Response to the Referee Wendy Meiring

We thank Wendy Meiring for the constructive comments on our manuscript. In the following list we will answer the questions.

2. Specific comments

2.1. When we use FPCA it is assumed that ozone values for each altitude level are normally distributed with a constant mean and variance. Histograms of the values for some altitude levels, e.g. layer 32, 33, 36, 50, 51, 54, show some skewness. However, the skewness is not present for layers where ozone is highly concentrated. Because we employ a functional approach, a transformation should be consistently applied to all altitude levels, and this is why we did not consider the transformation. Since skewness occurs only at layers where ozone is not very high, we expect the bias in the FPCA step resulting from using non-normal data to be small.

2.2. We subtracted overall mean ozone profile (altitude dependent) prior to FPCA thus a seasonal cycle is included in the covariance as well as in the PC scores. Indeed, variations in the PC scores is dominated by a strong seasonal cycle (see Fig 3, 8 and 9 in the manuscript). This is why we include a month term in the regression model (regression of the PC sores on the covariates of our interest), hoping that the seasonal cycle in ozone is identified via penalized regression cyclic cubic splines. However, we totally appreciate the suggestion. So we investigated this suggestion: we subtracted the mean seasonal cycle from the profiles before performing FPCA. We computed sample mean ozone profiles for each month via the method of smoothing splines and used these sample means as estimates of seasonal and altitude dependent mean profiles. When we filtered out the seasonal cycle from the profiles prior to FPCA, the PC scores no longer include the seasonal pattern, therefore the covariate of month is statistically insignificant in the regression model for score 1, 2, 4, and 5. Note that in the original analysis where the seasonal pattern is not filtered out in FPCA (thus in the PC scores), the covariate of month was found to be statistically significant for all PC scores. In the end, however, the new statistical approach changes neither the effect of covariates but month or the estimated ozone trends. As a result, we decided to keep the seasonal cycle in the analysis, as they display different features by score (e.g. semi-annual oscillation) that can be of scientific use. By removing seasonality in the first place, we would not be able to analyse such seasonal features (probably due to shrinkage).

2.3. As often reported in the literature, we expect time lags only for QBO to be present. Yes, we can compare with other studies. For instance, for profile data we can compare with e.g. Fig 4 of Miller et al. (2006) showed a negative influence of AO on ozone in the lower stratosphere, and we do as well find a slightly negative relationship for score 1, associated with such altitudes. For solar, Miller et al. (2006) found a positive influence of solar on ozone in the upper stratosphere, and we do as well find a slightly positive relationship for score 2 and 5, associated with such altitudes. The peaks of the solar cycles are around 1981, 1992 (and 2003) and indeed match the two volcanic periods that we removed (1982-1983; 1991-1993). Nevertheless, we feel that this lack of information for large values of the solar proxy will have a limited impact on our analysis (probably making some confidence intervals wider).

2.4. In order to investigate interaction effects between covariates (e.g. QBO-Solar, AO-Solar and QBO-AO) we used products of the values and created new variables, i.e. QS=QBO*Solar , AS=AO*Solar and QA=QBO*AO. Then we fitted those three new variables (as interaction effects) via penalized regression cubic splines. We concluded that these interaction effects were negligible as their corresponding Effective Degrees of Freedom (EDF) shrank to zero. Indeed, for variable selection, following Marra and Wood (2011), we add a very small number to the penalty matrix affecting only the penalty null space but not the penalty space. When the smoothing parameter for the interaction term is found to be sufficiently large, then the EDF for the term shrinks to zero. The EDF of the interaction terms were all less than 1 with p-values larger than 0.2. Consequently we concluded that the interaction effects were negligible.

2.5. We did not try GML, only REML, a special case of GML. We only compare the result of AMs (the smoothing parameter is estimated by GCV) and AMMs. We finally chose AMMs to represent the effects of the covariates, where the smoothing parameters are obtained via a REML approach, as it is known that the smoothing parameters derived from GCV methods are heavily affected by a misspecified error structure, e.g. correlated errors. In REML, to take into account the degrees of freedom lost from the fixed effects part, we integrate out the coefficients of the fixed effects from the likelihood function, and we maximize the profile likelihood (after the integration) function instead of the original likelihood function.

