Reply to review comments from reviewer #1

The paper entitled "Arctic spring and summertime aerosol optical depth baseline from long-term observations and model reanalyses, with implications for the impact of regional biomass burning processes" by Peng Xian and coauthors presents a comprehensive view on long-term measurements and modelling of aerosol optical depth (AOD) in the Arctic. They consider ground-based AERONET sun photometer measurements, observations by three spaceborne instruments, and results from three aerosol reanalyses as well as their composite to investigate (i) the consitency of the different data sets, (ii) the annual and seasonal variation as well as the long-term trend in AOD together with the importance of biomass-burning smoke, and (iii) statistics on the occurrence of extreme AOD events.

While the work is of interest to the readers of ACP, it is far to much material for one publication. This review is late, also because it is impossible to read the manuscript in one sitting. In fact, the content could be split in as much as three papers according to the list of topics provided above. Such an approach would lead to very good papers that could be much more reader-friendly than the current submission. This reviewer therefore recommends to reject the paper in its current form and to re-submit after a thorough revision of content and readibility. Alternatively, the work requires major revisions, shortening, and a decision on which of the three topics to focus in this particular submission.

Reply: We thank the reviewer for the comments on this manuscript. We intend to link remote sensing, ground observations, and reanalyses to provide comprehensive information on the Arctic AOD so that readers can have a consistent picture of the Arctic AOD status. It is known that the Arctic has far fewer observations compared to other regions of the world, so a single dataset or aspect (remote sensing vs modeling) is challenged to provide a true and comprehensive view of the Arctic AOD. We think it is essential to present the reanalyses results along with remote sensing and ground observations so that these complimentary data can be inter-supportive and comprise a rich and reliable picture of Arctic AOD. Surface-based AOD measurements stand for “accuracy”, and satellite products provide “coverage”, while model reanalyses provide information of “aerosol processes” that can help explain what’s observed. We think missing either one of the three components would greatly degrade the strength of the study.

The consistency of the different data sets is discussed in the manuscript with a highlight on the effect of quality control of the remote sensing datasets. We highlight the importance of quality control because our climatological AOD (less than 0.1 near 70N) is quite different from some other studies using off-the-shelf MODIS and MISR products (specifically Tomasi et al., 2015 of AOD value of 0.2 near 70N; our result is more in line with AERONET measurements; see section 6 discussion). The requirement of quality control on the remote sensing data for data assimilation, climate/trend analysis (our case here) purposes is demonstrated in numerous studies (e.g. citations within the manuscript for MODIS, MISR, CALIOP products, Zhang et al., 2006; 2010; 2017; Shi et al., 2011, 2013; Toth et al., 2018; Hyer et al., 2015). So we think quality control is necessary but it does not need to be further addressed as the methods used here are common.

In response to the reviewer’s concern on the length of the manuscript, we have split the manuscript into two separate manuscripts. One focuses on AOD climatology and trend (now

Part 1) and the other focuses on statistics of extreme AODs (now Part 2). Part 1 has 55 pages, including 13 figures and 4 Tables (and references). Part 2 has 34 pages including 10 figures and 3 tables (and references). Part 1 is similar to the original manuscript, except for the removal of the extreme AOD events and with marginal changes incorporating reviewers' and coauthors' comments. Part 2 focuses on extreme AOD events and with four additional figures and one additional table providing in-depth analyses of extreme AOD events (e.g., the geographical distribution of AODs at the 95th percentiles, a figure illustrating the trend of extreme AOD events). The added table (Table 1) is to provide AERONET site information and basic AOD statistics (similar to Part 1). We thank the reviewer's suggestion for splitting the paper into more than 1 papers.

Please find some more specific comments below:

- The paper is rather lengthy and would benefit from trimming the text and content to what's really needed. A start would be a shorter title such as, e.g. to Arctic spring and summertime aerosol optical depth baseline from long-term observations and model reanalyses.

Reply: The paper is split into two manuscripts as mentioned above. The titles are shorter than before.

