differently if stored in a section with a smaller diameter: although diffusion remains the same, the distance of travel for a molecule to impact an equivalent volume increases. Therefore, using at least 2 tubes, one characterized by a small diameter at the end that remains closed, and one characterized by a larger diameter at the end that remains open allows 10 keeping a high resolution for the stratosphere (by storing the stratospheric part of the sampled profile in the tube with the smallest diameter), while still sampling a consequent volume of air thanks to the larger tube. To maximize the total volume of the AirCore-HR and limit the impact of the diffusion distance the Aircore-HR was designed with tubes of two different diameters.

Figure 2 illustrates a comparison of the vertical resolution of CO₂ measurements that can be expected for air sampled with 15 different AirCores (for an analysis performed at 38.5 sccm, with a surface pressure Pmax of 1013.25 hPa and a given storage time of 3 hours). The resolution achievable with the first AirCore designed by NOAA (Karion et al., 2010) is shown in black. After 3 hours of waiting time before analysis, it is possible to achieve a vertical resolution of 300 m at 10 km and 2 km at 20 km.

In order to achieve a higher resolution along the whole atmospheric column, a design of a 300 m tube consisting of a 200 20 m of 1/8 in.(3.175 mm) tube and a 100 m of 1/4 in.(6.35 mm) tube linked together as one tube was selected for AirCore-HR. The increase in overall volume of the AirCore-HR allows a significant increase in resolution throughout the whole sampled air column (Fig. 2) albeit an increase of the overall weight. The resolution of the AirCore-HR for CO₂ is estimated to be better than 300 m up to 15 km and better than 500 m up to 22 km.

The resolution achievable by the light-weight AirCore-GUF designed and developed at Goethe University Frankfurt is also 25 shown in Fig. 2. AirCore-GUF is a 100 m long combining 3 tubes: a 20 m-long 8 mm tube, a 40 m-long 4 mm tube and a 40 mm-long 2 mm tube. It has been designed to flow under meteorological balloons, making compromises between weight and achievable resolution. Thanks to a third tube with thinner diameter, it enables a good resolution in the stratosphere (700 m at 20 km).

The storage time between landing and analysis of the sample is a key factor influencing the vertical resolution. The resolutions plotted in Fig. 2 are for a storage time of 3 hours. Figure 3 shows the degradation of the resolution for various storage 30 times of an air sample captured by the AirCore-HR. While a 6-hr delay (blue plot) will still preserve a resolution better than 300 m up to 20 km, waiting for 12-hr after landing to perform the analysis will reduce the resolution to 500 m at 20 km (green plot). The impact of the delay on the achievable vertical resolution with the sampled profile is also presented for a 24-hour delay (orange) and a week delay (red). It is very clear from this figure that to avoid loosing vertical resolution one of the 35 challenges of using AirCores is to quickly recover the sample and perform the analysis.



2.2 AirCore-HR experimental setup

In order to obtain the vertical resolution shown in Fig. 2, the AirCore-HR comprises two tubes linked together as one, yielding an overall length of 300 m, a weight of 14.3 kg and an inner volume of 2.967 L. The detailed characteristics are given in Table 1. Both tubes have been treated by Restek, Inc., with Sulfinert® coating to reduce interactions of the sample with the walls.

- 5 The overall design is plotted in Fig. 4. Both sides of the coil are connected to 3-way valves that allow ambient air to flow either through the AirCore-HR or through a bypass. This bypass consists in a 1 m long, 1/16 in.(1.5875 mm) diameter stainless steel tube that allows pulling air into the analyzer bypassing the AirCore-HR. During flight, in addition to this setting, a dryer consisting of a short length (10 cm) of stainless steel tube filled with fresh magnesium perchlorate is positioned at the open end of the tube (at the entrance of ambient air on the solenoid valve) to ensure that no moisture enters the tubes during sampling.
- 10 The AirCore-HR payload has been designed to fit into a polystyrene foam box. It is flown together with an electronic data package designed at LMD that collects meteorological data from a pressure sensor and 3 temperature probes and also controls the opening and closing of a solenoid valve at the open end of the AirCore. Temperature probes are placed along the AirCore in contact with various segments of the tube and allow monitoring the mean temperature along the coil during the flight. The pressure sensor is an absolute pressure sensor that measures the ambient air pressure during the flight.

15 2.2.1 Laboratory testing

Several tests were conducted in the laboratory under monitored conditions to evaluate the overall consistency of the AirCore-HR. In particular, the AirCore-HR has been tested for leaks at the junctions, and at the valves used as closing points on each side of the AirCores. To test the preservation of the concentration of the sample, only calibrated dry standard gases of two different values for both CO₂ and CH₄ are used. In repeated experiments under various conditions, it was noted that to reach 20 the optimal Picarro CRDS precision at 0.5 Hz of 0.07 ppm for CO₂ and 0.5 ppb for CH₄ the tubes conducting the sampled air have to be perfectly dry. Therefore, the analysis line is systematically dried out by flowing dry air through the bypass. Water vapor concentration is closely monitored with the Picarro to be lower than 0.002 % before conducting any tests with AirCore-HR. This method allows to eliminate significant biases and to obtain mean measurements.

2.2.2 Atmospheric gas standards

- 25 For testing and analysis of the AirCores, two calibrated gas standards are used. The cylinders are connected to a multiport valve allowing selection of one of the gases.

The first standard is composed of high concentration CO₂ and CH₄ of respectively about 400 ppm and 1900 ppb and referred to as ‘high concentration calibration standard’. The other standard is composed of lower concentration of CO₂ and CH₄ of about 360 ppm and 1700 ppb respectively and referred to as ‘low concentration standard’. The gas cylinders have been calibrated 30 on WMO scales at Laboratoire de Sciences du Climat et de l’Environnement (LSCE) (courtesy of Michel Ramonet and Marc Delmotte) and the exact calibrated values of the standard can be found in Tab. 2 where CO₂ concentrations are given on the WMOX2007 scale and CH₄ concentrations are given on the NOAA-2004 scale.



2.2.3 The Picarro CRDS Analyzer

All gas analyses of LMD AirCores were performed using one trace gas analyzers by Picarro, Inc., model G2310 (Crosson, 2008). The analyzer tightly controls the pressure and temperature in its measurement cell [187 hPa (140 torr) and 45°C], to achieve the above precision (see Sect.2.2.1). The sample flow rate was controlled by a critical orifice placed at the outlet, 5 limiting the flow at 38.5 sccm during analysis.

2.3 Processing method

Upon recovery, the AirCore-HR is plugged into the prepared analysis system. It is first kept closed on both ends, allowing to pull calibrated standards through the bypass into the analyzer. Once the values measured with the continuous analyzer are stabilized to the expected values for the calibration standard used as ‘push gas’, the analysis of the air captured in the coil can 10 start. This phase is very important to make sure that, after plugging the AirCore-HR in the system, the mixing ratio read by the Picarro is not contaminated by water vapor that can have entered the analysis chain. The collected sample is then analyzed by opening both ends simultaneously; the air is pulled from one end into the continuous analyzer and low concentration calibration standard is pulled through the other end. The top of the profile with the remaining fill gas is pulled first into the analyzer.

The calibrated gas standards given in Tab. 2 allow replacing the values read by the Picarro onto the WMO scale. The high 15 concentration standard is used as fill gas to have a noticeable difference between fill gas and stratospheric air sample at the top of the profile. The low concentration calibration standard is chosen to be used as push gas to have a noticeable difference of the mixing ratios compared with the expected values of CO₂ and CH₄ at the surface.

Several steps are required to accurately place the Picarro measurements on a vertical scale in order to retrieve the vertical profiles. The dry version of CO₂ and CH₄ provided by the Picarro, which are automatically corrected for an eventual drift of 20 the measurement due to water vapor are used. First, the mixing ratios are corrected for a bias from the Picarro measurement to the WMO scales. The correction is calculated thanks to the measurement of the calibrated standards by the Picarro at the time of analysis.

Figure 5 shows an example of CO₂ and CH₄ mixing ratios measured by the Picarro instrument during the StratoScience 2014 campaign. In order to extract the measurements corresponding only to the sampled air, the top and the bottom of the 25 profiles need to be defined. The top of the AirCore sample is considered to be at midpoint of the transition in concentration between the push gas and the remaining fill gas. This point corresponding to an estimated pressure of 0 hPa in the tube is marked with a green cross in Fig. 5. The bottom of the profile is defined at midpoint on the transition of concentration between ‘push gas’ and sampled air. It is marked with a red cross in Fig. 5.

As a first approach, it is assumed that the air entering the tube equilibrates the sample with ambient pressure and adjusts 30 very quickly with the mean coil temperature. As the characteristics of the AirCore (length, diameter) do not change, ambient pressure and mean coil temperature are the two main factors that regulate the number of moles in the AirCore. Using the ideal gas law:

$$PV = nRT \Leftrightarrow n = \frac{PV}{RT} \quad (4)$$



where P is the ambient pressure, V the inner volume of the AirCore, n the fraction of moles, R is the universal gas constant in $J.K^{-1}.mol^{-1}$ and T the ambient temperature in Kelvin.

With measured timeseries of pressure (P_i) and temperature (T_i) (Fig. 7), it is possible to relate the number of air moles in the tube (n_i) to the atmospheric pressure at any given time during the flight:

$$5 \quad n_i = \frac{P_i V}{R T_i} \quad (5)$$

This number is maximum when the AirCore reaches the Earth's surface, i.e. :

$$n^{max} = \frac{P_s V}{R T_s} \quad (6)$$

Where P_s and T_s correspond to the surface pressure and to the temperature of the AirCore when landing at the surface.