2.6. After including EP flux in our analysis of Arosa (following the referee's suggestion), we noticed that it is the most influential covariate for explaining the ozone variability, see Figure 1 (derived trends with and without EP flux in Boulder) and 2 (derived trends with and without EP flux in Arosa). The figures compare trends from the full regression model (including covariates of month, year, QBO1, QBO2, solar, AO, ENSO and EP flux) in black solid lines, and the trends from the regression model without EP flux in red solid line. We now feel much more confident that Arosa's results in terms of trends are reliable, and now report all these results.

The EP flux defines ozone transport from the equator to high latitudes that builds up ozone in winter time, but then ozone experiences relaxation through photochemistry during the summer and early fall. However, the rate of ozone destruction is fairly slow and thus there is a correlation between ozone built up throughout March and the amounts of TO observed in the following summer. That is why we used EP flux integrated from October to each consecutive month of the year, i.e. described in Dhomse et al. (2003). We found that adding the EP flux to the explanatory parameters changed the long-term trends in Boulder Umkehr data in two different ways. First of all, we found a difference in the trends in the middle of time series (1985 and 2000) when analysing trends with and without EP flux at altitude between 360 and 105 hPa. At the same time, at altitudes between 15 and 45 hPa we found an increased difference in trends at the end of time series (2000 to 2011). However, we found no significant effect of the EP flux contribution to ozone trends at higher altitudes (15-2 hPa) where transport plays a less important role as compared to the lower and middle stratosphere.

We find that use of the EP flux in trends analysis of Arosa Umkehr data at altitudes above 32 hPa produces similar effects to what we found for Boulder, see Figure 2. In the upper stratosphere, trends tend to be less negative in the last 10 years if EPflux is used in the regression. Thus, we can say that upper stratospheric ozone recovery (above 8 hPa or 35 km) above Arosa is more pronounced when we attribute some of the recent 10 years of ozone changes to the EP Flux variability. However, in the middle stratosphere (16-64 hPa) over Arosa we do not find negative trends as compared to trends over Boulder. The contribution of the EP flux is significant to the trend estimation at these altitudes and make trends less positive (however, it does not make trends negative). At lower altitudes trends in Arosa start to change and become negative below 64 hPa (below 20 km), whereas in Boulder trends become positive in the lower stratosphere. Arosa analysis show a large contribution of the EP flux in the lower stratosphere and troposphere (below 20 km) and makes resulting trends even more negative. It is not clear what other processes might be contributing to this changes over the last 10 years. We only account for the large scale transport contribution toward Arosa trends. There might be additional synoptic scale fluctuations that create recent negative changes in ozone in the troposphere and the lower stratosphere, and therefore these are observed in Arosa TO trends. (Steinbrecht et al., 2011).

Nonlinear synoptic waves can affect stratospheric ozone through vertical transport on time scales that are shorter than photochemical lifetime, and can produce sufficient contribution to long-term variability on regional scales (meaning that there will be a difference between ozone variability at Boulder or Arosa). It is important to quantify dynamical transport associated with changes in atmospheric circulation that affects long-term ozone changes in comparison to the chemically driven changes in ozone.

On the other hand authors also discuss that the pole-ward and equator-ward horizontal transport at middle latitudes (as predicted by the EP flux variability and is related to planetary wave forcing and changes in adiabatic Brewer-Dobson circulation) can be considered zonally averaged and should contribute similarly to Boulder and Arosa ozone variability. Hood et al. (1999) estimated that half of the middle latitude ozone trend can be attributed to the increase in pole-ward wave-breaking frequency between 1979 and 1998 during month of February. According to Hood and Soukharev (2005), the impact of the EP flux on ozone trends should increase with latitude. So, it should be more significant at Arosa as compared to Boulder.