- Entire paragraphs could be omitted as they are repeating points made earlier or are just redundant, e.g. lines 24-31 (not needed in the Abstract), 141-148, 176-182, 299-303 (why mention if the statement end with "is not used here"),...

Reply: Line 24-31: We think the inclusion of the discussions in the abstract is a personal preference. We prefer abstracts to be stand-alone with sufficient info for readers. Therefore, we kept the discussions in the abstract.

Line 141-148: The advantage of high temporal resolution biomass burning emissions used in the aerosol reanalyses was mentioned in two places in the manuscript: One in the introduction (listed line numbers), and the other in the discussion. We'd really like to highlight this point so we've kept it in the introduction as well as in the discussion.

Line 176-182, 299-303: These lines are removed following the reviewer's suggestion.

- The entire part about FLAMBE (description and results) could be omited. In fact, the point made here could be condensed down to something along the lines of "findings are also supported by burning emissions from FLAMBE" later in the discussion.

Reply: The FLAMBE biomass burning (BB) emission climatology and the trend, which are derived based on satellite observations, are a critical data source for revealing changes in BB aerosol patterns in the Arctic region. Thus, we would like to include an introduction of FLAMBE for the benefit/convenience of readers. The FLAMBE-related information is only one figure and it is kept in the manuscript.

- There are way too many figures for one publication. In addition, some information in these figures could be moved to the supplement to improve the discussion of the findings. For instance, the main figures could stick to the Multi-Reanalysis Concensus and their discussion could link to more detailed figures including the specific findings of the three models in the

supplement. The authors should re-evaluate if a figure that isn't thoroughly discussed in the text is needed in the manuscript.

Reply: See our reply to the first comment on the length of the manuscript. Regarding the usage of reanalyses, many of the figures contain AOD information from all three reanalyses and their consensus, because we intend to show the diversity and similarity of these reanalyses and avoid the consensus being dominated by any specific reanalysis product. We think this makes our result more convincing while providing information for readers interested in the difference of the reanalyses. We think every figure is discussed thoroughly except for some aspects that are supportive of other results in the manuscript (where we stated something like, for example, for the trend in reanalyses “consistent with the trend in remote sensing AOD”).

- The study makes use of height-resolved measurements from CALIOP and considers detailed aerosol re-analyses fields. The work would be even stronger of this information was to be used to also investigate the vertical distribution of Arctic aerosols. Such an attempt would partly compensate for the disadvantage of AOD to refer to column aerosol load.

Reply: As the reviewer commented earlier, the current manuscript is already long, so we prefer to focus on AOD only for this submission. We mentioned that the vertical distribution of aerosols for extreme events “is the topic for another manuscript” in the original submitted manuscript. We are working on that aspect and will report our findings in another manuscript. Thank you.

Reply to review comments from reviewer #2

"Artic spring and summertime aerosol optical depth baseline from long-term observations and model reanalyses, with implications for the impact of regional biomass burning processes" by Xian et al. takes a multi-sensor/dataset approach to characterizing Arctic aerosols climatologically and their trends over the past almost two decades. These results are interpreted geographically, seasonally, as well as by aerosol species and instrument sensors.

In general, my recommendation to the editor is minor revisions for this publication. While I am not familiar with all the literature out there on Arctic aerosols, this study seems to be quite comprehensive, which provides value in characterizing Arctic aerosols from many different angles across the entire region. However, there were a few scientific and presentation matters that should be addressed prior to publication.

Reply: We thank for the reviewer's comments, which we think helps to improve the clarity and presentation of the manuscript.

For the AERONET data, I wonder about how the availability of AERONET data plays out when using a 6-hour averaging interval. AERONET data is primarily a daytime measurement, therefore it is affected by the changing of daylight. For example, if there are more measurements closer to summer solstice because of daylight hours, does that impact the results? I am not sure how that would play out on the results here but see Appendix B of "The Diurnal Variation of the Aerosol Optical Depth at the ARM SGP Site" by Balmes et al. (2021, Earth and Space Science; doi.org/10.1029/2021EA001852) which showed that the changing of the season affected the diurnal cycle of AOD when considering AERONET measurements. Since AERONET is the basis for much of the comparison in this study, the averaging interval should be carefully considered to ensure the conclusions are not artifacts of data availability.