The critical orifice setting the flow during analysis at 38.5 sccm/min and the controlled settings of the Picarro analysis cell 10 ensure that the same number of moles are analyzed at every time step. In other words, during the sample analysis, the number of moles flown through the analyzer increases linearly with time. Hence, the number of moles at any time during the analysis is

$$n_i = n^{max} \frac{t_i}{\Delta t} \quad (7)$$

where Δt is the total time duration of the analysis between the defined top and bottom of AirCore sample.

15 Using equations 5 and 7, a specific pressure point can be associated to every Picarro measurement of the sample to retrieve the vertical profiles. Although the process is quite simple, the selections of start and end point of the sampled profile in the Picarro data as well as in the temperature and pressure data are delicate steps that have a direct impact on the resulting profiles (see Section 4.2). Two additional effects need to be taken into account: the pressure loss along the tube (P. Tans, pers. comm.), and the accounting of potential losses of air samples during the recovery process (see Section 3.2).

20 3 The StratoScience 2014 campaign

3.1 The EDS-Stratéole flight

AirCore-HR was flown for the first time during the Stratoscience campaign operated by the French space agency (CNES) in collaboration with the Canadian Space Agency (CSA) in Timmins (Ontario, Canada, 48.57 North -81.36 East) in August 2014. It took part to the third flight of the campaign: the “EdS (Effet de Serre – Greenhouse Effect) - Stratéole” flight.

25 The carrier consisted in a gondola that could accommodate a total of 8 instruments including the AirCore-HR. All these instruments (consisting of small packages of several kg) were brought together on the same structure with the aim of studying simultaneously several climate variables. In total, the Gondola weighed 248 kg.

In addition to AirCore-HR, two AirCores-GUF from Goethe University Frankfurt were also flown during this flight.



3.2 Flight trajectory

To fulfill the requirements of the 8 instruments, the EDS-Stratéole flight had a very specific flight trajectory. The takeoff (release of the balloon) took place on the 28th of August 2014 at 20:33 local time in Timmins (00:33, 29/08/2014 UTC). After the ascent phase, the flight consisted in a monitored and controlled descent with two stops. Following a short stop at the ceiling 5 at a barometric altitude of 14 hPa (29km), an evacuation trap allowed to let some gas out to engage in a descent phase down to a barometric altitude of 54 hPa (\approx 20 km); the balloon then stabilized in a slow descent phase during 6 hours down to the barometric altitude of 78 hPa (\approx 18 km). The separation between the flight chain and the balloon did not take place at the ceiling as for weather balloon flights but at the end of this slow descent at a barometric altitude of 78 hPa. The two elements 10 (flight chain and balloon envelope) were then separated and engaged separately in faster descent, finally both landed in a dry area 350 km South-East from Timmins at 7:28 local time (11:28, 29/08/2014 UTC).

Figure 6 shows the flight profile together with the main operating states of AirCore-HR and AirCore-GUF. First, during a preparation phase on the ground before flight (marked in blue), the AirCore-HR was filled with the high concentration calibration standard chosen as ‘fill gas’. Then, the AirCore-HR was placed on the gondola and opened on one end just before takeoff. During the ascent phase (marked in green) the AirCore-HR emptied as it equilibrated with ambient pressure, thus 15 evacuating fill gas. To preserve some part of the initial fill gas in the coil the AirCore-HR was closed at 19h Pa (\approx 27 km) through a signal sent to the solenoid valve. The AirCore-HR remained closed at ceiling (marked in red) and was then re-opened by sending another signal to the solenoid valve at 19 hPa during the descent phase. During all the descent phase 20 (marked in black), the AirCore-HR remained open at one end. As the coil equilibrated with ambient pressure, air was pulled into the tube. At landing, after the pressure sensors on the electronic package detected no more pressure change, the solenoid valve closed in order to preserve the sample while waiting for recovery.

Joint efforts of CNES and CSA teams allowed accessing the AirCores and performing the analysis less than 3 hours after landing. Unfortunately, at the end of the flight, the electronic circuit maintaining the solenoid valve closed experienced a short power cut of about an hour which resulted in sampled air evacuating from the AirCore. The AirCore-HR coil heated up after reaching the ground and since it had been exposed to cold temperatures during the flight. During this period, the heating that 25 occurred resulted in losing a fraction of the profile equivalent to the air sampled from 900 to 980 hPa. The loss of that fraction of the total sample had an impact on the retrieved vertical profiles (see Section 4.1).

The specific periods of interaction with ambient air of the AirCores-GUF are highlighted in Fig. 6 (b). The main difference between AirCore-HR and AirCore-GUF was the lack of a closing device for the latter. The Light AirCores from Goethe University Frankfurt thus remained open until recovery. Being less insulated than AirCore-HR and exposed to the same cold 30 temperatures during flight, AirCores-GUF lost a fraction of the profile equivalent to the air sampled from about 780 to 980 hPa.



3.3 Measurement of additional data

In order to determine the vertical profiles of CO₂ and CH₄ from the analysis of sampled air, measurements of several atmospheric parameters are needed (see Section 2.3). The two most important parameters are the ambient pressure and the mean coil temperature. Those parameters are recorded by the AirCore-HR electronic data package (Section 2.2). Figure 7 shows the evolution of coil temperature and ambient pressure measured during the flight. The temperatures recorded by the 3 temperature probes during flight are plotted in red (full, dashed, points) and reported on the right y-axis. Mean coil temperature is obtained by taking the mean of 3 temperatures recorded by independent probes located at different positions along the AirCore-HR. The ambient pressure during the flight is plotted in black and reported on the left y-axis.

Comparison between AirCore-HR and other pressure measurements highlighted a small drift in AirCore-HR data pressure recordings. Therefore the pressure profile recorded with the electronic of AirCore-HR has been corrected to fit the high precision of the records of a Paroscientific. Inc.© absolute pressure gauge which is characterized by an accuracy of 10 Pa and a precision of 0.1 Pa.

Additionally, GPS coordinates and altitudes from CNES were used to complete the dataset.

4 Results: The 0-25 km CO₂ and CH₄ profiles

15 4.1 The profiles

Figures 8 (a) and (b) show the CO₂ and CH₄ profiles measured during the StratoScience 2014 campaign. Each profile comprises about 1800 points on the vertical. As explained in Section 3.2, profiles stop at 900 hPa due to the sample loss after landing. Both CO₂ and CH₄ AirCore-HR vertical profiles reveal thin structures of the atmosphere and airmass transport signatures. Figure 8 (c) shows the ambient temperature recorded onboard during flight. From this ambient temperature profile the tropopause was estimated to be at 162.1 hPa according to the definition of the WMO thermal tropopause (Reichler et al., 2003).

In Fig. 8 (a), a strong decrease of CO₂ can be observed in the first layers above ground. This is coherent with CO₂ uptake by vegetation near the surface during the summer season. CO₂ then reaches higher values in the free troposphere (~393 ppm), with small variations (of 0.5-2 ppm) albeit 2 well-marked signatures at 700 and 600 hPa. CO₂ reaches its highest value of 396 ppm just above the tropopause. In the stratosphere, CO₂ values are expected to be lower since the exchange rate between upper troposphere and lower stratosphere takes several years (Andrews et al., 2001; Engel et al., 2002). Above ~110 hPa, CO₂ mixing ratios decrease slowly from 396 ppm to 385 ppm at 30 hPa albeit one structure captured at the very top of the profile between 30 and 40 hPa. This structure is correlated with a similar one at the same barometric altitude in the CH₄ profile in Fig. 8 (b).

As can be seen in Fig. 8 (a), part of the CO₂ profile between 70 and 90 hPa is not shown. This corresponds to the range of the 7-hour plateau phase (cf. Fig. 6) where unrealistically low CO₂ values were sampled (visible in the CO₂ data in Fig. 5 at the analysis times between 300 and 450 seconds). The alteration of CO₂ sampled in this range was possibly caused by the dryer. Indeed, the magnesium perchlorate used as drying agent at the entry point of the tube is slightly reactive with CO₂ and inert



with CH₄. Because of the long exposure to this drying agent during the plateau phase, enhanced by air coming in and out of the tube because of oscillations of the gondola around 80 hPa, the magnesium perchlorate might have impacted CO₂ sampled by the AirCore-HR. The dryer being inert to CH₄, no impact is seen on CH₄ profile.

The CH₄ vertical profile is presented in Fig. 8 (b). Mixing ratios of CH₄ have a small variability in the troposphere between 5 1800 ppb and 1880 ppb. The zoom on the tropospheric part (between 200 hPa and 1000 hPa) reveals pronounced structures captured in the troposphere, particularly in the region from 200 hPa to 700 hPa. These could be caused by transport or variability in the emissions. The strong decrease of CH₄ in the stratosphere is particularly well seen in Fig. 8 (b), with values of ~1800 ppb near the tropopause at 120 hPa to 1100 ppb at 30 hPa. Along the slopes, several structures can be identified around 80 hPa and between 30 and 40 hPa, revealing transport patterns in the stratosphere.