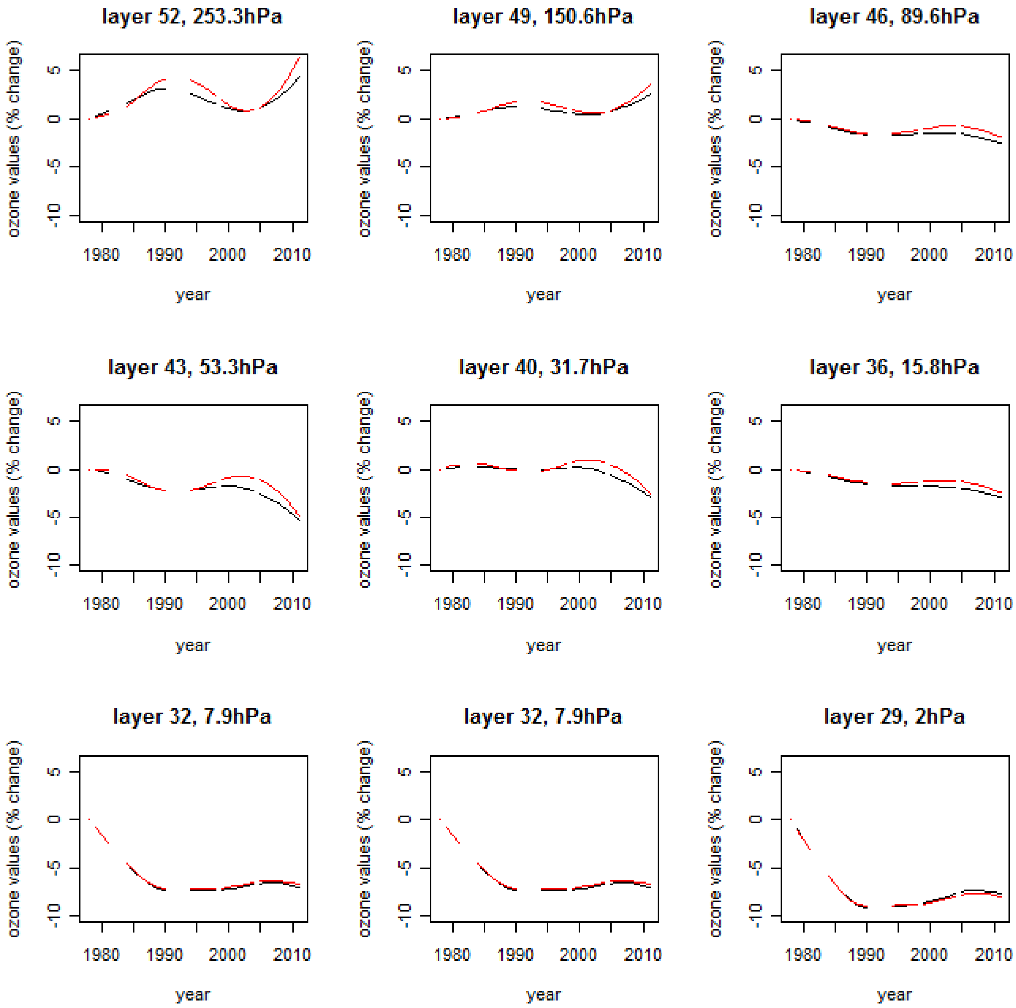

Figure 1: The derived trends of Umkehr profile in Boulder at selected layers. The solid black line is fitted from the full regression model, while the red solid line is fitted from the regression model without EP flux.

