Results of a Long-Term International Comparison of Greenhouse Gas and Isotope Measurements at the Global Atmosphere Watch (GAW) Observatory in Alert, Nunavut, Canada

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~~Planned Journal~~ **Submission: Atmospheric Measurement Techniques (AMT)**

Abstract

Since 1999, Environment and Climate Change Canada (ECCC) has been coordinating a multi-laboratory comparison of measurements of long-lived greenhouse gases in whole air samples collected at the Global Atmosphere Watch (GAW) Alert Observatory located in the Canadian high Arctic (82°28' N, 62°30' W). In this paper, we evaluate the measurement agreement of atmospheric CO_2, CH_4, N_2O, SF_6, and stable isotopes of CO_2 ($\delta^{13}C$, $\delta^{18}O$) between leading laboratories from 7 independent international institutions. The measure of success is linked to target goals for network compatibility outlined by the World Meteorological Organization's (WMO) GAW greenhouse gas measurement community. Overall, based on ~8000 discrete flask samples, we find that the co-located atmospheric CO_2 and CH_4 measurement records from Alert by CSIRO, MPI-BGC, SIO, UHEI-IUP and~~,~~ ECCC, versus~~and~~ NOAA (the designated reference laboratory) are generally consistent with the WMO compatibility goals of ±0.1 ppm CO_2 and ±2 ppb CH_4 over the 17-year period (1999 – 2016), although there are periods where differences exceed target levels and persist as systematic bias for months or years. Consistency with the WMO goals for N_2O, SF_6, and stable isotopes of CO_2 ($\delta^{13}C$, $\delta^{18}O$) has not been demonstrated. Additional analysis of co-located comparison measurements between CSIRO and~~,~~ SIO~~,~~ versus~~ and~~ NOAA or INSTAAR (for the isotopes of CO_2) at other geographical sites suggests that the findings at Alert for CO_2, CH_4, N_2O and $\delta^{13}C$-CO_2 could be extended across the CSIRO, SIO, and NOAA observing networks. ~~Two separate approaches are also~~The primary approach ~~-carried out for the entire sampling period,~~ to estimate ~~the~~an overall measurement agreement~~-~~ level was carried out~~-to determine the level of agreement as a collective offor the 7 individual laboratories as a collective;(1)~~by pooling the differences of all individual laboratories versus~~over the entire sampling records fromusing a~~ the designated reference laboratory~~. .~~ and determining the 95th percentile range of these data points~~ and (2) averaging the 2 standard deviations (2-sigma) of the means for all flask samples taken in each individual sampling episode over the entire sampling record~~. ~~-~~ Using this approach o~~O~~ver the entire data record, our best estimate of the measurement agreement range ~~level for these individual laboratories~~ is -0.51 to +0.53 ppm for CO_2; 0.09 to +0.07 ‰ for $\delta^{13}C$; -0.50 to +0.58 ‰ ~~-~~for $\delta^{18}O$;~~Tthe results for the first and second approach respectively over the entire data records are areFor~~ ~~CO_2, from 5691 samples, we derive a measurement agreement level of -0.51 to +0.53 ppm using the 95^{th} percentile range of the differences from NOAA measurements. Similarly, we derive a corresponding value of and ± 0.37 ppm for CO_2 using the mean of 2-sigma values from 923 individual weekly sampling episodes. For CO_2~~

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~~isotopes using INSTAAR measurements as a reference, we derive measurement agreement values of,~~ ~~-0.09 to +0.07 and ± 0.06 ‰ for δ^{13}C and,~~ ~~-0.50 to +0.58 and ± 0.31 ‰ for δ^{18}O,~~ ~~for the 95th percentile ranges and the mean of the 2-sigma values, respectively. For other gases, the corresponding values for both approaches are -~~-4.86 to +6.16 ~~and ± 3.62~~ ppb for CH$_4$; ~~for CH$_4$~~ ~~for CH$_4$,~~ -0.75 to +1.20 ~~and ± 0.64~~ ppb for N$_2$O and ~~for N$_2$O, and~~ -0.14 to +0.09 ppt for SF$_6$~~and ± 0.09 ppt~~ ~~for SF$_6$, respectively.~~. A secondary approach of using the average~~d~~ of ~~-~~2 standard deviations~~-~~ of the means for all flask samples taken in ~~each~~ each individual sampling episode provided similar results. These upper and lower limits represent our best estimate of the measurement agreement at the 95% confidence level for these individual laboratories, providing more confidence for using these datasets in various scientific applications (e.g., long-term trend analysis).

1. Introduction

For more than 60 years, scientists have been making high-precision measurements of atmospheric CO$_2$ [**Keeling, 1960**]. At first, the objective was to understand global features in well-mixed marine air by documenting CO$_2$ abundance, seasonal patterns, and trends. For this purpose, only a few remote sampling sites were established. Over time the emphasis has shifted to better understand the carbon cycle including emissions to and removal processes from the atmosphere. Today, a global observational network maintained by many laboratories operates high-precision measurements of long-lived greenhouse gases (GHGs) and complementary trace species at hundreds of locations [**WMO, 2019, 2022**]. The measurement community has held regular meetings on measurement technology since 1975, initiated by Charles David Keeling. Proceedings from these meetings are published in GAW reports [e.g., ~~**WMO, 20165, 2018, 202019;**~~ **GAW Report #229; 242; 255**], which are important references for existing and new laboratories. These reports include measurement target recommendations for GHG network compatibility. These targets reflect the scientifically desirable level of network agreement in measurements of well mixed background air so the data of different laboratories can be used together in global models or to infer regional GHG fluxes.

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Atmospheric measurements of CO$_2$ and other trace gas species and isotopes are ~~being~~ reported by many international laboratories and are often freely available either directly from the originating measurement laboratory [**Masarie et al., 1995, 2014, Ramonet et al., 2020,**

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Heimann et al., 2022] or from ~~world data centers [~~the WMO World Data Centre for Greenhouse Gases~~,~~ (WDCGG) [**https://gaw.kishou.go.jp**]. For nearly 30 years, atmospheric measurements of CO_2 have been used to derive estimates of CO_2 surface fluxes around the globe [**Heimann and Keeling, 1989; Tans et al., 1990; Fan et al., 1998; Bousquet et al., 2000; Gloor et al., 2000; Gurney et al., 2002; Peters et al., 2007; Chevallier et al., 2010; Peylin et al., 2013; Rödenbeck et al, 2018a, 2018b; Friedlingstein, et al., 2022**]. Similar studies have also been carried out for CH_4 [**Houweling et al., 2017**] and N_2O [**Schilt et al., 2010; Thompson et al., 2019**]. When all available datasets are used in those applications the users usually assume that these datasets are compatible and consistent over time. However, the~~The~~ applications may be limited by various types of inconsistencies between the datasets, including differences in scales or scale realizations and in sampling systems or procedures etc. When persistent bias exists between laboratories, the applications such as flux estimates derived by modelling systems using combined datasets on various spatial domains and temporal scales can have large uncertainties [**Masarie et al., 2001; Ramonet et al., 2020**]. To address potential bias, laboratories routinely evaluate measurement traceability and reproducibility within their own laboratory and also compare their measurements with those from other laboratories. Data providers in the measurement community are working hard to include uncertainties with their measurements in order to inform data users. For these reasons~~In this regard~~, evaluating and quantifying the inconsistencies/or biases/ or level of agreements for observational records within and between laboratories over time is important.

Commented [MR8]: Rev.2 L107- World data centre

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The widely adopted strategy for assessing the level of agreement of different atmospheric trace gas data-records is to conduct ongoing comparisons of the measurements of flask air collected at the same time and the same location [**Masarie et al., 2001; Masarie et al., 2003; Langenfelds et al., 2003**]. Based on these previous studies**,** which involved the comparison of only two laboratories at the same location, this~~such a~~ comparison strategy can reveal differences from air sample collection, storage, extraction and analysis, data processing, and maintenance of the laboratory calibration scale etc. Subtle problems can arise at any step in the measurement procedure. They can occur simultaneously and may exist in one or more of the participating laboratories. Identifying the cause(s) of these inconsistencies often proves difficult [**Masarie et al., 2001**]. Many laboratories often participate in additional comparison experiments designed to help elucidate the cause(s) of observed differences. Laboratories also realize that when comparison results are examined in near real-time, the information can be a valuable quality control measure where problems can potentially be detected and addressed soon after they develop [**Levin et al., 2020**]. A data comparison site administered by NOAA and ~~open~~ accessible exclusively to data providers ~~only~~, was established for on-going comparisons in 1999 and it continues operating today. This platform ~~It~~provides preliminary comparisons for quality control purposes and serves ~~is~~ as a~~n~~ good starting point for further in-depth analysis.

The Alert Observatory (ALT), Canada, along with the Mauna Loa Observatory (MLO), USA, and the Cape Grim Observatory (CGO), Australia, are designated as GHG comparison sites by WMO-GAW **[Miller, 2005]**, where well-mixed background air can be sampled and measured. Alert has the most extensive flask comparison program of the three with seven individual flask programs at any time, each focusing on a variety of measurements and respective scientific priorities. In addition**,** the corresponding comparison results among the three sites (ALT, MLO & CGO) can provide more information on site-specific inconsistencies and facilitate merging the data records from individual networks.

In this paper, we present the comparison results of atmospheric CO_2, CH_4, N_2O, SF_6, and the stable isotopes of CO_2 ($\delta^{13}C$, $\delta^{18}O$) measured by the 7 international institutions at Alert over the period of 1999-2016. Although some laboratories have measurements prior to 1999 and continue after 2016, this period was chosen because it includes the largest number of laboratories and species measured. ~~This is the first report of such a large-scale comparison study.~~ The participating institutions are Environment and Climate Change Canada (ECCC), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Max Planck Institute for Biogeochemistry (MPI-BGC), Heidelberg University, Institut für Umweltphysik (UHEI-IUP), Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Scripps Institution of Oceanography (SIO), and the National Oceanic and Atmospheric Administration (NOAA) in collaboration with the Stable Isotope Laboratory at the University of Colorado Institute of Arctic and Alpine Research (INSTAAR). Together with Alert results, we also present corresponding comparisons between CSIRO, SIO and NOAA at MLO and between CSIRO and NOAA at CGO for the same time period (1999-2016). This is the first report of such a large-scale comparison study. ~~It is preferable to have more~~While timely publications of the inter-comparison results are desirable, it can~~, but it becomes's~~ be challenging due to~~difficult with~~ the ~~large~~~~substantial~~large number of groups involved~~,~~ and on-going ~~changing~~ evolving parameters including ~~(such~~the adoption of ~~as e.g~~new calibration scales, data corrections and the~~) and~~ limited dedicated resources~~lack of~~ to carry out these ~~dedicated staff for this~~ exercises~~purpose~~.

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2. Methods

2.1 Types of Comparison

The commonly used measurement approaches for GHGs and related tracers include 1) discrete flask air samples collected in the field (commonly collected as a pair or as multiple flasks in series or in parallel) and shipped to a measurement laboratory or laboratories for analysis, and 2) continuous measurements in situ, conducted using analytical equipment located at the sampling location. The two approaches are complementary, and each approach will remain essential due to their respective advantages and disadvantages. In situ measurements can provide information at very high temporal resolution so that synoptic scale meteorological events can be observed, which may only by chance be captured by a weekly discrete air sample. In situ monitoring approach requires a physical facility with reliable power, easy access as well as a high degree of automation and internet capability to monitor the observation systems remotely. On the other hand, flask air samples are returned to the laboratories with sufficient air and many laboratories can measure multiple trace gases and their stable isotopes from a single discrete air sample. Also, the relatively low operating cost and minimal infrastructure requirements of flask sampling allows for spatial coverage involving more locations. Many laboratories have opted for an approach including discrete flask-air sampling and, when possible, in situ measurements at one or two key sites to balance temporal and spatial coverage and a suite of measured species.

This study presents two types of discrete flask comparisons, which are known as co-located and same-flask comparisons. The focus is the co-located comparisons but results from the same-air flask comparisons, as well as same-cylinder (Round Robins) comparisons, are included to help facilitate the interpretation of the co-located comparison results. These complementary comparisons could reveal cumulative differences due to errors introduced at one or more steps in the entire sampling and measurement process.

Co-located flask air measurement comparison: A co-located comparison generally describes a comparison of two or more measurement records derived using independent collection systems or methods and/or analytical systems at the same location, at approximately the same time and during predefined atmospheric conditions (i.e. wind

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direction and minimum wind speed requirements). When these conditions are met, observed differences are primarily due to experimental discrepancies instead of changes in the atmospheric signal. Co-located comparisons are designed to evaluate the measurement agreements within or between laboratories due to uncertainties associated from sampling procedures/systems, analytical procedures, data processing, and laboratory calibration scales. Potential errors could arise from any or all of the steps.

Same-flask air measurement comparison: A same-flask air comparison evaluates the independent measurement results when two or more programs or analytical systems measure air from the same “collected sample” container for the same suite of trace species. Typically, the same-flask air comparison sample is shipped from the remote sampling location to the closest participating laboratory or to the laboratory with lowest sample consumption. This same-flask sample is then shipped to a second participating laboratory for analysis. Additional laboratories or analytical systems could further analyze the sample provided there is sufficient air remaining in the flask, although the risk of sample contamination or alteration may increase. A same-flask comparison experiment evaluates the measurement agreement within or between laboratories caused only by measurement and data processing steps and not by sample collection procedures/systems. A problem during sample collection, such as contamination, could still potentially affect the air in the flask, but this should not impact the comparison results for same-flask analysis. Typically, only one flask of a pair is analyzed by both labs, thereby providing information whether the analysis procedure by one of the labs has caused contamination or altered the composition of the air in the flask. The reference laboratory for same-flask comparisons at Alert is ECCC.

Same-cylinder air measurement comparison: A same-cylinder air measurement comparison refers to an experiment in which two or more laboratories measure air in a pressurized cylinder for the same suite of trace species and then compare the independent measurement results. Like the same-flask air comparison experiment, the same-cylinder air comparison evaluates the measurement agreements within or between laboratories involving the overall uncertainties from analytical procedures (i.e., extracting air from the cylinder, introducing the aliquot of air into their detection system, measuring the sample) to processing the results and maintaining their laboratory calibration scales. Because the volume of air sample in a pressurized cylinder is orders of magnitude greater than that in a flask, many more laboratories can participate in the comparison, and each laboratory can make multiple measurements thereby obtaining an optimized measurement uncertainty. One drawback of the same-cylinder comparison is the added time and expense of shipping pressurized cylinders, which can be subject to strict international safety regulations. Consequently, the frequency for this type of comparison is from quarterly, at best, to every few years and the results only represent a snapshot in time. It should be noted that analyzers used to measure flask samples are not necessarily the same instruments that are used for cylinder air analysis in each laboratory, and this can contribute uncertainty and possibly bias to the comparison. It is important in these types of comparisons that at least one laboratory, generally the coordinating laboratory, measure the air before and after any other laboratories to characterize/quantify any composition changes that may have occurred during the period of comparison. In addition, it is important to note that ~~,~~ drifts in concentrations may occur ~~change due to~~ with cylinder depressurization.

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The WMO/~~ and~~ IAEA ~~co-sponsored~~ "Round Robin" (RR) comparison experiment, administered by NOAA, ~~-~~is one example of a same-cylinder air comparison experiment. This experiment is designed to assess the level of agreement within the participating laboratories and assess their ability to maintain links to the WMO mole fraction scales for CO$_2$, CH$_4$, and other trace gas species. There have been seven WMO/IAEA Round Robin experiments since first introduced in 1974; the most recent experiment started in November of 2020, includes participation by 59 laboratories [Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases (noaa.gov)] and is still ongoing. Round Robin results from RR# 5 and 6 from the participating laboratories are included in certain figures and in **Table S1**, if the results are on the same scale as the data used in this analysis**.**

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2.2 The Alert Dr. Neil Trivett Global Atmosphere Watch Observatory

Alert, Nunavut, is located on the northern tip of Ellesmere Island in the high Canadian Arctic (82°28' N, 62°30' W) far from the major industrial regions of the Northern Hemisphere. Alert is the site of a military station, Canadian Forces Station (CFS) Alert, and an ECCC Upper Air Weather Station. The Alert Dr. Neil Trivett Global Atmosphere Watch (GAW) Observatory (ALT) is located 6 km south of CFS Alert on a plateau 210 m above sea level. The land around Alert is covered with snow for almost ten months of the year and has a sparse covering of polar desert vegetation in the summer. The degree of contamination from the local environment is minimal, with winds originating from within the ENE sector, which includes CFS Alert camp [**Worthy et al., 1994**], less than 4% of the time. The ALT observatory is ideally situated for monitoring well-mixed air masses representative of very large spatial extent in the Northern Hemisphere. ALT has been the cornerstone of ECCC's atmospheric research program since 1975, and in 1986, was officially designated a WMO/GAW Global Observatory. The Observatory was officially renamed to the Dr. Neil Trivett Global Atmosphere Watch Observatory in 2006. With its existing infrastructure and strong multi-laboratory research activity, ALT is well positioned to support a multi-laboratory co-located atmospheric comparison experiment.

