Response to the comments from the referees

We thank the reviewers for their insightful and constructive comments. The time they spent on our manuscript is very much appreciated and has helped make the manuscript scientifically stronger and clearer.

Anonymous Referee #1

General remarks: This a very well written sound analysis of the banks and future emissions of HFCs. Scenarios either assume their restriction in the near future or their unabated usage for several decades to come. Furthermore, the effect of the destruction of the banks is nicely illustrated. I suggest to publish the manuscript in ACP, taking into account the suggestions from below.

Additional remark: It was really hard to read the figures. I had to blow up to 300% to properly see them. For example there is a mistake in Fig. 2, 3rd panel: issions should be emissions, which was really hard to see in the printed (100%) version.

Response: A few letters disappeared when the file was converted in the publishing process. We will pay attention that this does not happen again. The small size of the figure is also the result of the publishing process. We will ensure that the figure will be printed larger in the final version.

Minor issues:

Title: The term "commitments" is well-known in the scientific community related to ozone depleting substances. However, others might not understand this. Suggestion: maybe something like: Growing importance of banks on HFC emission

Response: We prefer to keep the current title. We think the public and policymakers have learned a lot about the concept of commitments to the long term, due to the use of that word in many climate change discussions around carbon dioxide and its long removal time. The word 'commitments' informs the reader of the full future impacts of HFCs.

P 32991 Line 20: not-in-kind definition: I am not sure if the definition of "not-in-kind" includes hydrocarbons. If not: not-in-kind alternatives and non-halogenated substances (e.g. hydrocarbons) could be mentioned.

Response: We use 'not-in'kind' here as non-halocarbon substitutes, as was done by McFarland (1991). So hydrocarbons are included in not-in-kind substitutes. We added the word 'here' to this sentence to be clear. In the remainder of the sentence there is already an example of hydrocarbons as not-in-kind substitutes for halocarbons.

P 32991 Line 25: The contributions of HCFCs and HFCs to climate change depend upon their atmospheric lifetimes and corresponding Global Warming Potentials (GWPs).
This sentence is somehow too simplistic. The GWP is related to emissions. The contribution to climate change depends on lifetimes and radiative efficiency well as on the abundance.

Response: Agreed. We have changed the sentence to "The contributions of emissions of HCFCs and HFCs to climate change depend upon their atmospheric lifetimes and radiative

efficiencies and thereby on their Global Warming Potentials (GWPs), as well as the total emission and hence the abundance".

P 32992 Line 8: Shouldn't Velders et al. (2012, Science) also be mentioned here?
Response: We agree and have added this reference here.

P 32995 Line 14: Isn't HFC-134a also replaced in the US and in Japan in MACs?
Response: In Europe HFC-134a has to be phased out in mobile AC because of the EU MAC directive. There is no similar obligation in the US and Japan, but it is likely that the EU MAC directive will affect, at least to some extent, the global use of HFC-134a in MAC.

P 32997 Line 4: Not-in-kind substitutes and non-halogenated substances?
Response: We have added '(non-halocarbon)' after 'not-in-kind' to avoid confusion. See also Section 1 for the definition of not-in-kind as used here.

P 33000 Line 2ff: It would possibly be better if the effect of the reduction could be shown as negative radiative forcing with a negative y-axis.
Response: Very good suggestion. We have changed to figure accordingly.

Anonymous Referee #2

General Comments

The paper raised an important issue regard to HFC's contribution to future climate change. Normally, the calculation of the greenhouse gases (e.g. CO2) contribution to climate change starts with annual emission, which then leads to increase of atmospheric concentration and consequently radiative forcing. The unique aspect of HFC's contribution, as properly pointed out by this paper, is that the production/consumption of HFCs may not cause emission immediately; instead, HFC production are stored in the "bank" and only released after the market lifetime of the products (e.g. A/C equipment). This "time bomb" effect of HFC production is a point worth conveying to mitigation policy community.

I recommend publication when the following specific comments are addressed.

Specific Comments

(1) Background: Why is the bank issue for CFC not as serious as HFCs?
In the introduction, a brief historical background of CFC use and its ban under Montreal Protocol is given. But it is still unclear to me why CFC is mostly used in rapidly-released application (also shown in the pie chart of Fig 1), and therefore the bank issue is not significant? Is it because the CFC chemical properties are more suitable for rapidly released applications? Or is it because the A/C and refrigeration use (medium time scale) demand was low that the time of 1980s? Maybe the authors can provide some more information on my question in section 2.

