Response to the Referee Jim Miller

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

1. We included an analysis of total column ozone from two sources (WOUDC published total ozone, and Umkehr total ozone by summing up all layers across the profile). It only uses the second step (i.e. the additive mixed effects regression model on the covariates: the only possible common solution to the trend analysis problem for profile and total column data sets) of our statistical analysis to derive trends as well as influences of covariates. As the referee points out, total column ozone is the integral of the profile, and therefore the influences of covariates are somehow integrated along the profile when carrying out the regression: this can result in a loss of accuracy whenever a covariate's influence varies with altitude, as we noticed in our full analysis for e.g. solar or EP flux. So, we emphasize that the total column ozone analysis may not yield as precise outcomes as a full profile approach.

For Arosa, we find that for total column ozone the trend is negative over the full period 1978-2011, see Figure 1. The figure shows derived trends using Total Ozone (TO) from WOUDC (in black solid line) and Umkehr (in red solid line) with the 95% confidence intervals (in dotted line with the matching colour). When carrying out our profile analysis, the trend is also negative for altitudes below approximately 63hPa, but can be slightly positive for altitudes slightly above 63hPa over 1978-2011, see black solid lines in Figure 10.

For Boulder, the trends derived from the two total column data sets differ in the middle of the analyzed period (1990-2005), see Figure 2. It creates almost a linear trend in Umkehr TO data (trend in red solid line and the 95% confidence intervals in red dotted line), while WOUDC dataset suggests very strong decline in TO until 1996 and then a very slow recovery until 2011 (trend in black solid line and the 95% confidence intervals in black dotted line). When the ENSO signal is not used as an explanatory parameter, the WOUDC trend becomes more negative at the end of time series and more in agreement with the Umkehr TO based trend, see Figure 3. The EP flux proxy plays an important role in deriving trends from both WOUDC and Umkehr for Boulder (Figure 6 and 7) and Arosa (Figure 4 and 5) record by making the 1997-2011 trend more negative. Without using the EP flux proxy, the derived trend in Boulder Umkehr TO data, see Figure 7, shows an increase in ozone from 1995 to 2006 with consequent decrease through 2011. Note that our profile analysis results in trends that are of various shapes for Boulder, see Figure 10, so they cannot readily be compared with TO trend analyses.

2. QBO was recorded at seven atmospheric pressure levels, 70, 50, 40, 30, 20, 15 and 10hPa. We implemented PCA on the QBO data to reduce its dimensionality (from 7 to 2). PCA on the QBO accounts for the lags in altitudes, not in latitudes. We took the time lag in the QBO effect from the equator to mid latitudes into account by using four-months lagged PC scores because a rule of thumb of 1 month per 10 degrees of latitude is often used in the literature. We also considered no lag, or 1 and 2 months lags, and no significant change was observed in the analysis, which coincides with the referee's statement.

3. We employed EP flux in our analysis, and profusely thank the referee for this suggestion. Indeed, the EP flux has the greatest influence for most scores as well as for total column ozone. In particular, as suggested by the referee, we noticed that the seasonal pattern is altered for score 5 (associated with the semi-annual oscillation), see Figure 8.

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). In our analysis we used the EP flux to explain TO and stratospheric ozone variations throughout the year. 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, see Figure 10: trends from the full model in black solid line and trends from the model without EP flux in red solid line for selected hPa atmospheric pressure level. 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 anlaysis of Arosa Umkehr data at altitudes above 32 hPa produces similar effects to what we found for Boulder, see Figure 9. It appears that in the upper stratosphere the effect of EP flux on Arosa trends is slightly larger than for Boulder. 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 EPFlux 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 the 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. This is consistent with the fact that the TO derived from Arosa WOUDC and Umkehr data continue to decrease after 1996. 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).

We agree with the reviewer that Sudden Stratospheric Warming (SSW) events above 30 km have the potential to warm the upper stratosphere and thus reduce ozone in the upper stratosphere through temperature-depended chemical cycle. However their impact on ozone is limited to the winter time (December-February). The EP Flux can be used as a proxy representing the planetary wave propagation to the upper stratosphere where it delivers the heat, and changes temperatures.

