Atmos. Chem. Phys.Discuss., 14, 21037−21063, 2014
www.atmos-chem-phys-discuss.net/14/21037/2014/
doi: 10.5194/acpd-14-21037-2014

Letter to the Editor of the ACP Manuscript "An estimation of the $^{18}O/^{16}O$ ratio of UT/LMS ozone based on artefact CO in air sampled during CARIBIC flights" *by* S. Gromov and C. A. M. Brenninkmeijer

S. Gromov (on behalf of all authors)

Correspondence to: S. Gromov (sergey.gromov@mpic.de)

Dear Dr. Kaiser,

We are very grateful for your great attention to this work and constructive comments that helped us to improve the quality of this manuscript significantly. Following your suggestions, we have prepared the revised version (please, find the pages with mark-up at the end of this letter). We have addressed all your comments (shown below italicised), on a few of them we have a different opinion, as we discuss in the following.

We appreciate very much the time you spent for editing this paper.

With kind regards,

Sergey Gromov

The manuscript appears fragmented due to the number of appendices and supplementary materials. I think the appendices can stay as they are (but see my comments below regarding their contents). However, please merge Figs. S2, S3 and S4 with the main text. Fig. S1 could stay in the supplementary information, but since this would just leave one figure in the supplementary information, you might want to merge it with the main text at an appropriate location as well.

We have merged the figures (including Fig. S1) from the supplement material with the main text of the revised manuscript.

My main concerns the so-called "contamination kinetic framework" in Appendix A. The term is misleading becase it implies some sort of kinetic modelling, which has no taken place. Instead, you appear to have some sort of regression analysis, but is unclear what was regresses against what and you might want to add a figure to illustrate this.

We disagree here with the understanding of the Editor that "framework" implies modelling. According to Oxford Dictionary, the definition of "framework" (http://www.oxforddictionaries.com/definition/english/framework) is:

> *1.1 A basic structure underlying a system, concept, or text.*

It is the structure or concept of what chemistry we conjecture might have happened in the CARIBIC−1 inlet/tubing that produced artificial CO with the oxygen signature of that of O_3. We also disagree that a "some sort of regression analysis" was done; it is necessary to understand which variables one needs to regress against which in order to obtain sensible information. We cannot put a set of concrete chemical equations because we do not know which (and how many) reactions have occurred. (That is why, by the way, we use a conceptual notation, see below.) Nonetheless, we could establish a functional dependency between the contamination strength and some parameters, *e.g.* $[O_3]$. Understanding and quantifying such dependency is only possible applying certain concepts, *i.e.* within a framework. Ultimately, our task here is to communicate to the Reader how one can tackle a problem with so many unknowns.

We note that the figure illustrating the regression (C_c as a function of $[O_3]$) is already included in the manuscript, see Fig.1 (d).

The mathematical presentation is completely incomprehensible and the units on the left hand side and right hand side of the equation do not match. The notation using round brackets is not defined. What does ... stand for? What are "stoichiometric factors"? I have only heard of stoichiometric coefficients. Why do these "factors" appear as indices? What do you mean by integral stoichiometric fractors? Maybe integer?

Eq. (A1) (first line) is given in a conceptual way (we refer to our answer above) – that is why it does not resemble "normal" chemical equations. We believe, however, that it does not impede a chemist (a physicist, a scientist) to understand it, does it? As an ellipsis commonly denotes "omitted", here, obviously standing in place of educts and products, it denotes some (unknown) educts and products. We could replace them with "R"s and "P"s, which will require additional explanation instead of current more intuitive way, and may even confuse the Reader, since some of "P"s may turn out to be "R"s in the next reaction. That is why it is difficult to use the conventional set of chemical equations here. Instead, we show the most important part – that X and O_3 have to react once or several times to produce CO. Further, why any "round brackets notation" has to be defined? Brackets are commonly used to separate a set of words, expressions, *etc.* Equations can also be separated. In our case, brackets separate equations according to the educt, *i.e.* we distinguish reactions of either O_3 or X, which are important for delivering oxygen and carbon to the final CO produced. The indices K and κ (which are explained below in this paragraph of the manuscript) denote how many reactions occur, *i.e.* how many times O_3 or X may have reacted in order to produce CO. As more than one reaction may happen before one CO molecule is produced, we have to account for the stoichiometry of this kinetic system. We, in contrast, have heard of "stoichiometric factors" (you may like to use the following link to get a notion on the amount of chemical literature using this term: https://www.google.de/search?tbm=bks&hl=en&q=%22stoichiometric+factor%22+&=&gws_rd=ssl). Essentially, "factor" and "coefficient" are often used with the same meaning – they define the proportionality, here between the number of reacted and produced molecules. Because our formulation is more conceptual and not a strict chemical one, we chose using "stoichiometric factors". (We admit that using "overall" suits here better than "integral" meaning, however, also the same.)

Furthermore, we ascertain that the units in Eq. (A1) (second line) *do match*:

C_c [nmol/mol] = $\lambda_{O3} \cdot k_c \tau_c \cdot [O_3]^2$ = [unitless]·[mol/nmol]·[nmol/mol]^2 = [nmol/mol]

This formulation does not pertain to chemical kinetics, it relates the amount of artefact CO (in mole fraction units) to the abundance of O_3 (in mole fraction units) measured concomitantly and uses mole fraction units for the sake of convenience (see also our answer below on the comment to l. 83). We certainly agree that using it in the same equation line is misleading (see the amendments to that we propose below).

What is the value of k_c you refer to.

One cannot infer (or use in calculation) the value of k_c without knowing the reaction time τ_c and yield λ_{O3} (which are not known, too). Nevertheless, we essentially require only the product of k_c, λ_{O3} and τ_c in order to estimate the contamination strength, and this value was derived and communicated in the manuscript (*i.e.* $C_c/[O_3]^2$ of $(5.19 \pm 0.12) \cdot 10^{-5}$ mol/nmol).

I suggest you rewrite this "framework" as a set of a chemical equations (this can be examples or placeholders) and derive any purported mathematical relationship from the corresponding kinetic rate equations (where applicable).

Due to reasoning outlined above, we are not able to formulate the framework in a strict system of chemical equations – at least in the way that will ease its understanding. As a consequence, we cannot derive any purported mathematical relationship, except of that general one shown in Equation (A1) (second line).

We agree, however, that the kinetic framework is poorly described and lacks clarity. To amend it, we split Eq. (A1) into three separate equations and add a more detailed description of the conceptual formulation we use (first line of Eq. (A1)) and of the ensuing mathematical relationships that were used in the regression. We propose the following amendment to the Appendix A:

Appendix A. Contamination kinetic framework

We infer the functional dependence of the CO contamination strength in the kinetic framework conceptually formulated as follows:

$$O_3 \xrightarrow{{}^{O_3}k_1} \left(\begin{array}{l} \left(\ldots + X \xrightarrow{{}^{X}k_r} \ldots \right)_K \\ \left(\ldots + O_3 \xrightarrow{{}^{O_3}k_r} \ldots \right)_{(\kappa-1)} \end{array} \right) \rightarrow \lambda_{O_3} CO \quad . \qquad \text{(A1)}$$

Eq. (A1) reads that production of an artefact CO molecules is initiated by O_3 (via either its decomposition or a reaction with an unknown educt) and is followed by a set of unknown reactions which proceed via unknown educts or products (denoted with ellipses), however requiring at some step an incorporation of carbon (donated by carbonaceous species X) and

oxygen (also possible in secondary O_3 reactions) atoms into final CO. Coefficients K and κ describe the stoichiometry of the system, *i.e.* how many reactions of X and O_3 (with the individual unknown rate coefficients ${}^{X}k_r$ and ${}^{O_3}k_r$) lead to production of one artefact CO, respectively. The yield λ_{O_3}, a diagnostic quantity, relates the amount of artefact CO molecules produced to the total number of O_3 molecules consumed in the system. Based on Eq. (A1), the functional dependence of the artefact CO component (denoted C_c, obtained by discriminating the C1 outliers from respective C2 data) on $[O_3]$ or [X] is generally formulated as (abundances in number density units are used)

$$C_c = \int_{\tau_c} \prod_{\kappa} {}^{O_3}k_r [O_3] \prod_{K} {}^{X}k_r [X] dt \ , \qquad \text{(A2)}$$

where τ_c denotes the contamination reaction time. Eq. (A2) defines the regression expression using which we attempted to fit the values of C_c as a function of κ, $[O_3]$, K and [X] (the latter was chosen iteratively from a set of carbonaceous species measured). Practically, however, this regression analysis ascertains that variations in C_c are exhaustively described using $[O_3]$ and κ. Furthermore, we find that no other species or operational parameter (*e.g.* temperature, pressure, flight duration, latitude, *etc.*) measured in C1 appear to determine (correlate with) C_c. Based on this, we can reduce Eq. (A2) to its final, simpler form, *viz.*

$$C_c = \lambda_{O_3} k_c [O_3]^{\kappa} \tau_c \ , \qquad \text{(A3)}$$

where k_c denotes the overall pseudo-first-order rate coefficient of the reaction chain that is exclusively propelled by O_3. The product $(\lambda_{O_3} k_c \tau_c)$ thus integrates the influence of the unknown (and likely invariable) [X], ${}^{X}k_r$, K and τ_c. Finally, regressing C_s using Eq. (A3) provides its best approximation as a function of $[O_3]$ at $\kappa = 2.06 \pm 0.38$, suggesting two chain steps involving O_3 or its derivatives. At $\kappa = 2$, the product $(\lambda_{O_3} k_c \tau_c)$ that proportionates the CO contamination strength and $[O_3]$ is found to be $(5.19 \pm 0.12) \cdot 10^{-5}$ mol/nmol ($\pm 1\sigma$, adj. $R^2 = 0.83$, red. $\chi^2 = 4.0$; mole fraction units are used here for convenience). The low uncertainty (within ±3%) of this estimate confirms an exclusive dependence of the contamination source on the O_3 abundance, as well as much similar reaction times τ_c. The regressed value of C_c as a function of $[O_3]$ is presented in Fig. 1 (d) (solid line). It is possible to constrain the overall yield λ_{O_3} of CO molecules in the artefact source chain to be between 0.5 and 1, comparing the magnitude of C_c to the discrepancy between the $[O_3]$ measured in C1 and C2 (±20 nmol/mol, taken equal to the $[O_3]$ bin size owing to the N_2O–O_3 and H_2O–O_3 distributions matching well between the datasets). Lower λ_{O_3} values, otherwise, should have resulted in a noticeable (*i.e.*, greater than 20 nmol/mol) decrease in the C1 O_3 abundances with respect to the C2 levels.

