

## ***Interactive comment on “Drivers of variations in the vertical profile of ozone over Summit Station, Greenland: An analysis of ozonesonde data” by Shima Bahramvash Shams et al.***

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Responses to anonymous reviewer #1:

We are thankful to the anonymous reviewers for their comments. We believe that our responses to these comments have significantly improved the manuscript. Below are our detailed responses. Note that any citations that appear in our responses have references in the bibliography of the manuscript.

Rev\_1: Interactive comment on “Drivers of variations in the vertical profile of ozone over Summit Station, Greenland: An analysis of ozonesonde data” by Shima Bahramvash

C1

Shams et al. Anonymous Referee #1 Received and published: 25 October 2018

Shima Bahramvash Shams et al. analyse ozonesonde data from Summit Station, Greenland to determine the primary drivers of ozone variations at this station by using a stepwise multiple regression analyses. They find that the QBO has the strongest influence for ozone variations over Greenland. This influence is not as strong found over other Arctic stations and thus the authors suggest that Greenland may be particularly sensitive to the QBO. This is a quite interesting study, but it lacks in presentation. I would suggest major revisions before this study can be considered for publication in ACP. I give detailed comments and suggestions for improvements below.

Response: We thank Reviewer #1 for such a thorough review and for helpful suggestions that have greatly improved the manuscript. Based on the Reviewer's comments and questions, we have added three additional high-latitude Arctic stations to this study (Ny-Ålesund, Alert, and Eureka). We also extended the time series by an additional 7 months. (Unfortunately, the ozonesonde launches were discontinued at Summit Station, Greenland in the summer of 2017.) Instead of using climatological data above the ozonesonde profiles, we now use ozone retrievals from the Microwave Limb Sounder (MLS) satellite instrument. The time period of our study is thus constrained by both the ozonesonde record at Summit and the availability of MLS data. The merged ozone profiles are of higher quality than those used in our original manuscript. We investigate the variation of seasonal cycle at these stations. These updates to our study allow us to now identify drivers of ozone variations that are common at the sites. The manuscript now examines the important drivers for different layers in the atmosphere and for the total column ozone for a particular sector of the Arctic. Thus, the Reviewer's comments have allowed us to expand the scope of the study, and we believe that this has greatly improved the manuscript.

General comments: So far, the results are mainly presented in a descriptive manner than really explaining something. Furthermore, the entire analyses is described and documented in much more detail than actually necessary for a research paper. 1)

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Therefore, I would first of all suggest to reduce the number of tables and figures to what is really needed. a. For example, the few values for latitude, longitude and altitude of the stations could be easily (if not already done so) given in the main text.

Response: Table 1 has been deleted.

b. Tables 2 and 3 could be provided (if necessary) in a supplement. The numbers from Table 4 which are important could be given in the main text of the manuscript or in the respective figures.

Response: Table 2 has been deleted. We decided to keep Table 3 because we feel that it's important to list the source of each proxy dataset. Figures 3, 4, 6 and 7 have been removed. Overall, we reduced the number of figures from 12 to 9, and we have included new version figures of some figures based on our updated analysis.

2) How can you justify an extrapolation to 60 km? From Figure 2 one can see that there are generally no ozonesondes measuring above 40 km, except the 2 balloons that measured up to 50 km that were removed from further analysis due to erroneous readings from the pressure sensor. That means extrapolation is done over an altitude range of at least 20 km. How can you be sure that your results are not just reflecting the climatological changes and not the actual changes? Why don't you extrapolate the profiles up to 30-40 km as it would match the typical maximum altitude for the measurements of the ozonesondes?

Response: Based on this Reviewer's comments and questions, we have improved our dataset substantially by using ozone retrievals from the Microwave Limb Sounder (MLS) to provide ozone profiles up to 60 km, instead of our previous use of the ozone climatology. This has improved the quality of ozone profiles that have low burst heights by using actual measurements of stratospheric ozone that are nearly coincident in both space and time with the ozonesondes. It should be noted that using MLS retrievals is the primary reason for differences in our current analyses versus our original analyses over Summit Station.