4. Yes, we agree. Changes in dynamical parameters would come from radiative and chemical mechanisms imposed by increases in Green House Gases (GHGs). Increase in GHG can warm stratosphere and thus directly affect ozone destruction rates that are temperature dependent (so called super-recovery). It could also change the transport patterns geographically and seasonally that can alter ozone at the lower stratosphere where dynamics play an important role.

5. After including the EP flux in our analysis of Arosa, we noticed that it is the most influential covariate for total column ozone, and for most parts of the profiles. Hence, we again thank the referee for the suggestion, and now feel much more confident that Arosa's results in terms of trends are reliable, and now report all these results. For instance, from the plots for WOUDC TO at Arosa, the removal of the EP flux covariate reduced the trend from -4 to -3 % when EP flux was removed, see Figure 4.

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.

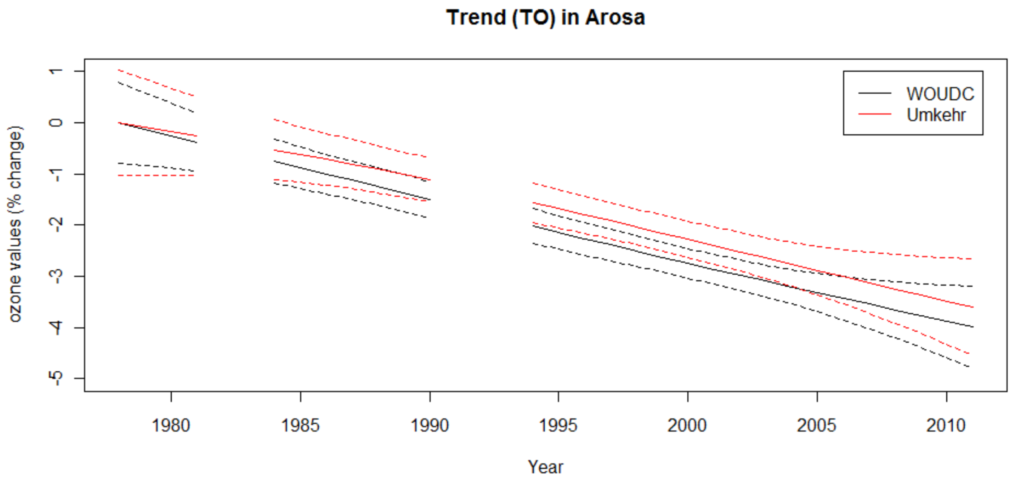

Figure 1: Derived trends from the regression model using WOUDC TO (in black solid line) and Umkehr TO (in red solid line) with the 95% confidence intervals (in dotted line with the matching colour) in Arosa.

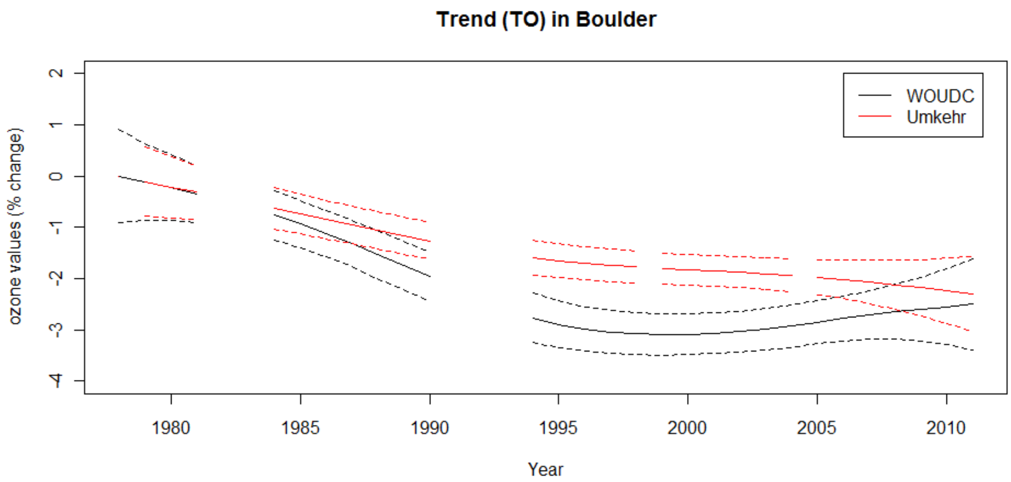

Figure 2: Derived trends from the regression model using WOUDC TO (in black solid line) and Umkehr TO (in red solid line) with the 95% confidence intervals (in dotted line with the matching colour) in Boulder.