10 A comparison between Fig. 8 (a) and (b) shows CO₂ variability is higher near the ground, whereas CH₄ variability is higher in the mid-to-upper troposphere and in the stratosphere. This is in agreement with the fact that CO₂ may have negative and positive anomalies at the surface (associated mainly with vegetation uptake and anthropogenic emissions) whereas CH₄ has mostly positive anomalies coming from the surface and negative anomalies coming from the stratosphere.

A comparison was performed with CO₂ and CH₄ forecasts from the Copernicus Atmosphere Monitoring Service (CAMS) 15 using the European Centre for Medium-range Weather Forecasts (ECMWF) model (Agusti-Panareda et al., 2014; Massart et al., 2014). This comparison is presented in Fig. 9. The tracer transport in the forecast is constrained with meteorological observations by re-initialising the forecast every 24 hours with operational ECMWF analyses, whereas the atmospheric CO₂ and CH₄ tracers are cycled from one 1-day forecast to the next, as in a free run. Therefore, the forecast is essentially a model simulation with state-of-the-art representation of tracer transport available in forecast mode (http://macc.copernicus-atmosphere.eu/d/services/gac/nrt/rt_fields_ghg). The CAMS-ECMWF CO₂ and CH₄ forecasts used here have a horizontal resolution of 20 around 16 km x 16 km and a vertical resolution of 137 levels from the surface to 0.01 hPa. These forecasts have been collocated in space and time with AirCore-HR landing coordinates. A constant bias of 24 ppb has been added to CAMS-ECMWF CH₄ forecast to ease the comparison.

The agreement between both CO₂ profiles (Fig. 9 (a)) is satisfying throughout the troposphere in terms of structures. The 25 forecast correctly reproduces the strong decrease in CO₂ from 800 hPa to the surface, as well as the increase in concentration from 800 hPa to 600 hPa, and a lower increase from 600 hPa. In the upper troposphere, from 300 hPa up to the tropopause at 150 hPa, the forecast displays different structures than those measured by the AirCore-HR. In the lower stratosphere (from 150 hPa to 90 hPa), the AirCore-HR and the CAMS-ECMWF forecasts both reveal a decrease in CO₂ starting from just above the tropopause up to the top of the stratosphere.

30 Although fewer vertical structures are seen in the forecast, the CH₄ mixing ratios and position of the broader vertical structures fit quite well with the measurements up to 200 hPa (Fig. 9 (b)). For lower pressures, the decrease of CH₄ measured by AirCore-HR is much more pronounced than the one simulated by the forecast. This is a known problem in the CAMS-ECMWF model which is currently being investigated (A. Agusti-Panareda, S. Massart, pers. comm.).



4.2 Associated uncertainties

Monte Carlo simulations were performed to assess the uncertainty associated with the retrieved constituent profiles. The retrieval process of the vertical profiles was iterated a 1000 times by randomly changing the original datasets within the estimated uncertainty range of every identified uncertainty source. This allowed to produce a set of 1000 slightly different outcomes for

5 the vertical profiles both in terms of mixing ratios and vertical position. A standard deviation of the mixing ratios at a given position was then calculated based on this dataset. In these simulations we took into account the following uncertainties :

(i) the precision of the gas analyzer: Picarro measurement precision was defined as a Gaussian standard deviation of the mixing ratios based on the instrument specification (i.e deviations of 0.5 ppb for CH₄ and 0.07 ppm for CO₂ (Crosson, 2008)).

10 (ii) the mean temperature profile: To account for the impact of temperature correction, the temperature profile was randomly chosen among the 3 profiles measured by the 3 probes.

(iii) the pressure profile : an uncertainty of 0.1 Pa corresponding to the precision of the Paroscientific. Inc.© absolute pressure gauge was used.

15 (iv) the selection of the sample: The choice of the exact midpoint of transition between either push-gas and sample, or remaining gas and sample (see Section 2.3) has an impact on the altitude of both ends of the profile. A random uncertainty of ± 1 Picarro measurement point was defined for both uncertainties.

(v) the potential loss of air sample resulting from the tube remaining open after landing as occurred during this flight (see Sect. 3.2): An uncertainty of ± 10 hPa was associated to the bottom pressure correction that was defined to take the air loss into account.

The uncertainties discussed here are related to the analysis and processing of the sampled air and are only valid for the 20 AirCore-HR in the case of this flight and may have different results in other situations. The CO₂ uncertainties do not take into account the potential interactions with the drying agent that are hard to quantify and need to be further studied (cf Section 4.3). The uncertainties associated to the AirCore-HR CO₂ and CH₄ profiles were calculated for the 5 uncertainty sources together but also separately to estimate the influence of each individual source of uncertainty. The overall resulting uncertainties associated to the mixing ratios of CO₂ are presented in Fig. 10 and those associated to the CH₄ mixing ratios are presented in Fig. 11. 25 Figures 10 (a) and 11 (a) show a reminder of the vertical profiles of CO₂ or CH₄ respectively. Figures 10 (b) and 11 (b) show the uncertainties without taking the uncertainty source (v) into account in order to illustrate what the expected uncertainties would be in an ideal case where the closing system would have worked. Figures 10 (c) and 11 (c) show the overall uncertainties associated to the vertical profiles accounting for all uncertainty sources previously listed.

Comparing Fig. 10 (b) with Fig. 10 (c) and Fig. 11 (b) with Fig. 11 (c) shows that, for both CO₂ and CH₄, the uncertainty 30 related to the bottom pressure correction has an important impact on the uncertainties estimated in the troposphere although in the stratosphere the uncertainties remain relatively not impacted by this. Indeed the fraction of the overall uncertainties (Fig. 10 (c) and Fig. 11 (c)) that is related to the loss of air is above 80% in the troposphere and drops to about 30% in the stratosphere. The dominating uncertainty source in the stratosphere is related to the selection of the sample. Mis-selecting the transition point between the gas in the AirCore sample and the calibrated standard by only one measurement has an important impact on



the positioning of the stratospheric part of the profiles. Indeed, the whole stratospheric air sampled by the AirCore accounts for about 8% of the total sample (~ 150 points out of ~ 1800 total points), but corresponds to ≈ 15 km of the 25 km profile. Hence, a difference of one point in the positioning of the profile does matter.

Overall, the average uncertainty on the CO₂ profile (Fig. 10 (c)) is 0.24 ppm throughout the column. The average uncertainty 5 in the troposphere is 0.25 ppm with relatively higher uncertainties in the bottom of the profile where important variations of CO₂ are measured, inducing that the slightest positioning uncertainty translates into mixing ratio uncertainties. For the whole stratosphere above 120 hPa, where the CO₂ profile is more stable, the average uncertainty drops to 0.11 ppm.

The average uncertainty on the overall CH₄ profile (Fig. 11 (c)) is 2.78 ppb. In the stratosphere, above the tropopause at 120 hPa, CH₄ uncertainties are quite variable along the profile, and can be as high as 10 ppb locally but on average are estimated 10 to be 6.42 ppb. Such high values stem directly from high vertical gradients in mixing ratios: in that case, the assumed error on the vertical positioning of the profiles translates into higher uncertainties. In the troposphere, the average uncertainty for the CH₄ profile is below 2 ppb with sometimes values up to 5 ppb where the vertical profile shows transport structures of 30 ppb or more along the vertical in the troposphere.

4.3 Comparison between AirCores with different resolutions

15 4.3.1 Overall comparison

Benefiting from the accomodation of several AirCores onboard the CNES gondola, the AirCore-HR profiles can be compared with those of the lighter AirCores-GUF (see Section 3). AirCore-GUF air samples were processed at LMD using the same methodology as for AirCore-HR (Section 2.3). The processing took into account the fact that AirCores-GUF remained open for 3 hours before being manually closed at recovery leading to the loss of the bottom of the profile between 980 and 780 hPa 20 (see Section 3.2). Both AirCore-GUF being identical, the comparison is presented with only one AirCore-GUF in order to focus on the comparison between AirCores with different resolutions. Figures 12 (a) and (b) show the comparison of AirCore-HR and one AirCore-GUF CO₂ and CH₄ profiles.

The particular descent profile of this flight had several impacts on the AirCore-GUF profiles:

(i) as for AirCore-HR, unrealistic low values of CO₂ were sampled during the long plateau phase that happened between 70 25 and 90 hPa;

(ii) since the lower resolution AirCore-GUF captured a smaller volume than AirCore-HR, two additional effects have impacted the profiles : (1) the stratospheric part of the profile was impacted by diffusion during the 7 hours plateau phase. Indeed, during the plateau phase at about 90 hPa, the air sampled from 20-90 hPa by AirCore-GUF remained in the first tube of 20 m / 8 mm diameter whereas it was stored over the 100 m / 1/4 in.(6.35 mm) tube for AirCore-HR. This lead to a more intense 30 diffusion in the AirCore-GUF sample.; (2) during the remaining time before analysis (descent phase from the plateau to the ground plus waiting time before analysis) the previously impacted air had time to diffuse with air sampled up to about 200 hPa.

Therefore, all the CO₂ sampled above 200 hPa with AirCore-GUF was probably altered by the combination of unrealistic low values of CO₂ acquired during the plateau phase and the diffusion effects. Only AirCore-GUF CO₂ sampled in the troposphere



below 200 hPa is shown to ensure that the profiles are compared where residual effects from this phase are minimal. Concerning CH₄, which was not impacted by the dryer during the plateau phase, only the difficulty of properly modeling the diffusion inside the tube remains. The full AirCore-GUF CH₄ profile is shown but the stratospheric part of the profile should thus be taken with caution.