Consider replacing the ambiguous term "mixing ratio" with the clearer and - by intuition - more easily understandable "mole fraction".

We would like to keep the term “mixing ratio”, because 1) It is widely used when measurements of trace gases like CO and O_3 are reported (also often in ACP), 2) We reduce the ambiguity by explicitly mentioning the tracer, *i.e.* “CO mixing ratio”, and 2) It will spare us from re-rendering several figures in the manuscript.

Please spell out "w.r.t." - there is no need to abbreviate this.

Spelled.

Lines 62, 66, 67 87, 102, 154, 289: Please delete the tilde signsand where necessary give the actual uncertainties of the values.

Done.

65: Please define STP - 1 bar, 273.15 K? 1.01325 bar, 298.15 K?

Done.

71: The delta and R indices not clear. 13C, 18O and 17O are not suitable superscript indices because they lead to a double superscript index; please use delta(18O), R(18O), R_st(18O) etc. instead.

For ultimate clarity, we decided to refrain from using indices for R. Regarding the δ-values, we keep the isotope mass number to identify them (*e.g.*, ${}^{13}\delta_c$ and ${}^{18}\delta_c$) to avoid double superscripting.

74: You might want to cite my re-evaluated 13C/12C isotope ratio (Kaiser, Geochimica et Cosmochimica Acta 2008, doi:10.1016/j.gca.2007.12.011) ... I am not saying you should.

We would like to keep the current reference. We are aware that this value is nominally outdated since the last re-determination of the carbon isotope ratio of the NBS 19 used to define the "hypothetical" V-PDB scale. Owing to the differences between the former (*i.e.*, assigned from PDB) and revised scales, a change in isotope composition implies *ex post facto* different absolute abundances derived using the same $\delta^{13}C$ values reported. The resulting $\delta^{13}C$ signatures presented here are sensitive to the choice of the $^{13}C/^{12}C$ standard ratio. Nonetheless, errors introduced by adopting outdated reference value are negligible compared to uncertainties introduced by the other factors, *e.g.* laboratory measurement or estimates with the MM. Using the re-evaluated $^{13}C/^{12}C$ ratio would imply re-calculation and re-plotting of all data, which we would like spare ourselves from. Ultimately, the $\delta^{13}C(CO)$ values we report may be easily recalculated employing the re-evaluated (or any other) $^{13}C/^{12}C$ standard ratio.

83: IUPAC has reserved square brackets are reserved for molar concentrations (units of mol dm–3). If you redefine their meaning, please avoid being ambiguous and use for either mole fraction or number density, not both. On p. 12, you use square brackets for number densities.

Although indeed in the kinetic calculations we used number densities (molecules/cm^3), we presented the formulation in Appendix A using mole fraction units in order to facilitate reporting of the contamination magnitude (*e.g.*, in nmol/mol). This is also seen in the $C_c/[O_3]^2$ ratio reported in mol/nmol units.

85: "every 130 s"

Replaced.

88: Add comma after "viz."

Added.

93: Replace "ibid., Panel (b)" with "Figure 1 b".

Replaced.

98: "stratospheric influence increases"

We reformulate it as "With O_3 rising, [CO] decreases to typical stratospheric values, ..."

110,195: Replace ; with .

Replaced.

119: Replace ibid.

Replaced.

145: use of subscript indices is not ideal because of length of index and space ("in situ")- use bracket index notation instead?: "Delta(WAS–in situ)"

We bracket index notation, thank you.

146: There should be brackets around (5.3±0.2) to indicate that the unit "nmol/mol" applies to the value and its uncertainty.

Corrected.

146 & Fig. 3: Define SD (sometimes you use sigma; what's the difference?).

We change "SD" to "standard deviation". Here we emphasise that the uncertainty quoted is the population standard deviation divided by the square root of the sample size. Below in this paragraph we also present the spread of Δ(WAS−*in situ*), which is the standard deviation of the population only.

151: "situ" needs to be subscript;

Corrected similar to that for l. 145.

167, 183: There is no advantage of using rho; please stick with [CO]/[O3].

We have replaced $\rho_{O3:CO}$ with "[O_3]:[CO]".

201: stilted language - please replace "It therefore stands to reason to conclude" by "We therefore conclude", you also use active language elsewhere, which tends to make papers usually much mor readable.

Corrected.

202: prior to

This was a typo, thank you.

213: allows estimating (or allows us to estimate)

Corrected.

227 equation numbering missing; please split into two equations (or substitute Ca = Ct + Cc into the first equation)

We adjust the second expression in this equation accordingly. The missing equation numbering is a typo; we did not intend to number this equation since we do not refer to it except within this paragraph.

227: i is not needed - can refer to any isotope.

Removed.

232: Eq. (2) does not match description in text below. Please rewrite the equation with delta_a on the left hand side.

*delta_a = delta_c + (delta_t - delta_c)*C_t/C_a*

Since C_t is fixed and C_a is increasing with increasing C_C this also simplifies your discussion.

Thank you, we have reformulated this equation which has indeed simplified the discussion.

255: Please delete "It is noteworthy". Everything in the paper should be noteworthy, otherwise it should be removed.

Replaced with “It is important to note”.

260-262: Unclear what you mean and the MM "does not ascertain results" - perhaps you are trying to say is that mixing model does provide any significant information on the delta(13C) value of the contamination?

Yes. We reformulate these statements as

> Taking the same subsets of samples, the concomitant ^{13}C signature matches $^{13}\delta_c = -(23.3\pm8.6)‰$, indeed at the upper end of the expected LMS $\delta^{13}C(CO)$ variations of $-(25-31)‰$. Because of that, the MM is likely insensitive to the changes in $\delta^{13}C(CO)$ caused by the contamination (the corresponding R^2 values are below 0.1).

280: Expand MPI-C.

Expanded.

288-290: Unclear what "by conjecturing an inhibition of the formation KIEs proportional to that measured at ~320 K" means.

We replace this statement with “by assuming that the formation KIEs become attenuated at higher pressures in a similar (proportional) fashion to that measured at 320 K”.

291: Unclear why this is missing - what does this refer to?

We reformulate this sentence as

> A decrease in $\delta^{18}O(O_3)$ of about $(5.9-7.6)‰$ is expected from such calculation, yet accounting for a mere one-half of the $(13.3-14.6)‰$ discrepancy between the stratospheric $\delta^{18}O(O_3)$ values and $^{18}\delta_c$.

320,321: Add space between value and unit.

Added.

324: Merge unit with value, remove s-1.

We admit the use of square brackets is misleading here (as well as further in this paragraph), we correct these occurrences. However, the reported value is the reaction rate coefficient, which by definition has units of reciprocal number density per unit time. It is therefore unclear to us why "s^{-1}" should be removed, or how the value can be merged with unit here. We propose using "$(6\cdot10^{-15}/\tau_c)$ $molec^{-1}$ cm^3 s^{-1}" instead. Alternatively, we will appreciate the Editor explicating this comment further.

327: There are no reactions that are this fast. Kinetic limit is about 2 x 10^(-10) cm3 s–1 (depends on the mass of the molecule).

Thank you. We change "rather high" to "unrealistically high" in this statement.

386: Write as m/z 45 (with m and z in italics - m/z this is a symbol, not a physical quantity; otherwise units would be required).

Corrected to "*m/z*".

392: Please separate into two equations. What is this tilde/equal sign supposed to mean? Please show explicitly how you calculated the coefficient of 7.2568·10−2 in the delta_b equation with all values going into the calculation- the description is not clear.