2.3 Flask Sampling ~~Parameters & Comparison Programs~~ at ~~the~~ ALT~~lert~~, MLO and CGO~~Observatory~~

2.3.1 Sampling timelines

~~As mentioned previously, the Alert program has the most extensive flask comparison program among the three GHGs comparison sites designated by WMO-GAW. **Table 1** summarizes t~~The species measured, types of comparisons (co-located / same flask), and timelines of comparison experiments conducted at Alert~~,~~ from ~~In this report, we present results for the period~~ 1999-2016 are summarized in **Table 1**. ~~As shown in **Table 1**,~~ I~~i~~ndividual laboratory participation and species measured were not consistent over the entire 17-year period. ~~;~~ F~~f;~~ for example, ~~the~~ ECCC's program for~~flask air sampling program for~~ CO_2 isotopes was terminated ~~was terminated~~ in December 2009 and LSCE's program for all trace gases and isotopes was discontinued~~terminated~~~~ceased~~ in September 2013. The same ~~-~~flask air comparison program for all trace gases at Alert has an end date of ~~was discontinued in~~ December 2013.

~~.~~ At MLO and CGO, co-located flask sampling was conducted by CSIRO, SIO and NOAA for the same species and similar time periods as ALT. ~~The LSCE flask air sampling was terminated in September 2013.~~

2.3.2 Sampling systems

Table 2.1 describes~~lists~~ the sample collection system at ALT for each laboratory~~'s sample collection system at ALT~~, including flask type, sampling frequency and apparatus used during the specified time period. Most laboratories at ALT used double-stopcock flasks, which allow for flow-through flushing~~,~~ prior to filling to an overpressure of 5 to 15psi. ~~;~~ E~~e~~xceptions include SIO, who used single-stopcock, evacuated flasks and CSIRO, who used some single-stopcock pressurized flasks from 1999 to ~~-~~2003. Air was typically dried using a

Commented [MR24]: Rev.3 L387- overpressure in flasks cryocooler before filling by ~~M~~most laboratories~~ dried the air prior to filling using a cryocooler~~, except SIO and NOAA, ~~-~~who didn't dry their air samples either by a cryocooler or by a ~~use a~~ chemical drier, ~~-~~and MPI-BGC, ~~-~~who used a $Mg(ClO_4)_2$ dryer until 2015 before ~~and then~~ switching~~ed~~ to a cryocooler. Sampling was conducted~~All samples were taken from~~ at a height of 10m~~ heights~~, except SIO and NOAA, whose intakes were roughly 2m and 5m, respectively.

At MLO, SIO's sampling was the same as ALT, but CSIRO's sampling used a chemical dryer instead of a cryocooler and had a 40m air intake. NOAA's sampling was similar to ALT, but some samples were also taken via an undried flow from their *in situ* system (40m). [**Conway et al., 1994** and **Dlugokencky et al., 1994**].

At CGO, CSIRO's sampling used a chemical dryer from 1999 to ~~-~~2014 and then switched to a cryocooler and new sampling system. NOAA's sampling at CGO was partially dried, ~~as opposed to~~in contrast to being undried at Alert. Samples from ~~B~~both laboratories were taken from 70m heights. [**Francey et al., 2003**] and [**Langenfelds et al., in press**]. **Table 2.2** outlines the various differences between sampling at ALT, MLO and CGO for CSIRO, SIO and NOAA.

Commented [LR(A25]: This Langenfelds et al. report is 'in press' at this moment awaiting finalisation of the Baseline 2014-16 edition (should be in coming months). It could be included as a reference if journal rules allow 'in press' or if it gets published before this paper.

~~described below, and~~ Further details about the sampling procedures of all laboratories~~'~~ ~~sampling~~ can be found in the Supplementary material (SI). ~~Noteable~~Notable impacts of certain sampling parameters on the results, are mentioned in the R~~r~~esults and D~~d~~iscussion (section 3).

Commented [MR26]: Rev.3 general discussion about sampling parameters

2.3.3 Sampling conditions

Table 3 provides the coordinated ALT weekly flask air collection schedule for ~~individual~~ participating laboratories.~~ Flask air samples were collected at Alert during persistent southwesterly wind conditions, when wind speeds were greater than 1.5 m s^{-1} for several hours prior to sample air collection.~~ The coordinated sampling schedule was devised to ensure that the flask samples for each individual laboratory are collected on the same day and as close in time as possible, within a 2-hour window. Small variations in sampling time are un~~not~~ likely to ~~contribute~~ result in notable discrepancies. Flask air samples were collected at Alert during persistent southwesterly wind conditions, when wind speeds were greater than 1.5 m s^{-1} for several hours prior to sample air collection. If ~~the~~ conditions ~~weren't appropriate~~ were unsuitable on the regular sampling day (Wednesday), sampling would be ~~delayed~~postponed to the following day. If conditions ~~weren't~~remained unfavorable by Friday, ~~the~~ sampling would ~~still be done~~proceed, but it was ~~noted~~acknowledged that conditions ~~weren't ideal~~were suboptimal.

Commented [MR27]: Rev.3 L281-283 regarding sampling conditions.

At MLO, sampling for all laboratories (NOAA, CSIRO and SIO) was ~~done~~conducted within an hour of each other and ~~also done~~ prior to noon (local time) in an effort ~~to try and~~ to avoid upslope, non-baseline wind conditions at the site.

At CGO for NOAA and CSIRO, sampling was ~~mostly done~~predominantly carried out under baseline conditions of 190-280°N wind direction and wind speeds exceeding ~~>~~ 5 ms^{-1} wind speed, or the data was subsequently ~~-~~filtered ~~afterwards~~ for baseline conditions.

~~In this report, we present results for the period 1999-2016. As shown in **Table 1**, individual laboratory participation and species measured were not consistent over the entire 17-year period; for example, the ECCC flask air sampling program for CO_2 isotopes was terminated in December 2009. The same flask comparison program for all trace gases at Alert was discontinued in December 2013. The LSCE flask air sampling was terminated in September 2013. Further details on the individual flask air sampling programs at Alert are described below.~~

2.4 Instrumentation and Analytical Methods

Instrumentation and methods used to measure the flask air samples collected at the sampling sites~~Alert~~ vary between the laboratories and continue to evolve within each laboratory. To the extent possible, each laboratory handles the ~~Alert~~ flask air samples and measurements in the same way as other flasks from their observing network. **Table 4** summarizes each laboratory's analytical instrumentation and calibration scales used for each species, for the period of this study. A brief summary of the instrumentation is provided below and calibration scales will be discussed in more detail in the results and discussion (section 3).

For CO_2, all laboratories except for NOAA and SIO used gas chromatography (GC) equipped with a nickel catalyst and flame ionization detector (FID) for the analysis of CO_2 in the flask~~the weekly discrete~~ air samples~~collected in flasks~~. The nickel catalyst converts CO_2 in the ~~air~~ sample to CH_4, permitting analysis of CO_2 using the FID. NOAA used non-dispersive infrared (NDIR) spectroscopy ~~for the analysis of CO2~~throughout and ~~.~~ SIO used an NDIR until 2012, and then switched to ~~when it was replaced by~~ a Cavity Ring Down (CRDS) analyser. The GC, NDIR and CRDS systems have comparable analytical precision, ~~with analytical repeatability ra~~ranging between 0.01 ppm (CRDS) and 0.05 ppm (GC). ~~.~~

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For stable isotope ratio measurements of atmospheric CO_2, all participating laboratories used Isotope Ratio Mass Spectrometry (IRMS). Before introduction of the sample into an IRMS, the CO_2 in the air sample is first extracted using either an off-line glass vacuum extraction system to prepare samples for later analysis [**Bollenbacher et al., 2000; Huang et al., 2013**], or using an on-line metal vacuum extraction system coupled directly to the mass spectrometer [**Trolier et al., 1996; Werner et al., 2001; Allison and Francey 2007**] for analysis within 1 hour of CO_2 extraction. All laboratories except ECCC and SIO used an on-line extraction approach; ECCC and SIO used an off-line technique where pure CO_2 samples were flame-sealed in ampoules after extraction and stored for variable lengths of time, ranging from one month to one year before IRMS analysis (it has been verified at ECCC that the isotopic compositions of CO_2 in ampoules do not change within the range of accepted uncertainty during a storage time of > 10 years). All the laboratories used dual-inlet mode for $\delta^{13}C$ and $\delta^{18}O$ measurements but employed different strategies to link the individual sample measurements to the primary scale VPDB-CO_2. **Table 5** details the various calibration strategies used and highlights the differences that exist between the laboratories. Since 2015, the WMO-GAW community has endorsed the JRAS-06 realization **[Wendeberg et al., 2013, WMO, 2011; GAW#194]** of the VPDB-CO_2 scale for reporting stable isotope measurements of atmospheric CO_2, but this has not been fully implemented by all laboratories. For each laboratory, the repeatability of $\delta^{13}C$-CO_2 and $\delta^{18}O$-CO_2 measurements are typically less than 0.02‰ and 0.04‰ (one-sigma), respectively.

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For CH_4, all participating laboratories used gas chromatography (GC) with flame ionization detection (FID) for analysis of CH_4, with typical analytical repeatability of less than 3 ppb. For N_2O and SF_6, all participating laboratories used gas chromatography (GC) equipped with an electron capture detector (ECD) for analysis of N_2O and SF_6 in the weekly collected flask air samples. The analytical repeatability for N_2O and SF_6 using GC-ECD is typically 0.2 ppb and 0.04 ppt respectively.

2.5 Data Preparation

All measurements used in this study have been screened by the originating laboratory to ensure that each sample and subsequent measurement have not been compromised during collection, storage and analysis. Each laboratory determines their own criteria for the quality control of their data and assigns the flags “valid”, “invalid” or “suspected”. These data files were provided to us by individual laboratories and have specific time stamps, which can be found in **Table S2**. These time stamps identify the state of the data used in this study, in terms of scale updates/ corrections etc., which is important information because the same datasets may be found in other data-repositories as updated versions with scale changes and /or modifications. As the data preparation is critical to the results, we describe the detailed methods for data preparation used in this study in the following sections.

Commented [MR31]: Rev.1 minor #2 storage corrections?

Commented [R(l|sh(32R31]: Added the word storage to show that some labs might have made storage corrections, as part of their quality control procedures.

Data Matching and Reference time Series: To match the appropriate co-located and same-flask measurements from the 7 laboratories for comparison, participants agreed to submit measurement results that include information on sample collection time (in Coordinated Universal Time (UTC)), collection method, flask identification, measurement value, quality control flag, and analytical instrument identification. Matching algorithms identify and separate same-flask measurements (samples with identical collection date/time and container ID) from co-located measurements. All data that have been flagged as “valid” by each individual laboratory, are used.

All same-flask measurements from ALT are differenced from measurements by ECCC, on a one-to-one basis (i.e., laboratory minus ECCC). All co-located flask measurements from ALT, CGO and MLO are differenced from the reference time series of NOAA for CO_2, CH_4, N_2O, and SF_6 and INSTAAR for $\delta^{13}C$ and $\delta^{18}O$ of CO_2 (laboratory minus NOAA or INSTAAR). Ideally, the reference time series should demonstrate consistency over the entire comparison period, have minimal gaps, and accurately represent the true abundance of the atmospheric trace gas constituents at the sites. In practice we do not have a single laboratory who we know to be the truth, so we must choose one that best meets our requirements. NOAA and INSTAAR were chosen because their records span the entire period of our study with minimal data gaps. Also, by hosting the WMO Central Calibration Laboratory for CO_2, CH_4 and N_2O, NOAA is well placed to assess measurements on the WMO scales and INSTAAR, by virtue of their close association, is an appropriate choice for the stable isotopes of CO_2. Further, NOAA/INSTAAR has extensive and well-documented quality control procedures in place to ensure internal consistency of its measurements [**Conway et al., 1994; Dlugokencky et al., 1994; Trolier et al., 1996**].

Co-located Data Pool and Analyses*:* Prior to any ALT, CGO and MLO co-located analyses, data pools were created for each site and species, consisting of no more than two valid measurements from each laboratory (including NOAA and INSTAAR) for each day of sampling (sampling episode). Since most participants collect a pair of air samples during each sampling episode, two measurement results are typically available. When more than two valid measurements exist for a given sampling episode from a laboratory, we select two at random from the set of available measurements. For example, three (and sometimes four) MPI-BGC flask air samples are collected during each sampling episode at Alert, so two measurements are selected at random from the available valid MPI-BGC measurements and added to the data pool. If there is only one valid measurement available from one of the laboratories, we do include that single sample in the data pool. This data pool process allows for a more equal representation for all laboratories. The first analysis performed using the ALT data pool, was the calculation of mean flask pair differences for CO_2, $\delta^{13}C$-CO_2, $\delta^{18}O$-CO_2, CH_4, N_2O and SF_6 for each participating laboratory and these can be found in **Tables S3** to **S8**. These flask pair differences could be used as a proxy of individual lab uncertainties. The discussion of these differences will be found in future sections.

For all sites, each laboratory's individual data points in the pool are differenced from the reference time series data in the same pool (i.e. NOAA or INSTAAR). In most cases, the reference time series has two data points, which are averaged and that value is then differenced from each point of the other laboratory. If the reference time series has only one data point for a certain sampling episode, that single point is used for each point of the other laboratory. Our co-located comparison strategy produces a set of difference time series (laboratory minus reference) for each individual trace gas species and isotope measurement record. Before analyzing the time series, we first examined characteristics of their distributions and found that, in general, they are not normally distributed (non-parametric). The statistical approach carried out in this study is based on the assumption of non-normal distributions. It is quite common to observe a pattern of systematic differences (bias) that can be persistent for many months and then change either abruptly or gradually into a different pattern. Thus, we summarize each distribution of individual differences using annual median values with an estimate of the 95% confidence interval (CI), which makes no assumptions about the distribution of the "true" difference population. The 95% CI is computed using methods described by [**Campbell et al., 1988**]. In this way, our initial statistics should not be unduly influenced by outliers. The final derived annual median deviations are compared to the target goals outlined by the WMO GAW greenhouse gas program to assess the level of agreements of individual datasets with the reference laboratory.

2.6 Level of Agreement between Multiple Measurement Records ~~at the Alert Observatory~~

In addition to the assessment of individual laboratory co-located comparisons, we attempt to estimate the overall level of grouped agreement from multiple measurement records for each species using two approaches. The first approach provides the 95th percentiles of the individual differences of all laboratory's measurements relative to NOAA's or INSTAAR's corresponding observation. However, because variations in NOAA's or INSTAAR's observational records might impact the results, we also report a second proxy for the level of grouped agreement, i.e., two~~-sigma~~ standard deviations (2-sigma) from the means of each weekly sampling episode, which would define a region that includes 95 percent of all the measurement values. Although less susceptible to bias by NOAA or INSTAAR, this grouped proxy is also not ideal because the introduction of new programs could potentially alter the mean and hence the 2-sigma of the group. In addition, the use of 2-sigma values is less reliable than using percentiles for skewed distributions. But by providing both measures for the level of agreement, we hope that any limitation of one measure over the other can be compensated when interpreting them together. The values determined by both methods reflect the overall maximum bias between the measurement records from multiple monitoring programs.

2.7 Data Visualization

For each trace gas ~~species~~ and isotope comparison, we have prepared one figure (Figures 1-6), consisting of several graphs each. For CO_2, δ^{13}C-CO_2, δ^{18}O-CO_2, CH_4 and N_2O, the figures ~~that~~ include~~s~~ five graphs each, from (a) to (e), ~~for CO_2, δ^{13}C-CO_2, δ^{18}O-CO_2, CH_4 and N_2O, respectively. For~~ but for SF_6 there are only four graphs labeled ~~as~~ (a) to ~~-~~(d) ~~for SF_6~~. These figures, along with three data summary tables, are designed to facilitate visualizing and interpreting our results. Graph (a) in these figures displays the time series of each

Commented [R(l|sh(33]: Rev.1 L617. Added a reference to Figures 1-6 laboratory's measurements. It highlights the long-term trend, seasonal patterns, and natural variability in the records and provides context for the comparison results. Graph (b) consists of several panels, each showing the individual co-located measurement difference (laboratory minus reference) for each laboratory. Differences exceeding the graph's y-axis range are plotted with an “X” symbol; however, these data points are still included in all analysis procedures. The dark shaded band, which is also shown in graphs (c) – (e), represents the WMO/GAW recommended target of measurement agreement for well-mixed air at remote sites in the Northern Hemisphere. Results from past WMO/IAEA Round Robin experiments [Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases (noaa.gov)] are plotted as differences (laboratory minus NOAA or INSTAAR) with yellow triangles, representing each laboratory's level of consistency with the reference lab on scale at the time of the experiment. **Table S1** shows Round Robin differences versus NOAA or INSTAAR for all laboratories over the time period (only RR data that are on the same scale as data in the paper have been included). Graph (c) shows, for each laboratory, the annual medians of the differences plotted in graphs (b) with the lower and upper limits of estimated 95% confidence intervals (CI). The fourth graph, Graph (d)**,** for~~ each laboratory,~~ all species except SF_6, shows the same analysis as that done at Alert in graphs (c) but for the co-located comparison experiments between SIO, CSIRO and NOAA at MLO and between CSIRO and NOAA at CGO. Graph (d) for SF6 is the same as Graph (e) for the others, which shows the individual co-located measurement difference (laboratory minus reference) for all the laboratories as a collective. The blue line shows annual values of 95th percentile ranges (2.5 and 97.5), and the pink line shows annual means of 2-sigma for the weekly sampling episodes. For comparison purposes, we have included the annual means, shown in yellow, of the 2-sigma for the combined weekly sampling episodes between CSIRO, SIO, and NOAA at MLO.

In addition to the main figures and tables, supplementary figures and tables are included for some species when applicable.

3. Results and Discussion

As we consider results from 17 years of comparison experiments at Alert, a practical indicator of success is if the measurement agreement reported here falls within the WMO/GAW recommended target levels for network consistency based on well-mixed background air records (**GAW Report #255)**. In other words, it could be assumed that using these records together would not introduce significant uncertainties, if the agreement between independent Alert atmospheric records is consistently within the WMO/GAW measurement agreement goal over the study period.