- 5 The comparison between AirCore-HR (black) and AirCore-GUF (blue) highlights that both CO₂ profiles (Fig. 12 (a)) have a good agreement in terms of structures. The profiles disagree on the absolute values but the structures captured with AirCore-GUF appear to be identical only at a different resolution.

For CH₄, Fig. 12 (b) reveals that the agreement is excellent between AirCore-HR and AirCore-GUF. The zoom on the tropospheric part (between 200 hPa and 1000 hPa) shows that the different AirCores capture the same structures and allow to 10 retrieve similar vertical profiles both in terms of structures and mixing ratios albeit at a different resolution. In the stratosphere, both AirCores capture the position and inclination of the decreasing slope of methane. However, some stronger differences can be seen in terms of mixing ratios between both profiles between 70 and 90 hPa or between 30 and 40 hPa. In these ranges, similar structures are captured by both AirCores but seem to be very strongly impacted by diffusion in the AirCore-GUF CH₄ profile. This illustrates the impact of diffusion, which is stronger for AirCore-GUF than for AirCore-HR during the long plateau 15 phase.

Overall, the comparison between both AirCores reveals that the high resolution captures more information on the vertical distribution along the atmospheric column.

4.3.2 Degradation of the resolution

To perform a fair comparison between the different AirCore profiles, the degradation of the resolution of AirCore-HR profiles 20 to that of lower resolution AirCore-GUF has to be performed. This exercise aims also at evaluating the theoretical calculation of the expected resolution (Section. 2.1).

The vertical resolutions shown in Fig. 2 were calculated for a standard atmosphere and air sampled from 10 hPa to a ground pressure of 1013.25 hPa. In order to account for the sampling that occurred during flight and how the sampled air was distributed within the tubes, the vertical resolution of AirCores-GUF was recalculated with the specific parameters of the flight for both 25 CO₂ and CH₄.

Degradation of the AirCore-HR profiles is performed through the convolution with a Gaussian window with a standard deviation of the lower vertical resolution at each given altitude:

$$g(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad (8)$$

where σ is the standard deviation (i.e the vertical resolution) at a given vertical position x.

30 It allows retrieving a degraded version of the profiles :

$$\text{degraded}X_{CH_4}(x_0) = \int CH_4(x)g(x-x_0)dx \quad (9)$$



The degraded version of the CO₂ profile is calculated similarly. To avoid the parts of the profiles that may have been affected by the strong diffusion during the long plateau phase in the flight profile, the comparison with degraded AirCore-HR profiles is only presented for pressures higher than 200 hPa.

The effect of the degradation of the AirCore-HR profile to the lower resolution of AirCore-GUF is presented in Fig. 13 (a)
5 and Fig. 14 (a). The differences between AirCore-GUF and the smoothed version of AirCore-HR (degraded to the vertical resolution of AirCore-GUF) are shown in Fig. 13 (b) and Fig. 14 (b).

The comparison of the the CO₂ profiles in Fig. 13 (a) shows that when the lower vertical resolution of AirCore-GUF is taken into account, both AirCores display very similar structures. However, a bias remains between both profiles. The difference between AirCore-GUF and the smoothed AirCore-HR (Fig. 13 (b)) highlights that this bias varies linearly from -1 ppm at 200
10 hPa up to 3 ppm at 780 hPa. The lower values of AirCore-GUF CO₂ up to 250 hPa could be explained as remaining impacts of diffusion with the very low values of altered CO₂ sampled at the plateau phase. The discrepancies (Fig. 13 (b)) then increase when going lower down in the troposphere, where humidity plays an increasing role. It is suspected that the individual dryers from different AirCores may affect the CO₂ samples differently when capturing CO₂ in a humid atmosphere highlighting that the interferences with CO₂ have to be studied more closely.

15 Concerning CH₄, the degraded AirCore-HR profile (pink) smears out the smaller structures that were captured by the high resolution and matches perfectly the AirCore-GUF profile both in terms of structures and mixing ratios. The difference between AirCore-GUF (blue) and the smoothed AirCore-HR profile (pink) vary between -2.7 and + 2.1 ppb (Fig. 14 (b)) which is in agreement with the 2.8 ppb average uncertainty that can be associated to the AirCore-HR profile (cf sect. 4.2). In addition to allowing the comparison of AirCore-HR profiles with those of lower resolution AirCores, the excellent agreement of both CH₄
20 profiles validates the computation of theoretical vertical resolution presented in Section 2.1.2.

5 Conclusions

In this paper, a new AirCore (AirCore-HR) allowing high resolution measurements of CO₂ and CH₄ from the ground up to almost 30 km is presented. Thanks to the combination of 2 tubes, it allows retaining air samples with a vertical resolution better than 500 m up to 20 km when the analysis is performed within 6 hours after landing of the instruments. As for any AirCore,
25 the final resolution depends on the delay between landing and analysis.

The AirCore-HR was flown for the first time on a multi-instrument gondola which allowed to perform comparisons of the vertical profiles retrieved with AirCore-HR and lower resolution AirCore-GUF. The degradation of the profile given by AirCore-HR to the resolution of AirCore-GUF revealed an excellent agreement between both profiles for CH₄ which fully validates the theory behind AirCores.

30 CO₂ profiles retrieved from the AirCores on this flight have revealed unexpected structures between 60 and 90 hPa when the flight experienced a long plateau phase of about 7 hours during descent, not seen on CH₄. It is suspected that the magnesium perchlorate used as drying agent at the inlet of the AirCores inert to CH₄ may have played a role in the alteration of CO₂ during this particular phase at low pressure. Moreover the comparison of CO₂ profiles has highlighted that the agreement is good in



terms of structures, but that an important and variable bias is seen between profiles. This bias is also suspected to come from potential interaction with the dryer and shows that CO₂ sampling aspects with AirCores as well as these potential impacts of the drying agent have to be further studied.

By designing a method taking into account all the sources of uncertainties in the processing of the data, the overall uncertainty 5 is estimated to be less than 3 ppb on the CH₄ profile and less than 0.3 ppm on the CO₂ profile. A particular issue during the flight with the closing system has led to the loss of part of the sampled air. Therefore the highest pressure point sampled by the AirCore-HR had to be corrected. An uncertainty of 10 hPa was associated to this correction and it was estimated that this uncertainty is responsible for ~80% of the overall uncertainty on the profiles. In an ideal case where the system would close and retain the complete sample, it would be possible to know more precisely the pressure at which air was sampled last and 10 thus to improve the overall uncertainty to about 0.1 ppm for CO₂ and 2 ppb for CH₄.

Comparison between AirCore data and forecasts from CAMS-ECMWF has yielded satisfying agreements between AirCore-HR profiles and simulated profiles. In particular, well pronounced vertical transport signatures in the troposphere in both CO₂ and CH₄ profiles are similar for both the forecasts and AirCore-HR profiles. In the stratosphere, AirCore-HR CH₄ profile seems to indicate that the decrease of stratospheric CH₄ in the forecasts is too slow, which may have an important impact when 15 deriving total or partial columns of CH₄ from the analyses.

This comparison illustrates the potential of AirCores to evaluate atmospheric transport models, as well as GHG satellite retrievals from TIR and SWIR instruments. Especially, light AirCores flown from weather balloons could be deployed at various locations to complete an effective system together with ground stations and regular aircraft campaigns. Such lightweight systems could also contribute to specific campaigns for calibration and validation of future space missions. In order to fit these 20 applications, the spatial and temporal resolution requirements necessary to evaluate the models or satellite retrievals efficiently need to be assessed.

Along with the development of robust lightweight systems, it is also important to continue development strategies of AirCores for large platforms carrying heavy payloads. Such platforms, flown during specific stratospheric balloon campaigns, allow unique multi-instrument measurements of the same or complementary atmospheric variables. The simultaneous use of 25 laser-diode spectrometers, cryosamplers and AirCores, that can only be performed during these specific campaigns are necessary to evaluate the retrievals performed with various AirCores and test improvements of the instruments.

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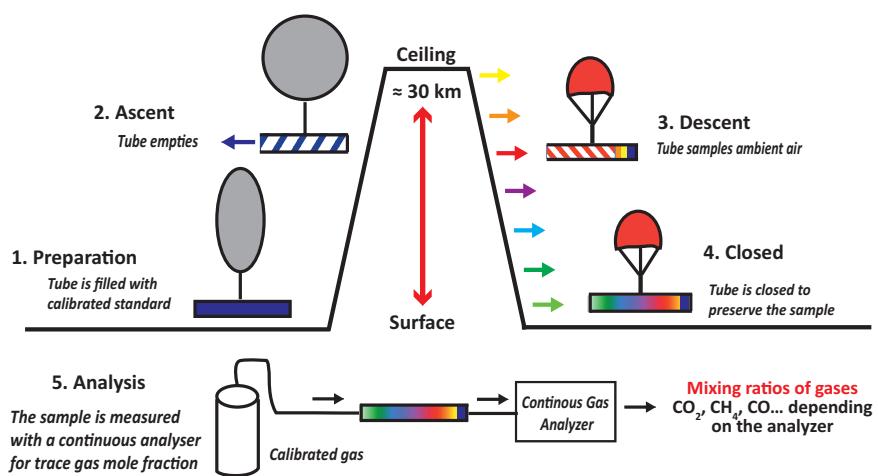