Reply: AERONET data is more available during summer than in springtime due to longer daylight. This is reflected in the difference of the total number of observations for JJA and MAM in Table 1. We expect some impact of summer vs spring sampling on the annually-averaged diurnal variation of the AOD if there is baseline AOD change between the two seasons (e.g. much higher summer AOD than spring AOD as shown in Appendix B of Balmes et al. (2021)). However diurnal variation of the AOD is not the focus of this manuscript, nor is the annual-mean diurnal cycle (actually, spring- and summer-averaged diurnal cycles would help avoid those spring vs summer sampling influences on the annually-averaged diurnal cycle). Nevertheless, we performed resampling of AERONET AOD data to demonstrate that our result is changed little by 6hrly vs daily sampling. Most of the Arctic AERONET sites have stable numbers of observations between 6-18hr local time (i.e., magnitude of the number of observations are stable between 6-18hr, while it drops at some earlier or later hours): so we generated AERONET daily AOD statistics with data restricted to 6-18hr local time. A supplemental table was produced to enable a direct comparison of Table 1 with the

6hrly statistics. The following text is added in section 2.4 AERONET AOD data introduction:

"To explore the potential impact of different temporal sampling on the result (e.g., Balmes et al., 2021), we generated AERONET daily AOD statistics (Table S1) to enable a direct comparison of Table 1 with the 6hrly statistics. In general, the mean and median of MAM or JJA AODs (including total, FM and CM AODs) at the ten AERONET sites change very slightly (mostly 0.00, or <=0.01). As expected, the standard deviation is smaller for the daily AOD case than for 6hrly AOD (due to temporal averaging)."

Table S1. Analogous table to Table 1 but using daily AOD statistics. The AERONET daily AOD statistics was generated with data restricted to 6-18hr local time when there are stable numbers of observations (i.e., magnitude of the number of observations are stable between 6-18hr, while it drops at some earlier or later hours).

sites	latitude	longitude	elevation (m)	region	MAM (mean|median|std)				MAM FMF		JJA (mean|median|std)				JJA FMF	
					total AOD	FM AOD	CM AOD	n	mean	median	total AOD	FM AOD	CM AOD	n	mean	median
Hornsund	77.0N	15.6E	12	Svalbard	0.10|0.09|0.05	0.07|0.06|0.04	0.03|0.02|0.03	215	0.72	0.76	0.08|0.06|0.07	0.06|0.04|0.07	0.02|0.01|0.02	302	0.76	0.81
Thule	76.5N	68.8W	225	Greenland	0.09|0.07|0.05	0.06|0.06|0.03	0.03|0.01|0.04	324	0.76	0.81	0.07|0.05|0.08	0.06|0.04|0.08	0.01|0.01|0.02	464	0.85	0.87
Kangerlussuaq	67.0N	50.6W	320	Greenland	0.07|0.06|0.03	0.05|0.04|0.02	0.02|0.02|0.02	295	0.69	0.72	0.07|0.05|0.05	0.05|0.04|0.04	0.01|0.01|0.02	476	0.77	0.82
Ittoqqortoormiit	70.5N	21.0W	68	Greenland	0.06|0.06|0.03	0.04|0.04|0.02	0.02|0.01|0.03	193	0.72	0.78	0.06|0.04|0.04	0.05|0.03|0.04	0.01|0.01|0.02	369	0.80	0.84
Andenes	69.3N	16.0E	379	Norway	0.09|0.07|0.06	0.05|0.04|0.04	0.03|0.02|0.04	226	0.67	0.72	0.08|0.06|0.05	0.06|0.05|0.05	0.02|0.01|0.02	331	0.75	0.79
Resolute_Bay	74.7N	94.9W	35	Canada	0.10|0.09|0.05	0.07|0.06|0.03	0.03|0.02|0.03	173	0.72	0.74	0.07|0.05|0.09	0.06|0.04|0.09	0.02|0.01|0.02	371	0.78	0.83
Barrow	71.3N	156.7W	8	Alaska	0.12|0.09|0.10	0.08|0.06|0.07	0.04|0.02|0.06	158	0.69	0.74	0.09|0.06|0.09	0.07|0.05|0.09	0.02|0.01|0.02	335	0.79	0.82
Bonanza_Creek	64.7N	148.3W	353	Alaska	0.11|0.07|0.09	0.06|0.04|0.07	0.04|0.02|0.04	297	0.64	0.65	0.18|0.09|0.27	0.16|0.06|0.26	0.02|0.02|0.02	445	0.78	0.82
Tiksi	71.6N	129.0E	17	Siberia	0.09|0.10|0.03	0.07|0.07|0.02	0.03|0.02|0.02	13	0.73	0.78	0.13|0.08|0.19	0.11|0.07|0.18	0.02|0.01|0.02	139	0.81	0.85
Yakutsk	61.7N	129.4E	119	Siberia	0.15|0.11|0.15	0.11|0.08|0.13	0.04|0.02|0.06	517	0.73	0.77	0.17|0.09|0.23	0.14|0.07|0.23	0.02|0.01|0.03	748	0.81	0.84