We separate Eq. (B1) accordingly (see below). The tilde/equal sign "≅" was used to denote "approximately equal"; however, since this mathematical notation is a not commonly used in ACP, we refrain from using it in the revised manuscript and explicitly state the approximation:

> The respective bias $^{13}\delta_b$ is quantified using
>
> $$^{13}\delta_b = 7.26\cdot10^{-2}\,\Delta^{17}\mathrm{O(CO)}\,, \qquad \text{(B1)}$$
>
> where the actual Δ^{17}O(CO) value is approximated from the natural CO MIF signal $^{17}\Delta_n$ and the typical O_3 MIF composition $^{17}\Delta_c$ as
>
> $$\Delta^{17}\mathrm{O(CO)} = (^{17}\Delta_n\,(C_a - C_c) + {}^{17}\Delta_c\,C_c)(C_a)^{-1}\,. \qquad \text{(B2)}$$

Regarding the calculation of the coefficient proportionating $^{13}\delta_b$ and Δ^{17}O(CO), we used the calculation apparatus which is exhaustively described by Assonov and Brenninkmeijer (2001) and thus is out of the scope of this paper. We add, however, additional information which we believe is sufficient for the Reader to follow our calculations, namely:

> The coefficient that proportionates $^{13}\delta_b$ and Δ^{17}O in Eq. (B1) is reckoned by linearly regressing the δ^{13}C(CO) biases (simulated using the calculation apparatus detailed by Assonov and Brenninkmeijer (2001)) as a function of Δ^{17}O(CO) varying within a (0−30)‰ range for the CO with initially unaccounted MIF (*e.g.*, the sample is assumed to be mass-dependently fractionated). It therefore quantifies some extra +(0.726±0.003)‰ in the analysed δ^{13}C(CO) per every +10‰ of Δ^{17}O(CO) excess.

393: What "remaining parameters"?

With this we implied the parameters C_t and C_c used in the calculations with the MM and derived in the contamination kinetic framework. We reformulate this statement (also in view of re-formulated Eq. (B2), see the answer to the previous comment) as follows:

> Here C_a and C_c denote the analysed CO abundance and contamination magnitude, respectively, used in the contamination kinetic framework (see Appendix A, Eq. (A3)) and in calculations with the MM (see Sect. 3.1).

collected onboard a passenger aircraft carrying an airfreight container with analytical and air/aerosol sampling equipment on long distance flights from Germany to South India and the Caribbean within the framework of the CARIBIC project (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container, http://www.caribic-atmospheric.com).

2 Experimental and results

2.1 Whole air sampling

[4] CARIBIC−1 (Phase #1, abbreviated hereafter "C1") was operational from November 1998 until April 2002 using a *Boeing* 767-300 ER operated by LTU International Airlines (Brenninkmeijer *et al.*, 1999). Using a whole air sample (WAS) collection system, twelve air samples were collected per flight (of 8−10 hours duration at cruise altitudes of 10−12 km) in stainless steel tanks for subsequent laboratory analysis of the abundances of various trace gases, including ^{14}CO. Large air samples were required in view of the ultra-low abundance of this mainly cosmogenic tracer (10−100 molecules cm^{-3} STP, about 40−400 amol/mol). (Hereinafter STP denotes dry air at 273.15 K, 101325 Pa.) Each C1 WAS sample (holding 350 litres of air STP) was collected within 15−20 min intervals representing the integral of the compositions encountered along flight segments of about 250 km. The overall uncertainty of the measured WAS CO is less than ±1% for the mixing ratio and ±0.1‰/±0.2‰ for $\delta^{13}C(CO)/\delta^{18}O(CO)$, respectively (Brenninkmeijer, 1993; Brenninkmeijer *et al.*, 2001). Isotope compositions are reported throughout this manuscript using the so-called delta value $\delta_i = (R/R_{st}-1)$ relating the ratio R of rare (^{13}C, ^{18}O or ^{17}O) over abundant isotopes of interest to the standard ratio R_{st}. These are V-SMOW of 2005.20×10^{-6} for $^{18}O/^{16}O$ (Gonfiantini, 1978; Coplen, 1994) and 386.72×10^{-6} for $^{17}O/^{16}O$ (Assonov and Brenninkmeijer, 2003), and V-PDB of 11237.2×10^{-6} for $^{13}C/^{12}C$ (Craig, 1957), respectively. As we mention above, the oxygen isotopic composition of the CO present in these WAS samples was corrupted, in particular when O_3 levels were as high as 100−600 nmol/mol.

[5] CARIBIC−2 (Phase #2, referred to as "C2") started operation in December 2004 with a Lufthansa *Airbus* A340-600 fitted with a new inlet system and air sampling lines, including PFA lined tubing for trace gas intake (Brenninkmeijer *et al.*, 2007). No flask CO mixing/isotope ratio measurements are performed in C2.

Deleted: ~
Deleted: ~
Deleted: ~
Deleted: [
Deleted:]
Deleted: *i*
Deleted: *i*
Deleted: *i*
Deleted: *iR*
Deleted: (*i* denotes ^{13}C, ^{18}O or ^{17}O)
Deleted: *i*

2.2 On-line instrumentation

[6] In addition to the WAS collection systems, both C1 and C2 measurement setups include different instrumentation for on-line detection of [CO] and [O_3] (hereinafter the squared brackets [] denote the abundance, *i.e.* concentration or mixing ratio, of the respective species). *In situ* CO analysis in C1 is done using a gas chromatography (GC)-reducing gas analyser which provides measurements every 130 s with uncertainty of ±3 nmol/mol (Zahn *et al.*, 2000). In C2, a vacuum ultraviolet fluorescence (VUV) instrument with lower measurement uncertainty and higher temporal resolution of ±2 nmol/mol in 2 s (Scharffe *et al.*, 2012) is employed, respectively. Furthermore, the detection frequency for O_3 abundances has also increased, *viz.*, from 0.06 Hz in C1 to 5 Hz in C2 (Zahn *et al.*, 2002; Zahn *et al.*, 2012).

Deleted: each

Deleted: ~

Deleted: mixing ratio

2.3 Results

[7] When comparing the CO abundances in relation to those of O_3 for C1 and C2, differences are apparent in the LMS, where C2 CO values are systematically lower. This is illustrated in Fig. 1 (a) which presents the LMS CO-O_3 distribution of the C2 measurements overlaid with the C1 *in situ* and WAS data. (The entire C1 CO/O_3 dataset is presented in Fig. 2.) For the *in situ* CO datasets we calculated the statistics (Fig. 1 (b)) of the samples with respective O_3 abundances clustered in 20 nmol/mol bins, *i.e.* the median and spread of [CO] as a function of [O_3] analysed. (The interquartile range, IQR, is used in the current analysis as a robust measure of the data spread instead of the standard deviation.) The data exhibit large [CO] variations at [O_3] below 400 nmol/mol that primarily reflect pronounced seasonal variations in the NH tropospheric CO abundance. With O_3 rising, [CO] decreases to typical stratospheric values, and its spread reduces to mere 3.5 nmol/mol and less, as [O_3] surpasses 500 nmol/mol. Despite the comparable spread in C1 and C2 [CO], from 400 nmol/mol of [O_3] onwards the C1 CO mixing ratios start to level off, with no samples below 35 nmol/mol having been detected, whereas the C2 levels continuously decline. By the 580 nmol/mol O_3 bin, C1 [CO] of $39.7^{+0.7}_{-3}$ nmol/mol accommodates some extra 15 nmol/mol compared to $25.6^{+1.2}_{-1.1}$ nmol/mol typical for C2 values. Overall, at [O_3] above 400 nmol/mol the conspicuously high [CO] is marked in about 200 *in situ* C1 samples, of which 158 and 69 emerge as statistically significant mild and extreme outliers, respectively, when compared against the ample ($n \gtrsim 3 \cdot 10^5$) C2 statistics. (The conventions here follow Natrella (2003), *i.e.* ±1.5 and ±3 IQR ranges define the inner and outer statistical fences (ranges outside which the data points are considered mild and extreme outliers) of the C2 [CO] distribution in every O_3 bin, respectively. The statistics include the samples in bins

Deleted: mixing ratios

Deleted: **Error! Reference source not found.**, Panel

Deleted: increasingly becomes

Deleted: ~

Deleted: ; t

with average [O_3] of 420−620 nmol/mol.) None of C1 CO at [O_3] above 560 nmol/mol agrees with the C2 observations. Because the CO levels cannot have changed over the period in question by the difference we find (up to 55%), artefacts and calibration issues need to be scrutinised.

[8] Unnatural elevations in the $^{18}O/^{16}O$ ratios of CO from WAS measurements are also evident, as shown in Figs. 3 and 4. The large $\delta^{18}O(CO)$ departures that reach beyond +16‰ are found to be proportional to the concomitant O_3 abundances (denoted with colour) and more prominent at lower [CO]. A rather different relationship, however, is expected from our knowledge of UT/LMS CO sources (plus their isotope signatures) and available *in situ* observations (Fig. 2, shown with triangles), as elucidated by Brenninkmeijer *et al.* (1996) (hereafter denoted as "B96"). That is, the more stratospheric CO is, the greater fraction of its local inventory is refilled with the photochemical component stemming from methane oxidation with a characteristic $\delta^{18}O$ signature of ~0‰ or lower (Brenninkmeijer and Röckmann, 1997). This occurs because the CO sink at ruling UT/LMS temperatures proceeds more readily than its production, as the reaction of hydroxyl radical (OH) with CO, being primarily pressure-dependent, outcompetes the temperature-sensitive reaction of OH with CH_4. Furthermore, as the lifetime of CO quickly decreases with altitude, transport-mixing effects take the lead in determining the vertical distributions of [CO] and $\delta^{18}O(CO)$ above the tropopause, hence their mutual relationship. This is seen from the B96 data at [CO] below 50 nmol/mol that line-up in a near linear relationship towards the end-members with lowest $^{18}O/^{16}O$ ratios. These result from the largest share of the ^{18}O-depleted photochemical component and extra depletion caused by the preferential removal of $C^{18}O$ in reaction with OH (fractionation about ~11‰ at pressures below 300 hPa, Stevens *et al.*, 1980; Röckmann *et al.*, 1998b).