Response: This is a good point. Banking of halocarbons used for refrigeration and AC played a similar role for CFCs in the 1980s than for HFCs now. The difference is that in the 1980s halocarbons were used not only for refrigeration and AC applications, but also in very large quantities for rapid-release applications. Because of environmental concerns in the 1970s of the impacts of CFCs, the use of it in, for example, spray cans was already reduced before the Montreal Protocol was agreed. Because of environmental concerns, the situation is now different for HFCs, which is used in very limited quantities in rapid-release applications.

Also, because of the phase-out of CFCs, the current and projected future banks are not thought to be very large compared with past cumulate production or current atmospheric concentrations. So, while there was indeed a sizable commitment in the past due to banks, it is no longer nearly as substantial.

Finally, the refrigeration and AC applications are currently less leaky than in the 1980s, increasing the relative importance of the banks of HFCs over those of the CFCs. We have added a few sentences to the text of Section 1 showing that environmental concern, citizen actions and national regulation played a role in the reduction in the use of rapid-release applications of CFCs in the 1980s and argue that environmental concerns also played a role in the limited use of rapid-release applications of HFCs.

We also added the following to the first paragraph of Section 1: "This represents a legacy, or commitment, of continued environmental impact from past production of CFCs, but its magnitude is relatively small since so much use of CFCs occurred in rapid-release applications and because production for the longer time scale release applications has been in decline for over two decades " .

(2) Methodology: How to estimate emission vs size of bank?

Regard to CFC and HCFC bank, the method of estimating the bank size is not properly described. If I understand correctly, in a given year, production = emission+ addition to the bank. The emission is derived using top-down approaches, while bank term is derived using bottom-up approaches instead of taking the difference between production term and emission term.

The authors stated "Emission factors, which represent the fraction of the individual banks that are released each year, are derived from the ratio of the top-down derived emissions and the bank estimates over the period 1999 to 2008". But the top-down derived emissions (based on observed atmospheric concentration) are total emission how did the authors partition the total emission into emission immediately after production and emission slowly released from the bank?

To make this clear, could the authors provide an example of estimates of banking time (or emission factor) for individual applications (AC vs foams) or individual chemicals?

Response: Emissions of CFCs and HCFCs are indeed derived from a top-down approach using observed mixing ratios, since this is expected to give more accurate estimates than a bottom-up approach. As discussed in the paper, banks could be derived solely from historic production data and top-down derived emission, but banks derived this way have likely larger and unknown uncertainties, because they are the result of an accumulating difference between two large numbers (Daniel et al., 2007).

Bank data for 2008 derived by a bottom-up approach (TEAP, 2009a) is considered to be more accurately known and therefore is used in the analyses. Banks for previous years are estimated backwards in time starting from 2008, using the difference between reported production data and top-down emissions. Emission factors are then calculated as the fraction of the bank emitted annually. The factor derived this way is an overall emission factor, which cannot be partitioned in factors for the different types of applications. In Figure 1 we therefore did not use this information, but data reported by AFEAS for short, medium, and long banking times. The methods we used in the scenarios of CFCs and HCFCs are described more extensively in a recent paper by Velders and Daniel (ACP, 2014 in press).

The overall emission factor is only relevant for the projection of the banks and emissions of CFCs and HCFCs past 2008. The factor might change over time, which is not taken into account in the scenario. But such changes are probably small for all CFCs and HCFCs, since currently most individual CFCs and HCFCs are emitted from a single type of application. For example, CFC-11 is currently emitted almost completely from closed-cell foams (long banking times), while CFC-12 is emitted from refrigeration and AC (medium banking times).

A reference to Velders and Daniel (2014) is added to section 3 as a source that more fully describes how the banks, emission factors, and emissions are calculated. The new text now reads: 'In other years, the bank at the start of a particular year is equal to the sum of the bank in the previous year and production from that year, with the emission from that year subtracted. Emission factors, which represent the fraction of the total bank of specific ODSs that are released each year, are derived from the ratio of the top-down derived emissions and the bank estimates over the period 1999 to 2008, and are used to calculate the depletion of the bank and annual emissions, past 2008. These emission factors are overall factors applied to the total bank of a specific ODS. Possible future changes in these factors are not taken into account in the scenario. But such changes are probably small for all CFCs and HCFCs, since currently most individual CFCs and HCFCs are emitted from a single type of application. For example, CFC-11 is currently emitted almost completely from closed-cell foams, while CFC-12 is emitted from stationary refrigeration and AC'.

