ACP-2019-239

Implications of constant CFC-11 concentrations for the future ozone layer

by Martin Dameris et al.

Reply to the referee #2 comments

In the following we give our first reply regarding the points raised by the reviewer. The statements and comments given by the referee are printed in black and our comments are presented in blue.

Answers to referee #2

We thank the referee for taking time to review this manuscript and for the comments. Before we will answer the points raised by the referee on a point to point basis, we want to add a general explanation to set our work into context.

Our analysis presented here is not aimed at specifically investigating the effect of the newly discovered emission and numerous possible "directly" related scenarios. Here we want to assess the impact of enhanced CFC-11 concentrations on the ozone layer as a sensitivity study. The recent paper by Montzka et al. (2018) triggered our interest in investigating this CFC-11 sensitivity and justifies (to some extent) such a sensitivity study as an extreme sensitivity. In particular we think that our sensitivity is new and interesting as

- CFC-11 concentrations are stable whereas other ODS decline as expected;
- we show when and where O3 loss due to additional CFC-11 occurs;
- we perform an ozone budget analysis showing compensation and buffering effects associated with different production and loss cycles (this has not been shown before);
- we show that even with these extreme CFC-11 concentrations it takes time to see the effect on O3 (due to strong interannual variability; this also implies that in addition to long-term monitoring of O3 the monitoring of ODS is crucial); and
- we can provide (most likely) an upper limit for possible scenarios; this could be seen as "what should be avoided/what could happen as a worst case (e.g. if a lot of the new production is actually stored in banks)" somewhat in the tradition of the Newman et al. (2009) paper.

We will try to make these points more clearly in the revised version of the manuscript.

Preface:

This paper details the effect of a very specific future scenario of CFC-11 on ozone recovery. It is a response to the recent measurements showing the CFC-11 values are not dropping as quickly as predicted by compliance to the Montreal Protocol and thus implying illegal emissions. It outlines this one simple scenario in sufficient detail and the paper is well written. However, it is severely lacking in answering the questions necessary to understand the effect of the newly discovered emissions (see below for details). Thus, I cannot recommend publication of this paper in anything like its present form. I suggest the authors rethink the scope of the problem and expand their study considerably.

The referee is right in saying that our model approach is simple. However, there is also a big knowledge gap regarding the future evolution of CFC-11 emissions and our main aim is not to distill specific scenarios. Nevertheless we believe that on the basis of our model study we can answer relevant questions which are related to the effects of the additional CFC-11 emissions (i.e. constant CFC-11 concentrations). From our point of view the model simulation (SEN) which has been

performed in addition to the reference simulation (REF) is certainly an extreme sensitivity study regarding CFC-11. Hopefully, it serves as an upper limit of possibilities regarding future CFC-11 emissions. It should not be considered as a specific future scenario that we deem likely. This study aims to assess the magnitude of possible ozone changes under constant CFC-11 concentrations. Since currently we do not have more detailed information about possible future CFC-11 emissions (either from illegal production or banks) such a "simple sensitivity study" is in our understanding justified. The goal of this paper is to answer questions which are related to the newly discovered emissions, but we do not claim that this is the actual path we are on. Moreover, this paper was not intended to answer questions which are focusing on the origin or sources of the additional CFC-11 emissions.

Furthermore, we do not aim at making a complete assessment. Our study rather aims to provide an insight into the reaction of the ozone layer with respect to unchanged (stable) CFC-11 concentrations in the coming years. (Further, once a new "most likely" emission scenario is agreed on we are willing to provide such a simulation.)

Last but not least, it is an interesting sensitivity study to keep CFC-11 constant, whereas other ODS are declining according to RCP scenarios (this is new and interesting in itself). To fully carve this out, we also investigate in detail ozone loss and production rates.

General comments:

The recent paper of Montzka et al. 2018 makes a strong case that there are illegal emissions of CFC-11 presently occurring and that these have been occurring since 2012 and even perhaps earlier. This brings up many questions for future ozone recovery including (but not limited to):

With our model study based on a comparison of two simulations using a chemistry-climate model (here EMAC) we would like to provide a qualitative and also a rough quantitative assessment of possible stratospheric ozone changes due to unchanged conditions regarding CFC-11 concentrations. It should help to assess the correct order of magnitude of ozone changes, which can be directly related to additional CFC-11 emissions.

Have the emissions to date affected future ozone recovery;

This question can be roughly answered on the basis of the available model data. Thank you for this question and we will discuss this point in more detail in a revised manuscript. Certainly the additional emissions until today will have an impact on the current and future ozone values; but these values are definitely much smaller than those derived from the calculated ozone changes (i.e. SEN minus REF).

How much more would continuation of the present emissions to various end dates affect ozone recovery;

This question can be similarly answered as the question before. Our suggestion is that we will discuss this point in more detail for instance in the final section of the paper. Here we could discuss more precisely the range of uncertainty, both regarding future evolution of CFC-11 emissions and also with respect to our model strategy.

