We thank the referees for their helpful comments and recommendations. In the following, we discuss the issues addressed by the referees and explain our opinions and the modifications of our manuscript.
We enumerate the referee comments and repeat them in bold face. The modifications of the manuscript are given in italics.
Simple typographical and technical corrections are not all explained in detail, but we applied these corrections to the manuscript.
The line numbers given by referee 3 are changed to the line numbers used in the manuscript published in ACPD to get a consistent numbering.

1 Comments Referee 1

1. **Major point: p.10479-10480: How sensitive are the calculated fractions to the date of initialisation (1 December) and how robust are the numbers in general? They are not quantitatively motivated by discrepancies between observations and the results for initialisations on 15 January. If one just goes back in time long enough, the mid latitude fraction would become even larger. Does the estimate makes sense? Finally: If the filament around 14 km , 12:15 is of vortex origin for air masses initialized at 15 January, then this should also be the case for 'December, 1st-air'. Otherwise the results indicate, that the mid-latitude air masses (from 1 December) didn't really mix after the vortex split, because they do not contribute to the vortex fraction initialized on January?**

   The initialisation date 1 December is not motivated by discrepancies between observations and the results for initialisations on 15 January, but it is motivated by of knowledge of the vortex split in December. This date was chosen to analyse the impact of the vortex split by means of comparisons between the passive tracers initialised on 15 January and the passive tracers initialised on 1 December. Indeed, it is expected that the simulated vortex fraction would decrease when using earlier initial dates. However, for periods with a stable polar vortex, this change would be rather small (see e.g. Steinhorst et al., 2005). Due to the SSW and the vortex split in mid-December 2009, however, the vortex experienced large changes. For that reason we chose to show results of two runs with different vortex tracers, initialised at 1 December and 15 January, respectively.
   There are large differences in the vortex tracer between the two intialisations that would not be present in the case of a stable vortex. The idea behind this is that these different initialisations give insight into how the vortex compositon changed during the December event and how this is reflected in the observations in March.
   We revised the second part of Sect. 6.2 to clarify this points:

In order to obtain more insight into the split event in December and the associated in-mixing of air masses into the vortex, we use the passive tracer experiment, where the passive tracers were initialised before the vortex split on 1 December 2009. *We chose this initialisation date to get a robust initialisation of the passive tracers before the split and mixing event in December, since the polar vortex was stable and coherent on 1 December.* The CLaMS vortex tracer initialised on 1 December is displayed in Fig. 7 at the time of observation. Inside the polar vortex the tracer only reaches maximum values of about 0.5 at flight altitude, which indicates that the observed air masses contain 50 % vortex air masses. Furthermore, the vortex filament at the end of the flight can hardly be seen. *Thus, there is a large difference between the vortex tracers of the two initialisation dates. The lower vortex fraction inside the vortex observed for the December initialisation is caused by in-mixing of air masses in mid-December. If no air masses had mixed into the vortex, the vortex tracers of both initialisations would be the same. As a consequence of this in-mixing of air masses in December, the composition of the vortex changed and, therefore, the vortex tracers of the two initialisations represent vortex air masses with different composition. A comparison between the passive tracers of both initialisations can now be used to gain information on the amount of air masses mixed into the vortex.* The difference of the passive tracers of both initialisations inside the polar vortex between 10:05 and 11:00 UTC (excluding the ascent and the vortex edge region) around flight altitude (≈ 450 K potential temperature) is illustrated in Fig. 8. The boxes show the average values of the passive tracers inside the polar vortex for both initialisation dates. Obviously, the polar vortex was very stable with respect to in-mixing of air masses after 15 January, which is illustrated by the very high average value of the vortex fraction (blue) for the January initialisation of ≈ 0.90. Hence, only very few air masses mixed into the vortex after 15 January. Thus, *the large reduction of the vortex fraction of the December initialisation (≈ 0.47) can be almost fully attributed to the in-mixing of air masses into the vortex during December. The difference between the vortex fraction of both initialisation dates (≈ 0.47 for December initialisation to ≈ 0.90 for January) gives a reasonable estimate of the amount of air masses mixed into the vortex in December.* These air masses account for about 45 % of the total air masses inside the re-established polar vortex at the end of December.

