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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Spatial regression analysis on 32 years total column ozone data" *by* J. S. Knibbe et al.

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This reply is a continuation of the general reply posted by Knibbe et al.

Authors Reply on Specific Comments by Reviewer #1

- Reviewer: "It is unclear to me why the choice of explanatory variables is restricted to PV and EP in the SH high latitudes, when EP, GEO and DAY show even stronger correlations in the NH."

Not restricting our analysis to fewer explanatory variables in the PHYS model in the Northern Hemisphere is explained in the general reply above. To summarize: Preliminary regression runs showed reasonable robustness of the obtained spatial patterns.

Although the intensity of the DAY, EP (and to a smaller extend GEO) signal may be overestimated in the Northern Hemisphere at high latitudes as a result of the large correlations in the region, we argue that our results provide sufficient information on how ozone relates to these explanatory variables when correlations are properly taken into account in the interpretations. Less robustness was found in the Antarctic region, which is why we made a choice for including the EP and PV variables in this region.

We clarify this issue in the revised paper by inserting the following at the end of section 2.2: "Despite these high correlations at the Northern Hemisphere, preliminary regressions with both of these variables included and either one of them included separately showed reasonable robustness of the obtained results up to approximately 50°N, whereas at higher latitudes we account for this correlation feature in the interpretations of regression results. For this reason we choose to include both EP and DAY for regressions performed at the Northern Hemisphere."

- Reviewer: "Is the separation of seasonal ozone variations, described by the physical variables EP, GEO, PV, and DAY (or the harmonics in STAT) from the seasonal response to the non-seasonal explanatory variables of group A unambiguous?"

The alternative variables (within group A) do not interfere much with the seasonal variables (group B). Multiplication of a variable with an harmonic function does not yield a variable which is dominated by seasonality in the degree that variables of group B are dominated by seasonality. An exception of this is the EESC_2 variable because the short term variability in EESC is extremely low. EESC_2, however, has a very specific seasonal behavior and a trend within this seasonality unlike any other included explanatory variable. It has been common practice in previous regression studies to multiply explanatory variables with much more harmonic functions, often without noting this subtle detail regarding interference with the Fourier series that conventionally account for seasonal ozone variations.

We added the following at the end of section 2.3 to clarify this issue: "Remark that these alternative variable are not necessarily dominated by the multiplied seasonal function. This is only the case for EESC_2, due to the extremely low short term variations in EESC. EESC_2 shows a very specific trend in this seasonality which is very different from the highly seasonal variables in group B. Therefore, the alternative variables hardly interfere with the parameterization of seasonal ozone variations in the regression models that are defined in the next section."

- p 5335 l 3 ff and Fig 3 top left, also Fig 4 top left: Reviewer: "I find it surprising that the EESC response is so low in Arctic spring (and in the Arctic in general)."

We agree that more attention should be given to the fact that we do not identify Arctic catalytic ozone depletion in our results as clearly as we do at the Antarctic in the seasonal analysis. This is due to the Arctic ozone hole occurring more irregular than the Antarctic hole. This is the reason that we do not apply such explicit treatment for the Arctic ozone hole as we do in the Antarctic ozone hole.

We now state in the discussion that the Arctic ozone hole is not clearly detected due to the Arctic ozone hole occurring more irregular than the Antarctic hole and in section 2.3 we state that we do not define an alternative variable for describing the Arctic ozone for this reason.

- p 5337 l 25ff, Figures 4 and 6: Reviewer: "The zonal asymmetry of the EESC2 (and EESC) regression coefficient is striking, particularly in the STAT model. Is this robust?"

Yes we find that these patterns are robust. However, there is some model dependence for the EESC_2 results when you compare these figures more closely. We described this in results section 3.2 and in the discussion section.

- p 5338 l 5ff: 1) Reviewer: "Why is the solar signal so weak in the area of strongest insolation i.e. the tropics?"