Figure 1. Schematic description of the 5 steps of the AirCore sampling method

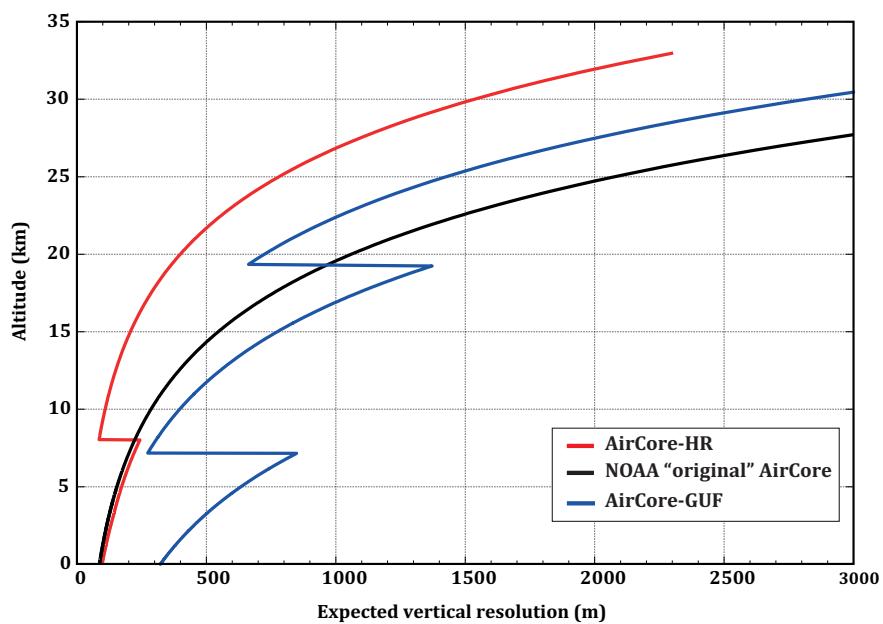


Figure 2. Comparison of the vertical resolution that can be expected with different AirCores for CO_2 measurements after 3 hours storage time before analysis. AirCore-HR (red), the original NOAA AirCore (black), AirCore-GUF (blue)

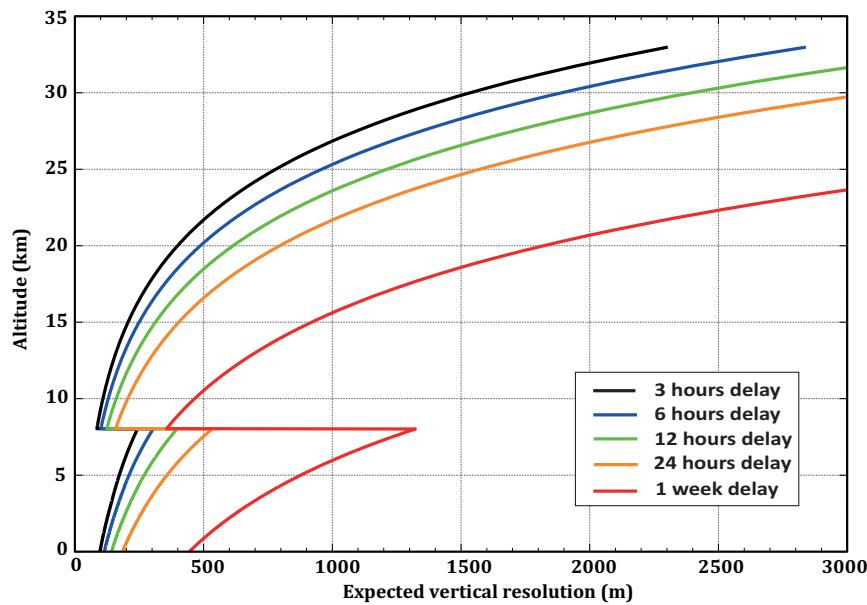


Figure 3. Impact of the time delay between landing and analysis on the expected vertical resolution of AirCore-HR, for a storage time of 3 hours (black), 6 hours (blue) and 12 hours (green), 24 hours (orange) and one week (red).

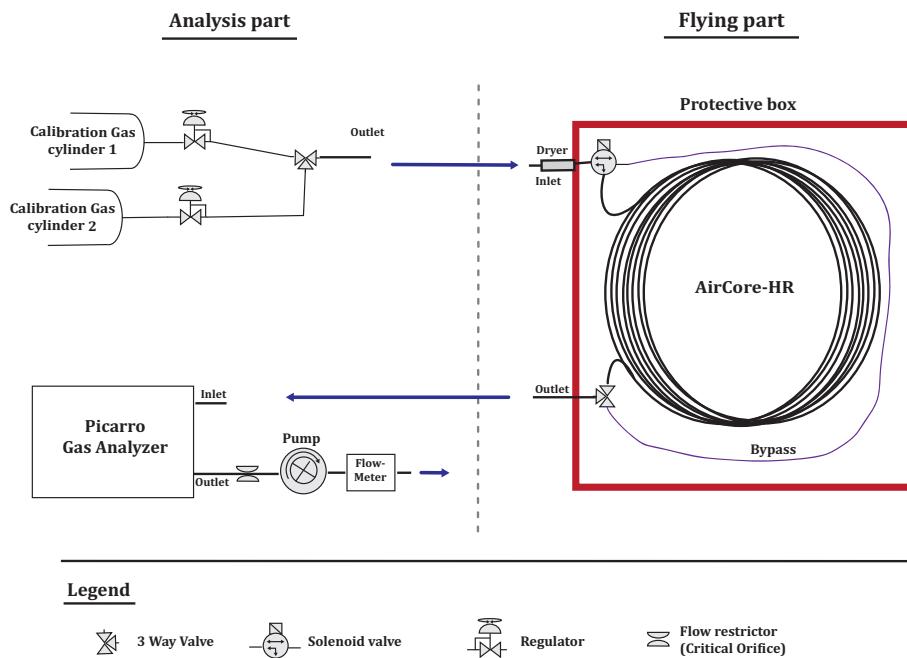


Figure 4. Overview of the AirCore-HR and analysis system

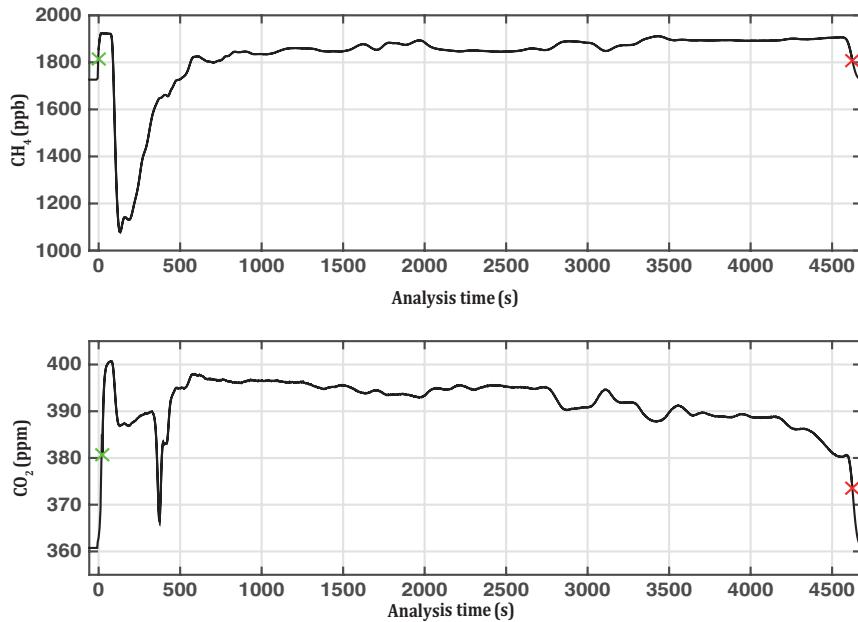


Figure 5. Picarro analysis of the AirCore-HR sample from “EdS-Stratéole” flight on 29 August 2014. (top) CH_4 mixing ratios as a function of the analysis time in seconds, (bottom) CO_2 mixing ratios as a function of the analysis time in seconds. The selected starting point of the sample is marked with a green cross and marks the 0 of the analysis time; the selected ending point of the Aircore-HR sample is marked with a red cross.