In this work, we assess the level of agreement for those individual measurement records at Alert by evaluating the differences related to the reference time series and evaluate these differences as annual and overall median values. When persistent differences exceed the WMO/GAW recommended targets, we then consider results from same-flask and same-cylinder experiments to confirm the differences if data is available. To support the results at Alert, the corresponding comparisons at MLO and at CGO are also evaluated.

We recognize that for some species, the network comparison goals may not be currently achievable within current measurement and/or scale transfer uncertainties and that these goals are targeted for application areas which require the smallest possible bias among different datasets for the detection of small trends and gradients. However, there are, of course, other application areas where such tight comparison goals may not be required, such as in urban emission estimates, long-term trend analysis, as well as in some regional modelling studies where uncertainties in air transport, for example, overshadow measurement uncertainties. Our work in this study could provide more confidence on the uncertainty estimation for these applications as well.

3.1 CO_2

All measurements are reported in this paper relative to the WMO X2007 CO_2 mole fraction scale [**Zhao and Tans, 2006**], except for those from SIO, which are reported on the SIO X08A scale [**Keeling et al., 2016~~02~~**]. This data analysis was completed prior to the latest scale upgrades by NOAA (as the WMO Central Calibration Laboratory) to the WMO X2019 scale and by SIO to the SIOX12A scale. Future comparisons within the WMO community should evaluate the implementation of these new scales. Measurements of atmospheric GHGs are reported in units of dry air mole fraction. CO_2 is reported as micromoles CO_2 per mole of dry air (μmol mol^{-1}), abbreviated ppm.

Commented [MR34]: Rev.1 L677-681.Does the X12 upgrade make a difference?

Commented [R(I|sh(35R34]: This is beyond the scope of this paper, but should be evaluated at a future time. A new reference- Keeling et al, 2016 shows very good agreement with NOAA.

As noted above**, Figure~~.~~ 1 (a)** shows the individual co-located atmospheric CO_2 measurement records from air samples collected at Alert (1999-2016). For reference, the average flask pair difference and 1-sigma (standard deviation) for each individual laboratory can be found in **Table S3**. **Figure~~.~~ 1 (b)** shows individual co-located measurement differences (laboratory minus NOAA) along with the darkly-shaded WMO recommended target level ~~of measurement agreement for well-mixed air at remote sites in the Northern Hemisphere (~~of ±0.1 ppm CO_2~~)~~. Results from the WMO/IAEA Round Robin experiments spanning this period are indicated by yellow triangles. The annual median values with 95% CI for each laboratory's difference distribution are shown in **Figure~~.~~ 1 (c)**. A summary of these results is listed in **Table S9~~6~~**.

The overall (1999-2016) median difference of all available individual measurements from each laboratory relative to NOAA (**Table S9~~6~~**) suggests that the CSIRO, MPI-BGC, SIO, UHEI-IUP and ECCC CO_2 records from Alert are consistent with the NOAA record to close to the WMO recommended ±0.1 ppm CO_2 window at the 95% CI~~.~~. However, it is important to be aware that at higher temporal resolution, e.g. yearly, we often observe median differences that exceed the WMO target for one or more consecutive years. As an example, ~~the annual differences between~~ ECCC ~~and NOAA measurements for~~has ~~2001-2007 show~~ a persistent bias of approximately -0.14 ppm from 2001-2007, which is then reduced ~~beginning~~ in 2008. ~~As a second example, annual median differences between~~ UHEI-IUP ~~and NOAA~~ meets the WMO recommended target window ~~for the first 5 comparison years (~~from 2005-2008,~~)~~ ~~and exceed the target window for 6 of the remaining 7 years (2009-2016) with a~~ but has a bias of approximately -0.13 ppm from 2009-2016; the reason for these differences are unclear. An instrument change by SIO in 2012, from an NDIR to a CRDS analyzer, can be seen as a slight reduction of noise in the difference data (Figure.1(b)), and the results seem to be slightly more positive after the change, but the results are still within the WMO target.

Commented [MR36]: Rev.3. cause of differences ?

Commented [R(I|sh(37]: Rev.3- discussion about SIO's instrument change

Measurement differences between LSCE and NOAA show that LSCE ~~co-located CO_2 measurements are~~is consistently high relative to NOAA, resulting in annual differences that exceed the WMO target. However, if we exclude results from the first two comparison years, the LSCE median value offset appears stable at approximately +0.11 ppm CO_2. These findings are consistent with annual median results from the same-flask comparison at Alert, where LSCE measurements tend to be greater than ECCC measurements of the same-flask sample (**Figure~~.~~ S1** and **Table S10~~9~~**). The overlaid WMO Round Robin results (**Figure~~.~~ 1(b), Table S1**) show reasonable consistency between the LSCE internal scale and the WMO CO_2 mole fraction scale.

Figure~~.~~ S2 shows median differences (laboratory minus NOAA) by month for each laboratory using data from the entire 17-year period. Overall, with the exception of SIO, we found no obvious evidence of significant seasonal bias in the co-located CO$_2$ difference distributions. The SIO measurements relative to NOAA during the May-September period relative to the October-March period possibly showed a bias on the order of 0.25 ppm. A similar monthly analysis (not shown here) using results from the SIO and NOAA co-located comparison experiment at Mauna Loa (MLO) did not show a similar seasonal bias result, suggesting that the observed seasonal bias between SIO and NOAA at Alert may be unique to this site. The reason for this is unclear; the sampling at both sites is very similar.

Figure~~.~~ 1(d) provides the results from similar co-located comparison experiments between CSIRO, SIO and NOAA at MLO, and at CGO, which are plotted with the results from Alert. **Table S1~~7 ~~1** shows that the overall median difference of all individual measurements of CSIRO relative to NOAA is -0.07 (95% CI: -0.09, -0.04 ppm) at MLO and 0.03 (95% CI: 0.02, 0.03 ppm) at CGO, respectively, which are relatively consistent with our findings at Alert of -0.05 (95% CI: - 0.06, -0.03) ppm. Also included in the figure are results from co-located comparison experiments between SIO and NOAA at MLO where the overall median difference is -0.11 (95% CI: -0.13, -0.10) ppm CO$_2$. This difference is larger than our findings at Alert of -0.02 (95% CI: -0.04, -0.01) ppm, but is still close to the target window of ±0.1 ppm.

Figure~~.~~ 1(e) shows individual co-located CO$_2$ measurement differences, in ppm, relative to NOAA for all the laboratories as a collective. Differences exceeding the y-axis range are plotted with an "X" symbol on the appropriate extreme axis. For the approach of using the 2.5 and 97.5 percentiles of ~~, we estimate an overall measurement agreement among the seven independent Alert CO$_2$ records resulting from t~~the aggregated~~ion of all the individual~~ differenced~~s~~ data ~~from NOAA~~ (laboratory minus NOAA), an overall collective agreement level of ~~to be~~ -0.51 to +0.53 ppm ~~window~~ (N=5691) was found for the seven laboratories~~over the period of 1999-2016~~. The corresponding data can be found in **Table S12~~8~~**. ~~This upper and lower limit contains 95% of the entire difference distribution from all laboratories and represents our best estimate of the measurement agreement within the laboratories.~~ For the approach of using annual means of the 2-sigma variation of weekly sampling episodes, an overall measurement agreement ~~among the seven independent Alert CO$_2$ records~~ is within the ± 0.37 ppm window (N=923) also at 95% of CI. For comparison purposes, we have included the annual means of the combined 2-sigma variation results at MLO (**Fig. 1(e)** and

Commented [MR38]: Rev 1. L724. What's the cause of the bias only at Alert?

Commented [R(l|sh(39R38]: The reason is unclear; could be many things, like differences in temperatures at the two sites.

Table S12~~8~~) shown as the yellow lines (no individual data points are shown) with a comparable result of ± 0.34 ppm (N=905).

The observed measurement differences (as annual medians) found in this study can also provide a first estimate of time-~~-~~dependent uncertainties of observations from a single laboratory. To assess the impacts of those uncertainties on related applications (e.g., long-term trend analysis), we estimate long-term trends of CO_2 from the six individual datasets (CSIRO, MPI-BGC, UHEI-IUP, SIO, ECCC, NOAA) for various 11 and 12-year time periods (2005-2016, 2005-2015, 2006-2016) via Nakazawa's curve-fitting routine (Nakazawa et al., 1997). **Table S13~~0~~** shows very consistent results for these applications. The long-term increases in CO_2 concentrations are 23.62 (2.15 ppm/year) ± 0.40 ppm (2-sigma) for 2005-2016, 21.11 ± 0.38 ppm (2-sigma) for 2005-2015, and 20.87 ± 0.22 ppm (2-sigma) for 2006-2016, respectively. The relative differences between the independent datasets are within a narrow range of 1.5 - 2.4 %, indicating that reliable results can be achieved from the~~o~~se individual datasets for long-term trend analysis (>10 years). It is likely that much larger relative uncertainties would be involved in annual growth rate determination using the corresponding datasets.

3.2 δ^{13}C of CO_2

Stable carbon isotopic ratio measurements in CO_2 are reported commonly as delta values [**McKinney et al., 1950; Craig, 1957; Faure, 1986; O'Neil, 1986; Gonfiantini, et al., 1993; Coplen, 1994; Hofes, 1996; Trolier et al., 1996**]. A delta value defined here is the relative deviation of two isotopic ratios between a sample and the standard, i.e., the primary VPDB-CO_2 or VPDB scale (VPDB: Vienna Pee Dee Belemnite). As the numerical value of a relative deviation is usually very small (close to 10^{-3}), it is normally multiplied by 10^3 and expressed in permil (‰) as in the following relationship [**Coplen, 1994; Coplen et al., 2002**]:

$$\delta^{13}C_{samp/VPDB\text{-}CO2} = [((^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{VPDB\text{-}CO2})-1] \times 10^3\ ‰$$

There is no single approach to the realization of the VPDB scale amongst individual laboratories (**Table 5**); in other words, although the laboratories have created local scales relative to VPDB through a link to NBS19, small inaccuracies in establishing this link may introduce scale differences between the measurement records. This should be kept in mind while interpreting the differences between the data records.

Figure~~.~~ 2(a) shows the individual co-located atmospheric δ^{13}C-CO$_2$ measurement records at Alert (1999-2016) and **Figure~~.~~ 2(b)** shows individual co-located measurement differences (laboratory minus INSTAAR) by laboratories. The average overall flask pair difference and 1-sigma standard deviation for each individual laboratory can be found in **Table S4**. The overall median difference results (**Figure~~.~~ 2(c), Table S14~~9~~**) seem to show that ECCC's δ^{13}C-CO$_2$ records from Alert agree with INSTAAR to within ±0.01‰ at the 95% CI, although the comparison period was relatively short (1999-2009) and the results change in both directions. Similar to the CO$_2$ results discussed previously, it is again important to be aware that at higher time resolution, we observe periods where the differences significantly exceed the WMO target and show changes in sign that persist for one or more consecutive years. For SIO, we observe a persistent positive offset between SIO and INSTAAR measurements with a median of 0.03 (95% CI: 0.02, 0.03) ‰, which exists for much of the comparison period. We also observe that while the overall median differences for CSIRO, MPI-BGC, and UHEI-IUP relative to INSTAAR exceed the WMO target window with persistent negative biases ranging from -0.02 to -0.03 (95% CI: -0.04, -0.02) ‰, the results suggest that the Alert δ^{13}C-CO$_2$ records from these 3 laboratories show more agreement with each other than with the INSTAAR reference. It is noted that INSTAAR's measurements are linked to the VPDB-CO$_2$ scale through the calibrations performed by MPI-BGC (the WMO Central Calibration Laboratory: CCL) via the JRAS-06 realization. The agreement between INSTAAR and MPI-BGC appears to be better after 2015, however, prior to 2015, a bias seems to persist (**Figure~~.~~ 2(c)**). As more laboratories within the community move towards linking their isotopic measurements of air CO$_2$ to the VPDB-CO$_2$ scale through the JRAS-06 realization and more comparison results are ultimately expanded over longer time periods and at larger spatial scales, this may improve our ability to assess some of the issues we are currently experiencing. All LSCE annual median values exceed the target window and show that LSCE co-located measurements are consistently more negative relative to INSTAAR with an overall median difference of -0.15 (95% CI: -0.16, -0.14) ‰ over the available period (2007-2013). LSCE is aware of ongoing issues with the traceability of their laboratory scale, which likely accounts for the observed results. Thus, we exclude LSCE measurements from our estimate of the grouped measurement agreement (discussed later). It is also noticed that based on T- test results (not shown), the calculated mean differences between laboratories and INSTAAR are statistically significant for almost all of the labs, although they are small; these results indicate that systematic differences do exist, which likely include scale realization differences.

Analysis of the median differences by month for each laboratory relative to INSTAAR (not shown) over the available periods suggests there are no significant seasonal dependencies. We also note that corresponding results from available Round Robin experiments (**Figure~~.~~ 2(b), Table S1**) seem generally similar to the individual flask measurement differences from INSTAAR, which provides evidence that analytical procedure, calibration methods and the approach for realization of the VPDB scale utilized by the participating laboratories may play an important role in the results.

Figure~~.~~ 2(d) and **Table S15~~10~~** show~~s~~ the similar co-located comparison experiments for δ^{13}C-CO$_2$ between CSIRO, SIO and INSTAAR at Mauna Loa (MLO) and between CSIRO and INSTAAR at Cape Grim (CGO). These results are also plotted with the results from Alert. The overall median difference of all individual measurements for δ^{13}C-CO$_2$ (CSIRO minus INSTAAR) is -0.02 (95% CI: -0.02, -0.01) ‰ at MLO and -0.01 (95% CI: -0.01, -0.01) ‰ at CGO, respectively, which are fairly consistent with the findings at Alert of -0.03 (95% CI: -0.03, -0.02) ‰. The corresponding median difference value of SIO from INSTAAR at MLO is 0.02 (95% CL: 0.02, 0.02) which is also close to the values of 0.03 (95% CL: 0.02, 0.03) at Alert.

For an estimation of the overall grouped measurement agreement among the six independent δ^{13}C-CO$_2$ records at Alert (LSCE has been excluded), the results from two approaches are included in **Figure~~.~~ 2(e).** The estimated overall measurement agreement (**Table S16~~1~~**) among the six independent Alert δ^{13}C-CO$_2$ records is within the -0.09 to +0.07 ‰ window (n=3256). The pink lines in **Figure~~.~~ 2(e)** represent the annual means of 2-sigma of each weekly δ^{13}C-CO$_2$ sampling episode. The estimated overall measurement agreement among the six independent Alert δ^{13}C-CO$_2$ records is within the range of ± 0.06 ‰ (n=899). For comparison purposes, the annual means of the 2-sigma values from MLO in **Figure~~.~~ 2(e)** (yellow lines) and **Table S16~~11~~**, show comparable results of ± 0.05 ‰ (n=756).

3.3 δ^{18}O of CO$_2$

Oxygen isotopic ratio measurements in CO$_2$ are also commonly reported as delta values. A delta value is defined as the relative deviation of two isotopic ratios between a sample and the standard (i.e., the primary VPDB-CO$_2$ scale). Similar to δ^{13}C, the numerical value of the relative deviation in δ^{18}O is usually very small and is normally multiplied by 10^3 and expressed in permil (‰), as in the following relationship:

$$\delta^{18}O_{samp/VPDB\text{-}CO2} = [((^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{VPDB\text{-}CO2})-1] \times 10^3 ‰$$

The “-CO_2” after VPDB indicates that the scale is linked via the CO_2 from the VPDB carbonate material by a standard procedure of acid digestion using phosphoric acid at 25 degrees Celcius [**McCrea, 1950; O'Neil, 1986; Brand et al., 2009; Wendeberg et al, 2011; Huang et al., 2013]**. If the local scale used by different laboratories does not follow the same procedure, then δ^{18}O-CO_2 results may not be compatible.

Figure~~.~~ 3(a) shows the individual co-located atmospheric δ^{18}O-CO_2 measurement records at Alert (1999-2016) and **Figure~~.~~ 3(b)** shows individual co-located measurement differences (laboratory minus INSTAAR) along with the recommended WMO target level of measurement agreement. For reference, the average flask pair difference and 1-sigma variability for each individual laboratory can be found in **Table S5.** The overall (1999-2016) median differences of all available individual measurements from each laboratory relative to INSTAAR (**Figure~~.~~ 3(c)**, **Table S17~~12~~)** show that the δ^{18}O-CO_2 records by MPI-BGC and ECCC are each roughly compatible with the INSTAAR record to within the WMO recommended ±0.05‰ target window, and SIO and CSIRO are just slightly higher than the target at the 95 % CI (by 0.01‰ and 0.03 ‰, respectively). Similar to CO_2 and δ^{13}C, larger systematic differences are observed in higher temporal-resolution windows~~. It is important to keep in mind that we observe significant variability in the results~~ and annual median values often exceed the WMO target ~~over the study period~~ in opposite direction~~sign~~s. For example, for CSIRO’s median differences from 1999-2009, the majority of the values ~~are~~ fall ~~roughly~~ within the target window. However,~~,~~ ~~but there is~~ a positive bias of approximately 0.16 ‰~~.~~ becomes noticeable from 2010 onwards. ~~of approximately 0.16 ‰.~~ LSCE measurements tend to be more negative relative to INSTAAR with an overall median value of -0.12 (95% CI: -0.15, -0.07) ‰ and UHEI-IUP measurements tend to be more positive relative to INSTAAR, with an overall value of 0.23 (95% CI: 0.20, 0.27) ‰.

