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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 #3

- Reviewer: "The autocorrelation must be included, or if it is in the current model, an explanation of how is needed."

Though we agree that autocorrelation is present in the ozone time series, it is of no concern for the main objective in our study, which is the spatial patterns that arise in the regression coefficients. The P-value approach is applied here and suffices in our opinion for this purpose since autocorrelation only affects the uncertainty assigned to

the regression coefficients. This only needs to be properly evaluated regarding the recovery rates where we make specific statements about significance in ozone recovery rates. Although the uncertainties in these estimates are much more dependent on the age of air parameter for the EESC variable and the modelled turn-around point in ozone for the PWLT estimates than on the autocorrelation, we agree to incorporate autocorrelation in the error handling for these trend estimates in the revised version.

We implement the method described in Press et al (1989) to account for autocorrelations of lag 1 in the error term for trend estimates. This has changed the standard errors of the recovery estimates. A description of this method is included in the revised manuscript, section 2.4, first paragraph.

- Reviewer: "I do not like but accept the definition of physical vs. statistical model, when in reality all the models presented here are statistical."

The regression models have been given the labels 'statistically oriented' and 'physically oriented' to emphasize their main difference. We are fully aware that they are both considered statistical regression models.

- Reviewer: "To the extent that the 'DAY' variable can be itself defined by Fourier harmonics the regression model will not be able to distinguish between the two."

The explanatory variable DAY approximates an harmonic function at low to mid latitudes but inhibits truncation of its seasonal pattern towards the poles, since a polar day lasts six months. At low to mid latitudes it is true that DAY can be well resembled by harmonics but so can any function with a strong cycle. The main purpose of these physically meaningful variables instead of harmonic functions is not to achieve a higher explanatory power, but to assign meaning to the specific phase and period in seasonal oscillation by attributing such variation to variables such as DAY, EP and GEO. For this reason we do not find the experiment of comparing DAY and GEO parameterized ozone variability to results characterized by the harmonics a useful suggestion in the scope of this study. We do agree that the PHYS model has the drawback that these highly seasonal variables may explain additional seasonal variation driven by other processes as well and we encourage more investigation to resolve this issue. This study gives our view on how far the current understanding has advanced. For example: the obtained results that correspond to DAY may seem unsatisfactory because we may not expect in situ ozone production at high northern latitudes in the amounts that these results imply. For a large part this is a feature of high correlations with the EP variable. However, we note that the DAY variable explains ozone variability from the tropics polewards, whereas for the EP flux this occurs north of 40 ĚŽN. The EP flux coefficients also increase towards the southern polar vortex in the Southern Hemisphere. For both hemispheres this is consistent with stratospheric ozone production occurring in the tropics and subsequent ozone transport towards higher latitudes as inferred from the EP dependence. In the revised version of the manuscript we have included this examination of results (discussion section on EP and DAY results).

- Reviewer:"I do not understand why the STAT model, with harmonics for each regression term, also includes the "alternate variables" with the pre-defined seasonal term."

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 behaviour 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 vari-

ations 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 do not interfere much with the parameterization of seasonal ozone variations in the regression models that are defined in the next section."

- Reviewer: "There is some confusion on the use of equivalent latitude vs. latitude."

We have used geographical latitudes throughout this study. We have changed 'equivalent' to 'geographical' in the first line of section 2.3 in the revised manuscript.

- Reviewer: "One of the unique aspects of this work is the analysis of the gridded data."

We include some extra emphasis on the spatial variations of the regression results in the revised manuscript. We have included the following text as second paragraph in the conclusion section: "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.".

- Reviewer: "The authors should consider including two regression terms for the volcanoes, rather than a single AERO term."

The AERO term represents the amount of stratospheric aerosols at 7 degree latitude bands. Therefore, it accounts for the spatial differences between the Pinatubo eruption and the El Chicon eruption. To account for different chlorine contents, we could use two variables instead of one for each eruption. But this would only matter where both eruptions affect the amount of stratospheric aerosols. Furthermore, including only one variable enables us to take other aerosol sources into account in similar degree. The studies referred to by the referee indicate aerosol effects even after dynamical effects into account, although the signal is not spatially consistent (ozone increase over Antarctica during Austral autumn). Furthermore, only at high (polar) latitudes there appears to be a strong aerosol signal [Brunner et al.]. It is also well known that large tropical volcanic eruptions affect poleward transport (Brewer Dobson circulation), which further complicates the inclusion of aerosols in a multi-variate regression. Additional research (submitted) reveals that due to these complexities, regression results are very sensitive for the exact choice of the aerosol proxy. Given the large uncertainties and freedom in parameter choice we would rather prefer to stick with what has been the standard methodology to include stratospheric aerosols in regression studies.

- Reviewer: “The authors might consider focusing on a few of the results where they get different results than expected or than in previous studies, and try to characterize these results in context with previous studies.”

The advice on focusing on the results that differ from previous studies is appreciated and taken into account in the revision. For instance, in the discussion section we added: “Interestingly, as the STAT model attributes more ozone variation to QBO and ENSO variables at higher northern latitudes as compared to PHYS model results, the PHYS results show a more persistent pattern of EESC and AERO ozone effects at high northern latitudes. The different characterization of seasonal variation in ozone in these models causes these small differences. Another difference is found in the EESC_2 results over Antarctica where a large part of ozone variations that could be interpreted as EESC driven according to the PHYS model (Figure 9) is accounted for by harmonic variables in the STAT model”

Also, in the conclusion section we added: “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 south-

ern polar vortex, clearly identified north of Antarctica, is large on total ozone columns.” as second paragraph.

- Reviewer: “When sensitivity to EESC age of air and PWLT turn around points are discussed, the authors should reiterate upfront the reason for the sensitivity tests.”

The sensitivity to the age of air and PWLT turn-around points are examined to see if they fit the expected trend of large air ages and later turn-around points towards the poles. The results are somewhat surprising though, especially for the PWLT results. A statement on significant difference is very difficult, since you have to take multiple testing into account. But differences in R2 values reaches up to 2% for the different regression fits, which is significant in our opinion. Adding this to some of the robust patterns we obtained in Figure 13 we feel that interpretation of these results is needed. We will clarify some of these issues in the revision. One possible interpretation is that the long term ozone prefers to be modeled by a smooth curve at the poles instead of an ad hoc turn around point, due to the high age of air in this region. The choice for the 3 year air age instead of the 5.5 in most of the EESC regressions may be due to the deviating proportion in ozone recovery rate versus ozone depletion rate in the EESC variables. The ozone feedback may be better explained by the 3 year version though the 5.5 year version may fit the turn-around point better. We do not conclude that these result properly show the air ages in the corresponding regions. Note that we have submitted a paper that in detail discusses the effects of different kinds of uncertainties in multi-variate regressions of total ozone, which has large consequences for both statistical significance of trends as well as the robustness of trend results derived from multi-variate analyses.

- Reviewer: “Is Table 7 the maximum ozone recovery rate or average?”

They are average recovery rates. Also, some numbers have been mixed up in table 7. This is corrected in the revised manuscript. Reviewer: “It is not clear what is causing the difference between the PWLT and EESC/EESC_2 results, but the authors should consider looking into this more and commenting in this paper."

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 on these results in the discussion section.

Reviewer: "There is a section of the conclusions that repeats information presented just prior. Maybe these sections can be combined."

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

- Moving "The reduced explanatory power At 55°S 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.

- Technical corrections are all applied accordingly.

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