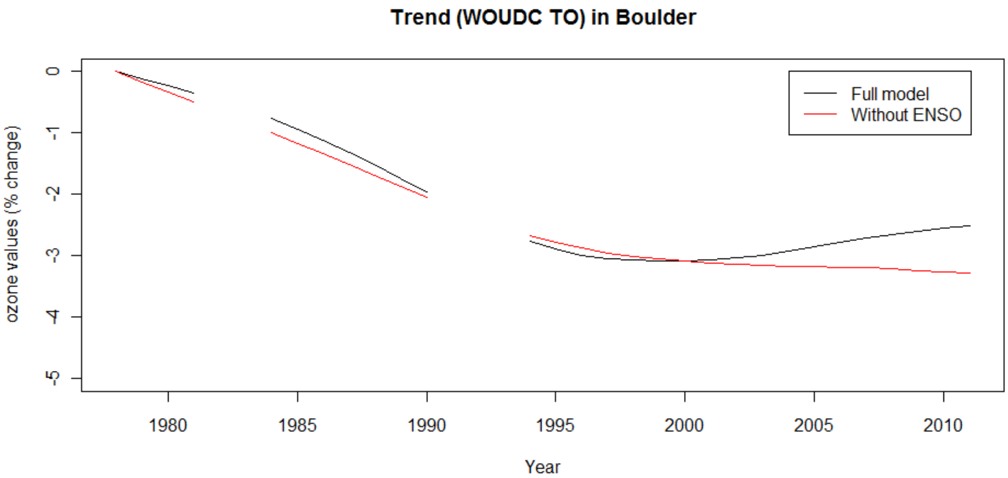

Figure 3: The derived WOUDC TO trend from the full regression model in black, and the derived WOUDC TO trend from the regression model without the ENSO signal in red.

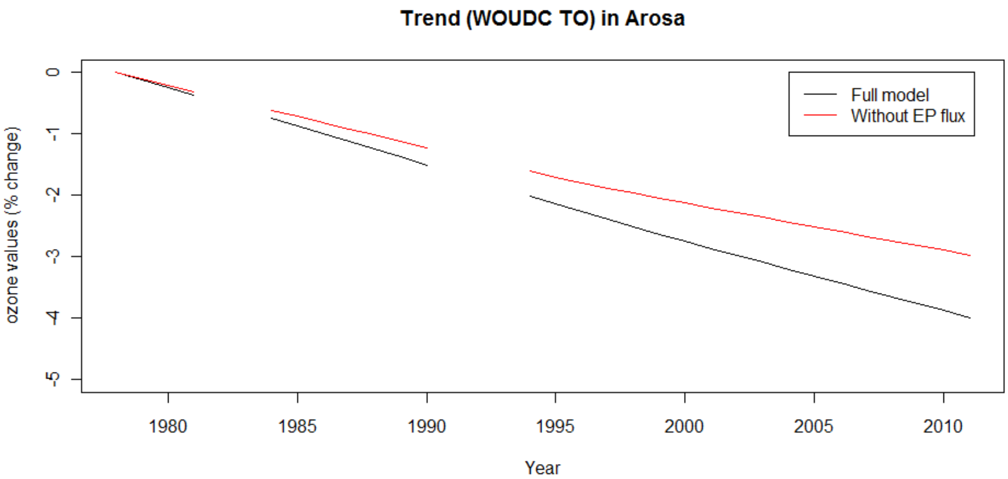

Figure 4: The derived WOUDC TO trend from the full regression model in black, and The derived WOUDC TO trend from the regression model without EP flux in red in Arosa.