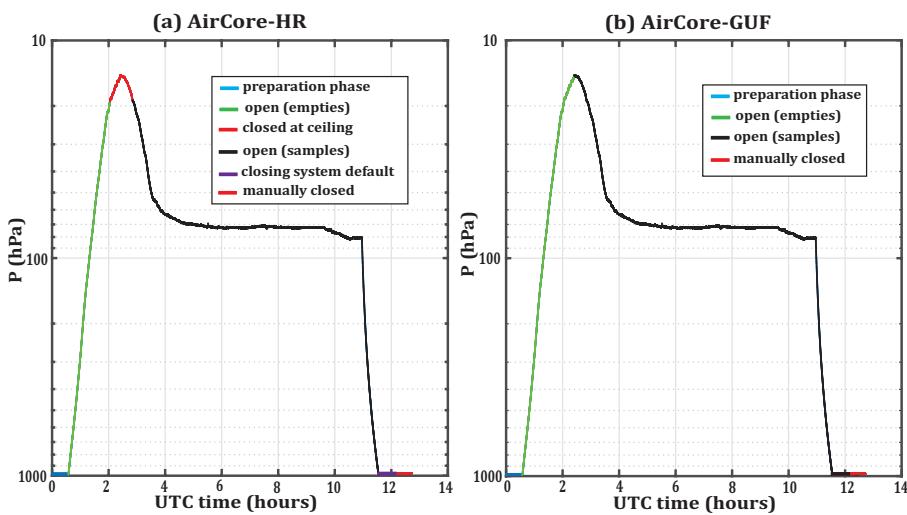


Figure 6. Flight plan from the StratoScience 2014 “EdS-Stratéole” flight on 29 August 2014 with main operating states of (a) AirCore-HR, (b) AirCore-GUF : the preparation phase, on the ground before flight (blue), ascent phase (green), descent phase (black), closed (red)

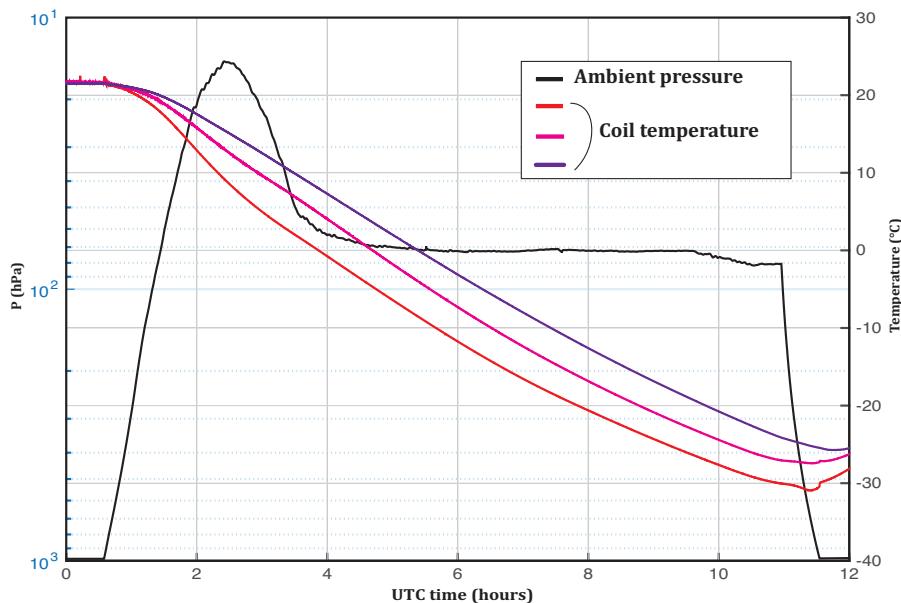


Figure 7. Recorded temperature from the 3 probes on the AirCore-HR and ambient pressure during flight “EdS-Stratéole” flight on 29 August 2014. The 3 temperature probes (red, pink and purple lines) are presented in °C in function of UTC time, the temperature axis is located on the right side. Ambient pressure (black line) is presented in hPa in function of UTC time, with the vertical scale on the left side.

Table 1. Characteristics of the AirCore-HR

Tube	1/4 in. tube	1/8 in. tube
Diameter (inches/cm)	0.25 / 0.635	0.125 / 0.3175
Width (inches/cm)	0.02 / 0.0508	0.02 / 0.0508
Inner diameter (inches/cm)	0.21 / 0.5334	0.085 / 0.2159
Inner radius (inches/cm)	0.105 / 0.2667	0.0425 / 0.10795
Length(m)	100	200
Volume (cm ³)	2235	732
Weight (kg)	7.48	6.82
Overall payload		
Overall payload Volume(cm ³)	2967	
Overall payload Weight	14.30	

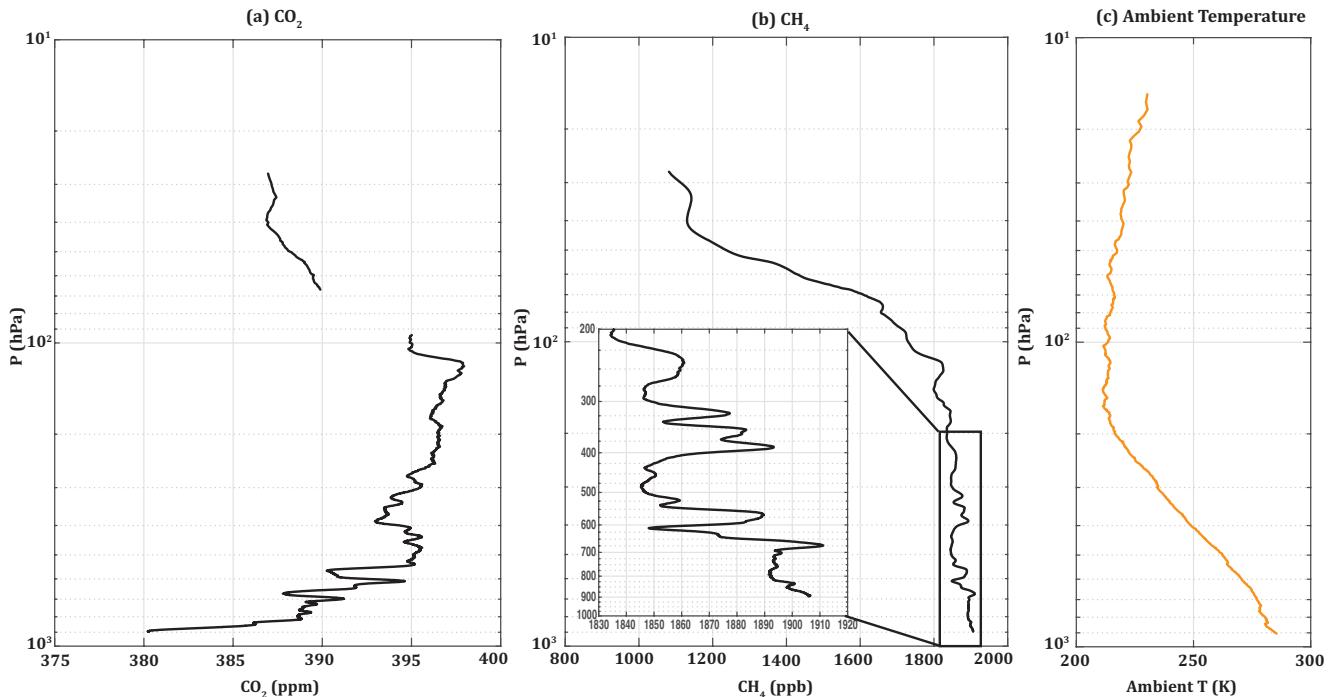


Figure 8. Vertical profiles retrieved from the air sampled with AirCore-HR on the “EdS-Stratéole” flight on 29 August 2014. (a) CO₂ (ppm), (b) CH₄ (ppb), (c) ambient temperature (K).

Table 2. Values of the calibrated gas standards using NOAA’s “WMO Scale” reference

Low Concentration standard:
CO ₂ 360.85 ppm ± 0.008 ppm
CH ₄ 1726.95 ppb ± 0.163 ppb
High concentration standard:
CO ₂ 401.31 ppm ± 0.004 ppm
CH ₄ 1922.33 ppb ± 0.168 ppb