[9] It is beyond doubt that the enhancements of C1 $C^{18}O$ originate from O_3, whose large enrichment in heavy oxygen (above +60‰ in $\delta^{18}O$, Brenninkmeijer *et al.*, 2003) is typical and found transferred to other atmospheric compounds (see Savarino and Morin (2012) for a review). In Fig. 2 it is also notable that not only the LMS compositions are affected but elevations of (3−10)‰ from the bulk $\delta^{18}O(CO)$ values are present in more tropospheric samples with [CO] of up to ~100 nmol/mol. These result from the dilution of the least affected CO-rich tropospheric air by CO-poor, however substantially contaminated, stratospheric air, sampled into the same WAS tank. Such sampling-induced mixing renders an unambiguous determination of the artefact source' isotope signature rather difficult, because neither mixing nor isotope ratios of the admixed air portions are known sufficiently well (see below).

Deleted: Fig. 3

Deleted: (see also Fig. S2 in the Supplementary Material)

Deleted: *ibid.*

Deleted: with high mixing ratios

[10] Differences between the WAS and *in situ* measured [CO] – a possible indication that the $\delta^{18}O(CO)$ contamination pertains specifically to the WAS data – average at $\bar{\Delta}$(WAS−*in situ*) = (5.3±0.2) nmol/mol (±1 standard deviation of the mean, n = 408) and happen to be random with respect to any operational parameter or measured characteristic in C1, *i.e.* irrespective of CO or O_3 abundances. The above mentioned discrepancy remained after several calibrations between the two systems had been performed, and likely results from the differences in the detection methods, drifts of the calibration standards used (see details in Brenninkmeijer *et al.*, 2001) and a short-term production of CO in the stainless steel tanks during sampling. The large spread of Δ(WAS−*in situ*) of ±3.5 nmol/mol (±1σ of the population) ensues from the fact that the *in situ* sampled air corresponds to (2−4)% of the concomitantly sampled WAS volume, as typically 6−7 *in situ* collections of 5 s were made throughout one tank collection of 17−21 min. The integrity of the WAS CO is further affirmed by the unsystematic distribution of the artefact compositions among tanks (an opposite case for $\delta^{18}O(CO_2)$ in C1 is discussed by Assonov *et al.*, 2009). Overall, the WAS and *in situ* measured CO mixing ratios correlate extremely well (adj. R^2 = 0.972, slope of 0.992±0.008 (±1σ), n = 408). However, both anomalies in [CO] and $\delta^{18}O(CO)$ manifest clear but complex functions of the concomitant [O_3]. That is, the C1 *in situ* and WAS data very likely evidence artefacts pertaining to the O_3-driven effect of the same nature. Below we ascertain and quantify these.

3 Discussion

[11] Three factors may lead to the (artefact) distributions such as seen for C1 *in situ* [CO] at the LMS O_3 abundances, namely:

[12] (i) Strong (linear) natural mixing, such as enhanced stratosphere-troposphere exchange (STE), when a [CO] outside the statistically expected range results from the integration of air having dissimilar ratios of the tracers' abundances, *viz.* [O_3]:[CO]. For example, mixing of two air parcels in a 15%:85% proportion (by moles of air) with typical [O_3]:[CO] of 700:24 (stratospheric) and 60:125 (tropospheric), respectively, yields an integrated composition with [O_3]:[CO] of ~580:40 which indeed corresponds to C1 data (this case is exemplified by the mixing curve in Fig. 1). Nonetheless, occurrences of rather high (compared to the typical 24−26 nmol/mol) stratospheric CO mixing ratios (in our case, ~40 nmol/mol at the concomitant [O_3] of 500−600 nmol/mol) are rare. For instance, a deep STE similar to that described by Pan *et al.* (2004) was observed by C2 only once (*cf.* the outliers at [O_3] of 500 nmol/mol in Fig. 1), whereas the C1 outliers were exclusively registered in some 12 flights during

Deleted: WAS
Formatted: Not Superscript/ Subscript
Deleted: *in situ*
Formatted: Not Superscript/ Subscript
Deleted: SD
Deleted: quoted mixing ratio
Deleted: WAS−*in situ*
Deleted: ~
Deleted: $\rho_{O_3:CO}$ =
Deleted: /
Deleted: $\rho_{O_3:CO}$
Deleted: $\rho_{O_3:CO}$

1997−2001. No relation between these outliers and the large-scale [CO] perturbation due to extensive biomass burning in 1997/1998 (Novelli *et al.*, 2003) is established, otherwise elevated CO mixing ratios should manifest themselves at lower [O_3] as well. Other tracers detected in CARIBIC provide supporting evidence against such strongly STE-mixed air having been captured by C1. That is, the binned distributions for the water vapour and de-trended N_2O (similar to that for [CO] *vs.* [O_3] presented in Fig. 1, not shown here) are greatly similar in C1 and C2. Whereas the small relative variations in atmospheric [N_2O] merely confirm matching [O_3] statistics in CARIBIC, the stratospheric [H_2O] distributions witness no [O_3]:[CO] values corresponding to those of the C1 outliers, suggesting the latter being unnaturally low.

[13] (ii) Mixing effects can also occur artificially, originating from sampling peculiarities or data processing. Since the CARIBIC platform is not stationary, about 5 s long sampling of an *in situ* air probe in C1 implies integration of the compositions encountered along some hundred metres, owing to the high aircraft speed. This distance may cover a transect between tropospheric and stratospheric filaments of much different compositions. The effect of such 'translational mixing' can be simulated by averaging the sampling data with higher temporal frequency over longer time intervals. In this respect, the substantially more frequent CO data in C2 (<1 s) were artificially averaged over a set of increasing intervals to reckon whether the long sampling period in C1 could be the culprit for skewing its CO−O_3 distribution. As a result, the original C2 data and their averages (equivalent to the C1 CO sample injection time) differ negligibly, as do the respective [O_3]:[CO] values. The actual C2 CO−O_3 statistic in the region of interest ([O_3] of 540−620 nmol/mol) remains insensitive to integration of up to 300 s. Furthermore, a very strong artificial mixing with an averaging interval of at least 1200 s (comparable to C1 WAS sampling time) is required to yield the averages from the C2 data with [O_3]:[CO] characteristic for the C1 outliers.

[14] (iii) In view of the above, it is unlikely that any natural or artificial mixing processes are involved in the stratospheric [CO] discrepancies seen in C1. We therefore conclude that the sample contamination in C1 occurred prior to the probed air reaching the analytical/sampling instrumentation in the container, since clearly elevated stratospheric CO mixing ratios are common to WAS and *in situ* data. Two more indications, *viz.* growing [CO] discrepancy with increasing O_3 abundance, and the strong concomitant signal in $\delta^{18}O(CO)$, imply that O_3-mediated photochemical production of CO took place. Further, by confronting the C1 and C2 [CO] measurements in a kinetic framework (detailed in Appendix A), we quantify the artefact CO component being chiefly a function of O_3 abundance as

Deleted: $\rho_{O_3:H_2O}$

Deleted: ' $\rho_{O_3:CO}$

Deleted: $\rho_{O_3:CO}$

Deleted: ; t

Deleted: $\rho_{O_3:CO}$

Deleted: It

Deleted: stands to reason to

$$C_c = b\cdot[O_3]^2,\ b = (5.19\pm0.12)\cdot10^{-5}\ [\text{mol/nmol}], \quad (1)$$

which is equivalent to 8−18 nmol/mol throughout the respective [O_3] range of 400−620 nmol/mol (see Fig. 1 (d)). Subtracting this artefact signal yields the corrected *in situ* C1 CO−O_3 distribution conform to that of C2 (*cf.* red symbols in Fig. 1 (a)).

[15] Importantly, since we can quantify the contamination strength using only the O_3 abundance, the continuous *in situ* C1 [O_3] data allows estimating the integral artefact CO component in each WAS sample and, if the isotope ratio of contaminating O_3 is known, to derive the initial $\delta^{18}O(CO)$. The latter, as it was mentioned above, is subject to strong sample-mixing effects, which is witnessed by $\delta^{18}O(CO)$ outliers even at relatively high [CO] up to 100 nmol/mol. Accounting for such cases is, however, problematic since it is necessary to distinguish the proportions of the least modified (tropospheric) and significantly affected (stratospheric) components in the resultant WAS sample mix. In reality, however, this information is not available, therefore we applied an *ad hoc* correction approach (which is capable of determining the contamination source (*i.e.*, O_3) isotope signature as well), as described in the following.