However, the overlaid available results from the periodic Round Robin experiments (**Figure~~.~~ 3(b) Table S1**) show less differences than those in flask samples between INSTAAR and the individual laboratories, including CSIRO, MPI-BGC, UHEI-IUP and ECCC; this infers that the larger differences observed in flask measurements might be due to variable moisture levels in the samples. Analysis of annual median differences by month for each laboratory relative to INSTAAR (not shown) does not suggest any seasonal dependencies.

Figure~~.~~ 3(d) and **Table S18~~3~~**, respectively, show the results of δ^{18}O-CO$_2$ from similar co-located comparison experiments between CSIRO and INSTAAR at Mauna Loa (MLO) and at Cape Grim (CGO), plotted with the results from Alert. The overall median difference of all individual measurements for CSIRO relative to INSTAAR is 0.18 (95% CI: 0.17, 0.19) ‰ at MLO and 0.21 (95% CI: 0.21, 0.22) ‰ at CGO, respectively. While the MLO and CGO results are more or less consistent with each other, they ~~are~~ do not ~~consistent~~ align with our overall findings at Alert, which show a value of 0.08 (95% CI: 0.06, 0.10) ‰.~~,~~ ~~h~~However, as mentioned before, CSIRO's median at ALT from 2010 onwards (0.16 ‰) is fairly similar to the overall value at MLO from 1999 to 2016~~.~~. Further data may be needed to make any comments on measurement consistency across entire networks for CSIRO and NOAA for δ^{18}O-CO$_2$. ~~In contrast, t~~The results ~~from co-located comparison experiments~~ between SIO and INSTAAR at Alert and at MLO show a consistent pattern in the difference distribution (SIO relative to INSTAAR) at both sites, with the overall median difference at MLO being 0.03 (95% CI: 0.02, 0.04) ‰ and the median difference at Alert being 0.06 (95% CI: 0.05, 0.08) ‰ and thus, it is likely that the comparison results at first estimation, are representative of measurement consistency across entire networks for SIO and INSTAAR.

Commented [MR40]: Rev.3 possible sampling implications

Commented [MR41]: ? After looking at the data again, found that it may be inconclusive about CSIRO at CGO

~~Therefore, results from co-located comparisons (CSIRO vs INSTAAR) at other locations (MLO and CGO) suggest that the comparison results between CSIRO and INSTAAR are specific to Alert and the findings could not be extended to other network records from CSIRO and INSTAAR. In contrast, the overall comparison results between SIO and INSTAAR at Alert and MLO show similarities and it is likely that the comparison results at first estimation, are representative of measurement consistency across entire networks for SIO and INSTAAR.~~

Finally, we estimate a grouped measurement agreement among the seven independent Alert δ^{18}O-CO$_2$ records by aggregating all individual differences from participating laboratories (relative to INSTAAR) to compute the 2.5 and 97.5 percentiles. This upper and lower limit contains 95% of the entire difference distribution from all laboratories and represents our best estimate of measurement agreement (blue lines in **Figure~~.~~ 3(e)**). **Table S19~~4~~** shows that the 7 independent co-located δ^{18}O-CO$_2$ records at Alert are compatible to within a -0.50 to +0.58 ‰ window (N= 2738). For the approach of using the means of the 2-sigma variation from weekly sampling events through the entire period, the corresponding overall measurement agreement is within the range of ± 0.31 ‰ (n=872; pink lines in **Figure~~.~~ 3(e)**).

For comparison purposes the annual means of the 2-sigma values from MLO in **Figure~~.~~ 3(e)** (yellow lines) and **Table S194**, show a smaller range of ± 0.19 (n=729) ‰.

3.4 CH_4

All CH_4 measurements are reported relative to the WMO X2004A CH_4 mole fraction scale, which is described by **Dlugokencky et al. [2005]** with updated information (2015) available at https://www.esrl.noaa.gov/gmd/ccl/ch4_scale.html (last access: 08/17/2022). Measurements of atmospheric CH_4 are reported in nanomoles (billionths of a mole CH_4) per mole of dry air and abbreviated ppb (parts per billion).

Figure~~.~~ 4(a) shows the individual co-located atmospheric CH_4 measurement records at Alert (1999-2016) and **Figure~~.~~ 4(b)** shows individual co-located measurement differences (laboratory minus NOAA) along with the recommended target level of measurement agreement and Round Robin results. **Figure~~.~~ 4(c)** shows the annual median values with 95% CI for each laboratory's difference distribution. The WMO/GAW recommended target range is again represented by the dark grey band. **Table S20~~15~~** summarizes these results.

The overall (1999-2016) median difference of all available individual measurements relative to NOAA (**Table S20~~15~~**) suggests that the CH_4 records of CSIRO, MPI-BGC, UHEI-IUP, and ECCC from Alert agree with NOAA within the WMO recommended ±2 ppb CH_4 compatibility target window. At higher resolution we sometimes observe differences that exceed the target window for one or more consecutive years, without known causes ~~and can shift from one year to the next resulting in an absolute change exceeding 2 ppb CH4~~. For example, a~~A~~nnual median differences between ECCC and NOAA generally show a consistent offset of approximately -1 ppb except 2003-2004 and 2007, where the offset lies slightly outside the target window. Similar results are observed between LSCE and NOAA where there is a consistent positive offset of ~2 ppb except for 2008 and 2009, where the offset of ~4 ppb lies outside the target window.

MPI-BGC and UHEI-IUP show fairly consistent agreement versus NOAA throughout the time period, with just one year outside the target window for MPI-BGC in 2012. A~~For example,~~ ~~a~~nnual differences for~~nces between~~ CSIRO ~~and NOAA for~~show a slightly negative bias ~~1999-2004 are biased by ~ -1 to -3 ppb relative to the ann~~from 1999-2008~~ual d~~ with one year outside of the target window, and a more positive bias~~ifference for~~ from 2009~~8~~-2016. ~~.~~ ~~Similar shifts in persistent offsets are observed between MPI-BGC and NOAA for some~~

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~~periods (e.g. 2007-2008 and 2011-2012). Annual median differences between UHEI-IUP and NOAA show consistent agreement throughout the entire measurement record and are well within the WMO recommended target window. Annual median differences between ECCC and NOAA generally show a consistent offset of approximately -1 ppb except 2003-2004 and 2007, where the offset lies slightly outside the target window. Similar results are observed between LSCE and NOAA where there is a consistent positive offset of ~2 ppb except for 2008 and 2009, where the offset of ~4 ppb lies outside the target window.~~

Results from the periodic Round Robin experiments (**Figure~~.~~ 4(b), Table S1**) are consistent with the co-located comparison results for each individual participating laboratory. Analysis of annual median differences by month for each laboratory relative to NOAA (not shown) does not suggest any seasonal dependencies.

~~The CH_4 comparison results presented here provide a defensible assessment of the level of consistency among the six independent atmospheric CH_4 records from Alert.~~ ~~**Fig. 4(d)**~~ ~~provides some additional evidence to support this assumption.~~ Results from similar co-located comparison experiments between CSIRO and NOAA at Mauna Loa (MLO) and at Cape Grim, (CGO) are plotted with the results from Alert in **Figure~~.~~4(d)**. As shown in **Table S21~~6~~**, the median difference of all individual CH_4 measurements from CSIRO relative to NOAA is 0.66 (95% CI: 0.38, 0.88) ppb for MLO, 0.11 (95% CI: -0.07, 0.32) ppb for CGO, and 0.01 (95% CI: -0.19, 0.21) ppb for Alert, respectively. The results are all within the WMO recommended compatibility target window. Therefore, the comparison results at the shared site such as Alert could be representative of measurement consistency across entire networks for CSIRO and NOAA for CH_4.

Finally, we estimate an overall measurement agreement among the six independent Alert CH_4 records of -4.86 to +6.16 ppb (N=4472) over the entire period of 1999-2016 (**Table S22~~17~~**), shown in blue lines in **Figure~~.~~ 4(e)**. For the approach of using the means of the 2-sigma variation from weekly sampling events through the entire period, the estimated overall measurement agreement among the six independent Alert CH_4 records is within the range of ± 3.62 ppb (n=887) (pink lines in **Figure~~.~~ 4(e)**). For comparison, we have included the annual means of the combined 2-sigma variation results of ±4.88 ppb (n=375) at MLO in yellow lines (**Figure~~.~~ 4(e)** and **Table S22~~17~~**).

3.5 N_2O

All N_2O measurements are reported relative to the NOAA 2006A N_2O mole fraction scale which is described by **Hall et al. [2007]** with updated information (2011) available at https://gml.noaa.gov/ccl/n2o_scale.html. Measurements of atmospheric N_2O are reported as a dry air mole fraction in nanomoles (billionths of a mole N_2O) per mole of dry air and abbreviated ppb (parts per billion). All N_2O measurements in this study were determined using GC-ECD analytical methodology. These systems typically achieved repeatability of 0.15 to 0.3 ppb, making the comparisons much noisier and therefore, more difficult to evaluate whether the WMO target goal of ±0.1 ppb has been achieved. Fortunately, several new spectroscopic methods are now available and capable of providing analytical repeatability of 0.04 to 0.1 ppb [**O'Keefe et al., 1999; Griffith et al., 2012**;]. These new methods have a potential to make comparisons less noisy and possibly easier to interpret.

Figures~~.~~ 5 (a)-(e) and **Tables S23~~18~~-S26~~0~~** provide the corresponding information for N_2O. The seasonal cycle is more clearly defined in the UHEI-IUP data set (**Figure~~.~~ 5(a))** than in the other data records due to better precision on their specific GC-ECD. Analytical precision of atmospheric N_2O measurement is estimated using agreement between measurements of air collected in two flasks sampled on the same apparatus at the same time. **Table S7** summarizes average flask pair agreement based on air samples collected at Alert. Using pair agreement to estimate short-term noise, we find UHEI-IUP and NOAA N_2O measurements of flask air with repeatability of 0.13 ± 0.08 ppb and 0.30 ± 0.26 ppb, respectively. The NOAA measurement is less precise because it is derived from a single aliquot of air whereas all other laboratories typically use an average of 2-4 aliquots of sample air. Both NOAA and INSTAAR are limited in the volume of sample that can be used for each of their analyses because of the very large suite of trace gas species measured from the NOAA flask air sample. This has a much more profound impact on estimated N_2O precision than for other trace gas species and isotopes.

The overall (1999-2016) median difference of all available individual measurements from each laboratory relative to NOAA (**Table S23~~18~~**) shows that the UHEI-IUP and ECCC N_2O records from Alert are roughly compatible with the NOAA record to within the WMO recommended ±0.1 ppb target window. However, as mentioned in each previous section, at higher resolution, ~~this overall result alone does not convey that at higher resolution,~~ we can observe median differences that well exceed the WMO target for many years.~~–~~ MPI-BGC differences show a consistently positive bias spanning from 2005 to -2014, which is reduced

Formatted: Space Before: 0 pt, After: 0 pt by approximately 2-fold in 2015-2016 when they switched from a Mg $(ClO_4)_2$ dryer to a cryocooler.~~;~~ MPI-BGC suggests ~~believes~~ that these impacts ~~results~~ were mostly ~~impacted~~ pronounced during the wetter~~,~~ summer months~~,~~ and attributes the issues to ~~that the problems were due~~a change in the supplier of the Mg $(ClO_4)_2$. A similar problem was ~~described~~ reported by **[Steele et al., 2007]**. There was no evidence of~~t~~ ~~ceof~~ bias for any of the other trace species. ~~Diffe~~Differences between LSCE and NOAA, which initially exceed the target by 1.2 ppb, steadily improve each year. By 2013, the final year of the comparison for LSCE, the annual median difference has improved by a factor of ~10, to 0.15 ppb but still falls outside the WMO target window. Because the results from the same-flask comparison experiment between LSCE and ECCC (**Figure~~.~~ S3**) show a similar difference pattern, this suggests that the sample collection process is not likely the cause of the observed co-located measurement differences. On the other hand, the same-flask air comparison results (**Figure~~.~~ S3, Table ~~S11~~S24**) for the other laboratories show that the median differences were mostly able to meet the target window, in contrast to the co-located comparisons, suggesting that there may be factors that are specific to the collection of the air itself causing some of the inconsistency among the various laboratories.

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Results from the periodic Round Robin experiments (**Figure~~.~~ 5(b), Table S1**) are consistent with the co-located comparison results for each participating laboratory. With~~In~~ regard to seasonal dependencies, an analysis of median differences by month (not shown) displayed consistent offsets for each month indicating that the date of sample collection had no bearing on the annual results.

Earlier, we mentioned that analytical precision (estimated from flask pair agreement) of NOAA measurements is about a factor of 2 worse than UHEI-IUP measurements (**see Table S7**). To explore the impact this may have on our findings, we computed differences relative to the more precise UHEI-IUP N_2O record (**Figure~~.~~ S4**). As expected, we find the uncertainty in annual median differences relative to the more precise UHEI-IUP N_2O record to be considerably smaller than when referenced to NOAA measurements. While the agreement between MPI-BGC and UHEI-IUP measurements improves and the differences of CSIRO and ECCC relative to UHEI-IUP remain more stable over time, our overall findings do not change.

The results from the co-located comparison experiments between CSIRO and NOAA at Mauna Loa (MLO) and at Cape Grim (CGO) (**Figure~~.~~ 5(d), Table S25~~19~~**) show the median difference of all individual N_2O measurements to be -0.17 (95% CI: -0.21, -0.13) ppb at MLO which is consistent with our findings in Alert of -0.17 (95% CI: -0.20, -0.13) ppb. At CGO this median difference is -0.03 (95% CI: -0.06, 0.00) ppb, which is slightly smaller than the ALT and MLO results. Considering the previously mentioned effects of water on the N_2O measurements, the differences ~~may be due~~could potentially arise from ~~to~~ site-specific sampling parameters, such as ~~differences in ALT co-located offsets versus same-flask offsets, it is reasonable to suggest~~ CSIRO's change to a cryocooler in 2014 at CGO or NOAA's use of a partially dried sample~~s~~ at CGO~~, but~~ (although not at MLO or ALT). However, pinpointing ~~Determining~~ the exact cause~~reason, however,~~ is beyond the scope of this paper. ~~that co-located comparison results between ALT and the CGO site may be potentially influenced by site-specific sampling procedure biases.~~

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Finally, we estimate a measurement agreement for the six independent Alert N_2O data records as a collective, to be within -0.75 to +1.20 ppb (N= 3957) over the entire period of 1999-2016 (**Table S26~~20~~**). For the approach of using the means of the 2-sigma variation from weekly sampling events we estimate a corresponding overall measurement agreement of ± 0.64 ppb (n=801) (pink lines in **Figure~~.~~ 5(e)**). For comparison, we have included the annual means of the combined 2-sigma variation results of ± 0.64 ppb (n=366) at MLO in yellow lines (**Figure~~.~~ 5(e)** and **Table S26~~0~~**).

3.6 SF_6

All measurements are reported relative to the NOAA X2014 SF_6 mole fraction scale. [**Hall et al., 2011; Lim et al., 2017**]. Measurements of atmospheric SF_6 are reported in picomoles (trillionths or 10^{-12} of a mole SF_6) per mole of dry air and abbreviated ppt (parts per trillion). All SF_6 measurements from the 4 laboratories in this study (MPI-BGC, LSCE, ECCC, and NOAA) were determined using GC-ECD analytical methodology. The estimated repeatability of SF_6 measurements, based on replicated injections of standard tank gas, using the dual N_2O/SF_6 GC-ECD system is ~0.04 ppt.

Figures~~.~~ 6(a)-(d) and **Tables S27~~1~~-S28~~2~~** show the corresponding information for SF_6**.** Please note that there is one less figure and table than the other species, because there are no SF_6 results from the other sites (MLO and CGO) and the last figure and table have been shifted up by one, compared to other species. **Table S27~~1~~ and Figure~~.~~ 6(c)** show that the MPI-BGC and NOAA SF_6 measurements meet the WMO recommended ±0.02 ppt SF_6

compatibility window in 11 of the 12 comparison years (2005-2016). Annual median differences between ECCC and NOAA measurements for 2003-2014 show a constant median offset of -0.05 ppt. The annual differences between LSCE and NOAA measurements for 2007 to 2010 show a similar average offset of approximately -0.05 ppt but showed good agreement from 2011 to 2013. Results from the periodic Round Robin experiments (**Fig. 6(b), Table S1**) are consistent with the co-located comparison results for each participating laboratory. Again, we find the analysis of median differences by month for each laboratory (not shown) does not indicate any seasonal dependencies.

We find the 4 independent co-located SF_6 records at Alert (**Table S28~~2~~**) are consistent to within a window of -0.14 to +0.09 ppt (N=2359) using 2.5 and 97.5 percentiles and ±0.09 ppt (N=723) using the mean of the 2-sigma approach over the time period, respectively. **Figure~~.~~ 6(d)** shows individual measurement differences relative to the NOAA reference for all laboratories, the WMO recommended target range (dark grey band), and our estimate of the overall measurement agreements (in blue and pink lines). There are no SF6 measurements at MLO or CGO to make general comparisons with the Alert data records.

4. Summary and Conclusions

We presented a comparison of measurements of CO_2, CH_4, N_2O, SF_6, and the stable isotope ratios of CO_2 ($\delta^{13}C$, $\delta^{18}O$) in co-located air samples collected at Alert, Nunavut, Canada by seven laboratories (ECCC, CSIRO, MPI-BGC, UHEI-IUP, LSCE, SIO, and NOAA (in collaboration with INSTAAR)) spanning 17 years. We also evaluated the consistency of measurements between certain laboratories (CSIRO, SIO & NOAA/INSTAAR) at three sites (ALT, MLO and CGO), where other co-located flask sampling programs operate.