An additional scientific issue I wonder about is that the CALIOP data only considers AODs greater than zero. Do other studies do this with CALIOP data? While there are instrument sensitivity limitations that preclude detecting all aerosols, leaving out when AOD=0 will artificially increase the mean AOD to a value not actually observed by the instrument. It is well documented that CALIOP cannot detect all aerosols and clouds and several of studies are cited in this reference, however, perhaps it would be more representative of the data to also include figures and data if AOD=0 is considered for CALIOP. Another option is the Level 3 AOD product which attempts to overcome the sensitivity issue. This data product is mentioned in the discussion but perhaps more discussion or a supplementary figure showing the various CALIOP AOD results from different data products and thresholds would be more representative of the instrument and data products.

Reply: We have now included more discussions in section 6 about the CALIOP AOD data used in the study and provided a supplemental figure (Fig. S2 in Part 1; also attached at the end of this reply document for your convenience) to help the comparison between the analysis with AOD=0 retained and removed. The artificial AOD value of zero is known by the CALIOP developing team and we are also well aware of the issue. We are hesitated to include AOD=0 into our study because those air columns with

AOD=0 from CALIOP actually represent air columns where CALIOP are blind to aerosol particles. Based on the paper first authored by Travis Toth (Toth et al., 2018), who is a coauthor of this paper, those air columns could have corresponding AOD (532 nm) of 0 to 0.1 or higher based on AERONET data. Giving the relative low mean AODs over or near the Arctic region, adding those air columns may likely introduce a low bias in climatological mean of AOD over the study region.

Toth T.D., J.R. Campbell, J.S. Reid, J.L. Tackett, M.A. Vaughan, and J. Zhang, Minimum Aerosol Layer Detection Sensitivities and their Subsequent Impacts on Aerosol Optical Thickness Retrievals in CALIPSO Level 2 Data Products, Atmos. Meas. Tech., 11, 499-514, https://doi.org/10.5194/amt-11-499-2018, 2018.

Our expanded discussion regarding this aspect in section 6 reads
"Often artificial AOD value of zero are observed over the Arctic in CALIOP V4.2 L2 and L3 data, resulted partially from algorithmically setting altitude bins with retrieval filled values in the aerosol profile to zero, as these represent undetectable levels of faint aerosol (i.e.,Toth et al., 2016; 2018). With AOD=0 values retained in the CALIOP V4.2 L2 data analysis (same processing in CALIOP V4.2 L3), the climatological seasonal mean AOD magnitude is much smaller (about half) than that shown in Fig. 3 and the AOD trends are slightly smaller than those in Fig. 9, although the spatial patterns of the seasonal AOD and trends are similar to those obtained with AOD data after removing the AOD=0 values (Fig. S4). After removing the pixels with filled and zero values, CALIOP AOD seasonal spatial AOD distributions are similar to those from MODIS and MISR. "

Below are minor comments I had and typos I found while reviewing:
Minor Comments:

The title is really long. Perhaps it should be shortened for brevity.
Reply: We think the current title represent the essence of the study and express the important implications for biomass burning processes, which we are really reluctant to remove.