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3) In this study the results for only one station are presented, but it would be more interesting to have such an analyses for several stations that can be compared to each other. As it is done now (with just mentioning the other two stations that however cannot be analysed because they do not provide measurements for all seasons) it is in my opinion not sufficient.

Response: We agree with this suggestion. Therefore, we have included data from Alert and Eureka, Canada and Ny-Alesund, Svalbard. This allows us to now investigate the drivers of ozone variations for an important sector of the Arctic. This has greatly improved our paper and made it much more relevant.

4) What is the reason for the QBO influence over Greenland. If you cannot find such an influence over other Arctic stations, how can you then be sure that this is not just a measurement artifact? This really needs some more discussion, analyses and scientific explanations to be sure that there really is a connection.

Response: We also agree with this suggestion. As a result of these questions and those from Reviewer #2, we have substantially changed our approach for selecting important proxies/drivers. We now use the stepwise multiple regression to choose drivers that are common to 3 or more of the 4 sites, which increases confidence that the specific proxies are important in this sector of the Arctic. We then use the important proxies in final regression models for each site. As before, we discuss the contributions of each of the proxies and how they affect ozone concentrations. This provides a much better physical understanding of how these parameters affect Arctic ozone.

Specific comments: M1) P1, L12: Here you state that "12 years" of data were used, but later you always state "11 years" of data were used.

Response: We have corrected all occurrences to 12 years. We actually added 7 additional months to the duration of the study to analyze 12 complete cycles of ozone data at all of the sites. We are constrained to this time frame by the availability of both the Summit ozonesondes and the MLS satellite data.

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M2) P1, L15: Extended to 60 km from which altitude? How many km are extrapolated?

Response: We no longer extrapolate any data in the creation of the ozone profiles. The profiles are now a merger of ozonesonde data from the lower atmosphere (up to the burst height) and MLS retrievals in the upper atmosphere. Figure 2 shows the histogram of the maximum height of ozonesondes at all stations.

M3) P2, L14-15: This sentence could be misleading and should thus be rephrased. The reason why there is less photochemical loss of O<sub>3</sub> is because if temperatures are warmer, there are less PSCs and if there are less PSCs there are less surfaces for heterogeneous reactions that convert the inert reservoir species into reactive species that destroy ozone.

Response: This has now been clarified in the text.

M4) P2, L17-18: This only holds with the current ozone loading. When the chlorine concentrations decline, there will be no longer massive ozone destruction due to chlorine. Thus, this sentence should also be rephrased.

Response: We agree with the Reviewer's comment, but we are not sure which sentence to rephrase on lines 17 and 18 based on this comment.

M5) P2, L26: Remote sensing instruments → from space or ground? Please be more precise.

Response: We referred to both ground-based and space-borne instruments. Most of ground-based instruments are transmission Fourier-transform spectrometers and many satellite instruments, such as OMI, need sunlight to function. We have clarified this in the text.

M6) P2, L27-29: I do not agree to this statement. There are plenty of satellite measurements providing global daily measurements of ozone. Not all satellite instruments are dependent on solar radiation. There are many satellite instruments that are capable of measuring during polar winter.

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Response: We understand that there are measurements from satellite instruments that operate in the Arctic winter, such as MLS. We have updated this sentence to describe MLS, because we now use MLS profiles in this study.

M7) P3, L19: This needs some more explanation. How is a climatology used to create a vertical profile?

Response: This section has been deleted and replaced with text explaining our use of MLS data.

M8) P4, L1: for analyses? Do you mean for this analyses?

Response: The sentence has been deleted.

M9) P5, L4: Column abundance in the vertical profile sounds a bit weird. Do you mean here "the total amount of ozone in the vertical column"?

Response: Yes. We have corrected this.

M10) P5, L16: What is the purpose of the extrapolation? To fill the missing levels or to extend the column?