From this work, we find that the co-located atmospheric CO_2 and CH_4 measurement records from Alert by CSIRO, MPI-BGC, SIO, UHEI-IUP, ECCC, and NOAA are compatible to the WMO network compatibility goals within ±0.1 ppm CO_2 and ±2 ppb CH_4 at the 95% CI, respectively, over the 17-year period. In addition, we find that the co-located comparison programs at MLO and CGO show similar agreement levels to those at Alert within a range of ±0.1 ppm for CO_2 between CSIRO, SIO and NOAA records and within a range of ±2 ppb for CH_4 between CSIRO and NOAA records. An important caveat to these CO_2 and CH_4 results is that we often observe periods where the biases between datasets exceed the WMO target levels and may persist as systematic bias for months or years, which could impact our observed compatibility. Our analysis shows that for δ^{13}C-CO_2, δ^{18}O-CO_2, N_2O and SF_6, our estimate of the overall measurement agreements during the time of this study exceeds the WMO recommended targets. Differences in the respective local scale implementations for the isotopes of CO_2, possible moisture effects for δ^{18}O-CO_2 and the analytical precision of the instruments used for N_2O and SF_6 are possible limiting factors for these results. In addition, the N_2O may have some biases introduced by sample collection procedures.

Further analysis shows that the overall results observed for CSIRO, SIO and NOAA/INSTAAR's CO_2, CH_4, and δ^{13}C- CO_2 for the study period are roughly consistent among the three sites (ALT, MLO & CGO), implying that merging these records could be done across these specific networks. However, for the δ^{18}O-CO_2 and N_2O records, future data may be needed to make definitive statements about compatibility across networks. ~~are less consistent between the sites, likely because they are vulnerable to the availability of water vapor, resulting in isotopic exchanges which are site specific. The notable differences between Alert and CGO for N_2O records (CSIRO vs. NOAA) are probably also due to potentially site-specific sampling procedure biases. Understanding site-specific or laboratory-specific artifacts is beyond the scope of this study.~~

Although most of the co-located independent CO_2 and CH_4 atmospheric records at Alert meet the WMO recommended targets when considering the results over the entire study period (1999-2016), meeting the compatibility targets for other trace gas species and stable isotopes in CO_2 continues to be a challenge. The independent measurement records could still be used together for various scientific applications (e.g., long-term trend analysis of CO_2 in Sect. 3.1), even though individual data points are not fully compatible with the WMO/GAW recommended targets. Furthermore, if we provide data users with the estimated overall measurement agreements for multiple records, they could then take these estimates into account, along with the measurement uncertainties from individual records, while using the data sets for relevant applications.

For each trace gas species and isotope, we have estimated an overall measurement agreement among the Alert records by aggregating all individual differences from each participating laboratory (relative to the NOAA or INSTAAR reference) and then computing the 2.5 and 97.5 percentiles for the entire available periods. This upper and lower limit contains 95% of the entire difference distribution from all participating laboratories and represents our best estimate of measurement agreement for these data records. The ranges of the estimated overall measurement agreement when combining all individual flask records from Alert over the entire available periods are -0.51 to +0.53 ppm for CO_2, -0.09 to +0.07 ‰ for $\delta^{13}C$-CO_2, -0.50 to +0.58 ‰ for $\delta^{18}O$-CO_2, -4.86 to +6.16 ppb for CH_4, -0.75 to +1.20 ppb for N_2O, and -0.14 to +0.09 ppt for SF_6, respectively. Using another alternative approach as discussed in Sect. 2.6., we provide the means of the 2-sigma of each weekly sampling episode, involving all participating laboratories over the entire available time period, which are ±0.37 ppm for CO_2, ± 0.06 ‰ for $\delta^{13}C$-CO_2, ±0.31 ‰ for $\delta^{18}O$-CO_2, ± 3.62 ppb for CH_4, ±0.64 ppb for N_2O and ±0.09 ppt for SF6, respectively. Results from this analysis reveal overall cumulative differences due to errors introduced at one or more steps in the entire atmospheric measurement process, including sampling and analytical procedures.

In summary, this study assesses the level of measurement agreement among individual programs by comparing co-located flask air measurements. ~~and provides more~~ It enhances confidence ~~abouton~~ in the uncertainty estimation while using those datasets either individually or collectively ~~in various~~ across diverse applications. Conducting such comprehensive analysis regularly is advisable to detect potential issues and ~~This type of in-depth analysis would be useful on a regular basis, to be aware of issues or to~~ monitor any scale ~~changes~~ and/or instrumentation changes. It's recommended that future analyses ~~should~~ be ~~performed~~ carried out every 2 years by a dedicated entity ~~party~~ and be ~~part of the~~ reported ~~regular~~regularly during WMO GGMT meetings.

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Data Availability

All raw data, matched co-located data, ~~and~~ supplementary tables, figures and material are included with this manuscript.

Author contributions

DEJW, LH and MKR designed and coordinated the overall flask sampling experiments at Alert, as well as the comparison effort. Each institute's program lead (DEJW, LH, PBK, RLL, CEA, AMC, SM, IL, MR[7], AJ, HM, RK) directed their own sampling, analysis and quality control programs. MKR, AC, RLL, SH, SM, MS, AJ, MR[8], and EJM performed the analysis for their corresponding institutes. KAM curated and analyzed the data and wrote several chapters of the initial draft. MKR further curated and analyzed the data. IL, CEA, FV, RK and SM provided additional input about the contents. MKR, LH and DEJW worked equally on several revisions and prepared the final manuscript together with FV, as well as reviews and edits by RLL, PBK, CEA, MM, GP, AMC, SM, IL, SH, AJ, HM, and RK.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

The authors would like to extend their gratitude to the conscientious care by the Alert Observatory operators and students in conducting the air sampling flask programs at Alert. We also truly appreciate the efforts of Andrew Platt, the Arctic station coordinator, for maintaining and coordinating the operations of all programs at Alert at a very high level. We would like to acknowledge the various laboratory technicians involved in the analysis of the flask samples at each institute, including those who are not co-authors (due to retirement), such as Patricia Lang and Eric Moglia from NOAA and Alane Bollenbacher from SIO. ~~A~~ ~~f~~Final acknowledgements are~~is~~ for Edward Dlugokencky from NOAA for his contributions to flask data quality control and John Mund from NOAA, for his work on the ICP website open to all laboratories for preliminary comparison exercises.~~.~~

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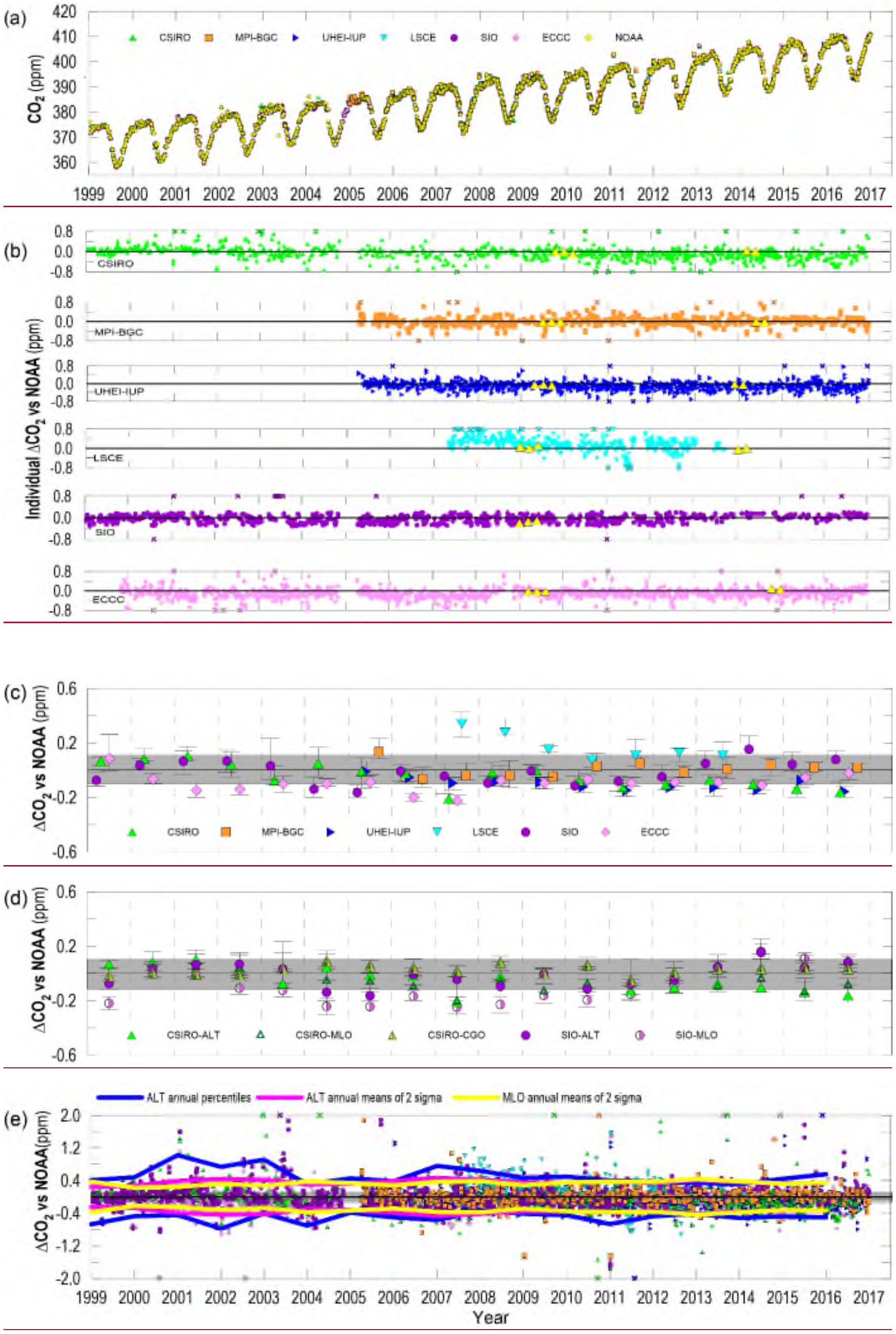
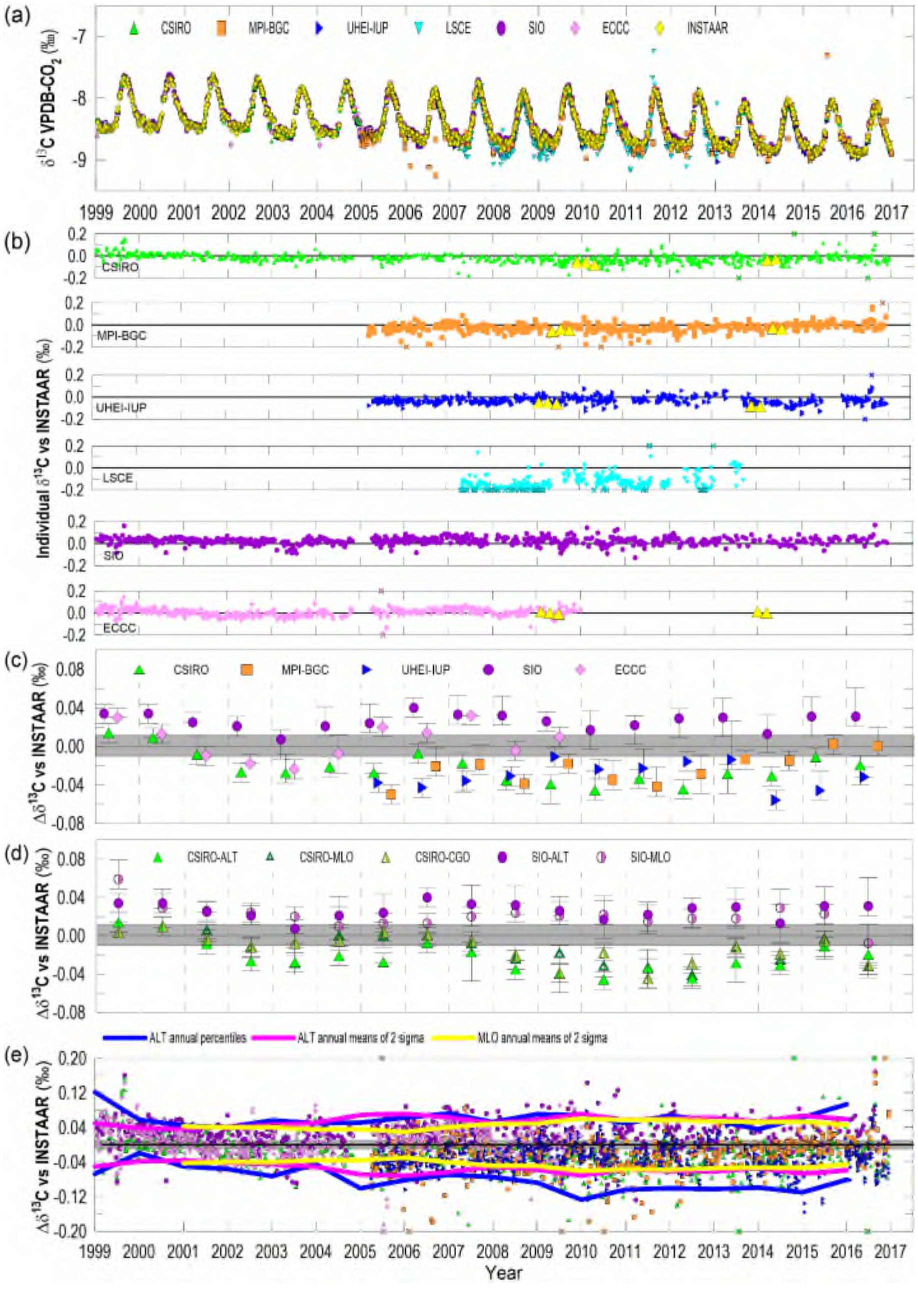

(a)
CO2 (ppm)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC
NOAA
(b)
Individual ΔCO2 vs NOAA (ppm)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC
(c)
ΔCO2 vs NOAA (ppm)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC
(d)
ΔCO2 vs NOAA (ppm)
CSIRO-ALT
CSIRO-MLO
CSIRO-CGO
SIO-ALT
SIO-MLO
(e)
ΔCO2 vs NOAA(ppm)
ALT annual percentiles
ALT annual means of 2 sigma
MLO annual means of 2 sigma
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year

Figure 1 Atmospheric CO_2 comparison results, in ppm, from flask samples taken at Alert, Canada (ALT), Mauna Loa, USA (MLO) and Cape Grim, Australia (CGO) by seven laboratories (CSIRO, MPI-BGC, UHEI-IUP, LSCE, SIO, ECCC, and NOAA). (a) Time series of each laboratory's measurements at ALT, showing long-term trends and seasonal patterns in the records. (b) Individual ALT CO_2 measurement differences (laboratory minus NOAA), in ppm. Differences exceeding the y-axis range are plotted with an "X" symbol on the outer axis. Results from the WMO/IAEA Round Robin experiments are overlaid in yellow triangles. The shaded grey band around the zero line, indicates the WMO/GAW recommended measurement agreement goal of ±0.1 ppm CO_2. (c) Annual median CO_2 differences (laboratory minus NOAA) at ALT in ppm, with the lower and upper limits of estimated 95% confidence intervals (CI). (d) Annual median CO_2 differences and 95% confidence limits, in ppm, of CSIRO minus NOAA at MLO and CGO, and SIO minus NOAA at MLO. Also included are results from ALT in (c). (e) Individual measurement differences (laboratory minus NOAA) at ALT, in ppm, for all the laboratories as a collective. Differences exceeding the y-axis range are plotted with an "X" symbol on the outer axis (some extreme outliers have been removed to produce the results). The annual 2.5 and 97.5 percentiles of the entire difference distribution from all laboratories at ALT are shown in blue (from -0.51 to +0.53 ppm). The pink lines show the annual means of the CO_2 ± 2-sigma variations of weekly sampling episodes at ALT (± 0.37 ppm) and the yellow lines show the annual means of the CO_2 ± 2-sigma variations of weekly sampling episodes at MLO (± 0.34 ppm).