2. **Technical: All Figures: Please use the same vertical axis origin (e.g. starting at 10 km), which facilitates comparison of plots and patterns.**

We changed the vertical axis of all plots to the range 10 - 20 km for better comparison, except for Fig. 1a, because we want to show the altitude range observed by the CRISTA-NF instrument.

3. **p.10475: Check mixing ratio units**

We changed the ozone VMRs to ppmv in the text and in Fig. 4a.

2 Comments Referee 3

1. **(1) Analysis of the mixing: The paper can be improved significantly, if the analysis of the mixing at the vortex edge is considered from a quantitative perspective.**

   Surely, the analysis of the mixing at the vortex edge from a quantitative perspective is very interesting, but there are a few problems. Firstly, the observation of mixing at the vortex edge by means of correlations and mixing lines is not possible because the precision of the measurements is not high enough to observe such mixing lines. Secondly, the quantification of the mixing across the vortex edge over a longer time period relies on reference measurements carried out in the younger vortex, which are at the moment not available for CRISTA-NF. Thirdly, the analysis of mixing across the vortex edge during the winter 2009/2010 by means of other data (e.g. satellite measurements) is surely interesting, but this goes beyond the scope of this paper.

2. **(2) The writing style could be advanced by applying more specific statements. This holds for the whole paper. Some examples are given below.**

   We revised the manuscript with respect to the writing style and applied more specific statements.

3. **Title: - the title doesn't reflect the height region of observations - "small-scale transport structures" is a rather vague, perhaps for some readers even misleading term; just say what you are talking about in the paper: observations of filaments at the vortex edge and the corresponding mixing - time period is not really necessary in the title**

   We changed the title:

   > *Observation of filamentary structures near the vortex edge in the Arctic winter lower stratosphere*

4. **Abstract: - I would suggest to use a more specific style; there are some imprecisions as:**
   o " .. observed altitude range .. ": not specified before o " .. show several structures ..": more specific as the observations certainly don't show the polar vortex but only portions of it etc.
   This sentence at lines 10/11 is kind of typical of some formulations

throughout the paper: you mix observations with interpretations from a model. I would recommend to differentiate clearly what is observed and what is simulated and what is the conclusion from both and additional arguments.
o line 12: "The situation ...": more specific which situation you are refering to o line 16: ".. very small-scale structures ..": more specific which part of the spectrum you are refering to o line 17: " .. use a model concept utilising artificial .." sounds strange to me; why not only ".. use artificial tracers .."??

We revised the Abstract and added more specific statements.

> We present two-dimensional cross-sections of volume mixing ratios for the trace gases CFC-11, O_3, and $ClONO_2$ with an unprecedented vertical resolution of about 500 to 600 m for a large part of the observed altitude range ($\approx$ *6 – 19* km) and a dense horizontal sampling along flight direction of $\approx$ 15 km. The trace gas distributions show several structures like *, for example, a part of the polar vortex and a vortex filament, which can be identified by means of ozone-CFC-11-relations.*
>
> The *observations made during this flight are interpreted using the chemistry and transport model CLaMS (Chemical Lagrangian Model of the Stratosphere). Comparisons of the observations with the model results are used* to assess the performance of the model with respect to advection, mixing, and the chemistry in the polar vortex. These comparisons confirm the capability of CLaMS to reproduce even very small-scale structures in the atmosphere *, which partly have a vertical extent of only 1* km. Based on the good agreement between simulation and observation, we *use artificial (passive) tracers, which represent different air mass origins (e.g. vortex, tropics),* to further analyse the CRISTA-NF observations in terms of the composition of air mass origins. *These passive tracers clearly illustrate the observation of filamentary structures that include tropical air masses.* A characteristic of the Arctic winter 2009/10 was a sudden stratospheric warming in December that led to a split of the polar vortex. The vortex re-established at the end of December. Our passive tracer simulations suggest that large parts of the re-established vortex consisted to about 45 % of high- and mid-latitude air.