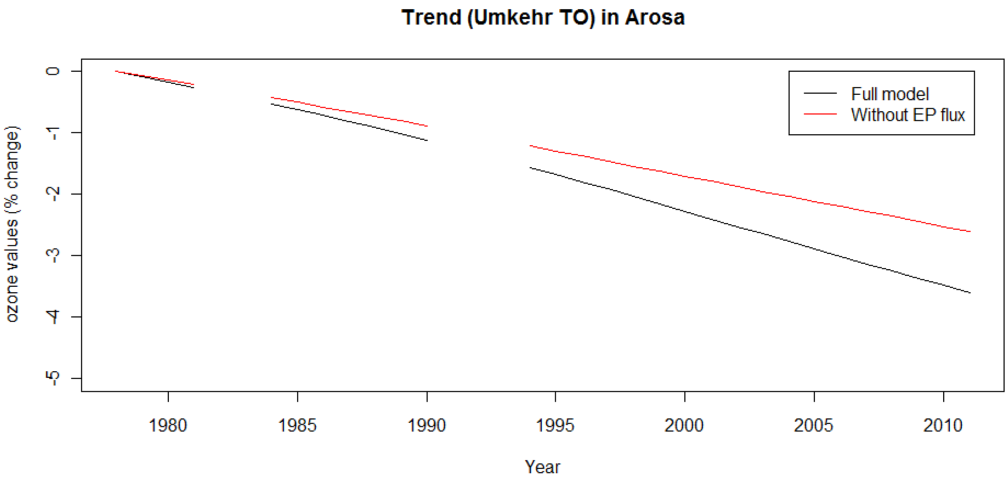

Figure 5: The derived Umkehr TO trend from the full regression model in black, and The derived Umkehr TO trend from the regression model without EP flux in red in Arosa.

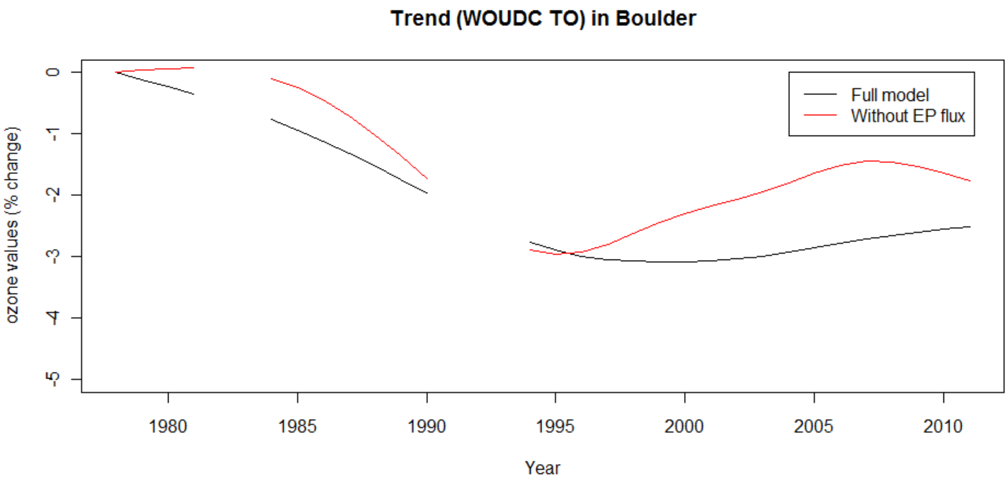

Figure 6: The derived WOUDC TO trend from the full regression model in black, and derived WOUDC TO trend from the regression model without EP flux in red in Boulder.

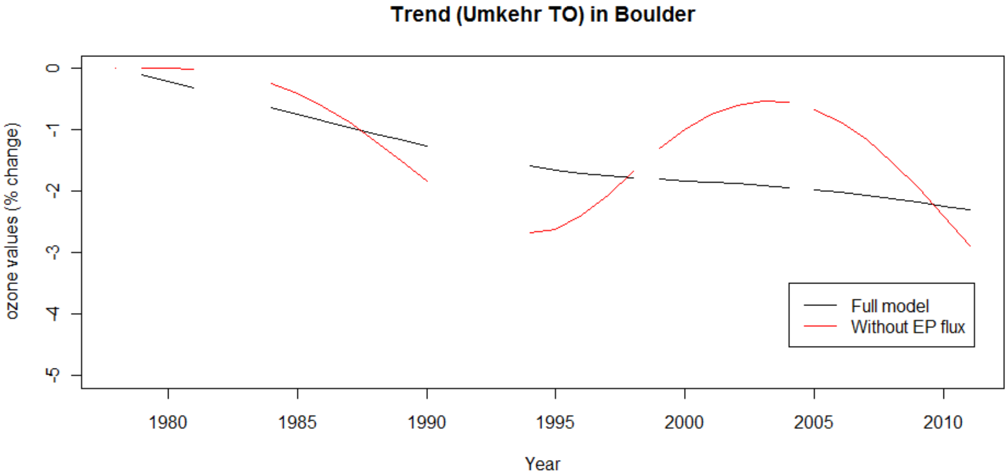

Figure 7: The derived Umkehr TO trend from the full regression model in black, and the derived Umkehr TO trend from the regression model without EP flux in red in Boulder.