3.1 Contamination isotope signatures

[16] Practically we resort to the differential mixing model (MM, originally known as the "Keeling-plot"), because it requires only the estimate of the artefact component mixing ratio, but no assumptions on the (unknown) shares and isotope signatures of the air portions mixed in a given WAS tank. The MM parameterises the admixing of the portion of artefact CO to the WAS sample with the "true" initial composition, as formulated below:

$$\begin{cases} \delta_a C_a = C_t\delta_t + C_c\delta_c \\ C_a \equiv C_t + C_c \end{cases},$$

where indices *a*, *c* and *t* distinguish the abundances C and isotope compositions δ (^{13}C and ^{18}O) pertaining to the analysed sample, estimated contamination and "true" composition sought (*i.e.*, C_t and δ_t), respectively. (Here the contamination strength C_c is derived by integrating Eq. (1) using the *in situ* C1 [O_3] data for each WAS sample.) By rewriting the above equation with respect to the isotope signature of the analysed CO, one obtains:

$$\delta_a = \delta_c + (\delta_t - \delta_c)C_t/C_a\,, \quad (2)$$

which signifies that linear regression of δ_a as a function of the reciprocal of C_a yields the estimated contamination signature δ_c at $(C_a)^{-1} \to 0$ when invariable "true" compositions (C_t, $^i\delta_t$) are taken (the Keeling plot detailing these calculations is shown in Fig. 5). We therefore apply the

Deleted: to

Deleted: e

Deleted: . ()

Deleted: ^{i}

Deleted: *i* may refer to

Deleted: or

Deleted: ^{i}

Deleted: .

Deleted: .

Deleted: .

Deleted: admixed portion

Deleted: $^i\delta_c$

Deleted: the measured ^{i}

Deleted: $_c$

Deleted: ^{i}

Deleted: $_c$

Deleted: (The Keeling plot detailing the calculations with the MM is shown in Supplementary Material, Fig. S3.) The MM described by Eq. (2) provides adequate results only for the invariable initial compositions (C_i, $^i\delta_i$),

Deleted: we

MM described by Eq. (2) to the subsets of samples picked according to the same reckoned C_t (within a ±2 nmol/mol window, $n > 7$). Such selection, however, may be insufficient: Due to the strong sampling effects in the WAS samples (see previous Section), it is possible to encounter samples that integrate different air masses to the same C_t but rather different average δ_t. The solution in this case is to refer to the goodness of the MM regression fit, because the R^2 intrinsically measures the linearity of the regressed data, *i.e.* closeness of the "true" values in a regarded subset of samples, irrespective of underlying reasons for that.

[17] Higher R^2 values thus imply higher consistency of the estimate, as demonstrated in Fig. 6 showing the calculated δ_c for C_t below 80 nmol/mol as a function of the regression R^2. The latter decreases with greater C_t (*i.e.*, larger sample subset size, since tropospheric air is more often encountered) and, conformably, larger variations in δ_t. Ultimately, at lower R^2 the inferred ^{18}O signatures converge to values slightly above zero expected for uncorrelated data, *i.e.* C1 $\delta^{18}O(CO)$ tropospheric average. A similar relationship is seen for the ^{13}C signatures (they converge around −28‰), however, there are no consistent estimates found (R^2 is generally below 0.4). Since such is not the case for $\delta^{18}O$, the MM is not sufficiently sensitive to the changes caused by the contamination, which implies that the artefact CO $\delta^{13}C$ should be within the range of the "true" $\delta^{13}C(CO)$ values. Interestingly, the MM is rather responsive to the growing fraction of the CH_4-derived component in CO with increasing $[O_3]$, as the $^{13}\delta_c$ value of −(47.2±5.8)‰ inferred at R^2 above 0.4 is characteristic for the $\delta^{13}C$ of methane in the UT/LMS. It is important to note that we have accounted for the biases in the analysed C1 WAS $\delta^{13}C(CO)$ expected from the mass-independent isotope composition of O_3 (see details in Appendix B).

[18] We derive the "best-guess" estimate of the admixed CO ^{18}O signature at $^{18}\delta_c$ = +(92.0±8.3)‰, which agrees with the other MM results obtained at R^2 above 0.75. Taking the same subsets of samples, the concomitant ^{13}C signature matches $^{13}\delta_c$ = −(23.3±8.6)‰, indeed at the upper end of the expected LMS $\delta^{13}C(CO)$ variations of −(25−31)‰. Because of that, the MM is likely insensitive to the changes in $\delta^{13}C(CO)$ caused by the contamination (the corresponding R^2 values are below 0.1). Upon the correction using the inferred $^{18}\delta_c$ value, the C1 WAS $\delta^{18}O(CO)$ data appear adequate (shown with red symbols in Fig. 2). That is, variations in the observed $C^{18}O$ are driven by (i) the seasonal/regional changes in the composition of tropospheric air and by (ii) the degree of mixing or replacement of the latter with the stratospheric component that is less variable in ^{18}O. This is seen as stretching of the scattered tropospheric values ([CO] above 60 nmol/mol) in a mixing fashion towards $\delta^{18}O(CO)$ of around −10‰ at [CO] of ~25 nmol/mol, respectively. The corrected C1 $\delta^{13}C(CO)$ data (shown in Fig. 7) are

Deleted: it

Deleted: *i*

Deleted: *i*

Deleted: *i*

Deleted: 13C

Deleted: worthy

Deleted: 18O

Deleted: 13C

Deleted: , which

Deleted: likely does not allow

Deleted: to ascertain this result as pertaining

Deleted: 18O

Deleted: Supplementary Material, Fig. S4

found to be in a ±1‰ agreement with the observations by B96, except for several deep stratospheric samples ([CO] below 40 nmol/mol). The latter were encountered during "ozone hole" conditions and carried extremely low ^{13}CO abundances, which was attributed to the reaction of methane with available free Cl radicals (Brenninkmeijer *et al.*, 1996).

3.2 Estimate of $\delta^{18}O(O_3)$

[19] The contamination ^{18}O signature inferred here ($^{18}\delta_c$ = +(92.0±8.3)‰) unambiguously pertains to O_3 and is comparable to $\delta^{18}O(O_3)$ values measured in the stratosphere at temperatures about 30 K lower than those encountered in the UT/LMS by C1 (see Table 1 for comparison). If no other factors are involved (see below), this discrepancy in $\delta^{18}O(O_3)$ should be attributed to the local conditions, *i.e.* the higher pressures (typically 240−270 hPa for C1 cruising altitudes) at which O_3 was formed. Indeed, the molecular lifetime (the period through which the species' isotope reservoir becomes entirely renewed, as opposed to the "bulk" lifetime) of O_3 encountered along the C1 flight routes is estimated on the order of minutes to hours at daylight (H. Riede, Max Planck Institute for Chemistry, 2010), thus the isotope composition of the photochemically regenerated O_3 resets quickly according to the local conditions. Virtual absence of sinks, in turn, leads to "freezing" of the $\delta^{18}O(O_3)$ value during night in the UT/LMS. Verifying the current $\delta^{18}O(O_3)$ estimate against the kinetic data, in contrast to the stratospheric cases, is problematic. The laboratory studies on O_3 formation to date have scrutinised the concomitant kinetic isotope effects (KIEs) as a function of temperature at only low pressures (50 Torr); the attenuation of the KIEs with increasing pressure was studied only at room temperatures (see Table 1, also Brenninkmeijer *et al.* (2003) for references). A rather crude attempt may be undertaken by assuming that the formation KIEs become attenuated at higher pressures in a similar (proportional) fashion to that measured at 320 K, however applied to the nominal low-pressure values reckoned at (220−230) K. A decrease in $\delta^{18}O(O_3)$ of about (5.9−7.6)‰ is expected from such calculation, yet accounting for a mere one-half of the (13.3−14.6)‰ discrepancy between the stratospheric $\delta^{18}O(O_3)$ values and $^{18}\delta_c$.

[20] Lower $^{18}\delta_c$ values could result from possible isotope fractionation accompanying the production of the artefact CO. Although not quantifiable here, oxygen KIEs in the $O_3 \rightarrow CO$ conversion chain cannot be ruled out, recalling that the intermediate reaction steps are not identifiable and the artefact CO represents at most 4% of all O_3 molecules. Furthermore, the yield λ_{O_3} of CO from O_3 may be lower than unity (see details in Appendix A). On the other hand, the inference that the contamination strength primarily depends on $[O_3]$ indicates that the kinetic frac-

Deleted: ^{18}
Deleted: $^{O}\delta_c$
Deleted: ^{18}
Deleted: ^{O}
Deleted: -
Deleted: conjecturing
Deleted: an inhibition of
Deleted: ~
Deleted: "missing" in
Deleted: ^{18}
Deleted: ^{O}
Deleted: ^{18}
Deleted: ^{O}

tionation may have greater effect on the carbon isotope ratios of the artefact CO produced (the $^{13}\delta_c$ values) in contrast to the oxygen ones. That is because all reactive oxygen available from O_3 becomes converted to CO, whilst the concomitant carbon atoms are drawn from a virtually unlimited pool whose apparent isotope composition is altered by the magnitude of the ^{13}C KIEs.

[21] Besides KIEs, selectivity in the transfer of O atoms from O_3 to CO affects the resulting $^{18}\delta_c$ value. The terminal O atoms in O_3 are enriched with respect to the molecular (bulk) O_3 composition when the latter is above ~+70‰ in $\delta^{18}O$ (Janssen, 2005; Bhattacharya *et al.*, 2008), therefore an incorporation of only central O atoms into the artefact CO molecules should result in a reduced apparent $^{18}\delta_c$ value. Such exclusive selection is, however, less likely from the kinetic standpoint and was not observed in available laboratory studies (see Savarino *et al.* (2008) for a review). For instance, Röckmann *et al.* (1998a) established the evidence of direct O transfer from O_3 to the CO produced in alkene ozonolysis. A reanalysis of their results (in light of findings of Bhattacharya *et al.* (2008)) suggests that usually the terminal atoms of the O_3 molecule become transferred (their ratio over the central ones changes from the bulk ~2:1 to ~1:0 for various species). Considering the alternatives of the O transfer in our case (listed additionally in Table 1), the equiprobable incorporation of the terminal and central O_3 atoms into CO should result in the $\delta^{18}O(O_3)$ value in agreement with the "crude" estimate based on laboratory data given above.