5. **page 10465, lines 11-16: It is not clear to me why this sentence is necessary; the link to the sentences before and after could be clearer**

We wanted to show, that the CRISTA-NF observations fill the gap between global satellite observations and airborne in-situ observations. The different types of observations can be used to analyse the different structures observed in the atmosphere (streamers, filaments and small-scale turbulence and mixing). CRISTA-NF is capable to observe filamentary structures with an enhanced vertical resolution compared to global satellite observations and a larger coverage compared to in-situ observations. Therefore, the CRISTA-NF observations give more insights into such filamentary structures than other measurements can do. We rephrased this part of the manuscript to clarify this point:

> These structures can be considered as part of a scale cascade from synoptic-scale streamers over elongated filaments down to small-scale three-dimensional turbulence. *Different types of observations are necessary to detect and analyse these structures. Synoptic-scale streamers were observed and analysed by several satellite limb-sounders, e.g. the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) instrument (e.g. Riese et al., 1999, 2002), whereas* in-situ observations on high-flying research aircraft provided a wealth of information on small-scale mixing processes (e.g. Hoor et al., 2002; Konopka et al., 2004). *The airborne Cryogenic Infrared Spectrometers and Telescope for the Atmosphere – New Frontiers (CRISTA-NF) instrument is well suited to fill the gap between global satellite observations and airborne in-situ measurements in terms of spatial resolution and coverage, since its observations offer a better vertical resolution than satellite observations and an enhanced coverage compared to in-situ measured.*

6. **page 10466, line 2: "successfully flown" probably better: "successfully employed"**

   Changed the text as follows:

   > The instrument was successfully *employed* on board M55-Geophysica during the tropical aircraft campaigns...

7. **page 10466, line 17: not clear here, what is meant by "passive tracer concept"**

   The passive tracer concept denotes the use of artificial tracers in the model, which represent different air mass origins (e.g. vortex, tropics). These passive tracers only undergo advection and mixing.
   We revised the manuscript at this point:

   > We analyse these observations based on ozone-CFC-11-relations and simulations with the Chemical Lagrangian Model of the Stratosphere (CLaMS; e.g. McKenna et al., 2002b,a). *CLaMS enables the use of artificial tracers (passive tracers) representing different air mass origins (e.g. vortex, tropics). These passive tracers are only advected and mixed and can be used to analyse the composition of origins of observed air masses (Günther et al., 2008).*

8. **page 10467, line 11: for which distance does the vertical sampling of 250 m hold?**

   The vertical sampling of the CRISTA-NF measurements is about 250 m in the whole observed altitude range between flight altitude and the lowest tangent height. We added this fact:

   > A Herschel telescope with a tiltable mirror scans the atmosphere with a vertical sampling of about 250 m *from flight altitude down to ≈ 5* km.

9. **page 10467, line 13: resolve symbols lambda and Delta lambda.**

   The symbol λ denotes the wavelength and the symbol $\Delta\lambda$ denotes the distance of two spectral points, which can be resolved by the measurements. Thereby, $\Delta\lambda$ depends on the spectrometer design (e.g. grating, slit width etc.). The fraction of both gives the spectral resolving power. We changed the text as follows:

   > The incoming radiance is spectrally dispersed by the two Ebert-Fastie (e.g. Fastie, 1991) grating spectrometers with different *spectral resolving powers of* $\lambda/\Delta\lambda \sim$ *1000 and 500 (*λ *denotes the wavelength and* $\Delta\lambda$ *denotes the distance between two spectral points, which can be resolved)*, respectively, and finally measured by semiconductor detectors (Si:Ga) that are operated at temperatures of about 13 K.

10. **page 10469, line 4: what is a "dynamically adaptive grid" for a Lagrangian model? Explain briefly!**

    The concept af the adaptive grid used in CLaMS is explained in the model description (McKenna et al., 2002a; Konopka et al., 2004). Briefly, the positions of the air parcels define the grid in CLaMS. As a consequence you get a time-dependent irregular grid of air parcels. During the advection step the air parcels move along trajectories calculated by means of meteorological wind fields. After each advection step the distances between one air parcel and its prior nearest neighbors are compared to critical distances. If two air parcels moved away from each other too far, a new air parcel is inserted in between. Additionally, if two air parcels get to close to each other, they are merged to one air parcel. By using the described algorithm the grid is dynamically adapted after each advection step, which produces the mixing. Additionally, the grid is quasi uniform, which means that the mean distance between the air parcels in one model layer remains within a small range. Therefore, the used grid is called dynamically adaptive grid. We revised the relevant part of the paper:

    > CLaMS simulates an ensemble of air parcels moving along trajectories, which are calculated by means of meteorological wind fields. *The grid in CLaMS is*