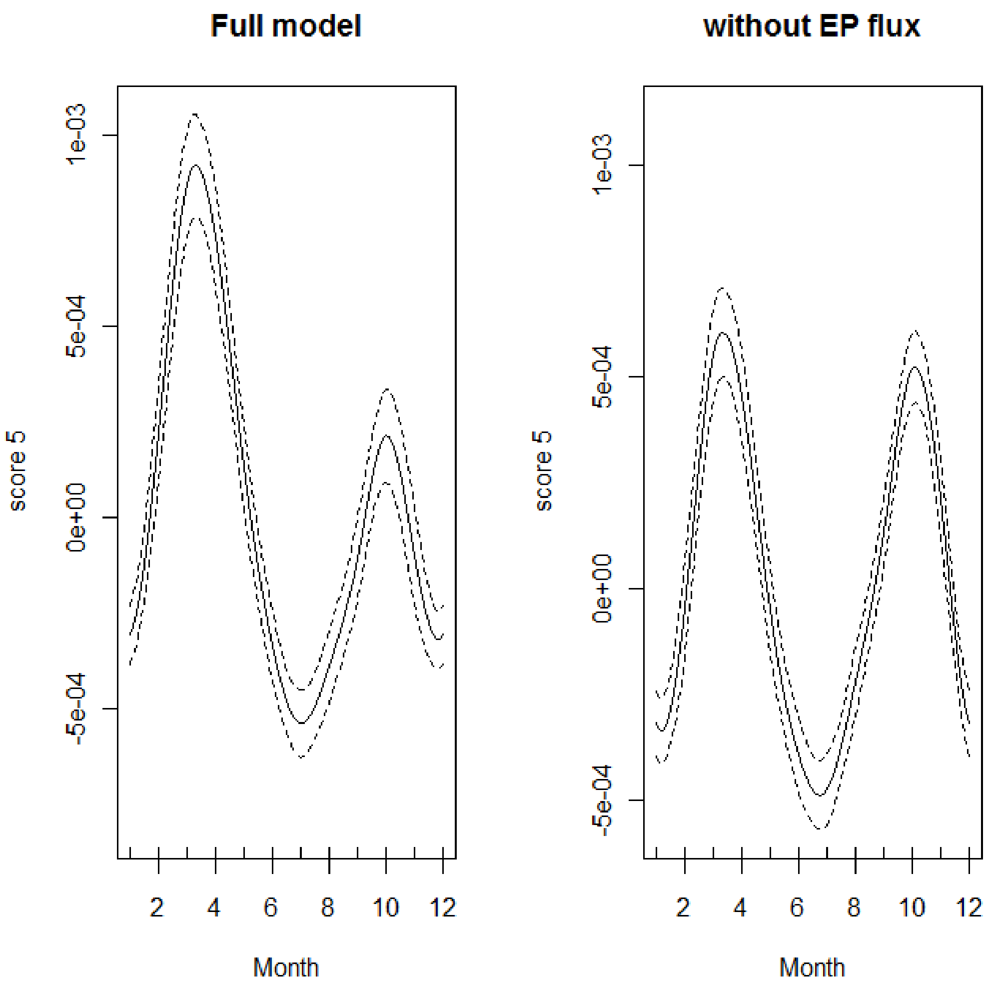

Figure 8: The fitted curve of month (score 5 in Arosa) from the full model in the left panel, and the fitted curve of month (score 5 in Arosa) from the model without EP flux in the right panel