The solar signal is not very strong in amplitude in (tropical) total ozone (Wohltmann et al.). Solar effects are stronger higher up in the tropical stratosphere, even though

in absolute sense the lower stratosphere contributes more (Hood et al., 1997). Solar effects are thus better identified in vertically resolved ozone than in total ozone, and correlations between tropical total ozone and the solar cycle are generally rather weak (Brunner et al., 2006; Wohltmann et al., 2007).

- p 5338 l 5ff: 2) Reviewer: "The strong and zonally asymmetric solar signal at high southern latitudes is indeed surprising. ... I wonder if there is a compensating misattribution between EESC2 and SOLAR?"

The correlation value between SOLAR and EESC_2 is -0.0069. There is no misattribution between these variables. It is possible, however, that in- or excluding EESC_2 in a regression de- or increases the residual ozone variation, so that SOLAR can be found significant more easily. But in fact, this feature is more common, as Soukharev and Hood (2006) found similar patterns in vertically resolved ozone dependencies with the solar cycle.

We added "A similar hemispheric asymmetry, with larger ozone influences at the Southern Hemisphere, is found in the effect induced by the solar cycle, with positive regression coefficients at low- and mid- latitudes for both hemispheres and barely significant features at the equator itself. This spatially persistent but weak solar signal is consisted with results of e.q. Soukharev and Hood (2006) on the solar cycle variation in ozone and Wohltmann et al. (2007)." in the discussion of the revised document.

- p 5338 l 25ff, and p 5345 l 18ff. Reviewer: "Given the strong correlation between EP and DAY, the attribution to DAY is not so clear to me, especially at high latitudes."

This point is a continuation of the first specific comment. The regression model does not distinguish well between in situ ozone production and the ozone transport. Results for DAY and EP both at high latitudes, north of approximately 50°N, have been overestimated. Though we made a general statement to be careful with such interpretations, we can address this issue more specifically for these results. Preliminary regression experiments have shown that the contribution for the DAY variable is more persistence at latitudes up to 50°N and the EP contributes more above this boundary. This has been examined by performing regression runs while in- and excluding either of these explanatory variables in turn. Precise quantification of these contributions is very difficult though.

We added “In the interpretations of these results, we must account for the high correlation values between EP and DAY at the Northern Hemisphere. Up to around 50N, the positive effect of DAY on ozone is likely due to in situ ozone production driven by exposure to solar radiation. Towards higher latitudes DAY’s regression coefficients are increasingly affected by correlation features with the EP variable complicating direct physical interpretations due to overestimation of regression coefficients” in the discussion section.

- p 5340 l 21 ff., and p 5344 l 6 ff: Reviewer: “How come this low explanatory power of the PHYS model at high northern latitudes?”

The lower performance of the STAT and especially the PHYS model at high northern latitudes shows that ozone variations in total ozone variation are less well understood. These statistical models do not appear to be well suited for describing total ozone variations because the persistent seasonal ozone cycle in the northern polar region this seasonal component can be accounted almost any set of explanatory variables that vary on seasonal timescales. Any choice in this set will affect short term and long term ozone variations differently and, subsequently, affect results for non-seasonal variables of group A in these models. In passing we note that the STAT model shows effects of the QBO variables up to high latitudes, whereas the PHYS model shows a more persistent pattern in the results for EESC, AERO and (to a smaller extend) SOLAR in the Northern Hemisphere. In the discussion section we added “The higher performance of the STAT model as compared to the PHYS model north of 70°N may be caused by extreme domination of stable seasonal variations in the ozone time series, which are better parameterized by the orthogonal harmonics in the STAT model.”

- pages 5344|21ff: Reviewer: “It is not clear to me why the age of air that fits best should decrease again from the mid-latitudes to polar latitudes – while at the same time the PWLT method gives results more in line with increasing age of air towards the poles, as one would expect.”

