Reply to Reviewer # 2

We thank the reviewer for his/her constructive and useful comments that help to improve the manuscript. We have considered every comment carefully. Please find our replies below. The reviewer's comments are in black, while our replies are in blue.

This study aims to demonstrate that a southward shift of the Brewer-Dobson circulation could be a reason for the observed spatial pattern of the age of air trend in the strato-sphere during the MIPAS observation record. This is done by analyzing the changes in the subtropical transport barrier position and their impact on the age-of-air distribution using MIPAS observations and CLaMS model simulations driven by ERA-Interim. The obtained results can benefit the interpretation of the recent age-of-air trend and provide important implications regarding the changes in the Brewer-Dobson circulation. However, more careful descriptions of the methodology and results would be required. I would advise the authors to revise the manuscript accordingly. Below, I present my general remarks and specific points.

1. It is important to describe whether the overall summary and statistics are sensitive to the choice of the latitudinal shift. There are large interannual variations in the transport barrier position during the two periods, and the average period is short (i.e., four years). Also, the interannual variability is largely different between MIPAS and CLaMS. It is thus required to carefully describe the statistics of the latitudinal shift (e.g., the statistical significance of the trend at each levels) in MIPAS and CLaMS and their influences on the estimated impact on the age-of-air distribution.

We will provide information on the uncertainties of the positions of the transport barriers, and on the uncertainty of the shift. These uncertainties will allow to judge if the shift is significant. Further, we will apply the (shift ± its uncertainty) on the age of air distributions of the first period and assess how far the resulting dipole patterns change within the shift uncertainties.

2. The interannual variation of the transport barrier mostly disappeared after 2009 in both hemispheres in CLaMS and in the southern hemisphere in MIPAS (Fig. 2); this could explain large parts of the latitudinal shift between the two periods.

It is true that the very strong QBO signal in CLaMS for the first period is no longer present in the second period. This might be in coincidence with the other changes happening in the stratosphere, i.e. another symptom of the same process, or an independent other process. We cannot judge from our observational basis which of the two possibilities apply. However, since we have selected the periods in line with the QBO oscillations we do not think that aliasing from the QBO variation leads to an extra shift between the periods.

The age spectrum at least should be obviously different in the absence of interannual variability, which may also influence the mean age through complicated transport processes, even if the period mean position is the same. This point needs to be discussed.

Within another study still to be published (Haenel et al., in preparation) we have applied altitude-dependent monthly mean zonal mean age of air (AoA) spectra calculated by CLaMS within the AoA calculation from MIPAS SF6 data and have analyzed the resulting AoA trends over the MIPAS observational period. The result, i.e. the altitude/latitude pattern of AoA trends was grossly the same as shown in this paper here. For this reason we do not think that the changes in the age of air spectra have a major impact on the findings of our paper here. However, we will include this aspect in our discussion.

3. MLS data is used to evaluate the position of the transport barrier and is compared with MIPAS and CLaMS. Although the mean latitudinal shift is similar, there are large differences between MLS and MIPAS (and CLaMS), for instance, in 2008 in the northern hemisphere and in 2012 in the southern hemisphere. These differences need to be discussed more thoroughly, and summary statistics must be shown.

Fig.1 of this reply presents the correlation of transport barrier positions derived from MIPAS and MLS, respectively, for the overlapping mission period (2004 to 2012). The correlation is good and follows, except for some very few outliers, the 1:1 line. The length of the lines marking the crosses indicate the uncertainties of the derived barrier positions for MLS and MIPAS, respectively. The solid line in the panels is the pdf of the differences between positions derived from MIPAS and MLS, respectively. The mean over the pdf and its standard deviation is indicated in each panel. The differences of the positions have a very small bias (0.4 deg at most), and the standard deviation is by far smaller than the positions themselves, i.e. the derivation of positions from MIPAS and MLS is consistent. We consider this as a sufficient confirmation that MIPAS and MLS provides very similar information regarding the positions of the transport barriers and their variability. The figure and its discussion will be included into the appendix of the revised paper.