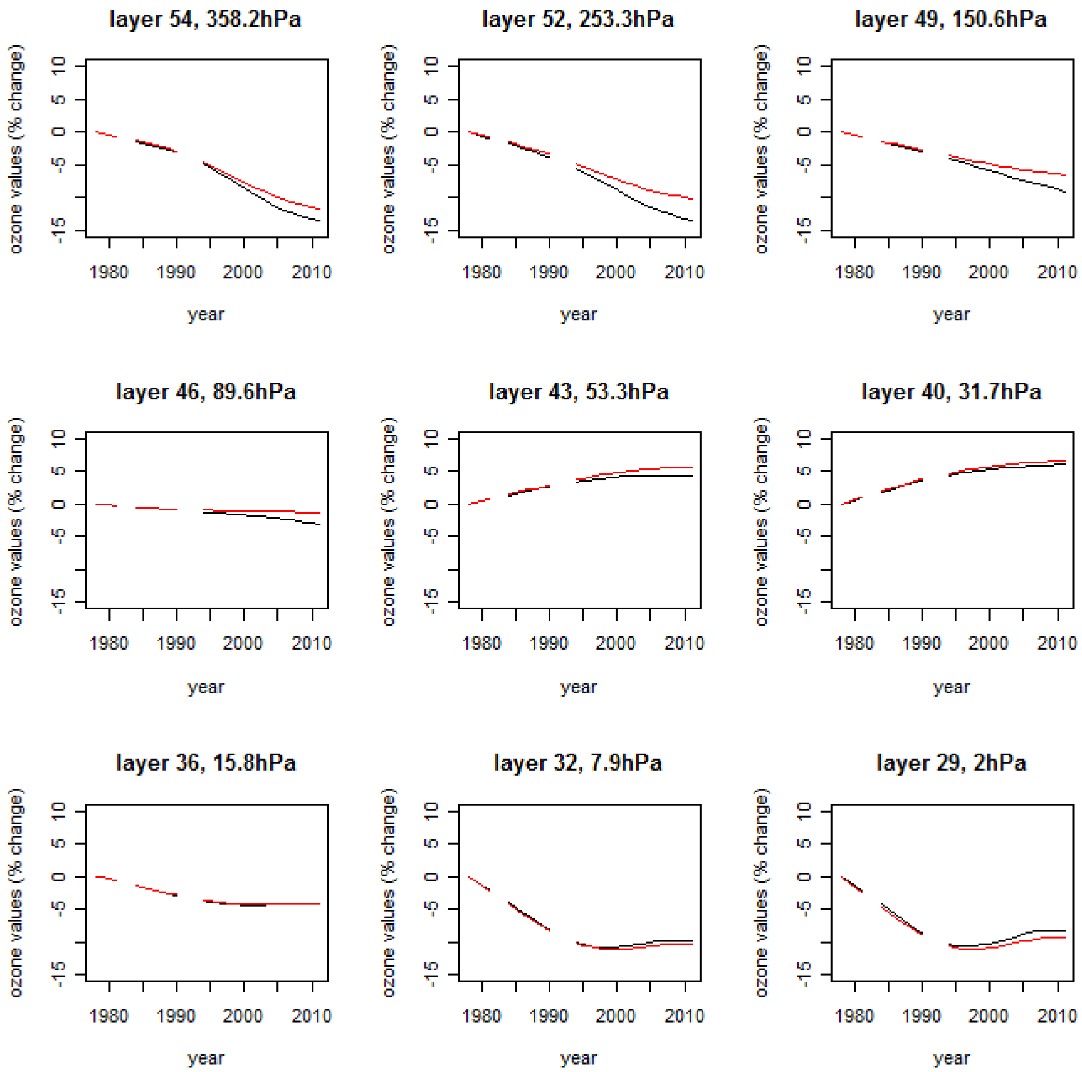

Figure 9: The derived trends of Umkehr profile in Arosa at selected layers. The solid black line is fitted from the full regression model, while the red solid line is fitted from the regression model without EP flux.