What if the emission increased, what would that do to future recovery;

As said in the paper (and also mentioned above) answering such a question is difficult and in parts speculative. If the CFC-11 emissions will increase (or hopefully decrease) this will certainly shift the date of full recovery. To answer this question in more detail would at least require two more

sensitivity model simulations (with higher or lower implied emission rates than in our SEN simulation), but the possible rates would be also arbitrary. Our sensitivity simulation can be taken probably as an upper limit; since the CFC-11 amount stored in banks is also not known, our sensitivity simulation with constant CFC-11 concentrations is not completely unrealistic; so with our REF and SEN simulations we are analyzing an extreme scenario.

What if there are banks of CFC-11 (and perhaps CFC-12) associated with the illegal emission;

As stated before, answering such a specific question (which is of course very interesting but highly speculative) would require more model simulations and would definitely burst our investigation. Since there are surely several other "if"-questions, which are interesting and waiting for answers, it is not our intention to work on all related questions. Our intention is focusing on the ozone changes due to constant CFC-11 concentrations.

The present paper does not address these questions in any detail. Instead it only addresses one simple scenario: if the mixing ratio of CFC-11 stays constant through 2050, what is the effect on ozone. This assumes that the emission rate of CFC-11 stays at a constant level slightly higher than any inferred emission estimated in Montzka et al. and that this emission stays constant for the next 3 decades.

It is not our intention to answer such questions as already pointed out. Our simulation was created in a way that the implied emissions are at the upper end of possibilities and therefore can be taken as an upper boundary for the assessment of ozone values. Certainly many other scenarios are possible and in principle could be "calculated" with our model; the number of possible future CFC-11 scenarios is arbitrarily high. Therefore this would be an endless story because many model simulations have to be carried out. In addition it is obvious that results might depend also on the specific model which is used. Thus, these questions could ultimately only be answered with a multitude of scenarios AND a multitude of models; this is clearly beyond the scope of our work!

From our point of view our assessment based on only two model simulations provides reliable information regarding the reaction of the stratospheric ozone with respect to unchanged CFC-11 concentrations and changes in the ozone production and loss cycles.

Ignoring that this scenario is unlikely to occur given the international response to this issue, the real problem with the paper is that so little of the problem space is explored. I see limited value in modeling one (unlikely) scenario in detail and ignoring all other possibilities.

As mentioned before, we take our sensitivity study as an upper boundary of possibilities. In addition to the arguments given above, we have also to keep in mind the computational costs for such a more extensive chemistry-climate model exercise. Other model systems, e.g. 2d models or models with a simplified chemistry scheme, might be more appropriate for such investigations with a larger amount of sensitivity studies.

I can only assume this choice was made because it is easy to implement in their model and it only took one new run. Unfortunately, the only question answered is that if a larger emission than inferred in Montzka et al. is continued for three decades it will have a negative effect on ozone recovery.

Due to the lack of more detailed information regarding the CFC-11 emission and its future evolution we decided to carry out only this model simulation under unchanged CFC-11 concentrations, which is the most simplified assumption you can make. As said already, here we try to investigate an extreme, or (hopefully) worst case scenario; it is certainly an interesting question as all other CFCs are assumed

to decrease. Our main interest is related to the question: "What must be avoided?" (a little bit like the Newman et al. (2009) "World avoided" paper).

This will surprise no one and in fact it can be predicted by computing the perturbation of EESC in 2050 by changing the CFC-11 mixing ratio between the ref value to the new value. This is a "back of the envelope" calculation.

In Section 3.3 (Stratospheric ozone budget) we have prepared and presented a detailed analysis of the model results with respect to the ozone production and loss cycles. And there are some "surprises", for instance that the effects are smaller than expected (as it will be calculated back of the envelope by using the EESC) due to some compensating effects by other ozone production and loss cycles. Our budget analysis nicely shows compensating effects for the global annual mean and in the upper stratosphere in the SH polar region, whereas in the lower stratosphere in the SH polar region the compensation does not occur. We show, which processes are buffering the additional O3 destruction through higher CFC-11 concentrations. We show where (altitude) and at which time O3 is decreased compared to the REF; these results are not easily obtained "back of the envelope"! Further we show that the additional emissions need time to affect the O3. It would have taken years to register some deviation in the O3 columns due to the additional emissions! And we have analyzed the effect of the temperature change on the chemistry.

I expect much more of the problem space explored in a paper addressing the effect of illegal emissions of CFC-11 on ozone recovery and with a chemistry-climate model to use. As stated above, I recommend that the author team rethink the issues the Montzka et al. paper uncovered and take a real stab at helping answering them. It is necessary to frame the problem in terms of various possibilities for the emissions (and bank changes) and then from there predict mixing ratio scenarios and finally model time series. Only then can the reader understand the scope of the problem and the possible effects on future ozone.

The chosen configuration of this model study has been used because we do not have more detailed information about future emissions available. Further, our study was triggered by the Montzka et al. (2018) paper, but we do not claim that our sensitivity represents the actual pathway of future emissions/concentrations. Instead we state, that it is most likely an extreme sensitivity study. A solution for our paper would be that in the final section (Discussion and conclusion) we will bring up some of the uncertainties (i.e. the CFC-11 emissions and also with respect to our model strategy) and make a more general discussion at the end which allows the reader to put our model study into the right context.

We very much hope that the referee can follow our argumentation line.