[22] Furthermore, the conditions that supported the reaction of O_3 (or its derivatives) followed by the production of CO are vague. A few hypotheses ought to be scrutinised here. First, a fast $O_3 \rightarrow CO$ conversion must have occurred, owing to short (*i.e.*, fraction of a second) exposure time of the probed air to the contamination. Accounting for the typical C1 air sampling conditions (these are: sampled air pressure of 240−270 hPa and temperature of 220−235 K outboard to 275−300 K inboard, sampling rate of ~$12.85 \cdot 10^{-3}$ moles s^{-1} corresponding to 350 L STP sampled in 1200 s, inlet/tubing volume gauged to yield exposure times of 0.01 to 0.1 s due to variable air intake rate, $[O_3]$ of 600 nmol/mol), the overall reaction rate coefficient (k_c in Eq. (A1) from Appendix A) must be on the order of ($6 \cdot 10^{-15}/\tau_c$) molec^{-1} cm^3 s^{-1}, where τ_c is the exposure time. Assuming the case of a gas-phase CO production from a recombining O_3 derivative and an unknown carbonaceous compound X, the reaction rate coefficient for the latter ($^X k_r$ in Eq. (A1) in Appendix A) must be unrealistically high, at least ~$6 \cdot 10^{-10}$ molec^{-1} cm^3 s^{-1} over τ_c = 1/100 s. This number decreases proportionally with growing τ_c and [X], if we take less strict exposure conditions. Nonetheless, in order to provide the amounts of artefact CO we detect, a

Deleted: 13
Deleted: c
Deleted: 18
Deleted: o
Deleted: .
Deleted: .
Deleted: .
Deleted: to
Deleted: 18
Deleted: o
Deleted: [
Deleted:]
Deleted: rather
Deleted: [
Deleted:]

minimum abundance of 20 nmol/mol (or up to 4 µg of C per flight) of X is required, which is not available in the UT/LMS from the species readily undergoing ozonolysis, *e.g.* alkenes.

[23] Second, a more complex heterogeneous chemistry on the inner surface of the inlet or supplying tubing may be involved. Such can be the tracers' surface adsorption, (catalytic) decomposition of O_3 and its reaction with organics or with surface carbon that also may lead to the production of CO (Oyama, 2000). Evidence exists for the dissociative adsorption of O_3 on the surfaces with subsequent production of the reactive atomic oxygen species (see, *e.g.*, Li *et al.*, 1998, also Oyama, 2000). It is probable that sufficient amounts of organics have remained on the walls of the sampling line exposed to highly polluted tropospheric air, to be later broken down by the products of the heterogeneous decomposition of the ample stratospheric O_3. Unfortunately, the scope for a detailed quantification of intricate surface effects in the C1 CO contamination problem is very limited.

4 Conclusions

[24] Recapitulating, the *in situ* measurements of CO and O_3 allowed us to unambiguously quantify the artefact CO production from O_3 likely in the sample line of the CARIBIC−1 instrumentation. Strong evidence to that is provided by the isotope CO measurements. We demonstrate the ability of the simple mixing model ("Keeling-plot" approach) to single out the contamination isotope signatures even in the case of a large sampling-induced mixing of the air with very different compositions. Obtained as a collateral result, the estimate of the $\delta^{18}O(O_3)$ in the UT/LMS appears adequate, calling, however, for additional laboratory data (*e.g.*, the temperature-driven variations of the O_3 formation KIE at pressures above 100 hPa) for a more unambiguous verification.

Appendix A. Contamination kinetic framework

[25] We infer the functional dependence of the CO contamination strength in the kinetic framework conceptually formulated as follows:

$$O_3 \xrightarrow{{}^{O_3}k_1} \left\{ \begin{array}{l} \left(\ldots + X \xrightarrow{{}^{X}k_z} \ldots\right)_K \\ \left(\ldots + O_3 \xrightarrow{{}^{O_3}k_z} \ldots\right)_{(\kappa-1)} \end{array} \right\} \rightarrow \lambda_{O_3} CO \quad \text{(A1)}$$

Eq. (A1) reads that production of an artefact CO molecules is initiated by O_3 (via either its decomposition or a reaction with an unknown educt) and is followed by a set of unknown reac-

Deleted: O_3-exclusive

Deleted: C_c by discriminating the C1 outliers from respective C2 data

Deleted: following

tions which proceed via unknown educts or products (denoted with ellipses), however requiring at some step an incorporation of carbon (donated by carbonaceous species X) and oxygen (also possible in secondary O_3 reactions) atoms into final CO. Coefficients K and κ describe the stoichiometry of the system, *i.e.* how many reactions of X and O_3 (with the individual unknown rate coefficients ${}^{X}k_r$ and ${}^{O3}k_r$) lead to production of one artefact CO, respectively. The yield λ_{O3}, a diagnostic quantity, relates the amount of artefact CO molecules produced to the total number of O_3 molecules consumed in the system. Based on Eq. (A1), the functional dependence of the artefact CO component (denoted C_c, obtained by discriminating the C1 outliers from respective C2 data) on $[O_3]$ or [X] is generally formulated as (abundances in number density units are used)

$$C_c = \int_{\tau_c} \prod_{\kappa} {}^{O_3}k_r [O_3] \prod_{K} {}^{X}k_r [X] dt \quad \text{(A2)}$$

where τ_c denotes the contamination reaction time. Eq. (A2) defines the regression expression using which we attempted to fit the values of C_c as a function of κ, $[O_3]$, K and [X] (the latter was chosen iteratively from a set of carbonaceous species measured). Practically, however, this regression analysis ascertains that variations in C_c are exhaustively described using $[O_3]$ and κ. Furthermore, we find that no other species or operational parameter (*e.g.* temperature, pressure, flight duration, latitude, *etc.*) measured in C1 appear to determine (correlate with) C_c. Based on this, we can reduce Eq. (A2) to its final, simpler form, *viz.*

$$C_c = \lambda_{O_3} k_c [O_3]^{\kappa} \tau_c \quad \text{(A3)}$$

where k_c denotes the overall pseudo-first-order rate coefficient of the reaction chain that is exclusively propelled by O_3. The product $(\lambda_{O_3} k_c \tau_c)$ thus integrates the influence of the unknown (and likely invariable) [X], ${}^{X}k_r$, K and τ_c. Finally, regressing C_c using Eq. (A3) provides its best approximation as a function of $[O_3]$ at $\kappa = 2.06 \pm 0.38$, suggesting two chain steps involving O_3 or its derivatives. At $\kappa = 2$, the product $(\lambda_{O_3} k_c \tau_c)$ that proportionates the CO contamination strength and $[O_3]$ is found to be $(5.19 \pm 0.12) \cdot 10^{-5}$ mol/nmol ($\pm 1\sigma$, adj. $R^2 = 0.83$, red. $\chi^2 = 4.0$; mole fraction units are used here for convenience). The low uncertainty (within ±3%) of this estimate confirms an exclusive dependence of the contamination source on the O_3 abundance, as well as much similar reaction times τ_c. The regressed value of C_c as a function of $[O_3]$ is presented in Fig. 1 (d) (solid line). It is possible to constrain the overall yield λ_{O_3} of CO molecules in the artefact source chain to be between 0.5 and 1, comparing the magnitude of C_c to the discrepancy between the $[O_3]$ measured in C1 and C2 (±20 nmol/mol, taken equal to the $[O_3]$ bin

Deleted: that

Deleted: or

Deleted:

Deleted: we find

Deleted: ,

Deleted: and k_c (the latter are obtained in a regression analysis). where

Deleted: leading to the artefact CO production with the respective yield λ_{O_3}. The individual rate coefficients ${}^{X}k_r$ and ${}^{O3}k_r$ pertain to the unknown compound(s) X and O_3 reacting with the integral stoichiometry factors K and κ, respectively.

Deleted: value of

Deleted: K

Deleted: the

Deleted: o

Deleted: based onThe relation defined by

Deleted: (A1)

Deleted: the

Deleted: for

Deleted: C_c

Deleted: ratio $C_c/[O_3]^2$ (essentially

Deleted: 1 to the reaction time τ_c and overall rate coefficient k_c

Deleted:)

Deleted: signifies

size owing to the N_2O−O_3 and H_2O−O_3 distributions matching well between the datasets). Lower λ_{O_3} values, otherwise, should have resulted in a noticeable (*i.e.*, greater than 20 nmol/mol) decrease in the C1 O_3 abundances with respect to the C2 levels.