(a)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC
INSTAAR
δ13C VPDB-CO2 (‰)
-7
-8
-9
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
(b)
Individual δ13C vs INSTAAR (‰)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC
0.2
0.0
-0.2
(c)
Δδ13C vs INSTAAR (‰)
CSIRO
MPI-BGC
UHEI-IUP
SIO
ECCC
0.08
0.04
0.00
-0.04
-0.08
(d)
Δδ13C vs INSTAAR (‰)
CSIRO-ALT
CSIRO-MLO
CSIRO-CGO
SIO-ALT
SIO-MLO
0.08
0.04
0.00
-0.04
-0.08
(e)
ALT annual percentiles
ALT annual means of 2 sigma
MLO annual means of 2 sigma
Δδ13C vs INSTAAR (‰)
0.20
0.12
0.04
-0.04
-0.12
-0.20
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year

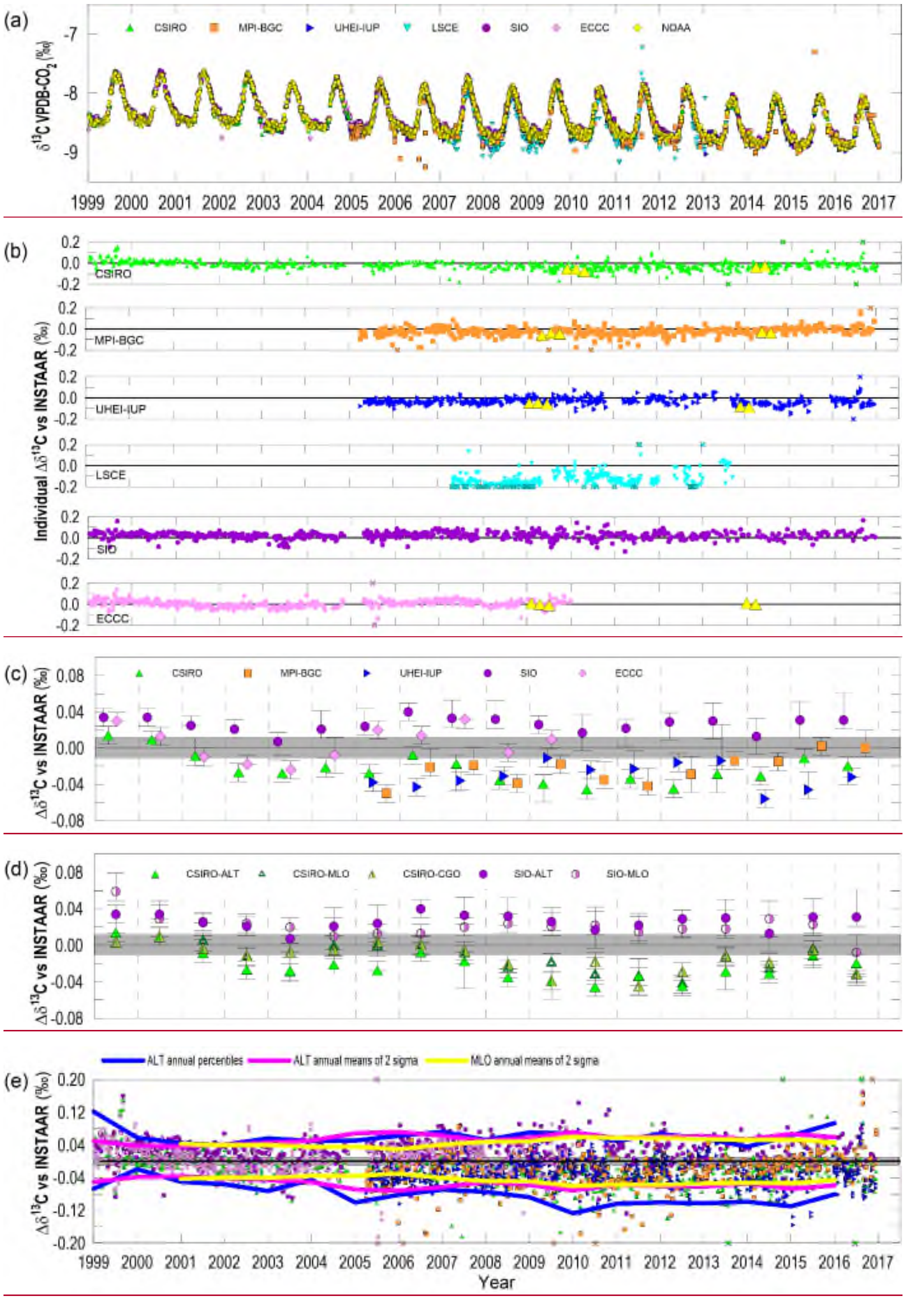
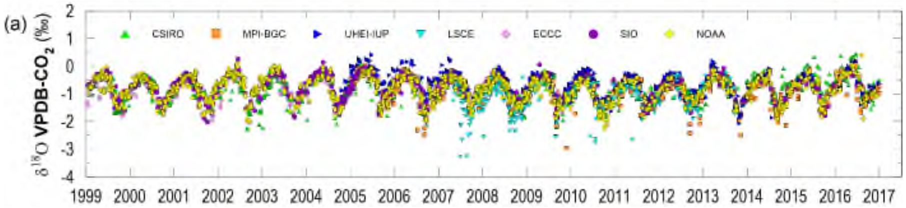


Figure 2 Atmospheric δ^{13}C-CO$_2$ comparison results, in permil (‰), from flask samples taken at ALT, MLO and CGO by seven laboratories. (a) Time series of each laboratory's measurements at ALT, showing long-term trends and seasonal patterns in the records. (b)

Individual ALT δ^{13}C-CO$_2$ differences (laboratory minus INSTAAR), in ‰. Differences exceeding the y-axis range are plotted with an “X” symbol on the outer axis. Results from the WMO/IAEA Round Robin experiments are overlaid in yellow triangles. The shaded grey band around the zero line indicates the WMO/GAW recommended measurement agreement goal of ±0.01 ‰. (c) Annual median δ^{13}C-CO$_2$ differences (laboratory minus INSTAAR) at ALT in ‰, with the lower and upper limits of estimated 95% CI. (d) Annual median δ^{13}C-CO$_2$ differences and 95% CI, in ‰, of CSIRO minus INSTAAR at MLO and CGO, and SIO minus INSTAAR at MLO. Also included are results from ALT. (e) Individual measurement differences (laboratory minus INSTAAR) at ALT, in ‰, for all the laboratories as a collective. Some extreme outliers have been removed to produce the results. The annual 2.5 and 97.5 percentiles of the entire difference distribution from all laboratories at ALT are shown in blue (-0.09 to +0.07‰). The pink lines show the annual means of ± 2-sigma variations of weekly sampling episodes at ALT (± 0.06 ‰) and the yellow lines show the annual means of ± 2-sigma variations of weekly sampling episodes at MLO (± 0.05‰).


(a)
δ18O VPDB-CO2 (‰)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
SIO
NOAA
2
1
0
-1
-2
-3
-4
1999
2000
2001
2002
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2013
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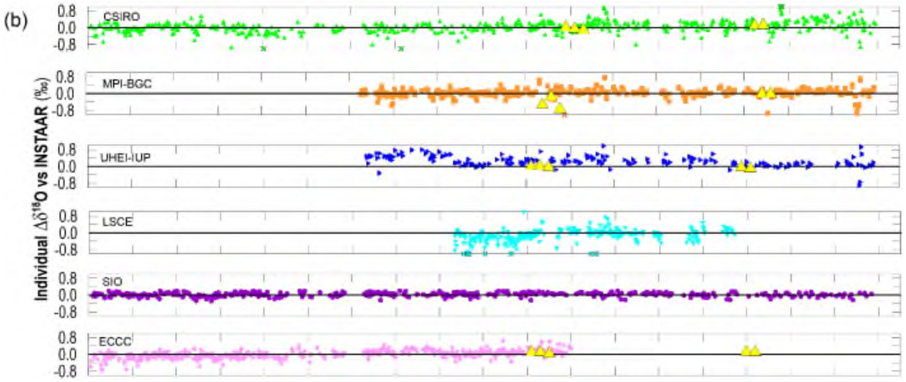
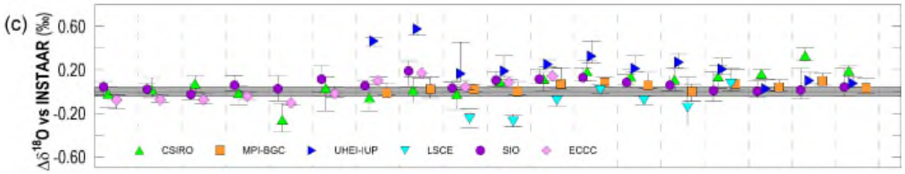
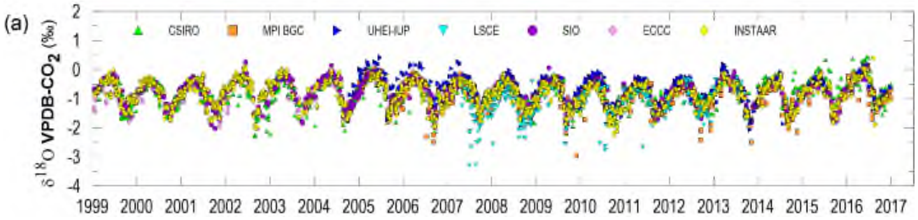
2015
2016
2017


(b)
Individual Δδ18O vs INSTAAR (‰)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC
0.8
0.0
-0.8


(c)
Δδ18O vs INSTAAR (‰)
0.60
0.20
-0.20
-0.60
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC


(a)
δ18O VPDB-CO2 (‰)
CSIRO
MPI BGC
UHEI-IUP
LSCE
SIO
ECCC
INSTAAR
2
1
0
-1
-2
-3
-4
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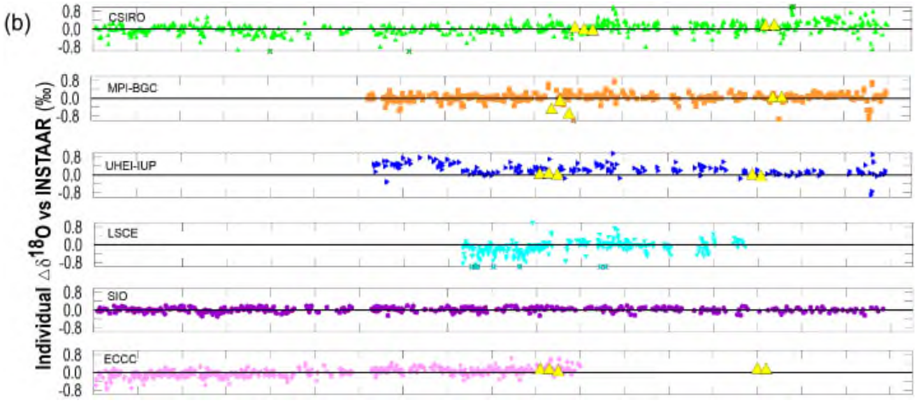
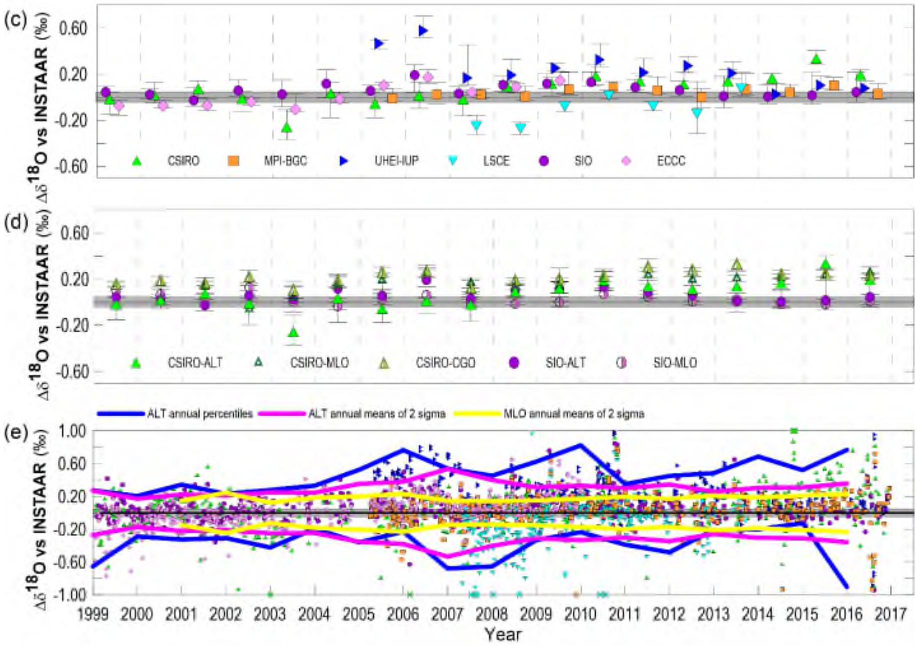

(b)
Individual Δδ18O vs INSTAAR (‰)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
SIO
ECCC
0.8
0.0
-0.8



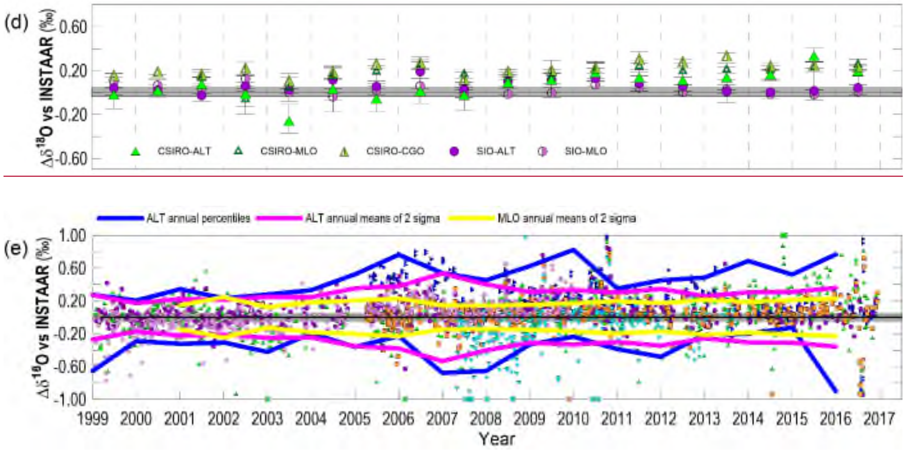


Figure 3 Atmospheric δ^{18}O-CO$_2$ comparison results, in permil (‰), from flask samples taken at ALT, MLO and CGO by seven laboratories. (a) Time series of each laboratory's measurements at ALT, showing long-term trends and seasonal patterns in the records. (b) Individual ALT δ^{18}O-CO$_2$ differences (laboratory minus INSTAAR), in ‰. Differences exceeding the y-axis range are plotted with an "X" symbol on the outer axis. Results from the WMO/IAEA Round Robin experiments are overlaid in yellow triangles. The shaded grey band around the zero line indicates the WMO/GAW recommended measurement agreement goal of ±0.05 ‰. (c) Annual median δ^{18}O-CO$_2$ differences (laboratory minus INSTAAR) at

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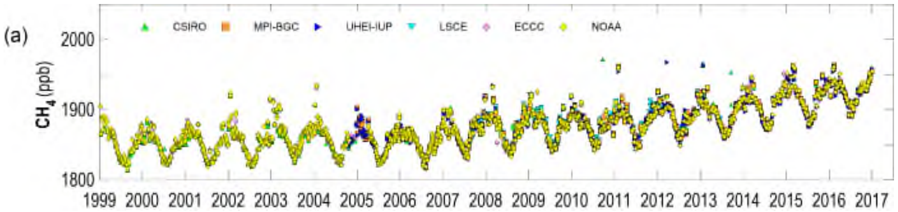
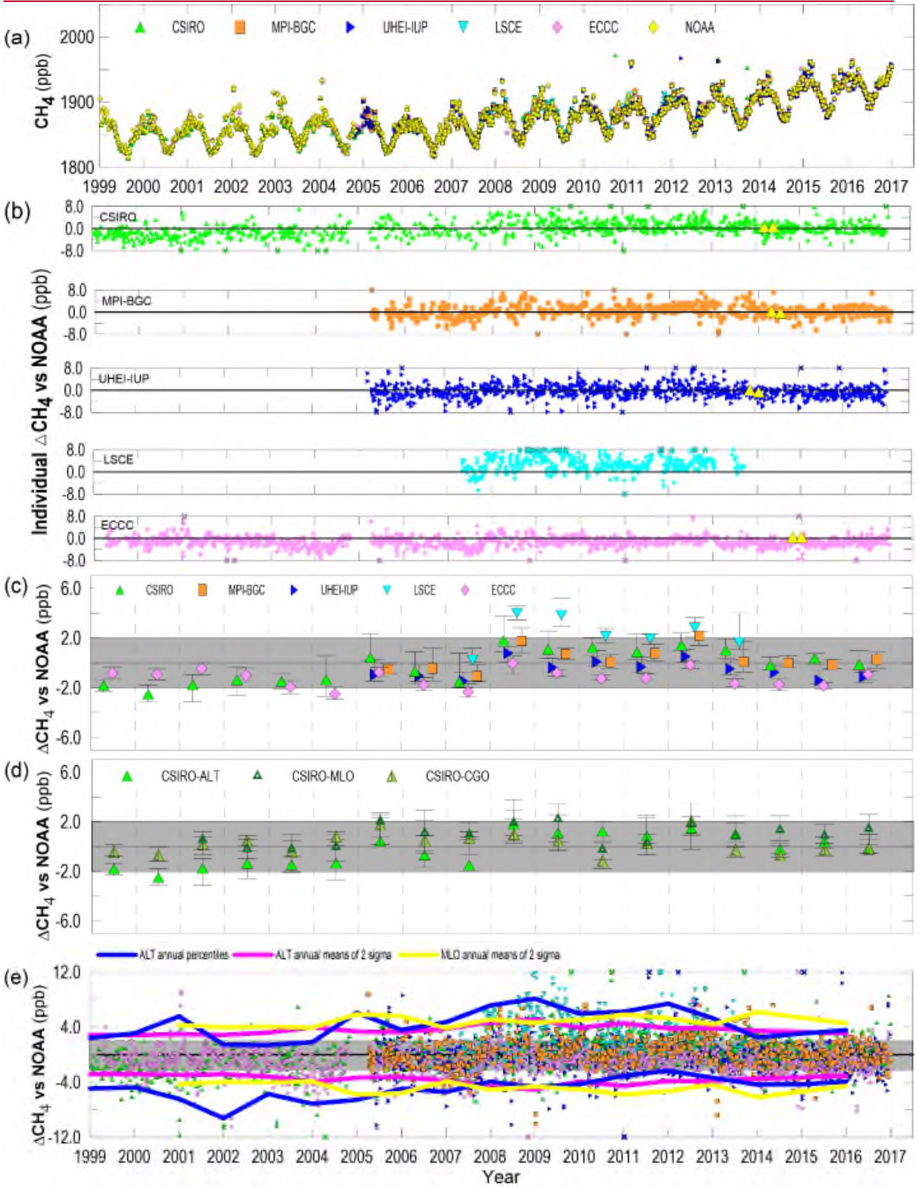
ALT in ‰, with the lower and upper limits of estimated 95% CI. (d) Annual median δ^{13}C-CO$_2$ differences and 95% CI, in ‰, of CSIRO minus INSTAAR at MLO and CGO, and SIO minus INSTAAR at MLO. Also included are results from ALT. (e) Individual differences (laboratory minus INSTAAR) at ALT, in ‰, for all the laboratories as a collective. The annual 2.5 and 97.5 percentiles of the entire difference distribution from all laboratories at ALT are shown in blue (-0.50 to +0.58‰). The pink lines show the annual means of ± 2-sigma variations of weekly sampling episodes at ALT (± 0.31 ‰) and the yellow lines show the annual means of ± 2-sigma variations of weekly sampling episodes at MLO (± 0.19‰).