Figure 13 shows an unexpected trend with better fits for decreasing air ages towards the poles for the PWLT results, whereas the EESC results yields a less pronounced trend of better fits for increasing air ages towards the poles (actually mid latitudes) that fits the expectations a little bit better, but indeed still not really as expected. The question on how to interpret these results is a valid one. The fundamental difference between these PWLT and EESC curves must be kept in mind: the PWLT has the advantage that the slopes of the two linear segments can be set independently from each other, whereas the EESC curve has the advantage of being a consistent smooth curve. In regions with low air ages (more instantaneous response to changes) and low latitudes we would expect a more sudden breakpoint in the ozone trend, whereas in regions with large air ages and high latitudes the ozone trend changes more smoothly (more delayed response to changes). This is likely what causes the EESC curve to better fit the data in polar regions. The reason for the better fit of 3 year air age EESC instead of EESC with higher air age parameters is probably related to the difference in ozone response rate on increasing ozone depleting substances and the currently decreasing amount of ozone depleting substances. This may be better represented by the 3 year air age EESC instead of an EESC variable with higher air age parameter. However, given the freedom in choice for the age of air and the EESC shape one should not over-interpret these results. Nevertheless, it remains unclear why the PWLT results in Figure 13 (middle plot) generate a trend of an earlier ozone turn-around point towards high latitudes.

At the end of section 2.4 we added “The piecewise linear trend (PWLT) characterization for long term ozone variation has the advantage that the slope in ozone recovery and ozone depletion periods can be estimated separately, whereas these slopes are proportionally fixed in the EESC curves. On the other hand the EESC parameterization yields a smooth curves instead of the ad-hoc turn around point in the PWLT characterization.". Additionally, we now elaborate more on these results in the discussion section.

- pages 5344ff, Sections 4 and 5: Reviewer: "I would suggest re-organising the discussion and conclusion sections a bit., ..., I miss some clear conclusions – take home messages – from the current work."

On reviewers advice we have revised the results, discussion and conclusion section. The most important changes are:

- Moving "The reduced explanatory power At 55S is related to the vortex edge itself. Regression studies focusing on the Antarctic ozone hole typically use either a dynamical definition like the equivalent latitude to define the vortex area, or stay sufficiently far away from the vortex edge (south of 70°S; e.g. Kuttipurath et al. (2013)). Hassler et al. (2011) have shown that the shape of the Antarctic vortex has changed somewhat during the last 30 years which has consequences for analyzing Antarctic ozone. However, given that this study focuses on the global patterns of ozone variability, use of a spatially variable definition of the vortex edge is not possible." from the conclusion section to the discussion section.

- Deleting "Three regions show reduced explanatory power in both models: the Antarctic vortex edge region, a tropical belt around 10°S and a smaller band over the northern edge of Africa extending into central Asia. The band with reduced explanatory power over the tropics and the smaller band over North Africa extending into Central Asia are due to a large component of white noise in the ozone time series." from the conclusion section, because these findings have been sufficiently addressed in the discussion section.

- Adding "As for post peak-EESC ozone trends, the results of our regressions indicate that standard methods for determining trend uncertainties likely underestimate the true

uncertainties in the ozone trends that can be attributed to decreasing EESC. Hence, great care has to be taken with discussing the statistical significance of these trends." in the conclusion section and "Based on these observations we conclude that ozone is recovering globally at a rate between 0.2 and 1.7 DU/year and between 0.9 and 3.1 DU/year for the Antarctic ozone hole period specifically. However, given the uncertainties discussed above it is not possible to determine an appropriate trend uncertainty level, hence no statistical significance of the recovery rates can be determined." at the end of the discussion section as one of our take home messages.

- Adding "This first spatial regression study yields pronounced patterns in longitude/latitude dimensions of ozone-regressor dependencies. The effect of ENSO on ozone is mainly identified at the Pacific. We don't find clear indications of aerosol effects on ozone at the Antarctic. The effect of the 11-year solar cycle appears to be more important in the Southern Hemisphere, especially between -50° and 100° in longitudes, which is currently unexplained. And the effect of the southern polar vortex, clearly identified north of Antarctica, is large on total ozone columns." as second paragraph in the conclusions section as take home message.

- Technical corrections are all applied accordingly.

Interactive comment on Atmos. Chem. Phys. Discuss., 14, 5323, 2014.