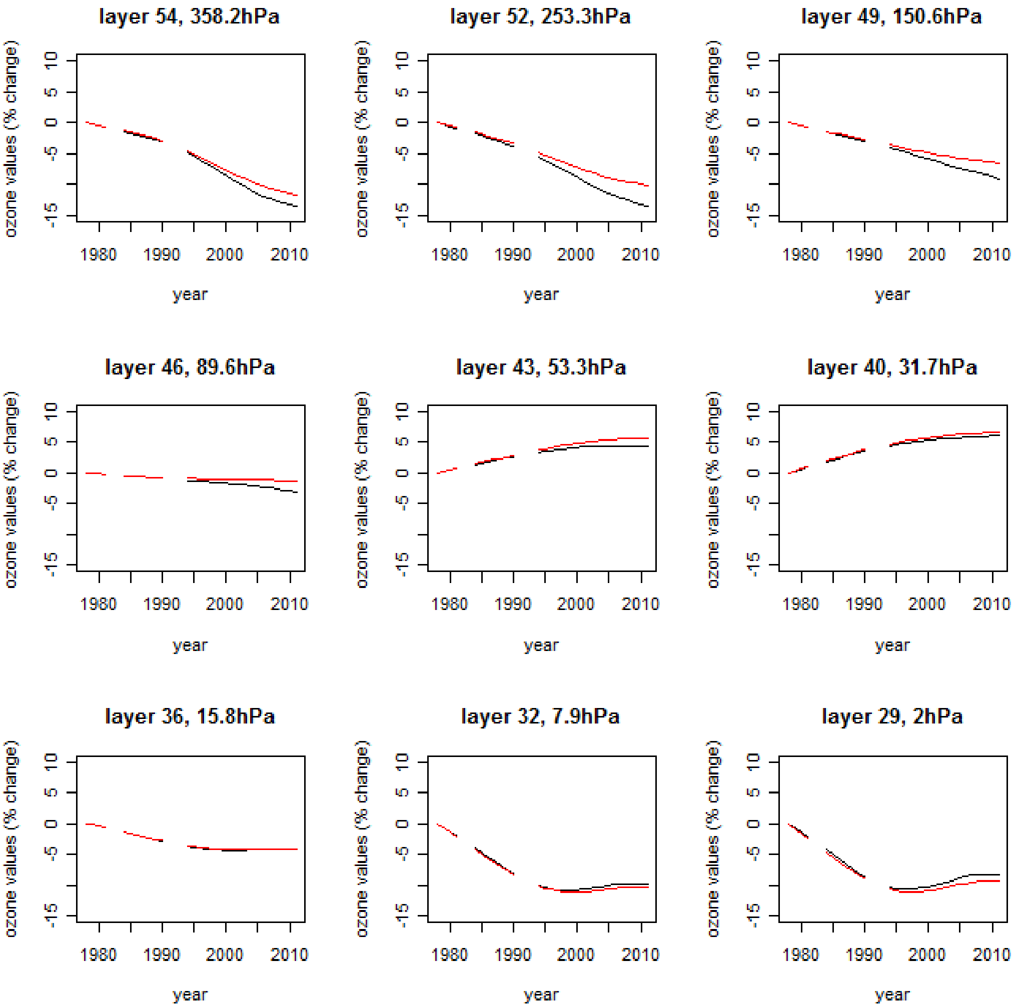

Figure 2: The derived trends of Umkehr profile in Arosa at selected layers. The solid black line is fitted from the full regression model, while the red solid line is fitted from the regression model without EP flux.

3. Technical Corrections/suggestions for edits

3.1. The source of data is WOUDC : WMO ozone and UV data centre and it is publicly available at `ftp://ftp.tor.ec.gc.ca/pub/woudc/Archive-NewFormat/UmkehrN14_2.0_1/`.

3.2. Thanks for the suggestion. We changed the manuscript accordingly.

3.3. We removed the AM section.

3.4. Thanks for pointing it out. We changed the manuscript accordingly and now the terminology used in the manuscript is consistent. We used penalized cyclic cubic regression splines for month term and penalized cubic regression splines for the rest. The penalized regression spline is a generalization of the smoothing spline with a more flexible choice of basis, penalties and knots. Unlike the smoothing spline where knots are placed at each observation, in the penalized regression spline approach the number of knots is typically far less than the number of observations.

3.5. The answer is addressed in 2.4.

3.6. We thank the referee for these clarifications and we revised the description of the paper Meiring (2007) in our manuscript.

3.7. (a) We changed the manuscript accordingly. (b) We have only one constant term in the model matrix $\mathbf{B}$, because a constant term for a spline basis of each covariate is stacked up. As a result, each $\mathbf{A}_j$ does not include a row/column for a constant but a row/column for a linear term. The current manuscript does not clearly explain the model matrix and penalty matrix of the regression model. And it is wrong that each $\mathbf{A}_j$ has two rows/columns of zero but one row/column. We thank the referee for asking for a clarification. We changed the manuscript accordingly and properly re-defined the matrices. (c) We changed the manuscript accordingly. (d) We used the sample mean of each score vector. (e) We changed the manuscript accordingly. (f) We changed the manuscript accordingly. (g) We changed the manuscript accordingly. (h) We did our best to improve the writing. (i) We changed the manuscript accordingly. (j) The parameters in the table shows the magnitude of seasonal pattern in the variance of the residuals. These parameters report the extent of heteroscedasticity in the residuals so we decided to keep the table. (k) It is γ not y. But not to make any confusion we change γ to $\tilde{\epsilon}$.

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