(a)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
NOAA
CH$_4$ (ppb)
2000
1900
1800
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017


(a)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
NOAA
CH$_4$ (ppb)
2000
1900
1800
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
(b)
Individual ΔCH$_4$ vs NOAA (ppb)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
8.0
0.0
-8.0
(c)
ΔCH$_4$ vs NOAA (ppb)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
6.0
2.0
-2.0
-6.0
(d)
ΔCH$_4$ vs NOAA (ppb)
CSIRO-ALT
CSIRO-MLO
CSIRO-CGO
6.0
2.0
-2.0
-6.0
(e)
ALT annual percentiles
ALT annual means of 2 sigma
MLO annual means of 2 sigma
ΔCH$_4$ vs NOAA (ppb)
12.0
4.0
-4.0
-12.0
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year

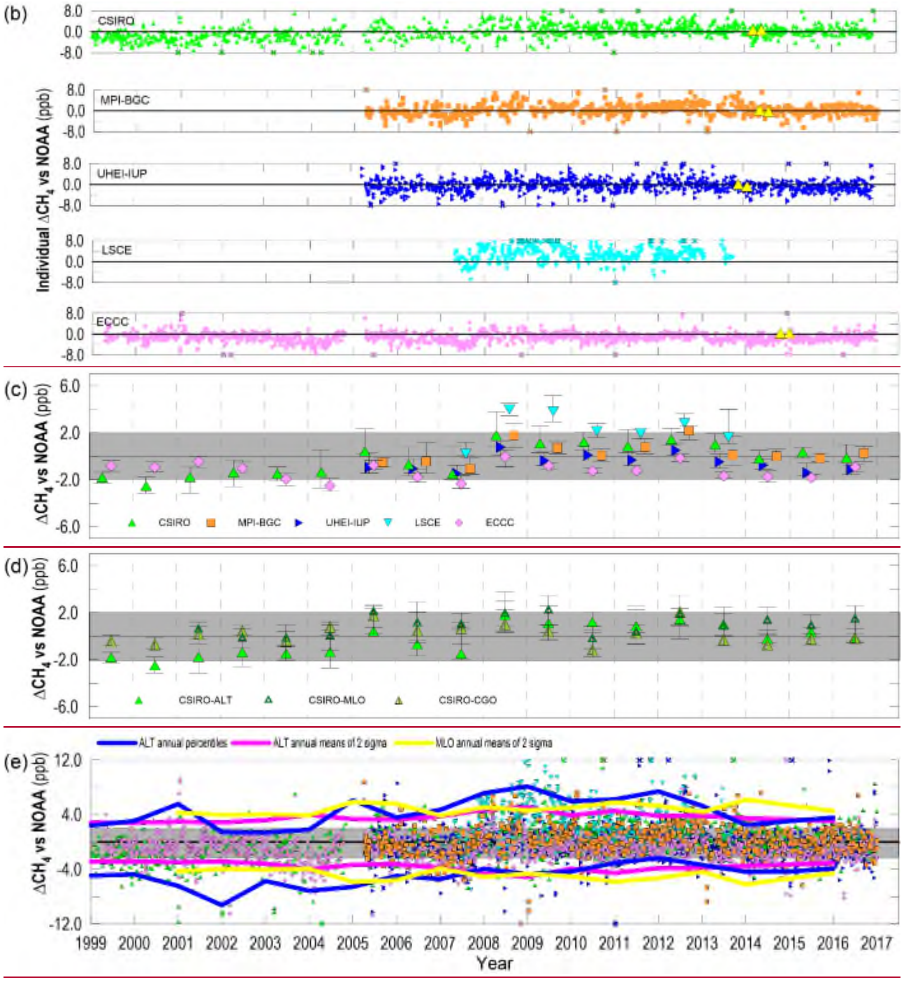
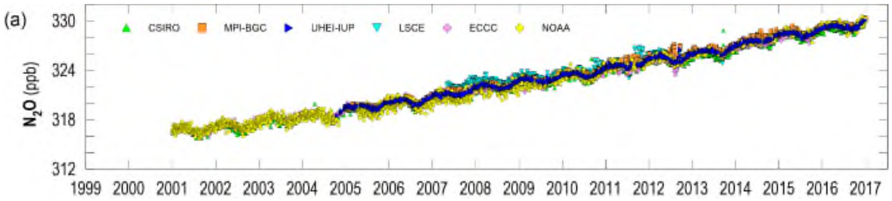
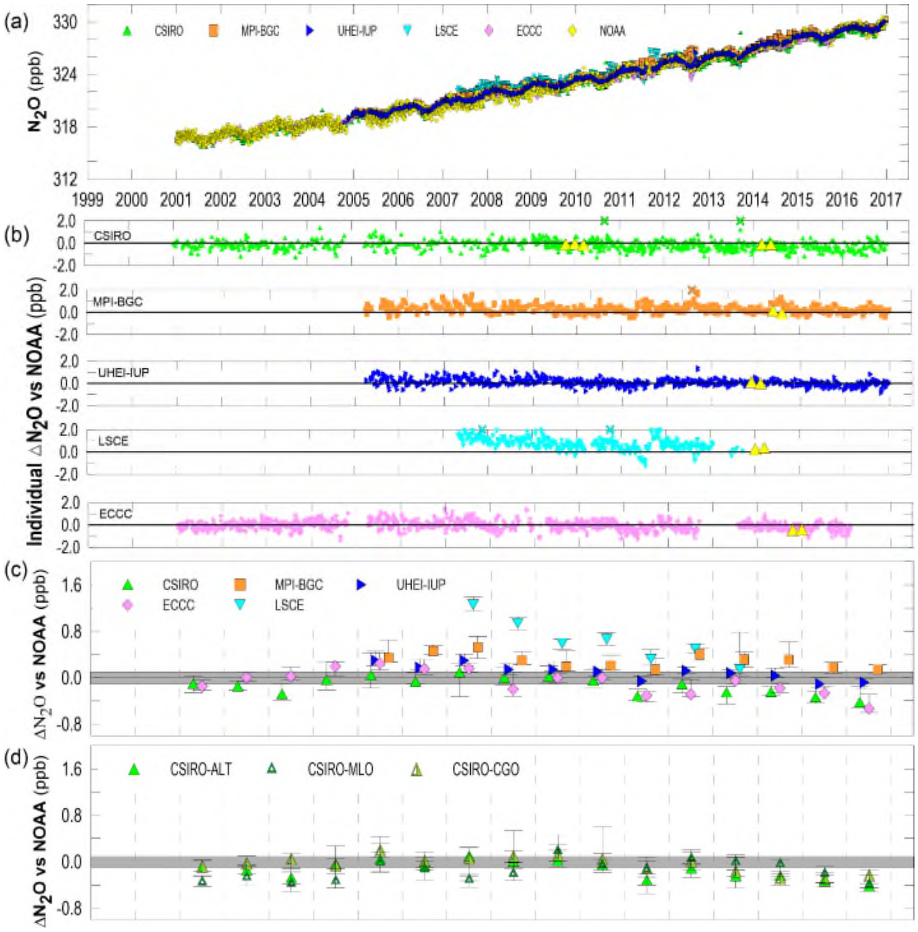


Figure 4 Atmospheric CH_4 comparison results, in ppb, from flask samples taken at ALT, MLO and CGO by six laboratories (CSIRO, MPI-BGC, UHEI-IUP, LSCE, ECCC, and NOAA). (a) Time series of each laboratory's measurements at ALT, showing long-term trends and seasonal patterns in the records. (b) Individual CH_4 differences (laboratory minus NOAA) at ALT, in ppb. Differences exceeding the y-axis range are plotted with an "X" symbol on the outer axis. Results from the WMO/IAEA Round Robin experiments are overlaid in yellow triangles. The shaded grey band around the zero line indicates the WMO/GAW recommended measurement agreement goal of ±2.0 ppb. (c) Annual median CH_4 differences (laboratory minus NOAA) at ALT in ppb, with the lower and upper limits of estimated 95% CI. (d) Annual median CH_4 differences and 95% CI, in ppb, of CSIRO minus

NOAA at MLO and CGO. Also included are results from ALT. (e) Individual differences (laboratory minus NOAA) at ALT, in ppb, for all the laboratories as a collective. Some extreme outliers have been removed to produce the results. The annual 2.5 and 97.5 percentiles of the entire difference distribution from all laboratories at ALT are shown in blue (-4.86 to +6.16 ppb). The pink lines show the annual means of ± 2-sigma variations of weekly sampling episodes at ALT (± 3.62 ppb) and the yellow lines show the annual means of ± 2-sigma variations of weekly sampling episodes at MLO (± 4.88 ppb).


(a)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
NOAA
N2O (ppb)
330
324
318
312
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017


(a)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
NOAA
N2O (ppb)
330
324
318
312
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
(b)
CSIRO
MPI-BGC
UHEI-IUP
LSCE
ECCC
Individual ΔN2O vs NOAA (ppb)
2.0
0.0
-2.0
(c)
CSIRO
MPI-BGC
UHEI-IUP
ECCC
LSCE
ΔN2O vs NOAA (ppb)
1.6
0.8
0.0
-0.8
(d)
CSIRO-ALT
CSIRO-MLO
CSIRO-CGO
ΔN2O vs NOAA (ppb)
1.6
0.8
0.0
-0.8

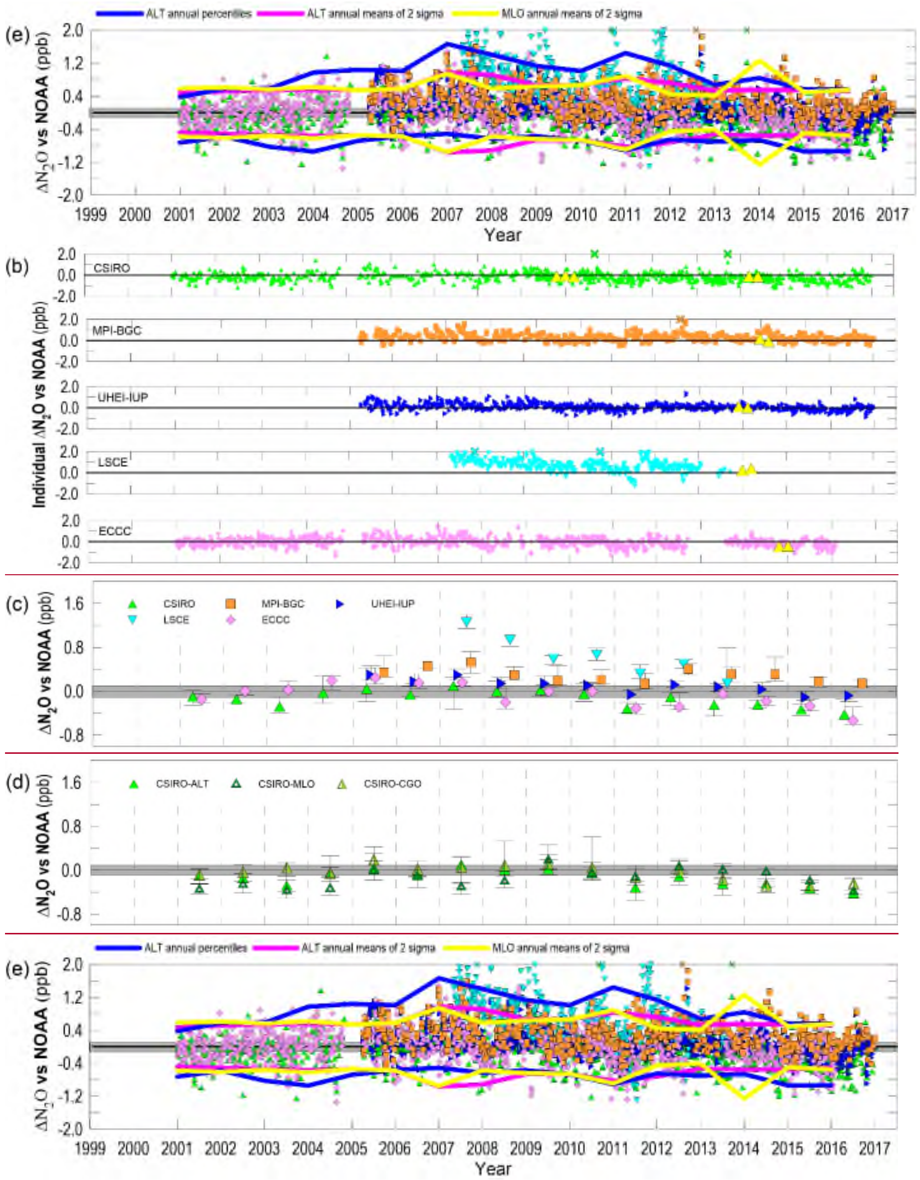
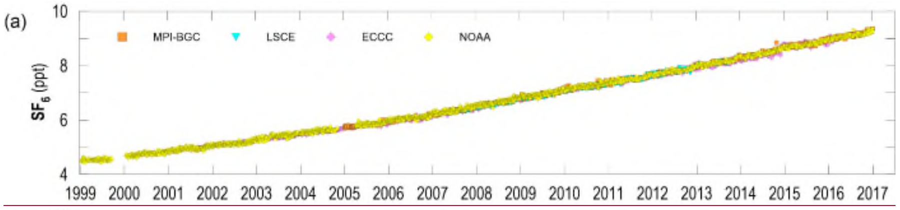
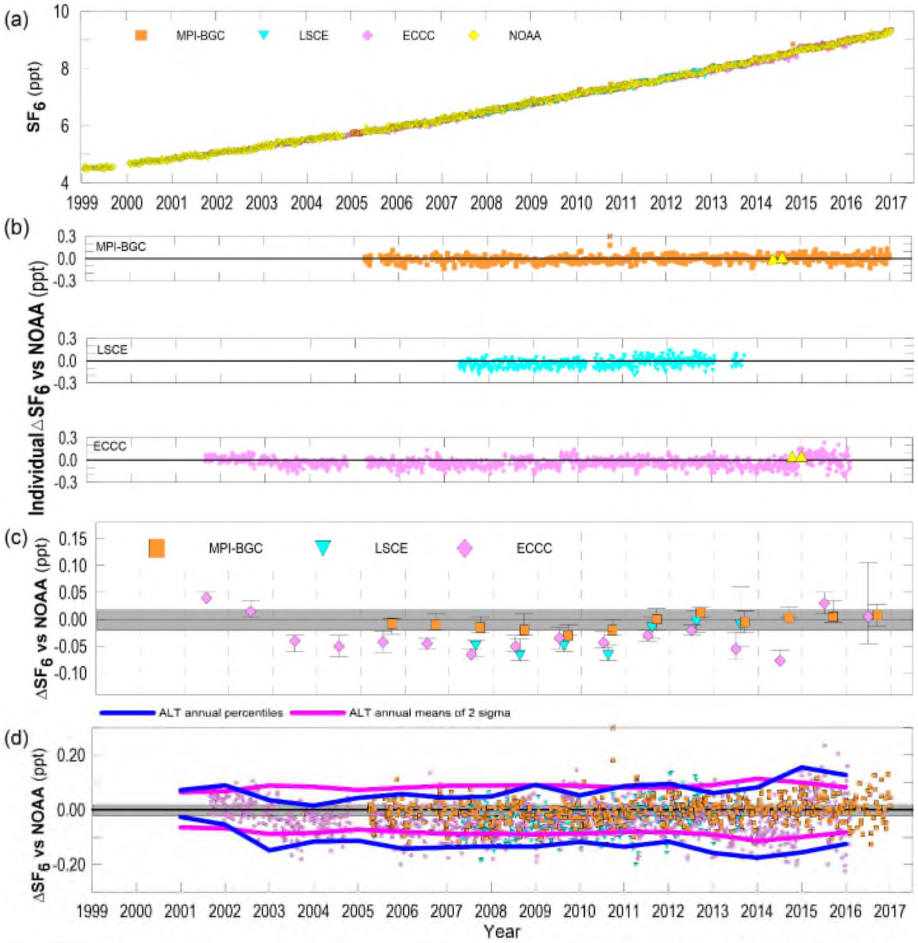
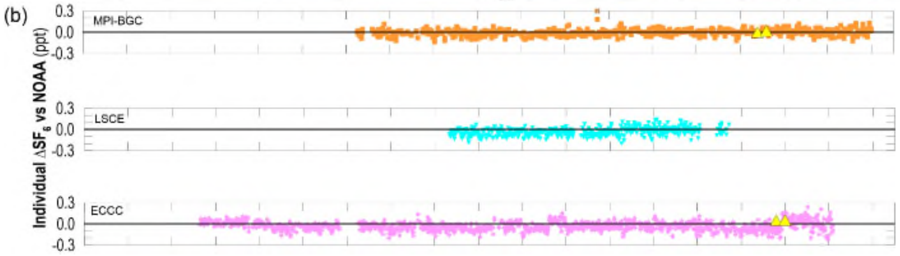


Figure 5 Atmospheric N$_2$O comparison results, in ppb, from flask samples taken at ALT, MLO and CGO by six laboratories (CSIRO, MPI-BGC, UHEI-IUP, LSCE, ECCC, and NOAA). (a) Time series of each laboratory's measurements at ALT, showing long-term trends and seasonal patterns in the records. (b) Individual N$_2$O differences (laboratory minus NOAA) at ALT, in ppb. Differences exceeding the y-axis range are plotted with an "X" symbol on the outer axis. Results from the WMO/IAEA Round Robin experiments are overlaid in yellow

triangles. The shaded grey band around the zero line indicates the WMO/GAW recommended measurement agreement goal of ±0.1 ppb. (c) Annual median N_2O differences (laboratory minus NOAA) at ALT in ppb, with the lower and upper limits of estimated 95% CI. (d) Annual median N_2O differences and 95% CI, in ppb, of CSIRO minus NOAA at MLO and CGO. Also included are results from ALT. (e) Individual differences (laboratory minus NOAA) at ALT, in ppb, for all the laboratories as a collective. The annual 2.5 and 97.5 percentiles of the entire difference distribution from all laboratories at ALT are shown in blue (-0.75 to +1.20 ppb). The pink lines show the annual means of ± 2-sigma variations of weekly sampling episodes at ALT (± 0.64 ppb) and the yellow lines show the annual means of ± 2-sigma variations of weekly sampling episodes at MLO (± 0.64 ppb).