> *defined by the positions of these air parcels and, therefore, this grid is time-dependent and irregular.* Each transport step consists of an advection step, in which the air parcels follow the trajectories, and a subsequent mixing step. The mixing step is realised utilising a dynamically adaptive grid. If the distance between an air parcel and one of its prior nearest neighbours falls below/exceeds a certain threshold criterion defined by the Lyapunov exponent λ_c *after an advection step*, the two air parcels are merged and a new air parcels is inserted in between the two former ones, respectively. The characteristics of a new or merged air parcel are the mean characteristics of the two prior air parcels. The mixing strength is adjusted by the Lyapunov exponent λ_c (logarithmic expansion rate), where a smaller value induces more mixing and vice versa. *By using this approach the grid is dynamically adapted after each advection step, which produces mixing and, additionally, leads to a quasi uniformity of the grid (the mean distance of the air parcels remains within a small range).* A detailed description of the dynamically adaptive grid is given by McKenna et al. (2002b) and Konopka et al. (2004).

11. **page 10471, lines 15-19: It is interesting, and probably not surprising, that CI is always ever low at the end of the measurement, i.e. at low altitudes. Does this occurence of tropospheric clouds correspond to exisiting satellite observations?**

It is absolutely correct that the CI is always low at the measurements for the lowest altitudes. The CI typically decreases with decreasing altitude because of the increasing aerosol background and water vapor continuum (see e.g. Spang et al., 2008). During the flight on March 2 the CI values decrease with decreasing altitude as expected and then in many cases (profiles) the CI falls from about 4 down to about 1 within 500 m. This jump is not expected in the case of cloud-free conditions, in which mainly the water vapor continuum causes the decrease. Simulation results by Spang et al. (2008) show that a decrease in CI caused by the increasing water vapor continuum is much slower. Hence, the decrease observed during the flight on March 2 is caused by optically very thick conditions due to an aerosol layer or a cloud. Thereby, the latter is the most probable situation.
The threshold value of 3.5 is chosen as a very conservative value to filter out cloud/aerosol influenced spectra and to get a reasonable value defining the transition region from cloud-free to cloudy conditions.
We added this facts to the manuscript:

> The CI is plotted at the tangent points of the CRISTA-NF measurements. The tangent point denotes the closest point of the LOS to Earth. *Under cloud-free conditions, the CI typically decreases with decreasing altitude because of the increasing aerosol and water vapor continuum (see Spang et al., 2008). During this flight the typical decrease is observed down to a certain altitude. But in many profiles the CI values then fall down from 4 to 1 within*

> *about 500*m *height difference. This steep decrease cannot be explained by the increasing water vapor continuum only. The presence of optically very thick conditions due to clouds (or an thick aerosol layer) are necessary.* Assuming a CI value of 3.5 as a *conservative threshold value to define this transition region*, cloud free conditions were present down to approximately 8 km during the flight. Below 8 km tropospheric clouds are visible indicated by a very low CI value (about 1) and dark blue colours.

12. **page 10471, lines 24-27: o correct spelling: European Centre for Medium-Range Weather Forecasts o What kind of reanalysis data were used? o It would be very helpful for the interpretation of the results to mention here that the flight on March 2 2010 took place after a major warming happened in the stratosphere in late January and that the vortex broke into two lobes in early February. So, the vortex was already quite disturbed and it was not as coherent and isolated as before the warming. It might be instructive to show a horizontal plot of the mPV at an isentropic surface together with the flight path to illuminate the situation and the mixing processes discussed in the paper.**

We corrected the spelling and moved the discussion about the polar vortex to this section of the paper. We used ECMWF operational analysis data for Fig. 2 and corrected this in the manuscript. Additionally, we will add a plot showing mPV at one pressure level, which corresponds to the flight altitude at the beginning of the flight. The revised part of the manuscript is as follows:

> The flight (flight 11 of the campaign) discussed in this paper took place on 2 March 2010. This flight is chosen because of the favourable measurement conditions during the flight (few aircraft manoeuvres, cloud free) and the interesting dynamical situation. *The polar vortex was very variable and unstable during the winter 2009/10. It split twice during two sudden stratospheric warmings. The first split occurred in December and the vortex re-established again at end of December. During this split event some mid-latitude air masses were included into the vortex. The second split took place in February and the two parts of the vortex rejoined in early March. The presence of polar stratospheric clouds together with very cold temperatures occurred in January, which led to chlorine activation. After the sun light was available, the ozone depletion inside the polar vortex started. A discussion about the evolution of the vortex is given e.g. by Dörnbrack et al. (2012) andvon Hobe et al. (2012). Thus, the analysed flight took place during the time period the vortex rejoined again.*
>
> Fig. 1 displays the flight path of the M55-Geophysica during this flight as a black line. The flight started at the airport of Longyearbyen on Spitsbergen heading towards northeast.