Response: As mentioned above in M2, we no longer extrapolate any profile data.

M11) P5, L22-24: I would not put the text into brackets. I would suggest to either remove the brackets or to put the text into a footnote.

Response: This entire paragraph has been deleted.

M12) P5, L25. What do you mean with "is used to 60 km"?

Response: This sentence has been deleted.

M13) P6, L34: What do you mean with "using data from the dates of ozonesondes"? Do you mean for the same dates as the ozonesonde measurements? Please rephrase accordingly.

C6

Response: Yes, this is what we mean. We have clarified this in the text.

M14) P7, L1: The given list of sources rather gives the links to the “data” used for the “proxies” than to the “proxies” themselves.

Response: Most of these entries are actually direct links to data that we used for the proxies. In the text we updated the sentence to “data sources and weblinks”.

M15) P7, L10: What do you mean with forward selection?

Response: “Forward selection” is a common technique for predictor selection that is describe in Wilks (2011). Wilks states that “stepwise regression” and “forward selection” are synonymous in the statistical literature.

M16) P7, L29: Minimal in four months? In which month do you get the absolute minimum?

Response: This sentence has been removed because Figure 6 has been deleted from the manuscript.

M17) P8, L15: In Fig 7b the minima are not that apparent? Why? Further, it would be worth (especially in Fig 7a) to mark these low areas during these winters for better visibility.

Response: Figure 7 has also been deleted from the manuscript.

M18) P8, L26: Also here the text should be either given without parentheses or as a footnote.

Response: Done.

M19) P9, L8: Winter accumulation? Accumulation of what? Of ozone?

Response: Yes, we were referring to ozone accumulation. This has been clarified in the text.

M20) P9, L18: What is FTS? Has the abbreviation been introduced?

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Response: This sentence has been deleted.

M21) P10; L3: “12 years” or “11 years”? The number of years used in not the same throughout the manuscript.

Response: See M1 above. This has been corrected.

M22) P10, L22: Positive of negative → What do you mean? positive “and/or” negative

Response: This should have read “positive or negative”. This has been corrected.

M23) P10, L24: Time trends? Do you mean time series or trends?

Response: We actually mean the “trends in the time series” over the 12-year period. This has been corrected.

M24) P11, L19-20: That is to simplify and could be misleading. The photochemical loss ozone is less than temperatures are warmer, because PSC will not form that are a necessary requirement for the processes leading to ozone depletion.

Response: This has been corrected.

M25) P12, L4: Please rephrase “changes in final model”.

Response: This has been rephrased.

M26) P12, L10: Also this sentence is formulated in that they that it could easily be misunderstood. The reactions involving the surfaces of Polar Stratospheric Clouds lead to ozone loss not the PSC itself.

Response: This has been corrected.

M27) P12, L16: Two times “layer”, thus one “layer” is obsolete.

Response: This has been corrected.

M28) P12, L22: Caused in part? Isn't it mostly this process? What other processes are responsible for the seasonal cycle?

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Response: We have deleted “in part”.

M29) P13, L1: This sentence should be rephrased. Not the equivalent latitude itself affect the ozone. It is just a different way for analysing/presenting the data and if course of the data is plotted on equivalent latitudes instead of latitude, the distribution or profile looks a bit different.

Response: We have corrected this.

M30) P14, L13: What is GrIS? Please clarify.

Response: “GrIS” stands for Greenland Ice Sheet and is defined on page 3 line 17.

M31) P14, L17: In global? But in your study only local ozone concentrations are considered. What do the here presented results mean for the ramifications of the Montreal Protocol?

Response: This is a valid point. We have deleted this sentence.

Technical corrections: T1) P1, L11: there are few. . . → there are only few. . .

Response: Done.

T2)P1, L21: due primarily → primarily due

Response: Done.

T3)P2, L13: weaken → “weak” or “weakening of the vortex”

Response: Done.

T4)P2, L19: arctic atmospheres → Arctic atmosphere

Response: Done.