(a)
MPI-BGC
LSCE
ECCC
NOAA
SF6 (ppt)
10
8
6
4
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017


(a)
MPI-BGC
LSCE
ECCC
NOAA
SF6 (ppt)
10
8
6
4
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
(b)
MPI-BGC
LSCE
ECCC
0.3
0.0
-0.3
Individual ΔSF6 vs NOAA (ppt)
(c)
MPI-BGC
LSCE
ECCC
0.15
0.10
0.05
0.00
-0.05
-0.10
ΔSF6 vs NOAA (ppt)
ALT annual percentiles
ALT annual means of 2 sigma
(d)
0.20
0.00
-0.20
ΔSF6 vs NOAA (ppt)
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year


(b)
MPI-BGC
LSCE
ECCC
0.3
0.0
-0.3
Individual ΔSF6 vs NOAA (ppt)

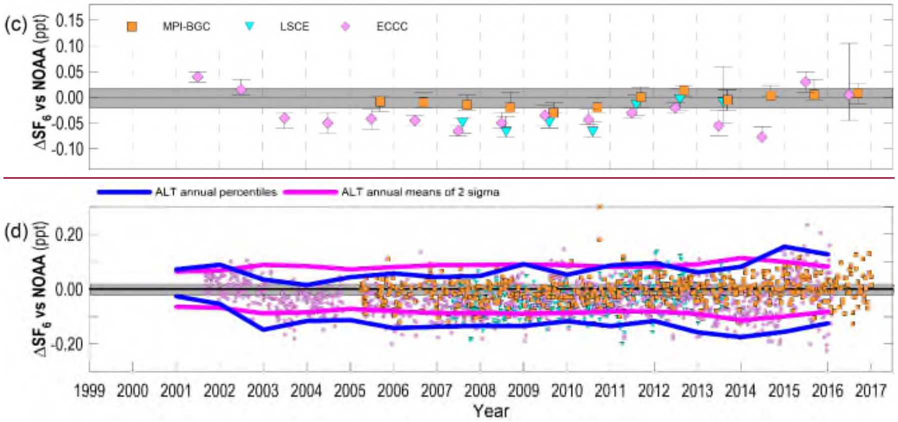


Figure 6 Atmospheric SF_6 comparison results, in ppt, from flask samples taken at ALT by four laboratories (MPI-BGC, LSCE, ECCC, and NOAA). (a) Time series of each laboratory's measurements at ALT, showing long-term trends and seasonal patterns in the records. (b) Individual SF_6 differences (laboratory minus NOAA) at ALT in ppt. Differences exceeding the y-axis range are plotted with an "X" symbol on the outer axis. Results from the WMO/IAEA Round Robin experiments are overlaid in yellow triangles. The shaded grey band around the zero line indicates the WMO/GAW recommended measurement agreement goal of ±0.02 ppt. (c) Annual median SF_6 differences (laboratory minus NOAA) at ALT in ppt, with the lower and upper limits of estimated 95% CI. (d) Individual differences (laboratory minus NOAA) at ALT, in ppt, for all the laboratories as a collective. The annual 2.5 and 97.5 percentiles of the entire difference distribution from all laboratories at ALT are shown in blue (-0.14 to +0.09 ppt). The pink lines show the annual means of ± 2-sigma variations of weekly sampling episodes at ALT (± 0.09 ppt) and there is no MLO data because neither CSIRO nor SIO measure SF_6.

Table 1. Summary of available observations and flask comparison types for each participating laboratory during the period of this study at ALT.

LAB	TYPE OF ICP		1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
ECCC	CO-LOCATED	CO_2, CH_4, N_2O, SF_6	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		δ13C, δ18O	■	■	■	■	■	■	■	■	■	■	■							
	SAME-FLASK	CO_2, CH_4, N_2O, SF_6	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
		δ13C, δ18O with MPI							■	■	■	■	■							
		δ13C, δ18O with CSIRO	■	■	■	■	■	■	■	■	■	■	■							
CSIRO	CO-LOCATED	CO_2, CH_4, N_2O	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		δ13C, δ18O	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	SAME-FLASK	CO_2, CH_4, N_2O				■	■	■	■	■	■	■	■	■	■	■	■			
		δ13C, δ18O	■	■	■	■	■	■	■	■	■	■	■							
NOAA	CO-LOCATED	CO_2, CH_4, N_2O, SF_6	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		δ13C, δ18O	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	SAME-FLASK	CO_2, CH_4, N_2O, SF_6	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
SIO	CO-LOCATED	CO_2	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		δ13C, δ18O	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	SAME-FLASK																			
UHEI-IUP	CO-LOCATED	CO_2, CH_4, N_2O							■	■	■	■	■	■	■	■	■	■	■	■
		δ13C, δ18O							■	■	■	■	■	■	■	■	■	■	■	■
	SAME-FLASK	CO_2, CH_4, N_2O							■	■	■	■	■	■	■	■	■			
MPI-BGC	CO-LOCATED	CO_2, CH_4, N_2O, SF_6							■	■	■	■	■	■	■	■	■	■	■	■
		δ13C, δ18O							■	■	■	■	■	■	■	■	■	■	■	■
	SAME-FLASK	CO_2, CH_4, N_2O, SF_6							■	■	■	■	■	■	■	■	■			
		δ13C, δ18O							■	■	■	■	■							
LSCE	CO-LOCATED	CO_2, CH_4, N_2O, SF_6									■	■	■	■	■	■	■			
		δ13C, δ18O									■	■	■	■	■	■	■			
	SAME-FLASK	CO_2, CH_4, N_2O, SF_6									■	■	■	■	■	■	■			

Table 2.1 Summary of flask type, sampling frequency and apparatus used for each participating laboratory during the period of this study at ALT.

GROUP	FLASK TYPE	SAMPLING FREQUENCY	FILLING APPARATUS	SAMPLE DRYING	INLET HEIGHT
CSIRO	**1999-Nov.2014*** ECCC flasks. **Nov 2014-present** CSIRO 0.5 L pressurized Double valves Teflon (PFA) o-rings ***See section SI for details**	**Variable. See SI for details**	**1999-Aug 2016** SIO sampler **Aug 2016-present** CSIRO/UHEI/ ECCC sampler	cryocooler	10 m Tower
MPI-BGC	**2005-present** 1 L pressurized Double valves PCTFE o-rings	triplet bi-weekly	MPI-BGC sampler	**2005-2015** $Mg(ClO_4)_2$ **2015-present** cryocooler	10 m tower
UHEI-IUP	**2005-present** 1 L pressurized Double valves PCTFE o-rings	1 pair weekly	**2005-Aug 2016** SIO sampler **2016-present** CSIRO/UHEI/ ECCC sampler	cryocooler	10 m tower
LSCE	**2007-2013** 1 L pressurized Double valves PCTFE o-rings	1 pair weekly	LSCE sampler	cryocooler	10 m tower
SIO	**1999-present** 5 L Evacuated Single valve Greased	1 pair weekly	N/A	None	arm's length above head
ECCC	**1999-present** 2 L pressurized Double valves Viton o-rings	1 pair weekly	**1999-Aug 2016** SIO sampler **2016-present** CSIRO/UHEI/ ECCC sampler	cryocooler	10 m tower
NOAA	**1999-present** 2.5 L pressurized Double valves PTFE Teflon o-rings	**1999-2011** 2 pairs weekly **2011-present** 1 pair weekly	Portable sampling unit (PSU)	None	5 m Sample line extending from sampler

Table 2.2 Differences of sampling between ALT, MLO and CGO

Group	**ALT**	**MLO**	**CGO**
CSIRO	Different flask types SIO O_2/N_2 sampler Cryocooler,10m,	CSIRO 0.5L flasks Flask pump unit (FPU) $Mg(ClO_4)_2$, 40m,	CSIRO 0.5L flasks FPU (1999-2014),$Mg(ClO_4)_2$; Sherpa unit (2014-2016), cryocooler, 70m,
SIO	Undried, ~2m	Undried, ~2m	N/A
NOAA	Portable sampler unit (PSU), undried, 5m	PSU, undried, 5m; also some flasks from *in situ* air stream, undried, 40m	PSU, partially dried using a condenser, 70m

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Table 3. Flask air collection schedule for each participating laboratory at ALT.

WEEK	**INDOOR FLASKS**	**Typical times (UTC)**	**INDOOR FLASKS (other)**	**Typical times (UTC)**	**OUTDOOR FLASKS**	**Typical times (UTC)**
1	ECCC (1 pair weekly)	14:00-14:30	MPI-BGC (triplet bi-weekly)	14:15-14:45	NOAA (1 pair weekly)	14:05-14:15
	CSIRO (1 pair as below ***)	14:30-15:00	LSCE (1 pair weekly)	14:45-15:15	SIO (1 pair weekly)	14:05-14:10
	UHEI-IUP 1 (pair weekly)	15:00-15:30				
2	ECCC 1 (pair weekly)	14:00-14:30	LSCE (1 pair weekly)	14:15-14:45	NOAA (1 pair weekly)	14:05-14:15
	UHEI-IUP (1 pair weekly)	14:30-15:00			SIO (1 pair weekly)	14:05-14:10

*** CSIRO: **biweekly** from Nov. to May; **weekly** rest of the year

Table 4. Summary of types of instrumentation, repeatability and scales used for the flask air analysis at each participating laboratory during the period of this study.

Laboratory	Species	Duration of instrument use	Instrument type	Calibration Scale
CSIRO	CO_2, CH_4	1999- 2016	GC-~~/~~FID[1]	X2007, X2004A
	N_2O	1999- 2016	GC-~~/~~ECD[2]	X2006A
	$\delta^{13}C$ and $\delta^{18}O$-CO_2	1999- 2016	IRMS[3]	Local (see Table 5)
MPI-BGC	CO_2, CH_4, N_2O, SF_6	2005- 2016	GC-~~/~~FID[4]/ GC-~~/~~ECD[4]	X2007, X2004A, X2006A, X2014
	$\delta^{13}C$ and $\delta^{18}O$-CO_2	2005- 2016	IRMS[3]	Local JRAS-06 (see Table 5)
UHEI-IUP	CO_2, CH_4, N_2O	2005- 2016	GC-FID[4]/ GC-ECD[4]~~GC/FID/ECD~~[4]	X2007, X2004A, X2006A
	$\delta^{13}C$ and $\delta^{18}O$-CO_2	2005- 2016	IRMS[3]	Local (see Table 5)
LSCE	CO_2, CH_4, N_2O, SF_6	2007- 2013	GC-FID[4]/ GC-ECD[4]~~GC/FID/ECD~~[4]	X2007, X2004A, X2006A, X2014
	$\delta^{13}C$ and $\delta^{18}O$-CO_2	2007- 2013	IRMS[3]	Local (see Table 5)
SIO	CO_2	1999- 2012	NDIR[5]	X08A
		2012- 2016	CRDS[6]	X08A
	$\delta^{13}C$ and $\delta^{18}O$-CO_2	1999- 2000	IRMS[7]	Local (see Table 5)
		2000-2016	IRMS[8]	Local (see Table 5)
ECCC	CO_2	1999- 2006	NDIR[9]	X2007
	CO_2, CH_4, N_2O, SF_6	1999- 2016	GC-FID[4]/ GC-ECD[4]~~GC/FID/ECD~~[4]	X2007, X2004A, X2006A, X2014
	$\delta^{13}C$ and $\delta^{18}O$-CO_2	1999- 2009	IRMS[3]	Local (see Table 5)
NOAA/ INSTAAR	CO_2	1999-2016	NDIR[10]	X2007
	CH_4, N_2O, SF_6	1999- 2016	GC-FID[4]/ GC-ECD[4]~~GC/FID/ECD~~[4]	X2004A, X2006A, X2014
	$\delta^{13}C$ and $\delta^{18}O$-CO_2	1999- 2016	IRMS[8]	Local JRAS-06 (see Table 5)
		2005- 2016	IRMS[11]	Local JRAS-06 (see Table 5)

[1] Carle 400 (repeatability of 0.05 ppm for CO_2, 3 ppb for CH_4)
[2] Shimadzu (repeatability of 0.2 ppb for N_2O)
[3] MAT252 (repeatability of 0.02 permil for ^{13}C-CO_2 and 0.04 permil for ^{18}O-CO_2)
[4] Agilent 5890/6890/7890 (repeatability of 0.05 ppm for CO_2, 3 ppb for CH_4, 0.2 ppb for N_2O, and 0.04 ppt for SF_6)
[5] APC model 55 (repeatability of 0.05 ppm for CO_2)
[6] Picarro (repeatability of 0.01 ppm for CO_2)
[7] VGII (repeatability of 0.02 permil for ^{13}C-CO_2 and 0.04 permil for ^{18}O-CO_2)
[8] Micromass Optima DI (repeatability of 0.02 permil for ^{13}C-CO_2 and 0.04 permil for ^{18}O-CO_2)
[9] Siemens Ultrama (repeatability of 0.05 ppm for CO_2)
[10] Licor (repeatability of 0.05 ppm for CO_2)
[11] GV Isoprime DI (repeatability of 0.02 permil for ^{13}C-CO_2 and 0.04 permil for ^{18}O-CO_2)

Table 5. Summary of δ^{13}C-CO$_2$ and δ^{18}O-CO$_2$ scale propagation and calibration strategies employed by each participating laboratory.

	CSIRO	**MPI-BGC**	**UHEI-IUP**	**SIO**	**INSTAAR**	**ECCC**
Realization of VPDB-CO$_2$ scale	local*	Local (JRAS-06)	local	local	JRAS-06	local
Realization approach and frequency	Calibration of pure CO2 was done in 1987, 1994 and 2009 using NBS19 and transferred to a suite of CO$_2$ -in-air standards that are independently maintained. The value assignment is consistent with the MPI-BGC scale for d13c.	Calibration was done at the time of implementation and is maintained by various high pressure air cylinders since then.	About once per year. Transfer to internal pure CO2 gases (Oberlahnstein and Pflanzenstandard) used for daily MSP calibration	A calibration was done in 1994 and maintained CO$_2$-in-air standards since	Current/recent CO2-in-air standards measured against MPI-BGC standards on JRAS-06. Previous standards tied through “linking standards”	Once per year since 2001 via NBS19, NBS18 & two lab-carbonate standards (Cal1 &2) measured together against the same CO$_2$ working reference
Primary reference material	NBS19	NBS19	Pure CO$_2$: RM8562, 8563, 8564	Carbonates: NBS19; Pure CO$_2$: NBS16,17;	NBS19 via JRAS-06 cylinders	Carbonates: NBS19 &NBS18
^{17}O correction	Brand et al., 2010	Santrock et al., 1985 with IUPAC recommended values for “lambda” and “k” coefficients (Brand et al., 2010).	Santrock et al., 1985 (with coefficients =0.5 and k=0.008335)	Craig 1957	Brand et al., 2010	Craig 1957/ Allison et al., 1995
N$_2$O correction	Mook and Jongsma (1987) using measured CO2 and N2o amount fractions.	Ghosh et al., 2004	Mook and Jongsma (1987) with measured N$_2$O	Mook and Jongsma (1987) with estimated N$_2$O	Mook and Jongsma (1987) with measured N$_2$O	Mook and Jongsma (1987) with measured N$_2$O
scale contraction correction	Explicitly monitored, small, and measurements corrected.	Monitored, negligible, no correction applied	Monitored, negligible, no correction applied		Monitored by surveillance cylinders, negligible due to identical treatment, not corrected for	Monitored, negligible, no correction applied
QAQC	Suite of surveillance cylinders. Use of air standards also corrects for uncorrected for variability.		Suite of surveillance cylinders		Suite of surveillance cylinders	Regularly daily monitoring during analysis using the ECCC "Big Delta" method, i.e., the relative difference between the two lab-carbonates

references	Allison and Francey, 2007	Wendeberg et al. 2011 and references therein	Neubert, R., 1998	Guenther et al., 2001;Bollenbacher et al., 2000; Lueker et al., 2020	Trolier et al., 1996, Michel, S., 2022	Huang et al., 2013

* A realization of VPDB via an MPI-BGC value-assigned tank and revisions to all CSIRO data is in progress.