Because of the description of the vortex evolution in Sect. 4 we shortened the description in Sect. 6.2:

> The history of the polar vortex during the whole winter is essential for the interpretation of the results for the passive tracers and the comparisons with the observations. *Thus, the two split events during the sudden stratospheric warmings in December and February have to be taken into account (see Sect. 4).* The CRISTA-NF observations took place in a part of the rejoining vortex at the beginning of March.

13. **Fig 2: Are the enhanced mPV values near 10 km altitude the sign of the tropopause? A similar plot of the squared Brunt-Väisälä frequency calculated from ECMWF data could shed some light on this question.**

    Thanks for this comment. We looked at the squared Brunt-Väisälä frequency for this flight and you can see the typically occurring maximum above the tropopause as expected (see e.g. Birner et al., 2006). Since both the squared Brunt-Väisälä frequency and mPV are in a similar way related to the gradient in potential temperature, this maximum is observed in mPV as well. Thus, these enhanced mPV values are a sign of the tropopause. We mentioned this fact in the manuscript and restricted the altitude range, in which mPV can be used and is used, to the region above this maximum, in numbers 11 km. The revised part of the manuscript is as follows:

    > Müller and Günther (2003) showed that modified PV is a very useful and valid quantity to study air masses in the vicinity of the polar vortex down to a potential temperature of about 350 K. *Enhanced values of mPV occur in the altitude between tropopause and a few kilometres above. This behaviour is similar to what is observed for the squared Brunt-Väisälä frequency (see e.g. Birner et al., 2006). Thus, the enhanced mPV values are a sign of the tropopause and have to be excluded from the analysis. Fig. 2 shows mPV only is in the altitude range from flight altitude down to 11* km.

14. **page 10473, line 20: I don't see the "steep gradient" in the CFC-11 values. It looks rather as a gradual transition not like a "mixing barrier". However, I have no comparison of these values for a vortex in its undisturbed evolution phase. So, a more quantitative assessment would be beneficial!**

    The largest gradient exists at flight altitude and it is decreasing with decreasing altitude. We showed the CRISTA-NF measurements of CFC-11 at flight altitude compared to HAGAR in-situ measurements in a preceding publication by Ungermann et al. (2012). At flight altitude you can see an increase of the CFC-11 VMRs by about 70 pptv within a few kilometers (a few minutes of the flight).

This steep increase can only be caused by an effective mixing barrier. At lower altitudes the mixing barrier weakens of course. We rephrased the manuscript to clarify this point.

> The steep gradient in the CFC-11 VMRs at the vortex edge (about 11:15 UTC) confirms that the edge acts as an effective mixing barrier. *The gradient is largest at the highest altitude (flight altitude), where an increase of the CFC-11 VMRs by about 70* pptv *within a few kilometres is observed (compare Ungermann et al., 2012), and gets smaller with decreasing altitude. Thus, the mixing barrier weakens with decreasing altitude until it vanishes.*

15. **page 10474, line 19-25????: Again: no reference is established to the history of the polar vortex including the sudden stratospheric warming!**
    I know that this issue is discussed later in Section 6.2 on the air mass origin but for an early understanding of the dynamics and the associated mixing processes, I recommend to shift a general overview of the vortex evolution into Section 4.

    We shifted the discussion about the evolution of the polar vortex to Section 4 (see above).

16. **page 10480, line 10: "the polar vortex was very stable after 15 January" This is not true as the vortex was first displaced and afterwards broken end of January and begin of February. What you probably mean is that the air inside the observed vortex lobe wasn't much impacted by mixing of outside vortex air, right?!**

    This is absolutely correct. We mean the stability of the polar vortex with respect to the in-mixing and not the replacement or deformation. We revised the manuscript at this point to clearly express what effects influenced the vortex and the air masses inside the vortex.

    > Obviously, the polar vortex was very stable *with respect to in-mixing of air masses* after 15 January, which is illustrated by the very high average value of the vortex fraction (blue) for the January initialisation of ≈ 0.90.

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