Appendix B. Corrections to measured $\delta^{13}C(CO)$ values due to the oxygen MIF

[26] Atmospheric O_3 carries an anomalous isotope composition (or mass-independent fractionation, MIF) with a substantially higher relative enrichment in ^{17}O over that in ^{18}O (above +25‰ in $\Delta^{17}O = (\delta^{17}O+1)/(\delta^{18}O+1)^{\beta}-1$, $\beta = 0.528$) when compared to the majority of terrestrial oxygen reservoirs that are mass-dependently fractionated (*i.e.*, with $\Delta^{17}O$ of ~0‰) (see Brenninkmeijer *et al.* (2003) and refs. therein). CO itself also has an unusual oxygen isotopic composition, possessing a moderate tropospheric MIF of around +5‰ in $\Delta^{17}O(CO)$ induced by the sink KIEs in reaction of CO with OH (Röckmann *et al.*, 1998b; Röckmann *et al.*, 2002) and a minor source effect from the ozonolysis of alkenes (Röckmann *et al.*, 1998a; Gromov *et al.*, 2010). A substantial contamination of CO by O_3 oxygen induces proportional changes to $\Delta^{17}O(CO)$ that largely exceed its natural atmospheric variation. On the other hand, the MIF has implications in the analytical determination of $\delta^{13}C(CO)$, because the presence of $C^{17}O$ species interferes with the mass-spectrometric measurement of the abundances of ^{13}CO possessing the same basic molecular mass (*m/z* is 45). When inferring the exact $C^{17}O/C^{18}O$ ratio in the analysed sample is not possible, analytical techniques usually involve assumptions (*e.g.*, mass-dependently fractionated compositions or a certain non-zero $\Delta^{17}O$ value) with respect to the $C^{17}O$ abundances (Assonov and Brenninkmeijer, 2001). In effect for the C1 CO data, the artefact CO produced from O_3 had contributed with unexpectedly high $C^{17}O$ abundances that led to the overestimated $\delta^{13}C(CO)$ analysed. The respective bias $^{13}\delta_b$ is quantified using

$$^{13}\delta_b = 7.26 \cdot 10^{-2}\, \Delta^{17}O(CO)\,, \qquad \text{(B1)}$$

where the actual $\Delta^{17}O(CO)$ value is approximated from the natural CO MIF signal $^{17}\Delta_a$ and the typical O_3 MIF composition $^{17}\Delta_c$ as

$$\Delta^{17}O(CO) = (^{17}\Delta_a (C_a - C_c) + {}^{17}\Delta_c C_c)(C_a)^{-1}\,, \qquad \text{(B2)}$$

Here C_a and C_c denote the analysed CO abundance and contamination magnitude, respectively, used in the contamination kinetic framework (see Appendix A, Eq. (A3)) and in calculations with the MM (see Sect. 3.1) . For the purpose of the current estimate it is sufficient to take $^{17}\Delta_n$ of +5‰ representing equilibrium enrichments expected in the remote free troposphere and UT/

Deleted: Furthermore

Deleted: *e*

Deleted: Knowing the contamination magnitude C_c and assuming the typical O_3 MIF composition being $^{17O17}\Delta_c$, t

Deleted: ^{13C}

Deleted: calculated

Deleted: 568

Deleted: ^{17O}

Deleted: *t*

Deleted: denotes the natural, *i.e.* expected "true" value of $\Delta^{17}O(CO)$.

Deleted: *t*

Deleted: *t*

Deleted: ,

Deleted: The remaining parameters

Deleted: C_t and

Deleted: in Eq. (B2)

Deleted: s

Deleted: and C_c equals estimated,

Deleted: reckoned

Deleted: derived

Deleted: the pertain

Deleted: to

LMS. For the O_3 MIF signature $^{17}\Delta_c$, the value of +30‰ (the average $\Delta^{17}O(O_3)$ expected from the kinetic laboratory data at conditions met along the C1 flight routes, see Sect. 3.2 and Table 1) is adopted. The coefficient that proportionates $^{13}\delta_b$ and $\Delta^{17}O$ in Eq. (B1) is derived by linearly regressing the $\delta^{13}C(CO)$ biases (simulated using the calculation apparatus detailed by Assonov and Brenninkmeijer, 2001) as a function of $\Delta^{17}O(CO)$ varying within a (0−30)‰ range for the CO with initially unaccounted MIF (*e.g.*, the sample is assumed to be mass-dependently fractionated). It therefore quantifies some extra +(0.726±0.003)‰ in the analysed $\delta^{13}C(CO)$ per every +10‰ of $\Delta^{17}O(CO)$ excess. The most contaminated C1 WAS CO samples at $[O_3]$ above 300 nmol/mol are estimated to bear $\Delta^{17}O(CO)$ of (6−12)‰ corresponding to fractions of (0.10−0.27) of the artefact CO in the sample. Accordingly, the reckoned $\delta^{13}C(CO)$ biases span (0.5−0.9)‰. Although not large, these well exceed the $\delta^{13}C(CO)$ measurement precision of ±0.1‰ and were corrected for, and therefore are taken into account in the calculations with the MM presented in Sect. 3.1.

Deleted: ^{13C}

Deleted: reckoned

Deleted: and

Deleted: 3

Deleted: (Assonov and Brenninkmeijer (2001))

Acknowledgements

[27] The authors are indebted to Claus Koeppel, Dieter Scharffe and Dr. Andreas Zahn for their work and expertise on the carbon monoxide and ozone measurements in C1 and C2. Hella Riede is acknowledged for comprehensive estimates of the species lifetimes along the CARIBIC flight routes. We are grateful to Dr. Taku Umezawa, Dr. Angela K. Baker, Dr. Emma C. Leedham, Dr. Sergey Assonov, the anonymous reviewer and Dr. Jan Kaiser for the helpful discussions and comments on the manuscript.

Deleted: and

Deleted: ACP

Deleted: s

References

Assonov, S. S. and Brenninkmeijer, C. A. M.: A new method to determine the ^{17}O isotopic abundance in CO_2 using oxygen isotope exchange with a solid oxide, *Rapid Commun. Mass Spectrom.*, **15**, 2426−2437, doi: 10.1002/rcm.529, 2001.

Assonov, S. S. and Brenninkmeijer, C. A. M.: A redetermination of absolute values for $^{17}R_{VPDB\text{-}CO2}$ and $^{17}R_{VSMOW}$, *Rapid Commun. Mass Spectrom.*, **17**, 1017−1029, doi: 10.1002/Rcm.1011, 2003.

Assonov, S. S., Brenninkmeijer, C. A. M., Koeppel, C., and Röckmann, T.: CO_2 isotope analyses using large air samples collected on intercontinental flights by the CARIBIC Boeing 767, *Rapid Commun. Mass Spectrom.*, **23**, 822−830, doi: 10.1002/rcm.3946, 2009.

Bhattacharya, S. K., Pandey, A., and Savarino, J.: Determination of intramolecular isotope distribution of ozone by oxidation reaction with silver metal, *J. Geophys. Res. Atm.*, **113**, D03303, doi: 10.1029/2006jd008309, 2008.

Tables

Table 1. Ozone $^{18}O/^{16}O$ isotope ratios from literature and this study

Domain	T (K)	P (hPa)	$\delta^{18}O(O_3)$ (‰)	Remarks
Stratosphere	190–210	13–50	83–93 (<3)	[1]
UT/LMS	220–235	240–270	89–95 (8)	[2]
			84–88 (6)	T
			91–98 (9)	TC
			112–124 (17)	C
Laboratory	190–210	~67	87–97 (6)	[3]
	220–235	~67	102–110 (6)	[3]
	220–235	240–270	95–103	[4]

Notes: Values in parentheses denote the average of the estimates' standard errors. The expected O_3 isotope composition on the V-SMOW scale is calculated from the O_3 enrichments ε reported relative to O_2 using $\delta^{18}O(O_3)_{V\text{-}SMOW} = \delta^{18}O(O_2)_{V\text{-}SMOW} + {}^{18}\varepsilon(O_3)_{O_2} + [\delta^{18}O(O_2)_{V\text{-}SMOW} \times {}^{18}\varepsilon(O_3)_{O_2}]$.

[1] Observations (see Krankowsky *et al.* (2007) and refs. therein), lowermost values (19–25 km). Quoted temperature range is derived by matching measured $\delta^{18}O(O_3)$ and laboratory data (see note [3]).

[2] This study, C1 observations (10–12 km). Letters denote the estimates derived using the data from Bhattacharya *et al.* (2008) and assuming only terminal (T), only central (C) and equiprobable terminal and central (TC) O_3 atoms transfer to the artefact CO.

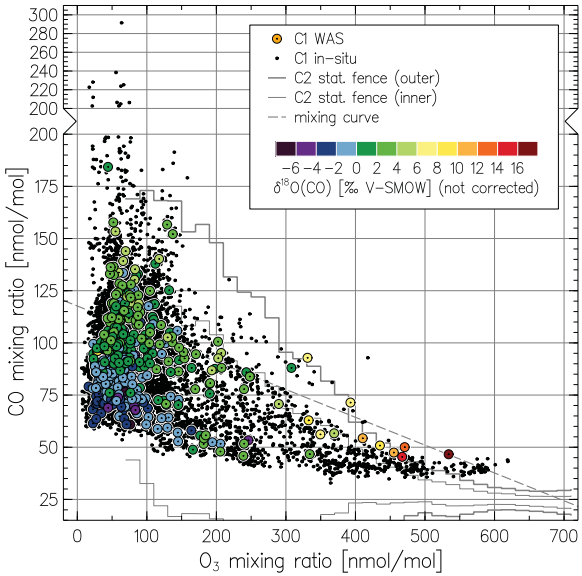
[3] Calculated using the laboratory KIE temperature dependence data summarised by Janssen *et al.* (2003).

[4] Calculated assuming a pressure dependence of the O_3 formation KIE similar to that measured at 320 K (see Guenther *et al.* (1999) and refs. therein).