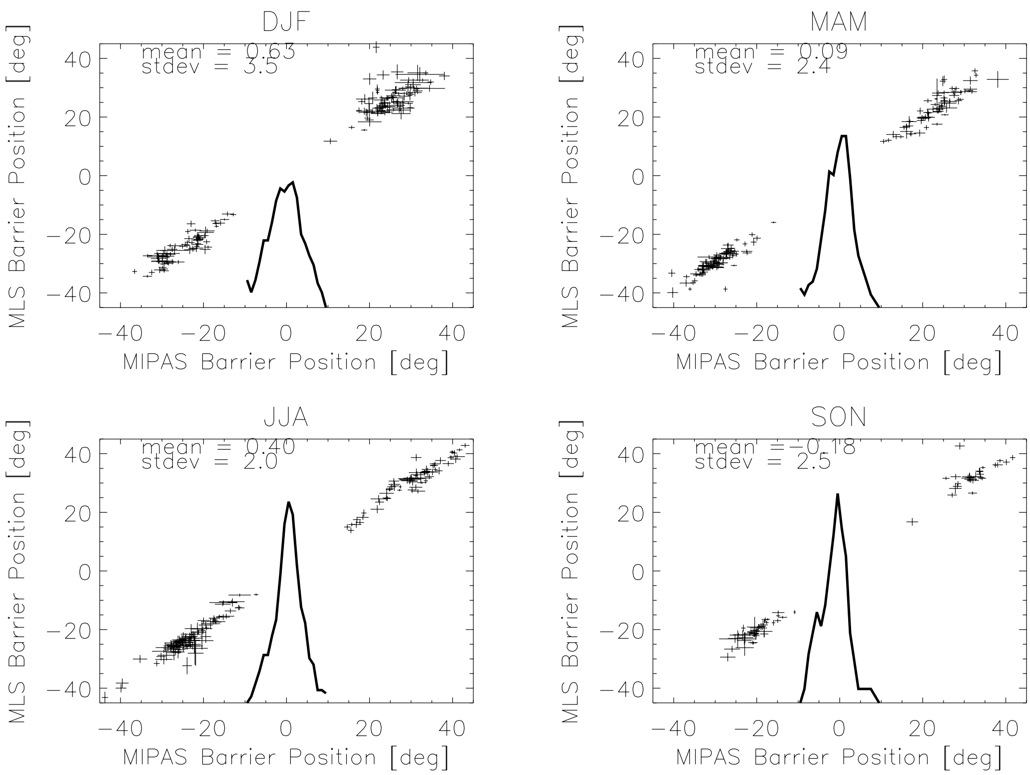

Fig. 1: Positions of transport barriers (crosses) from MIPAS N2O monthly averages (horizontal axis) vs. MLS N2O monthly averages (vertical axis) for the four seasons. The length of the lines marking the crosses indicate the uncertainty of the barrier positionderived from MIPAS and MLS, respectively. The solid line in the middle of the panel is the pdf of the differences of positions derived from MIPAS and MLS, respectively. Also provided in the panel is the mean over the pdfs and their standard deviations.

Also, descriptions would be required on why both MLS and MIPAS are needed and why only MIPAS is used for the age-of-air calculation in this study.

We have used both MIPAS and MLS data in order to demonstrate that two independent measurements provide consistent observations, and an instrument artifact can be largely ruled out (in case we used MIPAS only, both the AoA trend pattern and the shift of the transport barriers could be an instrumental artifact, for example a mis-location of the observations, occurring after a certain instant during mission lifetime). MIPAS is the only satellite instrument that provides age of air so far, as it is able to measure SF6 from which age of air is derived. This is the reason why only MIPAS data on age of air is used.

Information on the accuracy, precision, and coverage of each dataset would be helpful.

Some of this information has already been included in section 2 of the original paper. We will extend this section and provide more information on the data sets.

4. The CLaMS model performance needs to be evaluated more seriously. The authors show that the shift of the transport barrier position is similar between CLaMS and MIPAS. However, the mean position and the interannual variation exhibit large differences. Please provide a statistics summary on model performance and clarify if the model performance is sufficient for the purpose of this study.

The uncertainties of transport barrier positions and those of the shift will be added to Fig. 2 of the revised paper for CLaMS, too. The model performance with respect to the simulation of age of air and its variability has been analyzed in several papers, and good general agreement with observations has been found (see e.g. Pommrich et al., 2014; Ploeger et al., 2015). It is true that the transport barrier locations do not always agree between the three datasets regarding interannual variability, but the longer-term behavior (2002-2012) is very consistent, as is demonstrated in Fig. 2.