T5)P2, L23: remove space between parentheses and reference. P2, L28: remove space between parentheses and reference.

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Response: Done.

T6)P2, L31: for validation → for the validation

Response: Done.

T7)P3, L5: evaluate → validate

Response: Done.

T8)P3, L24: I would suggest to write instead of “this research” rather “this study” or “this research study”.

Response: Done.

T9)P4, L4: remove space between parentheses and reference.

Response:Done.

T10)P4, L8: ozonesonde → ozonesondes

Response: This sentence has been deleted.

T11)P4, L9: then an → then with an

Response: This sentence has been deleted.

T12)P4, L27: profiles has significant missing → the profiles has a significant amount of missing values

Response: This paragraph has been removed to minimize unnecessary information.

T13)P5, L5: defined using → defined by

Response: Done.

T14) P5, L6: thickness of compressed → thickness of a compressed gas

Response: Done.

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T15)P5, L11: Letters and numbers should put in the according sub and subscripts.

Response: Done.

T16)P5, L16: What do you mean with “appreciable ozone”. Wouldn’t the right wording be “applicable” or “measurable”.

Response: Done.

T17) P6, L18: either “retrieved from” or “measured by”.

Response: This sentence has been deleted.

T18)P6, L18-19: rephrase sentence to avoid repetition of “which”.

Response: This sentence has been deleted.

T19)P6, L24: in the section 4 → in section 4

Response: This sentence has been deleted.

T20) P6, L25: depend → depends

Response: Done.

T21)P6, L28: Write either “below” or “section 4”

Response: Done.

T22) P6, L30: Reference should be given here without parentheses.

Response: Done.

T23) P7, L28: add comma after “(in DU)”.

Response: This sentence has been deleted.

T24) P7, L29: in the ozone → in ozone

Response: This sentence has been deleted.

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T25) P9, L6: before ozone transport → before ozone is transported

Response: Done.

T26) P9, L19: March-September → March to September

Response: This sentence has been deleted.

T27) P9, L20: January-November → January to November

Response: This sentence has been deleted.

T28) P11, L29: influence → influenced

Response: This sentence has been deleted.

T29) P12, L21: impacts → is responsible for

Response: Done.

T30) P12, L29: in upper stratosphere → in the upper stratosphere

Response: Done.

T31) P13, L9: found insignificant → found to be an insignificant

Response: This sentence has been deleted.

T32) P14, L14: remove space between parentheses and reference.

Response: Done.

T33) P28, I4: with → which

Response: Done.

————— Responses to anonymous reviewer #2:

Rev\_2: The abstract summarizes well the content of the manuscript. It is a regression analysis of a 12-year ozone time series at Summit, Greenland. That’s it. There are a

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number of flaws in this work.

Response: We agree with the Reviewer that it is difficult to draw firm conclusions about Arctic ozone from data at a single station. Thus, in addition to using the ozone profiles from Summit Station, Greenland, we have added ozonesonde data from Alert and Eureka, Canada and Ny-Alesund, Svalbard to our study. This has allowed us to identify drivers of ozone variations that are common at the sites. The manuscript now examines the important drivers for different layers in the atmosphere and for the total column ozone for a particular sector of the Arctic. Thus, the Reviewer's comments have allowed us to expand the scope of the study, and we believe that this has greatly improved the manuscript.

Rev\_2\_M1) First, the column time series is built using an extrapolation method described as "robust" in the abstract (what does it mean here?). The altitude reached by the balloons does not exceed about 20-25 km during winter (see Figure 3). The only information used to extrapolate to 60 km is climatological. One can extrapolate in various ways, but is still left with climatological values above 20-25 km. Since a significant part of the total ozone column is climatological, some of the interannual variability signal is lost. They are essentially analyzing a vertically truncated time series. Sometimes, there is a hint of contradiction: It is stated that "Figure 4 shows that these methods agree well for most of the year", giving the impression the extrapolation methods give similar results. But, then, "The lack of an absolute reference for stratospheric ozone over Greenland make it difficult to choose which method is best. Therefore, the average of the four methods is used for subsequent analysis in this study." There is no justification or validation about the overall extrapolation. The reconstructed ozone column should be evaluated against independent data, which brings us to another critical point. They justify the use of this balloon dataset by claiming that "during winter; many remote sensing instruments for measuring ozone depend on solar radiation". However, several satellite instruments do not rely on sunlight, notably MLS. Why not combine/use these well-established datasets directly, or at least use them to evaluate