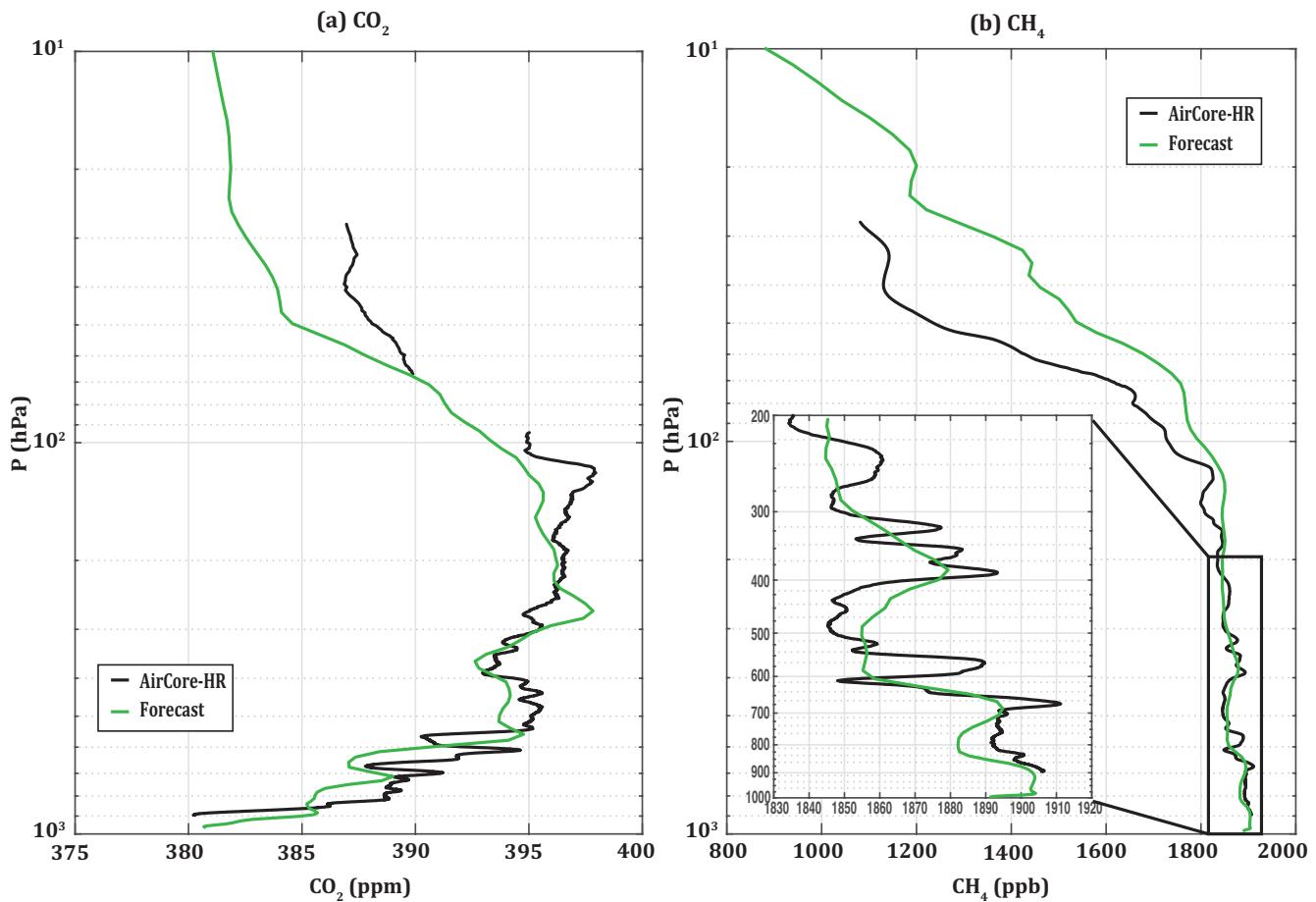


Figure 9. Comparison of AirCore-HR (a) CO_2 and (b) CH_4 vertical profiles (black) with co-located high resolution forecast (green) from CAMS-ECMWF at landing coordinates on 29 August 2014 at 12 UTC

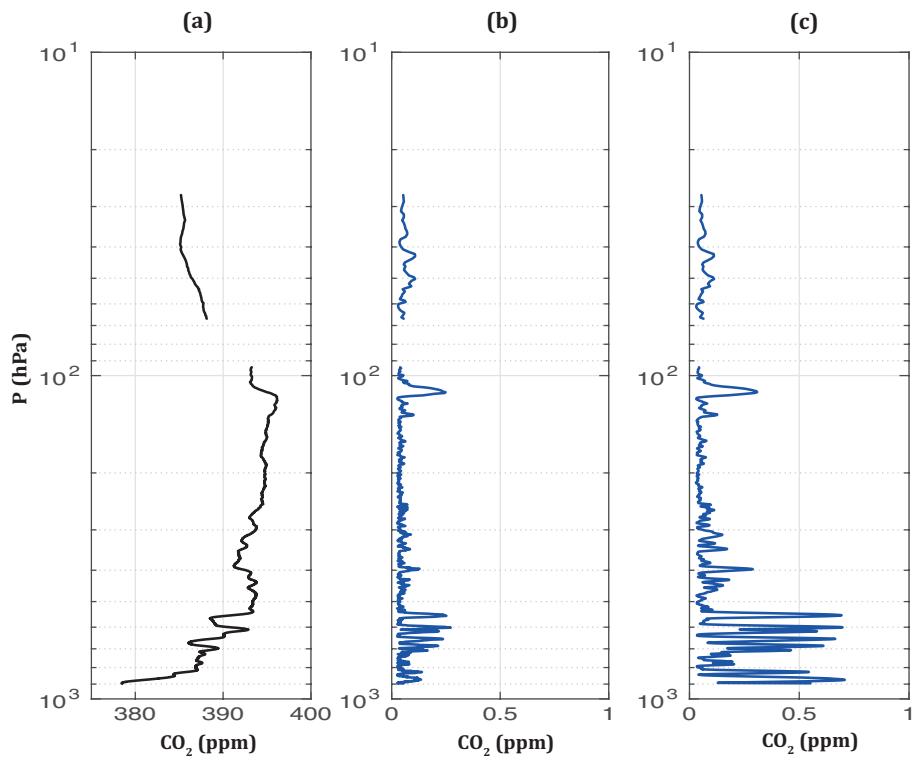


Figure 10. (a) AirCore-HR CO₂ vertical profile, (b) CO₂ uncertainty without taking the potential loss of air into account (see text uncertainty (v)), (c) overall CO₂ uncertainty

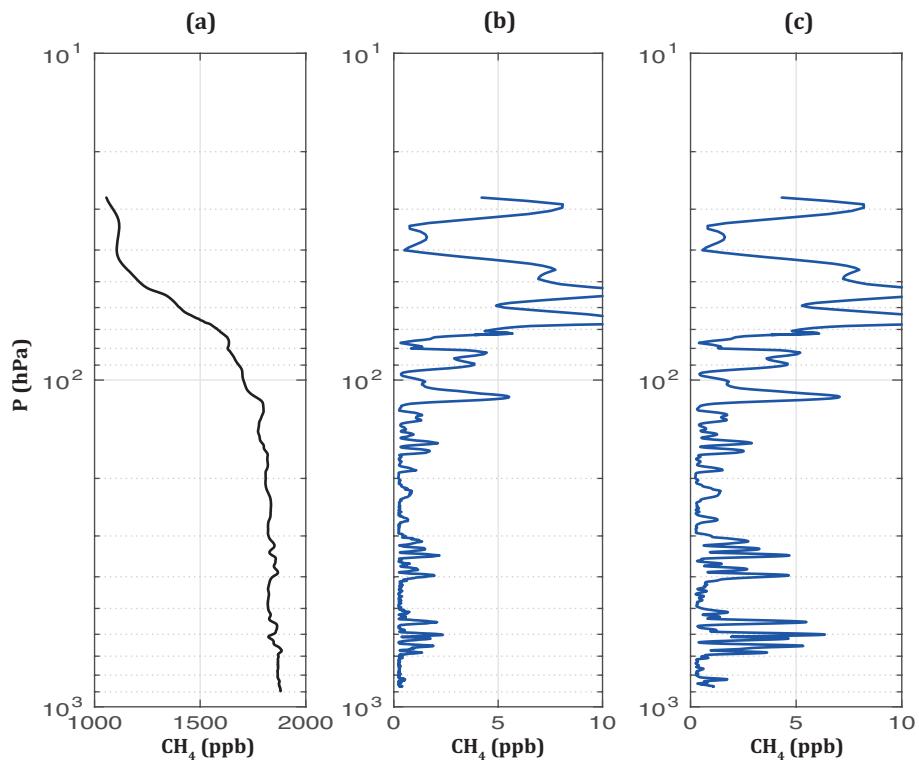


Figure 11. (a) AirCore-HR CH_4 vertical profile, (b) CH_4 uncertainty without taking the potential loss of air into account (see text uncertainty (v)), (c) overall CH_4 uncertainty

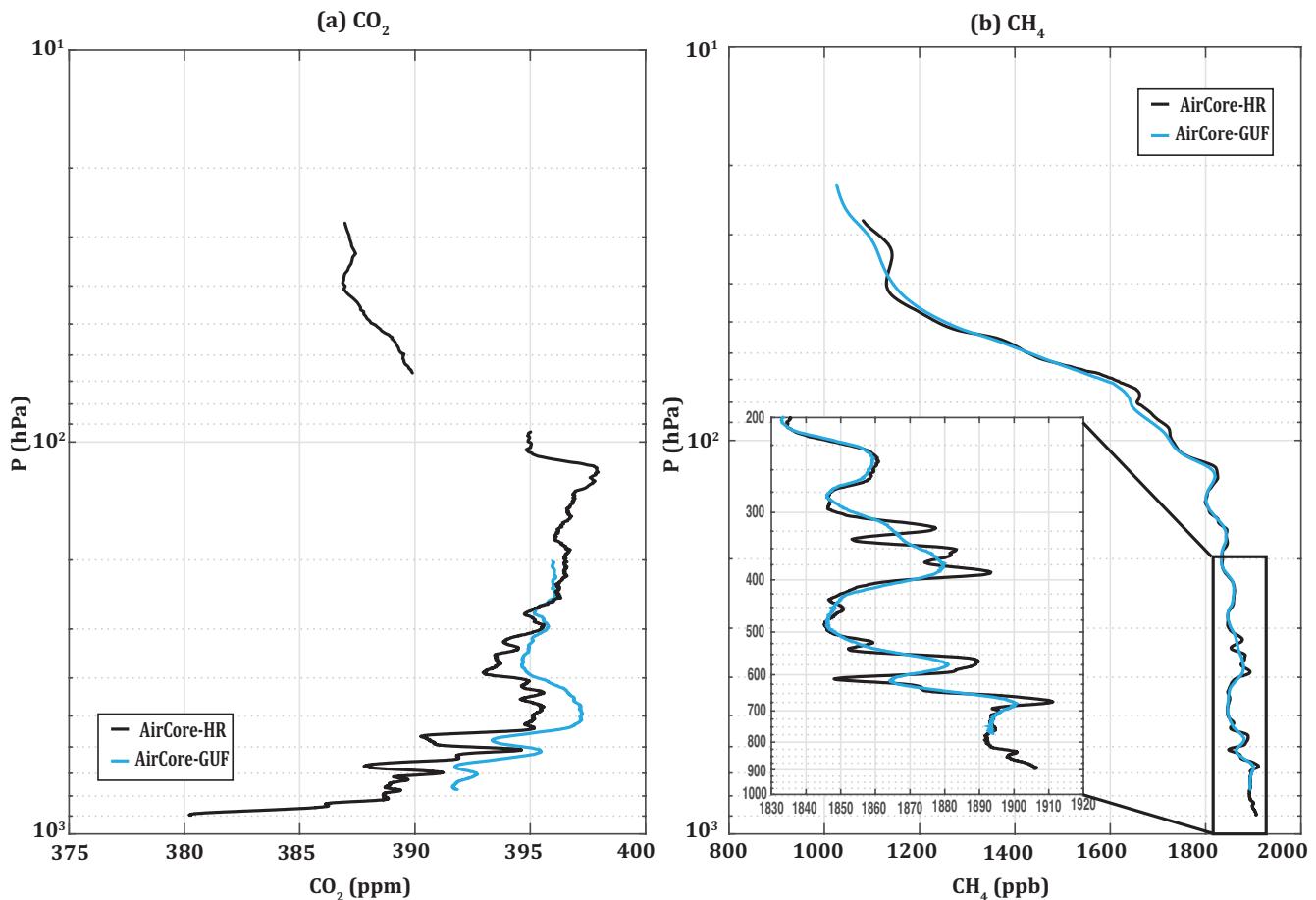


Figure 12. Vertical profiles retrieved from the air sampled with the AirCore-HR and an AirCore-GUF on the “EdS-Stratéole” flight on 29 August 2014. (a) CO_2 (ppm), (b) CH_4 (ppb).