Lines 138-139: "We define the Arctic/high-Arctic as regions north of 60°N/70°N, and sub-Arctic as regions between 60°N-70°N." It took me a second read through to understand this correctly. Since it is a definition sentence, it seems worth it to make it two sentences or edit it for clarity.
Reply: We have revised the statement to "We define the Arctic and the high-Arctic as regions north of 60°N and 70°N respectively. The lower-Arctic is defined as regions between 60°N-70°N.". We also changed all "sub-Arctic" to "lower-Arctic".

Data section: there is quite a lot of data used in this section so it leaves the reader a little overwhelmed to read through as well as to reference later on in the paper. Perhaps a table listing all the data described would be a useful summary to reference?
Reply: We have added the following table in the Appendix A and appended in the first paragraph of the data section "A summary of the datasets is provided in Appendix A."

Products	Data	resolution	time
MODIS (Moderate Resolution Imaging Spectroradiometer) C6.1L3	550nm AOD	1°x1° monthly	2003-2019
MISR (Multi-angle Imaging SpectroRadiometer) V23	558nm AOD	1°x1°, monthly	2003-2019
CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarisation) V4.2L2	532nm AOD	2°x5°, monthly	2006-2019
AERONET (AErosol RObotic NETwork) V2L3	SDA total, FM, CM AOD at 550nm	6hrly, monthly	2003-2019
MAN (Marine Aerosol Network) Level2	SDA total, FM, CM AOD at 550nm	6hrly, monthly	2003-2019
MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, v2)	Total and speciated AOD at 550nm	0.5°lat x0.63°lon, monthly	2003-2019
CAMSRA (Copernicus Atmosphere Monitoring Service Reanalysis)	Total and speciated AOD at 550nm	0.7°x0.7°, monthly	2003-2019
NAAPS-RA v1 (Navy Aerosol Analysis and Prediction System reanalysis v1)	Total and speciated AOD at 550nm	1°x1°, 6hrly, monthly	2003-2019
MRC (Multi-Reanalysis-Consensus)	Total and speciated AOD at 550nm	1°x1°, monthly	2003-2019
FLAMBE (Fire Locating and Modeling of Burning Emissions) v1.0	BB smoke emission flux	1°x1°, monthly	2003-2019

Note: These are final form of data used in the result section. Some pre-processing and quality-control were applied to remote sensing data as described in the data section.

Figure 1: "Warm colors represent fine mode and cool colors represent coarse mode." I think this should be more explicit to avoid confusion, e.g., "warm colors (red, orange, and pink) … cool colors (green and blue)"
Reply: Revised.

Line 765: "(i.e. the square …" should have a comma after the i.e
Reply: Corrected.

Line 989-997 and throughout: I think "95% percentile mark" should be "95$_{th}$ percentile mark"? 95% percentile sounds redundant
Reply: Revised accordingly.

Figure 16: I think there may be a typo in the caption as it says 12 September 2012 after August 5, 2021?
Reply: Thanks for capturing this typo. It is corrected.

Line 1078: "black colors, respectively"
Reply: Revised.

Line 1124: figures should be capitalized
Reply: Revised.

Line 1134: Does the parenthesis starting "(e.g. …" go all the way to line 1139? I think this should be rewritten, very challenging to make sense of a 5 line parentheses
Reply: We have broken this into two sentences to make it easier to read.

Line 1134 and 1143: should have a comma after e.g. I think this might be an issue throughout for i.e. and e.g. so check throughout the text
Reply: Thanks! This is corrected throughout the text.