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the ozone column reconstructed from climatological extrapolation?

Response: We agree with the Reviewer's comments. In response to the concerns of Reviewer #1 and to answer Reviewer #2's questions, we have eliminated the use of the climatology for constructing the ozone profiles. Instead we have improved the dataset substantially by using ozone retrievals from the Microwave Limb Sounder (MLS) to provide profiles up to 60 km. This has greatly improved the quality of profiles above the burst height of the ozonesondes because we now use MLS data that is nearly coincident in both space and time with the sondes.

Rev\_2\_M2) Second, the multiple regression analysis (MLR) is not clear to me. If I have understood correctly, Table 5 shows the fraction of observed variance explained by a number of proxies. No error bars are provided. I keep telling my students that numbers without error bars do not mean much. In addition, one of the hypotheses in MLR is that proxies are not correlated (aliasing issue). The problem is that some of proxies can sometimes be correlated in short time series, even if they are not physically correlated. In addition, some of the proxies used here are physically correlated (even if in a short time series, they might not be), for example VPSC and EHF or the influence of solar variability on high altitude ozone being dependent on the phase of the QBO etc... There is the need for assessing properly the effects of these possible correlations on the results and to estimate error bars. I would recommend not to use the standard errors (not reliable for short time series) but rather a Monte Carlo approach.

Response: We note that the Reviewer found our discussion of the MLR analysis to be unclear. We have attempted to improve our description of the analysis and our overall approach in our edited manuscript. We believe that these changes have greatly improved the paper. Although stepwise multiple regression (SMR) is commonly used in studies of atmospheric ozone variations (Appenzeller et al, 2000; Brunner et al, 2006; Kivi et al, 2007; Vigouroux et al, 2015; Steinbrecht et al, 2017), we have extended this analysis using the additional Arctic sites. By studying multiple sites, we now identify drivers that are common across this sector of the Arctic, which provides additional

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confidence as to what physical mechanism affect the ozone variations. We have been upfront regarding the correlation between the variables by calculating and discussing the covariance matrix between all of the proxy variables. There are only two variables that have significant correlation between them: the eddy heat flux and the volume of polar stratospheric clouds. Both Brunner et al (2006) and Wohltmann et al (2007) reported this as well and elected to include both variables because they have fundamentally different physical characteristics. As expected, the equivalent latitude (EQL) at 370 K and at 550 K are also correlated, but we avoid any issue with our analysis by not including these variables together; EQL at 370 K is used in the lower two layers of atmosphere, while EQL at 550 K is used in the upper two layers. Because we have chosen to continue to use SMR (based on the multitude of past studies that also have), we have taken the Reviewer's suggestion and report the standard error of our results. These are now listed in the Supplementary Material.

Rev\_2\_M3) Third, the outcome of the study does not warrant publication in a journal like ACP. Let's have a look at the abstract: " The monthly mean total column ozone reaches a maximum of about 400 DU in April, then decreases to minimum values between 275 and 300 DU in the late summer and early fall. The partial column ozone values peak at different times between late winter and early summer." There is nothing new about seasonal variations of polar column ozone. " There is a positive trend in the total column that is likely due to increases in springtime ozone, however, these trends are not robust given the short period of record". There is a trend but they don't know whether it is significant or indicative of something. At the end, I was wondering what a trend analysis of truncated 12-year time series at a specific location can bring? If the aim is to detect ozone recovery, why not use more data over the entire Arctic region? Then, the results of the MLR on individual proxies are presented in the abstract: "This analysis shows that the variations in total column ozone are due primarily to changes in the tropopause pressure, the quasi-biennial oscillation (QBO), and the volume of polar stratospheric clouds. The eddy heat flux is also important for variations in the partial column ozone in the different altitude regions." Again, it is not possible to see