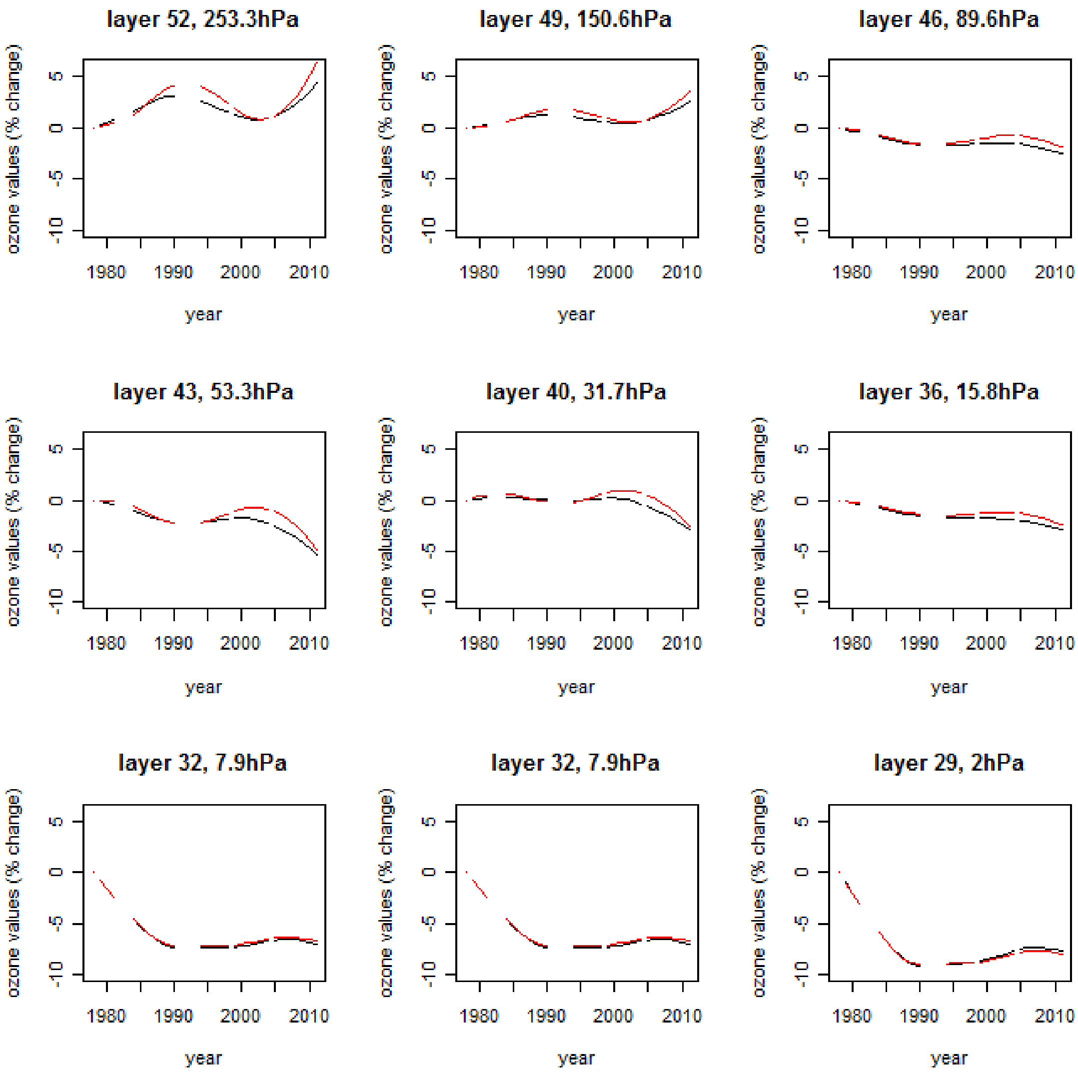

Figure 10: The derived trends of Umkehr profile in Boulder at selected layers. The solid black line is fitted from the full regression model, while the red solid line is fitted from the regression model without EP flux.

References

Dhomse, S., M. Weber, I. Wohltmann, M. Rex, and J. P. Burrows (2003). On the possible causes of recent increases in northern hemispheric total ozone from a statistical analysis of satellite data from 1979 to 2003. *Atmospheric Chemistry and Physics 6*, 1165–1180.

Hood, L. L., S. Rossi, and M. Beulen (1999). Trends in lower stratospheric zonal winds, rossby wave breaking behavior, and column ozone at northern mid-latitudes. *Journal of Geophysical Research 104*, 24321–24339.

Hood, L. L. and B. E. Soukharev (2005). Interannual variations of total ozone at northern midlatitudes correlated with stratospheric ep flux and potential vorticity. *Journal of Geophysical Research 62*, 3724–3740.

Steinbrecht, W., U. Köhler, H. Claude, M. Weber, J. P. Burrows, and R. J. van der A (2011). very high ozone columns at northern mid-latitudes in 2010. *Journal of Geophysical Research 38*, L06803.