Deleted: [
Deleted:]
Deleted: [
Deleted:]
Deleted: [
Deleted:]
Deleted: ^{18}O
Deleted: ^{18}O

Fig. 1. (a) Distribution of CO mixing ratios as a function of concomitant O_3 mixing ratios measured by CARIBIC in the LMS ([O_3]>300 nmol/mol). The shaded area is the two-dimensional histogram of the C2 measurements (all C2 data obtained until June 2013) counted in 5×1 nmol/mol size [O_3]×[CO] bins, thus darker areas emphasise greater numbers of particular CO−O_3 pairs observed. Small symbols denote the original C1 *in situ* measurements (black) and corrected for the artefacts (red); the C1 WAS analyses (11 of total 408) are shown with large symbols. Thin and thick step-lines demark the inner and outer statistical fences (ranges outside which the data points are considered mild or extreme outliers, see text) of the C2 data, respectively. The dashed curve exemplifies compositions expected from the linear mixing of very different (*e.g.*, tropospheric and stratospheric) end-members. (b) Statistics on CO mixing ratios from C1 and C2 data shown in box-and-whisker diagrams for samples clustered in 20 nmol/mol O_3 bins (whiskers represent 9th/91st percentiles). (c) Sample statistic for each CARIBIC dataset (note the C2 figures scaled down by a factor of 1000). (d) Estimates of the C1 *in situ* CO contamination strength C_c as a function of [O_3] (solid line) obtained by fitting the difference ΔCO between the C2 and C1 *in situ* [CO] (small symbols) in the kinetic framework (see Appendix A, Eq. (A1)). Step line shows the ΔCO for the statistical averages (the shaded area equals the height of the inner statistical fences of the C2 data). Large symbols denote the estimates of C_c in the C1 WAS data (slight variations *vs.* the *in situ* data are due to the sample mixing effects, see Sect. 3). Colour denotes the respective C1 WAS $\delta^{18}O(CO)$ (note that typically 6−7 *in situ* measurements correspond to one WAS sample).

Deleted: Note: The entire C1 CO/O_3 dataset is presented in the Supplementary Material, Fig. S1.



744 Fig. 2. (*accompanies Fig. 1*) Carbon monoxide and ozone mixing ratios measured in C1. Small black
745 symbols denote the C1 *in situ* measurements (n = 12753). The C1 WAS analyses (n = 408) are shown with
746 large symbols; colour denotes the concomitant $\delta^{18}O(CO)$ measurements. Thin and thick step-lines denote
747 the inner and outer statistical fences of the C2 data, respectively. The dashed curve exemplifies composi-
748 tions expected from the linear mixing of tropospheric and stratospheric end-members (see caption to Fig. 1
749 for details).

Deleted: (ranges outside which the data points are considered mild or extreme outliers)

Deleted: very different (*e.g.*,

Deleted:)

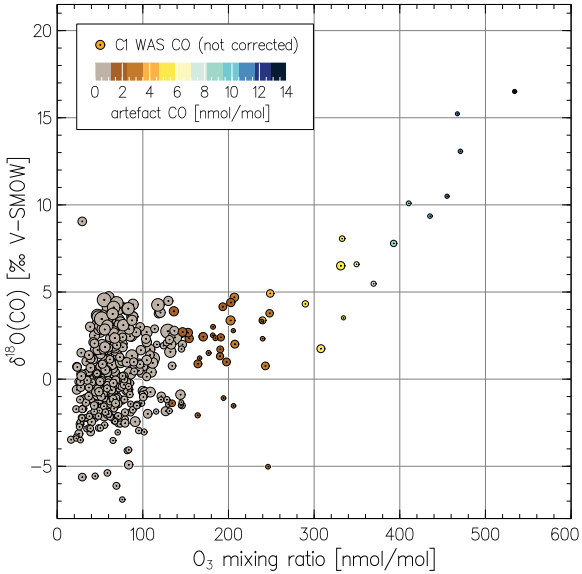


Fig. 4. Measured C1 WAS $\delta^{18}O(CO)$ (not corrected for artefacts) as a function of concomitant O_3 mixing ratio. Symbol colour denotes the artefact CO component (integral C_e per each WAS); symbol size scales proportionally to the WAS CO mixing ratio corrected for artefacts (see Sect. 3 for details).

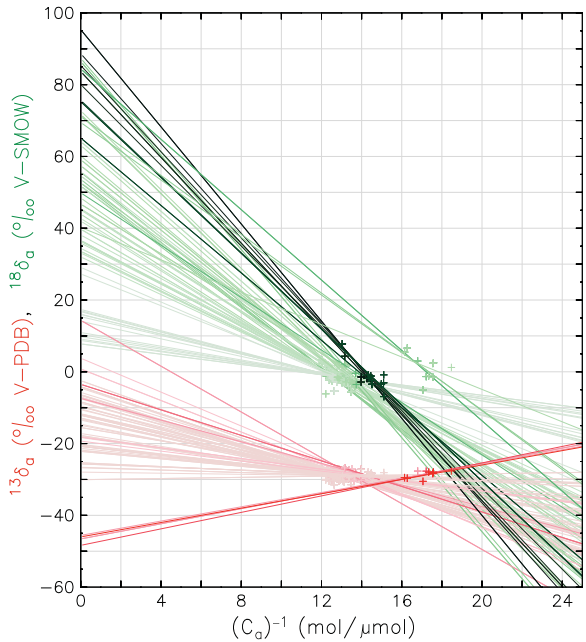


Fig. 5. Keeling plot of the data used in the calculations with the mixing model (MM). The C1 WAS isotope CO measurements are shown with symbols, solid lines denote the linear regressions through the various sets of samples selected by the MM (n = 80 sets are plotted). Colours refer to the $\delta^{13}C$ (red) and $\delta^{18}O$ (green) data, colour intensity indicates the coefficient of determination (R^2) of each regression, respectively. Darker colours denote higher R^2 values, with maxima of 0.92 for $\delta^{18}O$ and 0.54 for $\delta^{13}C$ data, respectively. The inferred contamination signatures ($\hat{\delta}_c$) are found at $(C_a)^{-1} \rightarrow 0$. Regression uncertainties are shown in Fig. 5. Note that because different subsets of samples contain same data points, some of the symbols are plotted over (*i.e.*, not all symbols contributing to a particular regression case may be seen).

Deleted: i

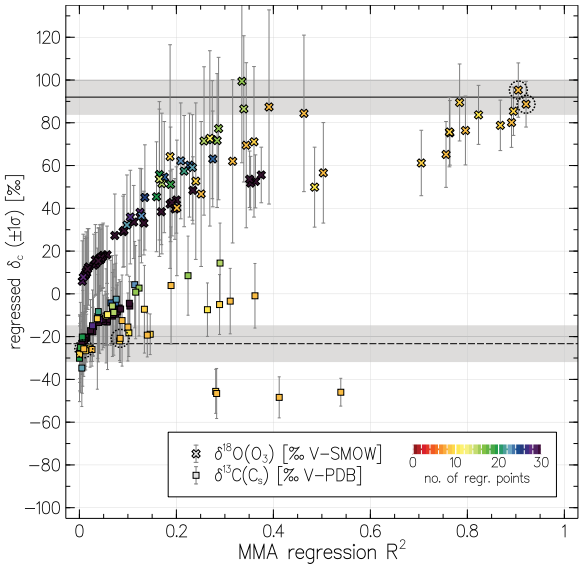


Fig. 6. Results of the regression calculation with the MM. Shown with symbols are the contamination source isotope signatures δ_c as a function of the respective coefficient of determination (R^2). Colour denotes the number of samples in each subset selected. Solid and dashed lines present the best guess ±1 standard deviation of the mean for the $\delta^{18}O(O_3)$ and $\delta^{13}C(C_c)$ estimates. Dashed circles mark the values obtained at highest R^2 for $^{18}O\delta_t$ regression (above 0.9). See text for details.

Deleted: i

Deleted: SD

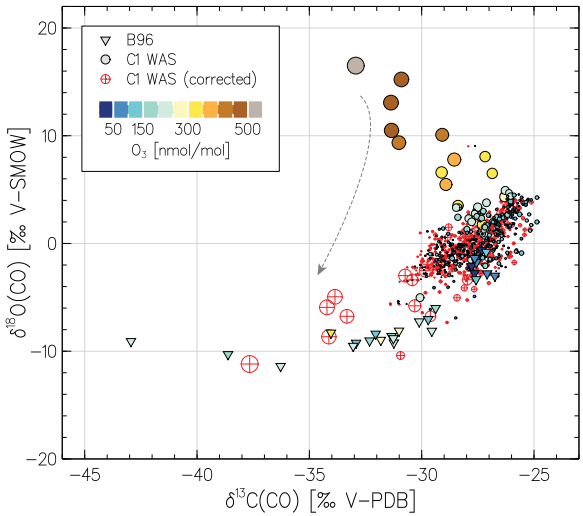


Fig. 7. $^{18}O/^{16}O$ and $^{13}C/^{12}C$ isotope composition of CO measured in C1. Triangles present the data from the remote SH UT/LMS obtained by Brenninkmeijer *et al.* (1996) (B96). Colour refers to the concomitantly observed O_3 abundances; note the extremely low [O_3] encountered by B96 in the Antarctic ozone-hole conditions. Filled and hollow circles denote the original and corrected (as exemplified by the dashed arrow) C1 WAS data, respectively, with the symbol size scaling proportional to the estimated contamination magnitude (see text for details).

Deleted: the manuscript