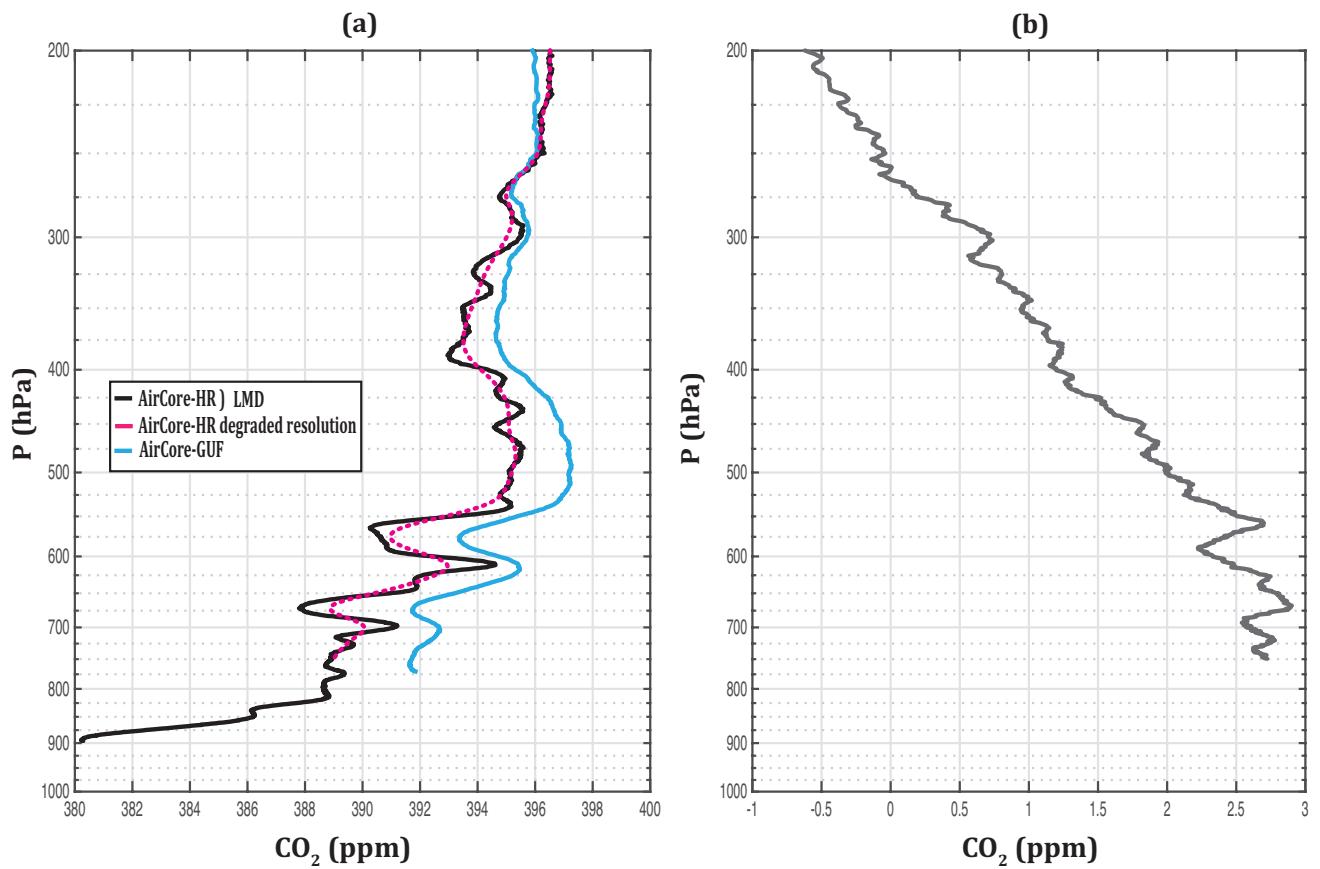


Figure 13. (a) CO₂ vertical profiles from AirCore-HR in full resolution (black), AirCore-HR “degraded resolution” (pink), AirCore-GUF (blue). (b) Residual of the difference AirCore-GUF - AirCore-HR “degraded resolution”.

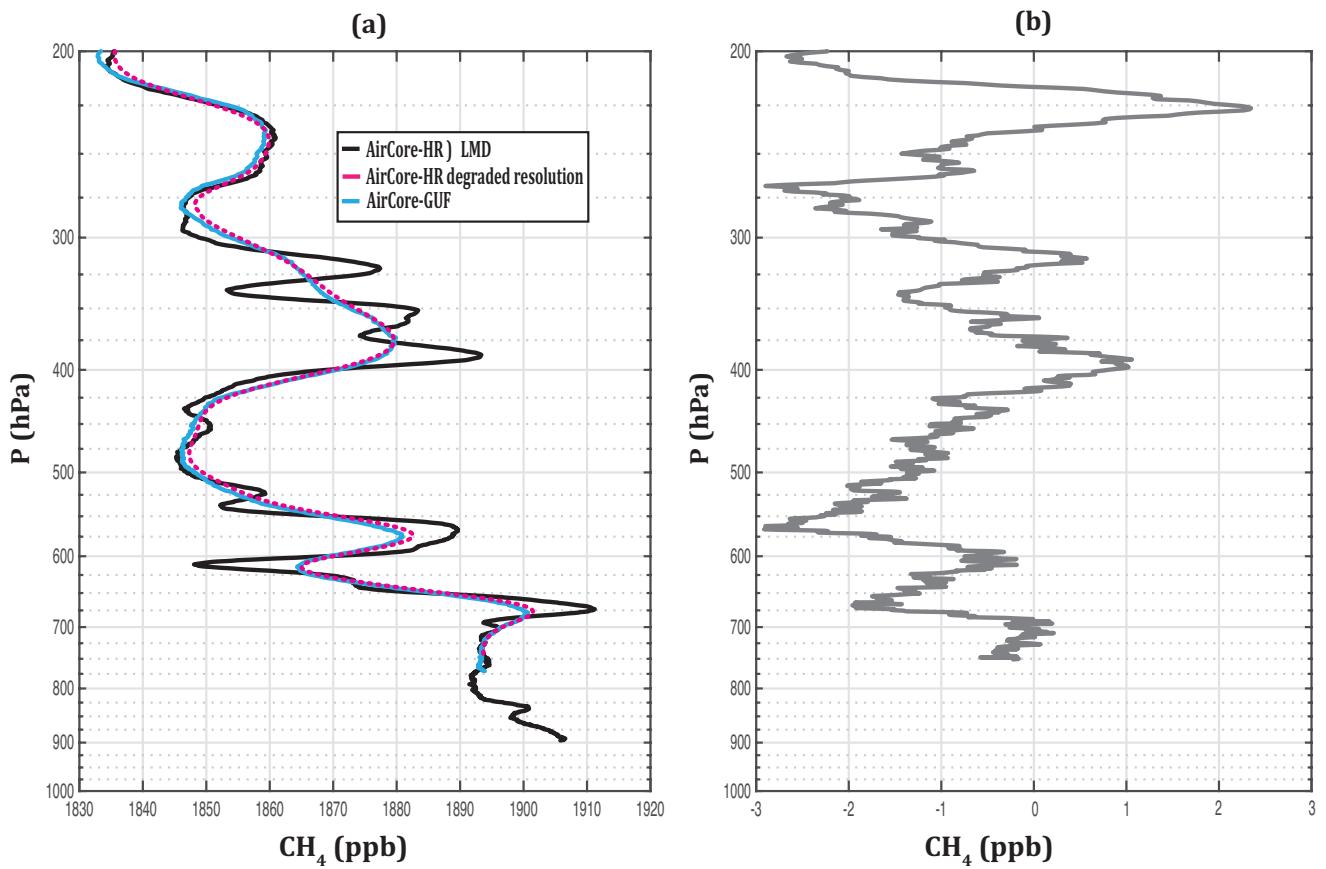


Figure 14. (a) CH_4 vertical profiles from AirCore-HR in full resolution (black), AirCore-HR “degraded resolution” (pink), AirCore-GUF (blue). (b) Residual of the difference AirCore-GUF - AirCore-HR “degraded resolution”.