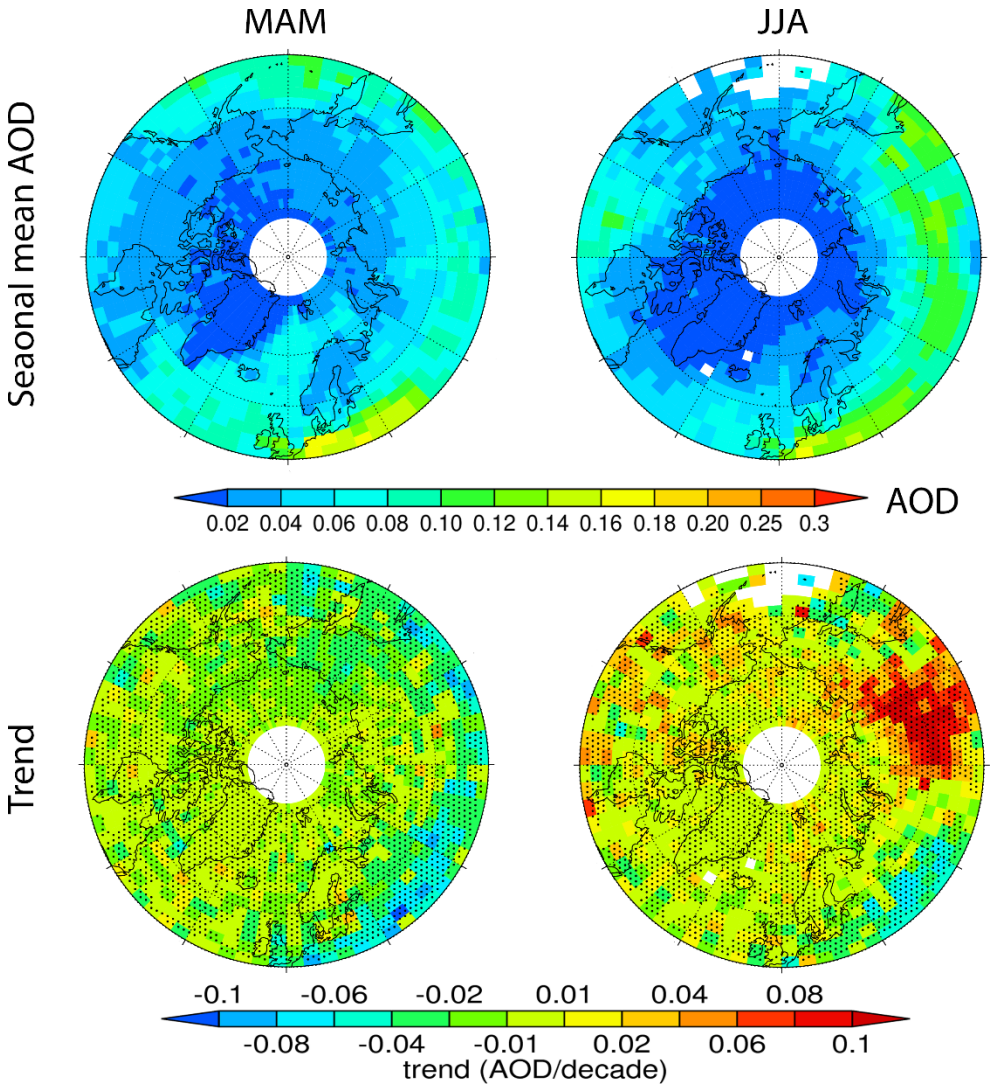

Figure S2. CALIOP mean climatological MAM (upper-left) and JJA (upper-right) AOD at 532 nm (2006-2019) and AOD trends (lower) derived with AOD=0 values retained in the CALIOP V4.2 L2 data analysis, to compare with CALIOP AOD seasonal climatology and trends derived with AOD=0 values removed in Fig. 3 and Fig. 9. White area means lack of data.