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whether the results obtained at this station are significant because there are no error bars, no such results (with error bars) presented for other stations, no comparisons to satellite-based studies or of other studies, explanations about what the results mean physically. The last sentence illustrates the level of analysis: "The importance of the QBO appears to be a unique characteristic for ozone variations over the Greenland Ice Sheet (when compared to other nearby Arctic Stations) and may be related to the fact that Greenland is particularly sensitive to the phase of the QBO." What does "unique" mean here when compared to 2 other stations only (whose results are not presented and discussed thoroughly)? For the authors, the fact that the QBO is an important driver in the LMR model "may be" related to the fact that Greenland ozone is sensitive to the phase of the QBO. It is self-explanatory, and a bit circular. The authors seem to doubt the MLR results. If ozone was not sensitive to the QBO, it should not appear as significant in the MLR analysis. And, vice-versa. The bottom line is that it is not possible to be conclusive with an MLR over a short time series at a single specific station. This cannot tell us anything new and "robust" about polar ozone.

Response: The aim of this paper is not to detect ozone recovery, but rather to identify important drivers of ozone variations at high-latitude Arctic sites. We report the trends of the time series, but this is not our primary focus. Based on the suggestions of both Reviewers, we have improved the quality of the ozone profiles by using MLS retrievals above the ozonesonde data. Our new Figure 3 shows that the sonde data are quite important and correct a positive bias in the MLS data in the lower atmosphere. Thus, we feel that it is a significant contribution to include the more accurate in situ ozonesonde measurements in the analysis of Arctic ozone. Most of the total column ozone is actually measured by the ozonesondes, and the only layer of partial column ozone that is significantly affected by the MLS retrievals (as opposed to the ozonesonde data) is the upper stratosphere. So we believe that this manuscript is an important contribution because it merges the advantages of both the ozonesonde and the MLS data. As stated above, we agree with the Reviewer that drawing firm conclusions from data at one station is difficult. Therefore, as stated above in Rev\_2\_M2, we now identify

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drivers that are common at the sites. We agree with the Reviewer that our conclusion regarding the effect of the QBO on ozone over Summit, Greenland was weak. However, our new results indicate that the QBO is also important in the troposphere and lower stratosphere at the other Arctic sites that we considered. Table 4 now summarizes all of the drivers that are important at 3 or more sites. It can be seen that different sets of drivers are important in the troposphere (TP, EQL, QBO), the lower stratosphere (EHF, VPSC, QBO) and the middle and upper stratosphere (EHF, EQL, VPSC). We believe that these results present a more complete understanding of ozone variations in this sector of the Arctic, and that the Reviewer's suggestions have greatly improved the overall conclusions of the manuscript.

Rev\_2\_M4) Fourth, there are too many unnecessary details provided in the text. Everybody knows how to calculate an ozone column from a profile, this could end up in an Annex. Some of the explanations are unclear and longwinded, some parts need to be rephrased. All the authors should re-read very carefully the entire manuscript. In summary, as it stands, I find it very difficult to be positive. I find the manuscript very far from being acceptable for ACP. Even after tackling the flaws in the methodology, I can't see what the results can bring in terms of new knowledge.

Response: We agree with the Reviewer that we provided too many details in the original draft; Reviewer #1 mentioned this as well. Therefore in the revised manuscript, we have removed many of the tables and figures. Most of the remaining figures and tables have been updated with results from the additional sites. We believe that the manuscript has been greatly improved by addressing the Reviewer's comments and questions with new results regarding the important drivers of variations in partial and total column ozone at these four high latitude Arctic stations.

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