5. It is described in P11L13 that the strongest negative trend of about -0.25 year/decade occurs in the northern tropics (from Fig. 6) and is consistent with trends derived from model calculations (e.g., Waugh, 2009), but this is confusing to me. The previous model calculations including the result of Waugh (2009) did not consider the effect of the latitudinal shift explicitly in their estimated age-of-air distribution, same as in the left panels in Fig 5 (not Fig. 6) in this study. I do not understand why these previous results can be compared with the result in this study after the influence of the latitudinal shift is removed (Fig. 6). I may be wrong, but further clarification would be useful.

It is not expected that free-running climate models reproduce the actual short term variability well or, at least, that they generate this variability at the same time as it occurs naturally. By the way, this limitation is the main reasoning behind comparing “specified dynamics” model runs (i.e. model runs driven in some way by re-analyses) instead of free model runs to observational data records. A long-term climatological trend (30 years or more) is also expected to provide an average over the shorter-term variabilities.

In our case, we understand the overall observed variation (i.e. the observational “trend”) to be caused by a long-term climatological part that can be captured by global climate models and, in addition, by some shorter-term (decadal or less) natural variability that is not well captured by the free-running climate models. We consider the shift of the circulation pattern as such a shorter-term variability. Removing that from the observational data should leave us with the long-term climatological trend. The latter can be (and has been) compared with the climatological trend from climate models, and it has been demonstrated that the remaining trend is closer to the long-term climatological trend from the models. Further shorter-term variability besides the wobbling of the tropical pipe is possibly also present and has not been removed in our study. Therefore a perfect agreement between the "cleaned" observational trend and the climatological trend from models is not to be expected.

- Specific comments:

P1L1" "is expected to accelerate..." Please describe what the expectation is based on.

We have referred to the relevant literature in the first sentence of the introduction (p1, l11-13). Most of the climate models predict an acceleration of the Brewer-Dobson circulation as a consequence of global warming. This is also said in the introduction. We do not exactly understand what the comment refers to.

P2L6: "380 and 420 K for the lower latitudes" Please describe the data used.

We refer here to the paper by Ploeger et al. (2015). Data used within this paper were CLaMS model results and MIPAS observational AoA data, the same as used in this study here. We will add this information to the revised version of the paper.

Section 2.3: Please describe the model resolution and discuss whether this is sufficient to realistically simulate the subtropical transport barrier.

As CLaMS is a Lagrangian model, the grid is irregular and varying over time. Therefore it is only possible to state an average distance between the model air parcels as resolution. We will include this information into the text: "The model resolution of the CLaMS simulations considered here is about 100km in the horizontal direction. In the vertical direction, the resolution is about 400m around the tropical tropopause (see Pommrich et al., 2014 for details)."

Miyazaki and Iwasaki (2007) should be Miyazaki and Iwasaki (2008).

This will be corrected.

Figure 1: Color bars are required. Please change the color scale to clearly indicate the differences.

A color bar will be added, and the color scale of Fig.1 will be changed so that the variation in the N2O vmrs can be seen more clearly.

Figure 3: Please change the colors for the lines and shaded areas.

We will change the color table of the background so that it can be better distinguished from the colored lines.

Figure 4: Please add the same results using MIPAS data and discuss the difference between CLaMS and MIPAS.

The figure with data from CLaMS was added to demonstrate that the shift of the transport barrier, applied to the full surf zone area, reproduces the observed hemispheric dipole pattern, in other words, that not only the transport barrier, but the full surf zone area is shifted. We do not see what an additional figure from MIPAS would help here. MIPAS N2O data fully reproduce the finding from CLaMS. Eckert et al. (2014) (their Fig. 19) already demonstrated that a shift of the ozone distribution explains the observed ozone trends not only around the transport barrier, but in the surf zones as well. We consider these two cases to be sufficient confirmation that the observed hemispheric dipole pattern can be produced by such a shift of the low and mid-latitude distributions. In the revised paper, we'll refer to the ozone example in the Eckert et al. (2014) paper as a second example based on observational data.