(3) Previous estimates.
Why did previous estimates not consider the buildup in the bank? Were they only considering the yearly emissions? Page 33001. Line 17. Could the authors give an example here or somewhere else in the paper of previous estimates that only considered the concentration/radiative forcing and ignore bank contribution?

Response: Several previous HFC scenario studies (IPCC/TEAP, 2005; Velders et al., 2009 Velders et al., 2012; UNEP/TEAP, 2009; Gschrey et al., 2011; and the RCPs, see Meinshausen et al., 2011) have considered banks in their modelling approach, but focused their discussion on the climate change effects in terms of emissions and radiative forcing. This is probably because immediate emissions play a central role in scenarios of climate change mitigation for most greenhouse gases. The role of HFCs for climate forcing is distinctly different from other greenhouse gases such as CO_2, CH_4 and N_2O, in the sense that for HFCs there is a delay of years between production and emission. Therefore, contrary to most other greenhouse, banks are formed and constitute a future commitment for climate change that is not visible when examining radiative forcing at any given time. We have added the following to Section 1 (page 32992) "In several previous HFC scenario studies (Velders et al., 2009;Velders et al., 2012;Gschrey et al., 2011;IPCC/TEAP, 2005;Meinshausen et al., 2011;UNEP, 2009a) banks have been considered in the modelling approach, but the focus in discussing climate change effects was only on emissions and radiative forcing".

Technical Corrections

Page 32996. Line 1. What information is provided in RCP? Just mixing ratio and radiative forcing?

Response: The data available from the RCPs are emissions, mixing ratios and radiative forcings. We have added this to the sentence.

Fig 2. In the last sentence of figure caption. I don't think radiative forcing is presented in this figure.
Please also note in Fig 2 caption (and maybe in some following figures) that "constant past 2050" means the demand and consumption is held as constant.
Fig 2. In The panel C, label for Y-axis misspelled "emission", label for X-axis misspelled "year".

Response: You are correct. The caption has been corrected.
The label 'constant past 2050' refers indeed only to production. We have added this to the caption and changed the label in panel B accordingly. Figure 4 and its caption have also been changed.
A few letters disappeared when the file was converted in the publishing process. We will pay attention that this does not happen in the final version of the paper..

Page 32991. Line 26. "GWPs are one type of measure of the relative impact of a gram of a greenhouse gas compared to carbon dioxide over one hundred years". This sentence does not read well. Please edit.

Response: The sentence has been changed to "The GWP is an index comparing the integrated radiative forcing of an emission of a greenhouse gas, integrated over typically one hundred years, relative to that of emitting the same mass of carbon dioxide".

Page 32992. Line 2. Please give an example of low-GWP HFCs.

Response: In Section 7 (Montreal Protocol) low-GWP HFCs and their applications are already mentioned. In this sentence we have now added a reference to Section 7.

Page 32994. Line 2. “These use observed: : :” This sentence is too long and not well structured. I don’t understand what is the constraint for what? Please rephrase.

Response: We have numbered the four items in the sentence to improve the readability. The term ‘constraints’ has been removed since it was redundant.

Page 33001. Line 1. “INCREASING importance of the bank … compared with cumulative production”. This statement seems to be contradicting with the statement of “The relatively greater importance of the production phaseout by 2100.” from the last page and with the Figure 3. From what I see, the importance of the bank is not increasing with time.

Response: You are correct. The word ‘increasing’ is misleading here, since the importance of the bank is not increasing in time. We want to address here that also for scenarios with lower emissions the HFC bank is more important than previously considered. We have changed the sentence to “… but the previously unseen importance of the future bank can be expected to be similar in a relative sense when compared with cumulative production”.

Page 33001. Line 5. ODSs is not defined

Response: Definition has been added to the sentence.

Fig 3. Y-axis label. The author used “GtCO2-eq” in the figures but “GtCO2eq” in the text. I think they need to be consistent

Response: We agree. The hyphens disappeared in the text during the editorial or publishing process. We will pay attention that it will be consistent in the final version of the paper.

Fig 4. Would it be better to reverse the sign of Y-axis to be negative and actually show the radiative forcing “reduction” following the measures of collecting and destroying the banks? I leave the choice to the authors.

Response: Very good suggestion. We have changed to figure accordingly.